Volume of natural gas released into the atmosphere in leakage situations - Review and analysis

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Abstract — The natural gas leakage rate plays an important factor in simulating leaks in gas transportation and distribution pipelines. The method for leakage rate calculation involves identifying the geometry and type of leak opening, associated with the application of the theories of thermodynamics and gas dynamics, as well as energy conservation equations. In this article, a review and analysis of the flow of gas released into the atmosphere in cases of accidents of this nature is carried out. Such a situation is critical, given that certain leaks can create very extensive danger zones around the immediate vicinity of the leak point.

I. INTRODUCTION

Natural gas as a source of clean and high-quality energy has enormous potential for use as a type of energy resource. With the development of the natural gas industry and the establishment of the gas pipelines and distribution networks, situations of possible leaks have been shown to be a major problem in economic matters and, mainly, in safety. Any leaks in natural gas pipelines will certainly cause contamination and environmental pollution problems. Threats become even more serious when natural gas and air mix in explosive concentrations, which may cause fires and even explosions.

The study of leaks in distribution networks and natural gas pipelines depends directly on the rate of leakage that has occurred, which will be the basis for studying the diffusion of gas and for predicting the consequences of the accident. In this line, it is possible to highlight the work of Montiel (1998), in which he proposed the study of models of holes with large dimensions, from holes of small dimensions. Zou et al. (2008) analyzed the thermal process of emission from a natural gas reservoir, establishing a corresponding mathematical model. Azman et al. (2011) a leak model established for the completely ruptured pipes, analyzing the corresponding pressure drop along the pipeline.

Hou et al. (2011) proposed the use of the FLUENT software, which corresponds to a computer simulation software in the area of fluid dynamics, aiming to simulate the diffusion of natural gas in the atmosphere as a result of leaks.

The process of leakage and diffusion of natural gas into the atmosphere characterizes the condition of a diffuse accident, with no reliable basis for an effective solution. In this context, the initial forecast of the volume of gas released into the atmosphere, after the occurrence of the leak, would allow initial actions to quantify the incident and, consequently, take appropriate actions to reduce risks and losses.

II.   THE NATURAL GAS LEAKAGE RATE IN PIPELINES AND DISTRIBUTION NETWORKS

European Pipeline Incident Data Group (EGIG) classifies pipeline leaks into three distinct groups: a) leaks occurring from small holes (leak hole diameter less than 20 mm); b) leaks occurring from holes with large dimensions (hole diameter greater than 20 mm, but smaller than the pipe diameter); c) complete rupture of the pipeline.

2.1 – Leaks occurring from small holes - for the present case, the following simplifying assumptions are assumed: (a) the flow is isentropic at the gas release point and adiabatic in the pipeline; (b) the flow model is essentially 1D; (c) the pipeline can be regarded as non-deformable and the interaction between the fluid and the pipeline due to vibration problems is negligible. From the differential equation of Euler kinematics, the adiabatic equation and the equation of an ideal gas, we have:
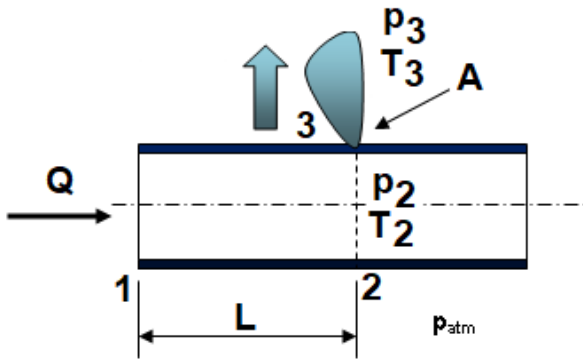

Fig. 1: Schematic of possible leakage

$$u_3 = \sqrt{\frac{2k}{k-1}\frac{ZRT_2}{M}\left[1-\left(\frac{p_3}{p_2}\right)^{\frac{k-1}{k}}\right]} \qquad (1)$$

valid, from the condition: $u_2 \ll u_3$.

Replacing Eq. (1) in the leakage mass flow equation, we can get the leakage rate:

$$Q = C_o p_2\, A \sqrt{\frac{2k}{k-1}\frac{M}{ZRT_2}\left[\left(\frac{p_3}{p_2}\right)^{\frac{2}{k}}-\left(\frac{p_3}{p_2}\right)^{\frac{k+1}{k}}\right]} \qquad (2)$$

The classification of the flow at the leakage point as sonic or subsonic can also be performed by comparing it with the so-called critical pressure ratio (CPR) given by:

$$CPR = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \qquad (3)$$

given: Q = mass flow [kg/s];

A = hole area [m^2];

M = molecular weight [kg.kmol^{-1}];

p = gas pressure [Pa];

p_{atm} = atmospheric pressure [Pa];

T = gas temperature [K];

Z = gas compressibility factor;

u = gas velocity [m/s];

C_o = discharge coefficient ($\cong 0.72$);

k = specific heat ratio;

R = 8314 = universal gas constant [J.kmol^{-1}.K^{-1}].

The ratio ($p_{atm}/p_2 >$ CPR) corresponds to a subsonic flow while the ratio ($p_{atm}/p_2 \leq$ CPR) corresponds to a sonic flow. For the sonic flow condition, equation (3) can be written in the following simplified form:

$$Q = C_o p_2\, A \sqrt{\frac{Mk}{ZRT_2}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \qquad (4)$$

and, for subsonic flow:

$$Q = C_o p_2 A \sqrt{\frac{2k}{k-1}\frac{M}{ZRT_2}\left[\left(\frac{p_{atm}}{p_2}\right)^{\frac{2}{k}}-\left(\frac{p_{atm}}{p_2}\right)^{\frac{k+1}{k}}\right]} \qquad (5)$$

2.2 – Leaks occurring from large holes - in these circumstances it becomes necessary to evaluate the flow conditions existing in the hole and in the pipeline.

2.2.1 - Subsonic flow in the tube and sonic flow in the hole - if confirmed, the following conditions:

$$\left(\frac{p_{atm}}{p_2}\right) < CPR$$

$$p_2 > p_1 Ma_1 \sqrt{\frac{2+(k-1)Ma_1^2}{k+1}} \qquad (6)$$

Eq.(4) prevails for calculating the rate of gas released into the atmosphere.

Ma corresponds to the Mach number, whose value translates a ratio between the relative speed of the gas and the speed of sound in this medium. Your expression is:

$$Ma = \frac{u}{\sqrt{\frac{kRT}{M}}} \qquad (7)$$

2.2.2 - Subsonic flow in the pipe and at the hole – now if confirmed, the following conditions:

$$\left(\frac{p_{atm}}{p_2}\right) \geq CPR$$

$$p_2 > p_1 Ma_1 \sqrt{\frac{2+(k-1)Ma_1^2}{k+1}} \qquad (8)$$

Eq.(5) prevails for calculating the rate of gas released into the atmosphere.

2.3 – Leaks that occur in the complete rupture of the pipeline - when the pipeline is completely ruptured, the mass flow rate of the natural gas pipeline:

$$Q = C_o p_2 A \sqrt{\frac{2M}{ZR}\frac{k}{k-1}\left[\frac{T_2 - T_1}{\left(\frac{T_1}{p_1}\right)^2 - \left(\frac{T_2}{p_2}\right)^2}\right]} \qquad (9)$$

III. PROPERTIES OF NATURAL GAS

Considering a typical chemical composition for natural gas - natural gas distributed by PETROBRAS in southern Brazil - we have:

Table.1: Natural Gas – Typical composition chemical

Components	Molar fraction (%)	Molar mass (kg/kmol)	p_c (MPa)	T_c (K)
CH_4	0.8901	16.043	4.596	190.6
C_2H_6	0.0593	30.069	4.883	305.4
C_3H_8	0.0185	44.096	4.250	369.8
n-C_4H_{10}	0.0042	58.123	3.796	425.2
i-C_4H_{10}	0.0031	58.123	3.648	408.2
n-C_5H_{12}	0.0011	72.151	3.370	469.70
i-C_5H_{12}	0.0008	72.151	3.380	460.4
n-C_6H_{14}	0.0008	86.178	3.010	507.5
N_2	0.0067	28.013	3.400	126.3
CO_2	0.0154	44.010	7.382	304.2
Natural Gas	1.0000	18.374	4.632	204.48

Table.2: Natural Gas – Specific heats [J/kg.K]

Components	Molar fraction (%)	C_p	C_v
CH_4	0.8901	2253.3	1735.1
C_2H_6	0.0593	1754.3	1477.8
C_3H_8	0.0185	1672.9	1484.4
n-C_4H_{10}	0.0042	1708.9	1565.9
i-C_4H_{10}	0.0031	1673.5	1530.5
n-C_5H_{12}	0.0011	1649.1	1533.9
i-C_5H_{12}	0.0008	1645.0	1529.8
n-C_6H_{14}	0.0008	1673.1	1576.6
N_2	0.0067	1037.5	740.71
CO_2	0.0154	869.34	680.43
Natural Gas	1.0000	2096.0	1643.6

$$k = \frac{C_p}{C_V} = \frac{2096}{1643.6} = 1,275 \qquad (10)$$

$$Z \cong 1,00 \qquad (11)$$

IV. LEAKS - CASE STUDY

4.1 – Leaks occurring from small holes – Case study

A section of carbon steel pipe with a diameter of 8 in ($\cong$ 203.2 mm) is also considered, transporting natural gas at a pressure p_1 = 35 bar = 3.5 MPa, being subjected to a leak located at a point (L) where the pressure p_2 = 27 bar = 2.7 MPa. For a supposedly constant gas flow temperature of 25°C, we have (p_{atm} = 1 bar = 0.1 MPa):

$$CPR = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{2.275}\right)^{\frac{1.275}{0.275}} = 0.55$$

$$\frac{p_{atm}}{p_2} = \frac{0.1}{2.7} = 0.038$$

$$\left(\frac{p_{atm}}{p_2}\right) < CPR - sonic\ flow$$

$$Q = C_o p_2\ A \sqrt{\frac{Mk}{ZRT_2}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

$$Q = (0.72)(2.7)\ A \sqrt{\frac{(18.374)1.275}{(1)8314(298.15)}\left(\frac{2}{2.275}\right)^{\frac{2.275}{0.275}}}$$

$$Q = \left(3.50(10^{-3})\right)A = \left(2.75(10^{-3})\right)d^2$$

Assuming holes varying between 2 and 20 mm (small holes), the values are obtained:

Table.3: Hole diameters x flow of gas released into the atmosphere

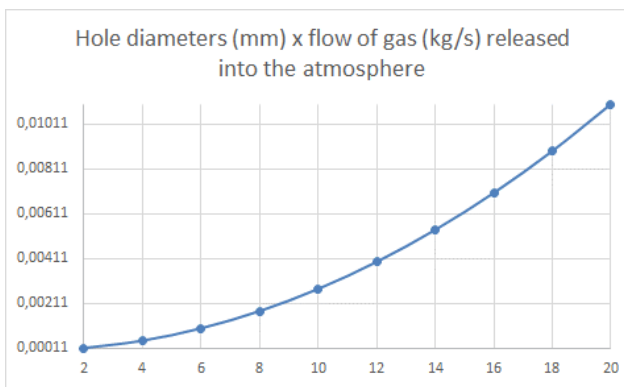| Hole diameters (mm)	Leakage mass flow (kg/s)
2	1.10×10^{-9}
4	4.40×10^{-8}
6	9.90×10^{-8}
8	1.76×10^{-7}
10	2.75×10^{-7}
12	3.96×10^{-7}
14	5.39×10^{-7}
16	7.04×10^{-7}
18	8.91×10^{-7}
20	1.10×10^{-6}

Fig. 2: Hole diameters x flow of gas released into the atmosphere

4.2 – Leaks occurring from large holes – Case study

Keeping the same flow assumptions defined in the previous item and a velocity $u_1 = 20$ m/s, we have:

$$CPR = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} = \left(\frac{2}{2.275}\right)^{\frac{1.275}{0.275}} = 0.55$$

$$\frac{p_{atm}}{p_2} = \frac{0.1}{2.7} = 0.038$$

$$\left(\frac{p_{atm}}{p_2}\right) < CPR$$

$$Ma_1 = \frac{u_1}{\sqrt{\frac{kRT_1}{M}}} = \frac{20}{\sqrt{\frac{1.275(8314)298.15}{18.374}}} = 0.048$$

$$p_2 > p_1 Ma_1 \sqrt{\frac{2 + (k-1)Ma_1{}^2}{k+1}}$$

$$p_2 > 3.5(0.048) \sqrt{\frac{2 + (0.275)0.048^2}{2.275}} - OK!$$

Thus:

$$Q = C_o p_2 A \sqrt{\frac{Mk}{ZRT_2} \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$$

$$Q = (0.72)(2.7) A \sqrt{\frac{(18.374)1.275}{(1)8314(298.15)} \left(\frac{2}{2.275}\right)^{\frac{2.275}{0.275}}}$$

$$Q = \left(3.50(10^{-3})\right)A = \left(2.75(10^{-3})\right)d^2$$

Assuming now holes varying between 20 and 200 mm (smaller than the pipe diameter), the values are obtained:

Table.4: Hole diameters x flow of gas released into the atmosphere

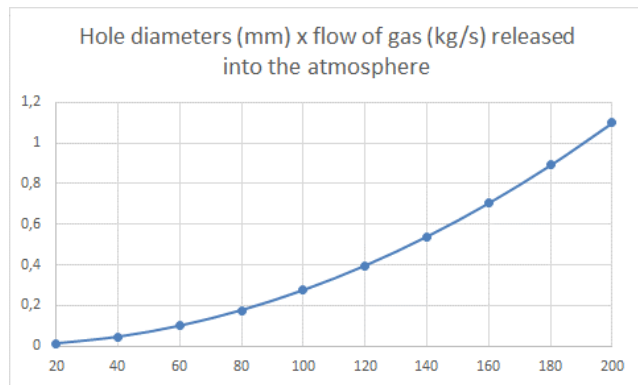| Hole diameters (mm)	Leakage mass flow (kg/s)
20	1.10×10^{-6}
40	4.40×10^{-6}
60	9.90×10^{-6}
80	1.76×10^{-5}
100	2.75×10^{-5}
120	3.96×10^{-5}
140	5.39×10^{-5}
160	7.04×10^{-5}
180	8.91×10^{-5}
200	1.10×10^{-4}

Fig. 3: Hole diameters x flow of gas released into the atmosphere

V.   CONCLUDING REMARKS

This article presents a comparative study of the volume of natural gas released into the atmosphere in situations of eventual leaks in the pipeline. In addition to the mathematical review of the respective models, a comparative analysis of problems is carried out considering small holes (< 20 mm) and holes with larger dimensions (above 20 mm, but below the pipe diameter). It is noted that the flow of gas released into the atmosphere is not negligible, identifying that the problem must be dealt with responsibly and in a time of action as soon as possible. Obviously, in these circumstances, it is assumed that the eventual leak is easily detectable by one of the several alternatives available for monitoring this type of situation.

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