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Simulation of Transient Flow in Gas Pipelines Using the Finite Volume Method

Simulación de Flujo Transitorio en Líneas de Gasoducto usando el Método de Volúmenes Finitos



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Abstract

The transient flow analysis is fundamental to the simulation of natural gas process, in order to adjust the system to real operative conditions and to obtain the highest level of efficiency, compliance and reliability. The simulation of natural gas pipelines and networks requires mathematical models that describe flow properties. Some models that have been developed year after year based on the laws of fluid mechanics that govern this process, interpreted as a system of equations difficult to solve. This investigation describes the fully implicit finite volume method for natural gas pipeline flow calculation under isothermal conditions and transient regime. The simplification, discretization scheme and implementation equations are approached throughout this paper. The model was subjected to two evaluations: sinusoidal variation of the mass flow and opening-closing valve at the outlet of the pipeline, it is compared with two models: fully implicit finite difference method and method of characteristics. This method proved to be efficient in the simulations of slow and fast transients, coinciding the flow oscillations with the natural frequency of natural gas pipeline.

Resumen

El análisis de flujo transitorio es fundamental en la simulación del procesamiento del gas natural, ya que permite ajustar los sistemas a condiciones operacionales que permitan obtener altos niveles de eficiencia. La simulación de tuberías y redes de gas natural requiere de modelos matemáticos que describen las propiedades del fluido. Existen modelos que se han desarrollado con base en las leyes de la mecánica de los fluidos que rigen estos procesos, y que presentan ecuaciones difíciles de resolver. En esta investigación se describe el método de volúmenes finitos totalmente implícito para el cálculo de flujo en líneas de gasoducto, bajo condiciones isotérmicas y régimen transitorio. La simplificación, discretización y la implementación de las ecuaciones son abordados a largo de este documento. El modelo fue sometido a dos evaluaciones: variación sinusoidal del flujo másico y apertura-cierre de válvula a la salida del gasoducto, mediante la comparación de dos modelos: método de diferencias finitas totalmente implícito y método de las características. Este método resultó ser eficiente en las distintas simulaciones de transitorios lento y rápido, coincidiendo las oscilaciones de flujo con su frecuencia natural.

Keywords:

gas pipelines, transient flow, compressible flow, isothermal flow, finite volume method

Palabras clave:

líneas de gasoducto, flujo transitorio, flujo compresible, flujo isotérmico, método de volúmenes finitos

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Introduction

Natural gas has come to occupy a significant place in the global energy scenario, with a continuous growth in demand, situation that represents a great challenge for the optimization of the infrastructure associated to gas transportation and distribution. Traditionally, the first stage of a gas transportation project begins with an economic evaluation that, from a technical point of view, uses a steady-state flow analysis to determine the system states parameters. As soon as this evaluation shows the project's economic feasibility, the design stage of the gas pipeline network begins. It is at this stage that the transient flow analysis is fundamental to the process simulation, in order to adjust the system to real operative conditions and to obtain the highest level of efficiency, compliance and reliability. The large investments associated with the costs of acquisition and installation of gas pipelines and compression stations requires an optimization study of the transportation system, which must be designed to operate under different gas-consuming scenarios, such as the load increase in peak hours, gas pipeline fractures facility maintenance, among others. The simulation of natural gas pipelines and networks requires mathematical models that describe flow properties. Some models that have been developed year after year based on the laws of fluid mechanics that govern this process, interpreted as a system of equations difficult to solve. Several iterative methods have been implemented for their resolution, using at the same time, different schemes of discretization and restrictive assumptions. There are various works related to the simulation of transient flow in gas pipelines, among which is the method of characteristics (MC). This method takes the partial differential equations system and transforms it into ordinary derivatives to then be numerically integrated. An advantage of the method is that it can handle discontinuities in the simulation, although the main disadvantage is that it is comparatively slow; the time steps must be small enough to satisfy the Courant-Friedrichs-Lewy Condition (CFL) (Issa & Spalding, 1972; Wylie & Streeter, 1978).

The Crank-Nicolson method (CNM) for isothermal gas flow, solve the continuity and momentum equations, node to node, applying a discretization scheme of finite differences (Guy, 1967; Heath & Blunt, 1969). The main disadvantage of this method is that it not always gives a stable solution according to the Von Neumann stability analysis for large time steps. The finite differences method (FDM) for isothermal flow in gas pipelines and networks (Kiuchi, 1994), integrates the system of equations in partial derivatives, using a totally implicit discretization scheme with some simplifications. After neglecting the convective term in the moment equation,

the Von Neumann stability analysis showed that the discretized equations are unconditionally stable. In a later study, the FDM for non-isothermal flow is applied (Abbaspour & Chapman, 2008), this time incorporating the convective term in the momentum equation, treating the compressibility factor as a function of temperature and pressure and considering the friction factor as a function of Reynold's Number and of the pipe roughness. On the other hand, Patankar (1980) presents the finite volume method (FVM), an alternative to represent and evaluate partial differential equations in the form of algebraic equations, expressing the principles of conservation of the underlying physics in forms of macroscopic balance of a specific property. Versteeg and Malalasekera (2007) indicate that integration of the control volume is what distinguishes FVM from other computational fluid dynamics (CFD) techniques. A relation between the numeric algorithm and the principles of mass conservation (continuity), momentum and energy, constitutes one of the main attractions of this approach and makes its concepts much easier to be understood by engineers. This research work consists in describing a simplified mathematical model, discretized with FVM, that allows computational simulation of gas flow transport for different entry and exit conditions, considering transient regime and that the fluid is transmitted in gas pipelines. The model is validated through comparison with known models.

Methodology

1. Constitutive equations

Issa and Spalding (1972), Van Deen and Reintsema (1983) and Thorley and Tiley (1987) develop equations 1-5, where they describe the properties of compressible single-phase one-dimensional flow, over a control volume of constant surfaces, framed within a gas pipeline (Figure 1). These equations are governed by fluid dynamics principles, they include the effects of wall friction and heat transfer and are position and time-dependent.

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho v) = 0 \quad (1)$$

- Momentum equation :

$$\rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial x} + \frac{\partial P}{\partial x} + \frac{f \rho v |v|}{2D} + \rho g \text{ sen } \theta = 0 \quad (2)$$

- Energy equation:

$$\rho \frac{\partial h}{\partial t} + \rho v \frac{\partial h}{\partial x} - \frac{\partial P}{\partial t} - v \frac{\partial P}{\partial x} - \frac{f \rho v^2 |v|}{2D} - q \rho = 0 \quad (3)$$

- State equation: $\frac{P}{\rho} = ZRT$ (4)

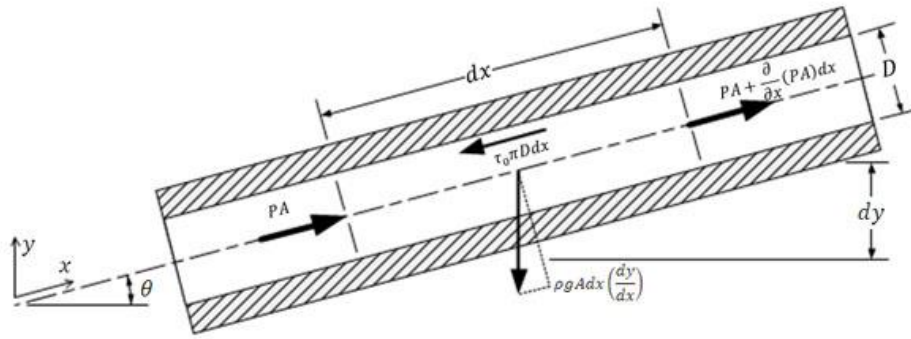


Figure 1. Newton's second law illustrated in a control volume.

- Wave propagation velocity:

$$c = \sqrt{\frac{ZRT}{1 - \frac{P}{Z} \left(\frac{\partial Z}{\partial P} \right)_T - \frac{ZR}{c_p} \left[1 + \frac{T}{Z} \left(\frac{\partial Z}{\partial T} \right)_P \right]^2}} \quad (5)$$

The friction factor f is calculated with Reynold's Number Re and the gas pipeline roughness ε/D with Colebrook equation 6, which combines flow regimes both partial and totally turbulent and is the most suitable for cases where the pipeline is operating in the transition zone (Mohitpour, Golshan & Murray, 2003).

$$\frac{1}{\sqrt{f}} = -2.0 \log \left(\frac{\varepsilon/D}{3.7} + \frac{2.51}{Re \sqrt{f}} \right) \quad (6)$$

The compressibility factor Z is obtained from equation 7 (Dranchuck, Purvis & Robinson, 1973).

$$Z = 1 + \left(0.31506 - \frac{1.0467}{T_r} - \frac{0.5783}{T_r^3} \right) \rho_r + \left(0.5353 - \frac{0.6123}{T_r} \right) \rho_r^2 + \frac{0.6895}{T_r^3} \rho_r^3 \quad (7)$$

2. Simplification

By considering that the flow is isothermal, it is assumed that temperature changes in the fluid are slow enough to be canceled by heat conduction and the environment that surrounds it; in consequence, the energy equation is neglected and the system is now conformed by the continuity equation 8, the momentum equation 9 and an approximate relation (equation 10), between the state equations and wave propagation velocity (Kiuchi, 1994).

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho v) = 0 \quad (8)$$

$$\frac{\partial}{\partial t} (\rho v) + \frac{\partial}{\partial x} (\rho v^2) + \frac{\partial P}{\partial x} + \frac{f \rho v |v|}{2D} + \rho g \sin \theta = 0 \quad (9)$$

$$c^2 \approx \frac{P}{\rho} = ZRT \quad (10)$$

In equation 9, the first two terms are inertial: the first one is transient, the second one is convective; the third one is the pressure drop; the fourth is the source term, and the fifth one is the gravity term. The Z factor in natural gas, for pressure and temperature ranges from 0.5 MPa to 6.5 MPa and from 280 K to 320 K. In both cases, this factor oscillates between 0.8 and 1.0, approximately. In addition, the values of the partial derivatives of Z with respect to pressure and temperature are negligible.

3. Discretization scheme

The FVM contains discretization schemes for the key treatment of transport phenomena, convection (transport due to fluid flow) and diffusion (transport due to variations in the variable from node to node), as well as the source terms (associated to the creation or destruction of the variable) and transient (variable variations with time).

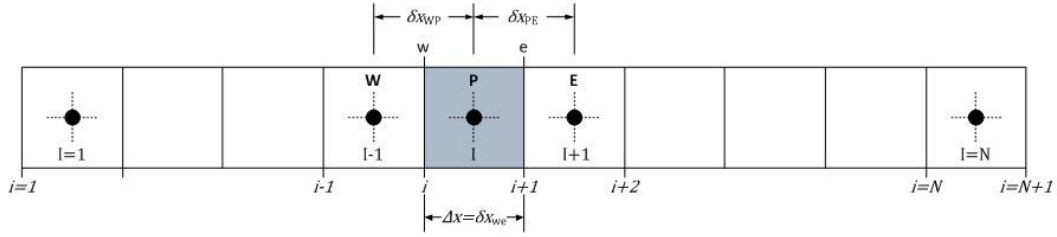
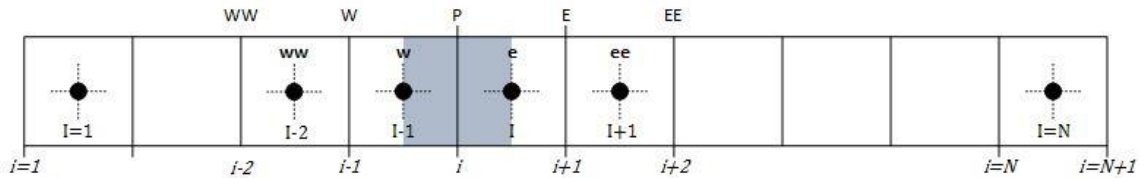
In the discretization mesh (Figure 2) the node I has as neighbors the nodes $I-1$ (to the left) and $I+1$ (to the right). Between the nodes $I-1$ and I , is the surface I that corresponds to the left face of the control volume constructed around I . Between the nodes I and $I+1$, is the surface $I+1$ that corresponds to the right face of the considered control volume. The distances between the surfaces (faces) and between the nodes (centers) are Δx . As the flow model geometry is one-dimensional, the control volume is calculated by $V = A \Delta x$.

Continuity equation: The velocities are located in their respective surface and the density, in the node or control volume center (Figure 2).

$$(\rho_I^{n+1} - \rho_I^n) A_I \frac{\Delta x}{\Delta t} + (\rho A v)_{i+1}^{n+1} - (\rho A v)_i^{n+1} = 0 \quad (11)$$

$$\text{Where: } \rho_i^{n+1} = \frac{\rho_{i-1}^{n+1} + \rho_i^{n+1}}{2}; \quad \rho_{i+1}^{n+1} = \frac{\rho_i^{n+1} + \rho_{i+1}^{n+1}}{2}$$

$$y \quad A_I = \frac{A_i + A_{i+1}}{2}$$


Figure 2. Discretization mesh for the continuity equation.

Figure 3. Mesh for the moment equation.

Momentum equation: The control volume is delayed in the mesh at a distance of $\frac{1}{2} \Delta x$ from node I (Figure 3), so that the pressures coincide in the nodes and the velocities coincide in the surfaces.

$$a_i v_i^{n+1} = \sum a_{nb} v_{nb}^{n+1} + (P_{I-1}^{n+1} - P_I^{n+1}) A_i + b_i \quad (12)$$

$$a_i = \rho_i^{n+1} A_i \frac{\Delta x}{\Delta t} + a_{i-1} + a_{i+1} + (F_I^{n+1} A_I - F_{I-1}^{n+1} A_{I-1}) + S_p A_i \Delta x \quad (13)$$

$$\sum a_{nb} v_{nb}^{n+1} = a_{i-1} v_{i-1}^{n+1} + a_i v_i^{n+1} \quad (14)$$

$$a_{i-1} = \max(0, F_{I-1}^{n+1} A_{I-1}) \quad (15)$$

$$F_{I-1}^{n+1} A_{I-1} = \frac{1}{2} \left[\left(\frac{\rho_{I-2}^{n+1} + \rho_{I-1}^{n+1}}{2} \right) v_{i-1}^{n+1} + \left(\frac{\rho_{I-1}^{n+1} + \rho_I^{n+1}}{2} \right) v_i^{n+1} \right] \left(\frac{A_{i-1} + A_i}{2} \right) \quad (16)$$

$$a_i = \max(0, -F_I^{n+1} A_I) \quad (17)$$

$$-F_I^{n+1} A_I = -\frac{1}{2} \left[\left(\frac{\rho_{I-1}^{n+1} + \rho_I^{n+1}}{2} \right) v_i^{n+1} + \left(\frac{\rho_I^{n+1} + \rho_{I+1}^{n+1}}{2} \right) v_{i+1}^{n+1} \right] \left(\frac{A_i + A_{i+1}}{2} \right) \quad (18)$$

$$b_i = (\rho v)_i^n A_i \frac{\Delta x}{\Delta t} + S_u^D -$$

$$S_u A_i \Delta x - \rho_i^{n+1} g A_i \Delta x \sin \theta \quad (19)$$

$$S_p = \frac{f \rho_i^{n+1} \bar{v}_i^{n+1}}{D} \quad (20)$$

$$S_u = -\frac{f \rho_i^{n+1} (\bar{v}_i^{n+1})^2}{2D} \quad (21)$$

It is established that \bar{v}_i^{n+1} is the value of the previous iteration.

If the Upwind (UW) scheme is used, then $S_u^D = 0$.

If the Total Variation Diminishing (TVD) scheme is used, then the source term correction is:

$$S_u^D = \frac{1}{2} F_{I-1}^{n+1} A_{I-1} [\alpha_{I-1} \psi(r_{I-1}^+) - (1 - \alpha_{I-1}) \psi(r_{I-1}^-)] (v_i^{n+1} - v_{i-1}^{n+1}) + \frac{1}{2} F_I^{n+1} A_I [\alpha_I \psi(r_I^+) - (1 - \alpha_I) \psi(r_I^-)] (v_{i+1}^{n+1} - v_i^{n+1}) \quad (22)$$

With

$$\alpha_{I-1} = 1 \text{ for } F_{I-1}^{n+1} > 0 \text{ and } \alpha_I = 1 \text{ for } F_I^{n+1} > 0,$$

$$\alpha_{I-1} = 0 \text{ for } F_{I-1}^{n+1} < 0 \text{ and } \alpha_I = 0 \text{ for } F_I^{n+1} < 0.$$

The flow limiting function UMIST is established to prevent the generation of spurious oscillations:

$$\psi(r) = \max \left[0, \min \left(2r, \frac{1+3r}{4}, \frac{3+r}{4,2} \right) \right] \quad (23)$$

$$\text{For } r_I^+ = \frac{v_i - v_{i-1}}{v_{i+1} - v_i}$$

$$r_{I-1}^+ = \frac{v_{i-1} - v_{i-2}}{v_i - v_{i-1}}$$

$$r_I^- = \frac{v_{i+2} - v_{i+1}}{v_{i+1} - v_i} \text{ and}$$

$$r_{I-1}^- = \frac{v_{i+1} - v_i}{v_i - v_{i-1}}.$$

4. Implementation

The FVM implementation consists in following the steps described in the algorithm 1, for a space-time domain of N control volumes and $t = 0, t + \Delta t, \dots, t_{max}$ seconds; calculating for these volumes and seconds (Figure 2) the pressure fields located in the nodes or centers (I) and velocities in the surfaces or faces (i), in the present time levels ($n + 1$), by means of the Tridiagonal Matrix Algorithm (TDMA) for coupled systems of prediction-correction based on the constitutive flow equations and adapted to initial conditions in the present time level (n) and boundary conditions in the natural gas pipeline's entry ($i = I$) or exit ($i = N + 1$).

Algorithm 1 Resolution for transient flow by FVM

Require: $T_{gas}, P_o, v_o, D, L, \theta, f, t_{max}, \Delta t, N$

Ensure: P, ρ, v

Step 1: Establish: $t = 0, n = 0$

Step 2: Calculate the compressibility factor Z

Step 3: Calculate initial density ρ_o

Step 4: Calculate initial conditions for stable flow: P^n, ρ^n, v^n

Step 5: Calculate boundary conditions for the time $t + \Delta t$:

$$P_1^{n+1} \text{ ó } P_N^{n+1}$$

$$\rho_1^{n+1} \text{ ó } \rho_N^{n+1}$$

$$v_1^{n+1} \text{ ó } v_N^{n+1}$$

Step 6: Establish:

$$P^{*n+1} = P^n$$

$$\rho^{*n+1} = \rho^n$$

$$v^{*n+1} = v^n$$

Step 7: Apply the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) or the Pressure Implicit with Splitting Operators (PISO) iterative algorithm until convergence.

Step 8: If $t < t_{max}$, then establish:

$$t = t + \Delta t$$

$$n = n + 1$$

return to step 5.

End If

Patankar (1980) proposes an algorithm named with the acronym SIMPLE. The procedure consists in systematically estimating and correcting velocities and pressures on an alternated mesh (algorithm 2). The discretized continuity (equation 11) is rewritten as a connection equation for pressure, that is:

$$a_I P_I^{n+1} = a_{I-1} P_{I-1}^{n+1} + a_{I+1} P_{I+1}^{n+1} + b_I \quad (24)$$

Where:

$$a_I = k A_I \frac{\Delta x}{\Delta t} + a_{I-1} + a_{I+1} + \left(\frac{1}{2} k v_{i+1}^{*n+1} A_{i+1} - \frac{1}{2} k v_i^* A_i \right) \quad (25)$$

$$a_{I-1} = \max \left(0, \frac{1}{2} k v_i^{*n+1} A_i \right) + d_i \rho_i^{*n+1} A_i \quad (26)$$

$$a_{I+1} = \max \left(0, -\frac{1}{2} k v_{i+1}^{*n+1} A_{i+1} \right) + d_{i+1} \rho_{i+1}^{*n+1} A_{i+1} \quad (27)$$

$$b_I = (\rho_I^n - \rho_I^{*n+1}) A_I \frac{\Delta x}{\Delta t} + \rho_i^{*n+1} v_i^{*n+1} A_i - \rho_{i+1}^{*n+1} v_{i+1}^{*n+1} A_{i+1}, \quad (28)$$

$$k = \frac{1}{ZRT}, \quad (29)$$

$$d_i = \frac{A_i}{a_i}. \quad (30)$$

The a_i value is calculated with equation 13.

Algorithm 2 SIMPLE

Require: $P^{*n+1}, \rho^{*n+1}, v^{*n+1}$ (initial conditions).

Ensure: $P^{n+1}, \rho^{n+1}, v^{n+1}$.

Step 1: Solve the discretized momentum equation:

$$a_i v_i^{*n+1} = \sum a_{nb} v_{nb}^{*n+1} + (P_{I-1}^{*n+1} - P_I^{*n+1}) A_i + b_i$$

Step 2: Solve the correction equation for pressure:

$$a_I P_I^{n+1} = a_{I-1} P_{I-1}^{n+1} + a_{I+1} P_{I+1}^{n+1} + b_I$$

Step 3: Correct pressure, density and flow velocity:

$$P_I^{n+1} = P_I^{*n+1} + P_I^{n+1}$$

$$\rho_I^{n+1} = \rho_I^{*n+1} + k P_I^{n+1}$$

$$v_i^{n+1} = v_i^{*n+1} + d_i (P_{I-1}^{n+1} - P_I^{n+1})$$

Step 4: If it does not converge, then establish:

$$P^{*n+1} = P^{n+1}$$

$$\rho^{*n+1} = \rho^{n+1}$$

$$v^{*n+1} = v^{n+1}$$

return to step 1.

End If

Another calculation procedure of pressure-velocity named with the acronym PISO was originally developed by Issa (1986) and presented by Versteeg and Malalsekera (2007) for the iterative calculation of compressible flow. The PISO algorithm implies one predictive step and two correcting steps (Figure 6) and it can be seen as an extension of SIMPLE with one additional corrective step to improve it. Thus, the second correction equation is established as:

$$a_I P_I^{n+1} = a_{I-1} P_{I-1}^{n+1} + a_{I+1} P_{I+1}^{n+1} + b_I, \quad (31)$$

where

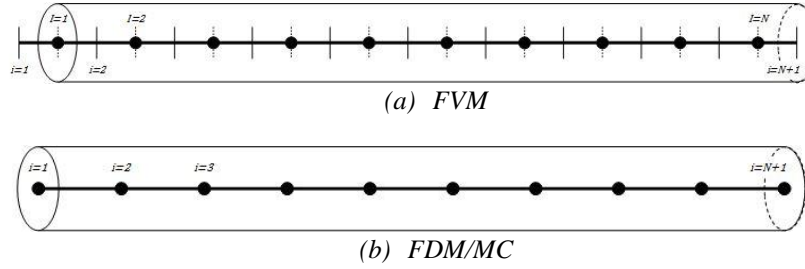


Figure 4. Discretization mesh employed for the simulations.

$$a_l = kA_l \frac{\Delta x}{\Delta t} + a_{l-1} + a_{l+1} + \left(\frac{1}{2} k v_{i+1}^{**n+1} A_{i+1} - \frac{1}{2} k v_i^{**n+1} A_i \right) \quad (32)$$

$$a_{l-1} = \max \left(0, \frac{1}{2} k v_i^{**n+1} A_i \right) + d_i \rho_i^{**n+1} A_i \quad (33)$$

$$a_{l+1} = \max \left(0, -\frac{1}{2} k v_{i+1}^{**n+1} A_{i+1} \right) + d_{i+1} \rho_{i+1}^{**n+1} A_{i+1} \quad (34)$$

$$b_l = \rho_i^{**n+1} d_i \sum a_{nb} (v_{nb}^{**n+1} - v_{nb}^{n+1}) - \rho_{i+1}^{**n+1} d_{i+1} \sum a_{nb} (v_{nb}^{**n+1} - v_{nb}^{n+1}) \quad (35)$$

Considering now that:

$$P^{**} = P^* + P' \quad (36)$$

$$\rho^{**} = \rho^* + kP' \quad (37)$$

$$v_i^{**n+1} = v_i^{*n+1} + d_i (P_{l-1}'^{n+1} - P_l'^{n+1}) \quad (38)$$

Algorithm 3 PISO

Require: $P^{*n+1}, \rho^{*n+1}, v^{*n+1}$ (initial conditions).

Ensure: $P^{n+1}, \rho^{n+1}, v^{n+1}$.

Step 1: Solve the discretized momentum equation: (SIMPLE).

$$a_i v_i^{*n+1} = \sum a_{nb} v_{nb}^{*n+1} + (P_{l-1}^{*n+1} - P_l^{*n+1}) A_i + b_i.$$

Step 2: Solve the first correction equation for pressure: (SIMPLE).

$$a_l P_l'^{n+1} = a_{l-1} P_{l-1}'^{n+1} + a_{l+1} P_{l+1}'^{n+1} + b_l.$$

Step 3: Solve the second correction equation for pressure:

$$a_l P_l''^{n+1} = a_{l-1} P_{l-1}''^{n+1} + a_{l+1} P_{l+1}''^{n+1} + b_l.$$

Step 4: Correct pressure, density and flow velocity:

$$P_l^{n+1} = P_l^{*n+1} + P_l'^{n+1} + P_l''^{n+1}.$$

$$\rho_l^{n+1} = \rho_l^{*n+1} + kP_l'^{n+1} + kP_l''^{n+1}.$$

$$v_i^{n+1} = v_i^{*n+1} + d_i (P_{l-1}'^{n+1} - P_l'^{n+1}) + \frac{\sum a_{nb} (v_{nb}^{*n+1} - v_{nb}^{n+1})}{a_i} + d_i (P_{l-1}''^{n+1} - P_l''^{n+1}).$$

Step 5: If it does not converge, then establish:

$$P^{*n+1} = P^{n+1}.$$

$$\rho^{*n+1} = \rho^{n+1}.$$

$$v^{*n+1} = v^{n+1}.$$

return to step 1.

End If

In order to obtain a convergence behavior indicator through the whole flow field, the global residue R_v is defined as the sum of local residues over all the control volumes domain (N), that is:

$$(R^v)^{(k)} = \sum_{i=1}^N |(\sum a_{nb} v_{nb})^{(k)} + (P_{l-1} - P_l)^{(k)} A_i + b_i^{(k)} - (a_i v_i)^{(k)}| \quad (39)$$

Results

Based on the comparison of flow simulations, two evaluations were made for a gas pipeline in horizontal position of 5 km length and 50 cm inner diameter. The fluid is natural gas, the operation temperature is $25 \text{ }^\circ\text{C}$ and the input pressure is set at 5 MPa . The gas pipeline's natural frequency is 0.0179 Hz , calculated by means of the relation $\omega_n = c/4L$ (Kiuchi, 1994). It initiates under flow conditions of steady-state. The Darcy-Weisbach friction factor is considered constant and equal to 0.008 . All the simulations were made with Scilab compiler, running the algorithms for FDM and MC. Simulations and the FVM were made under two implementation modalities: one applies the UW scheme in conjunction with the SIMPLE algorithm, while the other one uses the TVD-UMIST scheme with the PISO algorithm.

The proposed model and the reference models, were simulated for different sizes of space-time step, specifically test runs were done with time steps (Δt) of $1/10$, 1 and 10 s, section numbers or control volumes (N) of 10, 50 and 100, obtaining very good results for the models based in FVM and FDM, which was not the case working with MC, due to the stability condition CFL. With the purpose of preserving the iterative process stability for all the models, simulations with $\Delta t = 1$ s y $N = 10$, are shown in Figure 4.

His evaluation model is taken from Vieira and Torres-Monzón (2013) and Yow (1971), and it consists in the sinusoidal mass flow variation at the gas pipeline exit; it initiates with 20 kg/s in stable state; the flow variation amplitude is 10 kg/s and the oscillation period is 1800 s. In figures 5 to 8, the FVM gives nearly equal results as FDM, both for the mass flow and pressure along the gas pipeline, showing the same oscillation frequencies in each spectral signal. Comparison between FVM and MC gives similar values in the calculation of flow properties and the spectral analysis shows a slight phase shift.

1. Evaluation 1: Relatively slow transient flow

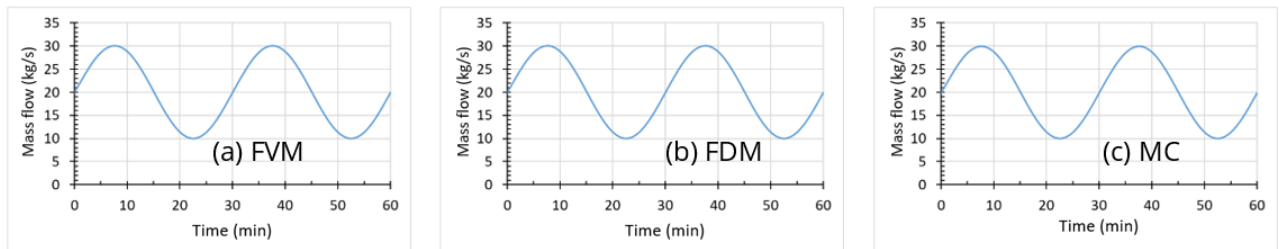


Figure 5. Mass flow calculated at the natural gas pipeline entry.

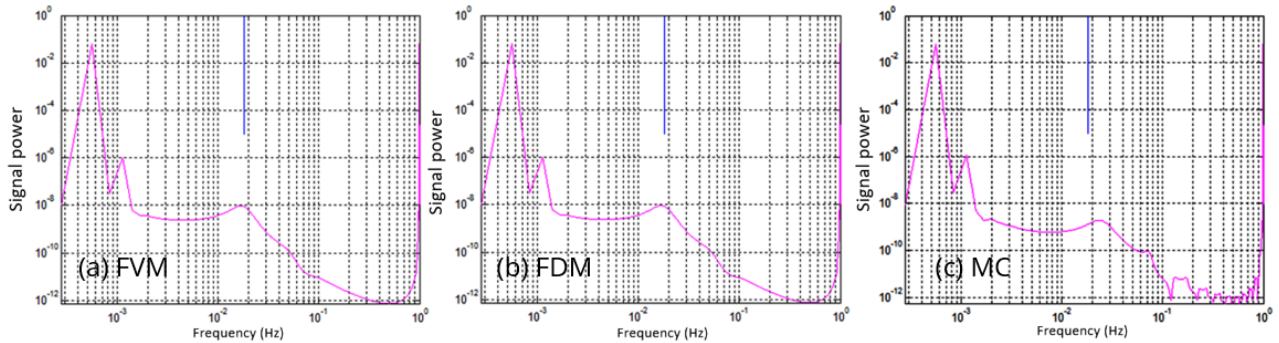


Figure 6. Spectral analysis for the wave signal generated by the mass flow at the natural gas pipeline entry compared with the natural frequency ω_n (blue line).

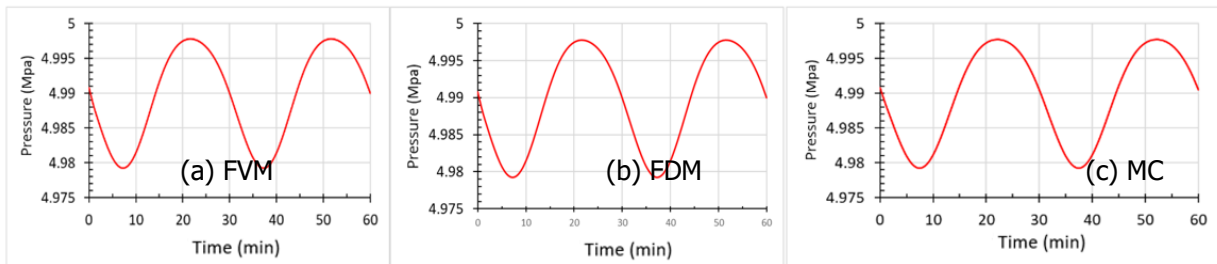


Figure 7. Calculated pressure at the natural gas pipeline exit.

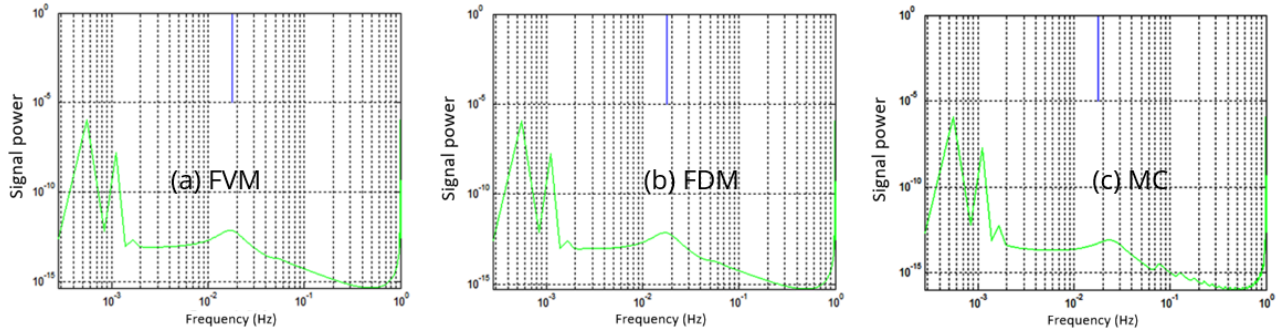


Figure 8. Spectral analysis of wave signal generated by pressure at the natural gas pipeline exit compared with the natural frequency ω_n (blue line).

2. Evaluation 2: Fast transient flow

Abbaspour and Chapman (2008) and Kiuchi (1994) propose as an evaluation model, the valve's opening and closure at the gas pipeline exit section. The valve opens after ten minutes, the mass flow increases from 0 to 80 kg/s and after twenty minutes in the same conditions, the valve completely closes. In figures 9 to 12, FVM agreed with FDM for mass flow and pressure, before and after opening but they disagreed after total closure for some minutes, both oscillated with the same frequencies, FVM showing bigger amplitude than FDM; this is

primarily due to that the alternative model considers the convective term in the iterative process, while the other model neglects this term. In the spectral analysis, after the exit valve is closed, both signals tend to a peak and coincide with the natural frequency, fact that indicates the presence of resonance in the gas pipeline. On the other hand, if FVM is compared with MC, both show differences, especially after total closure, although both models ended up converging in minutes. The oscillations differed in amplitudes and frequencies, the spectral analysis of MC showing a phase shift between the peak and the natural frequency.

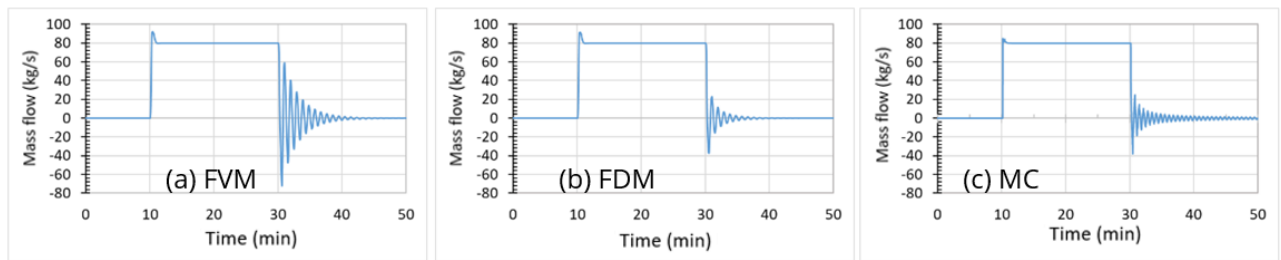


Figure 9. Mass flow calculated at the natural gas pipeline entry.

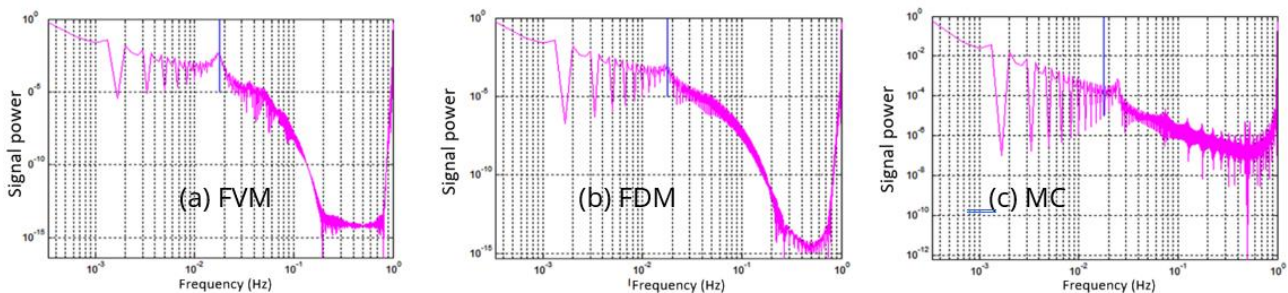


Figure 10. Spectral analysis for the wave signal generated by the mass flow at the natural gas pipeline entry compared with the natural frequency ω_n (blue line).

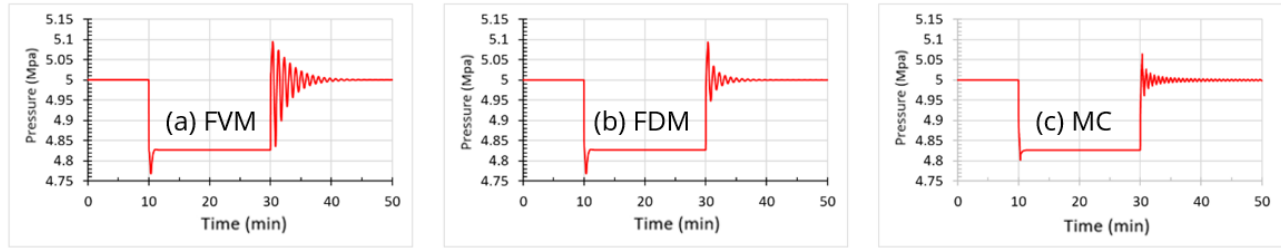


Figure 11. Calculated pressure at the natural gas pipeline exit.

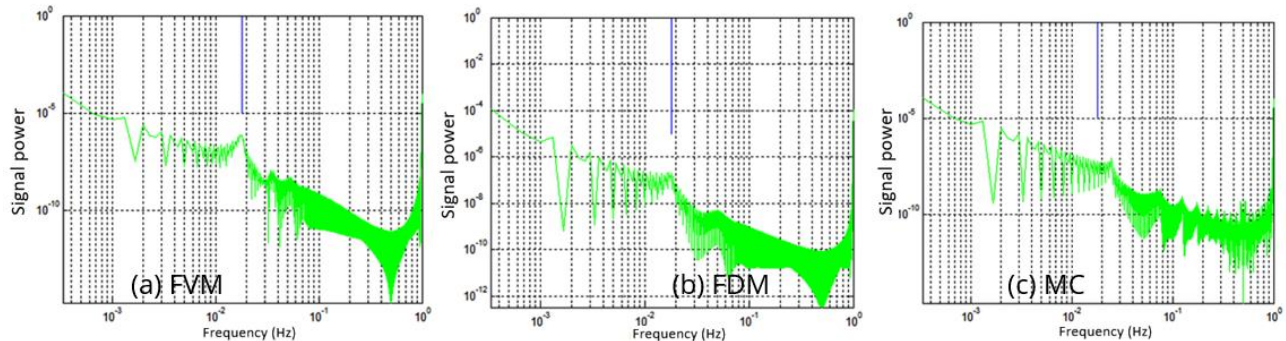


Figure 12. Spectral analysis of wave signal generated by pressure at the natural gas pipeline exit compared with the natural frequency ω_n (blue line).

Conclusions

The transient flow model based in FDM and FVM with two modalities: UW with SIMPLE and TVD-UMIST with PISO, subjected to transient flow problems for a wide range of space-time step sizes. Both resulted stable models and more tolerable to the CFL condition. The convective term of the momentum equation plays an important role in the gas flow calculation and it is not discarded for the FVM, because this term's effect is more significant when the flow rate decreases abruptly in the gas pipeline. Finally, taking as reference the previous exposition, the proposed model based on FVM turns out to be a reliable alternative for the calculation of isothermal flow in gas pipelines with an efficient response to slow and fast oscillations.

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Nomenclature

Source term of the system of equations to solve

\dot{m} Mass flow (kg/s)

A Cross section internal area of gas pipeline (m^2)

a Pressure-velocity coefficient of the system of equations to solve

b Source term of the system of equations to solve

C Specific heat ($J/kg-K$)

c Wave propagation velocity (m/s)

q Addition of heat per units of mass and time ($J/kg-s$)

R Gases Constant ($J/kg-K$)

r TVD Parameter

R^v Global residue of momentum equation

S Source term (Pa/m)

s Seconds

T Absolute temperature (K)

t Time (s)

v Flow velocity (m/s)

x Axial position (m)

y High (m)

Z Compressibility factor

D Gas pipeline intern diameter (m)

F Convective mass flow per unit area (kg/m^2-s)

f Darcy-Weisbach Friction Factor

g Gravity acceleration (m/s^2)

h Enthalpy (J/kg)

L Gas pipeline length (m)

N Maximum number of sections or control volumes of a gas pipeline

P Absolute pressure (Pa)

Greek Letters

α TVD Parameter

Δt Time step (s)

Δx Length of a section or volume control size (m)

μ Dynamic viscosity ($m^2/kg-s$)

ν Specific volume (m^3/kg)

ω_n Gas pipeline natural frequency (Hz)

ψ Flow limiting function under some TVD scheme

ρ Density (kg/m^3)

τ_0 Friction effort between the fluid and the pipeline (Pa)

θ Gas pipeline inclination angle (rad)