JOURNAL OF GAS TECHNOLOGY

Volume 8 /Issue 1 / Summer 2023 / Pages 05-14

Journal Homepage: http://jgt.irangi.org

Numerical Simulation in a Dynamic Regime of Natural Gas Flow in the Pipeline Network

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ARTICLE INFO

ORIGINAL RESEARCH ARTICLE

Article History:
Received: 28 June 2023
Revised: 25 July 2023
Accepted: 20 August 2023

Keywords:
Natural gas consummation
Network of natural gas
Unsteady flow
Compressible flow
Dynamic regime
Finite difference method

ABSTRACT

The purpose of this article is to present a comment manifests the pressure and flow supply in the case of consumptions in dynamic regime. The mathematical model is a system of nonlinear differential equations dealing with a compressible flow with the term of pressure drops, the temperature is considered constant and equal to that of the environment. The boundary conditions are given and the initial solution is unspecified, after the transitory solution, the periodic dynamic mode is established in a stable way. The discretization method used is that of fine differences with a structured mesh. The method of resolution is semi-implicit with a step of time which strongly depends on the number of CFL which ensures convergence. The chosen method is stable over time. The main results obtained are the validity of the method used to solve a dynamic problem, the precision of the calculations and the physical phenomenon which is clearly visible from the distribution of pressures and flow rates as a function of time and position.

DOR: 20.1001.1/JGT.2024.2015754.1031

How to cite this article
R. Haoui, Numerical Simulation in a Dynamic Regime of Natural Gas Flow in the Pipeline Network. Journal of Gas Technology. 2023; 8(1): 05-15. (http://jgt.irangi.org/article_712119.html)

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Available online 20 September 2023

1. Introduction

The study of the flow of natural gas in pipeline networks is of great importance in the distribution according to the needs of industrial consumers. If the consumption does not vary over time, the flow regime is purely stationary and the system of equations can be solved explicitly by an iterative method. On the other hand, in the case where the customers' consumption varies as a function of time over a period of 24 hours, the regime is then dynamic and the system contains non-linear unsteady differential equations. The method used in solving the problem is the finite difference method taking into account a given initial solution and the boundary conditions at the level of each consumption point. Of course that at the beginning of calculation the solution is purely in transient mode, after a few hours one reaches the periodic mode at the entry of supply pipe. Each section of the pipes is divided into several meshes in such a way that the friction coefficient and the compressibility factor can be considered constant. The time step is calculated to ensure the convergence of the calculation code with a CFL=0.4 for one supply pipe and 0.005 for two supplies pipes in the dynamic case, the results do not change for a CFL lower than 0.005. In the work of Farzaneh (2006), the unsteady resolution was not done using finite elements but by an integration where the variables p and t were taken as independent. The same in the work of Pambour (2015), where he used a numerical approach and the speed of the flow was neglected in front of the speed of sound, these results were compared to those of Simone. On the other hand, WangHai (2011) used the finite volume method with a semi-implicit scheme but the comparison was not made between the input and the output at the same time. Shanbi (2013) used the Newton-Raphson method as a technical solution between the different nodes of the network but he did not give information on the unsteady state in the pipes between the nodes.

2. Master Equations

The conservative equations governing the one-dimensional compressible flow are the equation of continuity, momentum and state since the flow is assumed isothermal at the ambient temperature, equations system used also by Farzaneh (2016).

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho V)}{\partial x}=0 \tag{1}$$

$$\frac{\partial(\rho V)}{\partial t}+\frac{\partial(\rho V^2+p)}{\partial x}+\frac{\lambda}{2d}\rho V|V|=0 \tag{2}$$

$$\frac{p}{\rho}=zrT \tag{3}$$

The compressibility factor is given by $z=f(p_r\, et\;\, T_r)$

Where ρ,V and p are the density, velocity and pressure of flow respectively. Equations (1) and (2) constitute the nonlinear partial differential equation system to be solved.

Berthelot established a more general relation for the determination of the compressibility factor:

$$z(p,T)=1+\frac{9}{128}\frac{p}{p_c}\frac{T_c}{T}\left(1-\frac{6T_c^2}{T^2}\right) \tag{4}$$

At constant temperature the compressibility factor takes the form:

$$Z(p,T)=1-a.p\ \ (a>0) \tag{5}$$

Where p_r and T_r are the reduced pressure and temperature such that:

$$p_r=\frac{p}{p_c}\ \ ;\ T_r=\frac{T}{T_c} \tag{6}$$

The average pseudo-critical pressure and pseudo-critical temperature of the gas mixture for a given mole fractions x_i of gas components are given by:

$$p_{cm}=\sum x_i p_{ci}\quad ;\quad T_{cm}=\sum x_i T_{ci} \tag{7}$$

In the following (Table.1) some gases are given with the critical temperature and pressure, Pascal (1972).

Table 1. Critical Pressure and Temperature for Natural Gas

Gas	Molecular weight (g/mol)	Boiling T (°C) at 1 bar	p_c (bars)	T_c (°C)
Methane CH_4	16.04	-161.58	45.80	-82.10
Ethane C_2H_6	30.07	-88.63	48.20	32.27
Propane C_3H_8	44.09	-42.06	42.00	96.81
Butane C_4H_{10}	58.12	-0.5	35.47	152.0
Isobutane	58.12	-11.72	36.40	134.9
Pentane C_5H_{12}	72.15	+27.85	32.90	197.2
Azote N_2	28.02	-195.78	33.49	-13.147

If we have the density d_{NG} of natural gas directly, the law used is that of the $CNGA$ (California Natural Gas Association):

$$\frac{1}{Z} = 1 + \left(344400\ 10^{(1.785 d_{NG})} \frac{p}{T^{3.825}}\right);\ p(psia), \qquad T(°R) \quad (8)$$

This method is used for pressures gauge p above 7 bar. For pressures below 7 bars, the compressibility factor is taken as unity.

The density of natural gas varies according to the composition, generally it is around 0.6. It can be determined by the relationship:

$$d_{NG} = \frac{M_{GN}}{M_{air}} \quad (9)$$

With

$$M_{NG} = \sum X_s M_s \quad (10)$$

where M_{NG} is the molar mass of the mixture, M_s and X_s are the molar mass and molar fraction of species s respectively.

An expression for the head loss coefficient λ valid for turbulent flow in pipeline transportation used in the article Hofer (1973), called Hofer's formula.

$$\lambda = \left\{2 \log_{10}\left[\frac{4.518}{Re}\log_{10}\left(\frac{Re}{7}\right)^{1.11} + \frac{e/d}{3.71}\right]\right\}^{-2} \quad (11)$$

cited in paper of K. A. Pambour et all (2015). Ther are many expressions of loss coeffition in litterature, see Ouyang (1996). Re is the reynolds number, e the absolute pipe roughness and d the pipe diameter.

3. Resolution Method

Since the flow is one-dimensional with nonlinear differential equations, the finite difference method is largely sufficient to solve the problem. Partial derivatives are replaced by finite differences. The temporal term is solved by a semi-explicit method, for example:

$$\frac{\partial F(i)}{\partial x} = \frac{F(i+1) - F(i-1)}{2\Delta x} \quad (12)$$

$$\frac{\partial F(i)}{\partial t} = \frac{F(i)^{n+1} - F(i)^n}{\Delta t} \quad (13)$$

The numerical resolution of the system of equation requires an initial solution and boundary conditions. If the initial solution is not real, the periodic dynamic regime is obtained after a transient regime after a few hours or a few ten hours if the pipe-line is longer. Convergence is ensured with a time step such as, Klaus (1996):

$$\Delta t = min\left[\left(\frac{\Delta x. CFL}{|V(i)| + a(i)}\right), \left(\frac{(\Delta x)^2. CFL}{2\,\mu/\rho\,(i)}\right)\right] \quad (14)$$

Where a is the speed of sound.

Concerning the boundary conditions, at the inlet the pressures are given and a single variable is extrapolated, at the outlet, the flow rates are known and two quantities are extrapolated, the others are therefore calculated. At the junction point J as represented in (Figure 1), the conservation of mass equation is used in its integral form to determine the instantaneous density at this point and therefore the pressure by using the equation of state, Pambour (2015).

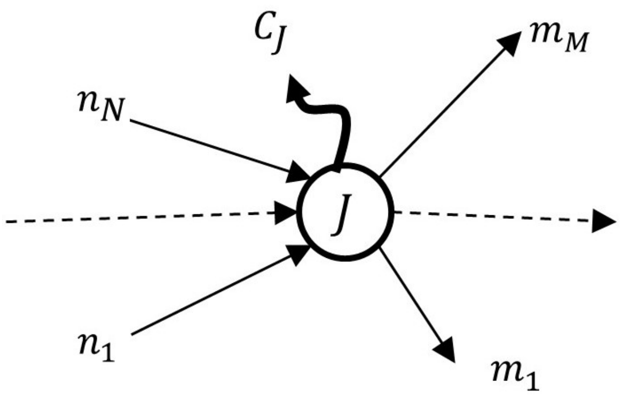

Figure 1. Presentation of Junction in Network

We have:

$$\int_{\mathcal{V}} \frac{\partial \rho}{\partial t}.d\mathcal{V} + \int_{s} \rho.(\vec{V}.\vec{n})\,ds = 0 \;\; ; \;\; [k\,g/s] \qquad (15)$$

This give:

$$\frac{\rho(i)^{n+1} - \rho(i)^{n}}{\Delta t}.volume + \sum_{m=1}^{M} \rho_{Jm}.V_{Jm}.S_m - \sum_{n=1}^{N} \rho_{Jn}.V_{Jn}.S_n = C_J \quad (16)$$

Where C_J is the consumption at the junction point if exist.

The control volume is such as:

$$volume = \sum_{n=1}^{N} (S.\Delta x)_n + \sum_{m=1}^{M} (S.\Delta x)_m \qquad (17)$$

The pressure is calculated from the equation of state:

$$p_J = z.r.T.\rho_J \qquad (18)$$

4.Application and Comparison

In dynamic mode, the consumptions are not generally constant; they are variable at the nodes where the customers are. Consumption at each network outlet is given as a function of time (Q,t). The flow in the gas pipeline is therefore in an unsteady state. The variation of the flow rate or the pressure at the outlet of a pipe influences all the parameters throughout the pipe (Figure 2). The pressure at supply point A is assumed to be constant $p(A,t) = p_A$, the consumption at points C_1 and C_2 are variable, the boundary conditions are $Q_1(C_1,t) = f(t)$ and $Q_2\ (C_2,t) = f(t)$ or else $P_1\ (C_1,t) = f(t)$ and $P_2\ (C_2,t)=f(t)$. The initial solution is preferably unknown if the network is already in operation. To do this, either we take the initial solution of a permanent flow or it starts from the state at rest. In this case, two flow regimes arise, the first is transient and the second is the periodic regime.

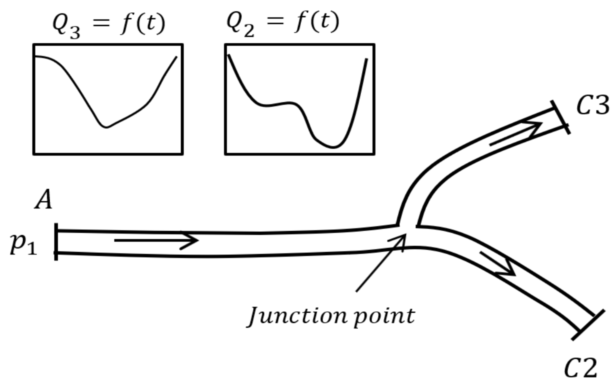

Figure 2. Typical Network for two Consumptions

4.1. Static Simulation

The supply pressure gauge at point A is 50bar and at consumption points C_1 and C_2 the pressure gauge is 5bar. Let us test the unsteady state computation with the finite difference method using an explicit first-order scheme. The length and the diameter of the three pipes are the same, the density of the natural gas is taken equal to 0.6 which gives a constant of gas r = 478.47 J/kg.K. Convergence is obtained after a certain number of iterations when the residual is less than 10^{-6} where the quantities stabilize and steady flow is obtained (Figure 3).

The time here is an iterative parameter. The calculation converges towards the stationary solution with the flow rate q_{m2} = 214 kg/s , different from the analytical solution q_{m2} = 213 kg/s given by the equation of a stationary flow such as:

$$q_m^2 = \frac{\pi^2 d^4}{16rzT} \frac{p_{inl}^2 - p_{out}^2}{\lambda \frac{L}{d} + 2\,ln\left(\frac{p_{inl}}{p_{out}}\right)} \qquad (19)$$

The 0.4% difference is caused by the accuracy of the calculations. If we increase the number of nodes, the computation time becomes enormous. The computer code is stable. The convergence took place at a residue on the density of the order 10^{-6}.

$$q_{m2} = 214.13 \text{ kg/s} \qquad ; q_{m3} = 214.13 \text{ kg/s}$$

$$q_{m1} = 428.45 \text{ kg/s}$$

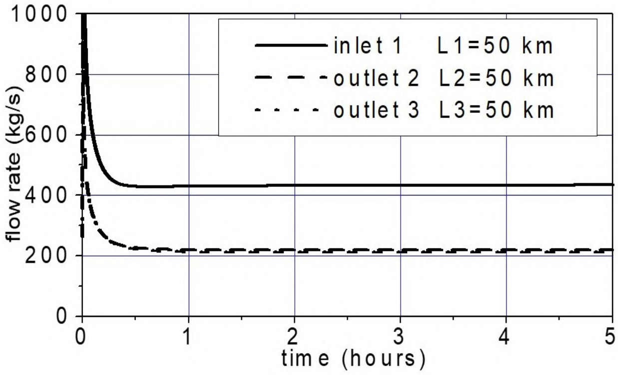

Figure 3. Flow Rate versus Time

The variation of the density at the junction point during the iterations is given by the following graph (Figure 4):

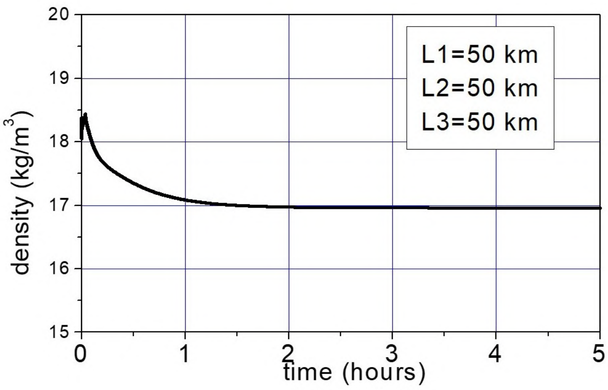

Figure 4. Density Variation in Junction Point versus Time

Let's increase the length of pipe ② to100 km (Figure 5) ; the flow rate becomes less than that of pipe ③.

$$q_{m2} = 171.63 \text{ kg/s} \qquad ; q_{m3} = 241.65 \text{ kg/s}$$

$$q_{m1} = 413.62 \text{ kg/s}$$

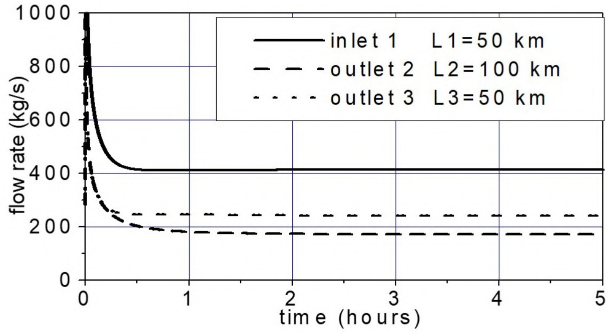

Figure 5. Flow Rate versus Time

4.2. Reserve of Gas (One Pipe)

This unsteady state can also be used to determine the emptying time or the gasometrical reserve. As soon as steady state is reached after 0.6 hours, it is allowed to operate until t=2 hours. A gas cut is made at the inlet of the pipe and the outlet pressure is always maintained at 5 bars, an emptying time of 1h8min is obtained. The calculation is stopped when the pressure at the pipe inlet becomes equal to the outlet pressure. The calculation gives a gas reserve:

```
reserve in kg =  835574.654531091900000
reserve in MMSCM =        1.13696600406411
reserve in hours =        1.11151005187929
Stop - Program terminated.
```

Note that in this case the output is directly connected to a consumer operating with a set point pressure equal to 5 bars. This means that consumption drops after the gas breaks (Figure 6 to 8). The 1 h 8 min emptying time is much higher compared to the case where the consumption was supposed to be invariable q_m = 479.37 kg/s calculated analytically and t = 28 min. In the case where only the pressure is imposed at the outlet, the consumption is calculated numerically using the finite difference method, the usable gas reserve in mass is the difference between the mass contained in the pipe at the time of the cut and the remaining mass when the pressure is everywhere equal to p_s = 5bars, i.e.:

$$M(kg) = \sum_{1}^{i_m-1} \frac{(\rho_i + \rho_{i+1})}{2}.S.dx - \frac{p_s}{rT}.S.L \qquad (20)$$

Or in standard m^3 such as:

$$V = \frac{M(kg)}{\rho} = \frac{M(kg)}{p_a}.r.T_a \qquad (21)$$

With: $p_a = 1$ atm et $T_a = 15$ °C.

It must be the same; it is the consumption time of the reserve that is deferring. The (Figure 9) shows the effect of the mesh refinement on the gasometrical reserve, the error is only 0.5% when going from 50 meshes to 1000 meshes. We observe the consistency of the calculation code when the step $\Delta x \rightarrow 0$.

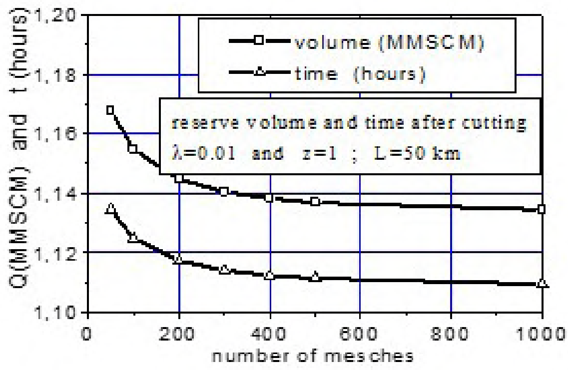

Figure 9. Effect of the Mesh Refinement on the Reserve

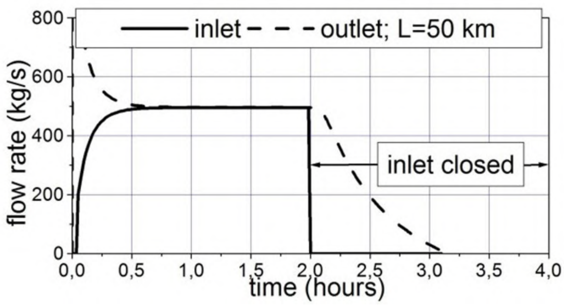

Figure 6. Flow Rate versus Time and Reserve

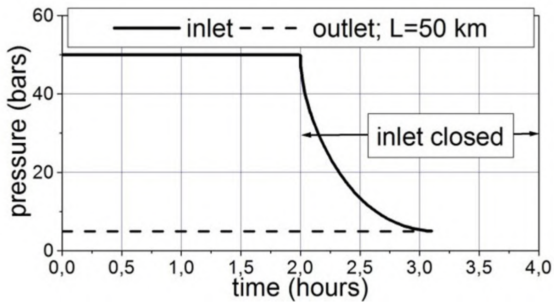

Figure 7. Pressure versus Time and Reserve

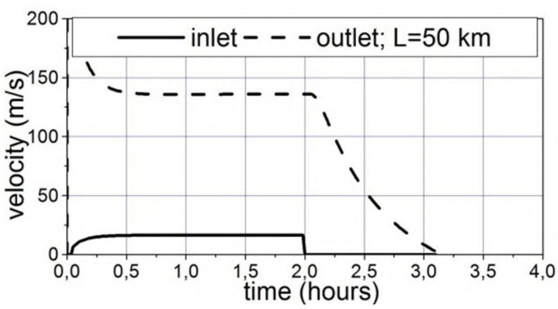

Figure 8. Velocity versus Time

4.3. Dynamic Simulation

4.3.1. Case of Two Consumptions and one Supply

We test a real case of two consumptions given in the following tables (Figure10):

$$L1 = 600\ km \quad \emptyset 1 = 389\ mm$$

Table 2. Pipeline Consumption at Outlet 2

L2 = 5km ; Ø2 = 310mm			
t **(heures)**	Q_2 **(m^3 S/h)**	***t*** **(heures)**	Q_2 **(m^3 S/h)**
0:00	8000	12:00	30000
1:00	10000	13:00	50000
2:00	11000	14:00	50000
3:00	13000	15:00	70000
4:00	14000	16:00	80000
5:00	16000	17:00	70000
6:00	20000	18:00	70000
7:00	25000	19:00	65000
8:00	25000	20:00	50000
9:00	26000	21:00	40000
10:00	27000	22:00	30000
11:00	28000	23:00	20000

Table 3. Pipeline Consumption at Outlet 3

L3 = 3km ; Ø3 = 206mm			
t (heures)	Q_2 (m³ S/h)	*t* (heures)	Q_2 (m³ S/h)
0:00	2000	12:00	15000
1:00	2500	13:00	20000
2:00	3000	14:00	12000
3:00	3000	15:00	15000
4:00	3700	16:00	18000
5:00	4000	17:00	19000
6:00	5000	18:00	22000
7:00	5200	19:00	21000
8:00	6000	20:00	19000
9:00	6500	21:00	17000
10:00	9000	22:00	15000
11:00	10000	23:00	11000

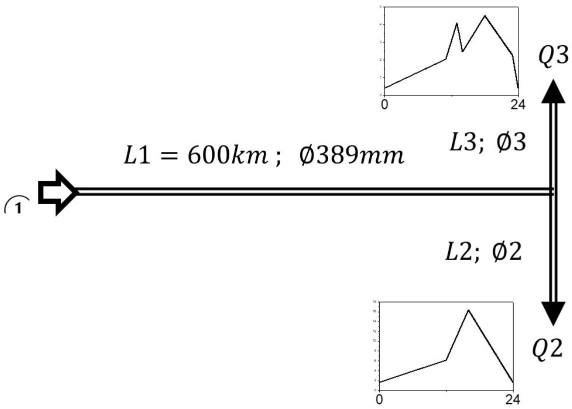

Figure 10. Two Consumptions and One Supply

The density of natural gas is 0.6. The real initial solution does not exist as a preliminary; the periodic solution is obtained after 48h preceded by the transient solution (Figure 11) . The objective is to determine the variation of the pressure as function of time at the outlet of the consumption pipes ② and ③ as well as the variation of the flow at the inlet of the supply pipe ①. It should be remembered that the pressure drop coefficient has a considerable influence on the results. The flow rate at the inlet is also function of time (Figure 12).

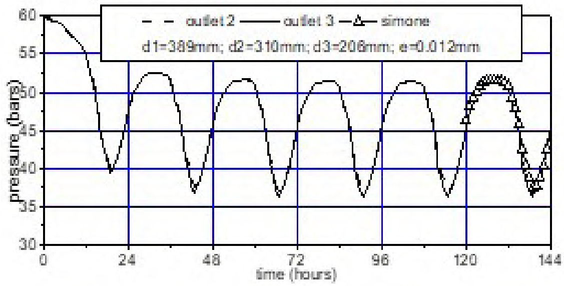

Figure 11. Periodic Pressure at Outlet

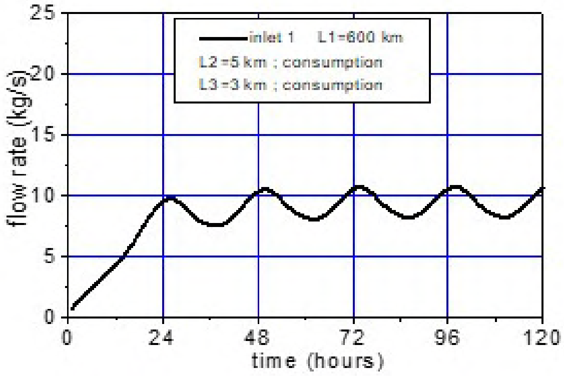

Figure 12. Flow Rate at Inlet versus Time

In a time interval equal to the period, the mass of gas entering the network equals the mass consumed. By numerical integration we find (Figure 13):

$$Q_1 = 954240\ kg \quad ; \quad Q_2 = 727799\ kg$$

$$Q_3 = 226572\ kg$$

This confirms the precision of the convergence and the consistency of the calculation code.

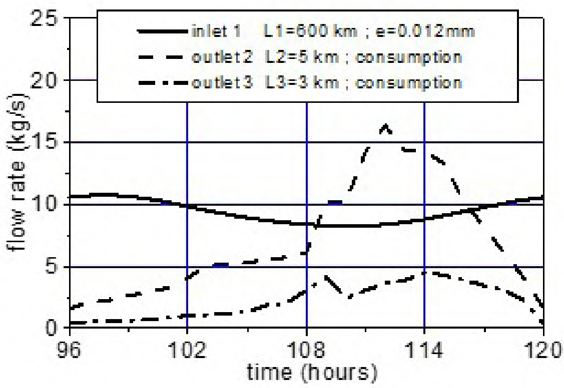

Figure 13. Flow rate of Periodic Regime versus Time

Now we are going to suppose consumption at the junction point J where $C_{jonction}=20000\ m^3\ S/h$ in a continuous way (Figure 14). In this case the rate flow at inlet of pipe increases and consequently the losses in the network, this requires lower pressures at the outlet of each pipe. The mass entering the pipe for $C_{jonction} = 20000\ m^3\ S/h$ is found to be equal to 1286560 kg instead of 954240 kg. The periodic regime is obtained after 72 hours. The following graphs show the variation of the flow at the inlet of the pipe (Figure 15) and the pressures at the points of consumption (Figure 16) . The solution is stable if the code is left running for longer. The (Figure 17) shown the variation of flow rate at the inlet and outlets in periodic regime.

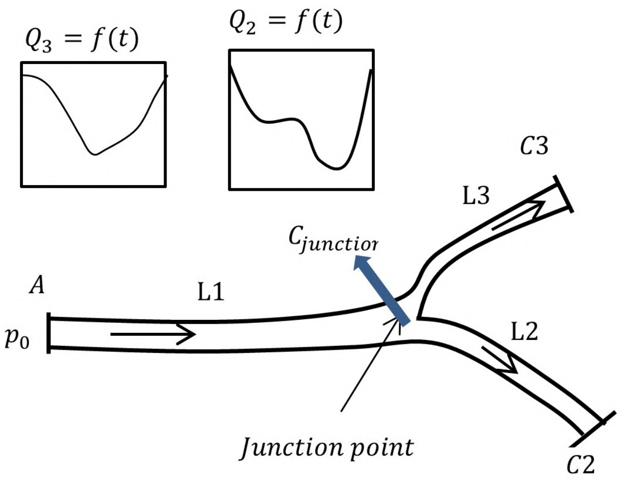

Figure 14. Network with Junction Consumption

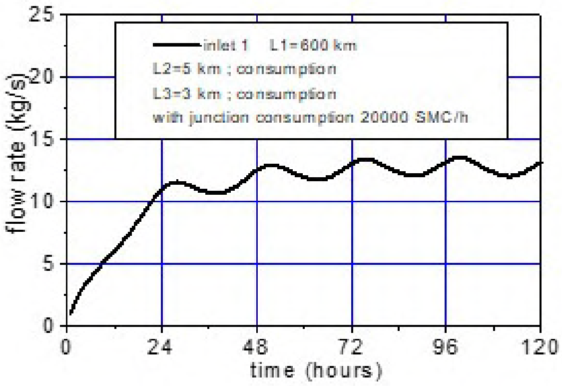

Figure 15. Flow Rate at Inlet versus Time

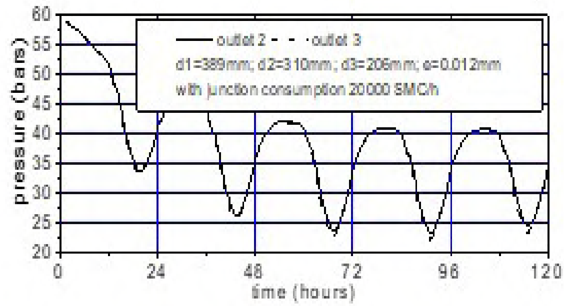

Figure 16. Periodic Pressure at Outlet

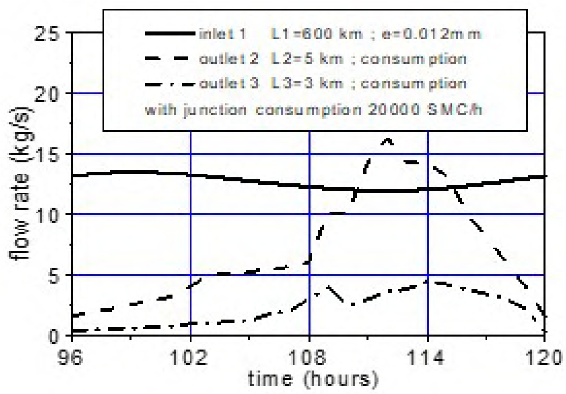

Figure 17. Flow Rate of Periodic Regime versus Time

4.3.2. Case of Two Consumptions and Two Supplies

We have two power supplies with the same pressure $p = 45$ bars and two consumptions as shown in thefigure 18. Flows at consumption points are given during 24 hours in NCM/h see (Figure 19).

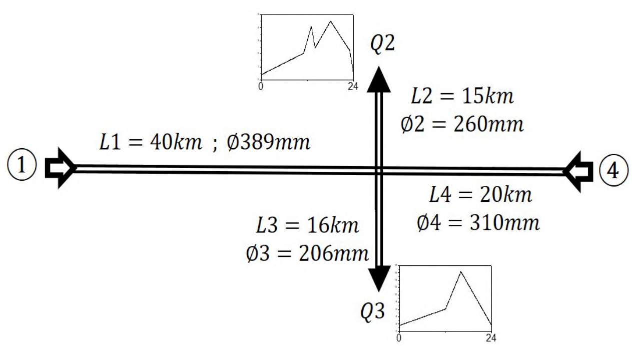

Figure 18. Two Consumptions and Two Supply

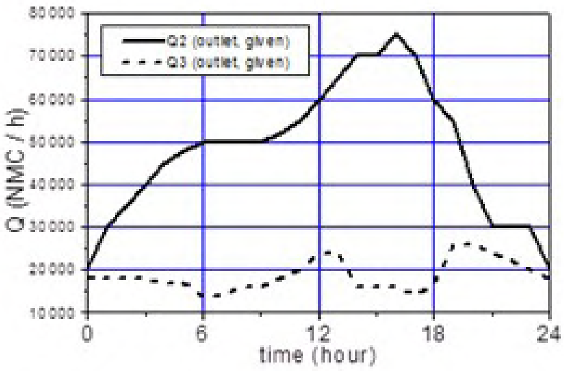

Figure 19. Two Consumptions Given

The initial solution starts from rest. After execution of the computer code, the periodic regime is obtained after6 hours, real time of start-up with the real initial conditions. The flow rates at supply points are shown in the (Figure 20). Note that the flow from the supply point ④ is negative in the calculations; the direction of the flow is taken to be directed to the right (Figure 21).

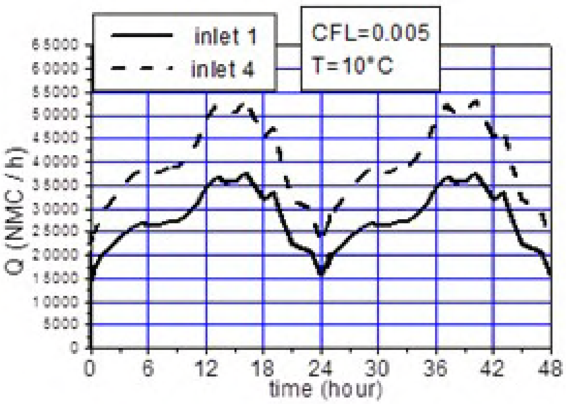

Figure 20. Flow Rate at Two Inlets in Periodic Regime

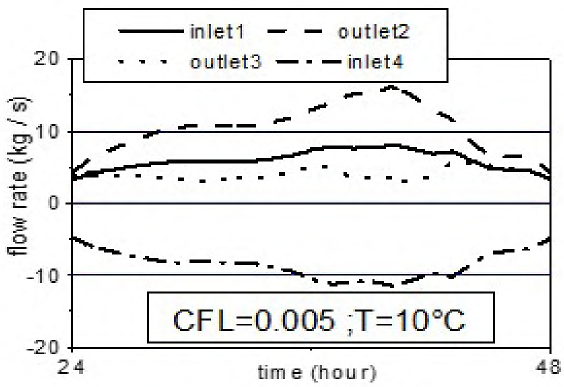

Figure 21. Flow Rate at Inlets and Outlets

The velocity at inlets and outlets of pipe is shown at (Figure 22). We can see that the velocity at inlet ④ is negative.

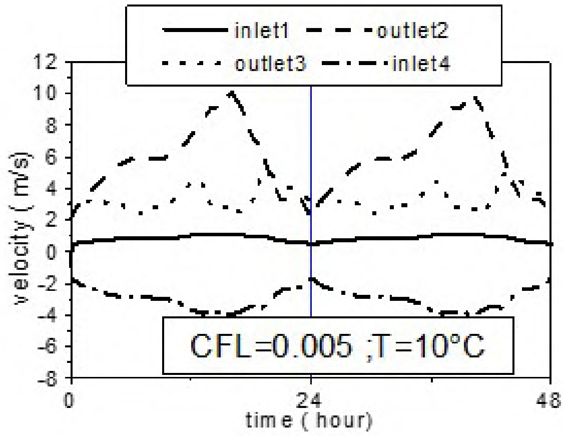

Figure 22. Velocities at Inlets and Outlets

Concerning the variation of the pressure at the points of consumption, are presented in the (Figure 23), we noticed that the pressures obtained are the same with a $CFL = 0.4$ while the convergence of the flows requires a $CFL = 0.005$ (Figure 24).

The Runtime is 36 minutes for $CFL = 0.005$ and $CPU = 1.67\ 10^{-6}{}_{s}$ / (it.mesh).

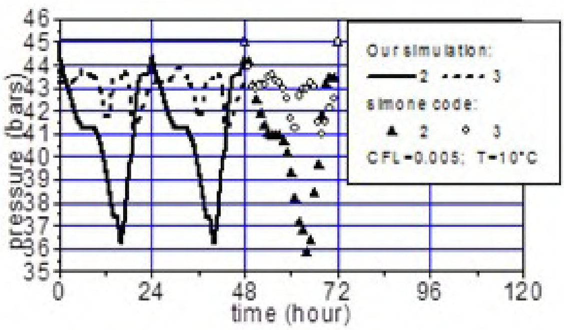

Figure 23. Results with Comparison

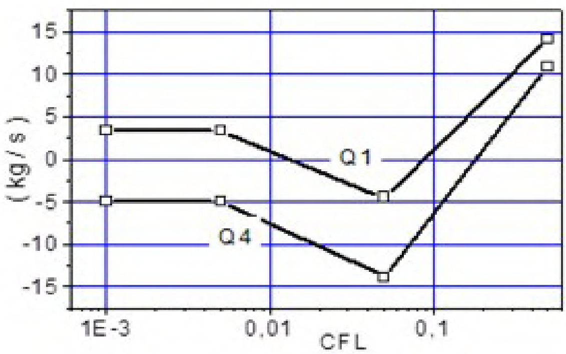

Figure 24. Effect of CFL on the Convergence

Conclusion

The finite difference method remains a good approximation for determining the behavior of the flow in a gas pipeline, the determination of the capacities in each section of the network, and the determination of the supply flow for variable or non-variable consumptions or pressures at the outlet of each section. In the case of a periodic dynamic regime, the computation time is a real parameter, on the other hand in the case of a static regime; the time is an iterative parameter. The choice of the CFL value and the spatial step Δx plays a decisive role in the convergence of the computer code. For the dynamic regime it was observed that the results do not change when the periodic regime is reached, which confirms the consistency of the numerical method. The initial solution does not influence the periodic mode but the transitory solution can take more or less time. The conservation of flows between the inlets and outlets of the pipes is confirmed in the period. We took into account the variation of the compressibility factor and the pressure drop coefficient along the pipes. A comparison was presented with the results obtained by Simone's code. The calculation at the level of the junction points is very delicate and requires a particular discretization of the conservation equations. It is clear that for 24 hours the sum of the flow rates entering equals the sum of the flow rates leaving the pipes. This result is more than sufficient to test that a calculation code is consistent and the calculations are precise.n.

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شبیه سازی عددی در یک رژیم دینامیکی جریان گاز طبیعی در شبکه خط لوله

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چکیـــــده

هدف از این مقاله ارائه نظری برای آشکارسازی فشار و جریان عرضه در حالت مصرف در رژیم دینامیک می باشد. مدل ریاضی سیستمی از معادلات دیفرانسیل غیرخطی است که با یک جریان تراکم پذیر با اصطلاح افت فشار سروکار دارد، دما ثابت و برابر با محیط در نظر گرفته می شود. شرایط مرزی داده شده و راه حل اولیه نامشخص است، پس از حل گذرا، حالت دینامیکی دوره ای به صورت پایدار برقرار می شود. روش گسسته‌سازی مورد استفاده، تفاوت‌های ظریف با مش ساختار یافته است. روش تفکیک نیمه ضمنی با یک مرحله زمانی است که به شدت به تعداد CFL بستگی دارد که همگرایی را تضمین می کند. روش انتخاب شده در طول زمان پایدار است. نتایج اصلی به دست آمده اعتبار روش مورد استفاده برای حل یک مسئله دینامیکی، دقت محاسبات و پدیده فیزیکی است که به وضوح از توزیع فشارها و نرخ جریان به عنوان تابعی از زمان و موقعیت قابل مشاهده است.

واژگان کلیدی: مصرف گاز طبیعی، شبکه گاز طبیعی، جریان ناپایدار، جریان تراکم پذیر، رژیم دینامیکی، روش تفاضل محدود