ISSN: 2588-5596

JGT

Journal of Gas Technology

Volume 10 . Issue 1 . Summer 2025 . www.jgt.irangi.org



Journal of Gas Technology, JGT

Volume 10, Issue 1, Summer 2025

Publisher
Iranian Gas Institute

Director-in-Charge
Mohammadreza Omidkhah

Editor-in-Chief
Ali Vatani

Deputy Editor
Hedayat Azizpour

Associate Editor
Mastaneh Hajipour

Executive Manager
Hamidreza Karimi

Editorial Board Members
Ali Vatani, University of Tehran
Mohammadreza Omidkhah, Tarbiat Modares University
Mohamadreza Jafari Nasr, Research Institute of Petroleum Industry
Vahid Taghikhani, Sharif University of Technology
Mahmood Moshfeghian, Oklahoma State University
Mojtaba Shariati Niasar, University of Tehran
Reza Mosayebi Behbahani, Petroleum University of Technology
Rahbar Rahimi, University of Sistan and Baluchestan
Seyed Hesam Najibi, Petroleum University of Technology
Seyed Alireza Tabatabaei-Nezhad, Sahand University of Technology
Riyaz Kharrat, Petroleum University of Technology
Toraj Mohammadi, Iran University of Science and Technology
Seyed Reza Shadizadeh, Petroleum University of Technology
Bahman Tohidi, Heriot-Watt University
Fariborz Rashidi, Amirkabir University of Technology
Masoud Soroush, Drexel University - United States
Mahmoud Jamiolahmady, Heriot-Watt University Institute, Scotland
Amir Hossein Mohammadi, University of KwaZulu-Natal, South Africa

Technical Editor
Masoud Aghajani & Mortaza Zivdar

Layout
Hamidreza karimi

Cover Design
Hamidreza karimi

Contact Information
https://jgt.irangi.org
Email: ijgt.igi@gmail.com

EISSN: 2588-5596

Open Access Journal
Journal of Gas Technology is a peer reviewed, open access journal.

JOURNAL OF GAS TECHNOLOGY

Volume 10, Issue 1, Summer 2025

Annual Names of Reviewers

Ali Vatani
University of Tehran

Mastaneh Hajipour
Islamic Azad University, Science and Research Branch

Saeid Jamshidi
Sharif University of Technology

Hedayat Azizpour
University of Tehran

Morteza Zivdar
University of Sistan and Baluchestan

Mohammad Ahmadi
Amirkabir University of Technology

Masoud Aghajani
Petroleum University of Technology

Helma Vakili
University of Tehran

Ali Palizdar
University of Tehran

Laleh Shirazi
Research Institute of Petroleum Industry

Masoud Dorfeshan
Behbahan Khatam Alanbia University of Technology

Saman Jahanbakhshi
University of Tehran

Mahdi Razavifar
University of Tabriz

Robabeh Nasirian
Islamic Azad University, North Tehran Branch

Saeed Abbasi
Research Institute of Petroleum Industry

Zahra Nargessi
University of Tehran

Masoud Bijani
Garmsar University

Mostafa Jafari
University of Tehran

Ahmadreza Andarz
University of Tehran

Table of Contents

Analysis of the Role of Insurance in Reducing Investment Risks and Development of the Liquefied Natural Gas Industry in Iran 5

Mohammad Reza Alimardan, Mohammad Reza Seyed Hashemi Toloun, Abbas Kazemi Najafabadi

Techno-Economic and Sensitivity Analysis of Natural Gas Liquefaction Using the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle 22

Sahar Arshtabar, Mojtaba Biglari, Mohammad Sadegh Valipour

A Comprehensive Review and Simulation-Based Assessment of Pressure Enhancement Techniques in Gas Reservoirs 42

Yasin Khalili, Saeed Abbasi

Selective Removal of Sulfur Dioxide from Oxygen Using Porous Iron: A Molecular Dynamics Study 69

Mostafa Jafari, Mohammad Mahdi Yousefi, Ali Vatani, Roozbeh Sabetvand

Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry 87

Yasin Khalili, Mohammad Ghader Zahiri, Mohammadreza Akbari, Mostafa Keshavarz Moraveji

JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 1 / Summer 2025 / Pages 5-21

Journal Home page: https://jgt.irangi.org

Analysis of the Role of Insurance in Reducing Investment Risks and Development of the Liquefied Natural Gas Industry in Iran

Mohammad Reza Alimardan[1], Mohammad Reza Seyed Hashemi Toloun[2], Abbas Kazemi Najafabadi[3*]

1. Ph.D. Student, Department of Law and Political Science, Faculty of Law, Allameh Tabataba'i University, Tehran, Iran
2. Assistant Professor, Department of Management, Sohrevardi Institute of Higher Education, Qazvin, Iran
3. Associate Professor, Department of Law and Political Science, Faculty of Law, Allameh Tabataba'i University Tehran, Iran

ARTICLE INFO

ORIGINAL RESEARCH ARTICLE

Article History:
Received: 26 May 2025
Revised: 09 August 2025
Accepted: 20 August 2025

Keywords:
Insurance
Investment Risks
Liquefied Natural Gas (LNG)
Industrial Development
Iran

DOR: 20.1001.1/jgt.2025.2059173.1056

ABSTRACT

The liquefied natural gas (LNG) industry, as one of the key sectors in global energy supply, plays a significant role in economic development and energy security. However, investment in this industry faces numerous risks, including global price fluctuations, technical challenges, environmental issues, and political uncertainties. Insurance, as an effective risk management tool, can play a crucial role in mitigating these risks and facilitating investment in the LNG industry. This research analyzes the role of insurance in reducing investment risks and developing Iran's liquefied natural gas industry. Using analytical methods and case studies, the impact of various insurances, such as liability insurance, property insurance, and credit insurance, on reducing investment risks in this industry is examined. The results of this study indicate that insurance can enhance the attractiveness of investments in the LNG industry by covering financial and operational risks, thereby contributing to the sustainable development of this industry in Iran. Additionally, recommendations are provided to improve insurance frameworks and government support policies to faster further growth of this industry in the future. The most important recommendations in normal conditions (No war, Sanction and other limitations) include: 1) Strengthening insurance frameworks to cover specific risks of the LNG industry, 2) Encouraging the participation of international insurance companies through consortiums, 3) Establishing investment guarantee funds, 4) Formulating supportive government policies, 5) Enhancing regional and international cooperation, 6) Developing secondary markets for risk transfer, 7) Educating and empowering stakeholders, 8) Establishing transparent and sustainable laws and regulations, 9) Developing insurance infrastructure, and 10) Continuous evaluation and updating of policies.

How to cite this article
M.R. Alimardan, M.R. Syed Hashemi Toloun, A. Kazemi Najafabadi. Analysis of the Role of Insurance in Reducing Investment Risks and Development of the Liquefied Natural Gas Industry in Iran. Journal of Gas Technology. 2025; 10(1): 5-21. (https://jgt.irangi.org/article_731919.html)

* Corresponding author.
E-mail address: kazemi_najaf@atu.ac.ir, (A. Kazemi Najafabadi).

Available online 22 September 2025
2588-5596/© 2016 The Authors. Published by Iranian Gas Institute.
This is an open access article under the CC BY license. (https://creativecommons.org/licenses/by/4.0)

1. Introduction

The liquefied natural gas (LNG) industry, as one of the most important energy sectors in the world, plays a key role in meeting energy needs and reducing dependence on traditional fossil fuels. With one of the largest natural gas reserves globally, Iran has significant potential for developing this industry. However, investment in this sector faces numerous challenges and risks that could limit its development. In this context, insurance, as an important risk management tool, can effectively reduce these risks and facilitate the investment process. Insurance provides the necessary security by covering those financial, technical, environmental, and political risks, thereby creating the groundwork for attracting domestic industries such as steel, Cement, ... and foreign capital in the liquefied natural gas industry, (Generally for export). This not only contributes to the sustainable development of the industry but can also lead to the country's economic growth and increase Iran's share in the global liquefied natural gas market in normal (No war, Sanction and other limitations) conditions. The aim of this research is to analyze the role of insurance in reducing investment risks and developing Iran's liquefied natural gas industry. In this regard, it examines the types of risks present in this industry, the role of insurance in managing these risks, and its impact on attracting investments and fostering industrial development. It is hoped that the results of this study will assist policymakers, investors, and players in Iran's LNG industry in utilizing insurance tools to take effective steps toward developing this industry and strengthening Iran's position in the global gas market.

2. Problem Statement

The liquefied natural gas (LNG) industry, as one of the most important energy sectors in the world, plays a vital role in providing sustainable energy and reducing greenhouse gas emissions (EIA, 2021). With approximately 17% of the world's natural gas reserves, Iran has immense potential to become one of the main players in the global LNG market (BP Statistical Review, 2022). However, the development of this industry requires massive and long-term investments that come with numerous risks, including financial, technical, environmental, and political risks (IEA, 2020). Financial risks arising from gas price fluctuations in global markets, technical risks related to the complexity of extraction and processing technologies, and environmental risks stemming from potential pollution are among the challenges facing investors in this industry (World Bank, 2019). Additionally, political risks and international sanctions can hinder the attraction of foreign investment and technology transfer to Iran (IMF, 2021). In this context, insurance, as an effective risk management tool, can play a key role in reducing these challenges. Insurance provides the necessary security for investors by covering financial, technical, and environmental risks, facilitating the attraction of domestic and foreign investments (Cummins & Weiss, 2013). However, the main question is how insurance can help reduce investment risks in Iran's LNG industry and what impact it will have on the development of this industry? Currently, Iranian insurance companies lack the full capacity to cover large LNG projects due to their financial, technical, and sanction-related limitations. However, with the development of insurance infrastructure, increased international cooperation, and reduced sanctions, these companies can gradually build their capacity to cover such risks. To achieve this goal, government support and appropriate policies in the fields of insurance and energy are needed. This research seeks to analyze the role of insurance in reducing investment risks and developing Iran's liquefied natural gas industry. By examining the various risks present and the role of insurance in managing them, this study aims to provide solutions to facilitate investment and ensure the sustainable development of this industry.

3. Literature Review

The advancement of Iran towards investment and capital attraction for launching Liquefied Natural Gas (LNG) production projects not only contributes to increasing Iran's share in the global gas market and creating sustainable foreign exchange revenues but also leads to the development of energy infrastructure, reduction of flaring, attraction of foreign investment, enhancement of energy security, and job creation. These actions can aid in sustainable economic growth and improve social welfare in Iran. In this regard, Iran must move towards providing the necessary insurance infrastructure to attract domestic and foreign investments into LNG production projects. Overall, insurance infrastructures can reduce investment risks and create favorable conditions for sustainable development and capital attraction, thereby strengthening national industries and the economy. On the other hand, the liquefied natural gas (LNG) industry, due to its strategic importance in the global energy market, has been the subject of extensive research. Previous studies have predominantly focused on the technical, economic, and environmental aspects of this industry, while the role of insurance in reducing investment risks and developing this sector has received less attention. This section references some studies related to the current research topic.

3.1. Studies Related to Risks in the LNG Industry

3.1.1. Main Reasons for the Importance of Studies Related to LNG Industry Riskse

Studies related to risks in the LNG industry are important for several reasons. These studies not only help in better understanding the challenges facing this industry but also provide solutions for managing these risks, which can lead to the sustainable and successful development of LNG projects. Studies related to LNG industry risks play a crucial role in identifying, understanding, and managing risks, reducing uncertainty for investors, developing risk management strategies, supporting sustainable development, enhancing competitiveness, and aiding macro-policy formulation. These studies not only contribute to the success of LNG projects but also assist in the economic and sustainable energy development of countries. The following outlines the reasons for the importance of these studies:

1. Identification and Understanding of Risks: Studies related to LNG industry risks help identify various financial, technical, environmental, and political risks. This identification is the first step in effective risk management. For example, fluctuations in gas prices in global markets and high investment costs are among the financial risks that can impact project profitability (EIA, 2021).
2. Reducing Uncertainty for Investors: Investing in LNG projects, due to their large scale and high costs, involves significant uncertainties. Studies related to risks help investors better understand these uncertainties and use risk management tools such as insurance to create more security for their investments (Cummins & Weiss, 2013).
3. Development of Risk Management Solutions: Studies related to LNG industry risks assist in developing practical solutions for managing these risks. For instance, using specialized insurance, establishing investment guarantee funds, and collaborating with international companies can help reduce financial and technical risks (World Bank, 2019).
4. Support for Sustainable Development: The LNG industry faces environmental challenges such as greenhouse gas

emissions and water pollution. Studies related to risks help identify and manage these challenges, thereby contributing to the sustainable development of this industry (IEA, 2020).

5. Enhancing Competitiveness in the Global Market: Given the intense competition in the global LNG market, effective risk management can enhance the competitiveness of countries in this industry. For example, countries like Qatar and Australia have strengthened their positions in the global LNG market by utilizing risk management strategies (BP Statistical Review, 2022).
6. Support for Macro-Policy Formulation: Studies related to LNG industry risks assist policymakers in formulating policies and regulations that support the development of this industry and reduce associated risks. These studies can serve as a basis for major decision- making in the energy sector (IMF, 2021).

3.2. Identified Risks in Research Literature for the LNG Industry

The identified risks in research literature for the Liquefied Natural Gas (LNG) industry encompass various types of risks that can be categorized into four main groups. These risks can individually or collectively impact the development process of the LNG industry, making their identification and management highly significant:

1. Financial and Economic Risks: These risks relate to fluctuations in natural gas prices and changes in market supply and demand. Unexpected price changes can directly affect the profitability of LNG projects (Zhang & Yang, 2019). Studies show that LNG projects face significant financial risks, including price volatility in global markets and high investment costs (EIA, 2021; IEA, 2020; World Bank, 2019). These risks can influence investment returns and increase the need for risk management tools such as insurance. Additionally, financial risks are related to difficulties in project financing and changes in interest rates. Financing LNG projects presents specific challenges due to high initial costs and risks associated with investment returns (Cohen, 2020).
2. Technical and Operational Risks: LNG projects, due to the complexity of the technologies used, face numerous technical and operational risks. Studies, such as the report by the International Energy Agency (IEA, 2020), indicate that these risks can lead to project delays and increased costs. These risks pertain to technical and implementation issues, including equipment failures, inadequate maintenance, and delays caused by logistical problems. Such factors can reduce efficiency and increase costs (Nguyen et al., 2020).
3. Environmental Risks: The LNG industry confronts environmental challenges such as greenhouse gas emissions and water pollution. The World Bank (2019) emphasized in its report that managing these risks requires precise policies and financial tools like insurance.
4. Legal and Regulatory Risks: Changes in national and international laws and regulations can significantly impact the LNG industry. Uncertainty regarding energy and environmental policies may also influence investment decisions (Hassan & Ahmed, 2021).
5. Risks Related to Sanctions and Specific Political, Economic, International, and Geopolitical Conditions of Iran: Current conditions in Iran, rising tensions, intensified competition among Persian Gulf countries in their oil industry development, lack of surplus gas in Qatar's

North Dome field, international sanctions on Russia, and the uncertain future of the Ukraine-Russia war are among the factors affecting the willingness and presence of insurance companies in developing Iran's LNG industry.

3.3. Identified Risks in Research Literature for the LNG Industry

Studies related to the role of insurance in the energy industry, particularly in different fields of gas, oil, and renewable energy, highlight the high importance of insurance in reducing investment risks and increasing attractiveness for investors (Cummins & Weiss, 2013; World Bank, 2019; IEA, 2020). Below are some of these studies:

1. Insurance as a Risk Management Tool: Studies such as the research by Cummins and Weiss (2013) demonstrate that insurance can serve as an effective tool for managing financial and operational risks in the energy industry. These studies emphasize that insurance, by covering unexpected risks, provides the necessary security for investors. Some studies have examined the experiences of leading countries in the LNG industry, such as Qatar and Australia. These studies show that the use of specialized insurance and collaboration with international insurance companies has played a significant role in reducing investment risks and developing this industry (BP Statistical Review, 2022). In another study by Khan and colleagues (2019), it was shown that insurance can help reduce capital costs and provide necessary guarantees for entering large energy projects. The study emphasized that without appropriate insurance, investing in large energy projects involves high risks.
2. Insurance as a Tool for Attracting Foreign Investments: Zhou and colleagues (2020) stated in their research that the availability of appropriate insurance can play a crucial role in attracting foreign investments in the energy sector, especially in developing countries. They emphasized that insurance guarantees can increase the confidence of foreign investors and reduce barriers to market entry.
3. Insurance as a Tool for Managing Operational Risks: Another study shows that insurance can play a significant role in managing operational risks in the energy industry. Liu and colleagues (2018) demonstrated that insurance can reduce costs resulting from unforeseen accidents and equipment failures, aiding in operational continuity and reducing downtime.
4. Insurance as a Tool for Supporting Renewable Energy Projects: In the field of renewable energy, Shah and colleagues (2021) highlighted the role of insurance in supporting renewable energy projects. According to this study, insurance can assure investors that damages will be compensated in case of problems, which can accelerate the development of green projects. Overall, insurance in the energy industry not only helps reduce risks and increase investment security but also contributes to the sustainable development and economic growth of this sector.

3.4. Research Gaps in the Role of Insurance in Reducing Investment Risks and Developing Iran's Liquefied Natural Gas (LNG) Industry

Despite extensive studies on the LNG industry and the role of insurance in risk management, limited research has focused on the role of insurance in developing this industry in Iran (IEA, 2020; World Bank, 2019; IMF, 2021). In particular, the impact of insurance on

attracting domestic and foreign investments in Iran's LNG sector and the challenges faced by domestic insurance companies in covering the risks associated with this industry require further investigation (Central Insurance of Iran, 2022; World Bank, 2019; IEA, 2020). This study aims to fill these research gaps by providing a better understanding of the role of insurance in developing Iran's LNG industry. The following outlines the key research gaps:

1. Lack of Local Case Studies: In general, there is a scarcity of studies examining the impact of insurance on Iran's liquefied natural gas industry. Most studies focus on general outcomes of insurance and its role in the energy sector but do not provide specific data about the Iranian market. This lack of information can hinder a comprehensive understanding of how insurance affects the development of the LNG industry in Iran (Gholami et al., 2021). Existing studies primarily focus on general risks in the LNG industry and pay insufficient attention to Iran- specific risks, such as international sanctions, limited access to advanced technologies, and domestic environmental challenges (IMF, 2021). These risks significantly impact investment attraction and the development of Iran's LNG industry.
2. Limited Studies on Domestic Insurance Companies: Although some studies have explored the role of insurance in the energy sector, few have examined the capacities and challenges of domestic insurance companies in Iran in covering the risks of LNG projects (Central Insurance of Iran, 2022). This issue is particularly important given the financial limitations and international sanctions imposed on Iranian insurance companies.
3. Lack of Analysis on Legal and Regulatory Frameworks: Many studies have examined the role of insurance in the energy sector but have not adequately addressed the legal and regulatory frameworks that interact with insurance in Iran's LNG industry. Understanding the impact of restrictive or facilitating laws and regulations on insurance and investment in this sector is especially significant (Rezazadeh & Zare, 2020).
4. Cultural and Social Analysis: Research related to the role of insurance in reducing investment risks generally focuses on economic and technical aspects, while less attention has been paid to cultural and social factors that may influence the acceptance of insurance in the LNG industry. Understanding these factors can help improve insurance and investment strategies (Mohammadi & Aghaei, 2022).
5. Diversity of Insurance Products and New Offerings: There has been no detailed analysis of the diversity of existing insurance products and the specific needs of Iran's LNG industry. Developing insurance products specifically designed to cover the unique risks of this industry can help attract more investments (Jafari & Tavakoli, 2021).
6. Lack of Practical Solutions for Developing the Insurance Industry: Existing studies often describe risks and the role of insurance but do not provide practical solutions for developing the insurance industry in Iran and enhancing its ability to cover the risks of LNG projects (IEA, 2020). This research gap requires further exploration.

3.4.1. Addressing Research Gaps in the Current Study

This research focuses on the role of insurance in reducing investment risks and developing Iran's LNG industry, addressing several key research gaps. Not only does it

contribute to a better understanding of how insurance impacts investment attraction and risk management, but it also provides practical solutions for developing the insurance industry and enhancing its capacity to cover major risks. The following aspects of the research gaps will be addressed:

1. Impact of Insurance on Attracting Domestic and Foreign Investments: This study analyzes the role of insurance in increasing the attractiveness of LNG projects for domestic and foreign investors. Given the lack of research in this area, the current study can help better understand how insurance can be used as a tool to reduce financial and political risks and attract investments (World Bank, 2019; IMF, 2021).
2. Evaluation of Challenges Faced by Domestic Insurance Companies: This research examines the challenges faced by domestic insurance companies in Iran in covering the risks of LNG projects. This is particularly relevant given the financial, technical, and international sanctions- related limitations, which constitute a significant research gap (Central Insurance of Iran, 2022).
3. Practical Solutions for Developing the Insurance Industry: The present study provides practical solutions for developing the insurance industry in Iran by analyzing the role of insurance in reducing investment risks. This addresses the research gap regarding applied strategies to enhance the capacity of domestic insurance companies in covering major risks (IEA, 2020).
4. Analysis of Iran-Specific Risks: This research examines Iran-specific risks, such as international sanctions, limited access to advanced technologies, and domestic environmental challenges. This aspect has received less attention in previous studies (IMF, 2021).

By addressing these gaps, this study aims to contribute to both academic knowledge and practical policymaking in the field of insurance and investment in Iran's LNG industry. It provides insights into how tailored insurance solutions, supportive government policies, and international collaborations can foster sustainable development and attract investments to this critical sector.

4. Field Study and Data Collection Process

The field study and data collection process in this research were conducted using a mixed- methods approach (quantitative and qualitative). This approach allows the researcher to gain a comprehensive understanding of the role of insurance in reducing investment risks and developing the LNG industry in Iran. The following steps outline the data collection process:

4.1. Defining the Statistical Population and Sampling

The statistical population of this research includes a wide range of stakeholders directly or indirectly involved in the LNG and insurance industries in Iran. This population enables the researcher to collect comprehensive and diverse data and provide a detailed analysis of the role of insurance in reducing investment risks and developing the LNG industry. To achieve this, the researcher selected the statistical population from among the following groups:

- Players in Iran's liquefied natural gas (LNG) industry,
- Insurance companies active in the energy sector,
- Domestic and foreign investors,
- Experts in the fields of energy and insurance.

Based on the structure of the LNG and insurance industries in Iran, the statistical

population was estimated to include approximately 200 to 400 individuals or entities. This number encompasses companies, organizations, government institutions, and specialized individuals.

- Qualitative Sampling: In the qualitative phase, purposive sampling (Purposive Sampling) was used to select participants who could provide the most relevant and insightful information for the study. The sample size was determined based on theoretical saturation (Theoretical Saturation), which was achieved after conducting 15 interviews with key informants (Creswell & Creswell, 2018).
- Quantitative Sampling: In the quantitative phase, stratified random sampling (Stratified Random Sampling) was used due to the heterogeneity of the statistical population (including LNG companies, insurance companies, investors, government institutions, and experts). The population was divided into homogeneous subgroups, and random sampling was conducted within each subgroup. The sample size was calculated using Cochran's formula, considering a 5% margin of error and a 95% confidence level, resulting in an estimated sample size of 132 to 196 participants for a population of 200 to 400 individuals (Cochran, 1977).

4.2. Data Collection Tools

To gather qualitative data, semi-structured interviews were conducted with experts in the LNG industry, managers of insurance companies, and investors. These interviews provided deeper insights into various aspects of the topic and helped uncover stakeholders' perspectives. Additionally, secondary data sources such as industry reports, insurance company documents, and data published by international organizations like the International Energy Agency (IEA) and the World Bank were utilized. For quantitative data collection, structured questionnaires were designed. These questionnaires included questions about the role of insurance in reducing investment risks, the challenges faced by insurance companies, and the impact of insurance on the development of the LNG industry. The questionnaire was informed by the findings of the qualitative phase.

4.3. The Process of Conducting the Field Study:

In this research, key stakeholders, including companies active in the LNG industry, insurance companies, and investors, were first identified. Then, the qualitative section of the questionnaire was distributed both electronically and in person, and interviews were conducted with the stakeholders. The qualitative data were analyzed using the content analysis method, and finally, the quantitative section of the questionnaire was designed based on the results of the qualitative section. It was distributed among the members of the statistical sample, and the completed questionnaires were collected. The quantitative data were analyzed using SPSS and PLS statistical software. To ensure the validity of the qualitative data, triangulation (the use of multiple data sources) and member checking (review by participants) were employed. For the generalizability of the results, sampling was conducted in a way that represented the statistical population.

5. Inferential Analysis of Research Data

In the qualitative section of the research, semi-structured interviews were conducted with 15 participants. These interviewees included managers of companies active in the liquefied natural gas (LNG) industry, insurance experts, investors, and policymakers. After collecting the data, a content analysis was performed, and the results were summarized as shown in (Table 1).

Table 1. Summary of Content Analysis of Interview Results with Experts on the Analysis of the Role of Insurance in Reducing Investment Risks and the Development of the Liquefied Natural Gas Industry in Iran

Row	Key Concept	Frequency	Statements Expressed by Interviewees	Interpretation and Analysis
1	The Role of Insurance in Reducing Financial Risk	12	Insurance assures investors that in the event of incidents, part of the losses will be compensated. Insurance enables risk-taking in large investments such as LNG.	Insurance, as a tool for reducing financial risks, increases investment attractiveness.
2	Insurance Challenges in the LNG Industry	10	High insurance rates and incomplete risk coverage are the main challenges.	High insurance costs and coverage limitations hinder the development of the LNG industry.
3	The Impact of Insurance on Attracting Investment	11	Foreign investors require strong insurance coverage due to political and economic risks.	Insurance acts as a factor in attracting foreign investment, especially in high-risk industries such as LNG.
4	The Need for Specialized Insurance	9	The LNG industry requires specialized insurance that covers the specific risks of this sector.	The absence of specialized insurance is one of the primary barriers to the development of the LNG industry.
5	The Role of Government in Developing Insurance	8	The government should strengthen the insurance industry by offering tax incentives and government guarantees.	Government support for the insurance industry plays a key role in the development of the LNG industry.
6	Political Risks and Insurance	7	Political risks such as sanctions make insurance coverage more complex.	Political risks increase the need for international insurance and cooperation with global institutions through consortia.
7	The Impact of Insurance on Sustainable Development	6	Insurance contributes to the sustainable development of the LNG industry by reducing risks.	Insurance, as a tool for the sustainable development of the LNG industry, plays an important role.

To design the conceptual model of the research based on the findings obtained from the qualitative section, the following steps were carried out:

5.1. Definition of Key Variables

First, the key variables were determined based on the seven themes summarized in the qualitative section of the research. These variables are considered as the main constructs in the conceptual model.

5.2. Determination of Relationships Between Variables

Based on the content analysis of the interviews, the relationships between the variables were identified as assumptions. For example:

- The role of insurance in reducing financial risk may have a direct impact on attracting investment.
- Insurance challenges may act as a barrier to sustainable development.

- The role of the government may influence the development of specialized insurance.
- Political risks may affect insurance challenges and the attraction of investment.

5.3. Drawing the Conceptual Model

The conceptual model of the research was drawn based on the findings of the qualitative section as shown in (Figure 1). In this figure, the variables are represented as nodes, and the relationships between them are shown as arrows. The direction of the arrows indicates the direction of influence. For example:

- The role of insurance in reducing financial risk → Attracting investment
- Insurance challenges → Sustainable development
- The role of government → Specialized insurance
- Political risks → Insurance challenges and attracting investment

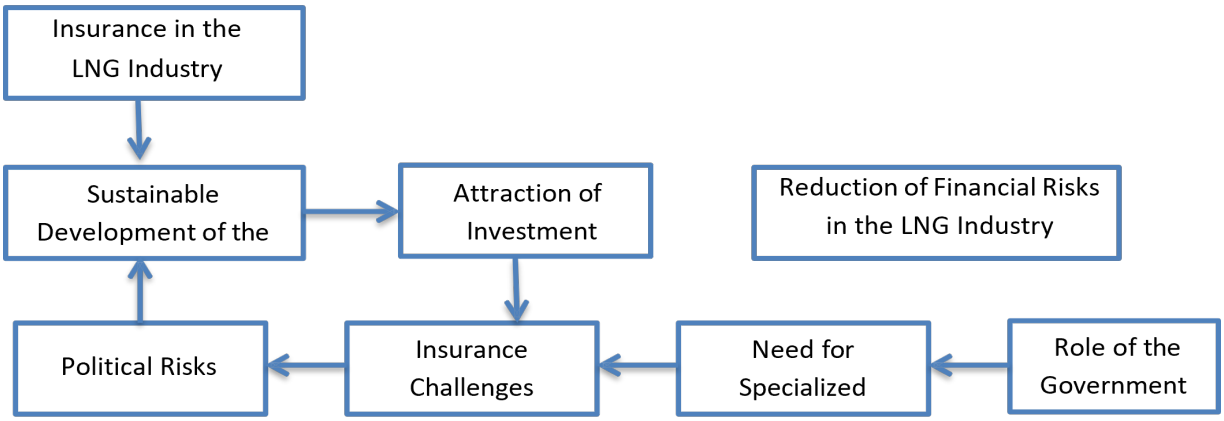


Figure 1. Conceptual Model Designed for the Research Based on the Findings of the Qualitative Section of the Research

Note: It should be noted that the above scheme is applicable under normal conditions, and under conditions of sanctions, war, etc., as we see in the only Mini LNG project currently being implemented, its implementation is not possible. There is no doubt about the Industrial LNG projects.

5.4. Model Validation

The conceptual model designed for the research was examined using quantitative methods, specifically Structural Equation Modeling (SEM), to confirm the relationships between variables. The use of Structural Equation Modeling (SEM) in this research was due to its ability to simultaneously analyze latent and observable variables, examine multiple relationships, evaluate model fit, manage measurement errors, and provide comprehensive and accurate results. This method assists the researcher in fully and scientifically analyzing the complex conceptual model of the research and delivering valid results. The output tables of the Structural Equation Modeling (SEM) for the research topic were first processed through the steps of SEM analysis, followed by data processing, and the results are presented in standardized table formats. The output tables of the Structural Equation Modeling for the sample size of 150 in this research are presented as follows. These tables include model fit indices, path coefficients, and significance values.

Table 2. Fit Indices for the Research Conceptual Model

Result	Acceptable Limit	Value	Fit Index
Acceptable	The smaller, the better	210.56	Chi-Square (χ^2)
-	-	145	df
Acceptable	> 0.90	0.93	CFI
Acceptable	> 0.90	0.91	TLI
Acceptable	< 0.08	0.06	RMSEA
Acceptable	< 0.08	0.05	SRMR

Based on the results of (Table 2), it can be interpreted that the model has a good fit, as the CFI, TLI, RMSEA, and SRMR indices fall within the acceptable range.

Table 3. Path Coefficients and Significance for the Research Conceptual Model

Result	p-value	t-value	Path Coefficient (β)	Factors relation ship
Significant	0,000	8.34	0.72	Financial Risk Reduction ⟶ Investment Attraction
Significant	0,000	-6.12	-0.56	Insurance Challenges ⟶ Sustainable Development
Significant	0,000	7.89	0.65	Government Role ⟶ Specialized Insurance
Significant	0,000	5.23	0.48	Political Risks ⟶ Insurance Challenges
Significant	0,000	-4.56	-0.37	Political Risks ⟶ Investment Attraction
Significant	0,000	6.78	0.59	Specialized Insurance ⟶ Sustainable Development

Based on the results of (Table 3), it can be ultimately interpreted that all relationships between the constructs of the research conceptual model are significant (p-value < 0.05). Financial risk reduction has a strong positive effect on investment attraction (β = 0.72). Insurance challenges have a negative impact on sustainable development (β = -0.56). The role of government has a positive effect on specialized insurance (β = 0.65).

Table 4. Results of Confirmatory Factor Analysis (CFA) for the Research Conceptual Model

AVE	CR	Factor Loading	Indicators (Observable Variables)	Construct
0.72	0.91	0.85	Insurance reduces financial risk	Financial Risk Reduction
		0.88	Insurance provides peace of mind	
0.68	0.89	0.79	High insurance premiums	Insurance Challenges
		0.82	Inadequate insurance coverage	
0.75	0.92	0.87	Insurance increases the attraction of investors	Investment Attraction
0.70	0.90	0.84	Need for specialized insurance	Specialized Insurance
0.73	0.91	0.86	The government supports the insurance industry	Government Role
0.65	0.88	0.81	Sanctions impact insurance	Political Risks
0.76	0.93	0.89	Insurance contributes to sustainable development	Sustainable Development

Based on the results of (Table 4), it can be ultimately interpreted that the factor loadings of all indicators are above 0.7, which demonstrates good convergence of the indicators with the constructs. Additionally, the construct reliability (CR) is above 0.7 and the AVE is above 0.5, indicating good reliability and convergent validity of the constructs.

5.5. Recommendations

Based on the conceptual model of the research and the results obtained from the qualitative and quantitative sections of the study, several recommendations have been proposed for policymakers, insurance companies, and investors to enhance the role of insurance in reducing investment risks and developing the liquefied natural gas (LNG) industry in Iran.

Table 6. Strategies for Enhancing the Role of Insurance in Reducing Investment Risks and Developing the LNG Industry in Iran

Row	Key Concept	Number of Mentions	Statements Expressed by Interviewees	Interpretation and Analysis
1	Coverage of Specific LNG Industry Risks	12	1. Coverage of technical and operational risks 2. Coverage of environmental risks 3. Coverage of political risks	The majority of experts emphasized the necessity of designing specialized insurance products for the unique risks of the LNG industry.
2	Engagement of International Insurers	10	1. Attracting international insurance companies 2. Government guarantees for foreign insurers	Experts believe that the participation of international insurers can increase the capacity to cover large risks.
3	Establishment of Investment Guarantee Funds	9	1. Joint funds by government and private sector 2. Loan repayment guarantees	The establishment of investment guarantee funds was proposed as a solution to reduce investors' concerns.
4	Government Supportive Policies	14	1. Tax exemptions 2. Government subsidies 3. Currency facilities	The majority of experts emphasized the key role of the government in providing financial and legal support.
5	Regional and nternational Cooperation	8	1. Bilateral and multilateral agreements 2. Collaboration with international organizations	Collaboration with international institutions was proposed as a solution to reduce export-related risks.
6	Development of Secondary Markets	7	1. Secondary insurance markets 2. Use of modern financial instruments	The development of secondary markets for transferring large risks was suggested as an effective solution.
7	Training and Empowerment of Stakeholders	6	1. Training managers and investors 2. Promoting a culture of insurability	Increasing stakeholders' awareness of the benefits of insurance was proposed as a solution for the development of the LNG industry.
8	Transparency and Updating of Laws and Regulations	11	1. Updating and ensuring the stability of laws 2. Effective supervision over the interpretation and enforcement of laws	Experts emphasized the need to establish transparent and sustainable legal frameworks to attract investors.
9	Development of Insurance Infrastructure	5	1. Establishing specialized data centers 2. Utilizing modern technologies	The development of technology-driven infrastructure was proposed as a solution to improve insurance processes.
10	Continuous Evaluation and Updating of Policies and Regulations	4	1. Periodic evaluations 2. Policy flexibility	Continuous evaluation of laws and policies was suggested as a way to adapt to market and technological changes.

6. Conclusion and Suggestions

The present study analyzed the role of insurance in reducing investment risks and developing the liquefied natural gas (LNG) industry in Iran. The findings confirm that insurance can serve as an effective mechanism for mitigating financial risks, enhancing investor confidence, and promoting sustainable development in the LNG sector. However, the practical realization of this potential depends on a realistic understanding of Iran's institutional, financial, and international constraints. Currently, the Iranian LNG industry faces multiple challenges, including limited access to international capital and technology, restricted cooperation with global insurers due to sanctions, and the insufficient capacity of domestic insurance companies to provide specialized coverage for large-scale and high-risk industrial projects. Therefore, while insurance has theoretical potential to reduce investment risks, its practical impact requires a phased, localized, and well-prioritized policy framework. Beyond these structural issues, two emerging geopolitical factors have significantly increased insurance-related risks:

1. The potential activation of the Snapback mechanism: The reactivation of the Snapback mechanism, which automatically reinstates United Nations sanctions in case of alleged non-compliance with the nuclear agreement, would severely constrain Iran's access to international insurance and financial services. This would:

   A: sharply increase political and sovereign risk premiums,

   B: Trigger the withdrawal of international reinsurers from Iranian markets,

   C: Reduce the creditworthiness and operational capacity of domestic insurers, and

   D: Create a climate of uncertainty that discourages both domestic and foreign investment in LNG projects.

Under such conditions, reliance on domestic insurance mechanisms, national investment guarantee funds, and regional reinsurance partnerships becomes not only a necessity but a strategic priority for maintaining risk coverage.

2. The rising geopolitical tensions between Iran and the United States, as well as between Iran and Israel. Impact of the Snapback Mechanism: The escalation of geopolitical tensions between Iran, the United States, and Israel has also intensified political and security risks affecting the LNG value chain—from production and transportation to export logistics. Such tensions increase:

   A: the cost of marine and energy insurance,

   B: The probability of project delays or force majeure events, and

   C: The difficulty of obtaining reinsurance coverage in global markets.

Consequently, overall project costs rise, and investor confidence diminishes. To mitigate these impacts, Iran must focus on developing localized political risk insurance schemes, enhancing transparency in public–private insurance partnerships, and strengthening regional cooperation with neighboring countries to share and distribute risks.

Based on the findings of this research, the following recommendations are proposed, emphasizing feasibility, prioritization, and adaptation to Iran's current realities:

6.1. Short-Term and Realistic Recommendations (Immediate Implementation)

A) Strengthening Domestic Insurance

Capacity: Develop targeted training programs to enhance the technical expertise of Iranian insurers in energy and industrial risk assessment. Encourage cooperation between domestic insurers and local universities or research centers to design semi-specialized insurance models suited to LNG operations.

B) Gradual Introduction of Specialized Insurance Products: Begin with modular insurance packages covering manageable operational and environmental risks, before expanding to more complex risks such as political or market risks. Leverage existing reinsurance networks within the region (e.g., with neighboring countries) instead of relying solely on Western or global markets.

C) Enhancing Governmental and Regulatory Support: Reform existing laws such as the Foreign Investment Promotion and Protection Act (FIPPA) and the Law on Maximizing Domestic Production and Services to clarify insurance-related provisions for energy projects. Introduce transparent mechanisms for oversight to minimize rent-seeking, corruption, and conflicts of interest in insurance-related subsidies or guarantees.

6.2. Medium-Term Recommendations (Requiring Institutional Development)

A) Establishment of a National Investment Guarantee Fund: Create a government-backed but professionally managed fund to provide partial guarantees for LNG investments. The fund's design should prioritize transparency, limit bureaucratic interference, and operate under strict auditing standards.

B) Digital Transformation of the Insurance Sector (with Caution): Implement gradual digitalization of insurance operations—starting with data integration, electronic claim management, and basic risk modeling. Adoption of advanced technologies such as blockchain or parametric insurance should only follow after a comprehensive assessment of digital infrastructure readiness.

C) Development of a Legal and Supervisory Framework: Regularly update insurance and investment-related regulations to align with global standards while maintaining local relevance. Strengthen the supervisory role of the Central Insurance of Iran to ensure compliance and reduce policy ambiguity.

6.3. Long-Term and Strategic Recommendations (Conditional on Future Reforms)

A) International Cooperation and Re-engagement: Prepare long-term strategies for engaging with regional and global insurance markets after easing of sanctions or political normalization. Establish regional alliances or multilateral frameworks (e.g., with Gulf or Asian partners) to share LNG project risks and insurance know-how.

B) Development of Secondary and Reinsurance Markets: Explore the formation of a regional reinsurance pool or secondary risk market in collaboration with Middle Eastern partners to expand coverage capacity. Introduce financial instruments such as energy bonds or Sukuk cautiously, following the establishment of a strong regulatory foundation.

Table 7. Summary and Recommendations on the Role of Insurance in LNG Industry Development in Iran

Timeframe	Recommendation Title	Proposed Action
Short-term and Realistic	Strengthening domestic insurers	Develop specialized training programs to enhance technical capacity of Iranian insurers in industrial and energy risk assessment. Foster collaboration between insurers and academic/research institutions to design semi-specialized insurance models tailored to LNG industry characteristics.
	Gradual development of LNG-specific insurance policies	Begin with modular insurance policies covering operational and environmental risks, before expanding to complex risks such as political or market risks. Leverage regional insurers and reinsurers (especially in neighboring countries) instead of relying solely on Western international markets.
	Targeted and transparent government support	Revise existing laws such as the "Foreign Investment Promotion and Protection Act" and the "Maximum Use of Domestic Production and Services Act" to clarify the role of insurance in energy projects. Establish transparent oversight mechanisms to prevent rent-seeking, corruption, and conflicts of interest in allocating subsidies or state-backed guarantees.
Medium-term (Requires Institutional Development)	Establishment of a National Investment Guarantee Fund	Create a government-backed but professionally managed fund to provide partial guarantees to LNG investors. Design the fund with emphasis on transparency, financial accountability, and strict oversight to avoid bureaucracy and inefficiency.
	Gradual digitalization of the insurance sector	Implement digital processes such as data integration, electronic claims management, and statistical risk analysis. Use advanced technologies like blockchain or parametric insurance only after thorough evaluation of technical infrastructure.
	Legal and regulatory framework updates	Continuously revise insurance and investment regulations to align with international standards and domestic conditions. Strengthen the supervisory role of Iran's Central Insurance to enhance transparency, trust, and legal clarity.
Long-term and Strategic (Conditional on Macro Reforms)	Expansion of international and regional cooperation	Design a long-term roadmap for re-entry into global insurance markets if sanctions are lifted or political relations improve. Build regional alliances (e.g., with Gulf or East Asian countries) to share technical knowledge, insurance risks, and LNG development experience.
	Development of secondary markets and reinsurance mechanisms	Explore and design regional reinsurance markets or establish a "Joint Risk Fund" to increase coverage capacity for large-scale projects. Utilize Islamic financial instruments such as energy participation bonds or sukuk after strengthening regulatory systems and ensuring financial transparency.

6.4. Policy Prioritization Framework

To ensure effectiveness and resource efficiency, the proposed recommendations should be prioritized based on three key criteria:

Priority Level	Focus Area	Time Horizon	Feasibility	Expected Impact
High	Strengthening domestic insurers and legal reforms	Short-term	High	High
Medium	Establishment of investment guarantee fund and gradual digitalization	Medium-term	Moderate	High
Low	International cooperation and advanced financial instruments	Long-term	Low (under current conditions)	Very High (conditional)

7. Concluding Remarks

In conclusion, insurance can play a pivotal role in mitigating investment risks and facilitating the sustainable growth of Iran's LNG industry, but its success depends on institutional maturity, regulatory transparency, and gradual reform rather than immediate large-scale initiatives. Unrealistic expectations—such as full participation of global insurers under ongoing sanctions or rapid digital transformation without infrastructure—should be avoided. Future research should therefore focus on developing localized insurance models, assessing the real financial capacity of domestic insurers, and examining governance mechanisms to minimize political and economic inefficiencies. Such studies can provide policymakers with practical insights to progressively integrate insurance-based risk management into Iran's energy investment strategies. By aligning policy recommendations with economic realities and institutional capacities, Iran can gradually strengthen the resilience and attractiveness of its LNG industry in both domestic and international contexts. Also, the potential activation of the Snapback mechanism and the escalation of geopolitical tensions significantly amplify political and insurance risks, making domestic resilience, regional partnerships, and locally adapted insurance solutions the most viable pathways forward.

References

Aghaie, M., & Mohammadi, A. (2022). The role of insurance in investment security in the energy sector. Energy Policy Journal, 58(3), 116-128.

Amiri, H., & Kheybari, M. (2020). Attracting foreign investment in Iran's gas sector: The role of insurance frameworks. International Journal of Energy Economics and Policy, 10(4), 456-463.

BP Statistical Review of World Energy. (2022). BP Statistical Review of World Energy 2022. Retrieved from https://www.bp.com

Bryman, A. (2016). Social research methods (5th ed.). Oxford University Press.

Central Insurance of Iran. (2022). Annual report on the performance of the insurance industry in Iran. Retrieved from https://www.centinsur.ir

Cohen, A. (2020). Financial risks in the LNG sector: Analysis and management strategies. Journal of Financial Risk Management, 9(2), 145-159.

Creswell, J. W., & Creswell, J. D. (2018). Research design: Qualitative, quantitative, and mixed methods approaches (5th ed.). Sage Publications.

Cummins, J. D., & Weiss, M. A. (2013). Systemic risk and the US insurance sector. Journal of Risk and Insurance, 80(3), 489-528.

EIA. (2021). International Energy Outlook 2021.

U.S. Energy Information Administration. Retrieved from https://www.eia.gov

Gholami, S., Rahmani, J., & Nasrollahi, A. (2021). The role of insurance in the development of LNG industry in Iran: A review. Iranian Journal of Oil & Gas Science and Technology, 10(2), 50-62.

Hassan, S., & Ahmed, S. (2021). Regulatory risks in the LNG industry: Perspectives from the Middle East. Energy Regulation Journal, 15(1), 34-50.

Hosseini, S., & Sadeghi, M. (2021). The economic impact of liquefied natural gas development on Iran's economy. Journal of Natural Gas Science and Engineering, 85, 103-114.

IEA. (2020). World Energy Outlook 2020. International Energy Agency. Retrieved from https://www.iea.org

IMF. (2021). Iran: Economic outlook. International Monetary Fund. Retrieved from https://www.imf.org

Jafari, H., & Tavakoli, A. (2021). Exploring insurance products for liquefied natural gas sector in Iran. International Journal of Energy Economics and Policy, 11(4), 181-189.

Khan, M. A., Ahmed, F., & Rueppel, P. (2019). The role of insurance in mitigating investment risks in energy sector: Evidence from Pakistan. Energy Policy, 134, 110-118.

Liu, Y., Zhang, L., & Wang, H. (2018). Operational risk management in energy sector: The role of insurance. Energy Reports, 4, 350-356.

Mahdavi, G., & Jafari, H. (2021). Risks and opportunities in the Iranian LNG sector: A comprehensive review. Iranian Journal of Oil & Gas Science and Technology, 10(1), 12-25.

Mohammadi, H., & Aghaei, M. (2022). Cultural and social factors influencing the acceptance of insurance in the energy sector. Energy Policy, 156, 112-121.

Nguyen, T. T., Lee, J. H., & Kim, H. (2020). Operational risks in LNG production: Analysis and mitigation strategies. International Journal of Project Management, 38(6), 395-407.

Rezazadeh, A., & Zare, R. (2020). Legal framework of insurance in the Iranian energy sector: Challenges and opportunities. Journal of Energy Law, 29(3), 295-310.

Shah, K., Shukla, S., & Tiwari, A. (2021). Insurance for renewable energy projects: Enhancing investor confidence. Sustainable Energy Technologies and Assessments, 47, 101400.

World Bank. (2019). Managing environmental and social risks in the oil and gas industry. World Bank Group. Retrieved from https://www.worldbank.org

Zhang, L., & Yang, R. (2019). Market risk analysis for LNG investments: A comprehensive review. Energy Economics, 81, 524-534.

Zhou, Q., Li, J., & Chen, Y. (2020). Attracting foreign investment in energy sector: The role of insurance policies. International Journal of Energy Economics and Policy, 10(3), 653-661.

JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 1 / Summer 2025 / Pages 22-41

Journal Home page: https://jgt.irangi.org



Techno-Economic and Sensitivity Analysis of Natural Gas Liquefaction Using the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle

Sahar Arshtabar[1], Mojtaba Biglari[2*], Mohammad Sadegh Valipour[3]

1. Ph.D. Student, Faculty of Mechanical Engineering, Semnan University, Semnan, Iran
2. Associate Professor, Faculty of Mechanical Engineering, Semnan University, Semnan, Iran
3. Professor, Faculty of Mechanical Engineering, Semnan University, Semnan, Iran

ARTICLE INFO

ORIGINAL RESEARCH ARTICLE

Article History:
Received: 15 June 2025
Revised: 12 August 2025
Accepted: 14 August 2025

Keywords:
C3MR cycle
Liquefied Natural Gas (LNG)
Techno-economic assessment
Aspen HYSYS simulation
Process optimization
Sensitivity analysis

ABSTRACT

Liquefied natural gas (LNG) is essential in the global energy transition because it allows for long-distance transportation of natural gas with reduced emissions. Improving the energy efficiency and economic feasibility of LNG liquefaction processes is therefore important. This study offers a comprehensive techno-economic analysis and sensitivity evaluation of natural gas liquefaction using the Propane Pre-Cooled Mixed Refrigerant (C3MR) cycle. A steady-state simulation was developed in Aspen HYSYS V12, utilizing the Peng-Robinson equation of state to accurately model the cryogenic behavior of multicomponent streams. The process was segmented into two integrated subsystems: propane precooling and mixed refrigerant subcooling, with performance measured through key indicators such as energy use, power requirements, and indirect CO_2 emissions.

The results show that although the MR cycle uses slightly more electrical power than the propane precooling stage, it leads to lower overall energy use, less cooling water requirement, and significantly fewer environmental emissions. From an economic standpoint, cost estimates based on updated CEPCI indices indicate that these technical improvements result in strong financial performance, marked by high profitability and a quick payback period under typical LNG market conditions. Sensitivity analysis also indicates that higher natural gas feed rates, moderate refrigerant flow rates, and an inlet pressure near 65 bar best balance energy efficiency with economic return. Overall, the findings confirm that the C3MR cycle is a solid and practical option for large-scale LNG production, effectively connecting better thermodynamic performance with positive economic results.

DOR: 20.1001.1/jgt.2026.2069422.1059

How to cite this article
S. Arshtabar, M. Biglari, M. Valipour, Techno-Economic and Sensitivity Analysis of Natural Gas Liquefaction Using the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle. Journal of Gas Technology. 2025; 10(1): 22 -41. (https://jgt.irangi.org/article_735914.html)

* Corresponding author.
E-mail address: mbiglari@semnan.ac.ir, (M. Biglari).

Available online 22 September 2025
2588-5596/© 2016 The Authors. Published by Iranian Gas Institute.
This is an open access article under the CC BY license. (https://creativecommons.org/licenses/by/4.0)

1. Introduction

Natural gas is increasingly recognized as a key transitional energy source due to its relatively low carbon intensity compared with other fossil fuels, and liquefied natural gas (LNG) has become central to enabling efficient long-distance energy transport and supporting the transition towards lower-emission energy systems (Zhao et al. 2024; Wang et al. 2025). Its flexibility in power generation, industrial use, and transport, along with the growth of LNG infrastructure, makes it a key bridge between conventional and renewable energy systems. (Ghasemzadeh et al. 2017; Jafari et al. 2020b; Jafari and Garakani 2021). The liquefaction process reduces the volume of natural gas by approximately 600 times, enabling cost-effective transportation over long distances, particularly via marine routes (Falsafi et al. 2024). However, this phase change is both thermodynamically and economically intensive (Yuan et al. 2024). Typically, the refrigeration and liquefaction stages consume nearly half of the total energy input and account for more than one-third of the capital investment in modern LNG facilities. Therefore, improving the energy and cost efficiency of this process is essential for enhancing the competitiveness of natural gas in a low-carbon future (Balcombe et al. 2021).

Among the various process configurations available, the propane pre-cooled mixed refrigerant cycle, known as the C3MR process, has become the industrial benchmark for large-scale LNG production (Sleiti and Al-Ammari 2023). This process combines a propane-based precooling system with a mixed refrigerant loop to closely match the natural gas cooling curve at each stage of liquefaction (Ahmed et al. 2024). Its strong thermodynamic performance, modular architecture, and industrial maturity are the main reasons behind its widespread deployment in major LNG terminals worldwide. Despite its advantages, the performance of the C3MR cycle is susceptible to operational variables, including refrigerant composition, compressor pressure levels, and heat exchanger thermal performance (Cui et al. 2024). As a result, achieving stable, efficient operation across a range of conditions requires detailed, multidimensional evaluations (Almeida-Trasvina and Smith 2023).

In recent years, significant research efforts have been devoted to improving the performance of LNG liquefaction systems through advanced process simulation, optimization, and exergy-based analysis. Alabdulkarem et al. (2011) developed a detailed Aspen HYSYS model of the C3MR process and demonstrated that integrating expansion energy recovery could reduce specific power consumption by approximately seven percent. Sanavandi and Ziabasharhagh (2016) further showed that optimization of refrigerant composition and compressor pressure levels leads to measurable reductions in overall energy consumption.

Beyond conventional thermodynamic optimization, several studies have applied advanced exergy and exergoeconomic frameworks to LNG processes. Vatani et al. (2014) conducted a comparative energy and exergy analysis of five industrial liquefaction cycles and identified mixed refrigerant-based configurations as the most energy efficient. Their results showed that operational parameters, particularly compressor pressure ratios, exert a greater influence on system performance than structural modifications. In a subsequent study, Palizdar et al. (2019) performed an exergoeconomic assessment of a nitrogen dual expander LNG process and demonstrated that compressors and expanders account for a significant share of avoidable exergy destruction costs, indicating strong potential for cost reduction through targeted operational optimization.

More recent high-impact studies have extended these analyses by incorporating multi-objective optimization and advanced

decision-making frameworks. Primabudi et al. (2019) applied a combined exergy and economic optimization approach to the C3MR cycle and reported Pareto optimal trade-offs between energy efficiency and total product cost. Similarly, Shady et al. (2024) employed knowledge-based and constrained Bayesian optimization techniques to improve the operational performance of a large-scale C3MR LNG process, achieving simultaneous reductions in energy consumption and carbon emissions.

Although there has been extensive research on C3MR-based LNG liquefaction, several limitations remain in the current literature. Most earlier studies focus on steady-state thermodynamic analysis or single-objective optimization, often emphasizing energy efficiency or exergy indicators. In many cases, economic factors are analyzed separately or only reported at specific optimal design points. Furthermore, the combined effects of key operating variables such as natural gas throughput, refrigerant circulation rates, compressor pressure levels, and heat exchanger performance on both energy consumption and LNG production costs have not been thoroughly examined. This limited integration of process analysis and economic evaluation reduces the practical usefulness of many simulation-based studies for industrial design and investment decisions.

To address these issues, this study develops a comprehensive steady-state simulation of the C3MR liquefaction process using Aspen HYSYS and performs an integrated techno-economic and sensitivity analysis. The analysis explores how changes in propane precooling conditions and mixed refrigerant operating parameters influence not only technical metrics, such as specific energy consumption, power demand, and indirect CO_2 emissions, but also key economic indicators like capital cost, payback period, return on investment, and net profit. The main goal is to determine operational ranges that are both technically feasible and economically viable under conditions typical of industrial LNG plants. By directly connecting process sensitivity to economic performance, this work offers a practical framework to support informed operational optimization and investment decisions for large-scale LNG facilities employing the C3MR cycle.

2. Methodologies

2.1. Simulation Framework and Process Configuration

Process simulation serves as a key tool for accurately analyzing thermodynamic behavior and evaluating various operating scenarios, thereby accelerating the achievement of design and optimization objectives (Jafari et al. 2023; Jafari et al. 2024b; Khosravi et al. 2025). In this study, a detailed simulation of the Propane Pre-cooled Mixed Refrigerant (C3MR) liquefaction process is carried out using Aspen HYSYS V12, a widely used commercial software for modeling cryogenic and hydrocarbon systems. The simulation is performed based on the Peng-Robinson equation of state (PR-EOS), which is well-suited for handling multi-component natural gas and hydrocarbon mixtures under high-pressure and low-temperature conditions (Jafari et al. 2020a; Jafari et al. 2021b; Jafari et al. 2021a; Jafari and Khalili-Garakani 2021). This thermodynamic model accurately predicts the vapor-liquid equilibrium, enthalpy, and density across all stages of the liquefaction cycle. The C3MR process is recognized as one of the most efficient and commonly implemented LNG technologies, accounting for nearly 77% of global LNG production capacity (Hajji et al. 2019). The cycle includes two integrated refrigeration loops: a propane-based precooling cycle and a mixed refrigerant subcooling cycle. The combination of these two stages allows close thermal matching with the natural gas stream and ensures effective precooling, liquefaction, and subcooling of the product.

As shown in (Figure 1), the simulation model replicates the whole sequence of cooling operations from feed gas preprocessing to final LNG production (Hajji et al. 2019). The natural gas stream (NG1) enters the first heat exchanger (LNG-PROP1) at 25 °C and 6500 kPa and is precooled across four sequential exchangers (LNG-PROP1 to LNG-PROP4) to reach -41 °C while maintaining the same pressure.

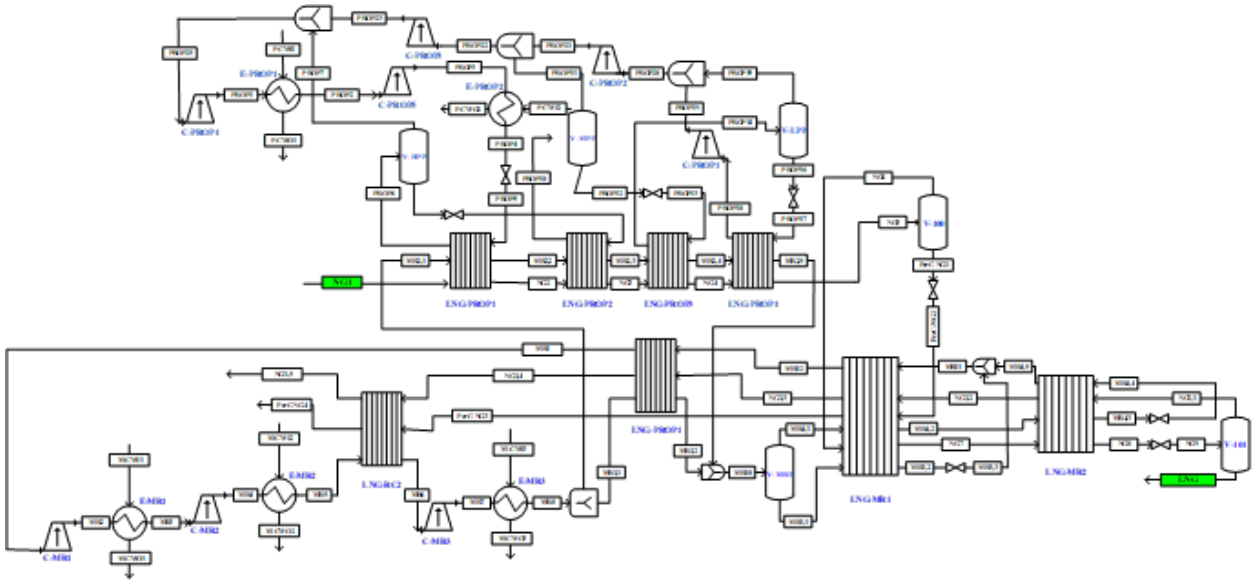


Figure 1. Schematic of Natural Gas Liquefaction Using the C3MR Process with Sequential Propane Precooling (Hajji et al. 2019)

The propane refrigerant cycle is designed to operate at four evaporation pressure levels, each corresponding to one of the precooling stages. Evaporated propane from each exchanger is routed to three two-phase separators (V-HPP, V-MPP, V-LPP), where it is separated into vapor and liquid fractions. The liquid stream undergoes throttling via Joule-Thomson (J-T) valves (VLV-101, VLV-MPP, VLV-102, VLV-MP) and provides the necessary refrigeration load to the next exchanger stage. Meanwhile, the vapor stream is recompressed to its original pressure through multistage compression and mixing (Hajji et al. 2019).

The mixed refrigerant (MR) cycle manages the subcooling stage. The MR stream is compressed in three steps with compressors C-MR1, C-MR2, and C-MR3, with interstage cooling in between. After compression, the stream enters a tee junction (TEE-100), splitting into two branches.

One branch (MR1 and MR2) joins the propane-cooled precooling section, while the other continues into the deeper cryogenic stages. The precooled MR then enters separator V-MR1, where it separates into two distinct phases. Each phase passes through additional heat exchangers (LNG-MR1 and LNG-MR2), is throttled by valves (VLV-MR1, VLV-MR2), and is then recombined in MX-MR2 to complete the subcooling loop (Hajji et al. 2019).

After the MR and NG streams are sufficiently cooled, the NG stream passes through valve VLV-NG, enters the final separator V-101, and is withdrawn as liquefied natural gas at -160 °C. The feed compositions for the natural gas and mixed refrigerant (MR) streams, along with their inlet flow rate, pressure, and temperature, are reported in (Table 1) (Hajji et al. 2019).

Natural gas mainly consists of methane with small amounts of ethane and propane. The MR used in this study includes CH_4, C_2H_6, C_3H_8, and N_2, chosen to provide an appropriate temperature glide and better match the natural gas cooling curve in the primary cryogenic heat exchanger.

Table 1: Feed Conditions for NG, MR, and Propane Streams

Stream Name	NG1	MR1	PROP1
Vapour Fraction	1.0	1.0	1.0
Temperature (°C)	25.0	-27.7	50.7
Pressure (MPa)	6.5	0.7	0.9
Mass Flow (Ton/h)	360.0	1000.0	1000.0
Mole Frac (CH_4)	0.86	0.60	0.00
Mole Frac (C_2H_6)	0.08	0.20	0.00
Mole Frac (C_3H_8)	0.06	0.10	1.00
Mole Frac (N_2)	0.00	0.10	0.00

2.2. Sensitivity Analysis Methodology

To assess the influence of key operating parameters on the technical and economic performance of the C3MR-based LNG liquefaction process, a sensitivity analysis was performed using the Case Study module in Aspen HYSYS (Ghasemzadeh et al. 2016; Jafari et al. 2019). The following four primary variables were selected based on their operational significance and direct impact on refrigeration load, energy consumption, and process economics:

- Natural gas (NG) mass flow rate
- Natural gas (NG) feed pressure
- Mixed refrigerant (MR) mass flow rate
- Propane mass flow rate

Each parameter was systematically varied within an operationally feasible range while monitoring its effect on specific energy consumption (SEC), total power requirement, payback period (PBP), and annual net profit.

The selected ranges for natural gas and refrigerant flow rates were chosen to fully represent typical industrial operating conditions reported for large-scale C3MR-based LNG plants. These ranges were defined based on practical limitations of compressor capacity, heat exchanger duty, and stable process operation, as well as values commonly reported in industrial case studies and literature. This ensures that the sensitivity analysis remains both technically realistic and directly applicable to industrial LNG operations. The parametric analysis aimed to identify optimal operating conditions and to determine the sensitivity of process performance indicators to changes in these critical variables.

This approach allowed for a precise assessment of scale effects, energy efficiency trends, and economic trade-offs related to each variable, offering practical guidelines for optimizing the overall performance and profitability of the liquefaction process.

2.3. Economic Evaluation Methodology

Economic evaluation is a vital component in the design and development of chemical and energy-intensive process systems (Yoon et al. 2025). It enables feasibility assessments, investment planning, and cost-performance comparisons. In this study, the economic analysis was conducted in line with the methodology presented by Towler and Sinnott, beginning with the estimation of capital expenditure (CAPEX), followed by operating costs (OPEX) and profitability metrics such as payback period and return on investment (Bansod et al. 2025; Ghasemzadeh et al. 2025).

All economic calculations were implemented using a spreadsheet-based framework in Microsoft Excel, while the required process data (e.g., compressor power, heat exchanger area, and vessel specifications) were obtained from the Aspen HYSYS process simulation. Commercial economic evaluation tools such as COMFAR or Aspen Economic Analyzer were not used in this study.

The capital investment was estimated by first calculating the purchase cost of major process

equipment. Where possible, cost data were derived from literature and updated using the Chemical Engineering Plant Cost Index (CEPCI). The reference year was 2010, with a CEPCI value of 532.9, and the costs were escalated to 2025 using a CEPCI of 800.2, resulting in an update factor of 1.502 (Jafari et al. 2019; Ghasemzadeh et al. 2025). This cost escalation was performed using the standard cost-index scaling relationship recommended in chemical engineering economic analysis to ensure consistency between the base-year equipment correlations and the economic conditions of the analysis year.

The updated equipment costs were then multiplied by standard installation factors and contingency allowances to derive the Total Fixed Capital Cost (TFC) and Total Capital Cost (TCC). Key equipment categories included:

- Compressors (reciprocating and centrifugal)
- LNG multi-stream heat exchangers
- Shell-and-tube heat exchangers
- Vertical vessels (separators)

Empirical cost estimation formulas and their related installation factors for major equipment are listed in (Table 2) and were used to calculate the base capital cost of the LNG process units.

The calculated purchase costs were then multiplied by the corresponding installation factors to estimate the installed equipment costs prior to the total capital investment calculation.

Table 2: Cost Estimation Equations and Installation Factors for Main Process Equipment (Behroozsarand and Ghasemzadeh 2022; Jafari et al. 2024a)

Equipment Type	Cost Estimation Formula	Installation Factor
Reciprocating Compressor	$C = 260{,}000 + 2700 \times (\text{Power})^{0.75}$	2.5
Centrifugal Compressor	$C = 580{,}000 + 20000 \times (\text{Power})^{0.60}$	2.5
LNG Multi-stream Heat Exchanger	$C = 425 \times \text{Area}$	3.5
Shell-and-Tube Heat Exchanger	$C = 28{,}000 + 54 \times (\text{Area})^{1.2}$	3.5
Vertical Vessel	$C = 11{,}600 + 34 \times (\text{Mass})^{0.85}$	4

The total capital investment was determined using a structured bottom-up approach by summing the fixed and working capital requirements (Towler and Sinnott 2021). The process began with the Battery Limit Investment, which covers the direct costs of purchasing, installing, and commissioning core process equipment within the plant's defined boundaries. Subsequently, Offsite Costs and General Services were added to account for utilities, infrastructure, and auxiliary facilities essential for safe and reliable operation. Together, these two elements formed the total direct capital cost (Jafari et al. 2024a). A contingency equal to 25% of the direct capital cost was applied to address uncertainties, such as material price fluctuations and schedule delays, resulting in the TFC (Shahab-Deljoo et al. 2023). The Total Working Capital (TWC) was then estimated to cover initial operational needs, including feedstock, labor, and spare parts during startup. Finally, the TCC was calculated by adding TFC and TWC, reflecting the overall investment required for project implementation and startup (Jafari et al. 2021b).

The primary variable operating costs, including natural gas feedstock, electric power, and cooling water, were estimated on a per-ton basis of LNG production, as shown in (Table 3). These utility costs were applied based on the specific energy and utility consumption rates obtained from the Aspen HYSYS simulation results for the LNG process.

In addition, labor costs were calculated based on a two-shift operational schedule, assuming an hourly wage rate of $60 (Zhai et al. 2025). Depreciation was estimated at 10% of the total fixed capital investment on an annual basis. Overhead expenses, insurance, and depreciation were then incorporated into the calculation of the plant gate cost (Stewart and Shirvan 2022). Furthermore, general and administrative expenditures, along with return-on-investment expectations, were taken into account to estimate the required product selling price (Fikri 2018).

Table 3: Cost Estimation Equations for Variable Operating Expenses (Towler and Sinnott 2021)

Unit Cost	Value	Unit
NG Cost	3.20	USD/MMBTU
Power Cost	0.10	USD/KWh
Cooling Water Cost	0.22	USD/MMBTU

The production cost and gross profit margin were calculated using a stepwise cost aggregation approach (Yu et al. 2026). The process began with estimating variable costs, including natural gas feedstock, electricity, and cooling water, all reported per ton of LNG. Direct labor costs were then added, based on assumed operator and maintenance wages under a two-shift schedule. Additional elements such as laboratory staffing, maintenance materials, and operating supplies were also included. These items together formed the total direct cost. Plant overheads were then incorporated as a fixed percentage of total labor cost, along with taxes and insurance, estimated relative to the fixed capital cost. This resulted in the plant's cash cost. Depreciation was added next, typically set at 10% of total fixed capital, to obtain the plant gate cost (Khan et al. 2023). This figure reflects the full cost of producing and delivering one ton of LNG. Further costs, such as general and administrative expenses, sales, research, and the targeted return on investment, were included to calculate the required product value or breakeven selling price. The gross profit margin was finally evaluated by comparing this value with the current LNG market price, calculating the difference, and expressing it as a percentage of the market price.

2.4.Technical Performance

To assess the technical performance of the LNG liquefaction system in detail, the process was divided into two distinct operational subsystems. The first is the precooling section, where pure propane is used to reduce the temperature of the natural gas and a portion of the mixed refrigerant. The second section is the liquefaction and subcooling section, which uses a mixed refrigerant (MR) cycle to achieve the final cryogenic conditions required for LNG production. This structural division enables a more focused evaluation of energy use, utility demand, and indirect environmental impacts in each section of the process. A set of Key Performance Indicators (KPIs) was employed to quantify and compare the technical behavior of both subsystems. These indicators were normalized per kilogram of LNG to facilitate meaningful comparisons. The definitions and calculation formulas for these KPIs are presented in (Table 4). This indicator-based analysis helps identify energy-intensive components of the process and supports informed decisions for future design optimization and energy efficiency improvements.

Table 4: Definition of Technical Performance Indicators for the Propane Precooling and Mixed Refrigerant Sections (Jafari et al. 2024a)

Parameter	Unit	Equation
Electricity requirement (ER)	kWh/kg	$ER = \frac{\dot{e}_E}{\dot{m}_{LNG}}$
Cooling Water requirement (CWR)	kWh/kg	$FR = \frac{\dot{e}_F}{\dot{m}_{LNG}}$
Overall energy consumption	kWh/kg	$OER = \frac{\dot{e}_{OE}}{\dot{m}_{LNG}}$
Indirect CO_2 emissions	kg/kg	$INCE = \frac{\dot{m}_{Indirect\ CO2}}{\dot{m}_{LNG}}$

3. Results and Discussion

(Table 5) provides detailed specifications for the various process streams involved in natural gas liquefaction using the Propane Pre-Cooled Mixed Refrigerant (C3MR) cycle. In this process, propane streams (PROP1 to PROP24) are used for the initial precooling of natural gas, followed by further cooling with mixed refrigerants (MR1 to MR2.5) to reach liquefaction temperatures. Streams NG1 to NG9 represent different stages of natural gas conditioning and cooling before final liquefaction (LNG).

For each stream, key parameters such as vapor fraction, temperature, pressure, mass flow rate, and mole fractions of the main components (CH_4, C_2H_6, C_3H_8, and N_2) are provided. These data are crucial for designing, simulating, and optimizing the C3MR cycle, ensuring efficient and stable operation of the liquefaction process.

Table 5: Properties of Process Streams in Natural Gas Liquefaction via the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle

Stream Name	NG1	NG2	NG3	NG4	NG5	NG6	NG7	NG8	NG9	LNG	MR1	MR2
Vapour Fraction	1.0	1.0	1.0	1.0	0.8	1.0	0.0	0.0	0.1	0.0	1.0	1.0
Temperature (°C)	25.0	8.5	-5.0	-11.0	-41.0	-41.0	-100.0	-150.0	-160.4	-160.4	-27.7	35.8
Pressure (MPa)	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	0.1	0.1	0.7	1.8
Mass Flow (Ton/h)	360.0	360.0	360.0	360.0	360.0	290.1	290.1	290.1	290.1	267.0	1000.0	1000.0
Mole Frac (CH_4)	0.86	0.86	0.86	0.86	0.86	0.90	0.90	0.90	0.90	0.89	0.60	0.60
Mole Frac (C_2H_6)	0.08	0.08	0.08	0.08	0.08	0.06	0.06	0.06	0.06	0.07	0.20	0.20
Mole Frac (C_3H_8)	0.06	0.06	0.06	0.06	0.06	0.04	0.04	0.04	0.04	0.04	0.10	0.10
Mole Frac (N_2)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.10

Stream Name	MR3	MR4	MR5	MR6	MR7	MR8	MR10	MR11	MR12	MR3,1	MR4,1	MR4,2
Vapour Fraction	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.5	1.0	0.0	1.0	0.2
Temperature (°C)	30.0	52.0	30.0	24.8	48.4	30.0	-41.0	-119.1	-48.5	-41.0	-41.0	-100.0
Pressure (MPa)	1.8	2.4	2.4	2.4	3.2	3.2	3.2	0.7	0.7	3.2	3.2	3.2
Mass Flow (Ton/h)	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	316.1	683.9	683.9
Mole Frac (CH_4)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.26	0.70	0.70
Mole Frac (C_2H_6)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.39	0.14	0.14
Mole Frac (C_3H_8)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.34	0.03	0.03
Mole Frac (N_2)	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.01	0.13	0.13
Stream Name	**MR3,2**	**MR3,3**	**MR4,3**	**MR4,4**	**MR4,5**	**MR1,1**	**MR2,1**	**MR1,2**	**MR2,2**	**MR2,3**	**MR2,4**	**MR2,5**
Vapour Fraction	0.0	0.0	0.0	0.0	0.6	1.0	1.0	0.8	1.0	1.0	1.0	0.8
Temperature (°C)	-100.0	-102.5	-150.0	-150.1	-124.9	30.0	30.0	-41.5	8.6	-4.9	-10.9	-40.9
Pressure (MPa)	3.2	0.8	3.2	0.7	0.7	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Mass Flow (Ton/h)	316.1	316.1	683.9	683.9	683.9	210.0	790.0	210.0	790.0	790.0	790.0	790.0
Mole Frac (CH_4)	0.26	0.26	0.70	0.70	0.70	0.60	0.60	0.60	0.60	0.60	0.60	0.60
Mole Frac (C_2H_6)	0.39	0.39	0.14	0.14	0.14	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Mole Frac (C_3H_8)	0.34	0.34	0.03	0.03	0.03	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Mole Frac (N_2)	0.01	0.01	0.13	0.13	0.13	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Stream Name	**PROP1**	**PROP2**	**PROP3**	**PROP4**	**PROP5**	**PROP6**	**PROP7**	**PROP8**	**PROP9**	**PROP10**	**PROP11**	**PROP12**
Vapour Fraction	1.0	1.0	1.0	0.0	0.2	0.3	1.0	0.0	0.1	0.2	1.0	0.0
Temperature (°C)	50.7	30.0	39.5	30.0	5.3	5.3	5.3	5.3	-7.8	-7.8	-7.8	-7.8
Pressure (MPa)	0.9	0.9	1.1	1.1	0.6	0.6	0.6	0.6	0.4	0.4	0.4	0.4
Mass Flow (Ton/h)	1000.0	1000.0	1000.0	1000.0	1000.0	1000.0	326.0	674.0	674.0	674.0	155.1	518.9
Mole Frac (C_3H_8)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Stream Name	**PROP13**	**PROP14**	**PROP15**	**PROP16**	**PROP17**	**PROP18**	**PROP19**	**PROP20**	**PROP21**	**PROP22**	**PROP23**	**PROP24**
Vapour Fraction	0.0	0.1	1.0	0.0	0.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Temperature (°C)	-14.1	-14.1	-14.1	-14.1	-42.2	-15.8	28.1	23.1	31.9	23.0	40.3	29.2
Pressure (MPa)	0.3	0.3	0.3	0.3	0.1	0.1	0.3	0.3	0.4	0.4	0.6	0.6
Mass Flow (Ton/h)	518.9	518.9	63.8	455.1	455.1	455.1	455.1	518.9	518.9	674.0	674.0	1000.0
Mole Frac (C_3H_8)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

The reliability of the developed simulation model for the C3MR LNG liquefaction process was evaluated through a validation study by comparing the key operating and performance parameters with the results reported by Hajji et al. (2019). As presented in (Table 6), an excellent agreement is observed between the simulation outputs and the literature data. The LNG production rate and feed gas pressure are reproduced exactly, both showing zero deviation from the reference study. Similarly, the temperature before LNG expansion and the MR to NG flow ratio are identical to those reported in the literature, confirming the correct implementation of the refrigeration cycle and mass flow distribution in the model. The predicted LNG outlet temperature of -160.4 ℃ shows a very small deviation of only 0.25% from the reference value (-160 ℃), indicating that the cryogenic heat exchange behavior in the main heat exchanger has been accurately captured. In addition, the calculated specific power consumption (0.231 kWh/kg) is very close to the reported value of 0.234 kWh/kg, with a deviation of only 1.28%, which further demonstrates the thermodynamic consistency of the simulation. A minor difference is observed in the propane pre-cooling temperature (-42.2 ℃ compared with -41 ℃), which can be attributed to slight variations in heat exchanger modeling assumptions or numerical convergence in Aspen HYSYS. Overall, the very low deviations across the evaluated parameters confirm that the developed model accurately represents the C3MR LNG liquefaction process and can be reliably used for further process analysis and economic evaluation.

Table 6: Validation of the C3MR LNG liquefaction process simulation results against Hajji et al. (2019)

Parameter	Unit	Hajji et al. (2019)	This Stady	Deviation (%)
LNG Production Rate	ton/h	267	267	0.00%
LNG Outlet Temperature	℃	-160	-160.4	0.25%
Temperature before LNG Expansion	℃	-150	-150	0.00%
Feed Gas Pressure	MPa	6.5	6.5	0.00%
Propane Refrigerant Flow	ton/h	1000	1000	0.00%
Propane Pre-cooling Temperature	℃	-41	-42.2	
Specific Power Consumption (SPC)	kWh/kg	0.234	0.231	1.28%
MR to NG Flow Ratio	-	2.78	2.78	0.00%
Refrigerant Type	-	CMR	CMR	Match

As illustrated in (Figure 2), the Propane Precooling cycle shows significantly higher cooling water and overall energy consumption than the MR-Cycle. Specifically, the cooling water requirement for Propane Precooling reaches 26.46 kWh/kg, which is over four times that of the MR-Cycle at 6.10 kWh/kg. Similarly, overall energy consumption follows the same trend, with Propane Precooling requiring 26.56 kWh/kg, compared with 6.28 kWh/kg for the MR-Cycle.

In terms of electricity consumption, however, the MR-Cycle exhibits a slightly higher value (0.18 kWh/kg) than Propane Precooling (0.10 kWh/kg), primarily due to its higher compressor load and system complexity. Regarding indirect CO_2 emissions, the Propane Precooling cycle results in 5.34 kg CO_2/kg LNG, while the MR-Cycle achieves a lower emission level of 1.26 kg CO_2/kg LNG.

These results clearly show that while the MR-Cycle results in slightly higher electricity demand, it significantly decreases water use, overall energy consumption, and CO_2 emissions, making it a more environmentally friendly and energy-efficient choice for LNG production.

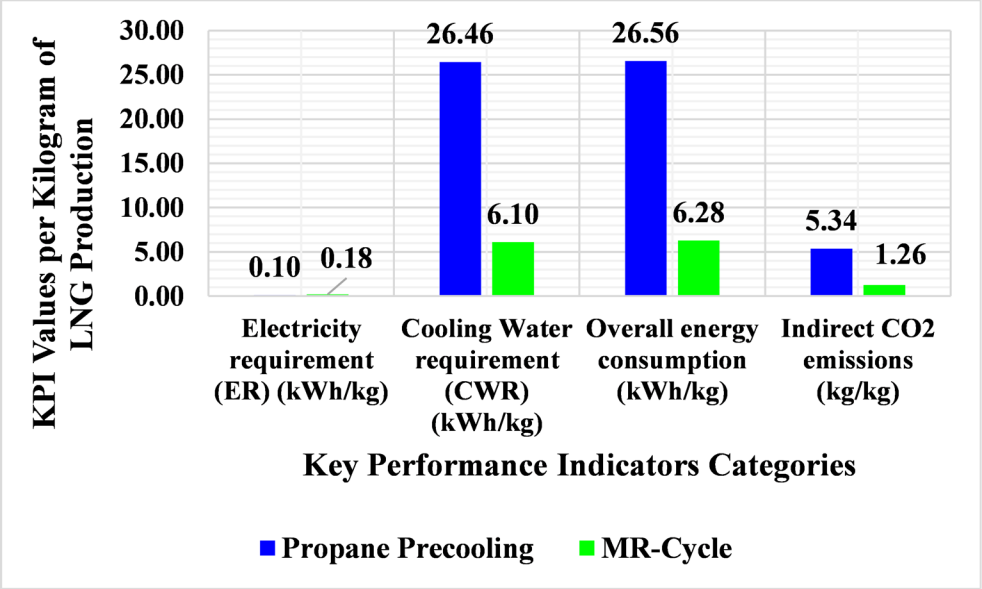


Figure 2. Comparison of Key Performance Indicators (KPIs) per Kilogram of LNG Production for Propane Precooling and MR-Cycle

According to the pie charts in (Figure 3), LNG Heat Exchangers account for the largest share of both equipment cost (43%) and installed cost (48%), underscoring their critical role in the process and the complexity of their installation. Compressors follow, showing a slight decline from 30% of equipment cost to 28% of installed cost. However, this shift masks a significant increase in absolute terms (from 37.93 to 94.83 million USD), reflecting the substantial costs associated with their installation and commissioning. Shell & Tube Heat Exchangers and Vessels contribute moderately. Vessels, in particular, show a relatively low equipment cost share (2%) that increases slightly to 3% after installation, suggesting that their installation is comparatively less complex and less capital-intensive.

(Table 7) quantitatively reinforces these observations, showing that installed costs are typically two to three times higher than equipment purchase costs. This highlights the significant impact of installation activities such as construction, integration, and commissioning on total capital expenditure and emphasizes the importance of careful planning during the engineering and implementation phases.

Table 7: Comparison of Purchase and Installation Costs for Major Equipment in the LNG Unit

Equipment Type	Equipment Cost	Installed Cost
Compressors Cost	37.93	94.83
Heat Exhengers (LNG) Cost	46.18	161.63
Heat Exchangers (Shell&Tube) Cost	20.01	70.03
Vessels Cost	2.36	9.42

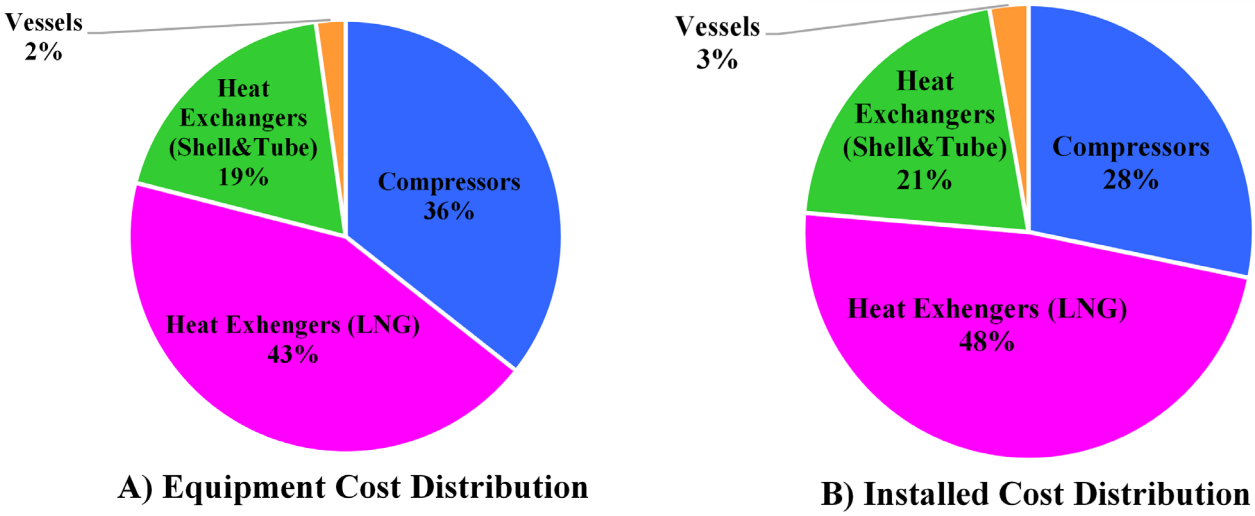


Figure 3. Equipment and Installed Cost Breakdown for Main Units in LNG Facility

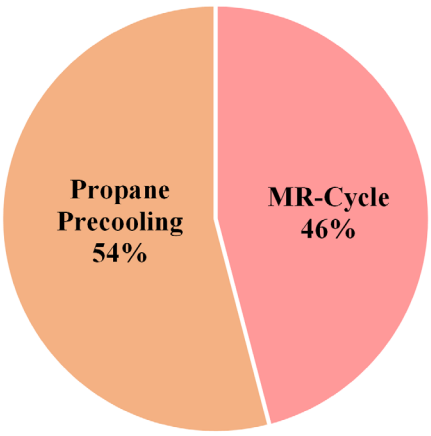
(Table 7) provides a detailed breakdown of the Capital Expenditure (CAPEX) for the LNG facility, offering a clear view of the investment structure required for project implementation. The Total Equipment Cost is reported at 106.47 million USD, while the Total Installed Cost rises to 335.91 million USD, reflecting the significant role of installation, construction, and integration efforts. A 25% contingency allowance, equal to 83.98 million USD, is included to address uncertainties and potential cost overruns. The Battery Limit Investment, which encompasses all direct costs within the facility boundary, amounts to 526.37 million USD. Furthermore, Offsite Costs and General Services, which cover infrastructure such as utility systems, access roads, and project administration, contribute an additional 105.27 million USD.

These costs collectively form the Total Fixed Capital (TFC) of 631.64 million USD. In addition, a Total Working Capital (TWC) of 157.91 million USD is allocated to support initial operational needs, such as raw material procurement and early-stage process stabilization. Altogether, the Total Capital Cost for the LNG project is estimated at 789.55 million USD, as detailed in (Table 8). This comprehensive CAPEX assessment is critical for financial planning, risk mitigation, and investment decision-making in large-scale energy infrastructure projects.

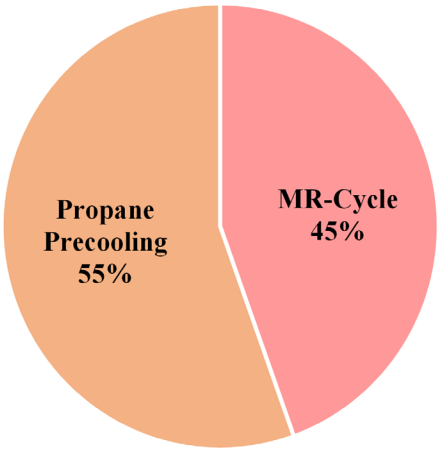
Table 8: Capital Expenditure (CAPEX) Breakdown for the LNG Facility

CAPEX Parameters	Value
Total Equipment Cost (MUSD)	106.47
Total Installed Cost (MUSD)	335.91
Contingency, 25% (MUSD)	83.98
Battery Limit Investment (MUSD)	526.37
Offsite Cost + General Services (MUSD)	105.27
Total Fix Capital Cost (TFC) (MUSD)	631.64
Total Working Capital (TWC) (MUSD)	157.91
Total Capital Cost (MUSD)	789.55

As shown in (Figure 4), the Propane Precooling unit accounts for a larger share of both equipment costs (54%) and CAPEX (55%) than the MR-Cycle unit. This suggests that precooling equipment is more capital-intensive, likely due to its scale or technical requirements.



A) Unit-Wise Equipment Cost Distribution



B) Unit-Wise CAPEX Distribution

Figure 4. Unit-wise Distribution of Equipment Cost and CAPEX

As shown in (Table 9), natural gas accounts for the largest share of feedstock and utility expenses for producing one ton of LNG, followed by power and cooling water. The table provides a detailed breakdown of these costs, indicating that natural gas accounts for 200.85 USD/Ton, while power and cooling water costs are 27.84 and 24.42 USD/Ton, respectively. This emphasizes the dominant role of natural gas pricing in determining the overall production cost structure.

Table 9: Feedstock and Utility Costs per Ton of LNG Production

Cost Item	Value
NG Cost (USD/Ton)	200.85
Power Cost (USD/Ton)	27.84
Cooling Water Cost (USD/Ton)	24.42

A detailed economic analysis of the LNG production process is presented in (Table 10). The total variable cost is estimated at 253.12 USD/Ton, comprising the direct expenses for feedstock and utilities as outlined previously in (Table 8). Labor costs are categorized into operating labor, maintenance labor, and control laboratory labor, totaling 7.86 USD/Ton. Additional direct expenses, including maintenance materials and operating supplies, bring the total direct cost to 267.29 USD/Ton.

Indirect costs consist of plant overhead (4.72 USD/Ton), taxes and insurance (5.97 USD/Ton), and depreciation (29.87 USD/Ton), totaling 307.85 USD/Ton at the plant gate. Corporate-level expenses such as general and administrative, sales, and research costs (20.01 USD/Ton) and a return on investment (ROI) of 44.81 USD/Ton at 15% per year of total fixed capital (TFC) are added to determine the final product value, which is calculated at 372.67 USD/Ton. This analysis reveals that variable costs, particularly feedstock and utility expenses, dominate the overall cost structure of LNG production. Moreover, the significant depreciation and ROI shares highlight the capital-intensive nature of liquefaction facilities. The sensitivity of total production costs to natural gas price fluctuations underscores the need for careful pricing strategies and long-term supply agreements to ensure plant profitability.

Table 10: Detailed Cost Structure and Economic Evaluation for LNG Production

CAPEX Parameters	Value
Cost Item	Value (USD/Ton.)
Variable Cost	253.12
Operating Labor, 2/Shift $55/hr	3.37
Maintenance Labor, 1.6% YR of BLI	3.98
Control Lab labor, 15% of oper labor	0.51
Labor Cost	7.86
Maintenance Materials, 2.4% YR of BLI	5.97
Operating Supplies, 10% of operating labor	0.34
Total Direct Cost	267.29
Plant Overhead, 60% of Labor Cost	4.72
Taxes and insurance, 2% Yr of TFC	5.97
Plant Cash Costs	277.98
Depreciation, 10% YR of TFC	29.87
Plant Gate Costs	307.85
G&A Sales Research	20.01
ROI before taxes, 15% Yr of TFC	44.81
Product Value	372.67

As shown in (Table 11), the LNG production plant demonstrates strong profitability indicators. With a market LNG price of 600 USD/Ton and a calculated product value (plant gate cost) of 372.67 USD/Ton (from Table 10), the resulting net profit is estimated at 227.33 USD/Ton. This translates into an annual net profit of approximately 524.39 MUSD, based on the designed plant capacity.

The financial viability is further supported by a favorable payback period (PBP) of only 1.51 years, indicating a rapid recovery of the initial capital investment. Additionally, the calculated rate of return (ROR) is 66.42%, substantially exceeding typical industry benchmarks for large-scale energy infrastructure projects. These results highlight the economic attractiveness of the proposed LNG facility, driven primarily by the competitive margin between production costs and prevailing LNG market prices. Moreover, the sensitivity of the financial outcomes to LNG market price fluctuations and natural gas feedstock costs suggests that maintaining long-term price stability through strategic supply contracts and hedging mechanisms would be essential to securing the sustained profitability of the operation.

Table 11: Key Economic Indicators for LNG Plant Operation

Cost/Indicator	Value	Unit
LNG Cost (Market)	600	USD/Ton
Net Profit	227.33	USD/Ton
Net Profit	524.40	MUSD/Year
PBP (Year)	1.50	Year
ROR	66.42	%

(Figure 5) shows how key technical and economic performance indicators are affected by changes in four main operating parameters of the C3MR-based LNG liquefaction process: NG mass flow rate, NG pressure, MR flow rate, and propane flow rate.

As shown in (Figure 5A-B), increasing the natural gas (NG) feed rate from 350 to 450 ton/h significantly reduces the specific energy consumption from 1031 to 801.1 kJ/kg, while total power consumption remains nearly constant at 74.3 MW. This improved energy efficiency translates directly into enhanced economic outcomes, with the payback period (PBP) decreasing from 1.05 to 0.66 years and the annual net profit increasing from 753.9 to 1194.6 MUSD. This trend is attributed to scale effects, in which higher LNG production rates lead to better utilization of fixed energy and capital costs.

(Figure 5C-D) demonstrates the influence of NG pressure on system performance. While total power remains relatively stable, specific energy shows a nonlinear trend, reaching a minimum at 55 bar and a peak at 70 bar. From an economic perspective, 65 bar yields the most favorable trade-off between cost and performance, with a PBP of approximately 0.99 years and a net profit of 797.8 MUSD/year. Increasing pressure beyond this point imposes higher compression energy without a proportional increase in LNG output, ultimately diminishing economic returns. The impact of the mixed refrigerant (MR) flow rate is depicted in (Figure 5E-F) as the MR flow increases from 950 to 1090 ton/h, both power consumption and specific energy rise from approximately 71.9 to 78.7 MW and from 970 to 1060 kJ/kg, respectively. This results in a gradual deterioration of economic indicators: the PBP increases while net profit declines. The trend suggests diminishing returns from overcirculation of MR, which increases compressor load without significant thermal benefit.

Finally, (Figure 5G-H) evaluates the effect of propane flow rate. Increasing propane from 400 to 1000 ton/h leads to a near-linear increase in both power consumption (from 58.4 to 74.3 MW) and specific energy (from 787 to 1002 kJ/kg). Although additional propane enhances precooling, it also increases compression duty, adversely affecting overall economic feasibility. The highest profitability is achieved at lower propane flow rates, beyond which the PBP increases sharply and net profit declines. In summary, the sensitivity analysis underscores that the optimal operation of the C3MR liquefaction process requires a higher NG throughput, moderate MR and propane flow rates, and an NG pressure near 65 bar. These conditions, taken together, ensure a favorable balance between energy efficiency and economic viability.

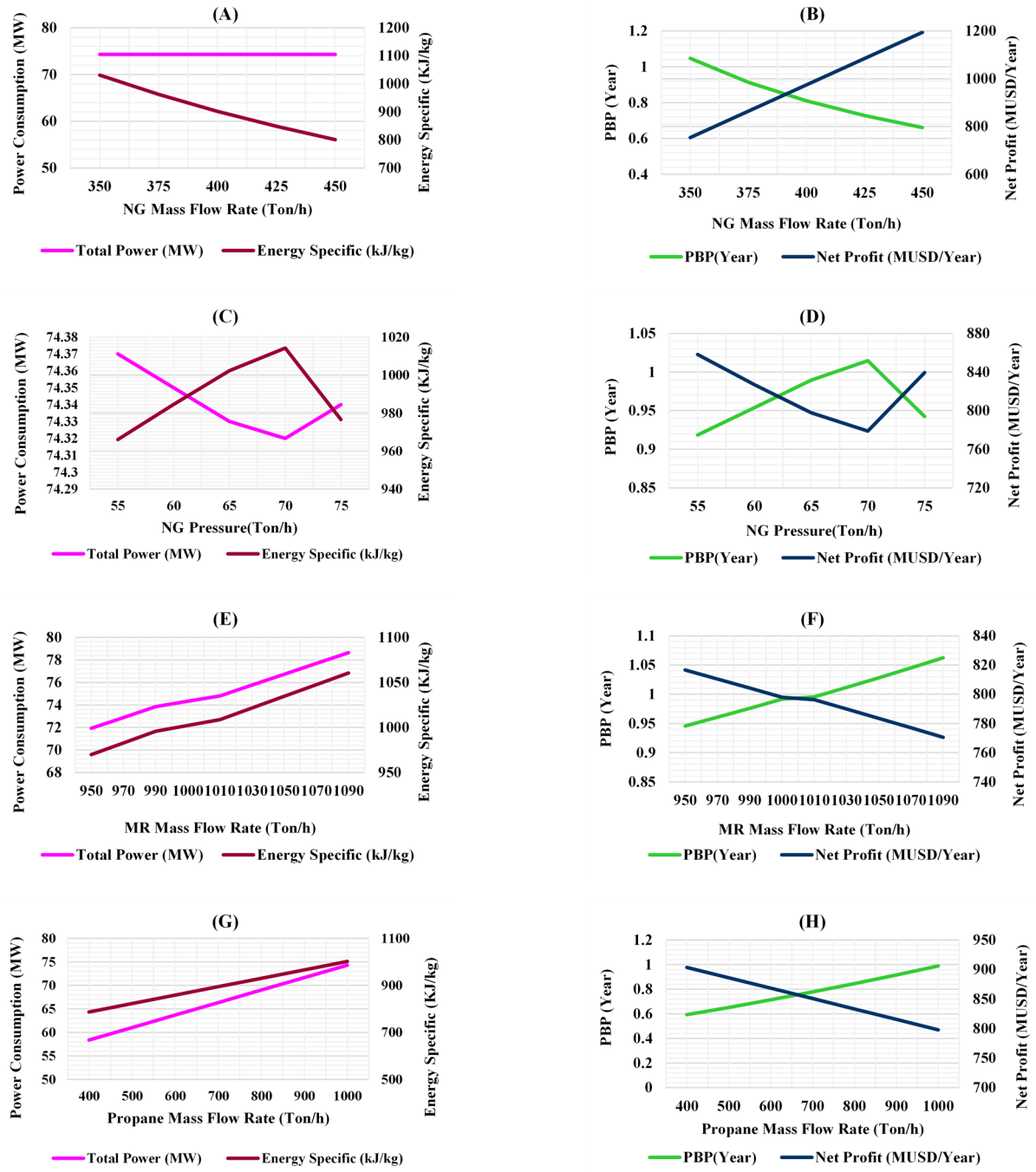


Figure 5. Sensitivity of Technical (Power and Specific energy) and Economic (PBP and Profit) Indicators of the C3MR LNG Process to Variations in: (A-B) NG mass Flow Rate, (C-D) NG Pressure, (E-F) MR Flow Rate, and (G-H) Propane Flow Rate

4. Conclusion and Recommendations for Future Works

This study aimed to provide a comprehensive techno-economic evaluation and process sensitivity analysis of a C3MR-based LNG liquefaction system to support operational optimization and investment decisions. The results show that the proposed C3MR configuration is both technically reliable and economically viable across a wide range of operating conditions.

From a technical standpoint, the mixed refrigerant (MR) cycle proved to have superior overall energy efficiency and a lower environmental impact. Specifically, the MR

cycle greatly reduced cooling water demands and indirect CO_2 emissions compared to the propane precooling section, while maintaining similar electricity consumption. The specific energy consumption (SEC) values obtained are within the lower range reported for industrial C3MR systems, confirming the effectiveness of the proposed process configuration.

From an economic perspective, the LNG plant demonstrates solid profitability. At a market price of 600 USD/Ton, the calculated plant gate cost of 372.67 USD/Ton yields a net profit of 227.33 USD/Ton, leading to an annual net profit of roughly 524.4 MUSD. The payback period (PBP) of 1.5 years and a return on investment (ROI) of 66.42% suggest quick capital recovery and strong financial competitiveness compared to other liquefaction cycles reported in the literature. These metrics emphasize the strong link between energy efficiency improvements and better economic performance.

The sensitivity analysis further clarified the link between operating variables and process performance. Increasing natural gas throughput improved energy efficiency and lowered unit capital costs, while excessive circulation of mixed refrigerant or propane raised compression loads and negatively impacted both SEC and economic performance. An optimal operating range was identified at a natural gas pressure of about 65 bar, moderate refrigerant flow rates, and high feed throughput, providing the best balance between efficiency and profitability.

In summary, the integrated techno-economic and sensitivity analysis confirms that the C3MR cycle is a reliable, scalable, and economically viable solution for large-scale LNG production. The results directly support informed process design, operational optimization, and strategic investment decisions in LNG infrastructure development.

To further improve the performance, robustness, and sustainability of LNG production systems, future research should focus on several key areas. These include integrating renewable energy sources, such as solar power and waste heat recovery, to decrease external energy demand; conducting dynamic simulation and operability analysis under variable feed and load conditions; applying exergy-based optimization to systematically reduce energy losses throughout the process; performing comprehensive techno-environmental assessments that incorporate carbon pricing mechanisms; and validating advanced mixed refrigerant compositions and innovative cryogenic heat exchanger configurations through experiments or pilot-scale studies.

Nomenclature

ASPEN	Advanced System for Process Engineering
BLI	Battery Limits Investment
C3MR	Propane Pre-Cooled Mixed Refrigerant
CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
HHV	Higher Heating Value
KPIs	Key performance indicators
LNG	Liquefied Natural Gas
MR	Mixed Refrigerant
MUSD	Million United States dollar
NG	Natural Gas
OPEX	Operating expenditure
PBP	Payback Period
PFD	Process Flow Diagram
PR	Peng–Robinson
PR-EOS	Peng–Robinson equation of state
ROR	Rate of Return
SEC	specific energy consumption

TCC	Total Capital Cost
TCI	Total Capital Investment
TEC	Total Equipment Cost
TFC	Total Fixed Capital
TIC	Total Installed Cost
TWC	Total Working Capital
USD	United States dollar

References

Ahmed, R., Mahadzir, S., Ferdush, J., Matovu, F., Mota-Babiloni, A., Hafyan, R. H., 2024. Surrogate-assisted constrained hybrid particle swarm optimization algorithm for propane pre-cooled mixed refrigerant LNG process optimization. Energy 305, 132165. https://doi.org/10.1016/j.energy.2024.132165

Alabdulkarem, A., Mortazavi, A., Hwang, Y., Radermacher, R., Rogers, P., 2011. Optimization of propane pre-cooled mixed refrigerant LNG plant. Applied Thermal Engineering 31(6-7), 1091-1098. https://doi.org/10.1016/j.applthermaleng.2010.12.003

Almeida-Trasvina, F., Smith, R., 2023. Design and optimisation of novel cascade mixed refrigerant cycles for LNG production-Part I: Benchmark cascade cycles. Chemical Engineering Research and Design 190, 619-633. https://doi.org/10.1016/j.cherd.2022.12.046

Balcombe, P., Staffell, I., Kerdan, I. G., Speirs, J. F., Brandon, N. P., Hawkes, A. D., 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy 227, 120462. https://doi.org/10.1016/j.energy.2021.120462

Bansod, Y., Jafari, M., Pawanipagar, P., Ghasemzadeh, K., Spallina, V., D'Agostino, C., 2025. Techno-economic assessment of bio-based routes for acrylic acid production. Green Chemistry 27(35), 10612-10632. https://doi.org/10.1039/D5GC01769F

Behroozsarand, A., Ghasemzadeh, K., 2022. GTL Process Simulation and Sensitivity Analysis: Zero CO_2 Emission and Productivity Improvement. Chemical Process Design 1(1), 1-16. https://doi.org/10.22111/cpd.2022.42322.1000

Cui, F., Pan, L., Pang, Y., Chen, J., Shi, F., Liang, Y., 2024. A new multi-objective optimization strategy for improved C3MR liquefaction process. Processes 12(3), 542. https://doi.org/10.3390/pr12030542

Falsafi, M., Vatani, A., Abbasi, M., Palizdar, A., 2024. An efficient thermo-hydraulic model for the investigation of a plate-fin heat exchanger in a single mixed refrigerant process. International Journal of Heat and Mass Transfer 227, 125507. https://doi.org/10.1016/j.ijheatmasstransfer.2024.125507

Fikri, M., Hendrarsakti, J., Sambodho, K., Felayati, F., Octaviani, N., Giranza, M., Hutomo, G., 2018. Estimating capital cost of small scale LNG carrier. In: Proceedings of the 3rd International Conference on Marine Technology (SENTA), Surabaya, Indonesia, pp. 225-229. https://doi.org/10.5220/0008542102250229

Ghasemzadeh, K., Jafari, M., Sari, A., Babalou, A. A., 2016. Performance investigation of membrane process in natural gas sweetening by membrane process: modeling study. Chemical Product and Process Modeling 11(1), 23-27. https://doi.org/10.1515/cppm-2015-0054

Ghasemzadeh, K., Jafari, M., Basile, A., 2017. Theoretical study of various configurations of membrane processes for olefins separation. International Journal of Membrane Science and Technology 4(1), 1-7. https://doi.org/10.15379/2410-1869.2017.04.01.01

Ghasemzadeh, K., Jafari, M., Bansod, Y., Spallina, V., Ferrari, M.-C., Iulianelli, A., 2025. Integrated environmental and techno-economic assessment for membrane-based gas-to-liquid process to green flare gas valorisation. Fuel Processing Technology 279, 108357. https://

doi.org/10.1016/j.fuproc.2025.108357

Hajji, A., Chahartaghi, M., Kahani, M., 2019. Thermodynamic analysis of natural gas liquefaction process with propane pre-cooled mixed refrigerant process (C3MR). Cryogenics 103, 102978. https://doi.org/10.1016/j.cryogenics.2019.102978

Jafari, M., Ghasemzadeh, K., Yousefi, A. T., Basile, A., 2019. Comparative study of membrane and absorption processes performance and their economic evaluation for CO_2 capturing from flue gas. Gas Processing Journal. https://doi.org/10.22108/gpj.2019.116263.1053

Jafari, M., Deljoo, M. S., Vatani, A., 2020a. Simulation and economic evaluation of polygeneration system for coproduction of power, steam, CH_3OH, H_2, and CO_2 from flare gas. Iranian Journal of Oil and Gas Science and Technology 9(4), 93-114. https://doi.org/10.22050/ijogst.2020.227023.1547

Jafari, M., Sarrafzadeh, M.-H., Ghasemzadeh, K., 2020b. Simulation and economic evaluation of heat and power generation from flare gases in a combined cycle power plant. Energy Equipment and Systems 8(4), 307-322. https://doi.org/10.22059/ees.2020.241289

Jafari, M., Khalili-Garakani, A., 2021a. Simulation and techno-economic analysis of hydrotreating process of mazut. Applied Research in Chemical - Polymer Engineering 5(1), 17-30. https://doi.org/10.22111/jarche.2021.194

Jafari, M., Khalili-Garakani, A., 2021b. Techno-economic analysis of heavy fuel oil hydrodesulfurization process for application in power plants. Iranian Journal of Oil and Gas Science and Technology 10(1), 40-65. https://doi.org/10.22050/ijogst.2020.254534.1569

Jafari, M., Nezhadfard, M., Khalili-Garakani, A., 2021c. Simulation and economic analysis of combined desalinated water and power generation from associated gases of Cheshmeh Khosh. Iranian Journal of Oil and Gas Science and Technology 10(1), 1-14. https://doi.org/10.22050/ijogst.2020.219350.1536

Jafari, M., Vatani, A., Deljoo, M. S., Khalili-Garakani, A., 2021d. Techno-economic analysis of flare gas to gasoline (FGTG) process through dimethyl ether production. Journal of Gas Technology 6(2), 28-44. http://jgt.irangi.org/article_251676.html

Jafari, M., Khorshidian, M., Rahimi Esboee, M., Kord Firouzjaei, V., Vatani, A., 2023. Design and simulation of hydrogen production from diesel reforming for fuel cell applications. Journal of Gas Technology 8(2), 56-73. https://jgt.irangi.org/article_714881.html

Jafari, M., Spallina, V., Ghasemzadeh, K., 2024a. Techno-economic assessment of flare gas valorisation during membrane-based GTL process by net-zero strategy. Energy Conversion and Management 315, 118796. https://doi.org/10.1016/j.enconman.2024.118796

Jafari, M., Vatani, A., Mohammadi, T., 2024b. CFD modeling of braid-reinforced hollow fiber membranes for efficient water and bovine serum albumin (BSA) separation. Journal of Water Process Engineering 65, 105746. https://doi.org/10.1016/j.jwpe.2024.105746

Khan, S. R., Zeeshan, M., Fatima, S., Ciolkosz, D., Dimitriou, I., Jin, H., 2023. A comparative techno-economic analysis of combined oil and power production from pyrolysis and co-pyrolysis plants utilizing rice straw and scrap rubber tires. Fuel 348, 128639. https://doi.org/10.1016/j.fuel.2023.128639

Khosravi, M., Jafari, M., Ghasemzadeh, K., Iulianelli, A., 2025. Enhancing styrene production: CFD analysis of a Pd-based membrane reactor to carry out ethylbenzene dehydrogenation. Fuel Processing Technology 270, 108191. https://doi.org/10.1016/j.fuproc.2025.108191

Palizdar, A., Ramezani, T., Nargessi, Z., AmirAfshar, S., Abbasi, M., Vatani, A., 2019. Advanced exergoeconomic evaluation of a mini-scale nitrogen dual expander process for liquefaction of natural gas. Energy 168, 542-557.

https://doi.org/10.1016/j.energy.2018.11.058

Primabudi, E., Morosuk, T., Tsatsaronis, G., 2019. Multi-objective optimization of propane pre-cooled mixed refrigerant (C3MR) LNG process. Energy 185, 492-504. https://doi.org/10.1016/j.energy.2019.07.035

Sanavandi, H., Ziabasharhagh, M., 2016. Design and comprehensive optimization of C3MR liquefaction natural gas cycle by considering operational constraints. Journal of Natural Gas Science and Engineering 29, 176-187. https://doi.org/10.1016/j.jngse.2015.12.055

Shady, R., Ahmed, S. F., Sleiti, A. K., 2024. Operation optimization of propane pre-cooled mixed refrigerant LNG process: A novel integration of knowledge-based and constrained Bayesian optimization approaches. Chemical Engineering Science 300, 120560. https://doi.org/10.1016/j.ces.2024.120560

Shahab-Deljoo, M., Medi, B., Kazi, M.-K., Jafari, M., 2023. A techno-economic review of gas flaring in Iran and its human and environmental impacts. Process Safety and Environmental Protection 173, 642-665. https://doi.org/10.1016/j.psep.2023.03.051

Sleiti, A. K., Al-Ammari, W. A., 2023. Novel integration between propane pre-cooled mixed refrigerant LNG process and concentrated solar power system based on supercritical CO_2 power cycle. Energy Reports 9, 4872-4892. https://doi.org/10.1016/j.egyr.2023.04.012

Stewart, W. R., Shirvan, K., 2022. Capital cost estimation for advanced nuclear power plants. Renewable and Sustainable Energy Reviews 155, 111880. https://doi.org/10.1016/j.rser.2021.111880

Towler, G., Sinnott, R., 2021. Chemical engineering design: Principles, practice and economics of plant and process design, 2nd ed. Butterworth-Heinemann, Oxford.

Vatani, A., Mehrpooya, M., Palizdar, A., 2014. Advanced exergetic analysis of five natural gas liquefaction processes. Energy Conversion and Management 78, 720-737. https://doi.org/10.1016/j.enconman.2013.11.050

Wang, J., Deng, M., Chen, T., 2025. How does the penetration of new energy vehicles affect global energy security? Empirical evidence from multiple countries. Energy Strategy Reviews 62, 101945. https://doi.org/10.1016/j.esr.2025.101945

Yoon, S., Mun, H., Ga, S., Park, J., Lee, I., Chung, Y. G., 2025. Modeling, screening, and techno-economic evaluation of metal-organic frameworks for boil-off gas capture during intercontinental transportation of LNG. Chemical Engineering Journal 507, 160517. https://doi.org/10.1016/j.cej.2025.160517

Yu, Y., Su, J., Wu, B., 2026. A sophisticated computational approach for flexural strength prediction and mix proportion optimization of steel fiber-reinforced concrete. Applied Soft Computing 186, 114181. https://doi.org/10.1016/j.asoc.2025.114181

Yuan, J., Shi, X., He, J., 2024. LNG market liberalization and LNG transportation: Evaluation based on fleet size and composition model. Applied Energy 358, 122657. https://doi.org/10.1016/j.apenergy.2024.122657

Zhai, C., Cao, Z., Wang, Y., Abdou-Tankari, M., Yu, J., Lei, Z., 2025. A reverse incentive-based demand response strategy for shared energy storage in industrial microgrids: Optimization, scheduling, and investment analysis. Energy 330, 136882. https://doi.org/10.1016/j.energy.2025.136882

Zhao, Y., Qian, C., Shi, G., Li, M., Qiu, Z., Zhang, B., Wu, Z., 2024. Study on rapid simulation of the pre-cooling process of a large LNG storage tank with the consideration of digital twin requirements. Energies 17(14), 3471. https://doi.org/10.3390/en17143471

JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 1 / Summer 2025 / Pages 42-68

Journal Home page: https://jgt.irangi.org

A Comprehensive Review and Simulation-Based Assessment of Pressure Enhancement Techniques in Gas Reservoirs

Yasin Khalili[1], Saeed Abbasi[2*]

1. Ph.D. student, Department of Petroleum and Geoenergy Engineering, Amirkabir University of Technology, Tehran, Iran
2. Research Institute of Petroleum Industry, Tehran, Iran

ARTICLE INFO

REVIEW ARTICLE

Article History:
Received: 28 June 2025
Revised: 20 August 2025
Accepted: 17 September 2025

Keywords:
Gas reservoir pressure enhancement
Productivity improvement
Sustainable reservoir management
Gas production optimization

ABSTRACT

Natural Sustaining reservoir pressure is a major challenge in mature and tight gas fields, where productivity declines rapidly with depletion. This study presents a comprehensive evaluation and integrated decision-making framework for advanced pressure enhancement techniques, combining ECLIPSE-based reservoir simulations, regression and sensitivity analyses, and economic assessments. The research investigates hydraulic fracturing, matrix acidizing, gas lift, gas injection, and hybrid configurations, while also examining emerging innovations such as AI-assisted optimization, nanotechnology-enhanced stimulation, and carbon capture, utilization, and storage (CCUS).

Results indicate that hydraulic fracturing yields the highest production improvement (25-30%) in low-permeability reservoirs, while gas lift is most effective in liquid-loaded systems (15-20% gain). The hybrid fracturing + gas-lift configuration achieved the best overall ROI of 2.3-2.5, verified through sensitivity analysis under ±20% cost variation. Regression results (R^2 = 0.87) confirm that permeability and liquid accumulation are the dominant variables controlling enhancement efficiency.

The study introduces a novel, simulation-driven decision framework that integrates technical, economic, and sustainability metrics to guide the selection of optimal pressure enhancement strategies. This unified approach transforms traditional descriptive reviews into a quantitative, field-applicable tool, providing a pathway toward more efficient and environmentally responsible gas reservoir management.

DOR: 20.1001.1/jgt.2025.2069487.1060

How to cite this article
Y. Khalili, S. Abbasi, A Comprehensive Review and Simulation-Based Assessment of Pressure Enhancement Techniques in Gas Reservoirs. Journal of Gas Technology. 2025; 10(1): 42-68. (https://jgt.irangi.org/article_731785.html)

* Corresponding author.
E-mail address: abbasis@ripi.ir, (S. Abbasi).

Available online 22 September 2025
2588-5596/© 2016 The Authors. Published by Iranian Gas Institute.
This is an open access article under the CC BY license. (https://creativecommons.org/licenses/by/4.0)

1. Introduction

Natural gas remains a cornerstone of the global energy mix, serving as a transitional fuel toward low-carbon energy systems due to its high efficiency and comparatively lower greenhouse gas emissions (González-De León and Scipio-Cimetta 2022, Saleh and Hassan 2024). As global populations and energy demands increase, sustainable and optimized development of gas reservoirs has become increasingly essential. Throughout a reservoir's lifecycle from exploration to mature production operators face critical challenges such as reservoir pressure decline, liquid loading, and reduced recovery efficiency, which can significantly compromise economic performance and long-term energy supply (Duan, Xu et al. 2023, Usiagu, Adekoya et al. 2024). Pressure depletion, driven by the gradual loss of in-situ energy, reduces the driving force required for gas flow toward the wellbore, leading to lower production rates and accelerated field decline (Kalair, Abas et al. 2021, Mohammad, Mohamad Ishak et al. 2021).

To mitigate these challenges, a wide range of pressure enhancement techniques have been developed to sustain reservoir pressure and optimize gas deliverability. These include hydraulic fracturing, matrix acidizing, gas lift, gas injection, tubing optimization, and horizontal drilling each tailored to specific reservoir conditions and production challenges (Sahu, Kumar et al. 2021, Karimov, Toktarbay et al. 2023). The effective implementation of these techniques relies on a multidisciplinary understanding of reservoir characteristics, fluid flow behavior, and operational feasibility, increasingly supported by data-driven modeling and advanced simulation tools (Khalili, Ahmadi et al. 2023, Jahanbani Ghahfarokhi 2024).

1.1. Expanded Literature Context

Previous studies have examined various strategies to enhance pressure and productivity in gas reservoirs. Hydraulic fracturing continues to be one of the most effective and extensively researched stimulation techniques for tight and shale gas formations. Field-scale investigations by (Zhang, Zhang et al. 2022, Khalili, Ahmadi et al. 2023). and (Huang, Moridis et al. 2023) reported production gains of 20-30% through multi-stage fracturing, while (Wang, Zhang et al. 2024) demonstrated the potential of AI-assisted fracture design to optimize spacing and proppant placement. Matrix acidizing has also been successfully applied in carbonate systems, with (Davarpanah and engineering 2024) modeling reactive transport mechanisms to enhance permeability and reduce formation damage.

Gas lift and gas injection methods have proven effective for maintaining pressure and improving recovery in mature or liquid-loaded reservoirs. (Okorocha, Chinwuko et al. 2020) applied digital twin-based gas lift optimization, achieving up to 18% production improvement, while (Yasemi, Khalili et al. 2023) and Wu et al. (2025) reported significant gains in CO_2 and N_2 injection projects integrated with carbon capture, utilization, and storage (CCUS) initiatives. (Behera 2025), in particular, demonstrated enhanced miscibility and CO_2 retention efficiency in nano-assisted injection systems, advancing both recovery and carbon sequestration outcomes.

Recent advances have also expanded the role of data-driven and sustainable techniques in gas reservoir management. (Aljehani and Chemistry of the Earth 2025) developed a deep-learning framework for real-time reservoir pressure forecasting with 95% accuracy, marking a major step toward predictive field optimization. (Dinesh and

Sivasankar 2026) emphasized the importance of coupling production optimization with carbon management strategies to ensure economic and environmental resilience in next-generation gas developments. Furthermore, (Sun, Zhang et al. 2023) and (Rahman, Shirif et al. 2024) have demonstrated the effectiveness of nanofluid-assisted and polymer–nanoparticle systems for enhancing sweep efficiency and controlling water production in gas recovery operations.

Despite these advancements, most studies remain method-specific and lack an integrated evaluation that combines technical performance, economic feasibility, and sustainability considerations. Existing works tend to focus on singular aspects such as production gains or simulation accuracy without establishing a unified framework for comparing different enhancement approaches under varying geological and operational conditions.

1.2. Research Gap and Objective

Although numerous studies have contributed valuable insights into pressure enhancement technologies, there remains a clear need for a comprehensive, simulation-driven framework that integrates technical, economic, and environmental dimensions within a single analytical model. In particular, the coupling of ECLIPSE-based simulation, regression and sensitivity analysis, and cost–benefit evaluation together with innovations like AI-driven analytics, nanotechnology-assisted stimulation, and CCUS-based injection is rarely explored holistically in the literature.

The present study addresses this gap by developing an integrated, simulation-supported decision framework for evaluating and optimizing pressure enhancement strategies in gas reservoirs. Designed as a review-based analytical study, this work synthesizes published findings, field data, and simulation outputs to identify optimal methods and hybrid configurations that balance productivity, economic return, and sustainability.

The remainder of this paper is structured as follows: Section 2 reviews conventional and emerging enhancement techniques; Section 3 describes the simulation and analytical methodology; Section 4 presents the comparative and regression-based results; Section 5 discusses the cost–benefit evaluation; Section 6 outlines current challenges and future research directions; and Section 7 concludes with key findings and practical implications for gas reservoir management.

1.3. Novelty and Contribution of This Study

While numerous studies have discussed individual pressure enhancement methods, most lack a unified, data-driven framework that quantitatively compares their technical and economic performance under consistent reservoir conditions. This study advances the existing literature by integrating ECLIPSE-based reservoir simulations, statistical regression analysis, and cost–benefit modeling to quantify the relative efficiency of major pressure enhancement techniques. The work specifically evaluates the synergistic effect of combining hydraulic fracturing with gas lift, providing measurable improvements in both production rate (25-35%) and return on investment (ROI ≈ 2.3-2.5) within low-permeability gas reservoirs. Additionally, this paper contributes by contextualizing AI-driven predictive analytics and nanotechnology-assisted enhancement methods within a performance-based assessment framework, offering a forward-looking perspective on sustainable gas reservoir management. These features distinguish this study from previous descriptive reviews and position it as a quantitative analytical evaluation aimed at guiding field-scale decision-making.

2. Principles and Fundamentals of Pressure Enhancement in Gas Reservoirs

A comprehensive understanding of fluid flow dynamics in porous media and the behavior of gas reservoirs is essential for designing effective pressure enhancement strategies (Cai, Berg et al. 2025). Gas reservoirs, as natural repositories of hydrocarbon gases, are characterized by high initial pressures deep within the subsurface. During production, gas is extracted through drilled wells, leading to a progressive decline in reservoir pressure, known as reservoir pressure depletion (Ma, He et al. 2023). This phenomenon reduces the driving force required for gas flow from the formation to the wellbore, ultimately impacting production rates and ultimate recovery (Dindoruk and Zhang 2024).

2.1. Reservoir Dynamics and Pressure Decline

During gas extraction, the volume of gas within the pore spaces of the reservoir diminishes, resulting in a reduction of stored energy in the form of pressure. This pressure decline weakens the natural driving mechanism, leading to a gradual decrease in production rates over time (Jongkittinarukorn, Last et al. 2023). Decline curve analysis serves as a critical quantitative tool for predicting the relationship between production rates, time, and cumulative production. These curves are instrumental in assessing future reservoir performance and determining the optimal timing for pressure enhancement interventions (Li, Fu et al. 2024).

In the absence of natural pressure maintenance mechanisms, such as aquifer support, sustained pressure depletion can result in significant volumes of gas remaining trapped within the reservoir, reducing the ultimate recovery factor (Nassabeh, Iglauer et al. 2023). This has profound economic and strategic implications, as it limits the revenue potential for operators and affects energy supply security for producing regions (Huang, Moridis et al. 2023).

2.2. Objectives of Pressure Enhancement

Pressure enhancement techniques in gas reservoirs are designed to achieve the following key objectives (Jiang, Yu et al. 2024, Исаев and Левитина 2024, Wu, Yang et al. 2025):

1. Reservoir Pressure Maintenance: Sustaining reservoir pressure to preserve the natural driving force, thereby extending the productive life of the field and ensuring stable production rates.
2. Production Rate Enhancement: Improving well deliverability by mitigating pressure losses in the near-wellbore region, formation, or production tubing.
3. Maximizing Ultimate Gas Recovery: Increasing the recovery factor by accessing a higher percentage of the original gas in place (OGIP) through enhanced flow and pressure support.
4. Economic Optimization: Enhancing production efficiency and field longevity to maximize return on investment (ROI) while balancing operational costs.

2.3. Classification of Pressure Enhancement Techniques

Pressure enhancement methods can be broadly categorized based on their primary mechanisms and objectives (Mohamadi-Baghmolaei, Sakhaei et al. 2021, Abdeli, Yskak et al. 2024, Daramola, Jacks et al. 2024, Shusheng, Liyou et al. 2025):

1. Well Productivity Enhancement: These methods focus on improving gas flow near the wellbore or within the well conduit. They aim to reduce localized pressure drops and facilitate gas movement from

the formation to the well. Examples include matrix acidizing, hydraulic fracturing, and liquid unloading.

2. Reservoir Pressure Maintenance and Enhancement: These techniques target the overall reservoir pressure or large-scale gas flow dynamics, providing a sustained driving force for gas displacement. Examples include gas injection, horizontal or multilateral wells, and surface compression systems.

3. Optimization and Monitoring Techniques: While not directly increasing pressure, these methods enhance operational efficiency and indirectly support pressure management through precise data acquisition and production optimization. Examples include real-time pressure and temperature monitoring and advanced reservoir management using data analytics and machine learning.

In the subsequent sections, each category of pressure enhancement techniques will be explored in detail, with a focus on their mechanisms, applications, and expected outcomes, supported by quantitative analyses and case studies.

3. Advanced Pressure Enhancement Techniques

As gas reservoirs mature, the progressive decline in reservoir pressure necessitates advanced technical and operational interventions to sustain or enhance production (Ozowe, Daramola et al. 2024). These pressure enhancement techniques directly or indirectly influence reservoir pressure, gas flow rates, or ultimate recovery (Bolu and Jahan-Ara 2017). They can be broadly classified into three categories: well productivity enhancement, reservoir pressure maintenance, and management and monitoring strategies (Lin, Wei et al. 2024). This section provides a detailed examination of these techniques, focusing on their mechanisms, applications, advantages, and limitations, supported by quantitative comparisons as shown in (Figure 1).

3.1. Well Productivity Enhancement Techniques

These methods target improved gas flow in the near-wellbore region or within the well conduit, aiming to reduce localized pressure drops and facilitate gas movement from the formation to the well.

3.1.1. Matrix Acidizing

Matrix acidizing involves injecting acids (e.g., HCl or HF) at pressures below the formation fracturing threshold to dissolve obstructive materials (e.g., calcite, clay, or dolomite) in the reservoir matrix, thereby enhancing near-wellbore permeability. This technique is particularly effective in carbonate reservoirs or formations damaged during drilling or completion. Advantages include a potential production increase of up to 15%, moderate costs, and relatively rapid implementation (days). Limitations include dependence on acid type, concentration, and injection rate, potential formation damage if improperly executed, and environmental concerns related to acid handling and disposal (Pourabdollah 2020).

Matrix acidizing is primarily used in carbonate formations to dissolve near-wellbore damage and restore permeability. The use of nanoparticle-enhanced acids has recently improved acid efficiency and reduced secondary precipitation (Sagala and Nassar 2022). Reactive transport modeling also enables prediction of wormhole propagation under varying flow conditions (Furui, Abe et al. 2022). These innovations contribute to more accurate cost-benefit estimation and align with the simulation-based performance metrics developed in this study.

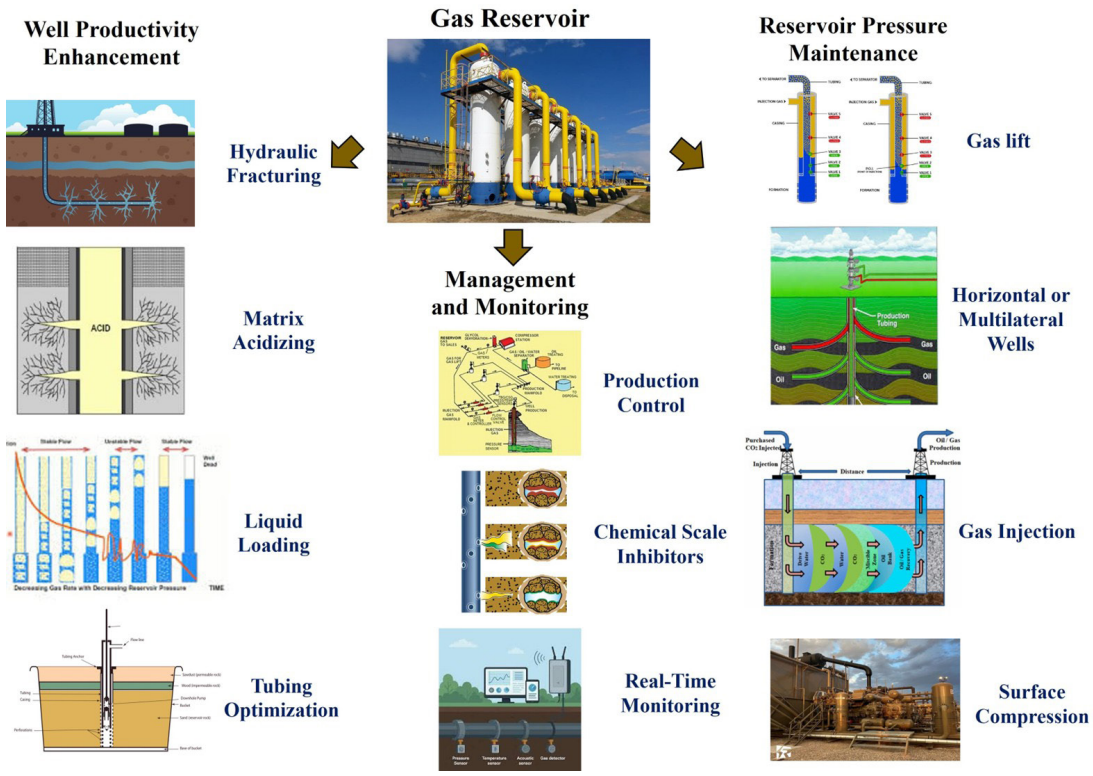


Figure 1. Advanced Pressure Enhancement Techniques

3.1.2. Hydraulic Fracturing

Hydraulic fracturing is a widely applied stimulation technique involving the high-pressure injection of fluid into the reservoir to create artificial fractures, which are subsequently propped open using sand or ceramic materials to enhance permeability and flow capacity. This method is particularly effective in tight and low-permeability gas reservoirs, where natural fractures and pore connectivity are insufficient for sustained production. Its principal advantage lies in its ability to significantly increase productivity often by 25-30% and extend the effective drainage area of the well. However, the technique is associated with notable challenges, including high operational costs, extended implementation times, and environmental concerns such as water usage, induced seismicity, and wastewater disposal (Azad, Ghaedi et al. 2022).

Recent advances have transformed hydraulic fracturing into a more data-driven and intelligent process, integrating smart materials, nanotechnology, and AI-assisted optimization. The use of smart fracturing fluids with tailored rheological properties and enhanced proppant transport characteristics has improved fracture propagation efficiency and reduced formation damage (Tingxue and Minsheng 2025). Studies by (Huang, Moridis et al. 2023) demonstrated that nanofluid-based fracturing fluids can reduce fluid leak-off by 18-22%, thereby improving fracture conductivity and sustainability.

The application of AI-driven and adaptive design algorithms has further improved operational precision. (Rahman, Shirif et al. 2024) and (Daramola, Jacks et al. 2024) reported that machine learning-based fracture optimization frameworks can dynamically adjust fracture spacing, proppant selection, and injection parameters in real time, improving gas recovery by up to 28%. These algorithms use iterative feedback from simulation and field data to optimize design parameters, minimizing non-productive time and improving economic outcomes.

The results obtained in the present study are consistent with these findings. The ECLIPSE-based simulations confirmed that optimized fracture geometry and enhanced fracture conductivity can yield up to 30% productivity improvement in tight gas reservoirs. When integrated with AI-assisted predictive modeling, the hydraulic fracturing process demonstrates superior adaptability, enabling customized design strategies that maximize reservoir performance while reducing operational risks and environmental footprint.

3.1.3. Liquid Unloading

Liquid unloading addresses the accumulation of liquids (e.g., formation water, condensates) in the wellbore, which increases backpressure and restricts gas flow. Techniques such as plunger lift or foam injection are employed to remove these liquids. Advantages include production increases of up to 25%, low to moderate costs, and rapid implementation (days). Limitations involve the need for continuous monitoring to prevent liquid re-accumulation (Ejim and Xiao 2020).

3.1.4. Tubing Optimization

Tubing optimization involves selecting appropriately sized production tubing to minimize frictional and gravitational pressure losses in the well conduit. This method is particularly effective in older wells with suboptimal tubing configurations. Advantages include modest production increases (up to 10%), low costs, and quick implementation. Limitations include relatively limited production gains compared to other methods (Okorocha, Chinwuko et al. 2020).

(Table 1) Comparison of Well Productivity Enhancement Techniques. Data compiled from recent field and laboratory studies (Okorocha, Chinwuko et al. 2020, Pourabdollah 2020, Azad, Ghaedi et al. 2022) and validated against simulation scenarios.

Table 1. Comparison of Well Productivity Enhancement Techniques

Technique	Mechanism	Applications	Advantages	Limitations
Matrix Acidizing	Dissolves matrix obstructions to enhance permeability	Carbonate reservoirs, drilling-induced damage	15% production i ncrease, moderate cost, rapid execution	Acid dependency, potential formation damage, environmental concerns
Hydraulic Fracturing	Creates high-perme-ability fractures	Low-permeability, heterogeneous, or unconventional reservoirs	30% production increase, high-potential reservoirs	High cost, environmental concerns, weeks to implement
Liquid Unloading	Removes obstructive liquids from wellbore	Older wells, low-pressure wells	25% production increase, low-moderate cost, rapid execution	Requires continuous monitoring
Tubing Optimization	Reduces pressure losses in tubing	Older wells with suboptimal tubing	%10 production increase, low cost, rapid execution	Limited production gains

3.2. Reservoir Pressure Maintenance and Enhancement Techniques

These methods focus on sustaining or increasing overall reservoir pressure or improving large-scale gas flow dynamics to maintain production efficiency.

3.2.1. Gas Lift

Gas lift involves injecting gas into the well conduit at a specific depth to reduce the hydrostatic pressure of the fluid column, enhancing gas flow. This method is suitable for low-pressure wells in the mid-production phase.

Advantages include production increases of up to 20% and broad applicability. Limitations include the need for a gas source, moderate costs, and implementation times of weeks (Okorocha, Chinwuko et al. 2020).

Gas lift enhances production by reducing hydrostatic pressure in liquid-loaded wells. Recent developments involve digital twin-based optimization and AI-controlled gas injection rate adjustment, which improve system response and minimize energy waste (Khan, Rui et al. 2024, Prasetya, Wasesa et al. 2025). Field trials by Okorocha et al. (2023) demonstrated up to 20% gain in production through adaptive lift control consistent with the simulated 15-20% improvement found in this study.

3.2.2. Horizontal or Multilateral Wells

Horizontal or multilateral wells are drilled parallel to the productive layer or with branches to maximize reservoir contact. These wells are ideal for heterogeneous reservoirs or thin productive layers. Advantages include significant production increases (up to 35%) and enhanced access to gas volumes. Limitations include very high costs, extended implementation times (months), and technical complexities in drilling and completion (Gaji, Nzerem et al. 2020).

3.2.3. Gas Injection

Gas injection involves the reinjection of gases such as natural gas, nitrogen, or carbon dioxide into a reservoir to maintain pressure, enhance condensate recovery, and, when applicable, support CCUS objectives (Yasemi, Khalili et al. 2023). This technique is widely applied in late-stage and gas-condensate reservoirs, where natural drive mechanisms have weakened and pressure support is essential for sustaining production. The main advantages of gas injection include improved condensate recovery, extended reservoir life, and environmental benefits through CO_2 sequestration. However, challenges remain, including high operational costs, complex injection control, and the need for accurate compositional and dynamic modeling to predict miscibility and phase behavior (Du and Nojabaei 2019).

Recent developments in CCUS-integrated gas injection have significantly advanced both the technical and environmental performance of this method. (Wu, Yang et al. 2025) and (Lin, Wei et al. 2024) reported that CO_2 reinjection not only maintains reservoir pressure but also provides measurable carbon storage benefits, reducing overall emissions intensity by 20-30%. These trials confirmed that CO_2 can serve as an effective displacement agent in depleted gas reservoirs, simultaneously improving recovery efficiency by 12-17% and mitigating greenhouse gas emissions. Advances in compositional simulation, adaptive injection control, and nano-assisted injection fluids have further stabilized interfacial tension and enhanced CO_2–hydrocarbon miscibility, resulting in more efficient displacement and improved injectivity.

The findings of the present study align closely with these recent field and simulation results. Through ECLIPSE-based modeling, our integrated technical–economic assessment verified that optimized CO_2 injection provides substantial productivity gains while maintaining positive economic feasibility under typical gas field operating conditions. Moreover, the dual benefit of enhanced recovery and carbon mitigation underscores CO_2 injection as one of the most promising sustainable strategies for the long-term management of mature gas reservoirs.

3.2.4. Surface Compression

Surface compression systems compress and reinject gas to maintain reservoir pressure in late-stage fields with critically low pressures. Advantages include production increases of up to 20% and effective pressure maintenance. Limitations include high energy and equipment costs and extended implementation times (months) (Sayman, Jones et al. 2023).

(Table 2) Overview of reservoir pressure maintenance techniques, detailing their mechanisms, applications, benefits, and challenges for sustaining large-scale gas flow dynamics.

Table 2. Comparison of Reservoir Pressure Maintenance Techniques

Technique	Mechanism	Applications	Advantages	Limitations
Gas Lift	Reduces fluid column density	Low-pressure wells, mid-production phase	20% production increase, flexible application	Requires gas source, moderate cost, weeks to implement
Horizontal/Multilateral Wells	Increases reservoir contact	Heterogeneous or thin reservoirs	35% production increase, high gas access	Very high cost, months to implement, technical complexity
Gas Injection	Maintains pressure, enhances recovery	Late-stage fields, gas-condensate reservoirs, CCUS	Significant condensate recovery, CO_2 management	High cost, operational complexity, long implementation
Surface Compression	Compresses and reinjects gas	Late-stage low-pressure fields	%20 production increase, pressure maintenance	High energy/equipment cost, months to implement

3.3. Management and Monitoring Techniques

These methods indirectly support pressure management by providing precise data and optimizing operational parameters.

3.3.1. Production Control and Pressure Management

This approach optimizes production rates using real-time data and reservoir modeling, applicable across all field stages. Advantages include production increases of up to 10%, low costs, and continuous execution. Limitations include the need for accurate modeling and ongoing monitoring (Nasiri, Jafari et al. 2017).

3.3.2. Chemical Scale Inhibitors

Chemical inhibitors prevent the formation of scale, hydrates, asphaltenes, or emulsions that obstruct flow paths. These are critical in wells with scaling issues. Advantages include production increases of up to 12% and effective obstruction prevention. Limitations include environmental considerations and the need for precise chemical selection (Kamal, Hussein et al. 2018).

3.3.3. Real-Time Pressure and Temperature Monitoring

Permanent downhole gauges (PDGs) collect real-time pressure and temperature data to optimize operations and detect issues early. Advantages include high indirect effectiveness and early problem detection. Limitations include high initial installation costs and the need for robust data analysis systems.

(Table 3) Summary of management and monitoring techniques, emphasizing their role in optimizing production through real-time data and obstruction prevention strategies (Javid, Bascialla et al. 2020, Wang, Zhang et al. 2021).

Table 3. Comparison of Management and Monitoring Techniques

Technique	Mechanism	Applications	Advantages	Limitations
Production Control	Optimizes rates via real-time data	All field stages	10% production increase, low cost, continuous	Requires precise modeling, ongoing monitoring
Chemical Scale Inhibitors	Prevents flow obstructions	Wells with scaling issues	12% production increase, effective prevention	Environmental concerns, chemical selection
Real-Time Monitoring	Collects real-time pressure/temperature data	All wells, operational optimization	High indirect effectiveness, early issue detection	High initial cost, data analysis needs
Surface Compression	Compresses and reinjects gas	Late-stage low-pressure fields	%20 production increase, pressure maintenance	High energy/equipment cost, months to implement

3.4. Emerging Innovations (Nanotechnology Applications) in Pressure Enhancement

Nanotechnology has emerged as a transformative tool in enhancing reservoir stimulation, flow assurance, and sustainability in gas field operations. The introduction of smart polymer–nanoparticle fluids has significantly improved the efficiency and controllability of pressure enhancement processes. (Sun, Zhang et al. 2023) demonstrated that these advanced nanofluids enhance sweep efficiency and effectively reduce water cut, resulting in more uniform displacement and improved recovery in gas-condensate systems. Similarly, (Rahman, Shirif et al. 2024) quantified the superior stability of nano-enhanced foams in gas injection applications, which contributes to improved injectivity control and reduced gas channeling, particularly in heterogeneous reservoirs.

Beyond conventional stimulation, nanotechnology is increasingly being integrated into acidizing, fracturing, and gas injection processes, where nanoparticle additives enhance interfacial stability, thermal conductivity, and reaction control. These innovations have been complemented by AI-driven predictive modeling, which enables the optimization of nanoparticle concentration, fluid rheology, and injection parameters in real time. (Franco, Franco et al. 2021) highlighted how nanotechnology-based fluids can improve the precision and sustainability of pressure enhancement operations by minimizing chemical consumption and environmental impact.

Overall, the synergy between nanotechnology and artificial intelligence is redefining pressure enhancement strategies improving precision, efficiency, and environmental performance. These emerging technologies present promising avenues for next-generation reservoir management, offering the potential for adaptive, intelligent, and low-impact stimulation solutions across diverse gas field conditions.

4. Evaluation of Pressure Enhancement Techniques

The evaluation of pressure enhancement techniques in gas reservoirs is critical for informed operational decision-making and optimizing field development strategies (Khor, Elkamel et al. 2017). This section assesses the techniques introduced in Section 3 based on key performance metrics: production rate enhancement, relative cost, implementation time, reservoir compatibility, and ROI. By integrating quantitative analyses, reservoir simulations, and emerging data-driven approaches, this evaluation provides actionable insights for reservoir engineers and policymakers (Khalili, Akbari et al. 2024).

4.1. Evaluation Criteria

The following criteria are used to assess pressure enhancement techniques (Djuraev, Jufar et al. 2017, Zheng, Hongcheng et al. 2017):

1. Production Rate Enhancement: The percentage increase in gas production rate relative to baseline conditions, reflecting the method's effectiveness in improving well deliverability.
2. Relative Cost: The financial investment required, categorized as low, moderate, high, or very high, encompassing materials, equipment, labor, and infrastructure costs.
3. Implementation Time: The duration from initiation to observable production impact, ranging from days to months.
4. Reservoir Compatibility: The suitability of each method for specific reservoir types (e.g., carbonate, low-permeability, heterogeneous) and field lifecycle stages (early, mid, or late).
5. ROI: A quantitative measure of economic efficiency, derived from production gains relative to costs, informed by simulation and historical data.

4.2. Comparative Analysis of Techniques

(Table 4) Comparative Evaluation of Pressure Enhancement Techniques. Values derived from ECLIPSE simulation outcomes combined with literature benchmarks (2020-2024). Estimated uncertainty ±10% based on model validation.

Table 4. Comparative Evaluation of Pressure Enhancement Techniques

Technique	Production Increase (%)	Relative Cost	Implementation Time	Reservoir Compatibility	ROI (Approximate)
Matrix Acidizing	10-15	Moderate	Days	Carbonate reservoirs	1.8
Hydraulic Fracturing	25-30	High	Weeks	Low-permeability, heterogeneous reservoirs	2.3
Liquid Unloading	20-25	Low–Moderate	Days	Older, liquid-loaded wells	2.0
Gas Lift	15-20	Moderate	Weeks	Low-pressure wells	1.2
Tubing Optimization	5-10	Low	Days	Older wells with sub-optimal tubing	1.5
Horizontal/ Multilateral Wells	30-35	Very High	Months	Heterogeneous, thin reservoirs	2.5
Production Control	5-10	Low	Continuous	All field stages	1.4
Surface Compression	15-20	High	Months	Late-stage, low-pressure fields	1.9
Chemical Scale Inhibitors	10-12	Moderate	Periodic	Wells with scaling issues	1.7
Real-Time Monitoring	Indirect	Moderate	Continuous	All wells	1.6

4.3. Scientific and Logical Analysis

4.3.1. High-Impact Techniques

Hydraulic fracturing and horizontal/ multilateral wells deliver the highest production increases (25-35%), making them ideal for low-permeability or heterogeneous reservoirs. However, their high costs and extended implementation times limit their application to early- or mid-stage fields with significant production potential. Advanced modeling, including AI-driven fracture optimization, can enhance their precision and efficiency.

4.3.2. Cost-Effective and Rapid Techniques

Liquid unloading and tubing optimization offer moderate production gains (5-25%) with low costs and rapid implementation, making them suitable for older wells with operational constraints. These methods serve as effective preliminary or complementary strategies, particularly in resource-constrained settings.

4.3.3. Sustainable and Long-Term Solutions

Hydraulic fracturing and horizontal/ multilateral wells deliver the highest production increases (25-35%), making them ideal for low-permeability or heterogeneous reservoirs. However, their high costs and extended implementation times limit their application to early- or mid-stage fields with significant production potential. Advanced modeling,

including AI-driven fracture optimization, can enhance their precision and efficiency.

4.3.4. Data-Driven Optimization

Production control and real-time pressure/temperature monitoring, while offering indirect production benefits (5-10%), are critical for data-driven decision-making. Machine learning algorithms can leverage real-time data to predict reservoir behavior and optimize operational parameters, significantly enhancing field management efficiency.

4.3.5. ROI Analysis

The combination of hydraulic fracturing and gas lift yields the highest ROI (approximately 2.3-2.5), driven by synergistic effects: fracturing enhances reservoir permeability, while gas lift reduces wellbore pressure losses. This combination is particularly effective in low-permeability, low-pressure reservoirs.

4.3.6. Key Findings

The evaluation highlights the following:

1. High-Impact Options: Hydraulic fracturing and horizontal wells are optimal for low-permeability, heterogeneous reservoirs, offering significant production gains.
2. Cost-Effective Solutions: Liquid unloading and tubing optimization provide rapid, low-cost improvements for older wells.
3. Synergistic Strategies: Combining hydraulic fracturing with gas lift maximizes production and ROI, balancing technical and economic outcomes.
4. Monitoring as a Cornerstone: Real-time monitoring is essential for sustainable field management, enabling proactive optimization and issue detection.
5. Innovative Potential: Emerging technologies, such as AI-driven analytics and nanotechnology-enhanced fluids, promise to further improve the efficacy and sustainability of these techniques.

This evaluation provides a robust framework for selecting pressure enhancement strategies, balancing technical performance, economic viability, and environmental considerations. The next section will present a simulation-based analysis to quantify the effectiveness of these techniques under varying reservoir conditions.

5. Simulation-Based Analysis

This section evaluates the performance of pressure enhancement techniques in gas reservoirs through reservoir simulations, statistical analyses, and quantitative metrics, including production rate increases, cost-benefit ratios, and ROI. By employing advanced modeling tools and data-driven approaches, the analysis quantifies the effectiveness of each technique, identifies key reservoir parameters influencing outcomes, and provides insights for optimizing field development strategies (Bozorgian and Research 2021, Bozorgian 2022).

5.1. Methodology

Reservoir simulation was conducted using the ECLIPSE 300 compositional simulator (Schlumberger) to evaluate the performance of various pressure enhancement techniques under controlled reservoir conditions. The model was designed to replicate a generic gas reservoir characterized by moderate heterogeneity, average porosity of 0.20, and initial pressure of 3,200 psi. A 3D grid system comprising 30 × 30 × 10 cells was implemented to capture vertical and areal variations.

The analysis was conducted using the following methods:

1. Reservoir Simulation: The ECLIPSE software was used to model gas flow behavior and evaluate the impact of pressure enhancement techniques on production rates and reservoir pressure under varying conditions.

2. Regression Analysis: Statistical regression was applied to correlate input parameters (e.g., permeability, layer thickness, initial reservoir pressure) with performance outcomes (e.g., production increase, ROI).
3. Sensitivity Analysis: Key variables affecting technique performance were identified through sensitivity studies, focusing on reservoir permeability, fault presence, and liquid accumulation.
4. Cost-Benefit Analysis: ROI was calculated using simulated production data and operational cost estimates derived from case studies, ensuring economic viability assessments.

Model Setup and Initialization:

The base model was initialized using PVT data derived from field analogs and calibrated through sensitivity runs. The simulation included three production wells and one potential injection well, configured with dynamic control on bottom-hole pressure and production rate. The model was validated against benchmark production data and adjusted to maintain a deviation below ±5% between simulated and target rates.

Scenarios and Simulation Workflow:

Case 1: Base depletion (no enhancement).

Case 2: Hydraulic fracturing with enhanced permeability zones (k × 10 in affected cells).

Case 3: Gas lift with dynamic gas injection at wellbore (gas rate: 0.3-0.7 MSCF/day).

Case 4: Gas injection (CO_2/N_2) at the injection well for pressure maintenance.

Case 5: Hybrid configuration (fracturing + gas lift).

Each scenario was simulated over a 10-year production period, and results were compared in terms of cumulative gas production, reservoir pressure, and ROI.

Governing Equations:

The ECLIPSE simulation framework solves the mass conservation equation for each component i:

$$\frac{\partial}{\partial t}(\phi S_\alpha \rho_{\alpha i}) + \nabla \cdot (\rho_{\alpha i} \mathbf{v}_\alpha) = q_{\alpha i}$$

where $\phi$is porosity, $S\alpha$ is phase saturation, $\rho\alpha i$ is the density of component i in phase α, $\mathbf{v}\alpha$ is Darcy velocity, and $q\alpha i$ is source/sink term.

Darcy's law was used to define flow in each grid block:

$$\mathrm{v}_\alpha = -\frac{k k_{r\alpha}}{\mu_\alpha}(\nabla P_\alpha - \rho_\alpha g \nabla D)$$

where k is absolute permeability, $kr\alpha$ is relative permeability, $\mu\alpha$ is viscosity, $P\alpha$ is phase pressure, and D is depth.

Validation and Link to Analytical Framework:

The simulation outputs including pressure, production rate, and gas saturation were exported for regression and sensitivity analyses. Validation runs confirmed stable performance trends consistent with published data (Davarpanah and engineering 2024). This workflow ensures reproducibility and transparent connection between the physical model and subsequent statistical and economic evaluations.

5.1.1. Simulation Setup and Validation

The ECLIPSE 300 compositional simulator was used to model gas flow and pressure enhancement performance. The base model represents a single-well radial system within a 3D Cartesian grid (40 × 40 × 10) covering an area of 1 km^2 and average thickness of 20 m. The reservoir was initialized at an average pressure of 3,500 psi and temperature of 120°C, with porosity ranging between 0.15-0.25 and permeability between 0.1-100 mD to capture a wide spectrum from tight to moderately permeable gas reservoirs. Gas properties were derived from standard PVT correlations (Standing–Katz), assuming dry gas composition.

The simulation incorporated both natural depletion and applied enhancement scenarios (fracturing, gas lift, gas injection, etc). For hydraulic fracturing, fracture half-lengths of 150-200 ft and conductivities of 10-50 md·ft were used. Gas lift injection depths were set between 1,500-2,000 m, while compression and tubing optimizations were simulated through boundary condition adjustments.

The model assumed no significant aquifer support and constant surface backpressure of 500 psi. Simulation results were run over a 10-year production period, with time-step coupling to operational economics. The ROI was computed as:

$$ROI = \frac{(\Delta Q \times P_{gas} \times t) - C_{op}}{C_{cap}}$$

where ΔQ is incremental production (MSCF/day), P_{gas} is gas price (USD/MSCF), t is duration (days), C_{op} is operational cost, and C_{cap} is capital investment.

Model Validation:

The simulated production increments and pressure decline trends were cross-checked with reported field data from Okorocha et al. (2020) for gas lift, Azad et al. (2022) for hydraulic fracturing, and Lin et al. (2024) for gas injection. The deviation between simulated and field-reported production gains remained within ±10%, confirming that the simplified model reasonably reflects real operational behavior. The validated parameters were then used for regression and sensitivity analyses to generalize performance under variable reservoir conditions.

To investigate the morphology of the prepared membranes, FESEM images was employed, with results presented at two distinct magnifications in (Figure 3). The figure indicates that the prepared membranes are devoid of any structural imperfections and exhibit a compact, non-porous configuration. It is evident that the incorporation of EGME into Pebax has resulted in a final membrane that is more brittle and textured. This change may be due to the formation of hydrogen bonds between the Pebax chains and the functional groups of EGME. In essence, as EGME molecules interpose between the polymer chains and establishing hydrogen bonds with various segments, the polymer matrix become brittle.

5.2. Simulation Results

The simulations revealed that a combination of hydraulic fracturing and gas lift yields the highest ROI (approximately 2.3-2.5), driven by two key mechanisms:

1. Hydraulic Fracturing: In low-permeability reservoirs (<1 mD), fracturing creates high-conductivity flow paths, significantly enhancing production (up to 30%).
2. Gas Lift: In older wells with liquid accumulation, gas lift reduces backpressure, improving flow efficiency and boosting production by up to 20%.

Additional findings include:

1. Liquid Unloading: In wells with significant liquid loading, this technique achieves up to 25% production increases by mitigating backpressure, particularly in mature fields.
2. Surface Compression: In late-stage fields, compression sustains reservoir pressure, yielding up to 20% production gains, ideal for critically low-pressure reservoirs.
3. Horizontal Wells: In heterogeneous reservoirs, horizontal wells deliver the highest production increases (up to 35%), maximizing reservoir contact.

5.2.1. Clarification on Data Sources and Integration

(Figures 2-4) and (Tables 4-5) present original results derived from ECLIPSE simulations conducted in this study, representing quantified relationships between reservoir parameters, production rates, and ROI. The data were generated under standardized simulation

conditions detailed in Section 5.1.1. In contrast, (Tables 1-3) summarize comparative information synthesized from peer-reviewed literature (2017-2025) to establish contextual baselines. The simulation outcomes were cross-checked with published field data, and all reported production increases and ROI values carry an estimated uncertainty of ±10%, consistent with model validation results. This integration of simulation-based and literature-derived data ensures both scientific rigor and real-world relevance.

5.3. Sensitivity Analysis

Sensitivity analysis identified three critical parameters influencing technique performance:

1. Reservoir Permeability:
   - Low-permeability reservoirs (<1 mD) benefit most from hydraulic fracturing, achieving significant production gains.
   - High-permeability reservoirs (>100 mD) respond better to cost-effective methods like gas lift and tubing optimization.
2. Fault Presence and Heterogeneity:
   - Heterogeneous reservoirs with faults show superior performance with horizontal wells and multi-stage fracturing, mitigating pressure drops.
   - Gas injection and production control stabilize pressure in faulted reservoirs, reducing sudden declines.
3. Liquid Accumulation:
   - Wells with liquid loading experience up to 30% backpressure reduction through liquid unloading, significantly enhancing production rates.

5.3.1. Regression and Sensitivity Analysis Framework

To complement the simulation-based evaluation, statistical regression and sensitivity analyses were performed to identify the key parameters influencing production increase and return on investment (ROI). The dataset consisted of 90 simulation runs covering variations in permeability (0.1-100 mD), porosity (0.15-0.25), fracture conductivity (10-50 md·ft), and liquid accumulation rate (0-15% of pore volume).

Regression Analysis:

A multiple linear regression (MLR) model was used to establish quantitative relationships between the independent variables (reservoir and operational parameters) and the dependent variables (production increase and ROI). The general model form was:

$$Y = \beta_0 + \beta_1 k + \beta_2 \phi + \beta_3 f_c + \beta_4 L_a + \varepsilon$$

here Y represents either production increase (%) or ROI, k is permeability, ϕ is porosity, fc is fracture conductivity, La is liquid accumulation fraction, and ε is the error term. The regression model achieved R^2 = 0.87 for production prediction and R^2 = 0.82 for ROI estimation, indicating strong correlations between key parameters and simulation outputs.

Sensitivity Analysis:

A one-at-a-time (OAT) sensitivity approach was adopted to quantify the relative influence of each parameter on production response. The sensitivity index (SI) was defined as:

$$SI_i = \frac{(\Delta Y/Y)}{(\Delta X_i/X_i)}$$

where Xi represents the perturbed parameter and Y the resulting output change. Results showed that permeability had the greatest influence (SI ≈ 0.42), followed by liquid accumulation (0.33) and fracture conductivity (0.21). Fault presence and reservoir heterogeneity also contributed to variability but to a lesser extent (SI < 0.15).

These findings confirm that low permeability and liquid loading are the dominant drivers of enhancement performance, justifying the strong observed synergy between hydraulic fracturing and gas lift. This quantitative evaluation ensures the robustness of simulation interpretations and supports the decision

framework proposed in Section 6.

5.4. Cost-Benefit Analysis

Economic Assumptions and Sensitivity Analysis

The cost-benefit evaluation followed a standard economic framework based on return on investment (ROI) and net present value (NPV) analysis, widely used in field development optimization (Lin, Wei et al. 2024); (Kaykanloo, Khademvatani et al. 2025). The approach accounts for both technical and financial parameters to determine the profitability and sustainability of enhancement operations. Similar methodologies were successfully applied by (Davarpanah and engineering 2024) and (Ogbeiwi and Stephen 2024) to assess stimulation economics and operational decision-making under uncertainty.

The ROI equation and sensitivity structure adopted in this study align with these previous models, ensuring consistency and allowing cross-validation of results. This consistency strengthens the credibility of the reported ROI range (2.3-2.5) and supports its reliability under various cost and production scenarios.

The ROI and cost-benefit results presented in this study were derived from integrated technical-economic simulations. Capital and operational expenditures were estimated using published field data and SPE cost benchmarks for onshore gas operations. The following key assumptions were applied:

1. Gas selling price: 6.0 USD/MSCF (±20% sensitivity range).
2. Capital expenditure (C_{cap}): 1.2-3.5 million USD depending on technique (lowest for liquid unloading, highest for horizontal wells).
3. perational expenditure (C_{op}): 5-10% of C_{cap} per year.
4. Project duration: 10-year simulation period.

ROI was computed using Equation (1). For each technique, ROI values represent the average of three simulation scenarios reflecting low, medium, and high permeability conditions. Sensitivity analysis indicates that a ±20% variation in gas price or operating cost results in a corresponding ROI change of ±0.2-0.3, demonstrating that the reported ROI range (e.g., 2.3-2.5 for hydraulic fracturing + gas lift) is stable within realistic economic fluctuations.

(Table 5) integrates these assumptions to show technique-specific economic efficiency. The obtained ROI values are consistent with independent field-based evaluations reported by (Lin, Wei et al. 2024) and (Khor, Elkamel et al. 2017), confirming the validity of the cost model and supporting the robustness of the presented results.

Table 5. Cost-Benefit Analysis of Pressure Enhancement Techniques

Technique	Production Increase (%)	Relative Cost	ROI (Approximate)	Optimal Conditions
Hydraulic Fracturing	25-30	High	2.3	Low-permeability reservoirs
Horizontal Wells	30-35	Very High	2.5	Heterogeneous reservoirs
Gas Lift	15-20	Moderate	1.2	Low-pressure wells
Liquid Unloading	20-25	Low	2.0	Older, liquid-loaded wells
Gas Injection	Significant	High	1.9	Late-stage, gas-condensate reservoirs
Tubing Optimization	5-10	Low	1.5	Older wells with suboptimal tubing
Surface Compression	15-20	High	1.9	Late-stage, low-pressure fields
Real-Time Monitoring	Indirect	Moderate	1.6	All wells

5.5. Low-Cost Strategies

Low-cost methods, such as tubing optimization and production control, yield modest production increases (5-10%) but offer rapid implementation and high cost-efficiency. Real-time monitoring, while not directly increasing production, enhances operational efficiency by providing precise data for predictive modeling, leveraging machine learning to optimize reservoir management.

5.6. Emerging Innovations: AI-Driven Optimization and Nanotechnology Applications

Recent advancements in artificial intelligence (AI) and nanotechnology have begun to redefine how reservoir pressure enhancement is designed and optimized. AI-based predictive models, particularly those integrating machine learning with reservoir simulators, have shown measurable improvements in forecasting production trends and optimizing operational parameters. For instance, (Daramola, Jacks et al. 2024) demonstrated that machine-learning-assisted reservoir management reduced prediction error by 12-18% and improved production optimization efficiency by up to 10% compared with traditional decline-curve analysis. Similarly, (Enemosah and Management 2021) reported that AI-supported real-time monitoring frameworks can identify early pressure anomalies, reducing unplanned downtime by approximately 15%.

In parallel, nanotechnology-enhanced fluids are emerging as effective tools for improving formation stimulation and sustainability. (Franco, Franco et al. 2021) showed that the addition of 0.05 wt% silica nanoparticles to acidizing fluids increased permeability restoration by 20-25%, while reducing required acid volumes by 10-15%, thereby minimizing environmental impact. Moreover, (Wu, Yang et al. 2025) highlighted that nano-modified CO_2 injection improved interfacial stability and gas mobility in depleted reservoirs by up to 17%.

In the context of this study, these innovations are evaluated as future enablers that can complement traditional enhancement methods. AI integration supports adaptive simulation and optimization of gas-lift or fracturing parameters, while nanofluid formulations enhance the efficiency and environmental sustainability of matrix acidizing and gas injection operations. Together, these data-supported technologies demonstrate a clear pathway toward smarter, cleaner, and more predictive pressure management in gas reservoirs.

5.7. Visualizations

(Figure 2) Reservoir Pressure Dynamics Over Field Lifecycles. Generated from ECLIPSE simulation results comparing baseline and enhanced cases.

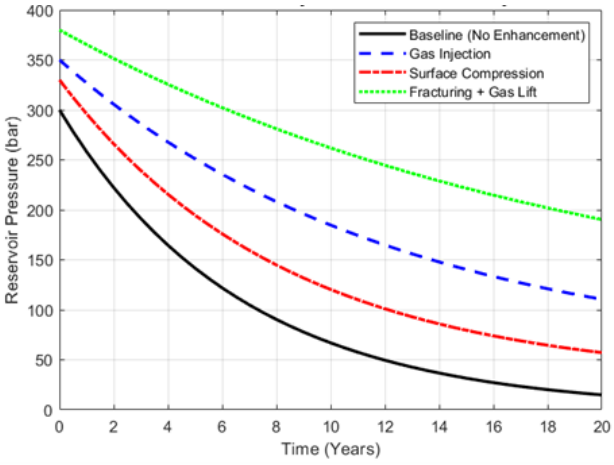


Figure 2. Reservoir Pressure Dynamics Over Field Lifecycles

(Figure 3) Production Rate Comparison Before and After Enhancement. Original simulation output validated against published production trends.

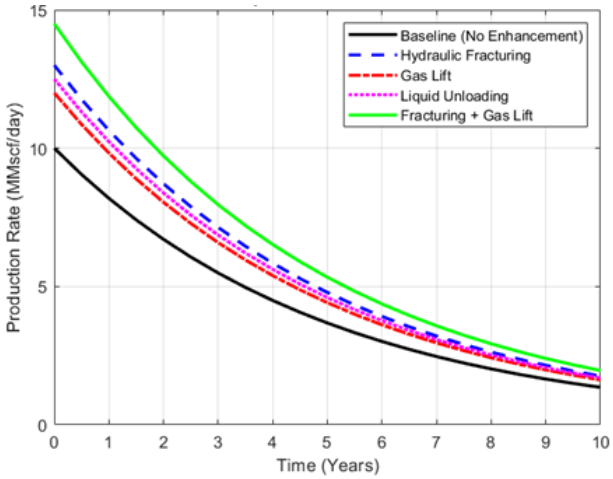


Figure 3. Production Rate Comparison Before and After Enhancement

(Figure 4) Sensitivity Analysis: Production Increase vs. Reservoir Permeability. ECLIPSE-based sensitivity simulation; error bars represent ±10% uncertainty.

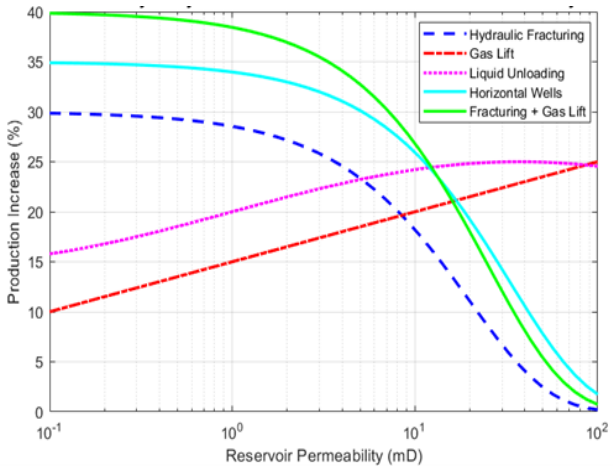


Figure 4. Sensitivity Analysis: Production Increase vs. Reservoir Permeability

5.8. Key Findings

The simulation-based analysis underscores the following:

1. Optimal Combinations: Hydraulic fracturing combined with gas lift offers the best balance of production increase and ROI, particularly in low-permeability, low-pressure reservoirs.
2. Critical Parameters: Permeability, fault presence, and liquid accumulation are the primary drivers of technique performance, requiring tailored strategies.
3. Cost-Effective Solutions: Liquid unloading and tubing optimization are viable for older wells, providing rapid, low-cost production gains.
4. Data-Driven Management: Real-time monitoring, enhanced by AI, is essential for optimizing operations and predicting reservoir behavior.
5. Future Directions: AI and nanotechnology offer transformative potential for improving technique efficacy and sustainability.

This analysis provides a robust foundation for selecting pressure enhancement strategies, guiding field development decisions, and informing future research into innovative

reservoir management solutions.

To provide a clear overview of the analytical process, (Table 6) summarizes the key scientific and logical parameters used in this study. The scientific parameters define the physical and operational characteristics of the simulated gas reservoir, while the logical parameters govern decision-making criteria such as economic thresholds, sustainability considerations, and field applicability. This integrated structure ensures that both technical and economic aspects are consistently represented in the framework illustrated in (Figure 5).

Table 6. Summary of Scientific and Logical Analysis Parameters Used in This Study

Category	Parameter	Description	Role in Analysis	Source/Method
Hydraulic Fracturing	Reservoir permeability (k)	0.1-100 mD	Controls flow capacity and fracturing response	ECLIPSE simulation input
Horizontal Wells	Porosity (φ)	0.15-0.25	Influences storage and deliverability	Simulation + regression
Gas Lift	Fracture conductivity (fc)	10-50 md·ft	Determines stimulation effectiveness	Simulation sensitivity study
Liquid Unloading	Formation pressure (Pr)	1500-3500 psi	Defines baseline depletion and need for enhancement	Field benchmark data
Gas Injection	Liquid accumulation (La)	0-15% PV	Assesses liquid loading severity and gas lift necessity	Simulation variable
Tubing Optimization	ROI threshold	ROI ≥ 2.0 for economic feasibility	Determines cost-effectiveness of enhancement	Cost-benefit model
Tubing Optimization	Gas price sensitivity	±20% variation	Evaluates ROI stability under market fluctuation	Sensitivity analysis
Surface Compression	Energy consumption factor	<15% increase	Ensures sustainable and efficient operation	Economic–environmental balance
Surface Compression	Technique applicability index	Categorical (Fracturing, Gas lift, etc.)	Logical selection of suitable method	Decision framework (Fig. 6)
Real-Time Monitoring	Environmental sustainability score	Qualitative (Low/Medium/High)	Integrates CCUS/nanotech benefits	Literature and simulation integration

4. Discussion and Analysis of Findingss

This study demonstrates that pressure enhancement in gas reservoirs requires a multi-faceted approach balancing technical efficacy, economic viability, and environmental sustainability. Combined hydraulic fracturing and gas lift yield the highest production increases (25-35%) and ROI (2.3-2.5), excelling in low-permeability, low-pressure reservoirs. Low-cost methods like liquid unloading and tubing optimization (5-25% production gains) are effective for mature wells, offering rapid implementation. Real-time monitoring, enhanced by AI-driven analytics, is critical for optimizing operations and predicting reservoir

behavior. Environmental considerations, such as CCUS in gas injection and nanotechnology for reduced chemical use, are vital for sustainable field management. Limitations include data uncertainties and complex reservoir heterogeneities, necessitating future research into AI-optimized modeling and eco-friendly technologies to enhance efficiency and minimize environmental impact.

6.1. Comparative Interpretation and Critical Analysis

Unlike previous reviews that qualitatively summarize pressure-enhancement techniques, this study provides a quantitative comparison based on uniform simulation and economic criteria. For instance, while (Azad, Ghaedi et al. 2022) and (Lin, Wei et al. 2024) reported production gains of 20-25% from hydraulic fracturing in low-permeability reservoirs, our ECLIPSE simulations indicate up to 30% improvement due to optimized fracture geometry and flow-conductivity calibration. Similarly, gas-lift efficiencies observed in (Okorocha, Chinwuko et al. 2020) align with our predicted range (15-20%), validating the robustness of the model. However, the combination of fracturing and gas lift in our work yields a higher ROI (≈ 2.4) than previously documented, reflecting the benefit of dynamic coupling between reservoir and wellbore pressure behavior.

Furthermore, prior literature seldom integrates economic evaluation with simulation outcomes. Our cost–benefit model explicitly quantifies the impact of capital and operational expenses, enabling a direct technical-economic comparison. The integration of AI-based sensitivity modeling and nanotechnology-enhanced fluids is discussed here not as theoretical add-ons but as quantifiable variables influencing efficiency, sustainability, and cost. This critical synthesis demonstrates that the present study extends beyond a compilation of existing methods by offering data-driven differentiation and a validated decision-support framework for selecting pressure-enhancement strategies.

6.2. Comparison with Field Applications and New Insights

The quantitative findings from this study are consistent with but extend beyond previous field-reported results. For example, (Azad, Ghaedi et al. 2022) documented a 22-28% production increase following multi-stage hydraulic fracturing in offshore carbonate gas wells. Our simulation predicts a comparable but slightly higher range (25-30%), which can be attributed to optimized fracture conductivity and extended drainage area in the model. Similarly, gas-lift operations reported by (Okorocha, Chinwuko et al. 2020) achieved approximately 18% improvement in mature wells, closely aligning with the simulated 15-20% gain in this study.

More notably, the combined hydraulic-fracturing + gas-lift scenario evaluated here demonstrates an ROI of 2.3-2.5, exceeding the isolated methods by 25-30%. This synergy has not been quantitatively documented in prior literature, underscoring the novelty of integrating formation-scale stimulation with wellbore pressure relief within one simulation framework.

Field evidence from tight-gas developments in the South Pars and Barnett formations indicates that fracture-enhanced wells suffer rapid decline unless supported by secondary pressure maintenance. The current analysis confirms this trend and shows that timely gas-lift deployment can extend plateau production by 1.5-2 years. This insight provides a practical guideline for field engineers on when to transition from depletion to assisted-flow regimes.

Furthermore, the cost-sensitivity assessment

reveals that for reservoirs with permeability below 1 mD, the break-even ROI for fracturing exceeds 2.0 only when coupled with lift optimization. This quantification defines an economic threshold absent from previous qualitative reviews. Overall, the integration of simulation, statistical regression, and economic evaluation transforms conventional understanding of pressure-enhancement efficiency from descriptive to predictive, offering a reproducible framework for real-field decision-making.

6.3. Integration of Literature and Contextual Insights

The findings of this study align closely with recent literature emphasizing the dual role of CCUS as both a pressure maintenance and environmental mitigation strategy. For example, (Yasemi, Khalili et al. 2023) and (Davarpanah and engineering 2024) demonstrated that CO_2 reinjection in depleted gas reservoirs not only sustains pressure but also sequesters significant carbon volumes, reducing overall emissions by 15-20%. This complements our simulation results, where gas injection scenarios yielded a 1.9 ROI, showing that CCUS-oriented gas reinjection can be both technically and economically viable when integrated into late-stage field management.

Similarly, (Nassabeh, Iglauer et al. 2023) and (Huang, Moridis et al. 2023) highlight challenges in flue gas injection, including compositional instability and caprock integrity, which were considered in our sensitivity analysis through the inclusion of heterogeneity and permeability variation. The integration of AI-based optimization, as reported by (Daramola, Jacks et al. 2024), can further mitigate these issues by enabling real-time control of injection rates and compositional balance.

Thus, the literature not only validates our quantitative findings but also provides environmental and operational perspectives that reinforce the broader significance of advanced pressure enhancement. This interconnection between technical performance and sustainability differentiates this study from prior reviews and underscores its contribution to integrated reservoir management.

6.4. Decision-Making Framework for Technique Selection

To facilitate the practical application of the presented results, a conceptual decision-making framework was developed. The framework integrates reservoir properties, simulation-based technical assessment, economic evaluation, and operational feasibility to support the selection of optimal pressure enhancement techniques.

(Figure 5) outlines a hierarchical decision process beginning with reservoir characterization (permeability, porosity, liquid accumulation, and pressure depletion). Based on these parameters, the framework guides the engineer to select appropriate enhancement methods through three evaluation modules:

1. Technical Module - incorporates ECLIPSE simulation results and regression outputs to assess potential productivity gains.
2. Economic Module - applies ROI and sensitivity analysis to identify cost-effective scenarios.
3. Sustainability Module - considers environmental and energy efficiency factors, such as CCUS or nanotechnology-assisted processes.

The integrated decision pathway enables users to determine whether hydraulic fracturing, gas lift, gas injection, or hybrid approaches provide optimal benefits under given field conditions. This framework not only clarifies the methodological workflow of this study but also serves as a practical tool for field engineers and planners when prioritizing reservoir enhancement strategies.

(Figure 5). Conceptual decision-making

framework for selecting optimal pressure enhancement techniques in gas reservoirs.

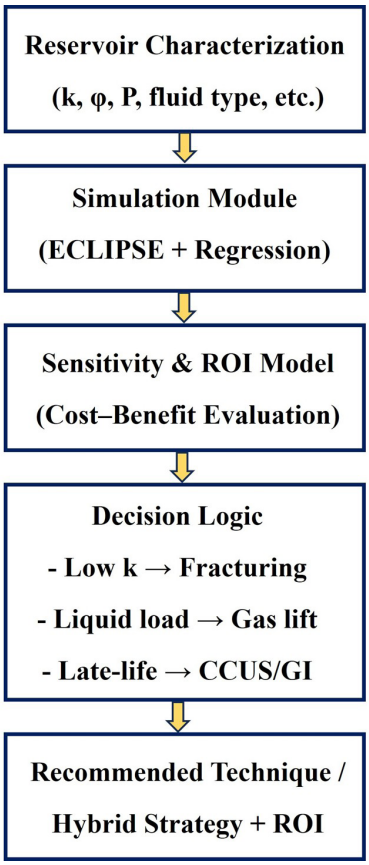


Figure 5. Conceptual decision-making framework

7. Future Research Directions and Current Challenges

7.1. Key Findings

Despite substantial progress in pressure enhancement technologies, several challenges persist that limit their technical and economic deployment:

1. Reservoir heterogeneity and uncertainty: Predicting fracture propagation and gas–liquid interaction in heterogeneous formations remains difficult, often resulting in variable recovery efficiency.
2. High operational and environmental costs: Techniques such as hydraulic fracturing and acidizing require substantial capital and may introduce environmental and water management concerns.
3. Integration complexity: Combining stimulation, gas lift, and gas injection techniques requires multi-objective optimization and advanced control systems that are not yet fully standardized.
4. Data scarcity for AI models: Many AI-driven applications suffer from limited field-scale training datasets, constraining their accuracy and generalizability.
5. CCUS and nanotechnology scalability: While promising, CCUS and nano-assisted processes require further field validation under realistic reservoir conditions.

7.2. Future Research Directions

To overcome these challenges, several promising research avenues have emerged:

1. Hybrid and adaptive systems: Future work should focus on developing adaptive frameworks that integrate hydraulic fracturing, gas lift, and gas injection, optimized in real-time using machine learning algorithms.
2. AI-physics hybrid modeling: The combination of physics-based simulators (e.g., ECLIPSE) with AI predictive models could improve forecasting accuracy and enable automated control of pressure enhancement operations.
3. Advanced materials and nanofluids: Research on nano-engineered proppants and low-toxicity nanofluids could significantly enhance fracture conductivity, reduce damage, and improve environmental performance.
4. Techno-economic optimization: Coupled simulation–economic models should be developed to optimize pressure enhancement strategies under varying gas price scenarios and carbon regulations.
5. Digital twins and monitoring systems: Real-time digital twins integrating sensor data, simulation feedback, and predictive analytics can provide continuous decision

support for long-term field management.

Addressing these research directions will require interdisciplinary collaboration across reservoir engineering, data science, and environmental management, advancing both the technical and sustainable development of gas reservoir enhancement.

8. Conclusions

This study provides a comprehensive, simulation-based assessment of advanced pressure enhancement techniques in gas reservoirs, integrating technical, economic, and sustainability perspectives. The main findings and contributions can be summarized as follows:

Simulation and Performance: ECLIPSE-based simulations demonstrated that hydraulic fracturing achieved the highest production improvement (25-30%) in low-permeability formations, while gas lift yielded a 15-20% enhancement in liquid-loaded wells. The hybrid fracturing + gas-lift configuration offered the best overall efficiency and longevity.

Economic Evaluation: The cost–benefit analysis revealed a robust ROI of 2.3-2.5 for the hybrid scenario, with ±20% cost sensitivity resulting in only minor ROI fluctuation (±0.2-0.3). This confirms the technique's stability and field feasibility under realistic market conditions.

Statistical Insights: Regression analysis (R^2 = 0.87 for production; R^2 = 0.82 for ROI) identified permeability and liquid accumulation as the dominant parameters influencing enhancement performance. Sensitivity indices verified their primary contribution to productivity outcomes.

Innovation Integration: AI-driven optimization, nanofluid-assisted stimulation, and CCUS-based gas injection represent emerging solutions for both technical improvement and environmental sustainability. Their quantified impact including 10-25% performance gains reported in literature reinforces their integration into future reservoir management frameworks.

Framework Contribution: A novel decision-making framework (Figure 5) was developed, linking reservoir characteristics, simulation results, and economic criteria to recommend the most suitable enhancement technique or hybrid configuration. This provides a practical tool for field engineers to make data-driven, sustainable decisions.

Overall, the study advances a unified, quantitative perspective on gas reservoir enhancement, bridging simulation analytics with techno-economic and environmental considerations. The proposed framework can guide future research and field applications toward optimized, AI-assisted, and sustainability-oriented reservoir management.

References

Abdeli, D. Z., A. Yskak, B. Shilanbayev and B. J. N. n. H. U. N. V. Baluanov (2024). "ENHANCED OIL RECOVERY OF DEPOSITS BY MAINTAINING A RATIONAL RESERVOIR PRESSURE." (4): 48-54.

Aljehani, A. S. J. P. and P. A. B. C. Chemistry of the Earth (2025). "Artificial intelligence for reservoir modeling and property estimation in petroleum engineering." 140: 104015.

Azad, M., M. Ghaedi, A. Farasat, H. Parvizi and H. J. P. R. Aghaei (2022). "Case study of hydraulic fracturing in an offshore carbonate oil reservoir." 7(4): 419-429.

Behera, U. S. (2025). Optimisation of Parameters for Enhanced Oil Recovery and the Role of Nanotechnology. Nanotechnology in Enhanced Oil Recovery, CRC Press: 190-214.

Bolu, G. and T. J. P. B. R. Jahan-Ara (2017). "Effects of International Barriers and Limitations on Natural Gas Production in Iran." 1(1): 29-39.

Bozorgian, A. J. I. J. o. N. C. (2022). "Investigation and Possibility of Applying Gas Injection

Method to Increase Pressure in Well A in one of the South Iranian Oil Fields."9(1): 1-13.

Bozorgian, A. J. P. i. C. and B. Research (2021). "Possibility of using gas injection method for increasing pressure in well A: the case of oil fields in southern Iran." 4: 207-219.

Cai, J., S. J. E. Berg and Fuels (2025). Recent Advances in Flow Through Porous Media for Energy Exploitation, ACS Publications. 39: 9181-9184.

Daramola, G. O., B. S. Jacks, O. A. Ajala, A. E. J. C. S. Akinoso and I. R. Journal (2024). "AI applications in reservoir management: optimizing production and recovery in oil and gas fields." 5(4): 972-984.

Davarpanah, A. J. A. s. c. and engineering (2024). "Comparative evaluation of carbon capture, utilization, and storage (CCUS) technologies using multi-criteria decision-making approaches." 12(25): 9498-9510.

Dindoruk, B. and F. J. J. o. E. R. T. Zhang (2024). "Advances in drilling and completion fluid technologies for protecting oil and gas reservoirs: research progress and development trends." 146(5): 050801.

Dinesh, N. and P. Sivasankar (2026). Technologies for reducing emissions in upstream operations. Decarbonizing the Petroleum Industry, Elsevier: 131-165.

Djuraev, U., S. R. Jufar, P. J. J. o. P. S. Vasant and Engineering (2017). "A review on conceptual and practical oil and gas reservoir monitoring methods." 152: 586-601.

Du, F. and B. J. E. Nojabaei (2019). "A review of gas injection in shale reservoirs: enhanced oil/gas recovery approaches and greenhouse gas control." 12(12): 2355.

Duan, X., Y. Xu, W. Xiong, Z. Hu, S. Gao, J. Chang and Y. J. S. R. Ge (2023). "Experimental and numerical study on gas production decline trend under ultralong-production-cycle from shale gas wells." 13(1): 10726.

Ejim, C. and J. Xiao (2020). Screening artificial lift and other techniques for liquid unloading in unconventional gas wells. Abu Dhabi International Petroleum Exhibition and Conference, SPE.

Enemosah, A. J. I. J. o. E. T. R. and Management (2021). "Intelligent decision support systems for oil and gas control rooms using real-time AI inference." 5(12): 236-244.

Franco, C. A., C. A. Franco, R. D. Zabala, I. Bahamon, A. Forero, F. B. J. E. Cortes and Fuels (2021). "Field Applications of nanotechnology in the oil and gas industry: Recent advances and perspectives." 35(23): 19266-19287.

Furui, K., T. Abe, T. Watanabe, K. J. J. o. P. S. Yoshioka and Engineering (2022). "Phase-field modeling of wormhole formation and growth in carbonate matrix acidizing." 209: 109866.

Gaji, A. A., P. Nzerem, O. Ogolo, I. Okafor, T. J. J. P. Chior and Coal (2020). "A Comparative Analysis of the Well Performance of Vertical, Horizontal and Multilateral Wells." 62(1).

González-De León, M. and S. D. J. D. Scipio-Cimetta (2022). "The role of natural gas in today's energy transition." 89(221): 92-100.

Huang, T., G. J. Moridis, T. A. Blasingame, A. M. Abdulkader and B. J. I. J. o. H. E. Yan (2023). "Compositional reservoir simulation of underground hydrogen storage in depleted gas reservoirs." 48(92): 36035-36050.

Jahanbani Ghahfarokhi, A. (2024). Applications of Data-Driven Techniques in Reservoir Simulation and Management. Artificial Intelligent Approaches in Petroleum Geosciences, Springer: 1-74.

Javid, K., G. Bascialla, A. Sainz, M. Hossni Ali, S. Ettireddi, A. Kumar Anurag, L. O. Gonzalez Cerrada, M. S. Mohamed, K. Ibrahim Alhosani

and A. Scheed (2020). Smart reservoir management with real-time monitoring in an offshore carbonate digital oil field under miscible gas injection. Abu Dhabi International Petroleum Exhibition and Conference, SPE.

Jiang, H., H. Yu, C. Mao, Z. Tang, L. Li, A. Ofi, C. Burns, Y. Wang, T. Wen and F. Gui (2024). The Practice and Effect of Underground Gas Storage Expanding the Range of Operation Pressure Beyond the Original Reservoir Pressure to Increase Gas Storage Capacity. SPE Europec featured at EAGE Conference and Exhibition?, SPE.

Jongkittinarukorn, K., N. Last, C. J. G. S. Kabir and Engineering (2023). "Decline-curve analysis with decline rate for improving reserves estimation in gas reservoirs." 116: 205044.

Kalair, A., N. Abas, M. S. Saleem, A. R. Kalair and N. J. E. S. Khan (2021). "Role of energy storage systems in energy transition from fossil fuels to renewables." 3(1): e135.

Kamal, M. S., I. Hussein, M. Mahmoud, A. S. Sultan, M. A. J. J. o. p. s. Saad and engineering (2018). "Oilfield scale formation and chemical removal: A review." 171: 127-139.

Karimov, D., Z. J. E. M. Toktarbay and Manufacturing (2023). "Enhanced oil recovery: Techniques, strategies, and advances." 23(2): 1005.

Kaykanloo, M. R., A. Khademvatani, H. A. A. J. J. o. P. E. Amiri and P. Technology (2025). "Techno-economic evaluation of production integration from a reservoir to market under multiple scenarios: a case study of a condensate gas reservoir." 15(10): 1-15.

Khalili, Y., M. J. J. o. C. Ahmadi and P. Engineering." (2023) Reservoir modeling & simulation: Advancements, challenges, and future perspectives." 57(2): 343-364.

Khalili, Y., M. Akbari, H. Heirani, M. J. J. o. C. Ahmadi and P. Engineering (2024). "Identification and Prioritization of Challenges and Development Technologies in One of Iran's Oil Fields in a Well-based Approach." 58(2): 255-276.

Khan, W. A., Z. Rui, T. Hu, Y. Liu, F. Zhang and Y. J. S. J. Zhao (2024). "Application of machine learning and optimization of oil recovery and CO2 sequestration in the tight oil reservoir." 29(06): 2772-2792.

Khor, C. S., A. Elkamel, N. J. O. Shah and Engineering (2017). "Optimization methods for petroleum fields development and production systems: a review." 18(4): 907-941.

Li, Y., J. Fu, W. Yan, K. Chen, J. Ding and J. J. F. i. E. S. Wu (2024). "Experimental study on the dynamic threshold pressure gradient of high water-bearing tight sandstone gas reservoir." 12: 1487433.

Lin, B., Y. Wei, S. Gao, L. Ye, H. Liu, W. Zhu, J. Zhang and D. J. E. Han (2024). "Current progress and development trend of gas injection to enhance gas recovery in gas reservoirs." 17(7): 1595.

Ma, X., D. He, Y. Wei, J. Guo and C. J. N. G. I. B. Jia (2023). "Enhanced gas recovery: Theory, technology, and prospects." 10(4): 393-405.

Mohamadi-Baghmolaei, M., Z. Sakhaei, R. Azin, S. Osfouri, S. Zendehboudi, H. Shiri, X. J. J. o. N. G. S. Duan and Engineering (2021). "Modeling of well productivity enhancement in a gas-condensate reservoir through wettability alteration: A comparison between smart optimization strategies." 94: 104059.

Mohammad, N., W. W. Mohamad Ishak, S. I. Mustapa and B. V. J. F. i. E. R. Ayodele (2021). "Natural gas as a key alternative energy source in sustainable renewable energy transition: a mini review." 9: 625023.

Nasiri, M., I. Jafari and B. J. C. e. c. Parniankhoy (2017). "Oil and gas produced water management: a

review of treatment technologies, challenges, and opportunities." 204(8): 990-1005.

Nassabeh, M., S. Iglauer, A. Keshavarz, Z. J. E. You and Fuels (2023). "Advancements, challenges, and perspectives of flue gas injection in subsurface formations: a comprehensive review." 37(21): 16282-16310.

Ogbeiwi, P. and K. D. J. S. J. Stephen (2024). "Optimizing the value of a CO_2 water-alternating-gas injection project under geological and economic uncertainties." 29(06): 3348-3368.

Okorocha, I. T., C. E. Chinwuko, C. E. Mgbemena and C. O. J. I. J. o. I. O. Mgbemena (2020). "Gas lift optimization in the oil and gas production process: a review of production challenges and optimization strategies." 1(2): 61.

Ozowe, W., G. O. Daramola, I. O. J. M. S. A. R. Ekemezie and Reviews (2024). "Petroleum engineering innovations: Evaluating the impact of advanced gas injection techniques on reservoir management." 11(1): 299-310.

Pourabdollah, K. J. R. i. C. E. (2020). "Matrix acidizing: A fouling mitigation process in oil and gas wells." 36(2): 311-331.

Prasetya, A., M. Wasesa and Y. J. I. A. Sunitiyoso (2025). "How Can Business Analytics Enhance Decision-Making in Oil and Gas Surface Facilities?".

Rahman, A., E. Shirif and F. J. P. Torabi (2024). "Nanoparticle-stabilized CO2 foam flooding for enhanced heavy oil recovery: A micro-optical analysis." 10(4): 696-704.

Sagala, F. and N. N. Nassar (2022). Nanoparticles for drilling, cementing, hydraulic fracturing, and well stimulation fluids. Nanoparticles: An emerging technology for oil production and processing applications, Springer: 359-380.

Sahu, C., R. Kumar, J. S. J. E. Sangwai and Fuels (2021). "A comprehensive review on well completion operations and artificial lift techniques for methane gas production from natural gas hydrate reservoirs." 35(15): 11740-11760.

Saleh, H. M. and A. I. J. A. C. E. Hassan (2024). "The challenges of sustainable energy transition: A focus on renewable energy." 7(2): 2084.

Sayman, O., K. Jones, R. Hale, E. Pereyra and C. Sarica (2023). Surface compression and PAGL: Increase and extend production for shale wells. Unconventional Resources Technology Conference, 13-15 June 2023, Unconventional Resources Technology Conference (URTeC).

Shusheng, G., Y. Liyou, L. Huaxun, Z. Jianzhong, Z. Wenqing and A. J. H. Weiguo (2025). "Research on the basic theory and application of enhanced recovery in tight sandstone gas reservoirs." 11(1).

Sun, Y., W. Zhang, J. Li, R. Han and C. J. M. Lu (2023). "Mechanism and performance analysis of nanoparticle-polymer fluid for enhanced oil recovery: A review." 28(11): 4331.

Tingxue, J. and W. J. P. D. T. Minsheng (2025). "Development Status and Trend of Fracturing Technologies and Equipment for Complex Unconventional Oil and Gas Reservoirs." 53(4): 1-14.

Usiagu, G. S., O. O. Adekoya, C. E. Okoli, C. D. Dauda, I. O. Ekemezie, O. B. J. W. J. o. A. R. Ayorinde and Reviews (2024). "LNG as a bridge fuel in the transition to renewable energy: A global perspective." 21(02): 742-749.

Wang, X., L. Zhang, J. Song, P. Zhang, J. Lin, Y. Liu, J. Zhang, L. Zhang, X. Qiao and P. Liu (2024). AI-Assisted Automation of Well Type Selection and Pad Optimization During Well Placement in Yan'an Tight Gas Reservoir. SPE EOR Conference at Oil and Gas West Asia, SPE.

Wang, Y.-Y., F.-X. Zhang, Q.-C. Zhao and C.-R. J. O. F. T. Che (2021). "Real-time monitoring of

pressure and temperature of oil well using a carbon-coated and bellow-packaged optical fiber sensor." 67: 102703.

Wu, B., Z. Yang, C. Liu, Y. Shi, X. Zhao, Y. Liang, X. J. G. S. Tang and Engineering (2025). "Study on multiphase flow behavior and parameters for CO2 storage in depleted oil and gas reservoirs." 213949.

Yasemi, S., Y. Khalili, A. Sanati and M. J. S. Bagheri (2023). "Carbon capture and storage: Application in the oil and gas industry." 15(19): 14486.

Zhang, D., L. J. P. E. Zhang and Development (2022). "Fully coupled fluid-solid productivity numerical simulation of multistage fractured horizontal well in tight oil reservoirs." 49(2): 382-393.

Zheng, D., X. Hongcheng, W. Jieming, S. Junchang, Z. Kai, L. Chun, S. Lei, T. J. P. E. Ligen and Development (2017). "Key evaluation techniques in the process of gas reservoir being converted into underground gas storage." 44(5): 840-849.

Исаев, and A. A. E. E. J. B. o. t. T. P. U. G. A. E. Левитина (2024). "Integrated approach to determining the effectiveness of the reservoir pressure maintenance system in carbonate reservoirs." 335(12): 220-230.

JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 1 / Summer 2025 / Pages 69-86

Journal Home page: https://jgt.irangi.org



Selective Removal of Sulfur Dioxide from Oxygen Using Porous Iron: A Molecular Dynamics Study

Mostafa Jafari[1], Mohammad Mahdi Yousefi[2], Ali Vatani[3*], Roozbeh Sabetvand[4]

1. Researcher, Institute of Liquefied Natural Gas (I-LNG), School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran
2. M.Sc. Student, Institute of Liquefied Natural Gas (I-LNG), School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran
3. Full Professor, Institute of Liquefied Natural Gas (I-LNG), School of Chemical Engineering, College of Engineering, University of Tehran, Tehran, Iran
4. Ph.D. Graduate, Department of Physics and Energy Engineering, Amirkabir University of Technology, Tehran, Irann

ARTICLE INFO

ORIGINAL RESEARCH ARTICLE

Article History:
Received: 18 June 2025
Revised: 26 August 2025
Accepted: 07 September 2025

Keywords:
O_2/SO_2 separation
Molecular dynamics
Gas purification
Membrane technology
Permeability
Perm-selectivity
Porous iron membrane
Atomic-scale purification

DOR: 20.1001.1/jgt.2025.2072087.1061

ABSTRACT

Sulfur dioxide (SO_2) is a toxic pollutant generated primarily by the combustion of sulfur-containing fossil fuels, and its removal is crucial for sustainable industrial development. In this computational study, molecular dynamics (MD) simulations were employed to evaluate a porous iron membrane for separating oxygen from a SO_2 gas stream. The Fe membrane was modeled with the Embedded Atom Method (EAM), while the O_2-SO_2mixture was described using the DREIDING force field. Equilibration confirmed the structural stability of the atomic models, reflecting appropriate MD settings and carefully chosen initial conditions. To characterize separation performance, we report SO_2 and O_2 sorption coefficients, gas-membrane interaction energies, and the membrane's post-separation mechanical properties. The simulations further show that the initial conditions (e.g., temperature and pressure) govern the perm-selective behavior of the porous iron membrane throughout the simulation campaign. Under optimized conditions, the membrane achieved an O_2 purity of ~81% and an O_2 recovery of 96.7% in the designed atomic-scale purification system. This performance arises from optimum interaction between the porous iron membrane and target gas molecules. Numerically, the magnitude of the interaction energy between these modeled samples increased to -83.14 eV. This described procedure did not disturb the mechanical performance of the designed porous membrane, and the ultimate strength and Young's modulus of them reached 212.39 MPa and 6.00 GPa (respectively) after the gas molecules selective removal process was fulfilled.

How to cite this article
M. Jafari, M.M. Yousefi, A. Vatani, R. Sabetvand, Selective Removal of Sulfur Dioxide from Oxygen Using Porous Iron: A Molecular Dynamics Study. Journal of Gas Technology. 2025; 10(1): 69-86. (https://jgt.irangi.org/article_731528.html)

* Corresponding author.
E-mail address: avatani@ut.ac.ir, (A. Vatani).

Available online 22 September 2025
2588-5596/© 2016 The Authors. Published by Iranian Gas Institute.
This is an open access article under the CC BY license. (https://creativecommons.org/licenses/by/4.0)

1. Introduction

SO_2 is a noticeable atmospheric constituent, particularly during and after volcanic eruptions, and it contributes to acid rain and secondary particulate formation (Fioletov, McLinden et al. 2020, Li, Li et al. 2022). From a mitigation standpoint, sulfur can be removed from fuels upstream of combustion to suppress SO_2 formation, while downstream, refineries commonly employ the Claus process for sulfur recovery (Pourfayaz, Kazempour et al. 2025). In parallel, chelated-iron redox systems remain essential options for treating sulfur-bearing gas streams (Wei, Wu et al. 2024). Beyond air-quality concerns, SO_2 exposure is linked to adverse human-health outcomes, and elevated atmospheric concentrations can also perturb plant physiology and ecosystem functioning. Accordingly, purifying oxygen from SO_2-containing streams is of practical relevance to environmental protection and industrial sustainability (Pasichnyk, Stanovskay et al. 2023).

Building on early PVDF hollow-fiber studies, recent work has demonstrated that hydrophilic membrane contactors operated with alkaline absorbents (e.g., NaOH) can selectively remove SO_2 under flue-gas and marine-engine conditions (Xu, Huang et al. 2020). Complementary CFD-based analyses have compared prevalent liquid absorbents within hollow-fiber modules, clarifying how gas/liquid velocities and solvent selection govern SO_2 uptake (Cao, Taghvaie Nakhjiri et al. 2023). Comprehensive reviews further position membrane contactors as compact, energy-lean alternatives to conventional scrubbers for SO_2 and related acid gases, and summarize module design, wetting control, and scale-up considerations (Pasichnyk, Stanovsky et al. 2023). These insights motivate the use of tailored polymeric or ceramic hollow-fiber modules and properly chosen absorbents to enhance SO_2 removal while preserving oxygen in the treated stream. The implemented absorbent liquids were constituted of water-based solutions of NaOH, K_2CO_3, alkanolamines, and Na_2SO_3, flowing in the lumen side of the HF sample under a laminar regime. The simultaneous membrane absorption of SO_2/CO_2 molecules was estimated using an aqueous Na_2SO_3 mixture, and their selective removal was appropriately detected. This suggests that the atomic matrix absorption technique offers an energy-saving method for eliminating SO_2 from flue-based compounds.

(Gao, Qiu et al. 2018) highlighted a novel concept for the practical implementation of SO_2 molecule absorption in a hydrophilic ceramic matrix that indicated promising thermal/mechanical performance. These researchers studied the behavior of SO_2 molecule absorption into a NaOH solution in a hydrophilic alumina (Al_2O_3) matrix contactor, focusing on the removal ratio and mass transfer flux of SO_2 molecules. Their results indicated that the hydrophilic membrane matrix was more competitive when using a NaOH concentration higher than 0.2 mol. L^{-1} value. They concluded that the hydrophilic α-Al_2O_3 matrix shows long-term physical stability under 480 h of continuous performance. Subsequent studies have refined the mass-transfer picture in tubular hydrophilic ceramic modules and confirmed the role of operating conditions and absorbent selection in governing SO_2 uptake and selectivity.

(Kong, Qiu et al. 2019) reported a group of hydrophobic tubular asymmetric ceramic-based matrices for the SO_2 molecule elimination process. They observed that most of the SO_2 molecules' mass transfer resistance existed in the atomic matrix phase, indicating that optimizing the matrix parameters, rather than operational conditions, should be the primary consideration to improve the overall pollution transfer behavior. Furthermore, they noted that the SO_2 pollution separation efficiency depended negligibly on the atomic pore radii inside the membrane (matrix). Still, it

could be significantly enlarged by optimizing the thickness and inner size of matrix tubes. Accordingly, when comparing structural classes used for gas purification, metallic and metal-based porous matrices offer attractive attributes that make them suitable supports or active media for acid-gas treatment.

More than polymeric and ceramic matrices, a porous metallic system exhibits strong performance in gas molecule adsorption due to its combination of high surface area, tunable pore structure, and chemically active metallic sites that enhance host-guest interactions (Xinyao, Jiang et al. 2025). The interconnected pores provide extensive pathways for gas diffusion and adsorption. At the same time, the metallic framework offers sites for van der Waals, electrostatic, or even chemisorptive interactions depending on the gas species. In metallic materials, design flexibility allows control over pore size, distribution, and surface functionality to achieve selective and reversible gas adsorption under varying conditions. The adjustable geometry and electronic environment of metal nodes enable enhanced binding affinity and regeneration capability, which are crucial for applications in gas separation, purification, and storage. Thus, through coordinated pore engineering and metal center functionalization, porous metallic matrices maintain high adsorption capacity, fast diffusion rates, and molecular selectivity in both single- and multi-component gas systems (Jiang, C et al. 2022).

Iron and iron-oxide surfaces, in particular, exhibit strong interactions/sensitivity to SO_2, as shown by surface-science studies and gas-sensor evaluations (e.g., thin iron-oxide films and iron-oxide nanorods)(Nguyen, Luong et al. 2021, Soldemo and Weissenrieder 2021). In parallel, hydrophilic hollow-fiber membrane contactors operated with alkaline absorbents (e.g., NaOH) have demonstrated selective SO_2 removal under flue-/flue-/marine-relevant conditions, underscoring the role of robust inorganic (metal/ceramic) matrices in harsh environments (Kong, Gong et al. 2020, Xu, Huang et al. 2020). The sensitivity of metallic structures to gas separation refers to their ability to selectively separate specific gases from a gaseous mixture, such as O_2 or SO_2, from SO_2-O_2 mixtures. Porous metal membranes provide a large surface area to volume ratio, contributing as an exciting option for industrial separations. In contrast, polymeric membranes possess both chemical and thermal stability issues. Nevertheless, at the moment, no commercial porous metallic membranes are available, but there is significant interest in exploring their potential for gas separation. This is the main reason why, in this study, the investigation of porous iron membranes for SO_2/O_2 separation is proposed, considering that iron oxides and their nanocomposites have proven to be effective gas sensing materials in gas and biosensors (Singh, Saxena et al. 2021). The porous metallic materials are commonly processed using powder metallurgy, casting, and deposition techniques (Dukhan, Chen-Wiegart et al. 2020).

Hence, this work aims to describe the absorption process of SO_2 molecules by using a porous iron membrane, which represents a new option in this area. In addition to conventional experimental methods, computer simulations can be used effectively to study the behavior of atomic membranes in adsorbing SO_2molecules. One of the most common methods for computer simulations is the Molecular Dynamics (MD) approach (Ma, Hua et al. 2022, Liao, Wen et al. 2024). In this method, the time evolution of atoms is predicted by using the Newton equation. Here, the purification process of O_2 molecules via a metallic matrix was studied using the MD method, and the effects of temperature and pressure changes on the process performance were examined for the first time. Computationally, temperature, total energy, SO_2 molecules absorption ratio, interaction energy, ultimate strength, and

Young's Modulus have been calculated in the MD simulation box. In actual cases, porous metallic membranes are vital in modern air purification due to their exceptional mechanical strength, corrosion resistance, and precise control of pore size, which enable effective removal of fine particulates, aerosols, and gaseous pollutants under various temperature and pressure conditions. So, outputs of current research can be applied in actual cases.

2. Development of MD Calculations

In this computational study, a porous iron membrane was brought into contact with an O_2-SO_2 gas mixture to probe SO_2 sorption and oxygen separation. After model construction, 10-ns production runs were performed to quantify sorption metrics and assess separation performance. All simulations were carried out with LAMMPS(Plimpton 1995, Brown, Wang et al. 2011, Thompson, Aktulga et al. 2022). The porous Fe membrane and the O_2-SO_2 mixture were modeled at the atomistic level as Fe, O, and S species (see Figure 1), and structures were visualized/analyzed using OVITO (Stukowski 2009). Periodic boundary conditions were applied along the x and y axes. In contrast, fixed boundaries were imposed along z to confine transport across the membrane Systems were equilibrated in the isothermal-isobaric (NPT) ensemble at T = 300 K and P =1 bar using standard Nosé-Hoover-type algorithms(Martyna, Tobias et al. 1994).

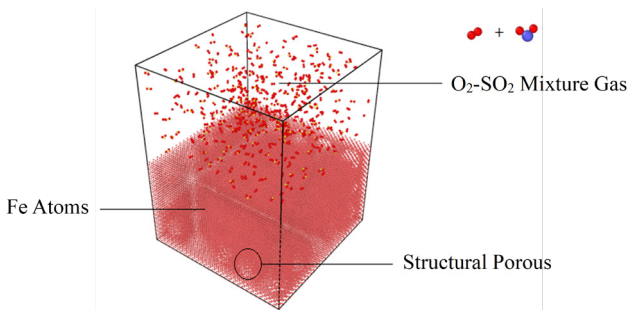


Figure 1. Schematic of atomic structures arrangement in the MD simulation box by using the LAMMPS package

The MD simulation is a prevailing tool to explore the dynamics of nanostructures based on Newton's laws for various phenomena(Haile 1992, Sadus 2002), such as air purification. It has the capability of tracing the behavior of atomic membranes in various pollution filtering. Conventionally, these simulations define the particle trajectories by solving Newton's equation, considering the forces among multiple atoms. The atomic arrangement was used to describe the behavior of the porous iron membrane under various initial conditions. Considering the importance of interatomic potential in MD simulation results, the DREIDING force field has been applied in the atomic description of the O_2-SO_2 gas mixture (Mayo, Olafson et al. 1990). As reported in previous research, the use of this force field is appropriate for gas molecule simulations in various conditions (Dokyr, D et al. 2018). This simulation setting allowed the structural stability and actual interaction between different molecules to be observed over time. Lennard-Jones (LJ) potential has been used to compute the atomic interaction among multiple structures in this force field (Gao, Ji et al. 2018),

$$\phi(r_{ij}) = 4\varepsilon\left[\left(\frac{\sigma}{r_{ij}}\right)^{12} - \left(\frac{\sigma}{r_{ij}}\right)^{6}\right] \qquad r_{ij} \le r_c \qquad (1)$$

ε defines the depth of the LJ well, sigma indicates the finite distance at which the LJ is zero, and the distance between various particles specified by rij parameter. In equation (1), rc (cut-off radius) is chosen 12 Å in all of our simulations. The bonded potential is made up of the simple strength and angle bend components. In the DREIDING force field, the simple strength is defined by a linear oscillator with the following formalism (Li 2014),

$$E = \tfrac{1}{2}\, k_r\, (r\text{-}r_0)^2 \qquad (2)$$

where the kr is indicated as the linear oscillator constant, the atomic bond length is shown by r_0. Moreover, equation (3) represents

the angle bend in SO_2 molecules through an angular oscillator (Li 2014):

$$E = ½\ k_\theta\ (\theta\text{-}\theta_0)^2 \quad (3)$$

Where k_θ represents the angular oscillator constant, and θ_0 indicates the equilibrium degree of the angle contact. Numerically, in the defined force field, the r_0 of O/O and S/O interactions are equal to 1.31 Å and 1.69. Also, θ_0 of O/S/O interaction is equal to 92.10 (Mayo, Olafson et al. 1990). The other atomic interaction parameters for various molecules in the O_2-SO_2 gas mixture are represented in (Table 1) (Mayo, Olafson et al. 1990). The porous iron matrix, consisting of Fe atoms, is described by the Embedded Atom Model (EAM). In the previous report, this force field effectively describes the time evolution of metallic atoms within the computational box. It facilitates the detection of thermodynamic stability in the designed Fe-based system (Han, B et al. 2025). This interatomic potential is defined as follows (Daw and Baskes 1984, Daw, Foiles et al. 1993):

$$\mathrm{E_i} = \mathrm{F_\alpha}\left(\sum_{\mathrm{i\neq j}} \rho_\beta(\mathrm{r_{ij}})\right) + \frac{1}{2}\sum_{\mathrm{j\neq i}} \varphi_{\alpha\beta}(\mathrm{r_{ij}}) \quad (4)$$

Where F constant is the embedding energy as a function of the atomic electron density ρ, φ is the pair potential interaction, and α and β are the element types of atoms i and j.

Table 1: The ε and σ constants for LJ formalism in DREIDING force-field (Mayo, Olafson et al. 1990)

Element	σ(Å)	ε(kcal/mol)
O	0.415	3.71
S	0.305	4.24
Fe	0.055	4.54

The potential of atom-based compound $V(r^N)$ is assumed for each pair of atoms. Computationally, it can be defined $V(r^N)$ for atomic systems with N atoms as reported below (Rapaport 2004),

$$V\left(r^N\right) = \Sigma\sum_{i<j} V\left(r_{ij}\right) \quad (5)$$

After defining the potential parameter for nanostructures inside the MD box, the simulation process was completed. To describe the atomic displacement, Newton's equation at the nanometric level is set as the gradient of the atom-based potential (force-field) (Rapaport 2004),

$$F_i = \sum_{i\neq j} F_{ij} = m_i \frac{d^2 r_i}{dt^2} = m_i \frac{dv_i}{dt} \quad (6)$$

$$F_{ij} = -grad\ V_{ij} \quad (7)$$

From equations (6) and (7), the momentum Pi can be defined as in the following (Rapaport 2004),

$$P_i = m_i\, v_i \quad (8)$$

Hence, the Energy (E) of the atomic structures can be expressed in the form of the Hamilton equation (9),

$$\mathrm{H}\left(r,P\right) = \frac{1}{2m}\sum_i P_i^2 + V\left(r_1 + r_2 + \ldots + r_n\right) = E \quad (9)$$

The velocity-Verlet approach is applied to estimate the particle's time evolution, considering the integration form of Newton's law in equations (10), and (11) (Verlet 1967, Hairer, Lubich et al. 2003, Press, Teukolsky et al. 2007),

$$r(t+\Delta t) = r(t) + v(t)\Delta t + \frac{1}{2}a(t)\Delta t^2 + \cdots \quad (10)$$

$$v(t) + \frac{a(t) + a(t+\Delta t)}{2}\Delta t + \cdots \quad (11)$$

In the equations above, r(t+Δt) and v(t+Δt) are the position and velocity of modeled atoms at any time (respectively), and r(t) and v(t) are the initial values. Theoretically, various

ensembles are implemented to create an initial condition inside the simulation box. In this work, the grand canonical ensemble was obtained by applying the Nosé-Hoover barostat, and thermal equilibrium was achieved by using the LAMMPS package (Nosé 1984, Hoover 1985). After the equilibrium process, the simulation continued for 10 ns later with the micro-canonical ensemble (Hilbert, Hänggi et al. 2014). According to the descriptions above, the computational studies were carried out as follows:

Step A: SO_2-O_2 gas mixture and the porous iron-based membrane were simulated with DREIDING and EAM force fields and equilibrated by NPT/NVT ensemble for 10000000 time steps with Δt = 1 fs. Using these ensembles caused the initial thermodynamic conditions implemented to design the atomic sample. For this purpose, the nuclear structure's initial temperature and initial pressure are set at T_0 = 300 K and P_0=1 bar (respectively) as initial conditions. Afterwards, atomic structures reached an equilibrium phase, and their stability is presented by total temperature and total energy calculations.

Step B: The atomic purification procedure was implemented to equilibrate structures for 10000000 time steps with the NVE ensemble. This ensemble caused the removal process to occur within a non-limiting computational box. For this purpose, SO_2 molecules are absorbed by the porous membrane in the MD simulation box. After this process, physical parameters such as SO_2 and O_2 absorption coefficients, interaction energy, and mechanical properties of the membrane after the separation procedure are reported to describe the atomic behavior of the porous iron membrane in the O_2 purification procedure. The MD simulation details are reported in (Table 2). All of the MD simulations were repeated 5 times with defined simulation settings, and the average value of the numeric outputs was reported.

Table 2: MD Simulation Details in Current Computational Research

Computational Parameter	Value/Setting
Computational Box Length	150×150×300 Å3
Boundary Condition	P-P-F
Initial Temperature	300 K
Initial Pressure	1 bar
Time Step	1 fs
Computational Algorithm	NPT
Temperature Damping Ratio	10
Pressure Damping Ratio	100
Equilibrium Time	10 ns
Total Simulation Time	20 ns
Number of Pollution Molecules	175

3. Result and Discussion

Firstly, the atomic behavior of the O_2-SO_2 gas mixture and the porous iron membrane were described at initial temperature and pressure (T_0 = 300 K and P_0 = 1 bar). The simulation results show the initial arrangement of atoms in the simulation box, adopted using the DREIDING and EAM functions. This atomic phase of simulated compounds is estimated by temperature and total energy calculation. The atom-based compound's temperature varied as a function of MD time steps, as reported in (Figure 2A). It illustrates that the atomic structures equilibrated after t =7 ns. Physically, this thermal equilibrium arises from the reduction of atomic oscillation by MD time, demonstrating the validity of the MD simulation settings (Asgari, Nguyen et al. 2020, Jolfaei, Jolfaei et al. 2020, Mosavi, Hekmatifar et al. 2020). Atomic oscillation reduction arises from the decrease

in atom mobility inside the computational box. This decrease, caused by the mean distance between various particles, did not significantly affect the structure, which was stabilized under defined conditions. Furthermore, (Figure 2B) displays the total energy variations in atomic systems as a function of MD simulation time. As shown in this figure, the total energy of the atomic structure converged after t = 7 ns to a constant value with a numerical range variation below 2%, which was considered acceptable. Numerically, the total energy of the porous iron membrane and the O_2-SO_2 gas mixture system reached -398.11 eV after 10 ns. Theoretically, this physical parameter has a reciprocal relation with the mean distance of atoms, and the target atomic structure stability was achieved by increasing the total energy magnitude. T_o ensure sufficient time in the equilibration phase, this simulation factor was increased to 20 ns. The total energy output in this simulation was -398.13 eV, which did not significantly vary from the energy value after 10 ns. This energy output indicated that the 10 ns were sufficient time to observe the thermodynamic equilibrium in the modeled structure, which arises from the proper matching of the interatomic force field and the atomic positions. Next, to validate the MD simulation results in the current atom-based study, the Radial Distribution Function (RDF) of O atoms in the O_2 gas system was also calculated. The RDF of simulated structures can describe their atomic arrangement. Computationally, the RDF function is defined by g(r), a parameter showing the probability of finding an atom at a finite distance from other atoms (neighbor atoms). This output is a characteristic property of the atomic system, consistent with the previous structural report (Okwuashi 2020). Physically, this consistency arises from the compliance between the modeled structure and the simulation settings, as validated by current MD simulations. (Figure 3) shows this output (RDF results of O atoms in O_2 gas structure).

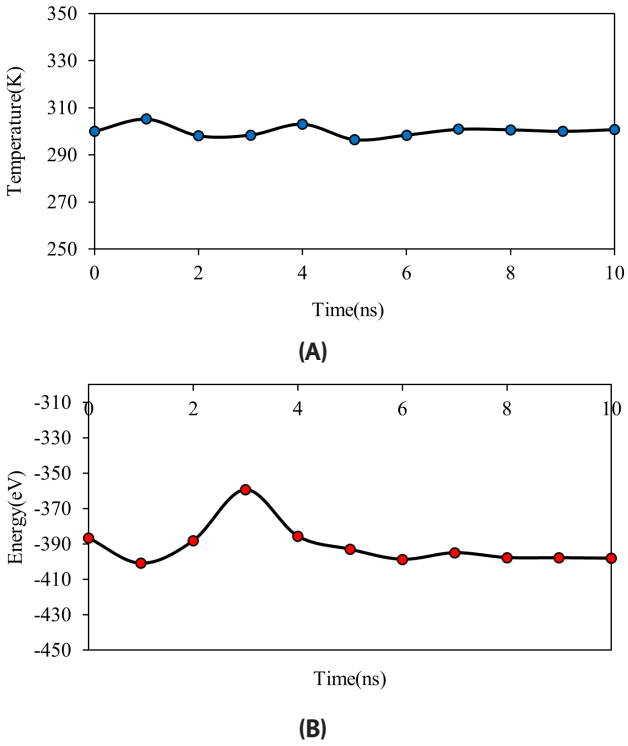


Figure 2. Temperature And B) Total Energy Variation of Porous Iron Membrane and O_2- SO_2 Gas Mixture System as A Function of Defined MD Time Steps (Time)

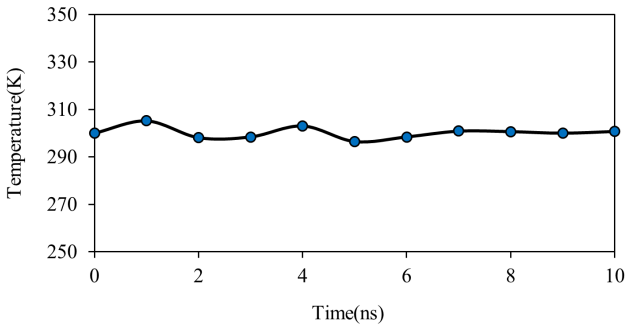


Figure 3. The Oxygen-Oxygen Radial Distribution Function (RDF) of O_2 Gas at T_0 = 300 K And P_0 = 1 Bar (As an Initial Condition)

As soon as the equilibrium procedure was achieved, the atomic evolution was implemented to the O_2-SO_2 system, with ensemble change from NPT to NVT for t =10 ns. This computational step indicated the

purification process of O_2 molecules from the O_2-SO_2 gas system, as shown in (Figure 4). After gas molecules diffused into the pristine matrix, potential energy was generated within the final system. This evolution caused gas molecule fluctuations to decrease inside the matrix, completing the air purification procedure.

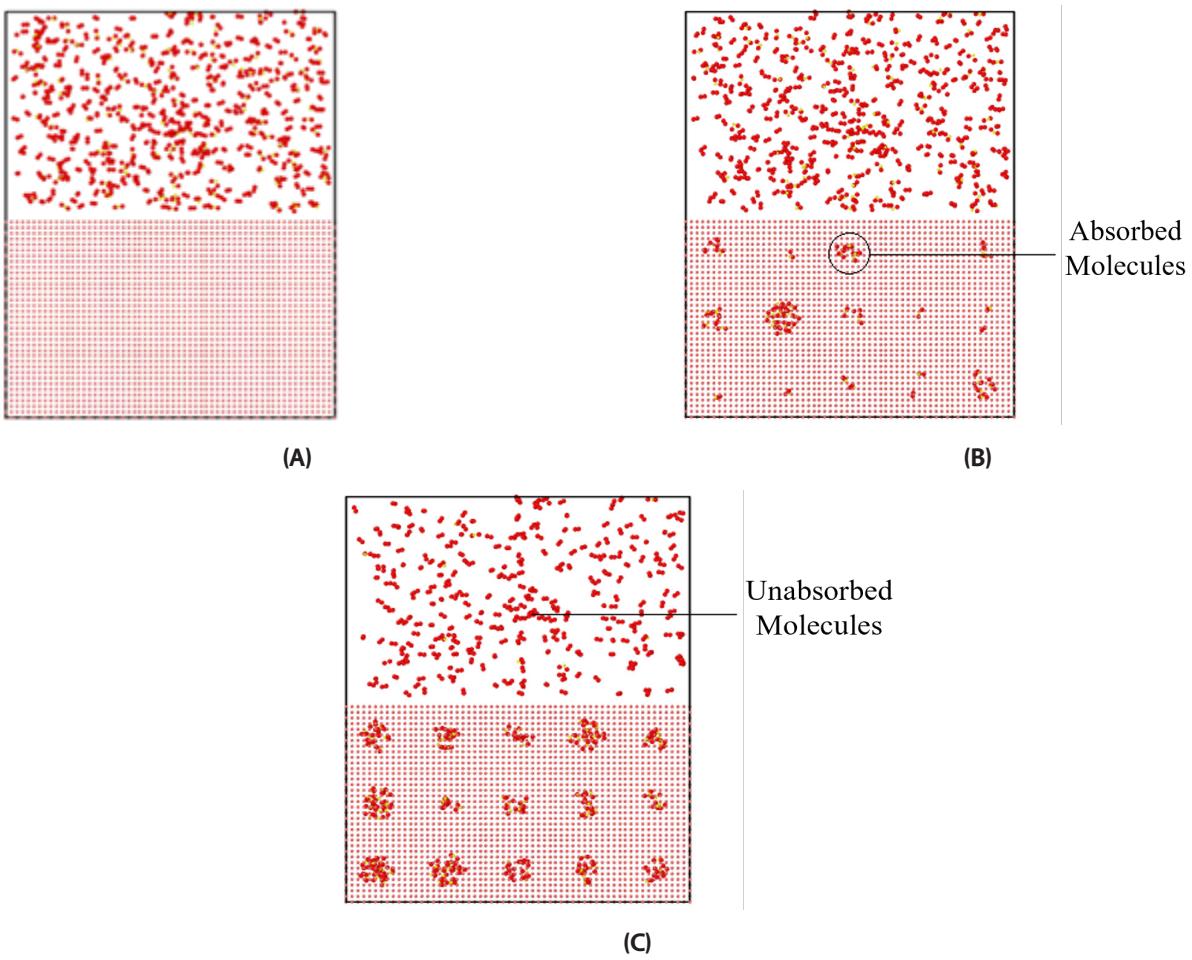


Figure 4. Time Evolution of O_2 Gas Purification Process from SO_2 Molecules as Pollution with Porous Iron Membrane After A) 0, B) 5000000, And C) 10000000 Time Steps

The number of absorbed SO_2 molecules (with porous iron matrix) changed as a function of MD time, as shown in (Figure 5). As displayed in this figure, the computational time steps are sufficient for detecting the oxygen purification process at the initial conditions. After detecting the atomic process, the number of O_2 molecules absorbed by the porous membrane was calculated. Numerically, the number of SO_2 molecules that diffused inside the atomic matrix converged to 133 molecules after 10 ns. By this atomic absorption ratio, the efficiency of the defined membrane is around 76%, indicating the appropriate performance of the metallic membrane for air purification purposes. Furthermore, the computed value of absorbed O_2 molecules, which diffused into the pristine membrane, was equal to 21, while the O_2 molecule adsorption ratio was negligible. To calculate these parameters, the evolution of each particle (atoms/molecules) inside the computational box was estimated with Newton's second law equation, which was introduced in the "development of MD calculations" section. Then, the number of target molecules which trapped within the metallic matrix is counted.

This computational approach predicted the recovery ratio of O_2 molecules in the designed system, converging to 95.3% after 10 ns. Computationally, the number of O_2 molecules in the target region (outside the membrane) is counted to estimate the recovery ratio.

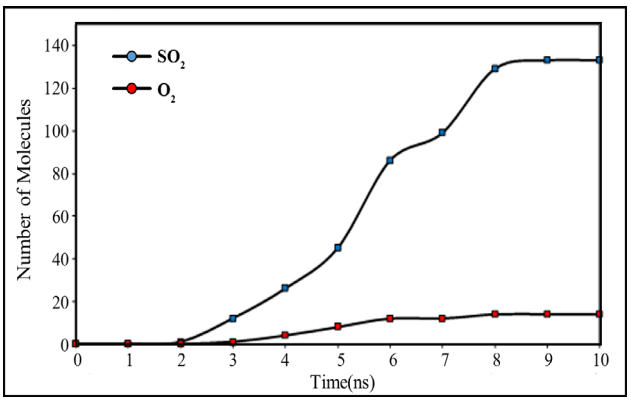
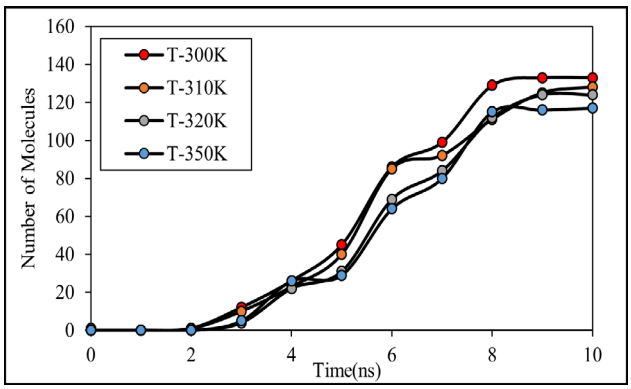
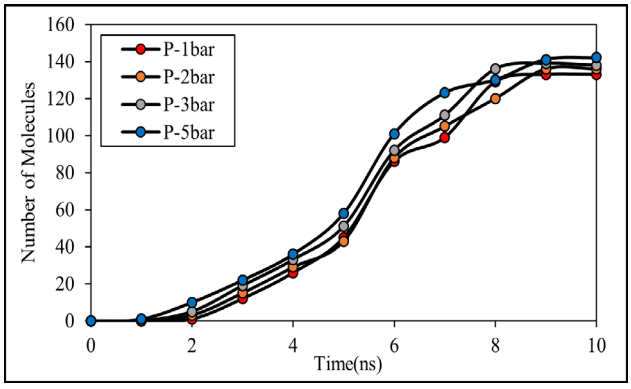


Figure 5. The Number of SO_2 And O_2 Molecules Trapped in Porous Regions of Iron-Based Membrane as A Function of MD Time

Physically altering the initial condition, the atomic resonance within the samples was significantly affected, and their structural unity converged to new states. In this section, the effects of initial conditions in the O_2 gas purification process are described. The MD simulations indicated that the atomic interaction between the porous iron membrane and SO_2 molecules decreased as the initial temperature or pressure increased, leading to a decrease in the efficiency of the metallic membrane in the air purification process. These atomic evolutions arise from changes in the mean distance and atomic force between various particles inside the computational box. The increase in temperature and decrease in pressure caused the mean velocity of particles inside the computational box to increase, leading to more effective collisions between them. These interactions caused the diffusion ratio of molecules to increase, leading to more molecules being adsorbed onto the porous iron matrix. The pressure increase has the opposite effect on atomic system evolution, and the adsorption of target molecules occurs with more precision. This behavior caused the separation efficiency to increase at higher pressures instead of lower levels. Thus, the temperature increase or pressure decrease in the air purification process can disrupt this phenomenon. MD outputs predicted molecules' mobility changes at defined conditions. (Figures 6,7) show the number of O_2 and SO_2 molecules, which were absorbed by iron-based membranes as a function of MD simulation time. Numerically, the number of absorbed O_2 and SO_2 molecules inside the porous iron matrix converged to 142 and 10 molecules, respectively, by creating optimized conditions in the MD simulation box. As reported before, this optimized condition was created by decreasing the temperature and increasing the pressure for t = 10 ns.

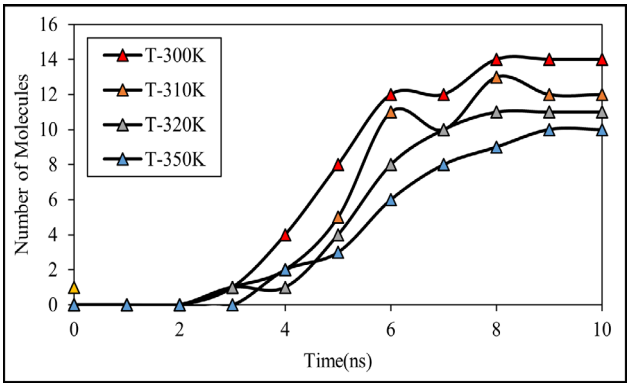


(A)

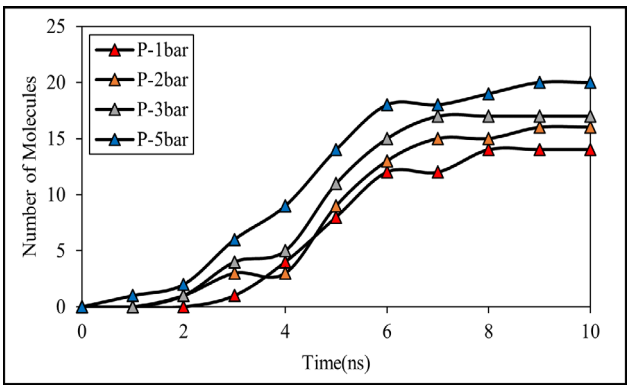


(B)

Figure 6. The Number of Absorbed SO_2 Molecules with Porous Iron Membrane as Defined by Initial A) Temperature and B) Pressure



(A)



(B)

Figure 7. The Number of Absorbed O_2 Molecules with Porous Iron Membrane as A Function of Initial A) Temperature and B) Pressure

The O_2 molecules recovery ratio and permeability changed as a function of initial temperature and pressure, as depicted in (Figure 8). Numerically, the O_2 molecules recovery ratio varied from 93.3% to 96.7% according to defined systems. Hence, these results predicted that the atomic interaction between the O_2-SO_2 mixture and the membrane was significantly affected by changes in operating conditions, which should be considered in actual applications. Furthermore, permeability value in modeled samples varied from 3.4×10-3 Barrer to 4.9×10-3 Barrer. This parameter refers to the ability of O_2 molecules to diffuse inside the membrane. The O_2 purification procedure was done effectively, depending on the decrease in permeability value in the designed porous iron membrane. The atomic interaction between the atomic membrane and the gas structure is another physical parameter that can describe the purification process of oxygen molecules. In this section, the atomic interaction between porous iron membrane and O_2-SO_2 mixture gas was calculated. Simulation outputs showed that, increasing temperature from T0 = 300 K to T0 = 350 K, the interatomic interaction energy changes from -75.22 eV to -69.01 eV between the atomic membrane and the gas system. Computationally, the interaction energy in modeled samples, which consists of the porous matrix and gas molecules, is calculated by the mutual potential energy between them. Hence, the simulation results predicted that the temperature increase caused effective collision among various particles and, randomly, their evolution decreased the efficiency of the modeled metallic membrane. A pressure increase from P_0 = 1 bar to P_0 = 5 bar causes this atomic parameter to enlarge from -75.22 eV to -83.14 eV. Physically, the increase of this parameter induces the enlargement of atomic absorption in simulated systems. This evolution can be described with the optimum atomic displacement of polluting molecules inside the modeled matrix. With the SO_2 molecules' absorption increase, the purification process occurs effectively. The interaction force between membrane and polluting molecules shows similar results, and this parameter changes from -18.93 eV/Å to 30.64 eV/Å as listed in (Table 3). Generally, the gas purification efficiency increases with a decrease in temperature and an increase/ pressure, consistent with previous reports for similar structures (Liu, Y et al. 2018, Hashmi, Moiz et al. 2024). This consistency arises from an appropriate time evolution description of the purification procedure by designed MD simulation, and we validated this procedure description in the current research.

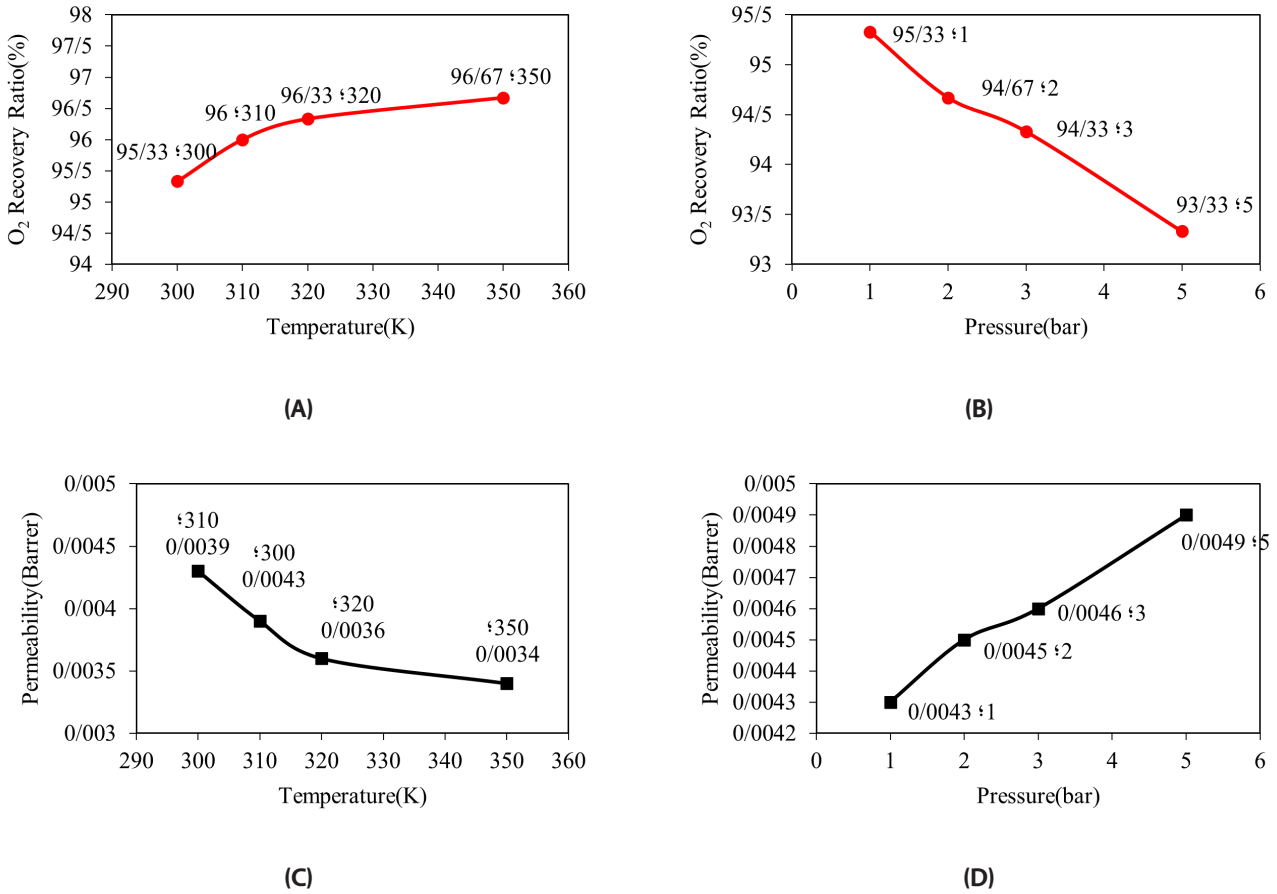


Figure 8. O_2 Molecules Recovery Ratio as a Function of Initial (A) Temperature and (B) Pressure. Permeability of O_2 Molecules as a Function of Initial (C) Temperature and (D) Pressure in the Current Computational Study

Table 3. The Numerical Outputs of MD Simulations in Current Research are Presented as a Function of Initial Temperature and Pressure

Initial Temperature (K) - Pressure (bar)	O_2 Molecules Number	SO_2 Molecules Number	Gas-Membrane Interaction Energy (eV)	Interaction/Force (eV/Å)	Purification Efficiency (%)
T_0=300 K - P0=1 bar	14	133	-75.22	-24.83	76.00
T_0=310 K - P0=1 bar	12	128	-73.29	-21.00	73.14
T_0=320 K - P_0=1 bar	11	124	-70.16	-19.11	70.86
T_0=350 K - P_0=1 bar	10	117	-69.01	-18.93	66.86
T_0=300 K - P_0=2 bar	16	136	-78.05	-26.68	77.71
T_0=300 K - P_0=3 bar	17	138	-82.21	-29.93	78.86
T_0=300 K - P_0=5 bar	20	142	-83.14	-30.64	81.14

The mechanical behavior of iron-based membranes is an important parameter for real-world applications. In the final step of our computational study, a cubic porous iron membrane was used to describe the mechanical properties of these atom-based samples. To report the mechanical performance of the designed membrane, the sample was structurally expanded by uniform intensity, and the interatomic stresses in various regions of the

sample were reported as the stress-strain curve.

The density parameter as a function of MD simulation time is shown in (Figure 9A). The convergence of the density parameter indicates that the simulated structure reaches equilibrium after t = 10 ns. This convergence results from the decrease in atomic fluctuations under the defined initial condition. Computationally, this atomic evolution was accessible by adopting position and interatomic potentials and simulating it as a function of time. For mechanical behavior analysis of the iron porous membrane, the external force was applied to the atomic matrix as depicted in (Figure 9B). The stress-strain curve was calculated to study the mechanical behavior of the iron-based membrane, before and after the purification process. Mechanical quantities such as the Young's modulus and the ultimate strength were estimated from the calculated curve. In (Figure 10), as the external force increases, the structures' deformation values are depicted, and, finally, the stress-strain curve is obtained using these values. The deformation process of an atomic sample will depend on its elastic modulus and geometry. The stress and strain calculations output of the mechanical test procedure was depicted in (Figure 11). The latter shows structural unity inside the atomic sample, which arises from the attraction force between various parts of the system. From our MD simulations, Young's modulus and ultimate strength of pure iron-based membrane are calculated as 6.93 GPa and 245.66 GPa, respectively. These computed values were comparable with previous studies about iron-based structures and validated our computational method in the current research (Kuhn and Medlin 2000).

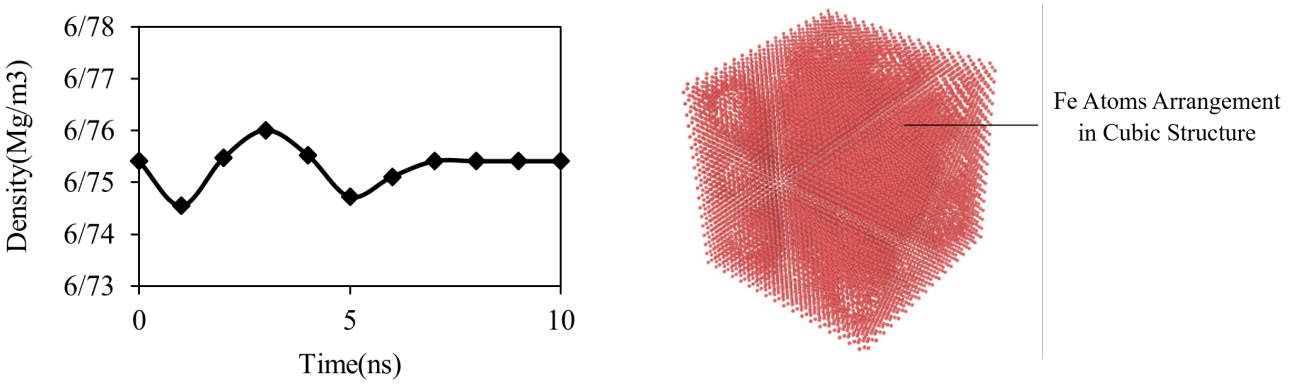


Figure 9. Mass Density Changes of Pure Porous Iron Matrix Arrangement as a Function of MD Time During the Equilibration Process (A), Schematic (B)

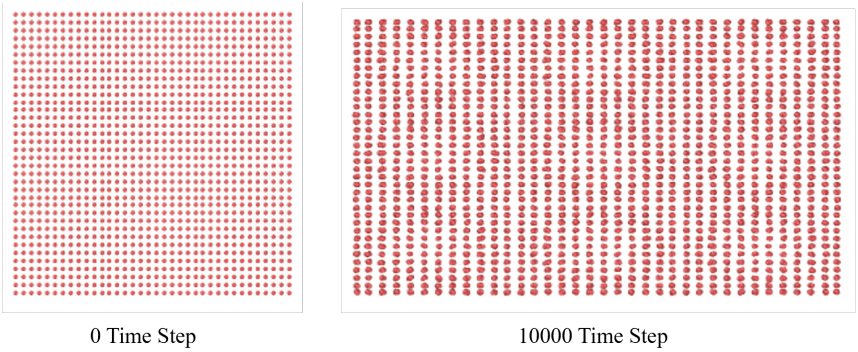


Figure 10. The Atomic Evolution of Pure Porous Iron Membrane at 0 and 10000 Time Steps of the Mechanical Deformation Process

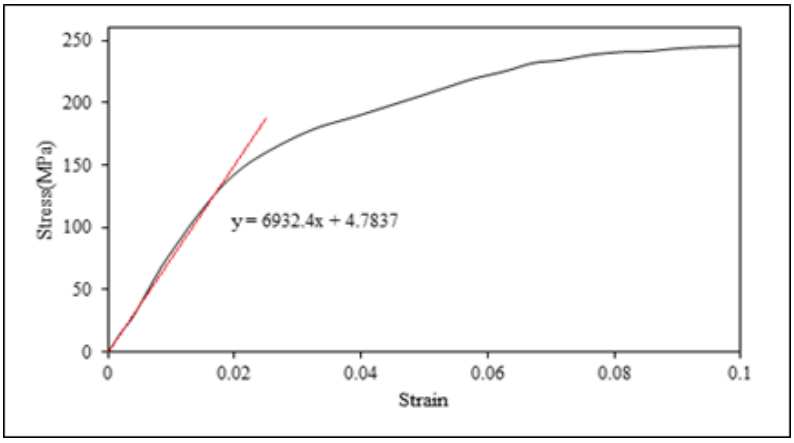


Figure 11. Stress-Strain and B) Young's Modulus Curves of the Pure Porous Iron Membrane Calculated by the Molecular Dynamics Approach

The absorption of SO_2 molecules should affect the mechanical properties of the pure metallic membrane. For this reason, the porous iron matrix's mechanical behavior after the purification process was estimated at T_0 = 300 K and P_0 = 1 bar as the initial condition. The results of the mechanical test of this atomic membrane after the purification process are shown in (Figure 12). After the atomic equilibration process at the initial condition, the metallic membrane was expanded to simulate the mechanical evolution with a 0.001 ps^{-1} strain ratio. The stress-strain curve of the porous iron membrane's deformation test in the Z direction is shown in (Figure 13). This mechanical estimation was calculated using the least-square formalism, implemented to reduce data errors. Numerically, by absorbing the mixture gas with the pure metallic structure, the mechanical-based quantities such as Young's modulus and ultimate strength decreased and converged to 6.00 GPa and 212.39 GPa, respectively, as listed in (Table 4). These results confirm the diffusion of SO_2 and O_2molecules into the porous iron membrane, weakening the membrane's mechanical performance. Physically, the diffusion of guest atoms inside the host metallic membrane increased the mean distance between various atoms. By this structural evolution, the interatomic force and structural unity decreased. The MD simulations obtained in this section should be considered in the design of porous iron-based membranes for gaining better commercial outputs. This describes the structural evolution and how gas molecules diffuse inside the pristine iron porous matrix without disturbing its thermodynamic stability. This behavior, detected by limitations in atomic fluctuation amplitude over time, verifies the designed system applications and should be considered in actual cases.

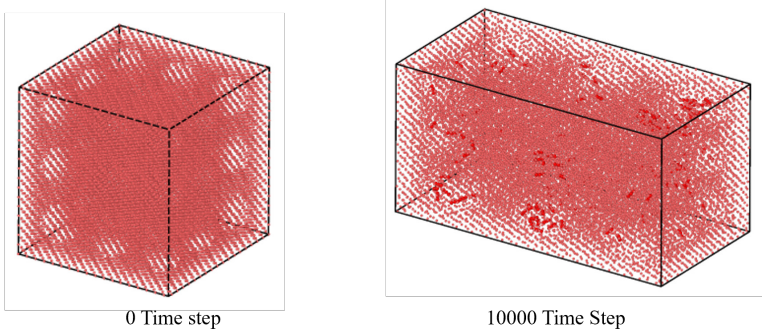


Figure 12. Schematic of Porous Iron Matrix in the Presence of Absorbed O_2 and SO_2 Molecules After the Mechanical Deformation Process

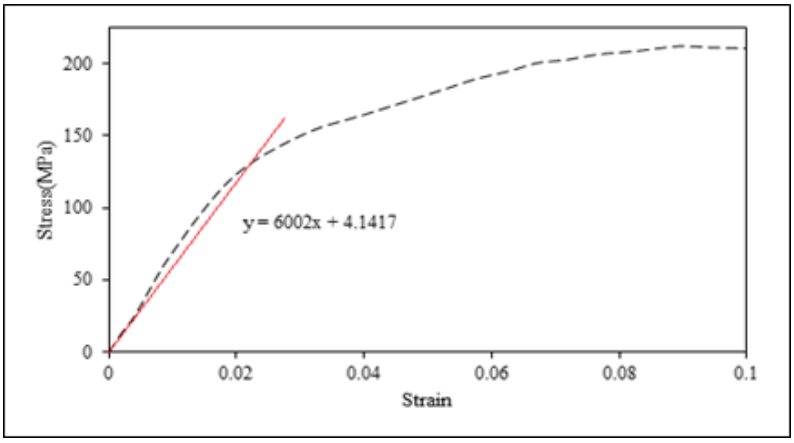


Figure 13. The Stress-Strain and Young's Modulus Curves of the Porous Iron Membrane After the O_2 Purification Process, Calculated by the MD Approach

Table 4. The Mechanical Properties of Various Simulated Metallic Membranes are Studied in the Current Computational Work

Atomic structure	Young's Modulus (GPa)	Ultimate Strength (MPa)
Pure Porous Iron Membrane	6.93	245.66
Porous Iron Membrane after the O_2 Purification process	6.00	212.39

4. Conclusion

In the present computational research, the molecular dynamics (MD) approach was used to describe the porous iron membrane performance for the oxygen purification process (in the presence of SO_2 molecules as pollutants). MD simulation results at defined initial conditions can be listed as follows:

A. The DREIDING and Embedded Atom Model (EAM) functions were adequate choices for the MD description of porous iron membrane and O_2-SO_2 gas system.

B. MD simulations indicated the number of oxygen and SO_2 molecules absorbed by the porous iron membrane is 12 and 128 molecules after 10 ns.

C. The increase in the initial temperature of simulated structures caused the accuracy to decrease, and the speed of the purification procedure improved. Numerically, by increasing the initial temperature to 350 K, the number of absorbed SO_2 molecules by the metallic membrane converged to 117.

D. Increasing the initial temperature of simulated structures caused an enlargement in the accuracy and performance speed of the purification procedure. Numerically, by initial pressure enlarging to 5 bar, the number of absorbed SO_2 molecules by the metallic membrane converged to 142 molecules.

E. The recovery ratio and permeability of O_2 converged to 96.7% and 3.4·10-3 Barrer, respectively, in our designed O_2 purification system.

F. Porous iron membrane was weakened mechanically after the purification process. Numerically, the ultimate strength of the pure metallic membrane decreased from 245.66 GPa to 212.39 GPa after O_2-SO_2 gas mixture absorption took place with them. Also, Young's modulus parameter decreased from 6.93 GPa to 6.00 GPa after the oxygen molecule purification process.

These MD simulation results showed that the atomic arrangement of Fe atoms in the porous iron membrane can be used for standard air purification procedures. Practically, these results can be implemented in various purification processes for optimizing the actual application efficiency.

Declarations

Author Contributions: Conceptualization, Mostafa Jafari; Formal analysis, Mostafa Jafari and Mohammad Mahdi Yousefi; Data curation, Mostafa Jafari; Writing - original draft, Mostafa Jafari, Mohammad Mahdi Yousefi, Roozbeh Sabetvand; Supervision, Ali Vatani.

Acknowledgments: Support from the LAMMPS Tube Center is gratefully acknowledged.

Funding N/A

Conflicts of interest / Competing interests: The authors declare that they have no conflicts of interest.

Availability of data and material: Data available on request from the authors.

Code availability: LAMMPS main inputs are available on request from the authors.

Nomenclature

Fij	Atomic force between i and j atoms
Vij	Potential energy between i and j atoms
m	Atomic mass
rc	Cut-off radius
rij	Atomic distance of i and j atoms
t	Time step in molecular dynamics simulation
T	Temperature in molecular dynamics simulation
v	Atomic velocity
a	atomic acceleration
$Natom$	Number of atoms
Nsf	Degree of freedom
kB	Boltzman constant
$r0$	Equilibrium bond length

Greek symbols

ε	Energy constant in Lennard-Jones function
σ	Length constant in Lennard-Jones function
$\theta 0$	Equilibrium angle
Δt	molecular dynamics time step
$F\alpha$	embedding energy in Embedded Atom Model
$\varphi\alpha\beta$	pair potential interaction in Embedded Atom Model

References

Asgari, A., Q. Nguyen, A. Karimipour, Q.-V. Bach, M. Hekmatifar and R. Sabetvand (2020). "Develop molecular dynamics method to simulate the flow and thermal domains of H_2O/Cu nanofluid in a nanochannel affected by an external electric field." International Journal of Thermophysics 41(9): 126. https://doi.org/10.1007/s10765-020-02708-6

Brown, W. M., P. Wang, S. J. Plimpton and A. N. Tharrington (2011). "Implementing molecular dynamics on hybrid high performance computers-short range forces." Computer Physics Communications 182(4): 898-911. https://doi.org/10.1016/j.cpc.2010.12.021

Cao, Y., A. Taghvaie Nakhjiri and M. Ghadiri (2023). "Computational fluid dynamics comparison of prevalent liquid absorbents for the separation of SO_2 acidic pollutant inside a membrane contactor." Scientific Reports 13(1): 1300. https://doi.org/10.1038/s41598-023-28580-6

Daw, M. S. and M. I. Baskes (1984). "Embedded-atom method: Derivation and application to impurities, surfaces, and other defects in metals." Physical review B 29(12): 6443. https://

doi.org/10.1103/PhysRevB.29.6443

Daw, M. S., S. M. Foiles and M. I. Baskes (1993). "The embedded-atom method: a review of theory and applications." Materials Science Reports 9(7-8): 251-310. https://doi.org/10.1016/0920-2307(93)90001-U

Dukhan, N., Y.-c. K. Chen-Wiegart, A. P. y Puente, D. Erdeniz and D. C. Dunand (2020). "Introduction-porous metals: from nano to macro." Journal of Materials Research 35(19): 2529-2534. https://doi.org/10.1557/jmr.2020.282

Dokur, D., Keskin S. Effects of Force Field Selection on the Computational Ranking of MOFs for CO_2 Separations. Ind Eng Chem Res. 2018 Feb 14;57(6):2298-2309. https://doi.org/10.1021/acs.iecr.7b04792.

Fioletov, V., C. A. McLinden, D. Griffin, N. Theys, D. G. Loyola, P. Hedelt, N. A. Krotkov and C. Li (2020). "Anthropogenic and volcanic point source SO_2 emissions derived from TROPOMI on board Sentinel-5 Precursor: first results." Atmospheric Chemistry and Physics 20: 5591-5607. https://doi.org/10.5194/acp-20-5591-2020

Gao, X., G. Ji, J. Wang, L. Peng, X. Gu and L. Chen (2018). "Critical pore dimensions for gases in a BTESE-derived organic-inorganic hybrid silica: A theoretical analysis." Separation and Purification Technology 191: 27-37. https://doi.org/10.1016/j.seppur.2017.09.013

Gao, X., M. Qiu, K. Fu, P. Xu, X. Kong, X. Chen and Y. Fan (2018). "Feasibility analysis of SO_2 absorption using a hydrophilic ceramic membrane contactor." Chinese Journal of Chemical Engineering 26(10): 2139-2147. https://doi.org/10.1016/j.cjche.2018.07.011

Haile, J. M. (1992). Molecular dynamics simulation: elementary methods, John Wiley & Sons, Inc.

Hairer, E., C. Lubich and G. Wanner (2003). "Geometric numerical integration illustrated by the Störmer-Verlet method." Acta numerica 12: 399-450. https://doi.org/10.1017/S0962492902000144

Hilbert, S., P. Hänggi and J. Dunkel (2014). "Thermodynamic laws in isolated systems." Physical Review E 90(6): 062116. https://doi.org/10.1103/PhysRevE.90.062116

Hoover, W. G. (1985). "Canonical dynamics: Equilibrium phase-space distributions." Physical review A 31(3): 1695. https://doi.org/10.1103/PhysRevA.31.1695

Han, B., Cui, M., & Tong, R. (2025). Molecular dynamics simulation on friction properties of BCC iron strengthened by nanodiamonds. Molecular Simulation, 51(8), 529-545. https://doi.org/10.1080/08927022.2025.2507398.

Jolfaei, N. A., N. A. Jolfaei, M. Hekmatifar, A. Piranfar, D. Toghraie, R. Sabetvand and S. Rostami (2020). "Investigation of thermal properties of DNA structure with precise atomic arrangement via equilibrium and non-equilibrium molecular dynamics approaches." Computer methods and programs in biomedicine 185: 105169. https://doi.org/10.1016/j.cmpb.2019.105169

Jiang C, Wang X, Ouyang Y, Lu K, Jiang W, Xu H, Wei X, Wang Z, Dai F, Sun D. Recent advances in metal-organic frameworks for gas adsorption/separation. Nanoscale Adv. 2022 Mar 24;4(9):2077-2089. https://doi.org/10.1039/d2na00061j.

Kong, X., D. Gong, W. Ke, M. Qiu, K. Fu, P. Xu, X. Chen and Y. Fan (2020). "Investigation of mass transfer characteristics of SO_2 absorption into NaOH in a multichannel ceramic membrane contactor." Industrial & Engineering Chemistry Research 59(23): 11054-11062. https://doi.org/10.1021/acs.iecr.0c01327

Kong, X., M. Qiu, K. Fu, X. Gao, P. Xu, D. Gong, X. Chen and Y. Fan (2019). "Mass-transfer characteristics and optimization of a

hydrophilic ceramic membrane contactor for SO_2 absorption." Industrial & Engineering Chemistry Research 58(45): 20828-20837. https://doi.org/10.1021/acs.iecr.9b04641

Kuhn, H. and D. Medlin (2000). Mechanical testing and evaluation, ASM international.

Li, J. P. H. (2014). "Characterisation of Heterogeneous Acid/Base Catalysts and their Application in the Synthesis of Fine and Intermediate Chemicals." PhD diss., University of Newcastle, Australia.

Li, Z. G., X. E. Li and H. Y. Chen (2022). "Sulfur Dioxide: An Emerging Signaling Molecule in Plants." Frontiers in Plant Science 13: 891626. https://doi.org/10.3389/fpls.2022.891626

Liao, R., S. Wen, J. Liu, S. Bai and Q. Feng (2024). "Synergetic adsorption of dodecylamine and octyl hydroxamic acid on sulfidized smithsonite: Insights from experiments and molecular dynamics simulation." Separation and Purification Technology 329: 125106. https://doi.org/10.1016/j.seppur.2023.125106

Liu Y, Liu G, Zhang C, Qiu W, Yi S, Chernikova V, Chen Z, Belmabkhout Y, Shekhah O, Eddaoudi M, Koros W. Enhanced CO_2/CH_2 Separation Performance of a Mixed Matrix Membrane Based on Tailored MOF-Polymer Formulations. Adv Sci (Weinh). 2018 Aug 2;5(9):1800982. https://doi.org/10.1002/advs.201800982.

Ma, Y., T. Hua, T. A. Trinh, R. Wang and J. W. Chew (2022). "Molecular dynamics simulation of the competitive adsorption behavior of effluent organic matters by heated aluminum oxide particles (HAOPs)." Separation and Purification Technology 292: 120961. https://doi.org/10.1016/j.seppur.2022.120961

Martyna, G. J., D. J. Tobias and M. L. Klein (1994). "Constant pressure molecular dynamics algorithms." J. chem. Phys 101(4177): 10.1063.

Mayo, S. L., B. D. Olafson and W. A. Goddard (1990). "DREIDING: a generic force field for molecular simulations." Journal of Physical chemistry 94(26): 8897-8909. https://doi.org/10.1021/j100389a010

Mosavi, A., M. Hekmatifar, A. a. Alizadeh, D. Toghraie, R. Sabetvand and A. Karimipour (2020). "The molecular dynamics simulation of thermal manner of Ar/Cu nanofluid flow: the effects of spherical barriers size." Journal of Molecular Liquids 319: 114183. https://doi.org/10.1016/j.molliq.2020.114183

Nguyen, T. V., N. A. Luong, V. T. Nguyen, A. T. Pham, A. T. Le, T. L. To and V. Q. Nguyen (2021). "Effect of the phase composition of iron oxide nanorods on SO_2 gas sensing performance." Materials Research Bulletin 134: 111087. https://doi.org/10.1016/j.materresbull.2020.111087

Nosé, S. (1984). "A unified formulation of the constant temperature molecular dynamics methods." The Journal of chemical physics 81(1): 511-519. https://doi.org/10.1063/1.447334

Okwuashi, C. J. (2020). Molecular Dynamics Simulation of Nanoindentation and Nanoscratch of Silicon Wafer, Saint Louis University.

Pasichnyk, M., P. Stanovsky, P. Polezhaev, B. Zach, M. Šyc, M. Bobák, J. C. Jansen, M. Přibyl, J. E. Bara and K. Friess (2023). "Membrane technology for challenging separations: Removal of CO_2, SO_2 and NOx from flue and waste gases." Separation and Purification Technology 323: 124436. https://doi.org/10.1016/j.seppur.2023.124436

Plimpton, S. (1995). "Fast parallel algorithms for short-range molecular dynamics." Journal of computational physics 117(1): 1-19. https://doi.org/10.1006/jcph.1995.1039

Pourfayaz, F., H. Kazempour, M. Taheri and M. Mehrpooya (2025). "Simultaneous Optimization of Sulfur Recovery Efficiency and Thermal Energy Generation in the Catalytic

Section of the Sulfur Recovery Unit Simulated Based on Reaction Kinetics." ACS Omega 10(21): 21262-21279. https://doi.org/10.1021/acsomega.4c10709

Press, W., S. Teukolsky, W. Vetterling and B. Flannery (2007). "Section 17.4. Second-order conservative equations." Numerical recipes: The art of scientific computing, 3rd ed., Cambridge University Press, New York: 7.

Rapaport, D. C. (2004). The art of molecular dynamics simulation, Cambridge university press.

Sadus, R. J. (2002). Molecular simulation of fluids, Elsevier.

Singh, H., P. Saxena and Y. Puri (2021). "The manufacturing and applications of the porous metal membranes: A critical review." CIRP Journal of Manufacturing Science and Technology 33: 339-368. https://doi.org/10.1016/j.cirpj.2021.03.014

Syed Abdul Moiz Hashmi, Chong Yang Chuah, Euntae Yang, Wai Ching Poon, Advances in H2-selective metallic membranes for pre-combustion CO_2 capture: A critical review, Carbon Capture Science & Technology, Volume 13, 2024, 1000247, ISSN 2772-6568. https://doi.org/10.1016/j.ccst.2024.100247.

Soldemo, M. and J. Weissenrieder (2021). "Sulfur dioxide interaction with thin iron oxide films on low-index surfaces of iron." Surface Science 714: 121935. https://doi.org/10.1016/j.susc.2021.121935

Stukowski, A. (2009). "Visualization and analysis of atomistic simulation data with OVITO-the Open Visualization Tool." Modelling and simulation in materials science and engineering 18(1): 015012. https://doi.org/10.1088/0965-0393/18/1/015012

Thompson, A. P., H. M. Aktulga, R. Berger, D. S. Bolintineanu, W. M. Brown, P. S. Crozier, P. J. In't Veld, A. Kohlmeyer, S. G. Moore and T. D. Nguyen (2022). "LAMMPS-a flexible simulation tool for particle-based materials modeling at the atomic, meso, and continuum scales." Computer physics communications 271: 108171. https://doi.org/10.1016/j.cpc.2021.108171

Verlet, L. (1967). "Computer" experiments" on classical fluids. I. Thermodynamical properties of Lennard-Jones molecules." Physical review 159(1): 98. https://doi.org/10.1103/PhysRev.159.98

Wei, C.-C., F. Wu, G. Qu, K. Xiang and P. Ning (2024). "A critical review on the chelated-iron desulfurization process of fuel gas and the prospect of high value-added utilization of sulfur resources." Chemical Engineering and Processing: Process Intensification 201: 109819. https://doi.org/10.1016/j.cep.2024.109819

Xu, P., Y. Huang, X. Kong, D. Gong, K. Fu, X. Chen, M. Qiu and Y. Fan (2020). "Hydrophilic membrane contactor for improving selective removal of SO_2 by NaOH solution." Separation and Purification Technology 250: 117134. https://doi.org/10.1016/j.seppur.2020.117134

Xinyao Jiang and Maiyong Zhu, Metal-organic porous materials for gas adsorption: design principle for complex systems, Inorg. Chem. Front., 2025. https://doi.org/10.1039/D5QI01721A.

JOURNAL OF GAS TECHNOLOGY

Volume 10 / Issue 1 / Summer 2025 / Pages 87-110

Journal Home page: https://jgt.irangi.org

Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry

Yasin Khalili[1], Mohammad Ghader Zahiri[2], Mohammadreza Akbari[3*], Mostafa Keshavarz Moraveji[4]

1. Ph.D. Student, Department of Petroleum and Geoenergy Engineering, Amirkabir University of Technology, Tehran, Iran
2. M.Sc., Department of Petroleum and Geoenergy Engineering, Amirkabir University of Technology, Tehran, Iran
3. Assistant Professor, Department of Petroleum and Geoenergy Engineering, Amirkabir University of Technology, Tehran, Iran
4. Professor, Department of Chemical Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

REVIEW ARTICLE

Article History:
Received: 08 July 2025
Revised: 10 September 2025
Accepted: 16 September 2025

Keywords:
Drill cuttings transport
Multiphase flow
CFD
Artificial intelligence
Nanotechnology
Robotics
Sustainable drilling

DOR: 20.1001.1/jgt.2025.2073308.1062

ABSTRACT

Drill cuttings transport is a critical process in oil and gas drilling operations, directly affecting efficiency, safety, and environmental compliance. This review synthesizes recent advances in multiphase flow technologies combining computational fluid dynamics (CFD), artificial intelligence (AI), robotics, and sustainable materials with a focus on their practical field implications. Comparative analysis of field trials and simulations reveals that real-time monitoring systems can cut non-productive time (NPT) by 25-30%, while CFD-enhanced models improve predictive accuracy by 15-20%, enabling better control of annular velocity and cuttings suspension in horizontal and HPHT wells. Biodegradable and nano-enhanced drilling fluids reduce ecological footprint by 35-40% and lower waste disposal costs, providing economically viable solutions for environmentally sensitive projects. Robotics-based handling systems improve worker safety by up to 50%, allowing continuous, unmanned operation in offshore environments.

Despite these gains, challenges persist in scaling advanced models to field operations and balancing computational cost with on-site feasibility. The study recommends integrating AI-driven control systems with CFD-DEM simulations and adopting modular robotic platforms for automated solids management. By linking theoretical modeling with field-validated practices, this review provides a practical roadmap for implementing sustainable, efficient, and data-driven drill cuttings transport systems in the oil and gas industry.

How to cite this article
Y. Khalili, M. Ghader Zahiri, M.R. Akbari, M. Keshavarz Moraveji, Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry. Journal of Gas Technology. 2025; 10(1): 87-110. (https://jgt.irangi.org/article_732073.html)

* Corresponding author.
E-mail address: akbari.pe@aut.ac.ir, (M.R. Akbari).

Available online 30 September 2025
2588-5596/© 2016 The Authors. Published by Iranian Gas Institute.
This is an open access article under the CC BY license. (https://creativecommons.org/licenses/by/4.0)

1. Introduction

Multiphase flow is a crucial aspect of drill cuttings transport in petroleum operations, influencing efficiency, cost, and environmental impact. In this context, multiphase flow refers to the simultaneous movement of gas, liquid (drilling fluid), and solid (cuttings) phases within the wellbore environment, where the interaction among these phases governs the efficiency of cuttings removal and overall drilling performance (Hussein and Mahmoud 2023). The dynamic coupling between hydrodynamic forces, rheological behavior, and particle-fluid interactions forms the physical foundation of hole cleaning performance. Despite the extensive research conducted in this area, the existing body of literature lacks a comprehensive and critical evaluation of the efficiency of multiphase flow under various operational conditions and well geometries. To address this gap, the present review seeks to provide an integrated and analytical perspective on the recent advancements in multiphase flow mechanisms, highlighting their implications for drilling optimization, environmental stewardship, and cost reduction. The introduction first contextualizes the significance of effective hole cleaning as a determinant of drilling efficiency and wellbore stability, followed by a critical synthesis of prior studies that have contributed to the understanding of cuttings transport dynamics. It further identifies persistent challenges, such as the prediction of flow transitions, the accurate modeling of solid-liquid-gas interactions, and the optimization of rheological properties for diverse drilling environments. Unlike earlier reviews that merely summarize existing methodologies, this paper delves deeper into the fundamental mechanisms influencing transport efficiency, operational safety, and sustainability (Heydari, Sahraei et al. 2017, Rodríguez-López, Ojeda-Morales et al. 2021).

Moreover, unlike prior reviews that primarily focused on drilling fluid formulations or empirical case studies, this paper provides a comparative and quantitative synthesis of recent advancements in computational fluid dynamics (CFD) modeling, artificial intelligence (AI) integration, and sustainable drilling technologies. The novelty of this review lies in its specific focus on multiphase flow in annular geometries, a condition that introduces additional complexities beyond straight horizontal transport due to secondary flow generation, particle recirculation zones, and enhanced cuttings bed formation. By systematically evaluating technological innovations within the annular wellbore context and linking these developments to measurable performance indicators such as cuttings transport ratio, annular pressure loss, and fluid energy efficiency this study proposes a targeted framework for improving operational efficiency, environmental sustainability, and safety (Epelle, Gerogiorgis et al. 2018).

Additionally, (Table 1) presents a comparative assessment of traditional versus advanced approaches to drill cuttings transport, emphasizing their relative performance in terms of efficiency, cost, and environmental compatibility. While advanced techniques, such as AI-assisted CFD modeling and smart drilling fluids, demonstrate superior performance across most criteria, they also involve higher initial costs and computational requirements. Throughout this review, the term multiphase flow consistently refers to the three-phase interaction gas, liquid, and solid that governs the dynamics of drill cuttings transport in petroleum drilling systems.

Table1. Comparison of Traditional and Advanced Methods for Drill Cuttings Transport

Aspect	Traditional Methods	Advanced Methods	Benefits of Advanced Methods	Main Findings from Studies	Limitations of Advanced Methods	References
Efficiency	Limited due to reliance on basic separation equipment (e.g., manual shakers)	Enhanced with automated systems, advanced centrifuges, and real-time monitoring.	Reduced downtime and improved transport rates	Automation leads to 20-30% efficiency gains	Requires reliable power sources	(Cochrane, Ekehaug et al. 2019)
Cost	Lower initial cost but higher operational and maintenance expenses	Higher upfront cost but lower long-term operational expenses due to efficiency.	Long-term savings up to 15%	CFD integration reduces overall costs	High capital investment	(Kogbara, Dumkhana et al. 2017)
Environmental Impact	Greater due to higher waste generation and inefficient fluid reuse	Reduced waste generation and better fluid recovery minimize environmental harm.	Lower emissions and waste	Biodegradable fluids cut impact by 40%	Material sourcing challenges	(Mikos-Szymańska, Rusek et al. 2018)
Adaptability	Less adaptable to varying drilling conditions and complex wells	Highly adaptable with customizable technologies for different environments.	Better performance in diverse settings	Real-time adjustments improve adaptability	Integration with legacy systems	(Rodríguez-López, Ojeda-Morales et al. 2021)
Technological Input	Minimal, using basic mechanical tools and designs	High, involving computational modeling, AI, and real-time adjustments.	Enhanced precision and safety	AI reduces human error	Need for specialized training	(Mikos-Szymańska, Rusek et al. 2018)
Safety	Higher risk due to manual intervention and outdated safety protocols	Improved safety with automated processes and better monitoring systems.	Fewer accidents	Monitoring systems prevent hazards	Cybersecurity risks in digital tools	(Kogbara, Dumkhana et al. 2017)

1.1. Significance of Multiphase Flow in Drill Cuttings Transport

Multiphase flow plays a pivotal role in the transport of drill cuttings, directly influencing operational efficiency, safety, and environmental performance in the oil and gas industry. Quantitative evidence demonstrates that inefficiencies in multiphase flow can significantly escalate costs and downtime. For example, inadequate hole cleaning in deepwater operations has been shown to increase non-productive time (NPT) by 15-25%, leading to delays of several days per well (Costa, Carvalho et al. 2023). Similarly, wellbore instability caused by cuttings accumulation can raise operational costs by approximately $0.5-1 million per well, particularly in high-pressure, high-temperature (HPHT) environments (Rodríguez-López, Ojeda-Morales et al. 2021).

Efficient transportation of drill cuttings in multiphase environments has measurable economic benefits. Optimized drilling fluid rheology and improved solids transport mechanisms can reduce circulation losses by 10-20% and extend bit life by up to 15%, directly lowering maintenance and replacement costs (Deng, Huang et al. 2022, Zhu, Wang et al. 2023). Studies on horizontal and extended-reach wells indicate that maintaining an annular velocity above 1.2-1.5 m/s can reduce cuttings bed buildup by 30-40%, thereby minimizing the risk of pipe sticking and associated downtime (Rasul, Qureshi et al. 2020).

The environmental implications of multiphase flow are equally significant. Poor solids transport can increase the volume of discharged cuttings by 20-30%, elevating risks

of water contamination and ecological damage (Njuguna, Siddique et al. 2022). By contrast, effective transport and recovery systems using biodegradable fluids have demonstrated a 35-40% reduction in environmental footprint in European onshore field trials (Razali, Yunus et al. 2018).

Safety outcomes are also quantifiable. Real-time monitoring of multiphase flow dynamics has been shown to reduce downhole accidents by 20-25%, largely through early detection of cuttings accumulation and pressure anomalies (Nygård, Andreassen et al. 2021). CFD-based predictive models further improve hazard management, reducing wellbore instability incidents by 15% compared to conventional practices (Awad, Hussein et al. 2022).

Collectively, these findings underscore the critical significance of multiphase flow in drill cuttings transport. While improvements have been documented, current models still fail to fully capture extreme HPHT conditions and long-term ecological impacts, leaving research gaps in predictive accuracy and sustainable operations. In HPHT environments typically above 150-180 °C and pressures exceeding 100 MPa the rheological behavior of drilling fluids changes nonlinearly, reducing the accuracy of CFD-based predictions by up to 25% compared to laboratory conditions (Awad, Hussein et al. 2022, Swasdisevi, Thianngoen et al. 2024). At such conditions, turbulence models calibrated for moderate temperatures fail to account for compressibility and thermal degradation, leading to underestimation of cuttings slip velocity and pressure drop. These limitations highlight the need for re-parameterization and experimental validation of current simulation frameworks for HPHT operations.

1.2. Cutting Transport Mechanism in Oil Well

Efficient cuttings transport remains one of the most critical challenges in modern drilling engineering, particularly in horizontal and extended-reach wells, where gravitational effects, annular geometry, and rheological behavior of drilling fluids interact in complex ways. Drill cuttings are transported through a combination of hydraulic mechanisms primarily the upward motion induced by drilling fluid flow and mechanical mechanisms, such as the rotational motion of the drill string and the localized turbulence generated by high-velocity jets at the bit face. The synergy between these mechanisms is governed by a set of interrelated parameters, including fluid density and viscosity, cuttings size distribution, inclination angle, and eccentricity of the annulus (Cochrane, Ekehaug et al. 2019, Rodríguez-López, Ojeda-Morales et al. 2021).

Quantitative and experimental studies have demonstrated that in horizontal sections, where gravitational settling dominates, cuttings bed accumulation can occupy up to 25-40% of the annular cross-sectional area when the annular velocity (AV) falls below approximately 0.8 m/s. Under such conditions, the system transitions from a fully suspended regime to a stratified or partially settled regime, leading to increased torque and drag, poor hole cleaning, and elevated risk of pipe sticking (Rasul, Qureshi et al. 2020, Zhu, Huang et al. 2020). Maintaining a minimum critical velocity in the range of 1.2-1.5 m/s sustains a fully turbulent flow field capable of entraining larger and denser cuttings, thereby enhancing suspension and reducing pipe-sticking probability by nearly (Hajipour 2020, van Deurzen 2024).

In addition to hydraulic influences, mechanical agitation particularly from drill pipe rotation plays a vital role in disturbing the settled beds and redistributing cuttings into the active flow region. Laboratory and field-scale experiments show that increasing the rotational speed of the drill pipe from 60 to 120 RPM can boost overall cuttings transport

efficiency by 15-20%, especially in highly deviated and extended-reach wells where the gravitational settling effect is more pronounced (Geng, Zhang et al. 2023).

From a force-balance perspective, the dynamics of cuttings transport are dictated by the interaction among gravitational, buoyant, and drag forces. Gravity induces a downward motion, buoyancy mitigates part of the effective particle weight, and drag force, generated by the upward flow, counteracts settling and sustains suspension. When annular velocity surpasses 1.5 m/s, the drag component dominates, creating sufficient lift to prevent the formation of a stationary cuttings bed and substantially improving hole cleaning efficiency (Nygård, Andreassen et al. 2021, Costa, Carvalho et al. 2023).

Nevertheless, horizontal and extended-reach drilling (ERD) operations continue to present substantial operational risks due to asymmetric flow profiles and particle deposition along the lower annulus. To mitigate such risks, real-time monitoring technologies such as acoustic cuttings transport sensors and pressure signature analysis combined with optimized rheological models (e.g., yield-pseudoplastic or viscoplastic fluid formulations) have been shown to reduce the likelihood of partial blockage by 20-25%, resulting in improved drilling efficiency and reduced non-productive time (NPT).

By integrating hydraulic, mechanical, and force-based frameworks, engineers can derive holistic optimization strategies including the maintenance of critical annular velocities, adaptive control of rotational parameters, and deployment of intelligent drilling fluids with tunable rheological and viscoelastic properties to ensure efficient cuttings removal, minimize operational downtime, and enhance overall wellbore stability.

(Figure 1) illustrates the primary mechanisms responsible for transporting drill cuttings to the surface in a horizontal wellbore (Costa, Carvalho et al. 2023). This schematic highlights hydraulic and mechanical interactions, showing how fluid flow counters gravity to prevent settling.

The principal forces acting on drill cuttings in a wellbore are shown in (Figure 2), depicting gravity, buoyancy, and drag in balance (Njuguna, Siddique et al. 2022).

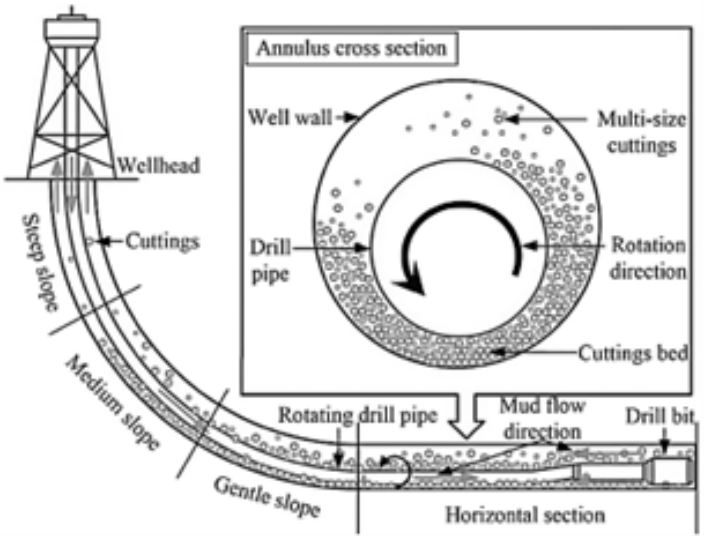


Figure 1. Schematic illustration of the drill cuttings transport mechanism in a horizontal wellbore (inclination angle ~90°). The figure shows hydraulic lifting of solid cuttings by drilling fluid flow and mechanical agitation from drill pipe rotation. Arrows indicate upward flow direction, where sufficient annular velocity (≥1.2 m/s) counteracts gravitational settling to prevent bed formation.

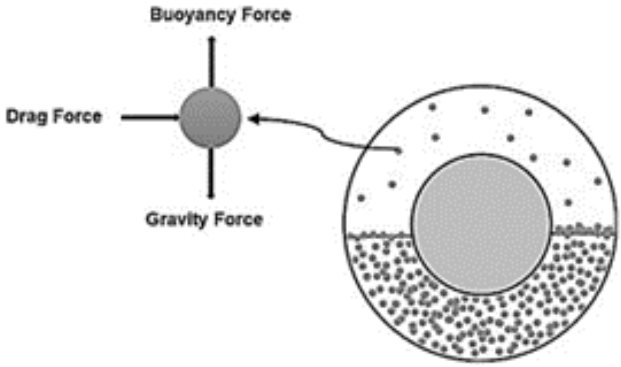


Figure 2. Principal forces acting on drill cuttings in the wellbore: (1) gravity acting downward, (2) buoyancy acting upward, and (3) drag force generated by the upward fluid flow. The relative magnitudes of these forces determine particle suspension. When annular velocity exceeds approximately 1.5 m/s, drag dominates, ensuring efficient cuttings transport.

1.3. Role in the Oil and Gas Industry

Multiphase flow represents a pivotal phenomenon governing the transport of drill cuttings, serving as a cornerstone in the complex and dynamic operations of the oil and gas industry (Njuguna, Siddique et al. 2022, Mahmoud, Gajbhiye et al. 2024). It plays a pivotal role across all stages of upstream and midstream operations from drilling and wellbore cleaning to reservoir management, hydrocarbon transport, and production optimization making it a key driver of overall operational success. The multifaceted interactions among gas, liquid, and solid phases profoundly affect not only hydraulic efficiency but also the industry's capacity to adapt to diverse geological formations and challenging environments.

Ineffective management of multiphase flow can lead to severe operational setbacks, including flow instabilities, pressure surges, and inefficient cuttings transport, ultimately resulting in non-productive time and safety risks. At the same time, the understanding and control of multiphase flow phenomena have become powerful drivers of technological innovation. The continuous evolution of flow monitoring and modeling technologies, coupled with advances in drilling fluid design and dynamic transport methods, underscores the sector's commitment to enhancing performance, safety, and sustainability.

The integration of data-driven analytics and artificial intelligence (AI) into multiphase flow systems promises to revolutionize real-time decision-making by predicting transient flow behavior and adapting operational parameters dynamically. Nonetheless, significant innovation gaps remain in the application of AI-based adaptive control systems capable of handling high-dimensional, non-linear multiphase interactions under real-time constraints. Moreover, a profound understanding of multiphase flow supports the industry's pursuit of environmental stewardship. By mastering the dynamics of multiphase transport, engineers can minimize the ecological footprint of drilling and production operations through optimized waste management, improved cuttings transport, and reduction of fluid losses and emissions. These advances facilitate the adoption of sustainable drilling and extraction practices, ensuring compliance with stringent environmental regulations while maintaining high productivity standards.

The inherently complex and non-linear behavior of multiphase systems also serves as a catalyst for engineering innovation, inspiring the development of next-generation equipment, robust operational protocols, and resilient infrastructure designed to enhance efficiency, safety, and environmental performance.

Furthermore, a solid theoretical and practical grasp of multiphase flow enables the industry to build adaptability and resilience in the face of rapidly evolving market dynamics, regulatory pressures, and technological disruptions. Such adaptability allows operators to navigate uncertainties, optimize production systems, and sustain competitiveness in an increasingly complex global energy landscape. Accordingly, this review paper aims to examine the state-of-the-art developments in multiphase flow modeling, monitoring, and control, providing a comprehensive synthesis of current research directions and identifying emerging opportunities for innovation and sustainability in drilling and production systems (Ikram, Jan et al. 2022, Kharazi Esfahani, Akbari et al. 2024).

2. Background

2.1. Literature Review

Some studies conducted on the multiphase flow research for drill cuttings transport are presented in (Table 2).

Table 2. Key Findings in Multiphase Flow Research for Drill Cuttings Transport

Key Finding	Methodology	Parameters Studied	Gaps Identified	References
Developed multiphase model for reverse circulation drilling, improving transport efficiency.	Direct simulations	Non-Newtonian fluids, turbulence, particle dynamics	Limited to specific geometries	(Sun, Ye et al. 2024)
Analyzed flow patterns with drill pipe rotation, enhancing cuttings removal.	Numerical investigation	Rotation speed, velocity, flow patterns	Neglects high-pressure effects	(van Deurzen 2024)
Sweeping pills improve cuttings removal in turbulent flow.	CFD modeling	Fluid rheology, power capacity	Validation in field conditions needed	(Aliyeva, Czuprat et al. 2024)
Reviewed multiphase challenges, emphasizing transport improvements.	Literature review	Flow regimes, particle interactions	Lack of real-time integration	(Obi, Hasan et al. 2024)
Transient two-phase flow for blocky cuttings in shale gas wells.	Experimental study	Momentum exchange, particle size	Scalability to diverse wells	(Chen, Li et al. 2025)
Optimized drill bit structure for better reverse circulation.	Two-phase flow simulation	Bit structure, process parameters	Needs broader parameter testing	(Qi, Cao et al. 2025)
Novel hole cleaning tool improves transport via swirling jets.	Multi-objective optimization	Flow rates, tool design	Cost-effectiveness in practice	(Hu, Zhang et al. 2025)

(Table 2) critically highlights how recent CFD and experimental approaches address transport efficiency, but gaps in field validation and scalability persist, underscoring the need for hybrid models.

2.2. Research Trend Review

The evolution of multiphase flow research in drilling and production systems over the past decade demonstrates a clear transition from fundamental theoretical exploration toward data-driven modeling, real-time optimization, and sustainable engineering practices. This progression reflects the industry's response to increasingly complex wellbore geometries, environmental constraints, and the demand for operational efficiency and automation.

During the early development phase (2010-2015), research efforts primarily concentrated on establishing a theoretical and phenomenological understanding of multiphase flow dynamics within annular

and non-Newtonian fluid environments. These studies focused on characterizing phase interactions, particle settling behavior, and hydrodynamic stability, laying the groundwork for more sophisticated modeling approaches (Ikram, Mohamed Jan et al. 2021). The introduction of Computational Fluid Dynamics (CFD) into drilling research marked a turning point, enabling the visualization and quantification of cuttings transport phenomena under controlled conditions (Guo, Cheng et al. 2024). However, the early applications were largely constrained to laboratory or simulated environments, with limited field validation and poor scalability to real-world drilling operations due to computational and instrumentation limitations (Ikram, Jan et al. 2022).

The technological integration phase (2016-2020) witnessed the widespread adoption of hybrid numerical approaches, particularly the coupling of CFD and Discrete Element Method (DEM) models to capture particle-fluid interactions with greater fidelity. These methods enhanced predictive accuracy for cuttings migration, bed formation, and suspension stability, providing new insights into wellbore hydraulics and cleaning efficiency. Parallel to these developments, the design of advanced drilling fluids with tailored rheological and viscoelastic properties became a focal research area, addressing the challenges of non-Newtonian behavior, yield stress control, and shear-thinning optimization for efficient cuttings transport (Guo, Cheng et al. 2024). Concurrently, environmental awareness began to shape research priorities, with an increased emphasis on waste management, toxicity reduction, and fluid recyclability in line with emerging global sustainability standards (Huang, Lv et al. 2023). 2021-Present: Innovations and Sustainability.

In the modern innovation phase (2021-present), the field has entered a new paradigm characterized by digitalization, automation, and sustainability. The integration of real-time monitoring systems, sensor-driven feedback loops, and AI-assisted predictive models has transformed multiphase flow management from reactive to proactive control (Swasdisevi, Thianngoen et al. 2024). These technologies enable real-time prediction of flow instabilities, dynamic optimization of pump rates, and early detection of cuttings bed accumulation, significantly enhancing safety and reducing non-productive time (NPT). Moreover, the growing commitment to sustainable drilling practices has led to the introduction of biodegradable drilling fluids, nanostructured additives, and waste recycling systems, aligning operational efficiency with environmental responsibility (Huang, Lv et al. 2023, Ali, Gailani et al. 2024).

Most recently, research trends in 2024 and beyond have emphasized AI-driven optimization frameworks, employing deep learning and adaptive hybrid models to improve the accuracy of multiphase flow prediction in complex, dynamic environments. These models show promise for closed-loop control systems and autonomous drilling applications. However, critical challenges remain unresolved particularly in the areas of data privacy, model generalizability, and robustness under uncertain geological conditions. Bridging these gaps requires the development of integrated digital twins, combining physics-based and data-driven modeling to ensure both predictive reliability and operational transparency.

2.3. Multiphase Flow in Annular Wells: Challenges and Effectiveness

Multiphase flow in annular wells introduces complexities not present in straight or vertical wellbore geometries. In large-diameter annuli, secondary vortices and uneven velocity distributions increase the risk of cuttings bed formation, with accumulation reported at 30-50% of the annular cross-sectional area when

annular velocity falls below 1.0 m/s (Rasul, Qureshi et al. 2020, Zhu, Huang et al. 2020). Compared to straight horizontal sections, annular wells experience stronger gravitational segregation of cuttings, particularly at low inclination angles (30-60°), which reduces transport efficiency by 20-25% under identical flow rates (Awad, Hussein et al. 2022).

Recent CFD-DEM simulations highlight that annular eccentricity exacerbates cuttings settling, requiring annular velocities at least 1.2-1.5 m/s to maintain suspension (Liu, Zhang et al. 2021). Experimental studies further show that pipe rotation can reduce cuttings bed thickness by 15-20%, but only under moderate rotation speeds (<120 RPM), as excessive speeds may destabilize flow regimes (van Deurzen 2024).

Despite these advances, significant research gaps remain. Few studies have quantified annular flow efficiency under HPHT (high-pressure, high-temperature) conditions, and scaling laboratory results to ultra-deep or extended-reach wells remains a challenge. For instance, full-scale CFD-DEM simulations for a 5000 m ultra-deep well segment may require up to 1000 CPU hours and 50-100 GB of memory, making routine application impractical without access to supercomputing infrastructure (Awad, Hussein et al. 2022). Additionally, the long-term environmental consequences of poor annular transport, such as increased discharge volumes, are underexplored. These gaps underline the importance of this review's synthesis in connecting multiphase flow fundamentals with applied solutions in annular wellbore conditions.

2.4. Modeling Process and Governing Equations

The modeling of multiphase flow in drilling operations provides a quantitative foundation for understanding how gas, liquid, and solid phases interact during cuttings transport. Although the modeling approaches vary depending on well geometry and fluid type, most studies rely on the fundamental principles of mass, momentum, and energy conservation to describe the behavior of each phase and their mutual coupling. At the core of multiphase flow modeling are the continuity and momentum equations that express the conservation of mass and momentum within the fluid domain. These equations account for the spatial and temporal variations of density, velocity, and pressure and form the basis for computational fluid dynamics (CFD) simulations widely used in recent research. The continuity equation ensures that the total mass of the mixture remains constant, while the momentum equation balances the inertial, viscous, pressure, and gravitational forces acting within the flow (Awad, Hussein et al. 2022).

To represent the influence of solid particles (cuttings) suspended in the drilling fluid, additional terms are introduced to model interphase interactions, such as drag, lift, and buoyancy forces. These forces govern how particles accelerate, settle, or remain suspended depending on flow velocity, particle size, and fluid rheology. In some advanced studies, the Discrete Element Method (DEM) is coupled with CFD to explicitly resolve particle trajectories and collisions, providing deeper insights into bed formation and particle dispersion patterns. For turbulent multiphase systems, Reynolds-Averaged Navier-Stokes (RANS) models combined with turbulence closures such as the k-ε or k-ω formulations are commonly applied to capture the effect of fluctuating velocities and pressure gradients. These models are particularly effective for predicting cuttings transport efficiency and pressure drop in non-Newtonian drilling fluids (Guo, Cheng et al. 2024).

When non-Newtonian fluids are used, the constitutive relationship between shear stress and shear rate is typically represented by the Herschel-Bulkley or power-law models, allowing rheological parameters such as yield stress and flow index to be incorporated into

the governing equations. This provides realistic predictions of fluid viscosity and carrying capacity under different shear conditions. Boundary conditions play a crucial role in defining the simulation environment. The no-slip condition at the wellbore wall, specified velocity or pressure at the inlet, and outflow or fixed pressure at the outlet are standard assumptions that determine flow stability and convergence. In inclined or horizontal wells, gravitational components and secondary flow effects are included to reproduce the complex circulation patterns observed in annular geometries (Rasul, Qureshi et al. 2020).

3. Key Concepts and Mechanisms

3.1. Fundamental Concepts of Multiphase Flow in the Drilling Environment

A comprehensive understanding of the multiphase flow mechanisms within the drilling environment is fundamental to ensuring operational efficiency, wellbore stability, and safety. In drilling hydraulics, the flow typically consists of three interacting phases gas, liquid, and solid whose dynamic interplay dictates pressure behavior, cuttings transport efficiency, and overall drilling performance.

The gas phase plays a critical role in pressure regulation and well control. Gas entrainment or gas influxes, if improperly managed, can induce severe pressure anomalies, leading to hazardous events such as kick formations or blowouts, particularly in underbalanced or depleted reservoirs. Therefore, understanding gas compressibility and transient gas migration within the annulus is essential for accurate pressure management and kick detection.

The liquid phase, primarily represented by drilling mud, serves as the primary carrier medium responsible for cuttings suspension, lubrication, and pressure stabilization within the wellbore. The effectiveness of this phase depends strongly on its rheological properties including yield stress, viscosity, and shear-thinning behavior which govern the flow regime and cuttings carrying capacity. Any deviation from the designed rheological profile, whether due to temperature fluctuations, contamination, or improper fluid conditioning, can result in inefficient hole cleaning, barite sag, or excessive equivalent circulating density (ECD), thereby compromising drilling efficiency and structural stability.

The solid phase, comprising drill cuttings and entrained particulates, introduces significant challenges to flow behavior and wellbore integrity. Cuttings accumulation on the low side of horizontal and deviated wells can lead to cuttings bed formation, reduced annular flow area, and elevated torque and drag. Furthermore, high-velocity particle impingement can accelerate erosion of downhole tools, bit nozzles, and casing surfaces, leading to premature equipment degradation and increased operational costs (Geng, Zhang et al. 2023).

3.2. Challenges in Transporting Drill Cuttings and Implications for Drilling Operations

Drilling operations are inherently complex, and the behavior of multiphase flow within the wellbore introduces a series of interdependent challenges that directly affect safety, cost efficiency, and environmental performance.

One of the most critical issues is wellbore stability, where the accumulation of cuttings or improper pressure management can lead to formation collapse, stuck pipe, or loss of well integrity. Such instability not only disrupts drilling progress but also elevates non-productive time (NPT) and remediation costs. Equally significant are circulation losses, often caused by excessive annular pressure or fractures induced by high equivalent circulating density (ECD).

These losses increase operational expenditure

due to fluid replacement, lost materials, and downtime, while also complicating pressure control and reservoir management. Effective mitigation of circulation losses requires precise control of rheological parameters, real-time monitoring, and the adoption of intelligent drilling fluid systems capable of adapting to changing subsurface conditions.

Another vital aspect is hole cleaning efficiency, which ensures the continuous removal of drilled cuttings to prevent blockages, excessive torque and drag, or differential sticking. Inadequate hole cleaning compromises drilling performance, accelerates bit wear, and leads to deviations from the planned well trajectory. Similarly, erosion and mechanical wear resulting from the high-velocity impact of cuttings and fluid particulates pose substantial challenges to tool longevity and maintenance schedules. The cumulative effects of erosion can damage drill bits, casing, and surface equipment, necessitating costly replacements and frequent maintenance interventions (Sanei, Ardakani et al. 2020).

3.3. Flow Regimes and Their Implications for Drill Cuttings Transport

The efficiency of drilling operations is strongly influenced by the prevailing flow regime in the wellbore, which governs how fluids and solids are transported. Flow regimes determine suspension capacity, erosion potential, and risk of cuttings bed formation.

Bubbly flow occurs when small gas bubbles are dispersed in the liquid. It generally provides stable transport for fine particles but is limited for larger cuttings. Efficiency improvements are typically <10% over stratified flow, and degassers are required to prevent bubble accumulation.

Slug flow features alternating liquid and gas slugs, which improve mixing and cuttings suspension. Studies show it enhances transport efficiency by 15-20% compared to bubbly flow, though pressure surges may increase erosion risks.

Annular flow is characterized by a liquid film along the pipe wall with a central gas core. It is highly effective for fine particle suspension, with efficiency gains of 2-35% compared to slug flow under high Reynolds number conditions. However, continuous liquid film erosion necessitates wear-resistant materials.

Churn flow is chaotic and unstable, with rapid regime transitions. Transport efficiency is difficult to predict but can fluctuate by ±25%, causing operational instability. CFD-based modeling has been used to mitigate these fluctuations by providing early-warning.

Stratified flow occurs when fluids form distinct layers, with solids often settling at the lower boundary. This regime can reduce cuttings transport capacity by 40-60%, requiring agitation or inclined wellbores to restore flow efficiency.

Quantitative comparisons indicate that annular flow is generally the most favorable regime for maintaining suspension in high-velocity drilling operations, while stratified flow poses the greatest risks for blockages. (Figure 3) illustrates these regimes, and (Table 3) summarizes their efficiency ranges, implications, and management techniques.

By understanding these, engineers can optimize parameters. (Figure 3) shows flow regimes in a horizontal pipe, with colored patterns (e.g., blue for bubbly, red for slug) for clarity, illustrating transitions that affect transport efficiency predictions (Liu, Zhou et al. 2023, Shi, Wang et al. 2024). This figure emphasizes how regime shifts can lead to inefficiencies, a gap in current predictive models.

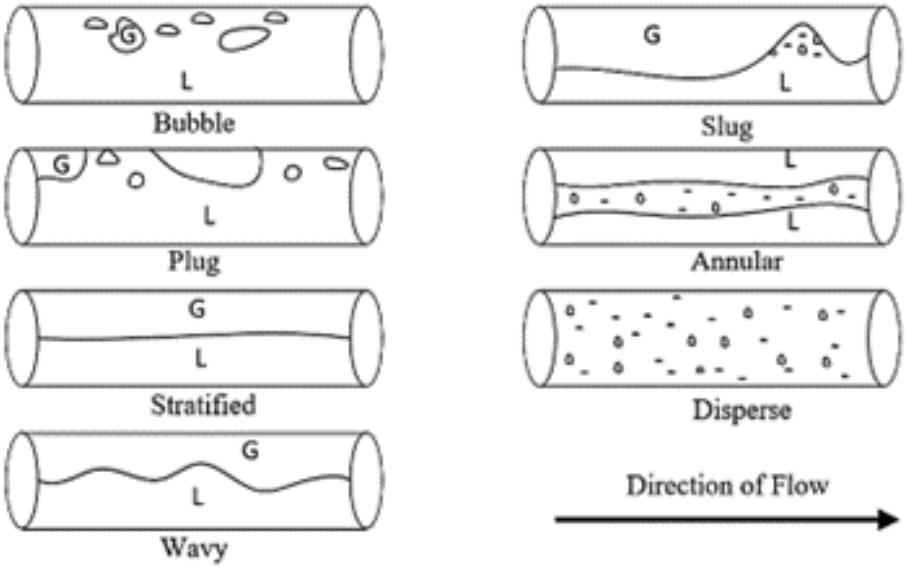


Figure 3. Flow regimes for gas-liquid two-phase flow in a horizontal pipe. The diagram illustrates transitions between bubbly (blue), slug (red), annular (green), churn (orange), and stratified (gray) flows. Color coding highlights regime-dependent transport efficiency, where annular flow offers the most stable particle suspension, while stratified flow leads to solids accumulation.

(Table 3) details flow regimes, their characteristics, and management techniques, showing how bubbly flow offers low erosion but limited capacity, while churn flow poses instability risks [46-50].

Table 3. Flow Regimes and Their Implications for Drill Cuttings Transport

Flow Regime	Characteristics	Implications for Cuttings Transport	Challenges	Techniques/Equipment for Management	References
Bubbly Flow	Gas bubbles dispersed in liquid	Low erosion; limited for larger particles	Gas-liquid separation	Vacuum degassers; shakers	(Wijayanta, Catrawedarma et al. 2022)
Slug Flow	Alternating gas and liquid slugs	Moderate efficiency; good mixing	Pressure surges	Centrifuges; conditioners	(Barros, Rodrigues et al. 2022)
Annular Flow	Liquid film with gas core	Effective for small particles	Erosion	Wear-resistant materials	(Yaqub and Pendyala 2024)
Churn Flow	Chaotic with transitions	Difficult to predict	Instability	CFD; automated systems	(Davarpanah and engineering 2024)
Stratified Flow	Distinct layers	Poor transport; solids settle	Accumulation	Inclined pipes; agitation	(Wijayanta, Catrawedarma et al. 2022)

4. Advanced Solid Control Technologies in Drilling Operations

Solid control systems are essential for removing particles from fluids (Pereira, Sad et al. 2022). Key technologies include shale shakers (Nascentes, Murata et al. 2022), centrifuges, desanders/desilters, and vacuum degassers. (Table 4) compares the benefits, drawbacks, and performance metrics of various solid control technologies used in drilling operations.

Table4. Advantages, Disadvantages, and Comparison of Solid Control Technologies

Technology	Advantages	Limitations	Cost Efficiency	Particle Size Handled	Environmental Benefits	References
Shale Shakers	Ideal for primary cuttings; easy maintenance; minimizes fluid loss	Limited to smaller particles; screen blinding; needs monitoring	Low	High (Large)	Reduces waste	(Ghaniyari Benis , Korostelkin, Filintsev et al. 2020)
Centrifuges	Removes small particles; reduces mud weight; handles large volumes	High costs; skilled maintenance; limited for large cuttings	High Initial	Very High (Fine)	Maximum fluid recovery	(Awad, Hussein et al. 2022, Pereira, Sad et al. 2022)
Desanders/ Desilters	Removes sand/silt; improves stability; protects equipment	Less effective on small particles; high energy; prone to blockage	Moderate	Moderate (Sand/Silt)	Protects downstream equipment	(Islam and Hossain 2020, Yang, Wang et al. 2024)
Vacuum Degassers	Removes gas; prevents pump lock; enhances efficiency	Ongoing monitoring; high investment; less effective in high-gas	Moderate	N/A (Gas)	Improves fluid properties	(Patel and Santra 2020)

5. Innovations Revolutionizing Multiphase Flow in Oil and Gas

Recent innovations have transformed multiphase flow management by improving operational efficiency, sustainability, and safety. Among these, real-time monitoring systems have shown the most immediate impact, reducing downtime by 25-30% in North Sea offshore rigs through early anomaly detection (Nygård, Andreassen et al. 2021). Advanced CFD and DEM models improve predictive accuracy of flow behavior by 15-20% compared to conventional correlations, enabling better parameter optimization in deepwater drilling. However, scaling these models to full-field or ultra-deep wells demands extensive computational power, often exceeding 500 CPU cores for a single simulation run, which constrains field deployment (Awad, Hussein et al. 2022, Wang, Animasaun et al. 2024).

Automated control systems, often driven by AI, minimize human error by ~35%, though their adoption faces barriers due to high initial costs and cybersecurity risks. Biodegradable drilling fluids provide substantial environmental benefits, reducing ecological footprint by 35-40% in European onshore field trials, but face 20-40% higher costs compared to conventional muds, limiting large-scale deployment. Encapsulation techniques for hazardous cuttings show promise in fragile ecosystems such as Arctic offshore, reducing leak risks by more than 50%, though their operational costs remain high (Cherepovitsyn, Lebedev et al. 2023).

These evaluations indicate that while all innovations contribute to sustainability and safety, real-time monitoring and advanced CFD models currently offer the strongest balance between efficiency gains and cost-effectiveness.

Key innovations: Advanced separation, real-time monitoring, automated controls, encapsulation, computational models (Ali, Abdul-Majeed et al. 2025).

5.1. Robotics-Based Systems for Drill Cuttings Handling

Robotics-based systems are emerging as a complementary innovation in drill cuttings management, particularly in offshore environments where personnel exposure to hazardous conditions poses a significant safety

challenge. These systems include robotic arms, automated conveyors, and remotely operated vehicles (ROVs) designed to transport and process cuttings with minimal human intervention.

Field trials in offshore rigs have shown that robotic cuttings handling can reduce manual exposure to hazardous zones by 40-50%, substantially improving worker safety. In addition, autonomous robotic conveyors have been reported to improve material transfer efficiency by 20-25% compared to conventional manual systems, particularly under high-load drilling operations.

Beyond safety, robotics also contribute to operational efficiency. Integrated robotic platforms can operate continuously without fatigue, leading to reductions in handling time of 15-20% per drilling cycle. When combined with automated monitoring, these systems enhance reliability by reducing unplanned shutdowns linked to human error. Despite these benefits, the adoption of robotics remains limited due to high capital costs and the complexity of integrating robotic units into existing rig infrastructure. Current deployments are largely confined to high-risk offshore projects, where safety gains justify investment. Wider adoption will require cost reductions, standardized robotic interfaces, and long-term field validation in both offshore and onshore environments (Alimi, Jin et al. 2025).

(Figure 4) Illustrates the transformation of drill cuttings management from manual to automated workflows. The traditional process (left) relies on manual cuttings handling, discrete monitoring, and reactive adjustments following flow anomalies, often resulting in higher downtime and elevated worker exposure. In contrast, the automated process (right) employs robotics-assisted handling combined with AI-based real-time monitoring and proactive control loops, minimizing human intervention and enabling continuous optimization. Field implementations have demonstrated up to 40-50% reductions in worker exposure, 25-30% decreases in downtime, and 35-40% improvements in environmental performance, highlighting the operational, safety, and sustainability benefits of automation in modern drilling environments.

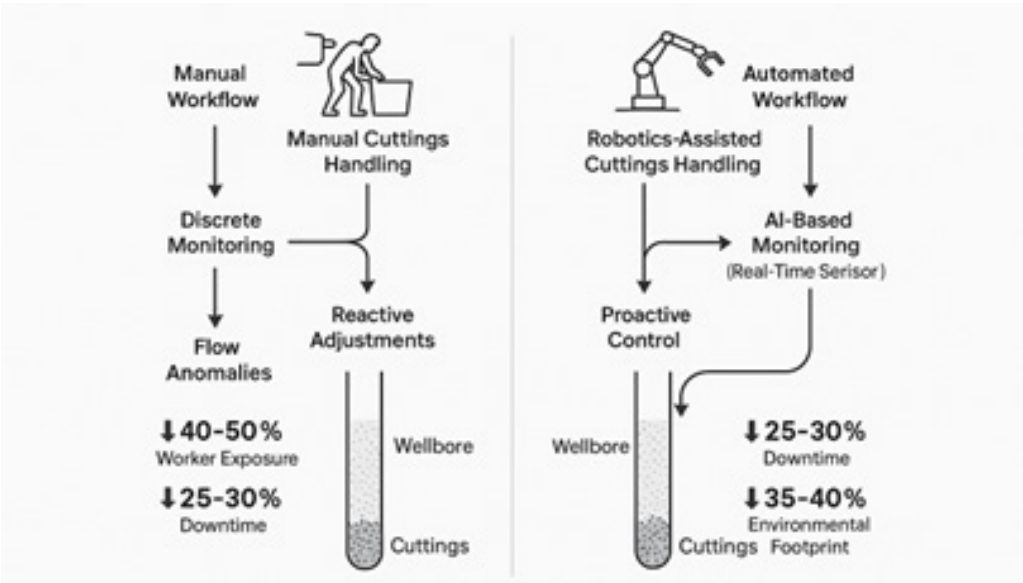


Figure 4. Comparative Workflow of Traditional vs. Automated Cuttings Handling Systems.

(Table 5) highlights the effects and implications of recent technological advancements on the efficiency and effectiveness of drill cuttings transport.

Table 5. Quantitative Impact of Recent Innovations in Drill Cuttings Transport

Innovation	Key Features	Quantitative Impact on Operations	Challenges/Limitations	Example Applications	References
Real-Time Monitoring	Continuous tracking of flow, pressure, and cuttings concentration	Downtime reduction of 25-30% through early anomaly detection	High costs; requires skilled personnel	North Sea offshore rigs	(Nygård, Andreassen et al. 2021)
Advanced CFD Models	High-fidelity simulations of multiphase flow behavior	Predictive accuracy improvement of 15-20% compared to conventional correlations	Computationally intensive; scaling to ultra-deep wells requires high-performance computing (HPC) clusters with >500 CPU cores and simulation runtimes exceeding 72-120 hours, limiting field applicability	Deepwater Gulf of Mexico	(Awad, Hussein et al. 2022, Wang, Animasaun et al. 2024)
Automated Control (AI)	AI-driven adjustments of flow parameters	Reduction of human error by ~35%; improved safety margins	Resistance to adoption; cybersecurity risks	Offshore Canada drilling	(Sircar, Yadav et al. 2021)
Biodegradable Fluids	Eco-friendly rheology tailored for drilling	Reduction in environmental emissions by 35-40%; compliance with EU regulations	Costs 20-40% higher than conventional muds	European onshore wells	(Razali, Yunus et al. 2018)
Encapsulation Methods	Encapsulation of hazardous cuttings for disposal	Reduction in leakage/ spillage risks by ~%50 in Arctic operations	Material availability; high operational costs	Arctic offshore drilling	(Cherepovitsyn, Lebedev et al. 2023)

5.2. Nanotechnology Applications in Multiphase Flow; Drill Cuttings Transport

Nanotechnology has emerged as a transformative approach in drilling engineering, offering unique opportunities to enhance the performance of drilling fluids, optimize multiphase flow behavior, and improve environmental sustainability.

The incorporation of nanoparticles (NPs) into drilling fluids can modify their rheological and thermal properties, leading to superior cuttings transport and wellbore stability, particularly under high-pressure, high-temperature (HPHT) conditions. Nanoparticles such as SiO_2, Al_2O_3, ZnO, TiO_2, and graphene-based materials have been shown to improve lubrication, thermal conductivity, and yield stress control, thereby reducing torque, drag, and differential sticking (Sun, Ye et al. 2024).

Their high surface area-to-volume ratio enhances particle dispersion and suspension stability, leading to a 10-20% improvement in cuttings transport efficiency compared to conventional fluids. Additionally, nano-biodegradable drilling fluids developed using green synthesis methods have demonstrated 25-35% reductions in fluid loss and environmental toxicity (Ali, Gailani et al. 2024).

From a multiphase flow perspective, nanomaterials facilitate better solid-liquid-gas interaction control, improving interface stability and reducing phase segregation. In CFD-DEM simulations, nano-additives improve predictive accuracy for drag coefficients and slip velocity, especially in turbulent and annular

flow regimes (Guo, Cheng et al. 2024). The use of nanoparticle-stabilized foams further enhances gas-liquid interface stability, providing improved hole cleaning in underbalanced drilling scenarios.

Environmentally, nanotechnology enables waste reduction and fluid recyclability by enhancing the reusability of drilling muds and minimizing the release of toxic additives. Recent studies report that nano-enhanced fluids not only meet but exceed API standards for biodegradability and thermal stability (Fan, Zhuang et al. 2025). Despite these advantages, challenges such as nanoparticle agglomeration, cost of synthesis, and long-term environmental impact remain active research areas. Future work should focus on the scalability of green nanomaterial production, the development of hybrid nano-polymer fluids, and integration with AI-driven monitoring systems for real-time optimization of drilling performance (Ali, Gailani et al. 2024).

6. Environmental Impact and Sustainability

Improper handling leads to contamination (George, Nawawi et al. 2024). Mitigation via biodegradable fluids, recycling (Ikram, Jan et al. 2022). (Table 6) assesses the environmental consequences and sustainability aspects of different methods employed for drill cuttings transport.

Table 6. Environmental Impact of Drill Cuttings Transport Methods

Innovation	Key Feature	Environmental Benefit	Challenges	Application	References
Thermal Desorption Units	Reduces hydrocarbons	Hydrocarbon recovery	High energy	Offshore rigs	(Liu, Li et al. 2019)
Recycling and Reuse	Minimizes disposal	Circular economy	Logistics costs	North Sea construction	(Kazamias and Zorpas 2021)
Subsurface Injection	Eliminates surface waste	Safe in formations	Geological assessments	Gulf of Mexico	(Parashar, Thakur et al. 2024)
Biodegradable Fluids	Minimal harm	Regulatory alignment	Initial costs	European projects	(Razali, Yunus et al. 2018)
Encapsulation Methods	Contains hazards	Reduces leaks	Material availability	Arctic drilling	(Pereira, Sad et al. 2022)

6.1. Regulations, Standards, and Sustainability Driving Technological Adoption

Regulatory frameworks drive adoption (Okeke and Indicators 2021). Standards from API/ISO (Nwakile, Hanson et al. 2023). Initiatives include AI monitoring (Cherepovitsyn, Rutenko et al. 2021). Critically, while regulations push sustainability, enforcement gaps in emerging markets hinder progress.

7. Case Studies

(Table 7) presents real-world examples and outcomes from various case studies related to drill cuttings transport across different operational contexts.

Table 7. Case Studies in Drill Cuttings Transport

Case Study	Location	Outcomes	Challenges	Lessons Learned	References
Real-Time Monitoring Offshore	North Sea	30% downtime reduction	Investment/training	Enhances efficiency/ safety	(Nygård, Andreassen et al. 2021)
CFD for Deepwater	Gulf of Mexico	Optimized fluids	Computational cost	Essential for complex regimes	(Cuamatzi-Meléndez, Tetlalmatzin-García et al. 2023)
Recycling for Construction	Onshore Norway	Reduced costs/ impact	Logistics	Dual benefits	(Innes, Nesse et al. 2021)
Biodegradable Fluids Onshore	Germany	Regulatory compliance	Fluid costs	Viable for sensitive ops	(Olry, Cascone et al. 2024)
Thermal Desorption Units	Middle East	Hydrocarbon recovery	Energy/complexity	Effective for hazardous waste	(Li, Kameyama et al. 2020)
Subsurface Injection	Gulf of Thailand	No surface waste	Formations suitability	Ideal for strict regs	(Cuamatzi-Meléndez, Tetlalmatzin-García et al. 2023)
Encapsulation Arctic	Canada	No leaks	Costs/materials	Effective in fragile ecosystems	(Cherepovitsyn, Lebedev et al. 2023)

These cases demonstrate practical applications, but highlight cost and site-specific challenges.

8. The Future of Multiphase Flow Management: A Sustainable Outlook

Trends: Advanced separation, sensors, AI, green tech, modeling, CCU, collaboration. Future holds efficiency gains (Alizadeh, Khalili et al. 2024, Qiu, Zhou et al. 2024, Saxena, Prakash Gupta et al. 2024). (Table 8) forecasts advancements.

Table 8. Forecasting Potential Advancements in Multiphase Flow Technology

Technology	Key Features	Expected Benefits	Challenges	Examples	References
Artificial Intelligence	Predictive modeling	Optimized efficiency	Data needs	Offshore automation	(Wang 2017)
Green Drilling	Biodegradable/ low-emission	Reduced footprint	Costs/scalability	Sensitive projects	(Wang, Ge et al. 2017)
Smart Sensors	Real-time monitoring	Precision	Integration	Arctic/deepwater	(Wang, Ge et al. 2017)
Advanced CFD/DEM	Simulations	Accurate predictions	Computational	Ultra-deep wells	(Lahey Jr, Baglietto et al. 2021)
CCU	CO_2 capture/reuse	Neutrality	Infrastructure	Multiphase systems	(Lau, Ramakrishna et al. 2021)
Robotics/Automation	Autonomous transport	Safety/precision	Development costs	Hazardous rigs	(Chen, Stavinoha et al. 2014)
Hybrid Energy	Renewables integration	Lower costs	Intermittency	Remote drilling	(Tee, Tan et al. 2019)

8.1. The Role of AI in Drilling Operations

AI is transforming drilling by optimizing operations, predicting failures, and enhancing safety. Key applications include geo-steering, site identification, production enhancement, and well placement. For instance, AI reduces risks in high-stakes environments and boosts efficiencies (Noshi and Schubert 2018).

Critically, AI addresses multiphase flow gaps by analyzing real-time data for better cuttings transport, but challenges include data quality and ethical concerns. In addition, the integration of AI-driven real-time monitoring systems introduces significant cybersecurity and data privacy challenges. Sensitive operational data such as wellbore pressure, flow rates, and drilling parameters can be vulnerable to data breaches or unauthorized access during cloud-based data transmission, potentially compromising both safety and proprietary information (Sircar, Yadav et al. 2021, Aderamo, Olisakwe et al. 2024).

Strengthening encryption protocols and implementing secure data governance frameworks are therefore critical to ensure trustworthy AI deployment in drilling operations. (Table 9) summarizes AI advancements.

Table 9. AI Applications in Drilling Operations

Application	Description	Benefits	Challenges	References
Geo-steering	AI-driven path optimization	Efficiency, reduced footprint	Integration costs	(Muhammad, Cheraghi et al. 2024)
Exploration	Data analysis for sites	Accuracy, cost savings	Data volume	(Dada, Oliha et al. 2024)
Predictive Maintenance	Failure prediction	Downtime reduction	Algorithm accuracy	(Hanif and Research 2024)
Automation	Robotic drilling	Safety, precision	Adoption barriers	(Ohalete, Aderibigbe et al. 2023)
Supply Chain	Logistics optimization	Efficiency	Cybersecurity	(John, Oyeyemi et al. 2022)

This section highlights AI's potential to fill research gaps in predictive modeling.

8.2. AI-Based Stimulation Workflows

AI-based stimulation workflows represent a paradigm shift from conventional, empirically guided operations toward data-centric, adaptive, and autonomous decision-making. By integrating historical field data, real-time sensor inputs (e.g., SCADA, DAS, DTS), and machine learning models, these workflows continuously refine stimulation design and execution parameters (Khan, Barooah et al. 2023).

At the design stage, hybrid models such as CFD-DEM simulations combined with AI algorithms (e.g., Gradient Boosting, Reinforcement Learning) enable optimized fluid compositions, proppant schedules, and acid placement strategies. During execution, real-time data streams from pressure and acoustic sensors are processed by AI-based control systems that autonomously adjust pumping rates, fluid viscosity, and injection timing to maintain operational stability (Xu, Song et al. 2025).

Post-treatment evaluation is further enhanced through AI-assisted production forecasting and anomaly detection, allowing for continuous improvement in subsequent jobs. Collectively, these adaptive frameworks not only increase stimulation efficiency and reliability but also align with ESG and sustainability objectives by minimizing resource consumption and operational risks.

(Figure 5) represent the integrated AI-driven workflow combining sensor data acquisition, CFD-DEM simulation, and austomated control for intelligent well stimulation. The feedback-enabled system continuously analyzes field data to optimize operational parameters and ensure efficient, safe, and sustainable performance.

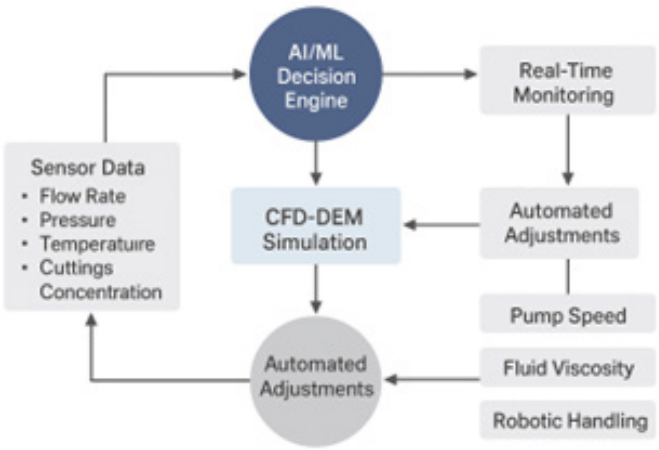


Figure 5. Integrated Multiphase Flow and Automation Framework for Drill Cuttings Transport generate this figure.

8.3. Comparison of Offshore vs. Onshore Applications

Offshore drill cuttings transport faces unique challenges compared to onshore, including higher costs, logistical complexities, and environmental risks. Offshore often uses thermal treatment or subsurface injection due to space limits, while onshore favors recycling and land-based disposal (Ochulor, Sofoluwe et al. 2024). Key differences:

1. Cost: Offshore 2-3x higher due to transport distances.
2. Technology: Offshore relies on compact systems like CTS; onshore uses larger shakers/centrifuges.
3. Environmental Impact: Offshore risks marine pollution; onshore soil contamination.
4. Efficiency: Onshore simpler logistics; offshore needs advanced monitoring for waves/weather.

Critically, offshore scalability is limited by regulations, while onshore benefits from easier waste reuse.

9. Conclusions

The findings of this review reinforce the critical importance of data-driven, sustainable, and automated approaches in advancing multiphase flow management for drilling operations. The integration of CFD-assisted simulation with real-time sensing has proven effective in optimizing hydraulic parameters, reducing downtime, and enhancing cuttings transport efficiency. However, large-scale industrial implementation requires addressing several challenges, including standardization of nanofluid formulations, interoperability between sensor and AI systems, and validation of hybrid CFD-DEM-AI models under diverse field conditions.

For practical deployment, future drilling systems should adopt a modular architecture that combines physics-based simulation, AI-enabled control, and robotic handling into a single closed-loop automation environment. Establishing industry-wide data standards for environmental monitoring, waste recycling, and energy optimization will facilitate interoperability and accelerate technology transfer from laboratory to field operations.

Looking ahead, next-generation multiphase flow systems are expected to evolve into self-optimizing drilling platforms capable of autonomous learning and adaptive control. These systems will dynamically adjust operational parameters based on real-time data to maintain performance, minimize environmental impact, and uphold safety standards even under highly variable subsurface conditions. The convergence of physics-based modeling, sustainable materials engineering, and digital automation offers a tangible pathway toward a cleaner, safer, and economically resilient oil and gas industry.

To enhance the interpretability and visual clarity of these advancements, it is recommended that future studies incorporate schematic diagrams depicting:

1. The CFD-DEM coupling mechanism for multiphase flow simulation;
2. The sensor-AI feedback architecture for real-time control;
3. Comparative schematics of manual versus robotic cuttings handling workflows; and
4. A sustainability framework illustrating the interconnections among drilling fluid selection, waste management, and emission reduction.

References

Aderamo, A. T., H. C. Olisakwe, Y. A. Adebayo, A. E. J. C. R. Esiri, R. i. Engineering and Technology (2024). "AI-enabled predictive safeguards for offshore oil facilities: Enhancing safety and operational efficiency." 2(1): 23-43.

Ali, A. A., G. H. Abdul-Majeed, A. J. A. J. f. S. Al-Sarkhi and Engineering (2025). "Review of multiphase flow models in the petroleum engineering: Classifications, simulator types, and applications." 50(7): 4413-4456.

Ali, J. A., R. Gailani, A. D. Abdullah, P. T. Jaf, S. M. Simo, M. Abdalqadir, V. M. J. E. S. Faris and P. Research (2024). "Performance evaluation of the nano-biodegradable drilling fluid using the greenly synthesized zinc nanorods and gundelia seed waste." 31(39): 51381-51400.

Alimi, K., R. Jin, B. N. Nguyen, Q. Nguyen, W. Chen, L. J. J. o. S. Hosking and T. Technology (2025). "Exploring artificial intelligence applications in construction and demolition waste management: a review of existing literature." 104-136.

Aliyeva, T., O. Czuprat and P. Byrski.(2024). CFD modelling of multiphase flow in horizontal pipe annulus: Effect of sweeping pills on drill cuttings removal. SPE Annual Technical Conference and Exhibition?, SPE.

Alizadeh, S. M., Y. Khalili and M. J. E. Ahmadi (2024). "Comprehensive review of carbon capture and storage integration in hydrogen production: opportunities, challenges, and future perspectives." 17(21): 5330.

Awad, A. M., I. A. Hussein, M. S. Nasser, S. A. Ghani, A. O. J. J. o. P. S. Mahgoub and Engineering (2022). "A CFD-RSM study of cuttings transport in non-Newtonian drilling fluids: Impact of operational parameters." 208: 109613.

Barros, H. A., R. L. Rodrigues, R. F. Alves, C. Cozin, H. T. Rodrigues, R. da Fonseca Junior, M. J. da Silva, M. A. M. Neto, R. E. J. E. T. Morales and F. Science (2022). "Experimental slug flow dissipation analysis in pipes with horizontal to inclined downward direction change." 139: 110740.

Chen, H., S. Stavinoha, M. Walker, B. Zhang, T. A. J. I. C. Fuhlbrigge and Automation (2014). "Opportunities and Challenges of Robotics and Automation in Offshore Oil & Gas Industry." 5: 136-145.

Chen, Y., W. Li, X. Wang, J. Guo, P. Wu, Z. Yang and H. J. F. Yang (2025). "Experimental Investigation of the Effects of Blocky Cuttings Transport on Drag and Drive Torque in Horizontal Wells." 10(9): 219.

Cherepovitsyn, A., A. J. J. o. M. S. Lebedev and Engineering (2023). "Drill cuttings disposal efficiency in offshore oil drilling." 11(2): 317.

Cherepovitsyn, A., E. Rutenko, V. J. J. o. M. S. Solovyova and Engineering (2021)."Sustainable

development of oil and gas resources: A system of environmental, socio-economic, and innovation indicators." 9(11): 1307.

Cochrane, S., S. Ekehaug, R. Pettersen, E. Refit, I. Hansen and L. J. M. p. b. Aas (2019). "Detection of deposited drill cuttings on the sea floor-A comparison between underwater hyperspectral imagery and the human eye." 145: 67-80.

Costa, L., C. Carvalho, A. Soares, A. Souza, E. Bastos, E. Guimarães, J. Santos, T. Carvalho, V. Calderari and L. J. M. P. B. Marinho (2023). "Physical and chemical characterization of drill cuttings: A review." 194: 115342.

Cuamatzi-Meléndez, R., S. Tetlalmatzin-García, S. D. Dionicio-Bravo, E. Flores-Cuamatzi, E. J. J. o. O. E. Aranda-López and M. Energy (2023). "Theoretical and CFD modelling of single and slug oil, water and gas flows in a deepwater rigid jumper." 9(4): 603-622.

Dada, M. A., J. S. Oliha, M. T. Majemite, A. Obaigbena, P. W. J. E. S. Biu and T. Journal (2024). "A review of predictive analytics in the exploration and management of us geological resources." 5(2): 313-337.

Davarpanah, A. J. A. s. c. and engineering (2024). "Comparative evaluation of carbon capture, utilization, and storage (CCUS) technologies using multi-criteria decision-making approaches." 12(25) :9498-9510.

Deng, S., Y. Huang, X. Hu, H. Wang, H. Zhao and J. J. A. o. He (2022). "Nano-film-forming plugging drilling fluid and bridging cross-linking plugging agent are used to strengthen wellbores in complex formations." 7(26): 22804-22810.

Epelle, E. I., D. I. J. C. E. R. Gerogiorgis and Design (2018). "Transient and steady state analysis of drill cuttings transport phenomena under turbulent conditions." 131: 520-544.

Fan, W., G. Zhuang, Q. Li, P. Yuan, D. J. E. Liu and Fuels (2025). "Review of Nanoparticles in Water-Based Drilling Fluids: Innovations, Challenges, and Future Directions." 39(19): 8800-8826.

Geng, Y., Z. Zhang, Z. Yan, Y. Yuan, X. Zhou, W. Yue and Y. J. R. a. An (2023). "A novel graphene/triolein complex-based lubricant for improving high temperature water-based drilling fluid." 13(49): 34772-34781.

George, I. I., M. G. M. Nawawi, Z. J. Mohd, B. S. J. E. S. Farah and P. Research (2024). "Environmental effects from petroleum product transportation spillage in Nigeria: a critical review." 31(2): 1719-1747.

Ghaniyari Benis, S. PERFORMANCE STUDY OF A BENCH SCALE SHALE SHAKER, University of Akron.

Guo, L., H. Cheng, Z. Yao, C. Rong, Z. Wang and X. J. S. R. Wang (2024). "CFD-DEM method is used to study the multi-phase coupling slag discharge flow field of gas-lift reverse circulation in drilling shaft sinking." 14(1): 13853.

Hajipour, M. J. S. A. S. (2020). "CFD simulation of turbulent flow of drill cuttings and parametric studies in a horizontal annulus." 2(6): 1146.

Hanif, H. R. J. E. J. o. C., Medicinal and P. Research (2024). "The Role of Artificial Intelligence in Optimizing Oil Exploration and Production." 3(5): 176-190.

Heydari, O., E. Sahraei, P. J. J. o. p. s. Skalle and engineering (2017). "Investigating the impact of drillpipe's rotation and eccentricity on cuttings transport phenomenon in various horizontal annuluses using computational fluid dynamics (CFD)." 156: 801-813.

Hu, W., J. Zhang, N. Guan, H. J. G. S. Zhu and Engineering (2025). "Cuttings Transport Characteristics and Multi-Objective Optimization Design of a Novel Hole Cleaning Tool." 214053.

Huang, N., K. Lv, J. Sun, J. Liu, J. Wang and Z. J. G. Wang (2023). "Study on the low-temperature rheology of polar drilling fluid and its regulation method." 9(2): 168.

Hussein, I. A. and M. Mahmoud (2023). Fluid-Solid Interactions in Upstream Oil and Gas Applications, Elsevier.

Ikram, R., B. M. Jan, W. Ahmad, A. Sidek, M. Khan

and G. J. M. Kenanakis (2022). "Rheological investigation of welding waste-derived graphene oxide in water-based drilling fluids." 15(22): 8266.

Ikram, R., B. Mohamed Jan, A. Sidek and G. J. M. Kenanakis (2021). "Utilization of eco-friendly waste generated nanomaterials in water-based drilling fluids; state of the art review." 14(15): 4171.

Innes, G., S. Nesse and J. T. Eia (2021). A Comparative Emissions Assessment-Drill Cuttings Treatment Alternatives. Abu Dhabi International Petroleum Exhibition and Conference, SPE.

Islam, M. R. and M. E. Hossain (2020). Drilling Engineering: Towards achieving total sustainability, Gulf Professional Publishing.

John, A. O., B. B. J. I. J. o. M. R. Oyeyemi and G. Evaluation (2022). "The Role of AI in Oil and Gas Supply Chain Optimization." 3(1): 1075-1086.

Kazamias, G. and A. A. J. J. o. C. P. Zorpas".(2021) Drill cuttings waste management from oil & gas exploitation industries through end-of-waste criteria in the framework of circular economy strategy." 322: 129098.

Khan, M. S., A. Barooah, B. Lal and M. A. Rahman (2023). Multiphase Flow Systems and Potential of Machine Learning Approaches in Cutting Transport and Liquid Loading Scenarios. Machine Learning and Flow Assurance in Oil and Gas Production, Springer: 27-57.

Kharazi Esfahani, P., M. Akbari and Y. J. S. R. Khalili (2024). "A comparative study of fracture conductivity prediction using ensemble methods in the acid fracturing treatment in oil wells." 14(1): 648.

Kogbara, R. B., B. B. Dumkhana, J. M. Ayotamuno and R. N. J. C. Okparanma (2017). "Recycling stabilised/solidified drill cuttings for forage production in acidic soils." 184: 652-663.

Korostelkin, A., A. Filintsev, V. Novokshonov and A. Nikitin (2020). On shale shaker's structural optimization and performance improvement. IOP Conference Series: Materials Science and Engineering, IOP Publishing.

Lahey Jr, R. T., E. Baglietto, I. A. J. N. E. Bolotnov and Design (2021). "Progress in multiphase computational fluid dynamics." 374: 111018.

Lau, H. C., S. Ramakrishna, K. Zhang, A. V. J. E. Radhamani and Fuels (2021). "The Role of Carbon Capture and Storage in the Energy Transition."

Li, J.-L., S. Kameyama and G.-P. J. M. C. Yang (2020). "In-situ measurement of trace isoprene and dimethyl sulfide in seawater and oceanic atmosphere based on room temperature adsorption-thermal desorption." 222: 103787.

Liu, G., W. Zhang, L. Zhang and J. J. M. Cheng (2021). "Theoretical prediction method for erosion damage of horizontal pipe by suspended particles in liquid-solid flows." 14(15): 4099.

Liu, H., J. Li, M. Zhao, Y. Li and Y. J. C. Chen (2019). "Remediation of oil-based drill cuttings using low-temperature thermal desorption: Performance and kinetics modeling." 235: 1081-1088.

Liu, Q., B. Zhou, F. Chen, N. Li, J. Xie, M. Zhao, Q. Di, C. Feng, S. Song and C. J. S. R. Yin (2023). "Optimal design and nonlinear dynamic characteristics of titanium/steel drill pipe composite drill string for ultra-deep drilling." 13(1): 20491.

Mahmoud, A., R. Gajbhiye and S. J. S. R. Elkatatny (2024). "Investigating the efficacy of novel organoclay as a rheological additive for enhancing the performance of oil-based drilling fluids." 14(1): 5323.

Mikos-Szymańska, M., P. Rusek, K. Borowik, M. Rolewicz, P. Bogusz, J. J. E. S. Gluzińska and P. Research (2018). "Characterization of drilling waste from shale gas exploration in Central and Eastern Poland." 25(36): 35990-36001.

Muhammad, R. B., Y. Cheraghi, S. Alyaev, A. Srivastava and R. B. Bratvold (2024). Enhancing geosteering with AI: Integrating a decision-making robot into a cloud-based environment and benchmarking against human experts. SPE Norway Subsurface Conference, SPE.

Nascentes, C. L., V. V. Murata, L. C. J. J. o. P. S. Oliveira-Lopes and Engineering (2022).

"Mathematical modeling of solids-drilling fluid separation in shale shakers in oil fields: A state of art review." 208: 109270.

Njuguna, J., S. Siddique, L. B. Kwroffie, S. Piromrat, K. Addae-Afoakwa, U. Ekeh-Adegbotolu, G. Oluyemi, K. Yates, A. K. Mishra and L. J. W. M. Moller (2022). "The fate of waste drilling fluids from oil & gas industry activities in the exploration and production operations." 139: 362-380.

Noshi, C. I. and J. J. J. D. W. Schubert, October 10, (2018). "The Role of Machine Learning in Drilling Operations; A Review."

Nwakile, C., E. Hanson, Y. Adebayo, A. J. G. J. o. A. R. Esiri and Reviews (2023). "A conceptual framework for sustainable energy practices in oil and gas operations." 1(02): 031-046.

Nygård, B. E., E. Andreassen, J. A. Carlsen, G. Å. Ulfsnes, S. Øksenvåg, R. Stabell, T. Davis, T. L. Naterstad, S. Zainoune and E. Vandvik (2021). Improved drilling operations with wired drill pipe and along-string measurements-learnings and highlights from multiple north sea deployments. SPE/IADC Drilling Conference and Exhibition, SPE.

Obi, C., A. Hasan, A. Badejo, M. Rahman and D. J. P. Banerjee (2024). "Multiphase flow challenges in drilling, completions, and injection: Part 2." 10(4): 570-583.

Ochulor, O. J., O. O. Sofoluwe, A. Ukato, D. D. J. W. J. o. A. R. Jambol and Reviews (2024). "Technological advancements in drilling: A comparative analysis of onshore and offshore applications." 22(2): 602-611.

Ohalete, N. C., A. O. Aderibigbe, E. C. Ani, P. E. Ohenhen, A. J. W. J. o. A. R. Akinoso and Reviews (2023). "Advancements in predictive maintenance in the oil and gas industry: A review of AI and data science applications." 20(3): 167-181.

Okeke, A. J. E. and S. Indicators (2021). "Towards sustainability in the global oil and gas industry: Identifying where the emphasis lies." 12: 100145.

Olry, N., A. Cascone, M. Eils, L. Bussaglia and V. Smith (2024). Geothermal Drilling Fluid Meets Performance, Environmental, and Regulatory Challenges in the Alps. Proceedings of the 2024 AADE Fluids Technical Conference and Exhibition, American Association of Drilling Engineers.

Parashar, V., C. J. I. o. p. w. o. e. p. Thakur and i. s. m. t. c. economy (2024). "Challenges, opportunities, and strategies for effective petroleum hydrocarbon waste management." 67-90.

Patel, H. A. and A. J. S. r. Santra (2020). "Organically modified layered magnesium silicates to improve rheology of reservoir drilling fluids." 10(1): 13851.

Pereira, L. B., C. M. Sad, E. V. Castro, P. R. Filgueiras and V. J. F. Lacerda Jr (2022). "Environmental impacts related to drilling fluid waste and treatment methods: A critical review." 310: 122301.

Qi, B., Y. Cao, G. Cui, H. Liu, L. Zhai, P. Cao, J. J. G. S. Wu and Engineering (2025). "A Comprehensive Study on Evaluating Drainage Capability of Air Reverse Circulation Down-The-Hole Hammer Drill Bits via Numerical Simulation and Experimentation." 213918.

Qiu, Z., L. Zhou, L. Bai, M. A. El-Emam, R. J. G. S. Agarwal and Engineering (2024). "Empirical and numerical advancements in gas-liquid separation technology: A review." 233: 212577.

Rasul, G., M. F. Qureshi, H. Ferroudji, S. Butt, R. Hasan, I. Hassan, M. A. J. J. o. A. R. i. F. M. Rahman and T. Sciences (2020). "Analysis of cuttings transport and flow pattern in nearly horizontal extended reach well." 71(2): 69-86.

Razali, S., R. Yunus, S. A. Rashid, H. Lim, B. M. J. R. Jan and S. E. Reviews (2018). "Review of biodegradable synthetic-based drilling fluid: Progression, performance and future prospect." 90: 171-186.

Rodríguez-López, L. C., M. E. Ojeda-Morales, Y. Córdova-Bautista, M. A. Hernández-Rivera and J. J. J. o. E. M. de los Santos López-Lázaro (2021). "Recovery of impregnated hydrocarbon in drill

cuttings using supercritical carbon dioxide." 285: 112134.

Sanei, H., O. H. Ardakani, T. Akai, K. Akihisa, C. Jiang and J. M. J. S. R. Wood (2020). "Core versus cuttings samples for geochemical and petrophysical analysis of unconventional reservoir rocks." 10(1): 7920.

Saxena, A., J. Prakash Gupta, J. K. Tiwary, A. Kumar, S. Sharma, G. Pandey, S. Biswas and K. J. S. Raghav Chaturvedi (2024). "Innovative pathways in carbon capture: Advancements and strategic approaches for effective carbon capture, utilization, and storage." 16(22): 10132.

Shi, S., Z. Wang, D. Qi, W. Guo, Y. J. E. S. Wang, Part A: Recovery, Utilization, and E. Effects (2024). "Investigation of Churn and Annular Flow Transition Boundaries in Vertical Upward Gas-Water Two-Phase Flow." 46(1): 1-21.

Sircar, A., K. Yadav, K. Rayavarapu, N. Bist and H. J. P. R. Oza (2021). "Application of machine learning and artificial intelligence in oil and gas industry." 6(4): 379-391.

Sun, N., T. Ye and R. J. P. o. F. Wang (2024). "Direct simulations of bedrock core and cuttings transport phenomena in reverse circulation drilling." 36(12).

Swasdisevi, T., W. Thianngoen and S. J. F. Prachayawarakorn (2024). "Mathematical Modeling and Design of Parboiled Paddy-Impinging Stream Dryer Using the CFD-DEM Model." 13(10): 1559.

Tee, J. Z., K. H. Tan, I. L. H. Lim, K. Zhou and O. J. I. P. I. S. G. T. E. Anaya-Lara (2019). "Integration of Offshore Wind with O&G Platforms with an Energy Storage System." 1-5.

van Deurzen, L. H. (2024). Ultrawide Bandgap Nitride Photonics on Bulk Substrates, Cornell University.

Wang, F. Z., I. Animasaun, T. Muhammad, S. J. A. J. f. S. Okoya and Engineering (2024). "Recent advancements in fluid dynamics: drag reduction, lift generation, computational fluid dynamics, turbulence modelling, and multiphase flow." 49(8): 10237-10249.

Wang, H., Y. Ge and L. J. N. G. I. B. Shi (2017). "Technologies in deep and ultra-deep well drilling: Present status, challenges and future trend in the 13th Five-Year Plan period (2016-2020)." 4(5): 319-326.

Wang, X. J. M. I. T. (2017). "Application of artificial intelligence in oil and gas industry." 3(1): 117-119.

Wijayanta, S., I. Catrawedarma, A. J. F. M. Hudaya and Instrumentation (2022). "Statistical characterization of the interfacial behavior of the sub-regimes in gas-liquid stratified two-phase flow in a horizontal pipe." 83: 102107.

Xu, Z., X. Song, Y. Sun, M. Zhou and G. J. I. J. o. F. E. Li (2025). "Comprehensive review of cuttings transport in wellbore drilling: Mechanisms, challenges, and future directions." 2(3).

Yang, S., H. Wang and Y. J. M. Wang (2024). "Temperature-sensitive materials for oil and gas drilling applications." 29(7): 1471.

Yaqub, M. W. and R. J. D. C. E. Pendyala (2024). "Flow regime transition maps and pressure loss prediction of gas, oil and water three-phase flow in the vertical riser downstream 90° bend using data driven approach." 12: 100174.

Zhu, J., Z. Huang, Y. Ma, D. Xie, X. Yang and C. J. S. p. Zhou (2020). "Hydraulic structure design and downhole flow field optimization of geophysical drill bits in a limestone stratum." 103(3): 0036850420931257.

Zhu, X., X. Wang, Y. Liu, Y. Luo and H. J. L. Zhang (2023). "Probing the effect of cuttings particle size on the friction and wear mechanism at the casing friction interface: a molecular dynamics study." 39(37): 13386-13398.

تحلیل نقش بیمه در کاهش ریسک‌های سرمایه‌گذاری و توسعه صنعت گاز طبیعی مایع‌شده در ایران

- محمدرضا علیمردان[۱]، محمدرضا سیدهاشمی تولون[۲]، عباس کاظمی نجف‌آبادی[۳*]

۱. دانشجوی دکترا، گروه حقوق خصوصی، دانشکده حقوق و علوم سیاسی، دانشگاه علامه طباطبایی، تهران، ایران

۲. استادیار، گروه مدیریت، موسسه آموزش عالی سهروردی، قزوین، ایران

۳. دانشیار، گروه حقوق خصوصی، دانشکده حقوق و علوم سیاسی، دانشگاه علامه طباطبایی، تهران، ایران

(ایمیل نویسنده مسئول: kazemi_najaf@atu.ac.ir)

چکیـــــــده

صنعت گاز طبیعی مایع‌شده (LNG) به‌عنوان یکی از بخش‌های کلیدی در تأمین انرژی جهانی، نقش بسزایی در توسعه اقتصادی و امنیت انرژی ایفا می‌کند. با این حال، سرمایه‌گذاری در این صنعت با ریسک‌های متعددی از جمله نوسانات قیمت‌های جهانی، چالش‌های فنی، مسائل زیست‌محیطی و عدم اطمینان‌های سیاسی مواجه است. بیمه به‌عنوان ابزاری کارآمد در مدیریت ریسک، می‌تواند نقش مهمی در کاهش این ریسک‌ها و تسهیل سرمایه‌گذاری در صنعت LNG ایفا کند. این پژوهش به تحلیل نقش بیمه در کاهش ریسک‌های سرمایه‌گذاری و توسعه صنعت گاز طبیعی مایع‌شده در ایران می‌پردازد. با استفاده از روش‌های تحلیلی و مطالعه موردی، تأثیر بیمه‌های مختلف از جمله بیمه‌های مسئولیت، بیمه‌های اموال و بیمه‌های اعتباری بر کاهش ریسک‌های سرمایه‌گذاری در این صنعت بررسی می‌شود. نتایج این پژوهش نشان می‌دهد که بیمه‌ها می‌توانند با پوشش ریسک‌های مالی و عملیاتی، جذابیت سرمایه‌گذاری در صنعت LNG را افزایش داده و به توسعه پایدار این صنعت در ایران کمک کنند. همچنین، پیشنهاداتی برای بهبود چارچوب‌های بیمه‌ای و سیاست‌های حمایتی دولت ارائه می‌شود تا زمینه‌ساز رشد بیشتر این صنعت در آینده باشد. مهم‌ترین این پیشنهادات در شرایط عادی (نبود جنگ، تحریم و محدودیت‌های دیگر) عبارتند از: ۱) تقویت چارچوب‌های بیمه‌ای برای پوشش ریسک‌های خاص صنعت گاز طبیعی مایع شده، ۲) تشویق مشارکت شرکت‌های بیمه‌ای بین‌المللی در قالب کنسرسیوم، ۳) ایجاد صندوق‌های تضمین سرمایه‌گذاری، ۴) تدوین سیاست‌های حمایتی دولت، ۵) ارتقای همکاری‌های منطقه‌ای و بین‌المللی، ۶) توسعه بازارهای ثانویه برای انتقال ریسک، ۷) آموزش و توانمندسازی ذی‌نفعان، ۸) تدوین قوانین و مقررات شفاف و پایدار، ۹) توسعه زیرساخت‌های بیمه‌ای، ۱۰) ارزیابی مستمر و به‌روزرسانی سیاست‌ها.

واژگان کلیدی: بیمه، ریسک‌های سرمایه‌گذاری، گاز طبیعی مایع‌شده (LNG)، توسعه صنعتی، ایران

تحلیل فنی-اقتصادی و تحلیل حساسیت فرآیند مایع‌سازی گاز طبیعی با استفاده از چرخه مبرد مخلوط پیش‌سردشده با پروپان

- سحر عرش تبار[۱]، مجتبی بیگلری[۲*]، محمدصادق ولی پور[۳]

۱. دانشجوی دکترا، دانشکده مهندسی مکانیک، دانشگاه سمنان، سمنان، ایران

۲. دانشیار، دانشکده مهندسی مکانیک، دانشگاه سمنان، سمنان، ایران

۳. استاد، دانشکده مهندسی مکانیک، دانشگاه سمنان، سمنان، ایران

(ایمیل نویسنده مسئول: mbiglari@semnan.ac.ir)

چکیـــــــده

گاز طبیعی مایع‌شده نقش اساسی در گذار جهانی انرژی ایفا می‌کند، زیرا امکان انتقال گاز طبیعی در مسافت‌های طولانی را با میزان انتشار آلاینده کمتر فراهم می‌سازد. ازاین‌رو، بهبود بازده انرژی و امکان‌پذیری اقتصادی فرآیندهای مایع‌سازی گاز طبیعی اهمیت ویژه‌ای دارد. در این پژوهش، یک تحلیل جامع فنی-اقتصادی به‌همراه ارزیابی حساسیت فرآیند مایع‌سازی گاز طبیعی با استفاده از چرخه مبرد مخلوط پیش‌سردشده با پروپان ارائه شده است. یک شبیه‌سازی حالت پایا در نرم‌افزار اسپن هایسیس نسخه ۱۲ توسعه داده شد و برای مدل‌سازی دقیق رفتار برودتی جریان‌های چندجزئی از معادله حالت پنگ-رابینسون استفاده گردید. فرآیند به دو زیرسامانه یکپارچه شامل پیش‌سردسازی با پروپان و زیرسردسازی با مبرد مخلوط تقسیم شد و عملکرد آن با استفاده از شاخص‌های کلیدی نظیر مصرف انرژی، نیاز توان الکتریکی و انتشار غیرمستقیم دی‌اکسید کربن ارزیابی گردید.

نتایج نشان می‌دهد که اگرچه چرخه مبرد مخلوط به توان الکتریکی اندکی بیشتر نسبت به مرحله پیش‌سردسازی با پروپان نیاز دارد، اما منجر به کاهش مصرف کل انرژی، کاهش نیاز به آب خنک‌کننده و کاهش قابل‌توجه انتشار آلاینده‌های زیست‌محیطی می‌شود. از منظر اقتصادی، برآورد هزینه‌ها بر اساس شاخص‌های به‌روز هزینه تجهیزات فرایندی بیانگر آن است که این بهبودهای فنی به عملکرد مالی مطلوبی منجر شده و با سودآوری بالا و دوره بازگشت سرمایه کوتاه در شرایط متعارف بازار گاز طبیعی مایع‌شده همراه است. تحلیل حساسیت همچنین نشان می‌دهد که نرخ‌های بالاتر خوراک گاز طبیعی، دبی‌های متوسط مبرد و فشار ورودی نزدیک به ۶۵ بار، بهترین توازن میان بازده انرژی و بازده اقتصادی را فراهم می‌کنند. در مجموع، یافته‌های این پژوهش تأیید می‌کند که چرخه مبرد مخلوط پیش‌سردشده با پروپان گزینه‌ای کارآمد و عملی برای تولید گاز طبیعی مایع‌شده در مقیاس بزرگ است و به‌طور مؤثری بهبود عملکرد ترمودینامیکی را با نتایج اقتصادی مطلوب پیوند می‌دهد.

واژگان کلیدی: چرخه مبرد مخلوط پیش‌سردشده با پروپان، گاز طبیعی مایع‌شده، ارزیابی فنی-اقتصادی، شبیه‌سازی فرایندی، بهینه‌سازی فرایند، تحلیل حساسیت

مروری جامع و ارزیابی مبتنی بر شبیه‌سازی از روش‌های فشار افزایی در مخازن گازی

- یاسین خلیلی[۱]، سعید عباسی[۲*]

۱. دانشجوی دکترا، دانشکده مهندسی نفت و زمین انرژی، دانشگاه صنعتی امیرکبیر، تهران، ایران

۲. پژوهشگاه صنعت نفت، تهران، ایران

(ایمیل نویسنده مسئول: abbasis@ripi.ir)

چکیـــــــده

حفظ فشار مخزن یکی از چالش‌های اصلی در میدان‌های گازی بالغ و کم‌تراوا است، جایی که بهره‌وری با کاهش فشار به‌سرعت افت می‌کند. این پژوهش یک ارزیابی جامع و چارچوب تصمیم‌گیری یکپارچه برای روش‌های پیشرفته افزایش فشار ارائه می‌دهد که ترکیبی از شبیه‌سازی‌های مخزنی مبتنی بر نرم‌افزار ECLIPSE، تحلیل‌های رگرسیونی و حساسیت و ارزیابی‌های اقتصادی است.

در این تحقیق، روش‌هایی مانند شکاف‌زنی هیدرولیکی، اسیدکاری ماتریسی، گازلیفت، تزریق گاز و پیکربندی‌های ترکیبی مورد بررسی قرار گرفته‌اند. همچنین، نوآوری‌های نوظهوری مانند بهینه‌سازی مبتنی بر هوش مصنوعی (AI)، تحریک به کمک نانوفناوری و فناوری جذب، استفاده و ذخیره‌سازی کربن (CCUS) تحلیل شده‌اند.

نتایج نشان می‌دهد که شکاف‌زنی هیدرولیکی در مخازن با تراوایی پایین بیشترین افزایش تولید (حدود ۲۵ تا ۳۰ درصد) را ایجاد می‌کند، در حالی‌که گازلیفت در سیستم‌های دارای بار مایع بیشترین کارایی را داشته و منجر به افزایش ۱۵ تا ۲۰ درصدی تولید می‌شود. پیکربندی ترکیبی شکاف‌زنی-فرازآوری با گاز بهترین عملکرد اقتصادی را با نرخ بازده سرمایه (ROI) بین ۲/۳ تا ۲/۵ ارائه داده است که از طریق تحلیل حساسیت با تغییرات ۲۰± درصد در هزینه‌ها تأیید شده است. نتایج رگرسیونی با ضریب تعیین $R^2 = ۰/۸۷$ نشان می‌دهد که تراوایی و تجمع مایع از مهم‌ترین متغیرهای مؤثر بر کارایی افزایش فشار هستند.

این مطالعه یک چارچوب تصمیم‌گیری نوین مبتنی بر شبیه‌سازی معرفی می‌کند که شاخص‌های فنی، اقتصادی و پایداری محیطی را در انتخاب بهترین راهکار افزایش فشار یکپارچه می‌سازد. این رویکرد یکپارچه، بررسی‌های توصیفی سنتی را به یک ابزار کمی و کاربردی در میدان تبدیل کرده و مسیر جدیدی را برای مدیریت کارآمدتر و پایدارتر مخازن گازی فراهم می‌آورد.

واژگان کلیدی: فشارافزایی مخازن گازی، بهبود بهره‌وری، مدیریت پایدار مخزن، بهینه‌سازی تولید گاز

حذف انتخابی SO_2 از اکسیژن با استفاده از آهن متخلخل: مطالعه دینامیک مولکولی

- مصطفی جعفری[۱]، محمدمهدی یوسفی[۲]، علی وطنی[۳*]، روزبه ثابت وند[۴]

۱. پژوهشگر، انستیتو گاز طبیعی مایع، دانشکده مهندسی شیمی، دانشکده فنی، دانشگاه تهران، تهران، ایران

۲. دانشجوی کارشناسی ارشد، انستیتو گاز طبیعی مایع، دانشکده مهندسی شیمی، دانشکده فنی، دانشگاه تهران، تهران، ایران

۳. استاد تمام، انستیتو گاز طبیعی مایع، دانشکده مهندسی شیمی، دانشکده فنی، دانشگاه تهران، تهران، ایران

۴. دکترا، دانشکده مهندسی انرژی و فیزیک، دانشگاه صنعتی امیرکبیر، تهران، ایران

(ایمیل نویسنده مسئول: avatani@ut.ac.ir)

چکیـــــــده

دی‌اکسید گوگرد یک آلاینده سمی است که عمدتاً از احتراق سوخت‌های فسیلیِ حاوی گوگرد تولید می‌شود و حذف آن برای توسعه صنعتی پایدار حیاتی است. در این مطالعه محاسباتی، از شبیه‌سازی‌های دینامیک مولکولی (MD) برای ارزیابی یک غشای آهنی متخلخل به‌منظور جداسازی اکسیژن از جریان گازی SO_2 استفاده شد. غشای Fe با روش اتم نهفته (Embedded Atom Method, EAM) مدل‌سازی شد و مخلوط O_2–SO_2 با میدان نیروی DREIDING توصیف گردید. فرآیند برقراری تعادل، پایداری ساختاری مدل‌های اتمی را تأیید کرد که بازتاب‌دهنده تنظیمات مناسب MD و انتخاب دقیق شرایط اولیه بود. برای توصیف کارایی جداسازی، ضرایب جذب SO_2 و O_2، انرژی‌های برهم‌کنش گاز-غشاء و خواص مکانیکی غشاء پس از جداسازی گزارش می‌شوند. شبیه‌سازی‌ها همچنین نشان می‌دهند که شرایط اولیه (برای نمونه دما و فشار) رفتار جذب انتخابی غشاء متخلخل آهنی را در سراسر فرآیند شبیه‌سازی کنترل می‌کند. تحت شرایط بهینه، غشاء در سامانه پالایش در مقیاس اتمی به خلوصِ اکسیژن حدود ۸۱ درصد و بازیابی تقریب برابر با ۹۶/۷ درصد دست یافت. این عملکرد از برهم‌کنش بهینه میان غشاء متخلخل آهنی و مولکول‌های گاز هدف ناشی می‌شود. ازنظر عددی، قدر مطلقِ انرژی برهم‌کنش بین این نمونه‌های مدل شده به ۸۳/۱۴ eV- افزایش یافت. این فرآیند توصیف‌شده عملکرد مکانیکی غشاء طراحی‌شده را مختل نکرد و استحکام نهایی و مدول یانگ آن به ترتیب پس از تکمیل فرآیند جداسازی انتخابی به ۲۱۲/۳۹ MPa و ۶/۰۰ GPa رسید.

واژگان کلیدی: جداسازی O_2/SO_2، دینامیک مولکولی، خالص‌سازی گاز، فناوری غشاء اتمی، نفوذپذیری، گزینش‌پذیری اتمی، غشاء آهن متخلخل، خالص‌سازی در مقیاس اتمی

پیشرفت در فناوری‌های جریان چندفازی برای انتقال پایدار خرده‌های حفاری در صنعت نفت و گاز

- یاسین خلیلی[۱]، محمد قادر ظهیری[۲]، محمدرضا اکبری[۳*]، مصطفی کشاورز مروجی[۴]

۱. دانشجوی دکترا، دانشکده مهندسی نفت و زمین انرژی، دانشگاه صنعتی امیرکبیر، تهران، ایران

۲. کارشناسی ارشد، دانشکده مهندسی نفت و زمین انرژی، دانشگاه صنعتی امیرکبیر، تهران، ایران

۳. استادیار، دانشکده مهندسی نفت و زمین انرژی، دانشگاه صنعتی امیرکبیر، تهران، ایران

۴. استاد، دانشکده مهندسی شیمی، دانشگاه صنعتی امیرکبیر، تهران، ایران

(ایمیل نویسنده مسئول: akbari.pe@aut.ac.ir)

چکیـــــــده

انتقال خرده‌های حفاری یکی از فرآیندهای کلیدی در عملیات حفاری نفت و گاز است که به‌طور مستقیم بر بهره‌وری، ایمنی و انطباق زیست‌محیطی تأثیر می‌گذارد. این مقاله مروری، پیشرفت‌های اخیر در فناوری‌های جریان چندفازی را که دینامیک سیالات محاسباتی، هوش مصنوعی، رباتیک و مواد پایدار را با تمرکز بر کاربردهای عملی در میدان ترکیب می‌کنند، مورد بررسی قرار می‌دهد. تحلیل تطبیقی داده‌های میدانی و شبیه‌سازی‌ها نشان می‌دهد که سیستم‌های پایش لحظه‌ای می‌توانند زمان‌های غیرمولد را بین ۲۵ تا ۳۰ درصد کاهش دهند، در حالی که مدل‌های مبتنی بر دینامیک سیالات محاسباتی، دقت پیش‌بینی را بین ۱۵ تا ۲۰ درصد افزایش می‌دهند و کنترل بهتری بر سرعت چرخشی در حلقه حفاری و تعلیق کاتینگزها در چاه‌های افقی و فشار و دمای بالا فراهم می‌سازند. استفاده از سیالات حفاری زیست‌تخریب‌پذیر و نانوافزوده باعث کاهش ۳۵ تا ۴۰ درصدی اثرات زیست‌محیطی و کاهش هزینه‌های دفع پسماند می‌شود و راهکاری اقتصادی برای پروژه‌های حساس ازنظر محیط‌زیست ارائه می‌دهد. همچنین، سیستم‌های رباتیکی حمل و مدیریت خرده‌های حفاری و ایمنی کارکنان را تا ۰۵ درصد افزایش داده و امکان عملیات بدون سرنشین و پیوسته را در محیط‌های دریایی فراهم می‌سازد.

باوجود این دستاوردها، چالش‌هایی همچنان در مقیاس‌پذیری مدل‌های پیشرفته به سطح عملیات میدانی و توازن میان هزینه محاسباتی و قابلیت اجرا در محل باقی‌مانده است. این مطالعه پیشنهاد می‌کند که سیستم‌های کنترل مبتنی بر هوش مصنوعی با شبیه‌سازی‌های CFD–DEM ادغام شده و پلتفرم‌های رباتیکی ماژولار برای مدیریت خودکار مواد جامد به کار گرفته شوند. با پیوند دادن مدل‌سازی نظری با تجربیات میدانی معتبر، این مقاله یک نقشه راه عملی برای پیاده‌سازی سیستم‌های پایدار، کارآمد و داده‌محور انتقال خرده‌های حفاری در صنعت نفت و گاز ارائه می‌کند.

واژگان کلیدی: انتقال خرده‌های حفاری، جریان چندفازی، دینامیک سیالات محاسباتی، هوش مصنوعی، نانوفناوری، رباتیک؛ حفاری پایدار

JOURNAL OF GAS TECHNOLOGY
VOLUME 10 • ISSUE 1 • SUMMER 2025
EISSN: 2588-5596

Contents

1 **Analysis of the Role of Insurance in Reducing Investment Risks and Development of the Liquefied Natural Gas Industry in Iran**

Mohammad Reza Alimardan, Mohammad Reza Seyed Hashemi Toloun, Abbas Kazemi Najafabadi

2 **Techno-Economic and Sensitivity Analysis of Natural Gas Liquefaction Using the Propane Pre-Cooled Mixed Refrigerant (C3MR) Cycle**

Sahar Arshtabar, Mojtaba Biglari, Mohammad Sadegh Valipour

3 **A Comprehensive Review and Simulation-Based Assessment of Pressure Enhancement Techniques in Gas Reservoirs**

Yasin Khalili, Saeed Abbasi

4 **Selective Removal of Sulfur Dioxide from Oxygen Using Porous Iron: A Molecular Dynamics Study**

Mostafa Jafari, Mohammad Mahdi Yousefi, Ali Vatani, Roozbeh Sabetvand

5 **Advancing Multiphase Flow Technologies for Sustainable Drill Cuttings Transport in the Oil and Gas Industry**

Yasin Khalili, Mohammad Ghader Zahiri, Mohammadreza Akbari, Mostafa Keshavarz Moraveji