6.6 NATURAL GAS PIPELINE ACCIDENTAL ANALYSIS

Y. J. Lin*
Bechtel Power Corporation, Frederick, Maryland

1. INTRODUCTION

Use of a simplified Bernoulli flow equation to determine release rate of liquefied gas from a refrigerated and pressurized container could provide an approximate estimate. However, for a pipeline with relatively long length, the omission of friction effect would result in overly conservative estimates. Using fundamental fluid dynamics, this paper describes a better approach to solve this problem. Real world values were used for ease of understanding.

2. MODEL DETAILS

The first scenario considered a pipe break occurring near the outdoor metering station. Because the pipe is under pressure, the release material would undergo rapid expansion. Therefore, a puff dispersion model was used. Prior to using the dispersion model, a reasonable release rate needs to be determined.

2.1 *Unconfined Flammable Cloud*

The steady-state release from the pipe break was assumed to be similar to a steady flow through a constant-area pipe. The main transmission line is treated as a reservoir containing natural gas (NG) at temperature T_o (280 K) and pressure P_o (1015 psi). Upon pipeline rupture, isentropic expansion is assumed to occur between this reservoir and the entrance to the branch pipeline. The resultant NG temperature and pressure are T_1 and P_1. At the break location, the NG temperature and pressure are T_2 and P_2 (see Figure 1).

The changes of fluid properties along the axial direction of a constant-area pipe may be obtained from the continuity equation, the energy equation, and the equation of state for a perfect gas (Yuan, 1967, John & Haberman, 1980). Thus,

$$P_0/P_1 = [(1 + (k-1)M_1^2/2]^{k/(k-1)} \qquad (1)$$

$$T_0/T_1 = 1 + (k-1)M_1^2/2 \qquad (2)$$

Where M denotes Mach number, and k = Cp/Cv = 1.32, Cp and Cv are the constant pressure and constant volume specific heat, respectively. The break flow rates are determined based on steady and adiabatic flow with friction from the junction to branch pipeline over a distance (L) of 30 m which has an inside diameter (D) of 0.26 m. Considering pipe friction, the Mach number at the junction of the branch pipeline with the main transmission line M_1 can be estimated.

$$4fL/D = 1/k(1/M_1^2 - 1/M_2^2) + [(k+1)/2k] \ln\{(M_1^2/M_2^2)[(k-1)M_2^2 +2]/[(k-1)M_1^2+2]\} \qquad (3)$$

The frictional factor (4f) of a 0.26-m diameter commercial steel pipe is 0.0132 (CRANE, 1998). Therefore, the frictional loss is 4fL/D = 0.0132 x 30 / 0.26 m = 1.5. Since the flow at the break location is sonic, the above equation has a solution of M_1 = 0.459 when M_2 = 1. Eqs. (1) and (2) can be solved: P_1 = 885 psia and T_1 = 271 K. The change in temperature and pressure is the result of accelerating the NG from the assumed stagnation conditions to a velocity at the entrance of the branch line. The velocity in the branch line can be estimated as:

$$u_1 = [2kR(T_0 - T_1)/(k -1)]^{0.5} \qquad (4)$$

Where R is the gas constant for NG. From Eq. (4), we obtain u_1 = 181.35 m/s.

The pressure at the break location is estimated as:

$$P_2 = P_1M_1\{2[1 + (k - 1)M_1^2/2]/(k + 1)\}^{0.5} \qquad (5)$$

P_2 = 384 psia is obtained. The gas velocity at the break location is,

$$u_2 = u_1/M_1\{2[1 + (k - 1) M_1^2/2]/(k + 1)\}^{0.5} \qquad (6)$$

u_2 = 372.41 m/s is obtained. Gas density at the break is estimated by:

$$\rho_2 = \rho_1 M_1\{(k + 1)/[2(1 + (k - 1)M_1^2/2]\}^{0.5} \qquad (7)$$

ρ_2 = 23.86 kg/m^3 is obtained. The gas discharge rate at the break location can be calculated as:

$$Q = \rho_2 u_2A = 23.86 \text{ (kg/m}^3) \times 372.4 \text{ (m/s)} \times \pi (0.13 \text{ m})^2 = 468.5 \text{ kg/s} \qquad (8)$$

This release rate is the continuous source term of the puff model.

<u>Puff Dispersion Model</u>

The puff model used to estimate NG concentration (X) is presented below (NRC, 1974):

$$X= Q[7.87 (\sigma_x^2 + \sigma_I^2) (\sigma_z^2 + \sigma_I^2)^{1/2}]^{-1} \exp[-1/2(x^2/(\sigma_x^2 + \sigma_I^2) + y^2/(\sigma_y^2 + \sigma_I^2) + z^2/(\sigma_z^2 + \sigma_I^2)] \qquad (9)$$

Y. J. Lin, 5275 Westview Dr. Bechtel Power Corp.
Frederick, MD 21703-8306
e-mail:ylin@bechtel.com

Where:
σ_x, σ_y, σ_z = horizontal (x, y) and vertical (z) dispersion coefficients, m;
σ_I = initial dispersion coefficient of the puff, m
= $[Q_I/(7.87\rho_o)]^{1/3}$, where Q_I is the puff release quantity, g, and ρ_o is the density of the gas at standard conditions, g/m^3;
x, y, z = distance from the puff center in the horizontal along wind, horizontal crosswind, and vertical cross-wind directions, respectively, m.

Wind speed does not enter into the determination of concentration directly, but does affect the time integrated concentration since it determines cloud passage time, such as x = ut. Where u is the wind speed, t is the time after release, and x is the downwind distance the puff has traveled.

In order to determine whether the puff concentrations are within the flammable limits, puff concentrations at various downwind distances should be calculated. NG would become flammable when its concentrations in air are within the lower (5%) and the upper (15%) flammable limits (Vincoli, 1991). To be conservative, stable conditions should be considered.

Flammable Mass Estimate

The relationship between an off-center concentration (X) and the centerline concentration of a puff (X_c) is in the form of an ellipse.

$$\ln(X/Xc) = -0.5\,[(y/\sigma_H)^2 + (z/\sigma_V)^2] \qquad (10)$$

Where,
$\sigma_H = (\sigma_h^2 + \sigma_I^2)^{1/2}$; $\sigma_V = (\sigma_v^2 + \sigma_I^2)^{1/2}$
σ_h = puff horizontal diffusion coefficient
σ_v = puff vertical diffusion coefficient
σ_I = initial dispersion coefficient of the puff, m

The flammable mass can be calculated using volume integration of a puff between the outer (lean) and the inner (rich) ellipsoids.

2.2 *Confined Pipe Leak*

When a pipe breaks or leaks inside a confined area (i.e., turbine building), the pipe release rate becomes irrelevant because the worst scenario would be when the NG fills up the entire building. Although the upper flammable limit for NG is 15%, the stoichiometric combustion indicates that to sustain indoor continuous burning, the NG concentration inside a building cannot be more than 9.5% in volume due to lack of oxygen supply. Normally, close to 80% of the NG is methane. The stoichiometric combustion of methane is presented below.

$$CH_4 + 2O_2 + 2(3.76)N_2 = CO_2 + 2H_2O + 7.52N_2$$

The above reaction indicates the concentration (in volume) of methane is 1/(1 + 2 + 7.52), which is equivalent to 9.5%. Thus, it is reasonable to assume that for NG to have complete continuous burning, the concentration cannot be more than 9.5%. Most likely, when NG leaks occur inside a building, the NG concentrations in certain parts of the building will be too rich or too lean to be involved in burning if an ignition source is available. However, to be conservative, it was assumed that the entire available free volume would be uniformly well mixed with a NG concentration of 9.5%. If we further assume the free volume available inside the building is about 90%, then the maximum available flammable NG mass (W) is estimated as: W_{NG} = building volume x NG density x 0.9 x 9.5%

3. CONCLUSION

Frictional effect is essential when estimating material release during a pipe break. Especially when the pipe is relatively long. A computational fluid dynamic (CFD) modeling study was also performed to evaluate the above estimates (Berkoe, 1999). The CFD results indicate that the flammable NG plume length was about half of that obtained by the above estimate. Therefore, the above approach is reasonable and conservative.

4. REFERENCES

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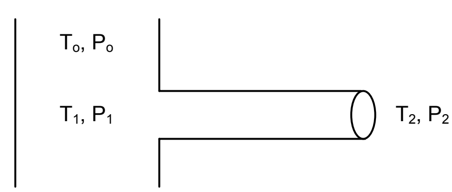

Figure 1. Main Line and Brach Line Sketch

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