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Simulation of natural gas flow through a conventional gate valve

Julio Cézar de Almeida[1], Alexandre Pescador Sardá[2], Leomar Gomes Júnior[3]
[1]*Postgraduate Program in Numerical Methods, University Federal of Paraná*
[2]*Mechanical Engineering Department, University Federal of Paraná*
[3]*Postgraduate Program in Numerical Methods, University Federal of Paraná*
Corresponding Author: j.cezar@ufpr.br

ABSTRACT
The presence of valves that allow the gas flow to be interrupted in a natural gas distribution network is a common and necessary operational practice. Emergency situations and/or scheduled maintenance are common and the flow can only be blocked using these devices. However, when the flow is reestablished, there will be a very high variation in local velocity because of the existing area restriction and of the network's operating pressure. The main objective of this work is to present the mathematical formulation corresponding to the flow through gate valves. It is also worth mentioning the presentation of some numerical examples considering real operational data.

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I. INTRODUCTION

According to the Brazilian National Agency of Petroleum, Natural Gas and Biofuels, natural gas is any hydrocarbon that remains in a gaseous state under normal atmospheric conditions, normally extracted from oil and/or gas reservoirs, whose chemical composition may present wet, dry and residual gases. The natural gas value chain is composed of several segments, among which the following can be highlighted: a) exploration and production; b) treatment and/or processing; c) liquefaction (when applicable, in the context of converting natural gas from the gaseous state to the liquid state, facilitating its packaging and transportation); d) transportation; e) regasification (when applicable); f) distribution; g) marketing. This work is interested in and focuses on the activity corresponding to the distribution of natural gas.

Natural gas distribution networks transport much smaller volumes of natural gas at lower pressures, using pipes, usually made of carbon steel or HDPE, and with smaller diameters than a gas pipeline (transmission lines). These networks are responsible for serving end consumers and include, in addition to the pipes, a set of pipe accessories, among which intermediate gate valves stand out. These valves are devices that interrupt the flow of gas when closed and allow full passage when open. They are basic and common valves, and are generally opened and closed manually or remotely.

The present study aims to evaluate how natural gas flows from a conventional gate valve, starting from its abrupt opening, given that it operates, as highlighted above, in a fully open or fully closed condition. These valves are normally closed due to a maintenance condition in the network, imminent risk resulting from a disaster condition, as well as to serve a potential new customer, initially not existing in the vicinity of this network.

II. MATERIAL AND METHODS

To describe and demonstrate the fundamental principles that represent mathematical modeling along a natural gas transport pipeline, the concept of control volume is considered, which can be considered as an arbitrary volume in space through which the fluid flows. Thus, a section of pipeline subjected to a certain volumetric flow is considered, along which a differential element of length is considered and through which the variation of the following parameters is assumed: pressure, velocity, cross-sectional area, temperature and specific mass. This is schematically illustrated in Figure 1:

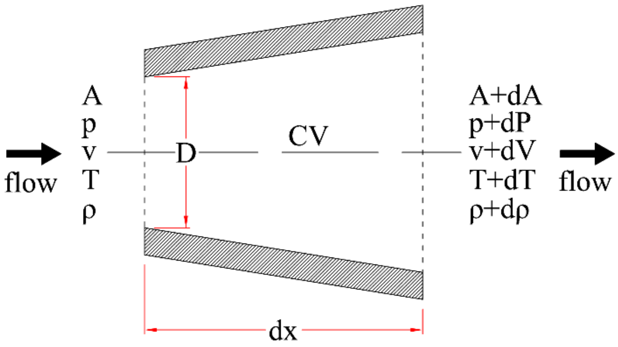

Figure 1: Control volume with variable area in a straight pipe section (Almeida et al., 2021).

From the principles of conservation of mass, conservation of momentum and conservation of energy, it becomes possible to demonstrate the following corresponding mathematical relationships (Almeida et al., 2013):

$$\frac{\partial \rho}{\partial t} + \mathrm{v}\frac{\partial \rho}{\partial x} + \rho\frac{\partial \mathrm{v}}{\partial x} + \rho \mathrm{v}\frac{1}{A}\frac{\partial A}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \mathrm{v}}{\partial t} + \mathrm{v}\frac{\partial \mathrm{v}}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + F_a = 0 \tag{2}$$

$$\frac{\partial u}{\partial t} + \mathrm{v}\frac{\partial u}{\partial x} - \frac{p}{\rho^2}\left(\frac{\partial \rho}{\partial t} + \mathrm{v}\frac{\partial \rho}{\partial x}\right) - (\dot{q} + F_a \mathrm{v}) = 0 \tag{3}$$

with: ρ = gas density
p = pressure
v = velocity
A = cross-sectional area of the duct
τ_W = shear stress
F_a = Darcy's friction force
x = coordinate measured along the axis of the duct
t = time
u = internal specific energy

The energy conservation equation presented above (equation 3) includes its derivatives in terms of the specific internal energy and the specific mass of the fluid. Alternatively, it can also be considered in terms of the entropy property. Therefore:

$$\left(\frac{\partial \rho}{\partial t} + \mathrm{v}\frac{\partial \rho}{\partial x}\right) = \frac{1}{c^2}\left(\frac{\partial p}{\partial t} + \mathrm{v}\frac{\partial p}{\partial x}\right) - \frac{\rho}{c^2}(k-1)(\dot{q} + \mathrm{v}F_a) \tag{4}$$

with: k = relationship between the specific heats of the fluid
c = speed of sound in fluid

III. GAS FLOW THROUGH A GATE VALVE

The simulation of the gas flow through the opening of a gate valve, normally located at specific points in the gas network, is sketched schematically, based on Figure 2, in which the indexes: 1 - corresponds to a point at which the fluid still occupies the entire cross-section of the pipeline; t (throat) - corresponding to a point where the cross-sectional area of the flow is minimal; out - represents the properties of the fluid outside the pipeline.

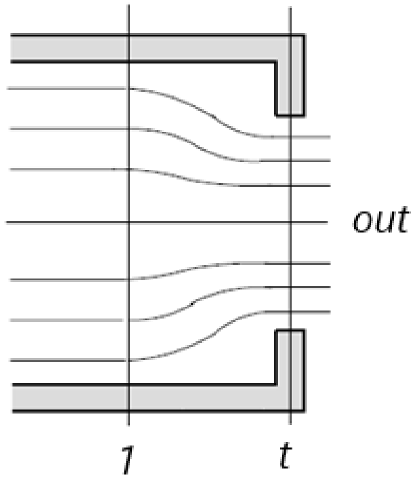

Figure 2: Schematic representation of flow through a valve (Almeida et al., 2013).

Assuming the premise of isentropic expansion between sections 1 and "t", as well as that the pressure at "t" is equal to the external pressure, it can be considered that the effects of friction and heat transfer are negligible (quasi-steady flow). Under these circumstances, equations (1) and (2) can be written in a simplified form, since the derivatives with respect to time become zero. Therefore:

$$\frac{\partial(\rho v A)}{\partial x} = 0 \tag{5}$$

$$\mathrm{v}\frac{\partial \mathrm{v}}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0 \tag{6}$$

Applying these same simplifications to equations (3) and (4):

$$\mathrm{v}\frac{\partial u}{\partial x} - \frac{p}{\rho^2}\left(\mathrm{v}\frac{\partial \rho}{\partial x}\right) = 0 \tag{7}$$

$$\left(\mathrm{v}\frac{\partial \rho}{\partial x}\right) = \frac{1}{c^2}\left(\mathrm{v}\frac{\partial p}{\partial x}\right) \Rightarrow \frac{dp}{dx} = c^2\frac{d\rho}{dx} \tag{8}$$

Since $c^2 = kp/\rho$, it becomes possible to consider (after applying the logarithm function):

$$2\,ln(c) = ln(k) + ln(p) - ln(\rho) \tag{9}$$

Whose differentiation in relation to the "x" coordinate results in:

$$\frac{2}{c}\frac{dc}{dx} = \frac{1}{p}\frac{dp}{dx} - \frac{1}{\rho}\frac{d\rho}{dx} \tag{10}$$

The combination of equations (5) to (10), with the corresponding integration between points 1 and "t", finally allows us to conclude:

$$\left(\frac{c_1}{c_t}\right)^2 = \left(\frac{\rho_1}{\rho_t}\right)^{k-1} = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \tag{11}$$

and:

$$c_1{}^2 + \frac{k-1}{2}\mathrm{v}_1{}^2 = c_t{}^2 + \frac{k-1}{2}\mathrm{v}_t{}^2 \tag{12}$$

or, ($\psi = A_t/A_1$) represents the relationship between the flow areas:

$$\mathrm{v}_t = \frac{1}{\Psi}\left(\frac{c_1}{c_t}\right)^{\frac{2}{k-1}}\mathrm{v}_1 \tag{13}$$

IV. SUPERSONIC FLOW CONDITION IN VALVE THROAT SECTION

The supersonic flow condition in the valve throat section is reached now when: $c_t = v_t$. Imposing this condition on equation (13):

$$c_t = \frac{1}{\Psi}\left(\frac{c_1}{c_t}\right)^{\frac{2}{k-1}}\mathrm{v}_1 \tag{14}$$

or even, after dividing the latter equation by c_1:

$$\frac{\mathrm{v}_1}{c_1} = \Psi\left(\frac{c_t}{c_1}\right)^{\frac{k+1}{k-1}} \tag{15}$$

Finally, replacing the relationship between areas in the previous equations, after the necessary adjustments, allows us to obtain:

$$\Psi^2 = \left(\frac{k+1}{k-1} - \frac{2}{k-1}\left(\frac{c_1}{c_t}\right)^2\right)\left(\frac{c_1}{c_t}\right)^{\frac{4}{k-1}} \tag{16}$$

V. NATURAL GAS - PROPERTIES

The main component of natural gas is methane, which reaches levels above 70% of the composition. Heavier hydrocarbons, such as ethane, propane and butane, and small percentages of other constituents, such as nitrogen and carbon dioxide, complete the composition. In general, however, the composition of natural gas can vary widely, depending on the parameters of the production, conditioning, processing, and transportation process. In Brazil, the specification of natural gas for commercialization and transportation is defined in Resolution No. 16, of June 17, 2008, proposed by the ANP (National Petroleum Agency). The properties of the natural gas mixture are required as input variables for the corresponding mathematical equations. Table 1 shows the properties of the main pure substances that are most frequently used to characterize a given gas sample (Almeida et al., 2013).

Component	M [kg/kmol]	T_c [K]	p_c [MPa]	c_p [J/kg.K]	c_v [J/kg.K]
CH_4	16.043	190.6	4.596	2253.3	1735.1
C_2H_6	30.069	305.4	4.883	1754.3	1477.8
C_3H_8	44.096	369.8	4.250	1672.9	1484.4
n-C_4H_{10}	58.123	425.2	3.796	1708.9	1565.9
i-C_4H_{10}	58.123	408.2	3.648	1673.5	1530.5
n-C_5H_{12}	72.151	469.7	3.370	1649.1	1533.9
i-C_5H_{12}	72.151	460.4	3.380	1645.0	1529.8
n-C_6H_{14}	86.178	507.5	3.010	1673.1	1576.6
N_2	28.013	126.3	3.400	1037.5	740.71
O_2	32.050	154.8	5.043	917.00	657.59
CO_2	44.010	304.2	7.382	869.34	680.43

Table 1: The chemical composition and other properties of natural gas (Almeida et al., 2013).

For a typical composition of a given natural gas, calculations corresponding to its main properties were performed based on the individual data in Table 1. This condition allowed the sequence of calculations corresponding to the case studies presented.

Chemical composition of natural gas analyzed:
CH4: 89.01
C2H6: 5.93
C3H8: 1.85
nC4H10: 0.42
iC4H10: 0.31
nC5H12: 0.11
iC5H12: 0.08
nC6H14: 0.08
O2: 0
N2: 0.67
CO2: 1.57
********PARTIAL RESULTS - PROPERTIES OF NATURAL GAS********
molecular weight: 18.3877 kg/kmol
density: 0.63485
constant gas: 452.1498 J/kg K
critical temperature: 204.569 K
critical pressure:4.633 8MPa
specific heat at constant pressure: 2178.1013 J/kmol K
specific heat at constant volume: 1724.6467 J/kmol K

VI. CASE STUDIES

Three case studies are presented, aiming to calculate the flow velocity at the outlet of previously closed gate valves. It was decided to consider residential/commercial distribution networks, which operate at low pressures, normally defined as 4 bar (HDPE PE80) or 7 bar (HDPE PE100). For all cases, room temperature is considered: 20ºC.

<u>Example 01</u>: HDPE network, with nominal diameter 63 mm, working at an operating pressure of 3 bar (= 300000 Pa), with a flow speed of 10 m/s (ψ = 0,70).

$$k = \frac{c_P}{c_V} = \frac{2178,10}{1274,65} = 1,708$$

$$\frac{p_1}{\rho_1} = RT_1 \Rightarrow \frac{300000}{\rho_1} = 452,15(293) \Rightarrow \rho_1 = 2,264\ kg/m^3$$

$$\left(\frac{\rho_1}{\rho_t}\right)^{k-1} = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{2,264}{\rho_t}\right)^{0,708} = \left(\frac{3}{1,01325}\right)^{\frac{0,708}{1,708}} \Rightarrow \rho_t = 1,20\ kg/m^3$$

$$c_t = \sqrt{\frac{kp_t}{\rho_t}} = \sqrt{\frac{1,708(1,01325.10^5)}{1,20}} = 379,76\ m/s$$

$$\left(\frac{c_1}{c_t}\right)^2 = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{c_1}{379,76}\right)^2 = \left(\frac{3}{1,01325}\right)^{\frac{0,708}{1,708}} \Rightarrow c_1 = 475,57\ m/s$$

$$\mathrm{v}_t = \frac{1}{\Psi}\left(\frac{c_1}{c_t}\right)^{\frac{2}{k-1}} \mathrm{v}_1 = \frac{1}{0,70}\left(\frac{475,57}{379,76}\right)^{\frac{2}{0,708}}(10) = 26,97\ m/s$$

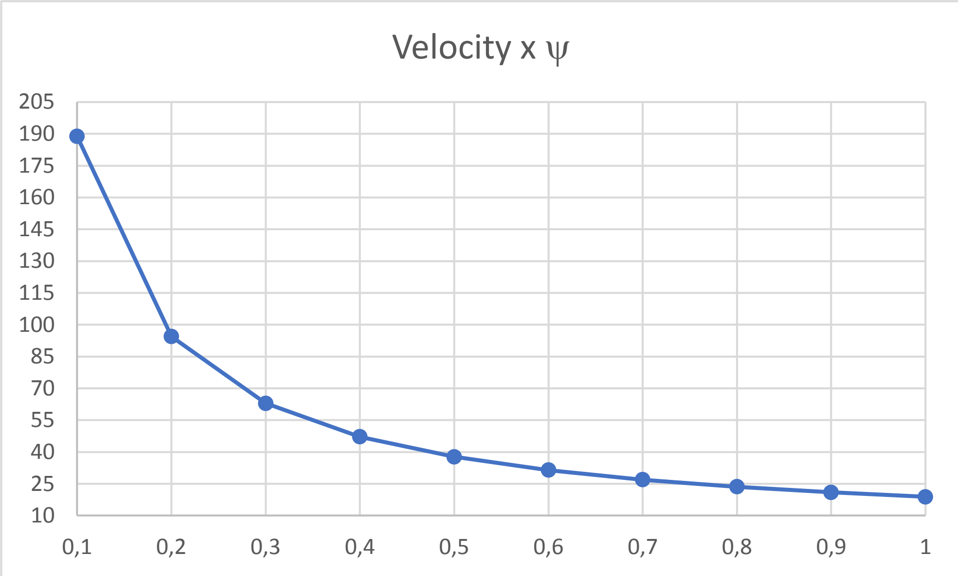

Figure 3: Valve outlet speed variation x area factor - Example 01.

<u>Example 02</u>: HDPE network, with nominal diameter 160 mm, working at an operating pressure of 6.6 bar (= 660000 Pa), with a flow speed of 18 m/s (ψ = 0,70).

$$k = \frac{c_P}{c_V} = \frac{2178,10}{1274,65} = 1,708$$

$$\frac{p_1}{\rho_1} = RT_1 \Rightarrow \frac{660000}{\rho_1} = 452,15(293) \Rightarrow \rho_1 = 4,982\ kg/m^3$$

$$\left(\frac{\rho_1}{\rho_t}\right)^{k-1} = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{4,982}{\rho_t}\right)^{0,708} = \left(\frac{6,6}{1,01325}\right)^{\frac{0,708}{1,708}} \Rightarrow \rho_t = 1,663\ kg/m^3$$

$$c_t = \sqrt{\frac{kp_t}{\rho_t}} = \sqrt{\frac{1,708(1,01325.10^5)}{1,663}} = 322,58\ m/s$$

$$\left(\frac{c_1}{c_t}\right)^2 = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{c_1}{322,58}\right)^2 = \left(\frac{6,6}{1,01325}\right)^{\frac{0,708}{1,708}} \Rightarrow c_1 = 475,67\ m/s$$

$$\mathrm{v}_t = \frac{1}{\Psi}\left(\frac{c_1}{c_t}\right)^{\frac{2}{k-1}} \mathrm{v}_1 = \frac{1}{0,70}\left(\frac{475,67}{322,58}\right)^{\frac{2}{0,708}} (18) = 77,03\ m/s$$

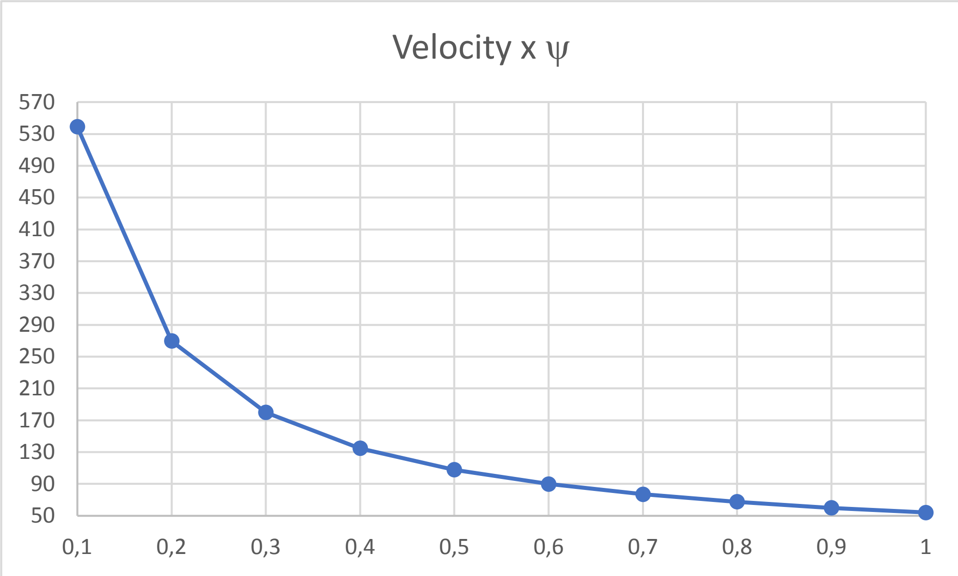

Figure 4: Valve outlet speed variation x area factor - Example 02.

<u>Example 03</u>: HDPE network, with nominal diameter 110 mm, working at an operating pressure of 5.5 bar (= 550000 Pa), with a flow speed of 6 m/s (ψ = 0,50).

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$$k = \frac{c_P}{c_V} = \frac{2178{,}10}{1274{,}65} = 1{,}708$$

$$\frac{p_1}{\rho_1} = RT_1 \Rightarrow \frac{550000}{\rho_1} = 452{,}15(293) \Rightarrow \rho_1 = 4{,}152\ kg/m^3$$

$$\left(\frac{\rho_1}{\rho_t}\right)^{k-1} = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{4{,}152}{\rho_t}\right)^{0{,}708} = \left(\frac{5{,}5}{1{,}01325}\right)^{\frac{0{,}708}{1{,}708}} \Rightarrow \rho_t = 1{,}542\ kg/m^3$$

$$c_t = \sqrt{\frac{kp_t}{\rho_t}} = \sqrt{\frac{1{,}708(1{,}01325.10^5)}{1{,}542}} = 335{,}01\ m/s$$

$$\left(\frac{c_1}{c_t}\right)^2 = \left(\frac{p_1}{p_t}\right)^{\frac{k-1}{k}} \Rightarrow \left(\frac{c_1}{335{,}01}\right)^2 = \left(\frac{5{,}5}{1{,}01325}\right)^{\frac{0{,}708}{1{,}708}} \Rightarrow c_1 = 475{,}68\ m/s$$

$$\mathrm{v}_t = \frac{1}{\Psi}\left(\frac{c_1}{c_t}\right)^{\frac{2}{k-1}} \mathrm{v}_1 = \frac{1}{0{,}50}\left(\frac{475{,}68}{335{,}01}\right)^{\frac{2}{0{,}708}} (6) = 32{,}31\ m/s$$

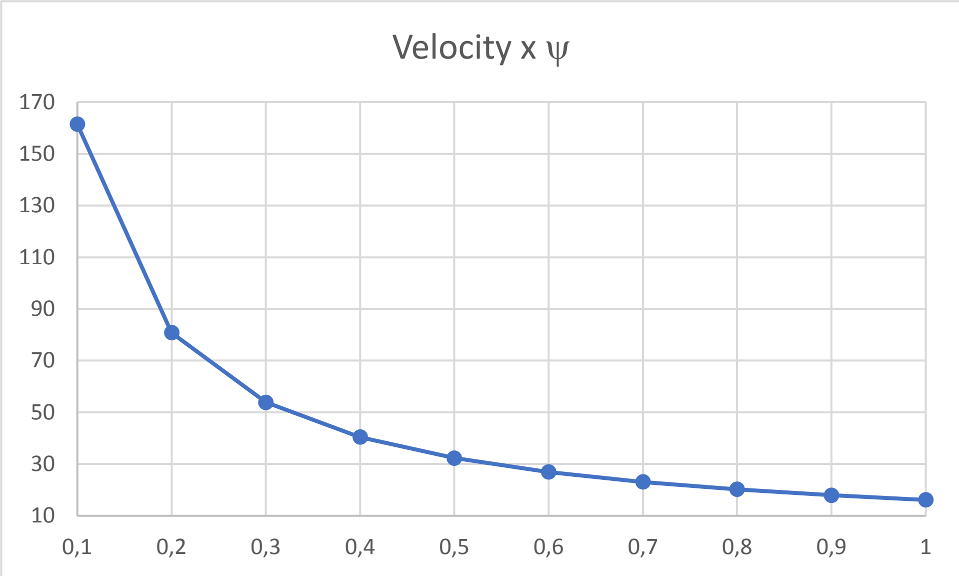

Figure 5: Valve outlet speed variation x area factor - Example 03.

VII. DISCUSSION AND CONCLUSION

The mathematical formulation of flow in natural gas distribution networks corresponds to a well-known and established practice. This same formulation for accessories such as valves, tees and derivations, however, requires a complementary and more detailed analysis.

This article provides a specific analysis for the case of gate valves, identifying the mathematical equations, boundary conditions and corresponding numerical examples. The results obtained clearly demonstrate the variations in flow that occur in these devices based on the operating pressure of the network and, mainly, the restriction of localized flow (valve throat).

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