RESEARCH ARTICLE | DECEMBER 17 2019

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AIP Conference Proceedings 2191, 020001 (2019)
https://doi.org/10.1063/1.5138734

Unsteady Simulation of Natural Gas Networks

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Abstract. Gas networks work with time-dependent flow demand and sometimes in emergency conditions or the presence of undesired situations. In this scenario, unsteady simulations are necessary to design, control and analyze gas network systems. The Gas Network Solver, developed by the authors, aims to simulate the behavior of gas transportation pipelines with large diameter and length as well as gas distribution networks with branching pipes. This paper focuses on the implementation of the pipe model that is the most significant component with dynamic characteristics. A finite difference method is used to solve 1-D equations of compressible viscous fluids. The gas in the pipes is considered in thermal equilibrium. Therefore, an isothermal approach is adopted. The unsteady model is tested through an application example of a looped gas network. The results, compared with numerical data of some studies in the literature, show good accuracy of the tool developed. In conclusion, it is analyzed the effect of the gas composition on the behavior of the network.

INTRODUCTION

In the last years, the global trade in natural gas grew significantly, by 9%. The largest recent project was the Nord Stream pipeline, which increases the transmission capacity from Russia to Europe across the Baltic Sea. Asian pipeline capacity has also been expanded, with connections between China, Myanmar and Central Asia, especially Turkmenistan. Other significant capacity additions have included West Africa and South America [1].

Gas networks are energy systems responsible for transport and distribute natural gas from a production site to several users' places. Pipelines are composed by consecutive ducts of thousands of km and large diameter. Distribution networks are characterized by several, looped or not, branches of pipes. The complex and the number of elements of these networks led to develop and use numerical tools for the evaluation of pressures and velocities of the gas flow. The prediction of network parameters, especially under unsteady and transient conditions, is essential to guarantee values required by regulatory authorities [2].

In literature, there are several works on steady-state [3, 4] and unsteady [5, 6–9] modelling and simulation of gas pipeline and gas looped networks. However, available models are not enough focused on the composition of the gas mixture and its influence on gas delivered to users. Gas proprieties, such as higher heating value, are different from references values if the origin of the source changes. Therefore, the impact of the composition on flow parameters of the network and energy of the gas delivered must be considered.

This paper aims to develop a gas network solver able to analyze unsteady and transient operational scenarios and different composition of the gas mixture. Unsteady isothermal 1-D equations are used to model pipes, which influence the dynamic behavior of the network directly. Independent time equations are considered for the other elements of the system (source nodes, junctions, delivered nodes) because the dynamic characteristics of these are negligible. An alternative approach to modelling gas consumption of the grid is used. The gas flow supplied to users is recalculated, considering the higher heating value and each specie of the mixture.

74th ATI National Congress
AIP Conf. Proc. 2191, 020001-1–020001-8; https://doi.org/10.1063/1.5138734
Published by AIP Publishing. 978-0-7354-1938-4/$30.00

MATHEMATICAL MODEL

The main problem of a gas network is to evaluate: gas pressure and composition at each node; velocity and pressure drop of each pipe. These values must be checked to satisfy the gas demand and respect gas Standards [2]. Natural gas is a mixture of hydrocarbon gases. Its composition is different depending on the location and, especially in the presence of biogas or hydrogen injections. The parameters used to characterize and compare different gas mixtures are:

- The Specific gravity, defined as the ratio between gas and air density at standard conditions;

$$SG = \rho_{0g}/\rho_{0a} \tag{1}$$

- The Wobbe index, which is a function of the higher heating value of the gas considered and the square root of the specific gravity.

$$WI = \frac{HHV_g}{\sqrt{\rho_{0g}/\rho_{0a}}} \tag{2}$$

If two gases have the same WI, combustion parameters and energy of the user's device do not change. The gas safety management regulations [2] define Wobbe index range (47.2–52.2 MJ/Sm^3) allowed to guarantee optimal combustion of the fuel in the devices connected to the grid.

Pipe model

Pipes are the linear element through which the gas is transported and distributed. The unsteady governing equations for isothermal gas flow are represented by (3, 4), where gas pressure and mass flow rate are the variables of the problem. Continuity equation (3) shows that in a pipe under transient conditions, the mass flow rate at the inlet is not equal to the mass flow rate at the outlet because it is stored into the pipe volume an amount of mass. This formulation of Momentum equation (4) considers convective inertia and gravity terms in comparison to formulations used in previous studies [7, 10]. The friction factor (λ) is the coefficient related to friction losses. It is a function of roughness (ε) and diameter (D) of the pipe and viscosity, velocity and regime of the fluid flow (Re). The equation (4) is formulated using the Darcy–Weisbach friction factor, which is calculated by the Colebrook–White [11] equation (5). An iterative procedure, which converges in a few iterations and does not affect the computational time, is used to solve this implicit equation.

$$\frac{\partial p}{\partial t} + \frac{Z_g R_g T}{A}\frac{\partial \dot{m}}{\partial x} = 0 \tag{3}$$

$$\frac{1}{A}\frac{\partial \dot{m}}{\partial t} + \frac{Z_g R_g T}{A^2}\frac{\partial}{\partial x}\left(\frac{\dot{m}^2}{p}\right) + \frac{\partial p}{\partial x} + p\,\frac{g}{Z R_g T_g}\sin\theta + \frac{Z_g R_g T}{2A^2 D}\lambda\frac{\dot{m}|\dot{m}|}{p} = 0 \tag{4}$$

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{2.51}{Re\sqrt{\lambda}} + \frac{1}{3.715}\frac{\varepsilon}{D}\right) \tag{5}$$

The compressible nature of the gas and the deviation from the ideal gas are described by the equation of state (6), which determines the relationship between gas pressure (p) and density (ρ). The Gas constant (R_g) is calculated by equation (7) where R_u is the universal gas constant, and M_g is the molar mass of the gas. Papay formulation [12] uses pseudo-critical reduced pressure and temperature of the mixture to calculate the value of Z.

$$p/\rho = Z_g R_g T \tag{6}$$

$$R_g = R_u/M_g \tag{7}$$

$$Z_g = 1 - 3.52\,p_r\,e^{-2.260\,T_r} + 0.274\,p_r{}^2\,e^{-1.878\,T_r} \tag{8}$$

Node model and Boundary conditions

Nodes are the element which connects two or more pipes or/and where a volume of gas is delivered or injected. At each node of the network is applied the Kirchhoff's First Law, which states that the algebraic sum of the gas mass flow is equal to zero (9). An additional equation (10) is introduced to guarantee the balance of each chemical specie k of the gas mixture. This equation is necessary when different gas sources are in the grid.

$$\sum_{i=1}^{n} \dot{m}_{in,i} - \sum_{j=1}^{n} \dot{m}_{out,j} = \dot{m}_{dmd} \tag{9}$$

$$\sum_{i=1}^{n} y_k M_k \dot{m}_{in,i} - \sum_{j=1}^{m} y_k M_k \dot{m}_{out,j} = y_k M_k \dot{m}_{dmd} \tag{10}$$

In a typical gas network, the pressure is imposed at source nodes, where the gas is injected; the gas flow rate is imposed at demand nodes, where the gas is delivered to industrial and residential customers. However, the gas consumption of user's devices depends on their energy demand. Therefore, when gas composition and higher heating value differ from standard values, it should be recalculated at each delivered node the gas flow demand.

In the Gas Network Solver are implemented two different approaches. The traditional flow method uses the standard volumetric flow rate (Q) and equation (11) to calculate the mass flow demand by final users. The new approach proposed is the energy method. Firstly, it evaluates the energy flow ($\dot{E}$) as a function (12) of the standard volumetric flow rate demand and the standard HHV. Secondly, it imposes the mass flow rate necessary to satisfy the gas consumption of user's devices calculated considering the energy request (13). One of these two ways can be chosen to set the correct boundary conditions or analyze different situations.

$$\dot{m}_{dmd} = \rho_{0g} Q/3600 \tag{11}$$

$$\dot{E} = HHV_{0g} Q/3600 \tag{12}$$

$$\dot{m}_{dmd} = \rho_{0g} \dot{E}/HHV_g \tag{13}$$

Finite difference numerical method

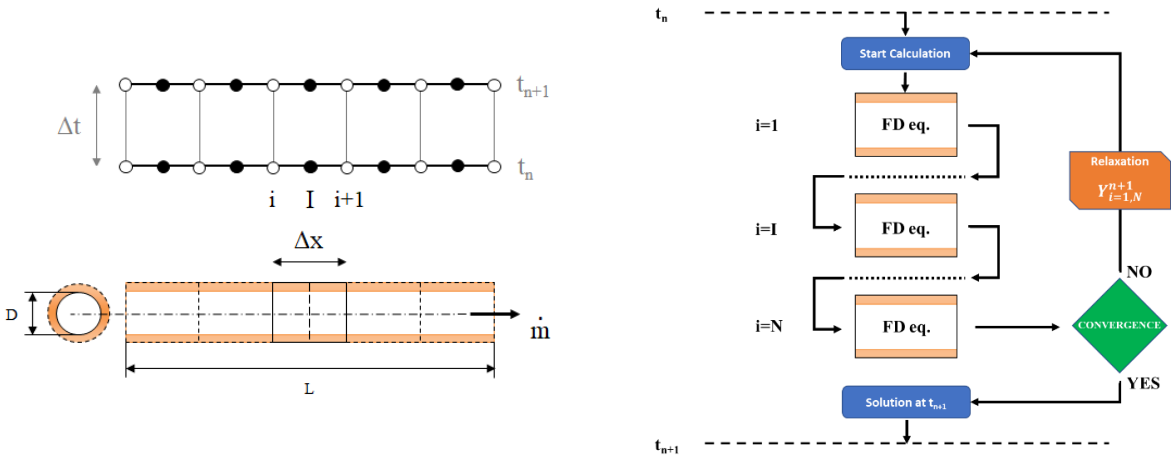
The one-dimensional flow through natural gas transportation and distribution pipes is modelled by the nonlinear partial differential equations (3, 4). In this paper, a finite difference method is used to solve the mathematical problem. The numeric schema is shown in figure 1a. A pipe is discretized in N finite volume of length Δx. The fluid variable (p, m) are stored at the border of the I-th volume (i, i+1) and evaluated at the middle of its (I) for each time step Δt of the simulation. Representing with Y a generic flow variable, the value at the middle of I-th volume, the spatial partial derivate and the time partial derivate are calculated by equations (14–17).

The fully implicit method [13], the first-order forward difference in time and the second-order central difference in space, makes the discretization scheme stable, independently on the time step Δt or the spatial discretization Δx assumed. The system of nonlinear algebraic equations obtained substituting equations (14–16) in (3, 4) is solved at each time step Δt by the iterative algorithm presented in figure 1b.

$$Y(x_I, t_n) = \frac{Y_{i+1}^n + Y_i^n}{2} + o(\Delta x^2) \tag{14}$$

$$\frac{\partial Y(x_I, t_{n+1})}{\partial x} = \frac{Y_{i+1}^{n+1} - Y_i^{n+1}}{\Delta x} + o(\Delta x^2) \tag{15}$$

$$\frac{\partial Y(x_I, t_{n+1})}{\partial t} = \frac{Y_{i+1}^{n+1} + Y_i^{n+1} - Y_{i+1}^n - Y_i^n}{2\,\Delta t} + o(\Delta t) \tag{16}$$

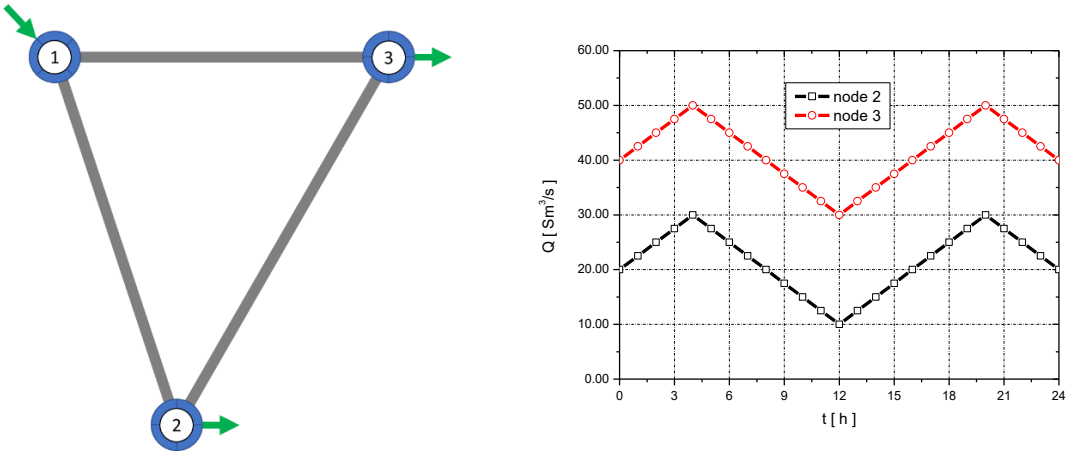


(a) (b)

FIGURE 1 . Finite difference method: scheme (a) and iterative algorithm to solve governing equations (b).

CASE OF STUDY: A LOOPED GAS NETWORK

The case of study, already analyzed in previous literature works, is the typical looped network in figure 2a. The gas network is composed of one source node (1) and two supply nodes (2, 3) which are located at the same altitude and connected by three pipes with the same diameter (D) and different length (L). Table 1 resumes geometrical data and layout of the network. The gas, which is injected at a temperature of 5 °C and a relative pressure of 50.00 bar, is considered in isothermal condition. Gas demands in node 2 and node 3 change as trends shown in figure 2b. Node 3, which is furthest from the source, reaches a maximum of 50 Sm^3/s and a minimum of 30 Sm^3/s during the day. Values of node 2 are 20 Sm^3/s less each hour in comparison with node 3. An unsteady regime of the network is created imposing these boundary conditions.



(a) (b)

FIGURE 2 . Case of study: gas network scheme (a) and volumetric gas flow demand during the day (b).

TABLE 1 . Network characteristic.

Pipe	Inlet node	Outlet Node	D [m]	L [m]
1	1	3	0.600	80’000
2	1	2	0.600	90’000
3	2	3	0.600	100’000

Validation of the Gas Network Solver

The numerical model is validated using data of published works [6, 7–9]. Different cases are simulated due to the different surface roughness value used in the previous works. Osiadacz [7] and Ke & Ti [8] consider a constant friction factor of 0.003. Otherwise, Taherinejad [6] uses a pipe surface roughness of 0.015 mm. The proprieties of the gas used in the model validation are shown in table 2.

Figures 3a and 3b show the evaluated values of relative pressure versus time in node 2 and node 3 for different values of friction factor (0.030 ÷ 0.012) used. Results of simulation show a good agreement of values evaluated with data of Elaoud [9] when a friction factor of 0.010 is assumed. Otherwise, the correct value of the pipe surface roughness is 0.01 mm if the Colebrook–White equation is turned on to calculate the value of λ. Therefore, the Gas Network Solver predicts, correctly, time and value of pressure peaks in supply nodes.

TABLE 2 . Gas proprieties and conditions.

Data	Value	Data	Value
M [kg/kmol]	17.153460	SG_0 [-]	0.584954
HHV_0 [MJ/Sm³]	38.84989	WI_0 [MJ/Sm³]	50.79592

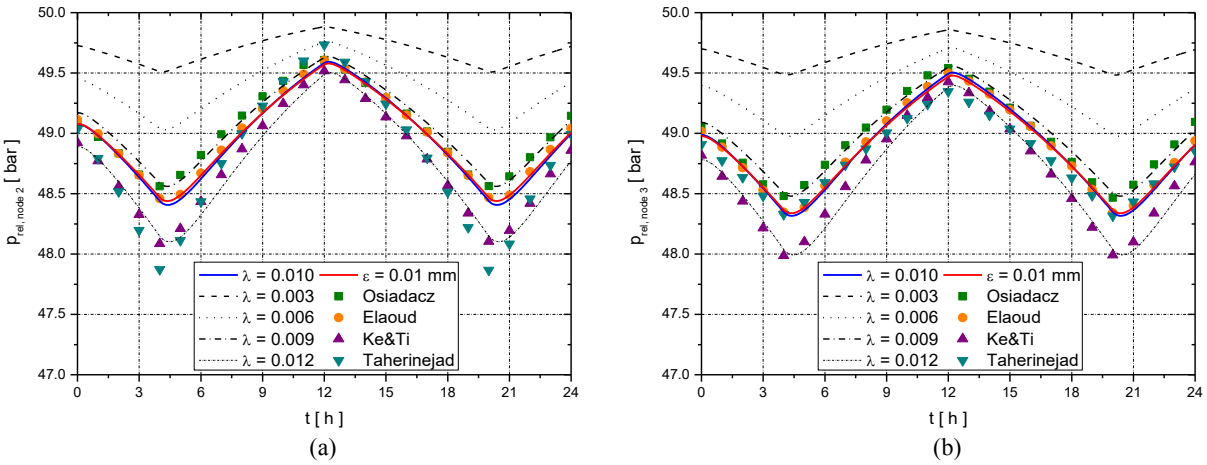


FIGURE 3 . Predicted relative pressure versus time in node 2 (a) and node 3 (b).

Effect of gas composition on the network behavior

Natural gas is a hydrocarbon gas mixture extracted from underground reserves located around the world, which components of the mixture change according to the gas origin. Therefore, the gas network is simulated using different gas mixtures to investigate effects of gas composition on its behavior. Table 3 shows the gas mixtures considered, which have been taken from the Italian Regulatory Authority for Energy, Networks and Environment [2]. The reference mixture is the Standard natural gas which is composed of a high percentage of methane and a low percentage of ethane, propane and nitrogen. Figure 4 shows how combustion parameters are very dependent on gas origin. For instance, the higher heating value of the Russian gas is 5% lower than the Algerian gas. Nevertheless, the Wobbe index and HHV of the eight compositions analyzed are included between the minimum and maximum admissible values [2].

Figures 5a and 5b show the results of the unsteady simulation for the standard gas mixture. Pressure values in the middle of the pipe (Node A, B, C) and at the delivered nodes follow the same periodic evolution of the gas demand imposed. Minimum and maximum peaks shift in the time respect to gas demand peaks due to the dynamic behavior of the network. The delay time at node 2 and node 3 is about 22 minutes for the minimum peaks and 12 minutes for the maximum peak. Pressure oscillation decrease and delay time of peaks increase moving from the delivered node to the source node. The different mass flow rate between the inlet and the outlet of pipes is another dynamic effect. Under unsteady conditions, it is stored into each pipe volume an amount of mass flow. The network works such as a gas

reservoir. During the day, the gas is stored (positive values) and thrown out (negative values) the pipes. The pipe 3, which connects node 2 and node 3, stores more mass flow than pipe 1 and pipe 2.

TABLE 3 . Molecular gas composition of the mixtures considered.

Type	CH_4	C_2H_6	C_3H_8	C_4H_{10}	C_5H_{12}	C_6H_{14}	CO_2	N_2	He
Standard	97.201	1.862	0.393	-	-	-	-	0.544	-
CH_4	100.000	-	-	-	-	-	-	-	-
Italian	99.348	0.098	0.300	0.006	-	0.005	0.039	0.472	0.002
Russian	96.401	1.675	0.512	0.152	0.029	0.017	0.303	0.898	0.013
Algerian LNG	90.631	7.480	1.190	0.291	0.006	0.001	0.001	0.399	0.001
North European	89.389	5.095	1.119	0.347	0.073	0.053	1.376	2.508	0.400
Algerian	88.120	7.866	1.223	0.160	0.023	0.012	1.606	0.890	0.100
Libyan	86.367	7.096	1.749	0.539	0.103	0.005	1.052	3.005	0.084

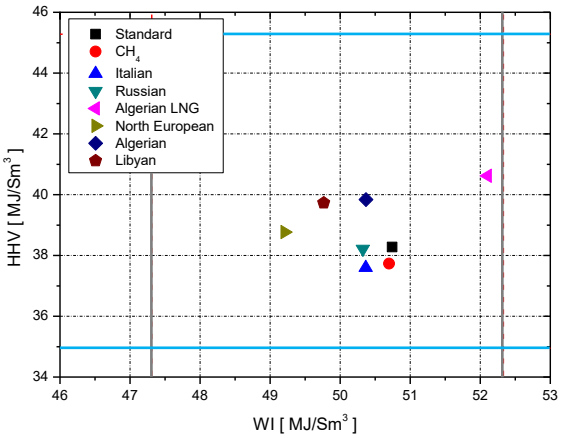


FIGURE 4 . Combustion proprieties for different gas composition.

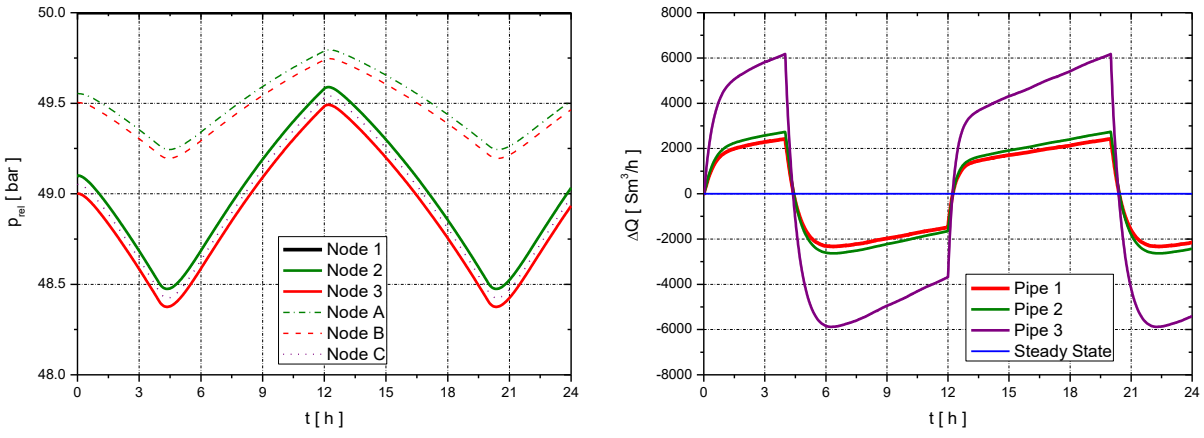


FIGURE 5 . Results for the standard gas composition (a): pressure; (b) standard volumetric flow.

The pressure droop evolutions for the different gas mixture and boundary condition methods are plotted in figures 6a, 6b, 6c and 6d. Pressure drop and amplitude of its oscillation can increase or decrease due to a variation of the gas composition. Differences from the standard mixture are between – 7% and + 6% for the energy method and between

– 3% and + 11% for the traditional flow method. For the same gas composition differences between the two methods used are greater. In the case of the Algerian LNG composition, maximum peak evaluated by the energy method is about 13% lower than the value calculated by the traditional flow method.

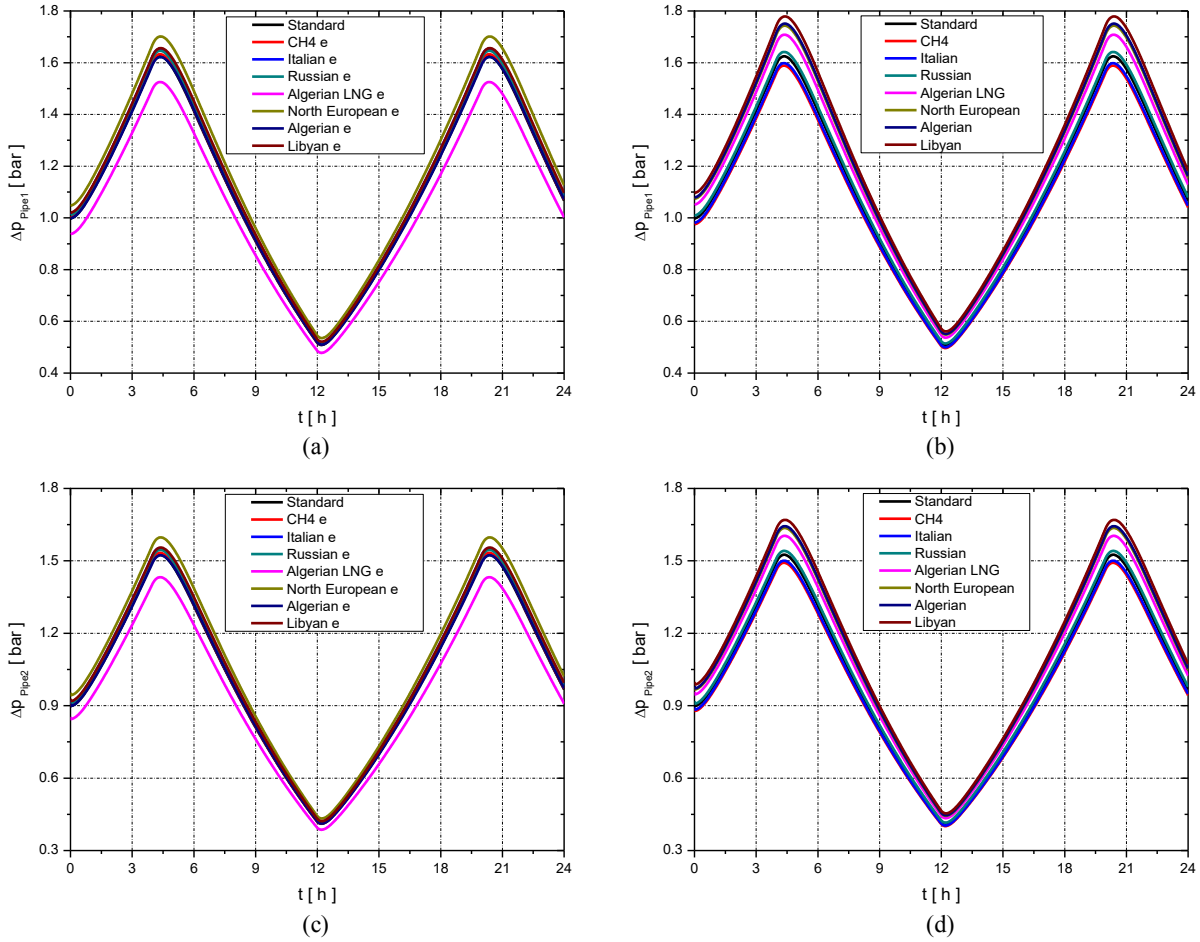


FIGURE 6 . Pressure drop in pipe 1 and pipe 2: energy method (a), (c) and traditional flow method (b), (d).

CONCLUSIONS

A numerical model able to simulate gas networks under unsteady and transient conditions was presented. The compressibility factor was calculated with the Papay formulation, which takes into account the composition of the gas mixture. Partial differential equations of the pipe model were solved using a fully implicit finite difference method. The discretization schema is the first-order in time and the second-order central in space. Gas consumption of users was formulated in two different ways. The tradition flow method imposes the standard volumetric flow at each delivered node. The energy method, which is the new approach proposed, imposes the gas flow necessary to match the energy required, independently of the mixture's composition.

In this paper, a looped network, studied in several previous works, was analyzed to test and validate the gas network solver. Results of simulations match with the literature data. Values and time of pressure peaks are predicted correctly. After that, the network was simulated with eight different gas compositions to show the advantages and potentiality of the present model. The type of mixture has a pronounced effect on the parameters of the network. When the proprieties of the mixture differ from the standard composition, the traditional flow method does not match energy consumptions. Therefore, the use of the energy method is more appropriate to simulate the real behavior of the network.

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