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Natural Gas Flow Through Pipelines – A Review

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ABSTRACT
The design and sizing of natural gas distribution and transmission pipelines includes, among other aspects, the definition of the most appropriate diameter for the pipe, which must take into account the required hourly flow rate, the assumptions of future demands and, of course, the installation costs. and operation.
The present work briefly reviews the general flow equation, correlating the flow parameters, commercial diameters and transmission factor, which is a direct function of the type of existing flow regime and the corresponding friction coefficient involved.

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I. INTRODUCTION

The deduction of the general flow equation for compressible fluids along pipelines, considering the steady-state condition (the properties of the fluid may vary in space, but are supposedly constant in time), is a recurring subject and enshrined in reference bibliographies on the theme. A good example of this nature can be identified in Mohitpour et al. (2000). This work proposes to evaluate the variation of parameters of the general flow equation, in the context of their respective influences on the type of flow regime evidenced in carbon steel, HDPE and polyamide pipes - materials that are established and accepted in transport pipelines and distribution of this nature.

Consider, therefore, Figure 1, which contemplates the concept of control volume (arbitrary volume in the space through which the fluid flows). In this small section of pipe, a differential length element is assumed through which the following parameters vary: pressure, speed, cross-sectional area, temperature, and specific mass. The fundamental equations of the of conservation of mass, conservation of momentum and conservation of energy are evidently covered throughout this analysis.

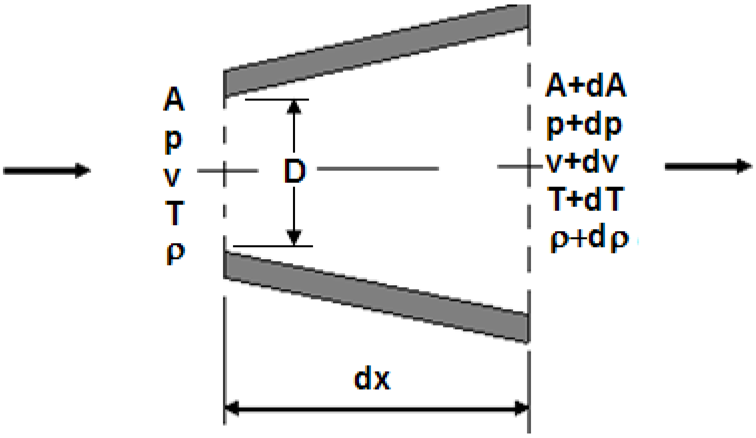

Figure 1: Control volume with variable area in a straight section of pipe, (Almeida, 2013)

II. GENERAL FLOW EQUATION FOR COMPRESSIBLE FLUIDS

Prioritizing the use of units belonging to the international system (SI), the following mathematical relationship can be demonstrated:

$$Q = \pi \sqrt{\frac{R}{464}} \frac{zT}{P} \left[\frac{\left({P_1}^2 - {P_2}^2 \right) - \frac{58 d {P_{ave}}^2 g}{R T_{ave} z_{ave}}}{L d T_{ave} z_{ave}} \right]^{1/2} \frac{D^{2,5}}{\sqrt{f}} \eta \tag{1}$$

where: Q = volumetric flow rate under reference conditions [m^3/s];
R = universal constant of perfect gases = 8314.41 [J/kmol.K];
z = gas compressibility factor under reference conditions (≅ 1);
T = gas temperature under reference conditions = 288,15 [K];
P = gas pressure under reference conditions = $1.01325.10^5$ [Pa];
P_1 = absolute gas pressure at the duct inlet [Pa];
P_2 = absolute gas pressure at the duct outlet [Pa];
d = relative density of gas;
P_{ave} = average gas flow pressure [Pa];
g = acceleration of gravity = 9.81 [m/s^2];
T_{ave} = average gas flow temperature [K];
z_{ave} = gas compressibility factor;
L = duct length - between reference points 1 and 2 [m];
$1/(f)^{1/2}$ = transmission factor;
f = Darcy coefficient of friction;
D = inner diameter of the duct [m];
η = efficiency factor (≅ 0.90).

According to Osiadacz (1987), the real volumetric flow is normally lower than that calculated by general flow equation because of friction generated in curves, accessories, impurities and even corrosion. To compensate for this condition, it is common to multiply the general flow equation by the efficiency factor, which normally varies between 0.8 and 1.

III. FLOW SCHEMES

The determination of the transmission factor directly depends on the flow regime in which gas transport occurs in pipelines. In gas transmission lines, operating at high pressures and moderate or elevated flow rates, one of two types of turbulent flow is observed: (a) entirely turbulent flow (flow in rough tubes), (b) partially turbulent flow (flow in hydraulically smooth tubes).

The flow regime, whether laminar or turbulent, is conventionally defined by the Reynolds number (Re) in the form:

$$Re = \frac{\rho v D}{\mu} \tag{2}$$

where: ρ = specific mass of gas [kg/m^3];
v = average fluid speed [m/s];
μ = fluid dynamic viscosity [Pa.s].

Mohitpour et al. (2000), presents, through intermediate mathematical simplifications and average values for some properties of natural gas, the following alternative equation for calculating the Reynolds number:

$$Re = 40.32 \frac{Qd}{D} \tag{3}$$

This last equation, although simplified, allows us to calculate the Reynolds number with reasonable precision. It is proven that Reynolds is practically constant along the duct, except for a significant variation in fluid viscosity. For Reynolds numbers below 2300 the flow is considered laminar. When the number of Reynolds is greater than 2300, the flow is considered turbulent and in this case, it can be characterized as being partially or completely turbulent. Between these two regimes there is still a third condition that represents the transition between the previous two, but most existing equations for the calculation of the transmission factor does not consider this condition.

Partial Flow Regimes and Totally Turbulent

In partially turbulent flow, the thickness of the laminar sublayer is greater than the roughness of the tube wall. For everyone effects are as if there were turbulent flow in a smooth duct. Therefore, the pressure loss is, in this case, independent of the roughness of the tube (Munson et al, 1998). The coefficient of friction, in this (sub)regime and for natural gas is normally calculated using the semi-empirical Prantl - von Kármán equation:

$$\frac{1}{\sqrt{f}} = -2\log(\frac{2.825}{Re\sqrt{f}}) \tag{4}$$

In a complementary way, the transmission factor for fully turbulent flow it is given by:

$$\frac{1}{\sqrt{f}} = -2\log(\frac{\varepsilon/D}{3.7}) \tag{5}$$

where ε is the absolute roughness of the duct and the relationship ε/D corresponds to the relative roughness. Reference bibliographies present characteristic roughness values of the main materials used in the construction of natural gas distribution and transmission networks. For the present work, roughness values of 0.007 mm for HDPE pipes and 0.0191 mm for carbon steel pipes are proposed.

Relative Density of Gas

The values to be considered for the relative density of the gas must be defined based on its most likely chemical composition. The relative density of the gas can be obtained, in this way, from the relationship between the molecular weight (MW) of the gas and the molecular weight of the air (28.9625 kg/kmol, in this case), whose mathematical expression corresponds to:

$$d = \frac{MW}{28.9625} \tag{6}$$

The molecular weight of the gas must be obtained from the molar fractions of its partial components, which must also be multiplied by their respective molar fractions. For the present work, however, an approximate value of 0.60 is considered for the relative density of gas.

Average Pressure and Average Gas Flow Temperature

The general flow equation includes portions corresponding to the average flow pressure and the average flow temperature, between two distinct reference points of the duct (1 and 2, in this case). In practice, however, it is proven that under normal flow conditions and considering the depths conventionally adopted for distribution and transmission ducts, the average temperature of the gas flow is equivalent to the local ambient temperature (adopted as 20^{o} C, in the present work).

For the case of average pressure, the following complementary equation is considered:

$$P_{ave} = \frac{2}{3}\left(P_1 + P_2 - \frac{P_1P_2}{P_1+P_2}\right) \tag{7}$$

IV. TRANSMISSION FACTORS FOR COMMERCIAL HDPE PIPELINES

Specifically for the case of HDPE pipes, used in the distribution of natural gas, there are standardized commercial external diameters (in mm), as well as relationships that allow the corresponding internal diameters to be identified. For the present work, is propose the definition of numerical values to the transmission factors corresponding to a predominant range of commercial diameters used in distribution networks of this nature. These values are compiled in Table 1.

Table 1: Transmission factors for commercial HDPE pipelines

Nominal outer diameter of the pipe [mm]	Duct wall thickness [mm]	Pipe inner diameter [mm]	Transmission factor
125	11.4	102.2	9.465
140	12.7	114.6	9.564
160	14.6	130.8	9.679
180	16.4	147.2	9.782
200	18.2	163.6	9.874
225	20.5	184.0	9.976

250	22.7	204.6	10.068

V. CASE STUDIE

Returning to equation (1) with the inclusion of pre-defined values for some of the parameters:

$$Q = \pi\sqrt{\frac{8314.41}{464}}\frac{288.15}{1.01325.10^5}\left[\frac{\left(P_1{}^2-P_2{}^2\right)-\frac{58(0.6)P_{ave}{}^2(9.81)}{8314.41(283.15)}\Big)}{L(0.6)283.15}\right]^{\frac{1}{2}}\frac{D^{2,5}}{\sqrt{f}}(0.9)$$

$$Q = 0.034\left[\frac{\left(P_1{}^2-P_2{}^2\right)-1.45.10^{-4}P_{ave}{}^2\Big)}{169.89L}\right]^{\frac{1}{2}}D^{2,5}\frac{1}{\sqrt{f}} \tag{8}$$

Also, assuming a mesh with a length of 2 km (2000 m), contemplating a pressure variation of 7 bar ($0.7.10^5$ Pa) to 5.5 bar ($0.55.10^5$ Pa), it becomes possible obtain for the range of diameters previously proposed:

$$P_{ave} = \frac{2}{3}\left(0.7+0.55-\frac{0.7(0.55)}{0.7+0.55}\right) = 0.628.10^5\ Pa \tag{9}$$

$$Q = 0.034\left[\frac{\left((0.7.10^5)^2-(0.55.10^5)^2\right)-1.45.10^{-4}\left(0.628.10^5\right)^2\Big)}{169.89(2000)}\right]^{\frac{1}{2}}D^{2,5}\frac{1}{\sqrt{f}}$$

$$Q = 2.485D^{2,5}\frac{1}{\sqrt{f}} \tag{10}$$

Table 2: Flow x Transmission factors

Nominal outer diameter of the pipe [mm]	**Pipe inner diameter [mm]**	**Transmission factor**	**Flow (m^3/s)**	**Flow (m^3/h)**
125	102.2	9.465	0.079	282.69
140	114.6	9.564	0.106	380.35
160	130.8	9.679	0.149	535.70
180	147.2	9.782	0.202	727.37
200	163.6	9.874	0.266	956.08
225	184.0	9.976	0.360	1295.83
250	204.6	10.068	0.474	1705.15

VI. DISCUSSION AND CONCLUSION

A comparative analysis of the increase in flow rate with the corresponding increase in pipe diameter demonstrates that for each new commercial diameter considered, there is an increase in flow rate that varies between 30 and 39% (for every two subsequent diameter ranges). On the other hand, a comparative analysis between the transmission factor (friction) and the variation in commercial diameters, demonstrates a practically constant variation in the order of 1% for every two subsequent diameters.

In view of the above, it can be considered that the effect of the transmission factor is practically insignificant when defining the diameter of the pipe to be considered. On the contrary, the diameter of the tube makes a very significant difference in the flow rate.

Therefore, the final definition of the diameter will be directly related to the material and labor costs to be considered in each project.

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