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Numerical Simulation of Natural Gas Pipeline in Dense and Hybrid Phases

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ABSTRACT

Transmission of natural gas via pipelines is predominantly employed due to its cost-effectiveness compared to other methods. Transportation of natural gas through pipelines faces several challenges, such as high energy consumption, significant pressure drops, and two-phase flow problems. In this study, the transmission of natural gas in dense, hybrid (regions of dense phase and near-dense phase), and vapor phases was investigated to address some of these limitations. Additionally, mathematical models of quadratic forms for the pressure drop in the dense phase and hybrid modes, in terms of the diameter, mass flow, and length of the pipeline, were proposed. According to the models, the pipeline diameter had a more significant effect on the pressure drop than the flow rate and pipeline length. Moreover, the results showed that the energy consumption of the heat exchanger for the hybrid mode was 35% less than the dense phase. On average, the densities in dense phase and hybrid modes were 2.5 times higher than the two-phase flow. The pressure drop and velocity in the dense phase and hybrid modes were 2.2 times less than the two-phase conditions. In the dense phase and hybrid modes, the capacity of the pipeline for natural gas transmission increased by 52% compared with two-phase gas transmission.

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1. Introduction

Natural gas is one of the most important sources of energy in the world. Natural gas is a hydrocarbon fuel that forms below the earth's surface (Chen et al., 2021; Dorao and Fernandino, 2011; Faramawy et al., 2016). Following the extraction and refining of natural gas, its transmission becomes the most critical phase. Several methods are used for transmitting natural gas, such as, liquefied natural gas, pipeline transport, converting gas to solid, gas to electricity, and gas to liquid (Thomas and Dawe, 2003). The optimal method depended on the volume and distance required for natural gas transmission. (Figure 1) illustrates the relationship between distance and the suitable volume for transmission using each method (Mokhatab et al., 2018). For example, if the distance is less than 2000 km, the pipeline method is acceptable. The most common method of transporting natural gas is the pipeline.

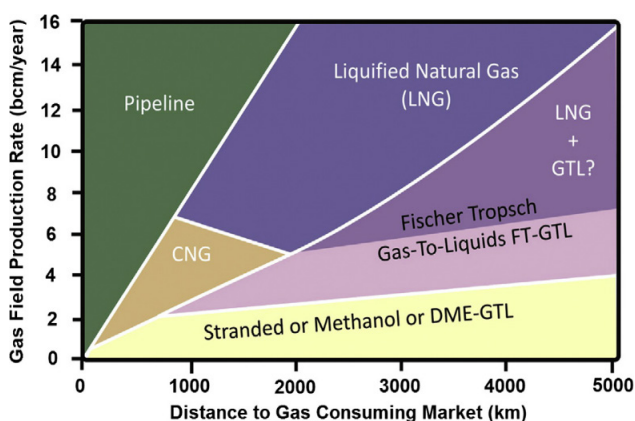


Figure 1. Gas Transmission Methods (Mokhatab et al., 2018)

Natural gas pipeline systems are crucial for advancing and transmitting natural gas due to their cost-effectiveness and reliability (Lanzano et al., 2013; Wei et al., 2023). The cost-effectiveness of natural gas transmission through pipelines has spurred substantial scholarly research in this field. Academic studies have focused extensively on

improving pipeline performance, particularly concerning operational pressure and diameter characteristics in natural gas transmission pipelines.

Gregori et al. (Gregory et al., 1979) conducted mathematical modeling and simulation of a 12-inch diameter pipeline using ethane. Their study considered variations in physical properties, employing one-dimensional energy and mass balance equations. Results emphasized significant impacts of physical property changes on temperature and pressure profiles. Moore et al. (Moore et al., 1980) explored high-pressure pipeline design and modeling, focusing on natural gas hydrodynamics. They utilized energy and flow equations for modeling and employed the Benedict-Webb-Rubin (BWR) equation to calculate gas properties. Their study involved analyzing eleven natural gas samples and comparing model predictions with actual pipeline data, showing consistent alignment. Pritt and Toth (Peretti and Toth, 1982) optimized natural gas transmission pipelines by identifying ideal compressor combinations and outlet pressures from compressor stations for optimized fuel gas delivery. Shariati et al. (Shariati et al., 1999) investigated a two-phase natural gas transmission pipeline to assess the effect of different hexane plus percentages. Their focus was on understanding liquid content variations with decreasing temperatures along the pipeline, finding increased liquid content as temperature drops. Gato et al. (Gato and Henriques, 2005) explored dynamic behavior of high-pressure natural gas flow through mathematical modeling. Zhang et al. (2006) conducted an investigation into gas transmission within pipelines, with a focus on analyzing pressure drop under adiabatic and isothermal conditions. Their findings indicated that the variations in pressure drop between the two conditions were negligible. Teng et al. (Teng et al., 2016) investigated gas transmission and analyzed pressure drop under isothermal and adiabatic conditions, finding density

decreases along the pipeline and negligible pressure drop variations. Mokhatab (Mokhatab, 2007) developed an analytical method using momentum and continuity equations to calculate temperature and pressure in natural gas pipelines containing hydrogen sulfide gas, showing close agreement with literature data. Chaczykowski et al. (2012) conducted numerical simulations of fast and slow fluid transients in pipelines to evaluate velocity, pressure, and temperature profiles. Witkowski et al. (Witkowski et al., 2018) simulated natural gas pipelines incorporating hydrogen, focusing on safety concerns. Abd et al. (2020) explored the influence of impurities on the properties of natural gas. Their analysis revealed that these impurities significantly affect pressure drop, and physical properties. Cristello et al. (2023) analyzed the influence of hydrogen on natural gas pipelines, highlighting its effects on pressure and velocity.

Recently, the transmission of natural gas in dense phase has been investigated. Transmission of natural gas in dense phase leads to a decrease in pressure drop in the pipeline. To transfer natural gas in the dense phase state, the natural gas pressure must be greater than the cricondenbar, and its temperature should be between the critical temperature and the cricondentherm (Zivdar, 2021).

Researches on the transmission of natural gas through pipelines in the dense phase are limited. However, we have made an effort to review the most relevant studies on dense-phase pipeline modes. Botros (Botros, 2002) investigated an experimental work to determine the thermodynamic equation of state in the dense phase mode. The results showed that the Peng-Robinson equation of state was in good agreement with the experimental data. Vera et al. (Vargas-Vera et al., 2020) simulated an undersea pipeline in the dense phase mode and compared results with the two-phase mode. Results showed that in the dense phase mode

the pressure drop was about 100% less than the Two-phase case. Zivdar and Abrofarakh (Zivdar, 2021) simulated a gas pipeline in the dense phase mode and compared results with a vapor phase. They showed that when natural gas was transported in the dense phase, the number of the compressor stations were reduced. Also, they showed that the cooling duty of dense phase was 563 MW. Almora et al. (Almara et al., 2023) examined the physical properties of natural gas in supercritical conditions. Their study indicated that the density behavior in supercritical phase resembles that of liquids, while its viscosity is similar to gases. Prasad et al. (Prasad et al., 2023) investigated the transportation of natural gas in supercritical conditions through mathematical modeling. Their findings showed that natural gas at a flow rate of 800 kilograms per second can be transported up to 4801 kilometers without compression.

Although the transmission of natural gas in dense phase mode has advantages, however, due to the low cricondentherm temperature of natural gas, this method requires extensive cooling of natural gas. Additionally, a comprehensive study and development of mathematical models are crucial to improve the understanding of pipelines in this phase. According to our review and to the best of our knowledge, there have been no studies investigating natural gas in combined dense and hybrid phases, along with the development of mathematical modeling for these phases. Therefore, this study proposes the transmission of natural gas in a hybrid phase (combining dense phase and near dense phase) to decrease the required cooling energy. Additionally, the results of the hybrid mode were compared with those of the dense phase and two-phase flow. Finally, quadratic models for the pressure drop in dense phase and hybrid modes were developed, considering pipeline diameter, mass flow, and length.

Table 1. Mole Fraction of Components, Masjed Soleyman to Mahshahr Gas Pipeline (Mokhatab, 2007)

Components	Mole fraction (%)
H ₂ S	25.6
N ₂	0.2
CO ₂	9.9
C ₁	62.9
C ₂	0.7
C ₃	0.2
iC ₄	0.06
nC ₄	0.09
iC ₅	0.04
nC ₅	0.05
C ₇	0.26

2. Mathematical Modeling

2.1. Physical Model

The pipeline information of the Masjed Soleyman is shown in (Table 2). At two-phase (normal mode), the inlet pressure and temperature of the pipeline are 80.29 bar and 35 degrees Celsius, respectively. To transmit the natural gas of Masjed Soleyman in the dense phase, its pressure must be higher than 112 bar and its temperature between -27 to 19 degrees Celsius. Also, to transmit the natural gas in the hybrid mode, its pressure must be higher than 110 bar and its temperature between 17 to 35 degrees Celsius. (Table 3) shows specifications of inlet pipelines for the three cases.

Table 2. Pipeline specifications, Masjed Soleyman pipeline (Mokhatab, 2007)

Specification	Value
Length (km)	168
Diameter (cm)	48.26
Wall thickness (mm)	14
Mass flow (kg/s)	59.12
Inlet Pressure (bar)	80.29
Inlet Temperature (°C)	35
Ambient temperature(°C)	15
Permissible outlet pressure (bar)	55

Table 3. Specifications of Inlet Conditions for the Three Cases

State	Temperature (°C)	Pressure (bar)
Two- phase flow	35	80.29
Dense phase	19	122
Hybrid	35	122

For simulating the pipeline, the system is modeled as steady-state, compressible, and one-dimensional. The steady-state assumption implies that the properties of the system, such as pressure, temperature, and velocity, do not change with time. The compressible flow of natural gas was considered because the density and volume of the gas can change with variations in pressure and temperature. Additionally, frictional losses within the pipeline were determined using the Darcy friction factor, which represents the flow resistance resulting from the interaction between the gas and the pipeline's internal surface. Physical properties such as density, viscosity, heat capacity, and thermal conductivity vary with temperature and pressure. Therefore, an equation of state for high-pressure natural gas mixtures is also required to describe the relationship between natural gas density, pressure, and temperature, and to calculate other thermodynamic properties accurately. In this study, the equation of state was employed to calculate thermophysical properties due to the presence of a hydrocarbon system and high-pressure conditions (Saffari and Zahedi, 2013).

Thermo-hydrodynamics modeling of natural gas requires equations of continuity, momentum, and energy. These equations are as follows (Helgaker and Ytrehus, 2012):

$$\nabla \cdot (\rho u) = 0 \text{ (continuity)} \quad (1)$$

$$0 = -\nabla p - f_D \frac{\rho}{2D} u|u| = 0 \text{ (momentum)} \quad (2)$$

$$\rho A C_p u \cdot \nabla T = \nabla \cdot (Ak \nabla T) + f_D \frac{\rho A}{2D} |u|^3 + Q_w \text{ (energy)} \quad (3)$$

$$\rho = f(T, p) \quad (4)$$

Where A , ρ , u , p , f_D , D , C_p , T , k and Q_w are area, density, velocity, pressure, Darcy friction factor, diameter, heat capacity, temperature, thermal conductivity and heat exchange with the surroundings through the pipeline, respectively. The first and second terms on the right-hand side in Eq. (2) represents the gradian pressure and viscous pressure drop. both for turbulent and laminar flow regimes (Darcy friction factor), respectively. The term on the left side of Eq. (3) (energy) represents convection heat transfer. The first, second and third terms on the right side of Eq. (3) represent the conduction heat transfer, friction heat dissipation due to viscous and external heat exchange through the pipeline wall, respectively.

The expression of the Darcy friction factor in Eq. (2) is shown as follows (Haaland, 1983):

$$\frac{1}{\sqrt{f_D}} = -1.8 \log_{10} \left(\frac{e}{D} \right)^{1.11} + \frac{69}{Re} \quad (5)$$

Where e and Re are pipe wall roughness and Reynolds number, respectively. The expression of the Reynolds number in Eq. (5) is shown as follows:

$$Re = \frac{\rho u D}{\mu} \quad (6)$$

The expression of Q_w in Eq. (3) is shown as follows (Haaland, 1983):

$$Q_w = hZ(T_{env} - T) \quad (7)$$

In this study, we consider a buried and insulated pipeline. The overall heat transfer coefficient includes contributions from internal film resistance, wall resistance and external film resistance (Figure.2), Eq. (8).

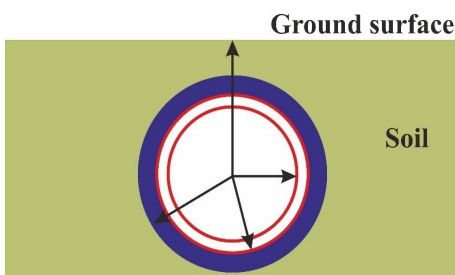


Figure 2. Cross-section of the Pipeline

$$hZ = \frac{1}{\frac{1}{r_i h_i} + \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi k_{wall}} + \frac{\ln\left(\frac{r_{ins}}{r_o}\right)}{2\pi k_{ins}} + \frac{\ln\left(\frac{r_{soil}}{r_{ins}}\right)}{2\pi k_{soil}} + \frac{1}{r_{soil} h_o}} \quad (8)$$

Where r_i , r_o , r_{ins} , r_{soil} , k_{wall} , k_{ins} , k_{soil} , h_i , h_o are the inner radius, outer radius, insulation radius, soil radius, thermal conductivity of the pipeline, thermal conductivity of the insulation, thermal conductivity of the soil, internal heat transfer coefficient and external heat transfer coefficient respectively. Nusselt number inside of the pipeline is as follows (Haaland, 1983):

$$Nu_i = \frac{h_i D}{k} \quad (9)$$

$$Nu_i = \frac{\frac{f_D}{8} (Re - 1000) Pr}{1 + 12.7 \sqrt{\frac{f_D}{8}} (Pr^{\frac{2}{3}} - 1)} \quad (10)$$

The expression for Pr in Eq. (9) is shown as follows.

$$Pr = \frac{C_p \mu}{k} \quad (11)$$

Nusselt number outside the pipeline is as follows:

$$Nu_o = 0.3 + \frac{0.62 \sqrt{Re_{air} Pr_{air}^{\frac{1}{3}}} \left(1 + \left(\frac{Re_{air}}{282000} \right)^{\frac{5}{8}} \right)^{\frac{4}{5}}}{\left(1 + \left(\frac{0.4}{Pr_{air}} \right)^{\frac{2}{3}} \right)^{\frac{1}{4}}} \quad (12)$$

2.2. Physical Properties

Since the variations of the temperature and pressure in the pipeline are significant, the physical properties change along the pipeline. Duo to high pressure system, the behavior of natural gas is real gas. The density and heat capacity are calculated from Peng-Robinson equation. Botros (2002) showed that the Peng-Robinson equation is suitable for dense-phase natural gas; therefore, this study used this equation for density calculation. Also, Brokaw equations and kinetic theory were used to calculate viscosity and thermal conductivity of natural gas, respectively. Brokaw (1965) established the suitability of the

Brokaw equation for natural gas; therefore, this equation was used in this study for viscosity calculation. The density in Equations (1) to (3) is not constant. Therefore, Equations (1) to (4) are coupled. For example, the mixture density from Peng- Robinsons is as follow (Haaland, 1983):

$$Z_{mix}^3 + MZ_{mix}^2 + NZ_{mix} + r = 0 \quad (13)$$

$$M = B_{mix} - 1 \quad (14)$$

$$N = A_{mix} - 2B_{mix} - 3B_{mix}^2 \quad (15)$$

$$r = B_{mix}^3 + B_{mix}^2 - A_{mix} B_{mix} \quad (16)$$

$$A_{mix} = \sum_{i=1}^k \sum_{j=1}^k x_i x_j A_{ij} \quad (17)$$

$$B_{mix} = \sum_{i=1}^k x_i B_i \quad (18)$$

$$A_{ii} = 0.45724 \left(\frac{\left(\frac{p}{p_c} \right)}{\left(\frac{T}{T_c} \right)^2} \right) \alpha_i \quad (19)$$

$$A_{ij} = (1 - K_{ij}) \sqrt{A_{ii} A_{jj}} \quad (20)$$

$$\rho = \frac{p M_W}{RT Z_{mix}} \quad (21)$$

Where, Z_{mix} is compressibility factor of the gas mixture; k is the number of components; x is mole fraction; p is pressure; T is temperature; p_c is critical pressure; T_c is critical temperature. K is interaction parameter.

2.3. Boundary Conditions

Equations (1), (2) and (3) require boundary conditions for velocity (mass flow), pressure, and temperature. The boundary conditions in this study are as follows:

$$u|_{z=L} = u_{out} \quad (22)$$

$$u_{out} = \frac{m}{\rho A} \quad (23)$$

$$p|_{z=0} = p_{in} \quad (24)$$

$$T|_{z=0} = T_{in} \quad (25)$$

$$\nabla \cdot q|_{z=L} = 0 \quad (26)$$

Where u_{out} , m , p_{in} , T_{in} and q are outlet velocity, mass flow rate, inlet pressure, inlet temperature and heat flux, respectively. For the inlet of the pipeline, the inlet pressure and temperature for each phase were considered. Additionally, for the outlet of the pipeline, the velocity was used. The reason for this choice is that the mass flow rate is constant due to the conservation of mass, and the velocity depends on the mass flow rate. Moreover, Eq.(26) is typically used for the outlet boundary of the energy equation because the temperature variation between the outlet node and its adjacent node is insignificant.

COMSOL Multiphysics version 6 was used to solve the continuity, momentum and energy equations. COMSOL Multiphysics solves a finite element discretization of the continuity, momentum and energy equations. Also, the Peng- Robinson equation of state was used to calculate the physical properties of the natural gas, simultaneously.

3. Results and Discussion

3.1. Simulation of the Pipeline

(Figure 3) illustrates the dense and hybrid regions within the phase envelope based on the Majed Soliman natural gas composition (Table 3). In this Figure, the pressure of the dense phase region was at least 112 bar and the temperature should be between -27 and 19 °C. Also, in this Figure, hybrid phase is also shown. The pressure of the hybrid phase was at least 100 bar and the temperature should be between 19 and 35°C. The phase envelope in (Figure 3) is plotted using Aspen Plus and the Peng-Robinson equation. (Figure 4) shows the process flow diagram of two- phase flow, dense phase and hybrid. In two-phase mode, the natural gas enters the pipeline at a given temperature and pressure, then the exited natural gas enters the separator and the liquid separate from the gas phase, then the natural gas flows into the compressor and the pressure reaches 80.29

bar. Finally, the natural gas enters the heat exchanger and its temperature reduced to 35 degrees Celsius. In the dense phase state, the compressor first increases the pressure to 122 bar and then the heat exchanger reduces the natural gas temperature to 19 °C. In this state, the natural gas enters the dense phase region. In the hybrid mode, the compressor increases the pressure to 122 bar and then the heat exchanger reduces the natural gas temperature to 35 °C. In this mode, the natural gas enters the hybrid region. The difference between

dense phase and hybrid mode is the inlet temperature of the pipeline. The temperature of hybrid mode is higher than the dense phase mode. In this research, Aspen plus V12.1 and Peng-Robinson equation of state were used to calculate the duty of the heat exchangers and the compressors duties. Equations of continuity, momentum and energy were solved simultaneously using COMSOL Multiphysics and Peng-Robinson equation of state to determine pressure, velocity, physical properties and temperature of the pipeline.

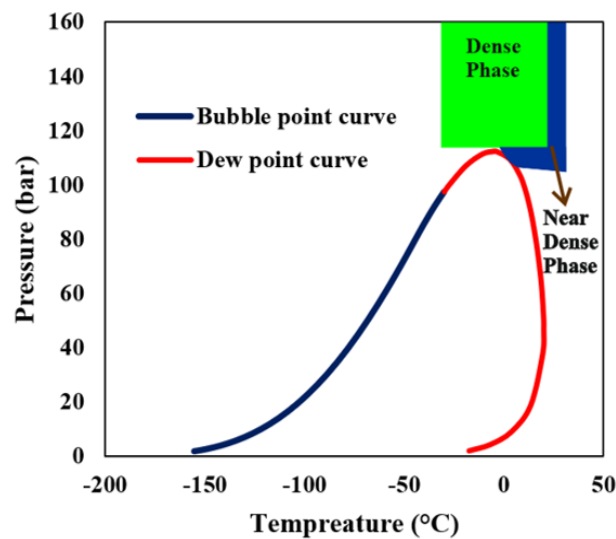


Figure 3. Masjed Soleyman Natural Gas Phase Envelope, Dense Phase Region, and Near Dense Phase Region

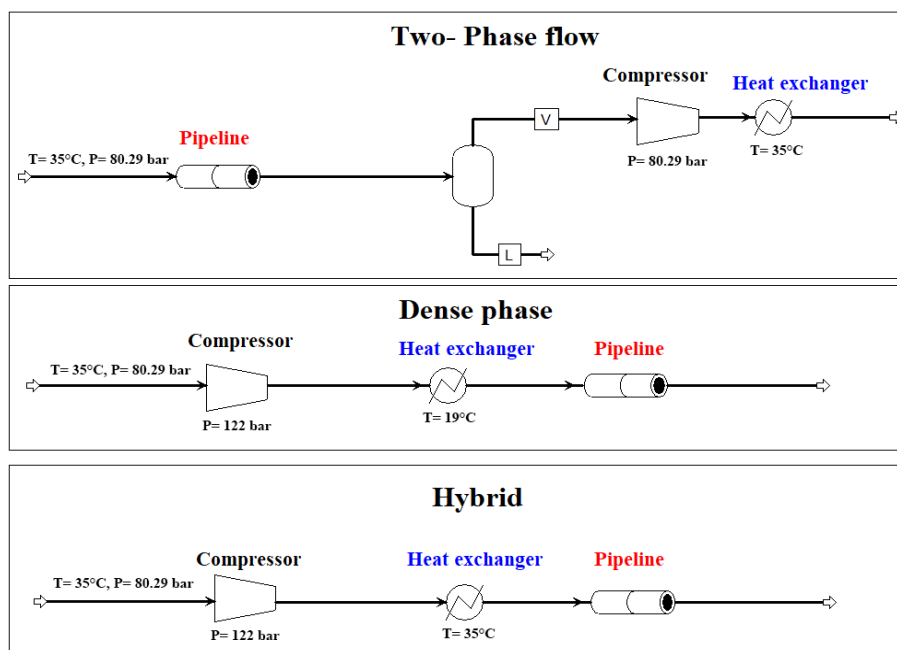


Figure 4. Process Flow Diagram of two- Phase Flow, Dense Phase and Hybrid Mode

(Table 4) shows the required compression power and the duty of the heat exchangers for both dense phase and hybrid mode. Due to the fact that the inlet temperature and pressure of the compressors are the same in both modes, the power of the compressors are also the same. Due to the fact that the inlet temperature of the pipeline for hybrid mode is higher than dense phase, the duty of hybrid mode is 35 % less than dense phase.

Table 4. Power of the Compressors and Duty of the Heat Exchangers

Mode	Power of compressor (MW)	Duty of heat exchanger (MW)
Dense phase	2.87	-9.71
Hybrid	2.87	-6.37

3.2. Density Effect

It is necessary to understand the density variations in the pipelines since it is related to volumetric flow and velocity. As density increases, the volumetric flow rate corresponding to a specific mass flow rate decrease, resulting in a reduction in fluid velocity. In this state, if the viscosity of the fluid is almost unchanged, according to the continuity and momentum equations, as the velocity reduced, the pressure drop is also reduced. (Figure 5) shows the density profiles along the pipeline. On average, the density in dense phase and hybrid modes is 2.5 times higher than the two-phase flow. The density profiles in the dense phase and hybrid modes are similar to liquids. The changes in density for the dense phase, hybrid mode, and two-phase mode are 8.7%, 11.1%, and 25%, respectively. Small variation of density in the pipeline causes small variation in volumetric flow, velocity, and pressure drop. Moreover, the variation in density in the hybrid mode differs from that in the dense phase and two-phase flow. This difference is attributed to the distinct temperature and pressure conditions in this phase. Compared to the dense phase, the variation in density in the hybrid mode

is influenced by higher temperatures, while the variation in the hybrid mode differs from the two-phase flow due to higher pressure. Consequently, the higher temperature difference between the natural gas flow and the surrounding environment in the initial section of the pipeline leads to an increase in density (the temperature of the natural gas decreases with increasing pipeline length). After 100 kilometers, the density decreases due to the pressure drop, and the effect of temperature variation becomes less significant as the temperature difference between the natural gas and the environment decreases.

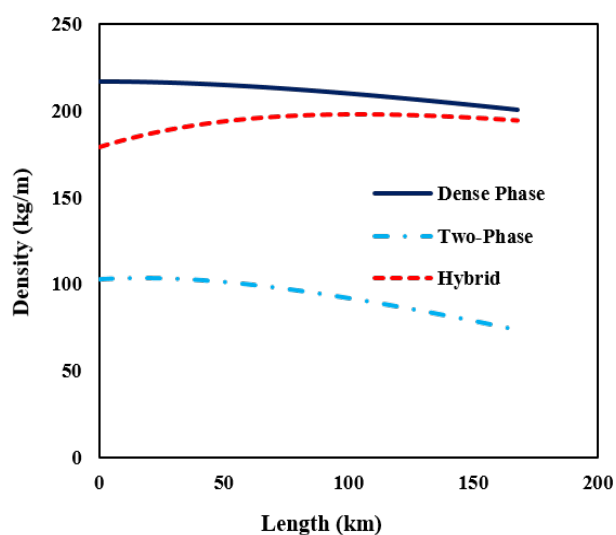


Figure 5. Density Profiles in Dense, Hybrid, and Two-phase Flow Modes

3.3. Viscosity Effect

(Figure 6) presents the viscosity profiles for the dense phase, hybrid, and two-phase flow modes. The viscosity variations in all three states are similar to gases. Moreover, the viscosities of the three phases are nearly identical, indicating that the frictional effects associated with viscosity are consistent across these phases. While the dense phase and hybrid state exhibit densities comparable to liquids and significantly higher than vapor, their viscosities remain similar to gases. Consequently, viscosity has a negligible impact on the comparative results, while density differences play a more critical role in influencing flow behavior.

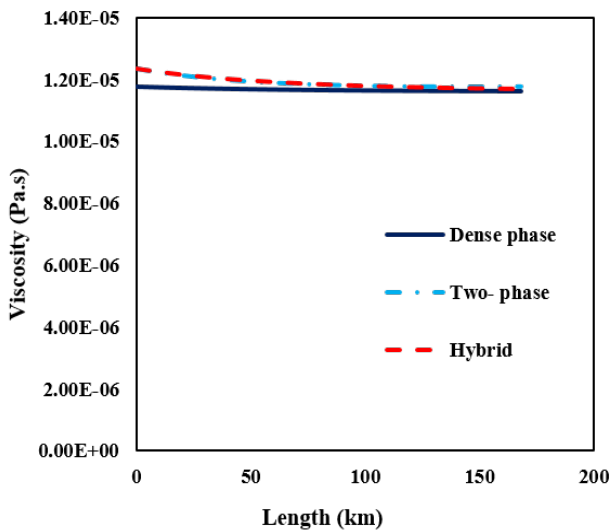


Figure 6. Viscosity Profiles in Dense Phase, Hybrid, and Two-phase Flow Modes

3.4. Pressure Drop

(Figure 7) shows the pressure-drop profiles of the pipeline for dense phase, hybrid, and two-phase flow modes. In the dense phase and hybrid modes, the pressure drop is lower compared to the two-phase mode, primarily due to differences in density. The higher density in the hybrid and dense phases, compared to the two-phase flow, is attributed to the higher pressure in these phases. Since the mass flow rate remains constant for all three phases, a higher density results in a lower volumetric flow rate and consequently a lower velocity of natural gas. Since the pressure drop is directly related to flow rate and frictional resistance within the pipeline, the decrease in velocity leads to a lower pressure drop in both the dense and

hybrid phases. The lower velocity in the dense and hybrid modes results in reduced turbulence and friction compared with the two-phase flow.

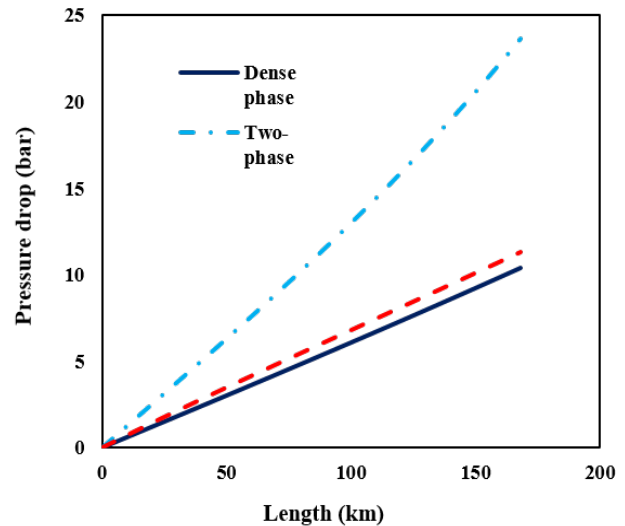


Figure 7. Pressure-drop Profiles in Dense, Two-phase, and Hybrid Modes

3.5. Effect of Phase

(Figure 8) illustrates the temperature and pressure profiles of the pipeline for dense phase, hybrid, and two-phase flow modes on the phase envelope. Additionally, the inlet and outlet conditions of the pipeline are depicted. As shown, the profile for the two-phase case enters the two-phase region, resulting in two-phase flow. This occurrence leads to issues such as high-pressure drop and potential damage to the pipeline. In contrast, the dense phase and hybrid profiles indicate only single-phase flow, thereby eliminating the problems associated with two-phase flow.

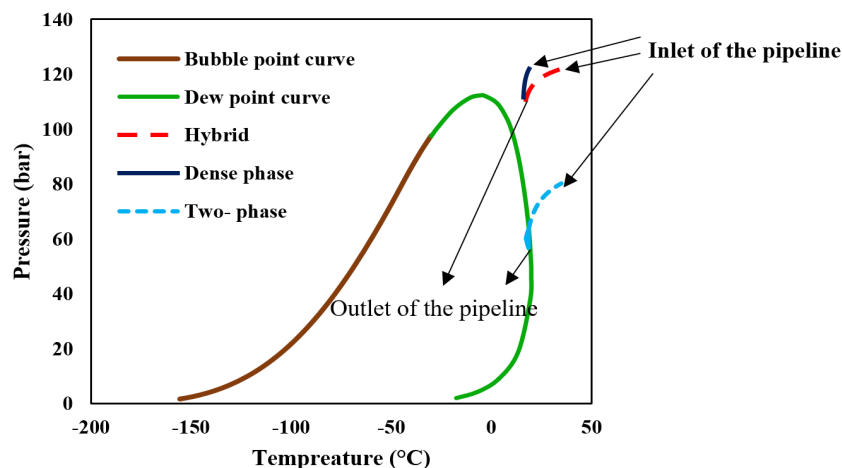


Figure 8. . Pressure and Temperature Profiles in Dense Phase, Hybrid, and Two- phase Flow Modes

3.6. Velocity

(Figure 9) shows the natural gas velocity profile in the pipeline for dense phase, hybrid, and two-phase flow modes. On average, the gas velocities in the dense phase and hybrid modes are 2.2 times smaller than the two-phase flow. Since the velocities in the dense phase and hybrid modes are lower than the two-phase flow, the possibility of pipeline erosion and associated problems is eliminated.

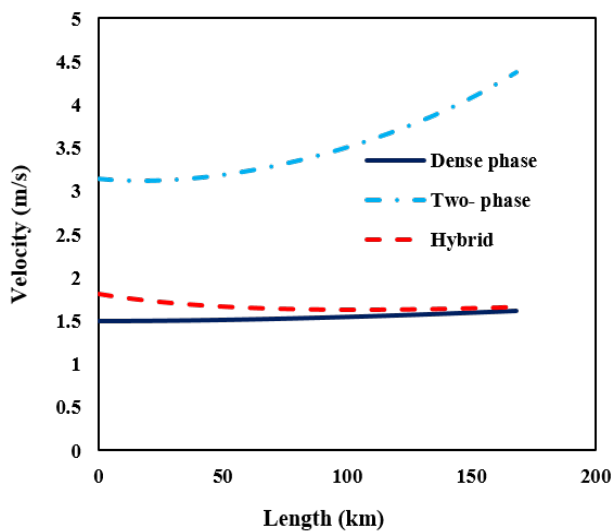
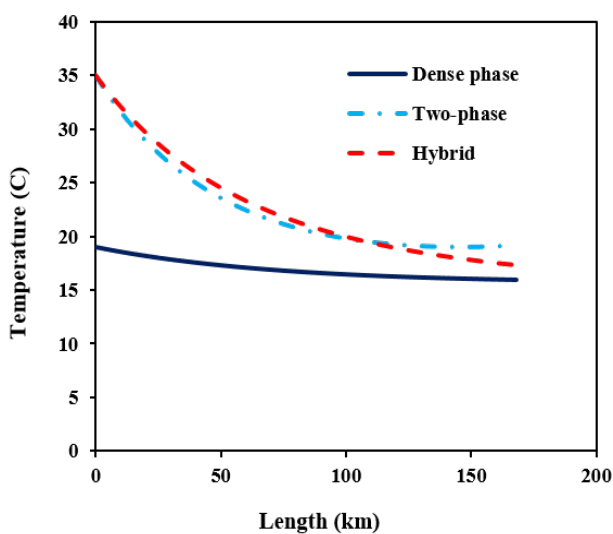


Figure 9. Velocity Profiles in Dense Phase, Two-phase and Hybrid Modes

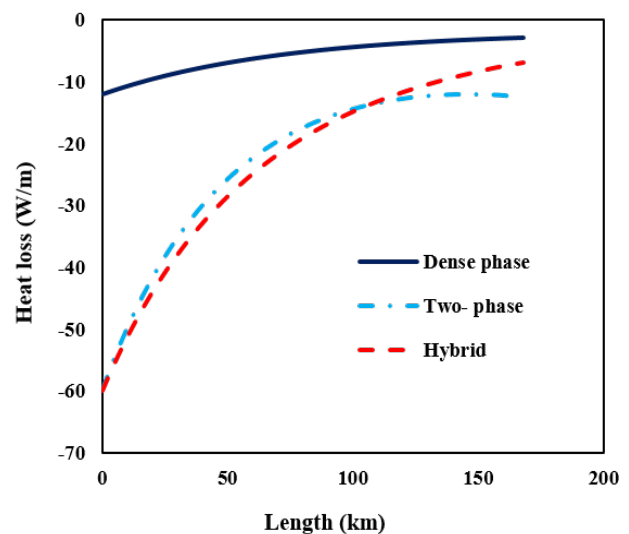


(A)

3.7. Heat Transfer

(Figure 10A) shows the temperature profiles in the pipeline for dense phase, hybrid, and two-phase flow modes. The temperature variations are smaller in the dense phase because the difference between its inlet temperature and the environmental temperature is smaller. Additionally, the temperature profiles for the hybrid mode and two-phase flow are almost identical because the inlet temperatures for these phases are similar. Moreover, the temperature variation for all three phases decreases as the pipeline length increases because the temperature difference between the natural gas flow and the environment diminishes.

(Figure 10B) shows the heat loss profiles in the pipeline for dense phase, hybrid, and two-phase flow modes. The heat loss in the dense phase is lower than in the hybrid mode and two-phase flow because the temperature difference between the natural gas flow and the environment in this phase is smaller than in the other two modes. The maximum heat loss in the dense phase, hybrid, and two-phase modes are 12, 60, and 59.9 W/m, respectively.



(B)

Figure 10. Temperature (A) and Heat Loss (B) Profiles in Dense Phase, Two-phase, and Hybrid Modes

3.8. Transmission Capacity

One of the major advantages of natural gas transmission in dense phase or hybrid modes is the increase in gas transmission capacity. (Figure 11) shows the pressure drop versus gas mass flow rate. The capacity increase has been investigated in two cases with the limitation of two-phase flow formation. Therefore, the maximum amount of gas that can be transmitted in dense phase or hybrid mode is 90 kg/s, which is 52% higher compared to normal conditions. In this state, the pressure drops in dense phase and hybrid modes are 27 and 30 bar, respectively.

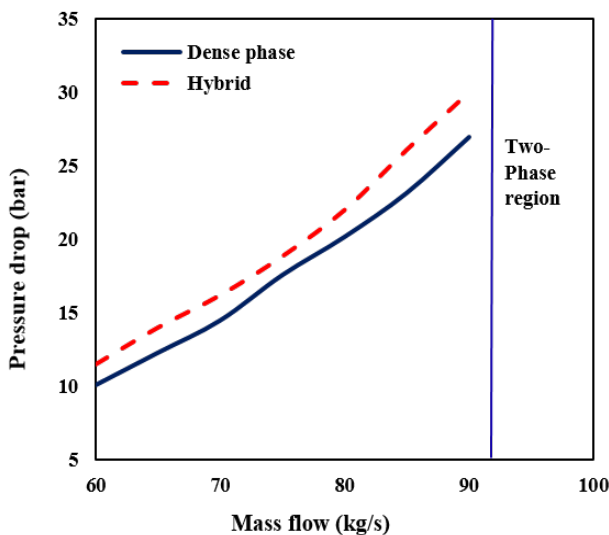


Figure 11. Variation of Pressure-drop versus to the Mass Flow Rate in Two Cases

3.9. Validation

Validation of simulation results is a crucial step to ensure confidence in the results. To achieve this, the results of Moreh et al. (Moore et al., 1980) were used for validation purposes. Detailed information on natural gas components and pipelines one to three were reported earlier (Moore et al., 1980). Pressure and temperature outputs from these pipelines were used to validate the simulation results. (Table 5) compares the simulated pressure and temperature outputs with the actual outputs from the three pipelines. The validation results indicate that the maximum error between the simulation results and Moreh et al.'s results is 4.55%. (Table 6) demonstrates the validation of the present model using experimental data for high-pressure natural gas. The study by Sletfjerding (1999) investigates the pressure drop at various mass flow rates. The maximum and average relative errors between the present model and the experimental data are 6.0% and 4.8%, respectively. Therefore, there is a good agreement between the simulation results and the pipeline outputs.

Table 5. Validation of outlet pressure (MPa) and temperature (K) from simulation results (Moore et al., 1980)

Pipeline	Outlet Pressure (Pipeline)	Outlet Pressure (Simulation)	Relative Error (%)	Outlet Temperature (Pipeline)	Outlet Temperature (Simulation)	Relative Error (%)
1	2.26	2.15	2.15	283.2	283.3	0.03
2	4.66	4.55	4.55	290.6	288.9	0.58
3	3.59	3.57	3.57	280.6	282.4	0.64

Table 6. Comparison of Pressure Drop Between the Present Model and Experimental Data (Sletfjerdning, 1999)

Mass flow rate (kg/s)	Pressure (bar)	Temperature (°C)	ΔP (mbar): Experimental	ΔP (mbar): Present model
3.046	71.77	36.30	0.93	0.94
5.999	72.33	37.26	3.12	3.25
14.61	71.01	37.43	19.09	20.28
17.65	71.79	37.43	27.56	29.22
20.45	71.42	37.45	37.34	39.47
23.04	70.78	37.24	47.93	50.60
25.86	70.82	37.15	60.58	63.71
28.46	70.54	36.95	73.59	77.50
32.86	69.79	36.87	98.45	104.77

4. Statistical Analysis

The Response Surface Method can produce extensive data from a few trials and is powerful in distinguishing the interaction effects between factors on the results, along with determining the optimal conditions. However, in multivariable operations containing different effective factors, an initial screening design before optimization seems essential. Design-Expert software v13 was used to analyze the data and the regression coefficients (Bezerra et al., 2008; Said and Amin, 2015). A three-level Box-Behnken scheme was used to indicate the relative importance of the selected factors for the proposed models of the pressure drop in dense phase and hybrid modes using numerical trials. In this research, the factors are diameter, mass flow, and length of the pipeline. (Table 7) shows the factors and their ranges. Also, (Table 8) shows the levels of the factors and their corresponding results. Numerical trials (solving equations of continuity, momentum, and energy) were accomplished according to the shown trial plan (Table 8). The quadratic regression equations for the pressure drop in dense phase and hybrid modes in terms of diameter, mass flow, and length of the pipeline are given by Equations (27) and (28), respectively.

(Tables 9) and 10 present the p-values for

each model and factor in the dense phase and hybrid mode, respectively. A p-value below 0.05 signifies a significant effect, whereas values above 0.05 indicate a negligible influence. For the pressure drop model in both modes, the quadratic effects of mass flow area (A^2) and length (C^2), as well as the interaction between mass flow rate and length (AC), have no significant impact on pressure drop. Other factors exhibit a significant effect on pressure drop, as their p-values are below 0.05.

(Figure 12A) and (Figure 12B) show the predicted pressure drop in dense phase and hybrid modes, respectively. According to the values of R^2 , the predicted values are in good agreement with the actual values. According to the models and their coefficients, it is clear that the diameter has a significant effect on the pressure drop compared to the mass flow and length of the pipeline.

Table 7. Factors and Their Range

Factor	Low Level	High Level
m: mass flow (kg/s)	60	90
D: diamete (m)	0.45	0.75
L: Length (km)	100	200

Table 8. Factors and Their Corresponding Results

Run	m. (kg/s)	D (m)	L (km)	ΔP (bar) of the dense phase	ΔP (bar) of the hybrid
1	75	0.75	200	1.93	2.06
2	75	0.45	100	14.91	17.04
3	90	0.6	200	9.21	10.076
4	90	0.45	150	37.73	43.64
5	60	0.6	100	1.97	2.19
6	75	0.75	100	0.97	1.08
7	60	0.6	200	3.95	4.22
8	75	0.45	200	33.53	37.3
9	60	0.75	150	0.92	0.99
10	90	0.6	100	4.53	5.13
11	75	0.6	150	4.68	5.14
12	90	0.75	150	2.09	2.30
13	60	0.45	150	14.09	15.50

$$\Delta P(\text{bar}) = -91.73 + 3.38m - 354.70D + 1.02L - 2.49mD - 0.58DL + 459.69D^2 \quad (27)$$

$$\Delta P(\text{bar}) = -109.23 + 3.93m - 403.84D + 1.18L - 2.98mD - 0.64DL + 528.85D^2 \quad (28)$$

Table 9. The Analysis of Variance of Dense Phase Mode (Eq. 27)

Model Terms	Sum of Squares	Degree of Freedom	Mean Square	p-value (Significant)
Model	193.5700	9	193.5700	0.0061
A-m	188.6900	1	188.6900	0.0062
B-D	1112.7400	1	1112.7400	0.0011
C-L	141.4200	1	141.4200	0.0083
AB	126.2300	1	126.2300	0.0093
AC	18.7700	1	18.7700	0.0578
BC	77.9700	1	77.9700	0.0149
A ²	3.4600	1	3.4600	0.2297
B ²	213.9600	1	213.9600	0.0055
C ²	9.5800	1	9.5800	0.1047

Table 10. The Analysis of Variance of Hybrid Mode (Eq. 28)

Model Terms	Sum of Squares	Degree of Freedom	Mean Square	p-value (Significant)
Model	2265.4000	9	251.7100	0.0104
A-m	258.5900	1	258.5900	0.0100
B-D	1432.4600	1	1432.4600	0.0018
C-L	173.8500	1	173.8500	0.0148
AB	179.9600	1	179.9600	0.0143
AC	26.4400	1	26.4400	0.0867
BC	92.9300	1	92.9300	0.0271
A ²	4.1000	1	4.1000	0.3380
B ²	283.1800	1	283.1800	0.0092
C ²	14.2500	1	14.2500	0.1453

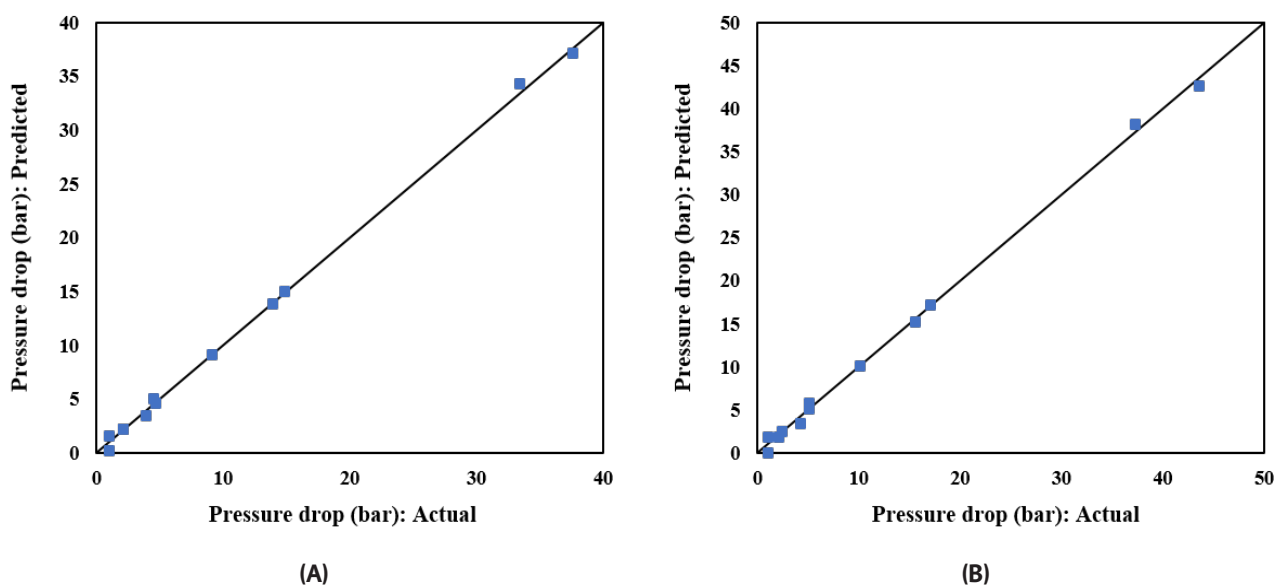


Figure 12. Comparison of Predicted and Actual Pressure Drop of the Dense Phase (A) and the Hybrid Mode (B)

5. Conclusion

In this study, the performance of natural gas pipelines in dense phase and hybrid modes was

evaluated. These modes reduced issues such as high pressure drop, high velocity, low capacity,

and the formation of two-phase flow. The main findings are as follows:

- The pressure drops and velocities in the dense phase and hybrid modes were, on average, 2.2 times lower than in two-phase flow. This suggests that transporting natural gas in dense phase or hybrid mode is a suitable method to mitigate pressure drop concerns in pipelines.
- The densities in dense phase and hybrid modes were, on average, 2.5 times higher than in two-phase flow. Thus, increasing the density in these modes helps reduce velocity and pressure drop.
- The viscosities in dense phase and hybrid modes were similar to those of gases, indicating no significant concern about an increased pressure drop due to viscosity when transporting natural gas in these modes.
- The maximum gas flow rate that can be transmitted in dense phase or hybrid mode is 90 kg/s, which is 52% higher than under normal conditions. Therefore, if additional capacity is needed, using dense phase or hybrid mode can increase pipeline capacity.
- The duty of the hybrid mode was 35% lower than that of the dense phase mode. This suggests that the transmission of natural gas in hybrid mode is more suitable than in dense phase mode when the cricondentherm temperature (maximum temperature of the dew point curve) is low.
- Quadratic models for pressure drop in dense phase and hybrid modes, in terms of diameter, mass flow rate, and pipeline length, were proposed.
- Pipeline diameter had a greater impact on pressure drop compared to mass flow rate and pipeline length.

Nomenclature

A	Area (m ²)	<i>Subscripts</i>	
C_p	Heat capacity (J kg ⁻¹ K ⁻¹)	in	inlet
D	Diameter (m)	out	outlet
e	Surface roughness (m)	env	environment
f_D	Darcy friction factor (-)	<i>Greek Letters</i>	
h	Overall heat transfer coefficient (W m ⁻² K ⁻¹)	μ	Gas viscosity (Pa s)
k	Thermal conductivity (W m ⁻¹ K ⁻¹)	ρ	Gas density (kgm ⁻³)
p	Pressure (Pa), Perimeter (m)		
Pr	Prandtl number (-)		
QW	Heat exchanged with the environment (Wm ⁻¹)		
r	Outer radius of the pipeline (m)		
Re	Reynolds number (-)		
T	Temperature (°C)		
u	Velocity (ms ⁻¹)		

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شبیه‌سازی عددی خط لوله گاز طبیعی در فازهای متراکم و ترکیبی

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چکیده

انتقال گاز طبیعی از طریق خطوط لوله به دلیل مقرون‌به‌صرفه بودن نسبت به سایر روش‌ها به‌طور گسترده مورد استفاده قرار می‌گیرد. با این حال، حمل گاز طبیعی از طریق خطوط لوله با چالش‌هایی مانند مصرف بالای انرژی، افت فشار قابل توجه و مشکلات جریان دوفازی مواجه است. در این مطالعه، انتقال گاز طبیعی در فازهای متراکم، ترکیبی (مناطق فاز متراکم و نزدیک به فاز متراکم) و دوفازی برای کاهش برخی از این محدودیت‌ها مورد بررسی قرار گرفت. علاوه بر این، مدل‌های ریاضی با فرم درجه دوم برای افت فشار در فاز متراکم و حالت ترکیبی بر اساس قطر، جریان جرمی و طول خط لوله پیشنهاد شدند. بر اساس این مدل‌ها، قطر خط لوله تأثیر بیشتری بر افت فشار نسبت به دبی و طول خط لوله داشت. نتایج همچنین نشان داد که مصرف انرژی مبدل حرارتی برای حالت ترکیبی ۳۵ درصد کمتر از فاز متراکم است. به‌طور متوسط، چگالی در فازهای متراکم و ترکیبی ۲/۵ برابر بیشتر از جریان دوفازی حاصل شد. افت فشار و سرعت در فازهای متراکم و ترکیبی ۲/۲ برابر کمتر از شرایط جریان دوفازی به دست آمد. همچنین، ظرفیت خط لوله برای انتقال گاز طبیعی در فازهای متراکم و ترکیبی ۵۲ درصد بیشتر از انتقال گاز در شرایط دوفازی محاسبه شد.

واژگان کلیدی: فاز متراکم، حالت هیبریدی، خط لوله، گاز طبیعی