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A simple model for the release rate of hazardous gas from a hole on high-pressure pipelines

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Abstract

It is very important to estimate the mass flow rate of possible accidental releases from the gas pipeline, in order to perform the hazard analysis or the risk based management in the gas facilities. This paper presents a simplified model to estimate the release rate from a hole on the high-pressure gas pipeline. It consists of a correction factor accounting for the pressure drop through pipeline due to the wall friction loss, and the release rate without friction loss. The model, whatever kind of gas may be considered, has some positive deviation from the theoretical complex equations, and it ranges from about 0 up to 20%. The deviation will reduce to zero, as the release point approaches to the reservoir. It increases with the specific heat ratio of gas and the dimensionless hole-size which is the effective area of the hole divided by the cross-sectional area of the pipe. The model is compared with damage areas of real accidents with success. It overestimates the release rate slightly and may be a useful tool to estimate the release rate quickly in performing the hazard analysis or the risk based management in the gas facilities.

Keywords: Release rate; Hazard analysis; Gas pipeline; Friction loss; High-pressure release

1. Introduction

The physical process involved in the emission of many hazardous gases is very complex, and some cases are not very well understood. In a real flow situation, the frictional force is present and may have a decisive effect on the resultant flow characteristics. The inclusion of the friction term in the equation of motion makes the flow analysis far more complex.

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Nomenclature

a	sonic velocity (m/s)
A_h	hole area (m^2)
A_p	cross-sectional area of pipeline (m^2)
c_p	specific heat capacity at the constant pressure (J/(kg K))
C_D	discharge coefficient
d	diameter of pipeline (m)
f_F	Fanning friction factor
h	enthalpy (J/kg)
L	length of pipeline (m)
$\bar{L}$	dimensionless length of pipeline scaled with friction factor
M	Mach number
M_w	molecular weight of gas (kg/mol)
p	pressure inside the pipeline (N/m^2)
p_0	pressure at reservoir (N/m^2)
p_a	atmospheric pressure (N/m^2)
p_t	stagnation pressure (N/m^2)
Q	mass flow rate (kg/s)
$Q\|_{L=0}$	mass flow rate without friction loss through pipeline (kg/s)
$\bar{Q}$	dimensionless mass flow rate
Q_h	mass flow rate through hole (kg/s)
Q_n	mass flow rate through nozzle (kg/s)
Q_p	mass flow rate in pipeline (kg/s)
R	gas constant (N m/(K mol))
Re	Reynolds number
T	temperature (K)
T_t	stagnation temperature (K)
c_v	specific heat capacity at the constant volume (J/(kg K))
u	gas velocity (m/s)

Greek letters

α	dimensionless hole-size; $A_h C_D / A_p$
γ	specific heat ratio
ε	wall roughness of pipeline (m)
ε_1	length of nozzle (m)
ε_2	path length through hole (m)
η	parameter
ρ	gas density (kg/m^3)
τ_f	shear stress due to the wall friction (N/m^2)

It is the subject of continuing research by engineers, physicists, and more recently, those studying the non-linear dynamic systems [1,2]. The first step in any hazard analysis is the characterization of the potential gas release. Most of the sophisticated dispersion models, the fire models, and the explosion models available for the hazard analysis are of little use unless the specifics of the release can be fairly well defined [3]. For the purpose of the hazard analysis, several formulas of release rate offer the approximate solutions of specified conditions [4,5]. They provide the useful information for determining quickly the consequences of an accident by hand calculator, including the rate of release and the total quantity of gas released. This information is valuable for evaluating the safety of existing processes or new process designs, and improving the safety of process. But there seems to be no simple model to calculate the release rate quickly from a hole on the gas pipeline.

In the transport of the natural gas at high pressure through the pipeline, greater care is taken to design and maintain the installations associated with pipeline to ensure their safe operation [1]. The pipeline may cross through both rural and heavily populated areas. Rupture of the pipeline can lead to the various outcomes, some of which can pose a significant damage to the people and the properties in the immediate vicinity of the failure location. Hazard area associated with the high-pressure natural gas pipeline is directly proportional to the square root of the release rate [6].

Some developments and modifications of the theoretical complex equations are required to make a simplified model for calculating explicitly the release rate from a hole on the high-pressure gas pipeline. There exists always some uncertainty, since the physical properties of the materials are not adequately characterized, or the physical processes themselves are not completely understood. The release rate is strongly dependent of the scale of the physical processes involved. Some researchers studied them by the full scale experiments [7]. In the development of a simple model, it should be considered conservatively to ensure safety.

The purpose of this paper is to propose a simple release model that is appropriate in the high-pressure transmission pipeline, and to validate the model with the full scale experiments and the consequences of real accidents.

2. Equations for release rate

Consider a pipeline connected by a converging nozzle, with the flow provided by a reservoir at pressure p_0 and releasing from a hole on the pipeline as shown in Fig. 1. The subscript t represents the stagnation conditions. For the high flow rate, it is usually valid to assume the isentropic flow in the nozzle and the hole with the adiabatic flow along the pipeline. The lengths of the nozzle and the hole (ε_1, ε_2) are very small compared with the pipe length. Therefore, the friction loss through the nozzle and the hole are small enough to be ignored, compared with total friction loss. Most of the buried gas pipelines are coated with low conductive polyethylene for corrosion protection.

The mass release rate can be estimated by using the static or stagnation pressure of the moving gas. The static pressure along the pipeline is shown in Fig. 2 as well as the stagnation pressure. The static pressure of the moving gas is the property experienced

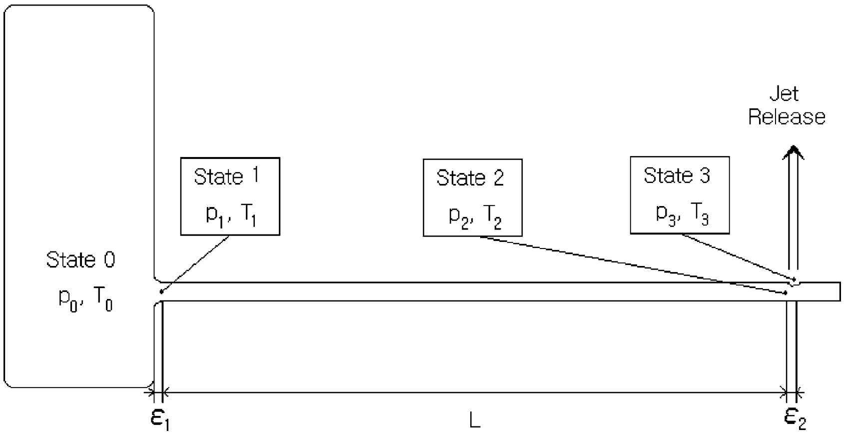

Fig. 1. The system under study.

by an observer moving at the same velocity with the gas. The stagnation pressure is the property experienced by a fixed observer, with the gas having been brought to the rest at him.

2.1. Flow rate through nozzle

Assuming the isentropic flow, energy balance through the nozzle can be expressed as following [8]:

$$\int_{p_0}^{p_1} \frac{\delta p}{\rho} + \frac{1}{2}(u_1^2 - u_0^2) = 0 \tag{1}$$

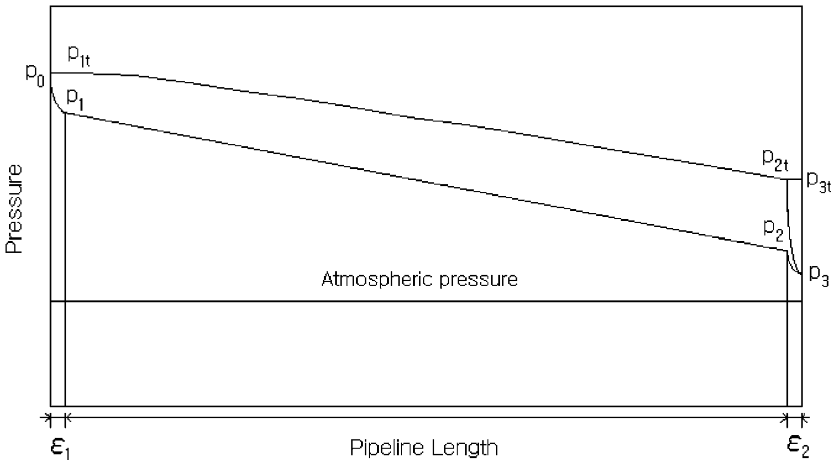

Fig. 2. Pressure drop through pipeline length (subscript t: stagnation conditions).

where ρ is the gas density, u the gas velocity, and p is the static pressure. Subscript 0 denotes the property at the reservoir, and subscript 1 denotes the property in the pipeline just after leaving the reservoir, i.e. in the nozzle. The gas velocity at the reservoir is zero.

For the isentropic expansion of a perfect gas, density and temperature may be described as follows [9]:

$$\rho = \rho_0 \left(\frac{p}{p_0} \right)^{1/\gamma} \tag{2}$$

$$T = T_0 \left(\frac{p}{p_0} \right)^{(\gamma-1)/\gamma} \tag{3}$$

By integrating Eq. (1), the velocity at nozzle is given:

$$u_1^2 = 2\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0}\left(1-\left(\frac{p_1}{p_0}\right)^{(\gamma-1)/\gamma}\right) = 2\frac{\gamma}{\gamma-1}\frac{p_0}{\rho_0}\left(1-\frac{T_1}{T_0}\right) \tag{4}$$

By the way, the velocity can be expressed in Mach number as following [8]:

$$u_1^2 = a_1^2 M_1^2 = M_1^2 \frac{\gamma R T_1}{M_\mathrm{w}} \tag{5}$$

where M is Mach number, M_w the molecular weight of gas, γ the specific heat ratio of gas, and R is the gas constant. Substituting above equations into Eq. (4) and using the perfect gas law, we obtain the temperature and the pressure:

$$T_1 = T_0 \left(\frac{2}{(\gamma-1)M_1^2 + 2} \right) \tag{6}$$

$$p_1 = p_0 \left(\frac{2}{(\gamma-1)M_1^2 + 2} \right)^{\gamma/(\gamma-1)} \tag{7}$$

Mass flow rate through the nozzle can be calculated by using Eq. (5):

$$Q_\mathrm{n} = \frac{\pi d^2}{4}\rho_1 M_1 \sqrt{\frac{\gamma R T_1}{M_\mathrm{w}}} = \frac{\pi d^2}{4} M_1 \sqrt{\gamma \rho_1 p_1} \tag{8}$$

where d is the diameter of pipeline and Q_n is the mass rate of the flow leaving the reservoir.

2.2. Flow rate through pipeline

Flow rate through the pipeline can be estimated from the momentum equation with a term accounting for the frictional forces acting on the fluid.

By applying the momentum balance for steady-state flow, following equation is written [10]:

$$-\delta p - \tau_\mathrm{f}\frac{4}{d}\,\delta L = \rho u\,\delta u \tag{9}$$

where τ_f is the shear stress due to the wall friction and L is the length of pipeline.

Divided by the pressure, Eq. (9) will be rearranged with Fanning friction factor:

$$-\frac{\delta p}{p} - f_{\mathrm{F}}\rho u^2 \frac{2}{pd}\delta L = \frac{\rho u}{p}\delta u \tag{10}$$

where

$$f_{\mathrm{F}} = \frac{\tau_{\mathrm{f}}}{0.5\rho u^2}$$

In the zone of completely rough flow, Fanning friction factor does not depend on Reynolds number, and can be given explicitly as the following equation [11]:

$$f_{\mathrm{F}} = \frac{1}{4[1.14 - 2.0\log(\varepsilon/d)]^2}, \quad \frac{\varepsilon}{d} \gg \frac{9.35}{Re\sqrt{4 f_{\mathrm{F}}}} \tag{11}$$

where Re is Reynolds number and ε is the average roughness of pipe. Typical value of the roughness is 46 μm for the commercial steel pipes.

It is desirable to integrate Eq. (10) to obtain, for example, an expression for Mach number and the pressure change over a given pipeline length. To get Mach number (M) in terms of the pipeline length (L), the pressure (p) and the gas velocity (u) are to be eliminated by using the continuity equation, the perfect gas law, and the definition of Mach number as below.

The continuity equation is written as below:

$$\frac{\delta\rho}{\rho} + \frac{\delta u}{u} = 0 \tag{12}$$

By the perfect gas law and Eq. (12), the pressure term is given as

$$\frac{\delta p}{p} = -\frac{\delta u}{u} + \frac{\delta T}{T} \tag{13}$$

By the definition of Mach number, the velocity term is derived with perfect gas law:

$$\frac{\delta u}{u} = \frac{\delta M}{M} + \frac{1}{2}\frac{\delta T}{T} \tag{14}$$

Substituting above equations into Eq. (10), we obtain the next equation:

$$\left(\frac{1}{2}\frac{\delta T}{T} - \frac{\delta M}{M}\right) + 2\gamma M^2 f_{\mathrm{F}}\frac{\delta L}{d} + \gamma M^2\left(\frac{\delta M}{M} + \frac{1}{2}\frac{\delta T}{T}\right) = 0 \tag{15}$$

For adiabatic flow, the temperature term may be expressed in Mach number:

$$h + M_{\mathrm{w}}\frac{u^2}{2} = c_p T + \frac{M^2}{2}\gamma RT = \text{constant}$$

or

$$\frac{\delta T}{T} + \frac{(\gamma - 1)M\,\delta M}{1 + ((\gamma - 1)/2)M^2} = 0 \tag{16}$$

where h is the enthalpy of gas and c_p is the specific heat capacity of gas at the constant pressure.

By substituting Eq. (16) into Eq. (15), an expression for Mach number varying over a given pipeline length is given as below:

$$\frac{4 f_{\mathrm{F}} \gamma\, \delta L}{d} = \frac{2\,\delta M}{M^3}\left[\frac{1-M^2}{1+((\gamma-1)/2)M^2}\right] \tag{17}$$

Eq. (17) can be integrated now along the pipeline from the state 1 to the state 2 as indicated in Fig. 1:

$$\frac{4 f_{\mathrm{F}} \gamma L}{d} = \left(\frac{1}{M_1^2}-\frac{1}{M_2^2}\right) + \frac{\gamma+1}{2}\ln\left[\frac{M_1^2(2+M_2^2(\gamma-1))}{M_2^2(2+M_1^2(\gamma-1))}\right] \tag{18}$$

where the subscript 2 denotes the properties in the pipe just before leaving to the atmosphere.

The temperature at the state 2 can be found from Eq. (16) in terms of Mach number:

$$\frac{T_2}{T_1} = \frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_2^2} \tag{19}$$

Pressure versus Mach number can be also found from Eq. (10) by eliminating L and u:

$$\frac{\delta p}{p} = -\frac{\delta M}{M}\left[\frac{1+(\gamma-1)M^2}{1+((\gamma-1)/2)M^2}\right] \tag{20}$$

Integration between the limits p_1 and p_2 gives the following:

$$\frac{p_2}{p_1} = \frac{M_1}{M_2}\sqrt{\frac{2+(\gamma-1)M_1^2}{2+(\gamma-1)M_2^2}} \tag{21}$$

Mass flow rate through the pipe can be calculated, likewise Eq. (8), as following:

$$Q_{\mathrm{p}} = \frac{\pi d^2}{4} M_2 \sqrt{\gamma \rho_2 p_2} = A_{\mathrm{p}} M_2 p_2 \sqrt{\frac{\gamma M_{\mathrm{w}}}{R T_2}} \tag{22}$$

where A_{p} is the cross-sectional area of pipeline and ρ_2 is the density of gas at the state 2 which can be calculated by the perfect gas law using Eqs. (6), (7), (19) and (21).

2.3. Flow rate through hole

For the perfect gas with the constant specific heat capacity, mass flow rate from the hole can be expressed in terms of the stagnation pressure and temperature:

$$\begin{aligned} Q_{\mathrm{h}} &= A_{\mathrm{h}} C_{\mathrm{D}} M_3 p_3 \sqrt{\frac{\gamma M_{\mathrm{w}}}{R T_3}} \\ &= A_{\mathrm{h}} C_{\mathrm{D}} M_3 p_{2\mathrm{t}} \sqrt{\frac{\gamma M_{\mathrm{w}}}{R T_{2\mathrm{t}}}\left(\frac{2}{(\gamma-1)M_3^2+2}\right)^{(\gamma+1)/(\gamma-1)}} \end{aligned} \tag{23}$$

where

$$T_3 = T_{2t}\left(\frac{2}{(\gamma-1)M_3^2+2}\right)$$

$$p_3 = p_{2t}\left(\frac{2}{(\gamma-1)M_3^2+2}\right)^{\gamma/(\gamma-1)}$$

where the subscript t represents the stagnation properties and the subscript 3 denotes the properties just after leaving from the pipeline to the atmosphere, while A_h is the hole area and C_D is the discharge coefficient. The stagnation properties at state 2 are of the same value as those at state 3, because of no friction loss assumed at the hole as shown in Fig. 2. In case of a full-bore rupture, the mass flow rate can be estimated by assuming the discharge coefficient as the unity (1) and the cross-sectional area of pipe for the hole area [12].

By the mass balance between the states 2 and 3, which are shown in Fig. 1, Mach number at the state 2 can be solved by the following equation:

$$\alpha = \frac{M_2}{M_3}\frac{p_2}{p_3}\sqrt{\frac{T_3}{T_2}} = \frac{M_2}{M_3}\left[\frac{(\gamma-1)M_3^2+2}{(\gamma-1)M_2^2+2}\right]^{(\gamma+1)/(2\gamma-2)} \quad (24)$$

where α is the dimensionless hole-size which is the effective hole area ($A_h C_D$) divided by the cross-sectional area of the pipe (A_p).

If the flow is choked at the hole, i.e. M_3 equals 1, Mach number at the state 2 can be simplified as the following equation:

$$\alpha = M_2\left[\frac{\gamma+1}{(\gamma-1)M_2^2+2}\right]^{(\gamma+1)/(2\gamma-2)} \quad (25)$$

The mass release rate can be solved by solving the Mach number from the state 3 backwards to state 1 using Eqs. (25) and (18), and solving the nozzle flow rate using Eqs. (6)–(8).

3. Simplified model

Total pressure drop is equal to the sum of the pressure drop over the pipeline and the pressure drop due to the isentropic expansion. The gas release rate may be estimated by calculating the stagnation pressure drop along the pipeline and the isentropic expansion at the hole as shown in Fig. 2. Pressure drop for the stationary flow in a pipeline can be estimated by well-known Fanning equation. However, Fanning equation does not account for the effect of the pressure drop due to the density change of gas, which consequently will be expanded. By Fanning relation is given the local pressure drop along the pipeline:

$$\frac{\delta p}{\delta L} = -4 f_F \frac{\rho u^2}{2d} \quad (26)$$

where p is the pressure inside the pipeline, L the length of pipeline, f_F the Fanning friction factor which is a function of the roughness of the inside wall and Reynolds number, ρ the gas density, u the gas velocity, and d is the pipeline diameter.

Gas velocity is determined by the mass flow rate in the pipeline:

$$u = 4\frac{Q}{\rho\pi d^2} \tag{27}$$

With the gas velocity being substituted, Eq. (26) can be integrated as shown below:

$$\int_{p_0}^{p_{2t}} \rho\,\delta p = -32\frac{f_F L Q^2}{\pi^2 d^5} \tag{28}$$

By integrating Eq. (28) with Eq. (2), the mass flow rate through a pipe can be given approximately as a function of the pressure, the diameter of the pipe, and the pipeline length:

$$Q_p \cong \frac{\pi d^2}{4}\sqrt{\frac{\rho_0 p_0 d}{2 f_F L}\left(\frac{\gamma}{\gamma+1}\right)\left(1-\left(\frac{p_{2t}}{p_0}\right)^{(\gamma+1)/\gamma}\right)} \tag{29}$$

The relations between the mass flow rate and the pressure drop due to the free expansion at the hole can be solved by using Eq. (23):

$$\begin{aligned} Q_h &= A_h C_D M_3 \sqrt{\gamma \rho_{2t} p_{2t}\left[\frac{2}{(\gamma-1)M_3^2+2}\right]^{(\gamma+1)/(\gamma-1)}} \\ &\cong \frac{\pi d^2}{4} M_3 \alpha \sqrt{\gamma\rho_0\left(\frac{p_{2t}}{p_0}\right)^{1/\gamma} p_{2t}\left[\frac{2}{(\gamma-1)M_3^2+2}\right]^{(\gamma+1)/(\gamma-1)}} \end{aligned} \tag{30}$$

where α is dimensionless hole-size which is the effective area of the hole divided by the cross-sectional area of pipe ($A_h C_D/A_p$). The density at the state 2 is approximated by assuming the isentropic expansion through pipeline.

By the mass conservation, the mass flow rate through the pipeline calculated by Eq. (29) is equal to the mass flow rate at the hole calculated by Eq. (30). The stagnation pressure at the state 2 is given below:

$$p_{2t} = p_0\left(\frac{1}{\eta+1}\right)^{\gamma/(\gamma+1)} \tag{31}$$

where

$$\eta = \alpha^2 M_3^2 \frac{2 f_F L}{d}(\gamma+1)\left(\frac{2}{(\gamma-1)M_3^2+2}\right)^{(\gamma+1)/(\gamma-1)}$$

If the stagnation pressure at the state 2 is greater than the critical pressure, Mach number at the hole M_3 is unity, and Eq. (30) can be simplified as following:

$$Q = \frac{((\pi d^2\alpha)/4)\sqrt{\gamma\rho_0 p_0 (2/(\gamma+1))^{(\gamma+1)/(\gamma-1)}}}{\sqrt{1+((4\alpha^2 f_F L)/d)(2/(\gamma+1))^{2/(\gamma-1)}}}, \quad \text{for } \frac{p_a}{p_{2t}} \le \left(\frac{2}{\gamma-1}\right)^{\gamma/(\gamma-1)} \tag{32}$$

where p_a is the atmospheric pressure and p_{2t} is the stagnation pressure at the state 2 as indicated in Fig. 2.

The mass release rate can be made dimensionless as well as the pipeline length scaled with the friction factor:

$$\bar{Q} = \frac{Q}{Q|_{L=0}} = \frac{Q}{((\pi d^2\alpha)/4)\sqrt{\gamma\rho_0 p_0\left[2/(\gamma+1)\right]^{(\gamma+1)/(\gamma-1)}}} \tag{33}$$

$$\bar{L} = \frac{f_F L}{d} \tag{34}$$

The dimensionless release rate is rewritten in a simpler form:

$$\bar{Q} = \frac{1}{\sqrt{1 + 4\alpha^2\bar{L}[2/(\gamma+1)]^{2/(\gamma-1)}}} \tag{35}$$

The flow rate, $Q|_{L=0}$, is the same as the release rate without friction loss through the pipeline. The dimensionless release rate depends on the specific heat ratio, the dimensionless hole-size, and the dimensionless pipeline length. If $\alpha^2\bar{L}$ in Eq. (35) is several times greater than the unity, the dimensionless release rate is inversely proportional to the dimensionless hole-size and the square root of the dimensionless pipeline length.

4. Calculations and discussion

The dimensionless release rate decreases sharply with the dimensionless pipeline length especially near the gas reservoir, but it is influenced slightly with the varying specific heat ratio as shown in Figs. 3 and 4.

As discussed in the previous section, the simplified model has some deviation from the theoretical solution due to the isentropic expansion assumed to calculate the density of gas and the stagnation pressure, which are used in turn to estimate the pressure drop through the pipeline. The simplified model always overestimates the release rate as shown in Fig. 5. The deviation has the maximum with the dimensionless pipeline length as shown in Figs. 6 and 7. The maximum takes larger value as the specific heat ratio gets higher and as the dimensionless hole-size gets bigger. It shifts nearer toward the reservoir as the dimensionless hole-size gets bigger.

The specific heat ratio is bound from 1.0 to 1.67 for gases. When translational energy is assumed to make up internal energy like as a monoatomic gas, the classical thermodynamics allows us to predict the heat capacity as following [13]:

$$c_v = \tfrac{3}{2}R \tag{36}$$

With the ideal gas relation, the specific heat ratio can be evaluated:

$$\gamma = 1 + \frac{R}{c_v} = 1.67 \tag{37}$$

For a diatomic molecule, the total internal energy is $5/2kT$ at the low temperatures, that is, $3/2kT$ in the translational energy and $2/2kT$ in the rotational energy. The specific heat ratio

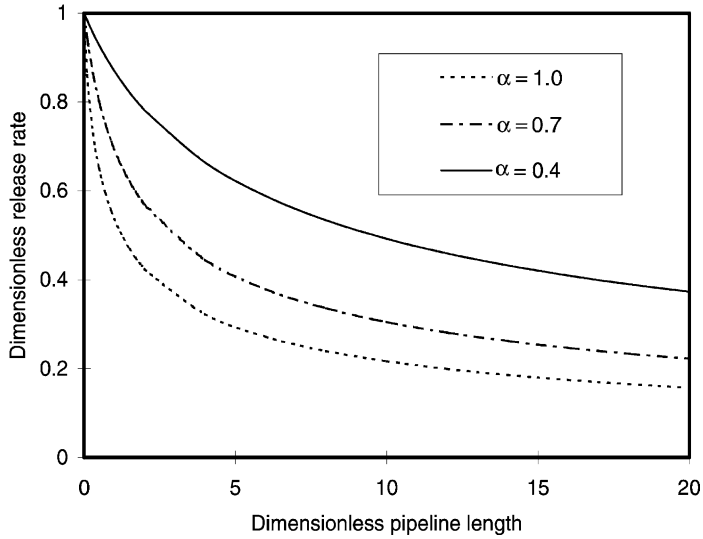

Fig. 3. Release rate varying with the dimensionless length ($\gamma = 1.42$).

of the diatomic molecule at the low temperatures is about 1.4. However, as the temperature gets higher, the total internal energy approaches to $7/2kT$ by adding the vibrational energy, $2/2kT$, and the specific heat ratio will be 1.23. For some typical gases in the chemical process, the value of the specific heat ratio ranges from 1.1 to 1.5 [14]. Therefore, whatever kind of gas gushes out through a full-bore rupture, the error involved in the simplified model ranges from 8.0 to 20% as shown in Fig. 7, if the release point is not too close to the reservoir.

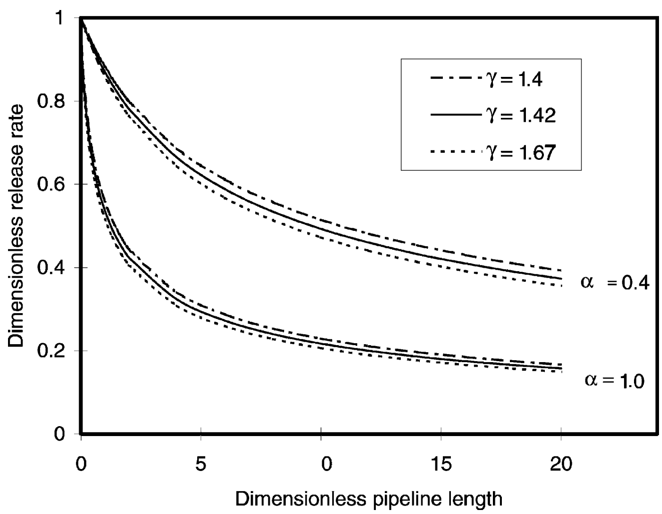

Fig. 4. Release rate varying with the specific heat ratio.

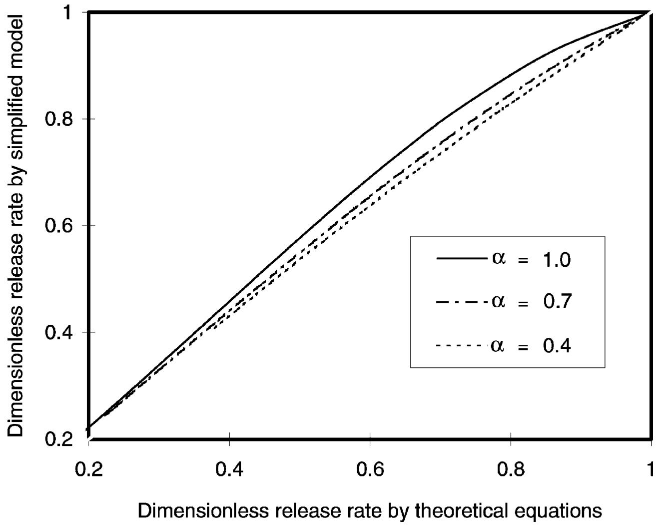

Fig. 5. Release rate by the simple model and by the theoretical equations.

The hazard distance from the gas facilities may be affected directly by the release rate. Cloud size of hazardous gas is at first approximation proportional to release rate, when only the gas dispersion is considered [15]. However, based on the heat radiation from a jet fire of flammable gas, the hazard distance appears to be proportional to the square root of the release rate [6]:

$$r \propto \sqrt{Q} \tag{38}$$

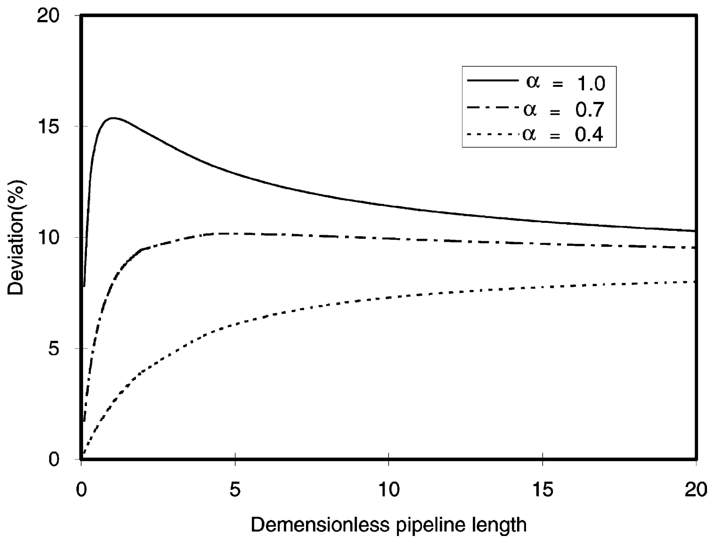

Fig. 6. Deviation from the theoretical equations ($\gamma = 1.42$).

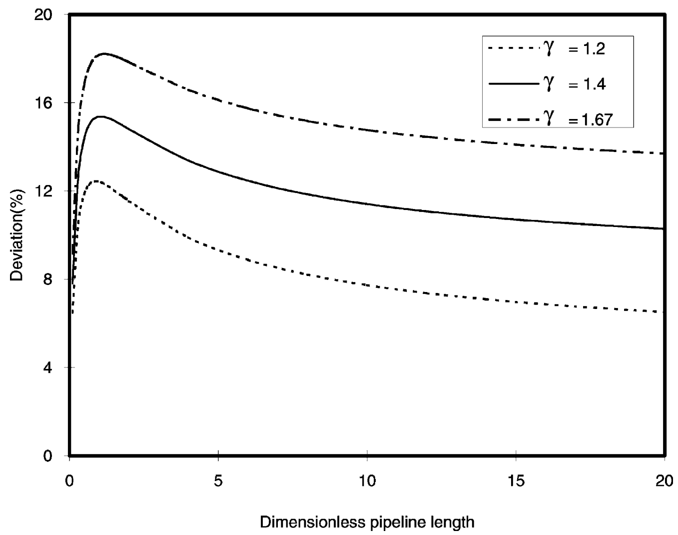

Fig. 7. Deviation from the theoretical equations for full-bore rupture.

Beyond the radial distance, r, from the flame source, a typical wooden structure would not be expected to ignite and burn. The radiation intensity needed to ignite the wood is about 15 kW/m^2 [16].

Consequences of the real accidents associated with the natural gas pipeline are listed in Table 1. The source of jet flame is not always located in the center of the burned area. The location depends on the tilt of jet flame and the meteorological condition. In the credible worst case, the center may be located on the periphery of the burned area.

With the specific heat ratio of the natural gas at room temperature ($\gamma = 1.42$) and with the average roughness of steel pipeline ($\varepsilon = 46\,\mu m$), the hazard distance from the failure

Table 1
Accidents of the natural gas transmission pipeline

Accident number	Diameter of pipeline (m)	Operating pressure (bar)	Length of pipeline (km)	Failure mode
1	0.762	51.5	24.5	Rupture
2	0.762	70.7	29	Rupture
3	0.508	55.0	18	Rupture
4	0.700	67.5	18	Rupture
5	0.355	56.5	16.6	Rupture
6	0.914	68.95	44	Rupture
7	0.610	54.6	12.8	Rupture

Sources of data: (1) The National Technical Information Service (Report N. PB 244-547); (2) The National Technical Information Service (Report N. PB 87-916501); (3) The National Technical Information Service (Report N. PB 268-606); (4) The State Government on behalf of the Committee for Economics and Transport of the Bavarian Diet (Erlangen, Bavaria, 25 March 1984); (5) The National Technical Information Service (Report N. PB 202868); (6) http://www.bst-tsb.gc.ca/eng/reports/pipe/1994/ep94h0036.html; (7) The National Technical Information Service (Report N. PB 95-916501).

point of the gas transmission pipeline associated with the jet fire can be estimated from the following equation [6]:

$$r = 10.285\sqrt{Q} \tag{39}$$

Compared with the theoretical equations, therefore, the hazard distance is over-predicted from as much as 3.9 to 20% with the simplified release model. The simplified model may be used for the hazard analysis, calculating conservatively the released rate. If the second term in the square root of the denominator in Eq. (32) is several times higher than the unity, the hazard distance may be estimated approximately as following:

$$r = 1.512\frac{p_0^{1/2} d^{5/4}}{L^{1/4}} \tag{40}$$

where p_0 is the stagnation pressure at the gas reservoir, d the pipe diameter and L is the pipeline length.

According to the chronology of the accidents, ignition of the released gas takes place from a few minutes to several hours after the pipeline rupture happened, and the jet fire sustains for several hours. Therefore, the release rate during the sustained jet fire can be calculated with the steady-state assumed as discussed above. The hazard distance estimated by the above equations is compared with the area of burn in the actual accidents. The hazard distance estimated by the above equations is slightly larger than the burned distance in the real accidents as shown in Table 2. The deviation by the simplified model from the theoretical complex equations is about 4% in the positive side. The error incurred from using the simplified model may be acceptable for the hazard analysis of the natural gas transmission pipeline.

A full scale experiment of the natural gas release following the rupture of the transmission loop pipeline was reported [17]. In the experiment, the loop line was ruptured by the deliberate explosion. The pipeline is 76.74 km long and 914 mm wide of diameter, and operating at the pressure of approximately 60 bar. Detonation of the explosive charge made a section of pipe cut off as long as 12 m. During the first 60 s following the rupture, the total mass of gas released was approximately 240 t, but at 5 min after the rupture, within which the steady-state reached presumably, the release rate reduced to approximately 1.5 t/s. The

Table 2
Hazard distance by the model and burned area in the accidents

Accident number	Hazard distance (m)		Area of burn
	Theoretical equations	Simplified model[a]	
1	186	194	213 × 122 (m^2)
2	209	218	213 × 152 (m^2)
3	123	128	36,421 (m^2)
4	206	215	200 radius (m)
5	80	83	108 × 74 (m^2)
6	235	245	178 radius (m)
7	168	176	55,850 (m^2)

[a] Using Eq. (40).

gas gushed out from the burst bore sections located 31.35 km away from one end of the loop and 44.89 km away from the other end. With the above equations, the release rate just after the rupture can be calculated as 14.2 t/s by taking zero length of the pipeline. The steady-state rate is estimated to be 0.985 t/s by the theoretical equations or 1.072 t/s by the simplified model. The release rate may slow down rapidly from 14.2 to about 1 t/s with time. The experimental value in the 5 min after the rupture might has reached to about 96% of the predicted value from the model.

The mass release rate, for the hazard analysis associated with the gas transmission pipeline, can be explicitly estimated by using the simplified model above. The dimensionless release rate ($\bar{Q}$) could be seen as a kind of correction factor accounting for the friction loss through the pipeline. Therefore, the release rate can be calculated by multiplying the dimensionless release rate given by Eq. (35) and the mass release rate without friction loss through the pipeline calculated with $L = 0$ in Eq. (32).

5. Conclusions

Estimation of the gas release rate from the ruptured pipeline is very important for the hazard analysis of possible release scenarios that can happen at the given gas facilities. A simplified model has been derived to estimate the release rate from a hole at the high-pressure gas pipeline. It consists of a correction factor ($\bar{Q}$) for the pressure drop through the pipeline due to the friction loss and the release rate from a hole without friction loss ($Q|_{L=0}$). The model has some positive deviation from the theoretical equations, which ranges from about 8 up to 20% for the full-bore rupture, whatever kind of gas may be considered, if the release point is not too close to the reservoir. The deviation increases with the specific heat ratio of gas and the effective hole-size divided by the pipe diameter.

Estimated by the simplified model, the hazard distance, within which a typical wooden structure may ignite, is slightly wider than the maximum width of burned area in the real accidents of the natural gas transmission pipeline. The deviation by the simplified model from the theoretical complex equations is about 4% in the positive side, and it may be acceptable for the hazard analysis of the natural gas transmission pipeline.

The model will be a useful tool to estimate the release rate quickly for the hazard analysis or the risk based management in the gas facilities.

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