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Modeling of gas release following pipeline rupture: Proposing non-dimensional correlation

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ABSTRACT

Conveying natural gas through a pipeline is widely accompanied by accidents in industries. It is important to perform hazard analysis by estimating the amount of released gas at the first step immediately after the happening. The present study proposes a new approach to evaluate the gas release rate and released mass by introducing non-dimensional equations for simulating quasi-one-dimensional transient compressible flow in a ruptured gas pipeline. These equations are derived from Euler equations. The hyperbolic governing equations are solved numerically by the explicit MacCormack's method. The influence of different dimensionless physical parameters on release rate are then investigated; among which relative pressure, relative hole diameter and friction term are the most important parameters. Results show that the release rate has the similar behavior for a wide range of operating pressures from 60 psig (0.4 MPa for distribution pipeline) to 1000 psig (6.9 MPa for transmission pipeline). Since choking condition happens in rupture area, release rate is not a function of pipeline pressure. Therefore, relative hole diameter and friction term are the only effective parameters in this case. By introducing an indicator and its criterion for long pipelines it could be seen that not only is this indicator dependent on geometry (i.e. ratio of length to diameter of pipe), but it also belongs to flow regime (i.e. friction coefficient). Finally, general relations for natural gas release rate in any physical condition are proposed by exploring effective dimensionless parameters on released mass.

1. Introduction

Nowadays natural gas transmission network is prevalent due to the fact that transferring liquefied natural gas is either more costly or seeks highly complicated technology. Pipeline facilities are always exposed to some hazards and also could be damaged by corrosion, accident and human error. After damage; if any; enormous amounts of gas emerges into the atmosphere which contaminates the environment, and furthermore it may cause economic loss. In order to measure the economic loss or managing probable risks, it is initially best to assess the released gas.

Transient condition in pipelines is divided into two categories: slow and rapid transients. Slow transients occur due to fluctuation in demand, whereas rapid transients are caused by a break, rapid shutdown valves or startup or another failure in system (Thorley and Tiley, 1987). Primary researches in gas pipeline break were done by Flatt (1986) who surveyed the adiabatic flow after full bore rupture using method of characteristics. Choking condition and significant friction force in a long pipeline have caused numerical difficulties due to singularity at the rupture position. In order to achieve a high accuracy, a second-order polynomial scheme was implemented for interpolation. Flatt's results showed that the frictional flow with $\lambda L/D \approx 1000$ had a completely different behavior compared with the frictionless flow in a way that the volume of loss in frictionless flow is much higher than that of frictional flow. Lang (1991) studied compressible transient flow after full bore rupture in isothermal and adiabatic conditions of pipeline by using a Legendre based spectral method which its results showed that the rate of gas release is approximately the same for both of boundary conditions, while real flow lies between these two limiting conditions. A coupled space-time least square spectral method using a C^{11} type p-version hierarchical interpolations in space and time is described by C.A. Dorao and M. Fernandino (2011) for rapid and slow one-dimensional transient compressible flow.

Olorunmaiye and Imide (1993) investigated one dimensional transient isothermal flow in natural gas pipeline rupture using method of characteristics. Results were based on linear characteristics with quadratic interpolation that had sufficient accuracy and

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Nomenclature

a	Speed of sound (m/s)
A	Area (m^2)
C_v	Specific heat at constant volume (J/kg K)
D	Diameter (m)
D_e	Leakage area diameter (m)
e	Internal energy (J/kg)
E_L	Outlet energy (J/s)
F	Friction term
F_f	Friction force (N)
L	Pipe length (m)
m_L	Outlet mass flow rate (kg/s)
P	Pressure (Pa)
R	Gas constant (J/kg K)
S_m	Outlet mass source term
S_e	Outlet energy source term
t	Time (s)
T	Temperature (K)
V	Velocity (m/s)
W_f	Work of friction (J)
x	Spatial coordinate (m)
Z	Compressibility factor

Greek symbols

Δ	Difference
γ	Specific heat ratio
λ	Darcy friction factor
ρ	Density (kg/m^3)

Subscripts

0	Reservoir
1	Upstream end
2	Pipeline center line at rupture position
3	Rupture position
a	Ambient
e	Exit nozzle
end	End
f	Friction
i	Initial; element number
in	Inlet
L	Leak
N	Downstream end
p	Pipe

less curvature effect of characteristic lines on isothermal flow than adiabatic condition by Flatt (1986). The predicted release rate of isothermal flow was 18% lower than Flatt's results that had been based on adiabatic condition.

A mathematical model was developed by Montiel et al. (1998) to cover a major gap between classical hole and pipe models. The hole model is suitable for cases with a hole diameter far smaller than the diameter of the pipeline, since the pipe was considered as a tank, whereas the pipe model is used for a complete breaking of the pipeline. These models are based on an adiabatic frictional flow (Fanno flow) from reservoir to rupture area and isentropic at the release point. Yuhua et al. (2002) improved Montiel's works (1998) by correcting ideal gas assumption for a high pressure long pipeline. Their results demonstrated that for a long high pressure pipeline more than 1.5 Mpa, the mass of gas release during the sonic flow was more than 90% of the total mass of gas release. Jo and Ahn (2003) proposed another simplified model based on Fanning equation to estimate the gas release rate in high pressure pipelines. In his model change in kinetic energy was neglected, but in order to take into account friction and pressure drop effects it contains a correction coefficient. Regardless of gas type this model has an error up to 20 percent in comparison to other complex mathematical models; the more the release point approaches the entrance of the pipeline, the less is the deviation. Luo et al. (2006) derived a simple model to estimate gas release rate by correcting Jo and Ahn (2003) model considering kinetic energy changes in a high pressure pipeline. These modifications decreased error to less than 7 percent.

Oke et al. (2003) studied transient flow in the high pressure pipeline by applying the method of characteristics. The aforementioned method modeled mass release of a pipeline containing condensable hydrocarbon and it could be used for a two phase flow. Results indicated that conventional modeling for gas release which assumed pipeline as a tank and used orifice was not appropriate. This model is closer to practical behavior of discharge by enumerating radial and axial flow effects in the plain of release. Efficient numerical modeling outflow in pipeline networks containing multi-component hydrocarbon mixtures with method of characteristics was developed by Mahgerefteh et al. (2006a, 2006b) in which the impact of pipeline bends, branches and coupling were shown in the pipeline system configuration. Ouchiha et al. (2012) discussed transient process in the natural gas pipeline. The method of characteristics was employed for the analysis of two transient categories the first one which is due to charging pipeline as a temporary storage and the second one due to daily demand variation in isothermal condition. The transient compressible flow in full bore rupture was studied by Nouri-Borujerdi (2011). He used high order implicit finite difference method in order to reduce the calculation time with a high accuracy. A short time after rupture the pressure at the rupture point had a noticeable decrease as a result choking occurred. A proposed mathematical model using a fully implicit numerical scheme was developed by Burlutskiy (2013) to analyze rapid decompression process in a shock-tube for a multi-component gas mixture.

In this paper, by introducing non-dimensional hyperbolic conservation equations a new approach is proposed to estimate gas release rate in a wide range of operating pressures, easily and rapidly. When a pipeline is damaged, concerned authorities need to calculate gas release rate in order to assess probable dangers or to estimate the economic loss without wasting time. While all previous literature consequences have concentrated on modeling of specified cases, the present study generalizes the results for any operating condition by making non-dimensional governing equations. Having been surveyed dimensionless effective parameters of gas release rate, unique mass discharge functions are developed. The proposed functions easily estimate discharged mass without running a computer program. Unlike other numerical models, the present hole model is created with source terms by which the impact of downstream flow and boundary conditions are also considered in governing equations. Furthermore, no specific criterion for long pipelines has been proposed yet, however, being long has been used as an assumption in previous researches. But the present study clearly recommends an indicator for long pipelines and clarifies its limits. Results are then validated by comparing to analytical solutions of Fanno flow (John, J. E. A., 1984), mathematical gas release model of Yuhua et al. (2002) and experimental transient results of shock tube by Botros et al. (2010).