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An integrated quantitative hazard analysis method for natural gas jet release from underground gas storage caverns in salt rock. II: A sample computation and parametric study

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A B S T R A C T

It is of great importance and necessity to perform quantitative hazard analysis on possible accidental leakage from gas storage cavern in salt rock. To improve the working safety in the cavern, an integrated quantitative method for hazard analysis on natural gas jet release from caverns in salt rock was presented. In this paper, a sample of gas storage cavern in salt rock was analyzed to demonstrate the presented method. Furthermore, the factors that influence the hazard range of leakage accidents from gas storage cavern in salt rock were discussed. The results indicated that the release rate diminishes with increased pipe length due to friction in steady-state. Meanwhile, the hazard distance from production casing also diminishes with increased pipe length. As the pipeline gets as long as several kilometers, the predicted hazard distance will be constant. However, the hazard distance increases with increasing the operating pressure and pipeline diameter.

1. Introduction

Owing to the continuous growth of global population, the requirement of raw materials and energy has also kept increasing during the past decades. Thus, the field of underground gas storage caverns in salt rock, which plays such a major role in the national Strategic Energy Reserve system and daily lives of human beings, has also become more prosperous and attractive at the same time (Yang, Liang, Wei, & Yang, 2005). However, common storage caverns usually store a large amount of hazardous substances and complex production processes are needed for excavation. A very serious consequence may happen once these highly flammable or toxic substances are ignited or released accidentally (Li et al., 2010; Wickenhauser, Wagg & Barbuto, 2006; Xie, Li, Zhao, & Zhang, 2009). Therefore, it is of great importance and necessity to assess the eruption hazard of natural gas from storage caverns in salt rock for protecting lives and properties.

Among all the available safety analysis techniques, quantitative risk analysis (QRA) approaches have been applied to identify and estimate risks on natural gas pipelines (Crowl & Louvar, 2002; Diaz Alonso, Gonzalez Ferradas, Jimenez Sanchez et al., 2008; Han & Weng, 2010; Stephens, Leewis, & Moore, 2002). However, a limitation exists regarding these widely used methods for risk analysis and assessment. These existing methods have not been suitable for comprehensively analyzing various accident consequences, such as combustion and explosion which have different physical models and may cause different harms to people as well as influence the spatial distribution of individual and societal risks.

Alternatively, in this work, we proposed an integrated quantitative method for hazard analysis on natural gas eruption from underground gas storage caverns in salt rock, which is composed of the calculation model of gas leakage rate, the analysis of consequences and the probability assessment of harms.

Although more and more researchers have used QRA to analyze fires and explosions of the transmission gas pipelines, few of them have explored risk analysis on underground gas storage caverns in salt rock. In this research, an integrated hazard analysis method with pipe operation and source release properties was proposed to calculate the hazardous range of natural gas (NG) eruption from gas storage cavern in salt rock. As part of an integrative computational tool for a NG release and evacuation project, the influence of source release parameters on hazard range of NG eruption were investigated. Of the source release parameters, pipeline length, pipeline operating pressure, release hole diameter and pipe diameter were taken into account. The computational results could not only provide information on NG release under various conditions, but also provide the foundation of decision-making for further fire and/or explosion evaluation and evacuation.

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2. Computational frame

The proposed integrated hazard analysis method is constituted of three interconnected components: *I*, the revised model for gas leaking rate calculation; *II*, the consequence analysis; and *III*, the model of probability assessment for harm. The method is illustrated by the flow chat in Fig. 1. Within each component, the calculated quantities are denoted by rounded rectangles while the adopted models are encompassed by the rectangles.

2.1. Gas leaking rate calculation

In an accident of gas pipeline rupture, the gas leaking rate should be calculated at first since both the produced heat and pressure critically depend on the leakage amount. The leaking process is actually an isentropic adiabatic expansion process, which can be described by either the hole model, the pipe model, the approximate fitting algorithm or the dynamic differential equation model (Han & Weng, 2010). However, the hole model is only good for calculating the gas leaking rate through a small diameter hole, and the pipe model works well only when the pipelines are full-bore ruptured (Dong, Gao, Zhou, & Feng, 2002). Here we proposed a revised and simplified model by which the gas leaking rate can be calculated for any hole sizes and release situations (both sonic or subsonic flow).

2.2. Thermal radiation computation for fireball and jet fire

There are four critical parameters for assessing fireball's thermal radiation hazards, including the mass of fuel involved, the fireball's diameter, duration and thermal emissive power (CCPS, 1999).

Several models are available in literature to calculate these parameters (Hadee & Lee, Fay & Lewis, Lihou & Maund, Marshall, TNO, CCPS, Roberts and Lees models), which had been discussed in depth by Yang, Fang, and Zhang (in press). Based on Yang's discussion, the fireball's diameter and duration were calculated in this work by using the TNO model (Van den Bosch & Weterings, 2005), while the mass of fuel involved was obtained by solving the gas release model. The Roberts model (Roberts, 1982) was selected for calculating fireball's lift-off height. The radiation levels at the receiving surfaces one or two flame lengths away from the fireball were calculated by using the CCPS solid flame model (CCPS, 2010), where the far-field radiation levels (more than two flame lengths away from the fireball) were calculated using the Roberts point source model (Roberts, 1982).

The 'Thornton-model' was proposed by Chamberlain in 1987 to predict the flame shape and radiation field of jet fires (Van den Bosch & Weterings, 2005). This model has been developed over several years and validated by the wind tunnel experiments and the both onshore and offshore field tests. In this model, the flame is considered as a solid body with a uniform surface emissive power. The flame shape is approximated by a frustum of a cone. Numerous laboratory data and field experiences have shown that the flames are fully stable over a much wider ambient and flow condition ranges than those indicated in API RP 521. Therefore, in this paper, the 'Thornton-model' was adopted to calculate the thermal radiation from jet fires.

2.3. Blast wave's parameters computations

TNT equivalent method is the simplest and most widely used method for modeling vapor cloud explosions. Actually, the most dangerous factors which impact on human and constructions are the peak overpressure and impulse caused by blast of vapor cloud explosion. Specially, the duration of a blast is the most vital factor

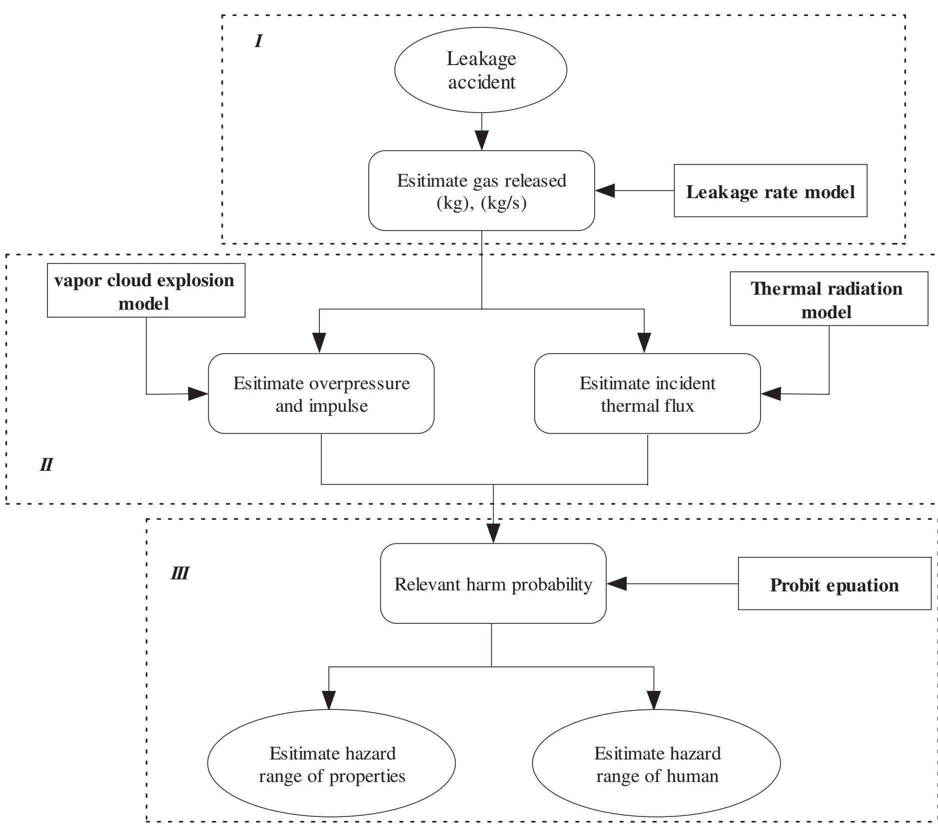

Fig. 1. Framework of the integrated quantitative hazard analysis method.

Table 1
Basic computational parameters of NG jet cases in steady state.

L (m)	D (m)	P_1 (MPa)	T_1 (K)	ρ_1 (kg/m^3)
1200	0.216	17	323	0.68
M_w (kg/kmol)	H_C (J/kg)	P_a (Pa)	T_a (K)	ρ_a (kg/m^3)
17.1	5.24×10^7	1.013×10^5	293	1.22
R (J/mol K)	μ (kg/m s)	ε (μm)	γ	RH
8.3145	1.01×10^{-5}	46	1.3	60%

which demolishes the unattached buildings. In this paper, the models of quantitative hazard assessment and probit equation including impulse were employed to investigate the hazardous areas where vapor cloud explosion could happen.

2.4. Damage to people and buildings

Consequence analysis of the natural gas storage cavern is mostly concentrated on physical effects of accidents, including jet flame, fireball and CVCE, etc. The effects of these accidents, such as heat and pressure, can be quantitatively described according to the corresponding formulas and they rely on the leaking rate. Based on the dose–effect relationship between the doses of concrete harmful load such as heat or pressure and recipient categories such as death or injuries, the function of probability unit of fatality can be calculated and the death probability percentage can be obtained by looking up the corresponding tables.

A variety of radiant heat flux levels and associated injury or damage levels were reported in literature. According to the laboratory experimental data on the damage of heat referring to burns from thermal radiation, the fatality of a person from heat effect can be calculated according to the equation recommended by Fu, Huang, and Fu (2008), Pula, Khan, Veitch, and Amyotte (2006), Yu (2000), Lees (1996), and LaChance, Tchouvelev, and Engebo (2011).

Possible effects of overpressure events on human include both direct and indirect effects. The main direct effect is the sudden increase in pressure from the event. Significant increases in pressure can cause damage to pressure-sensitive organs such as lung and ears. According to the laboratory experimental data on the damage of overpressure referring to eardrum rupture and lung hemorrhage, the fatality of a person from explosion overpressure can be evaluated by using the equation recommended by Diaz Alonso, Gonzalez Ferradas, Jimenez Sanchez et al. (2008) and Diaz Alonso, Gonzalez Ferradas, Sanchez Perez et al. (2008).

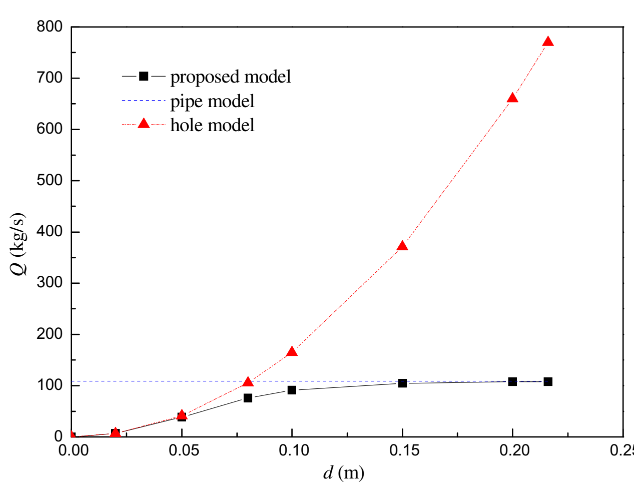

Fig. 2. Relationship between gas leaking rate and hole diameter (P_1 = 17 MPa, L = 1200 m).

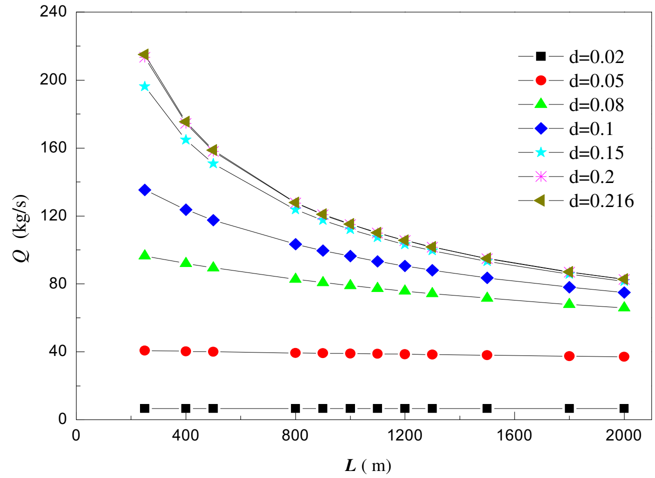

Fig. 3. Relationship between gas leaking rate and hole diameter (P_1 = 17 MPa).

3. Effects of source release parameters

To approve the validity of the proposed model, a scenario of natural gas storage cavern in salt rock was applied. In order to calculate the hazard, the initial accident hypothesis was assumed under the principle of worst presume as follow: (1) for the consequence analysis of gas release, a failure in production casing causes an orifice with the diameter of 0.02, 0.05, 0.08, 0.1, 0.15, 0.2, and 0.216 m; (2) for the consequence analysis of fireballs, a failure of full-bore rupture, and the valve closing time was set to be 120 s, and "LD 50" values have also been specified. LD 50 is the lethal dose (LD) where 50% of exposed population would die (LaChance et al., 2011); (3) for the consequence analysis of jet fire and CVCE, a failure of full-bore rupture, and the release flow-rate always lower than the maximum possible flow-rate in the production casing, and thermal dose levels have also been used to define "Dangerous Dose" levels which are usually defined as the dose resulting in death to 1% of the exposed population in 10 s; (4) for the calculations of the damage to properties, "Dangerous Dose" values (1% of structure failure) have also been used.

Studies indicated that source release parameters had important impacts on the hazard range of NG eruption. The source release parameters that affecting the NG eruption include pipeline length,

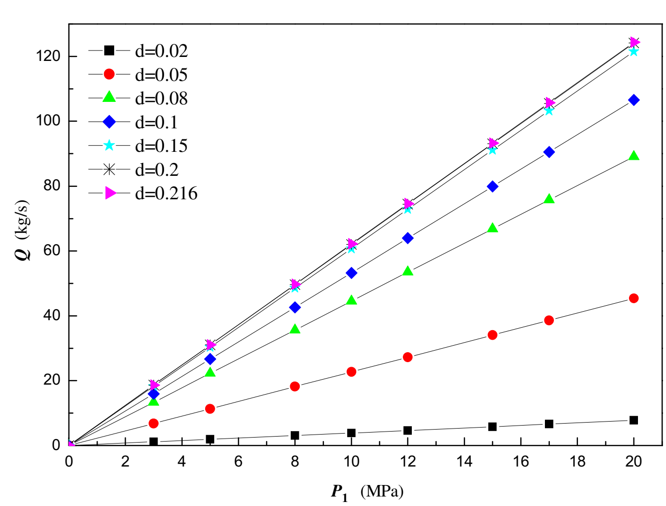

Fig. 4. Relationship between gas leaking rate and operating pressure (L = 1200 m).

Table 2
Range of damage caused by thermal radiation from fireball.

Type of damage	Hazard distance R' (m)	Thermal dose calculated (kJ/m^2)	Threshold dose (kJ/m^2)
Death	231/302	438	375
Second degree burn	294/377	290	250
First degree burn	455/573	128	125
Wood ignited	282/363	312	330 (Yu, 2000)

Note: point source model/solid flame model for the column of hazard distance.

Table 3
Range of damage caused by thermal radiation from jet fire.

Type of damage	Hazard distance R' (m)	Thermal radiation intensity calculated (kW/m^2)	Threshold intensity (kW/m^2)
Death	1.82	41.99	37.5
Second degree burn	2.23	27.81	25
First degree burn	3.32	12.23	12.5
Wood ignited	85.00	15.00	12.5

operating pressure of pipeline, release hole diameter and pipe diameter (Dong, Xue, Yang, & Yang, 2010). In the following texts, these factors were investigated and discussed in detail.

3.1. Release rate

The direction of natural gas (NG) eruption from the sample natural gas storage cavern is normal to the ambient wind direction, and the release area ranges from a small hole to full-bore rupture as described in the above presume (1). The basic computational parameters for steady cases are listed in Table 1.

When the proposed release rate model was applied, the empirical discharge coefficient C_d was supposed to equal to 0.61.

In computational fluid mechanics, gas flow is considered as a reversible and adiabatic process, complying with the gas state equation and Poisson equation. In order to adjust the deviation from ideality, a compressibility factor Z is introduced in the state equation. Accordingly, the state equation of real gas is given as:

$$P = \frac{\rho Z R T}{M_w}$$

Here Z is assumed to be constant over the pipe length of interest. According to the study of CCPS (2010), the compressibility factor Z can be calculated as follow:

$$Z = \frac{100}{100 + 1.734 P^{1.15}}$$

Based on the above proposed model as well as the parameters, the release rate for NG eruption from different holes at the operating pressure $P_1 = 17$ MPa under steady state are shown in Fig. 2. It can be seen that the proposed model of leaking rate was universal for calculating the release rate of high-pressure NG. When the diameter of the orifice was close to that of the pipeline, the release rate calculated from the proposed model was almost equal to that from one of the pipe models. And the proposed model showed perfect appropriateness for calculating the release rate of rupture at different pipeline length.

The source release parameters mainly affect the source release rate and therefore affect the hazard range of gas eruption. These parameters include operating pressure of storage cavern P_1, pipeline length L, pipeline diameter D and gas release hole diameter d. The effects of pipeline length L and operating pressure P_1 on the release rate at different holes under steady state are shown in Figs. 3 and 4. The results showed that the gas release rate increased linearly with increasing operating pressure, and decreased non-linearly with prolonging pipeline length.

3.2. Jet fire and fireball

When a failure of full-bore rupture of the production casing happened, the empirical discharge coefficient C_d was supposed to equal to 1. Based on the parameters listed in Table 2, the hazard distance of fireball and jet fire for natural gas storage caverns was calculated, and the results are listed in Tables 2 and 3. It can be seen that the marginally higher thermal radiation of fireball and jet fire that calculated by the proposed integrated hazard analysis method gave a better fit to the threshold of thermal radiation dose and intensity (Baker, Cox, Westine, Kulesz, & Strehlow, 1983; CCPS, 1999; Lees, 1996; Pape, Mniszewski, Longinow, & Kenner, 2010). And it was also shown that the integrated method is practical for conservatively estimating heating harm from fireball and jet fire.

The source release parameters mainly affect the source release rate and therefore affect the hazard range of gas release. Figs. 5 and 6 show the effects of parameters P_1, D and L on the hazard range of jet fire and fireball when leakage of natural gas from storage cavern in salt rock happens. The results indicated that the hazard distance from production casing of underground natural gas storage cavern in salt rock diminishes with prolonging length. As the pipeline gets

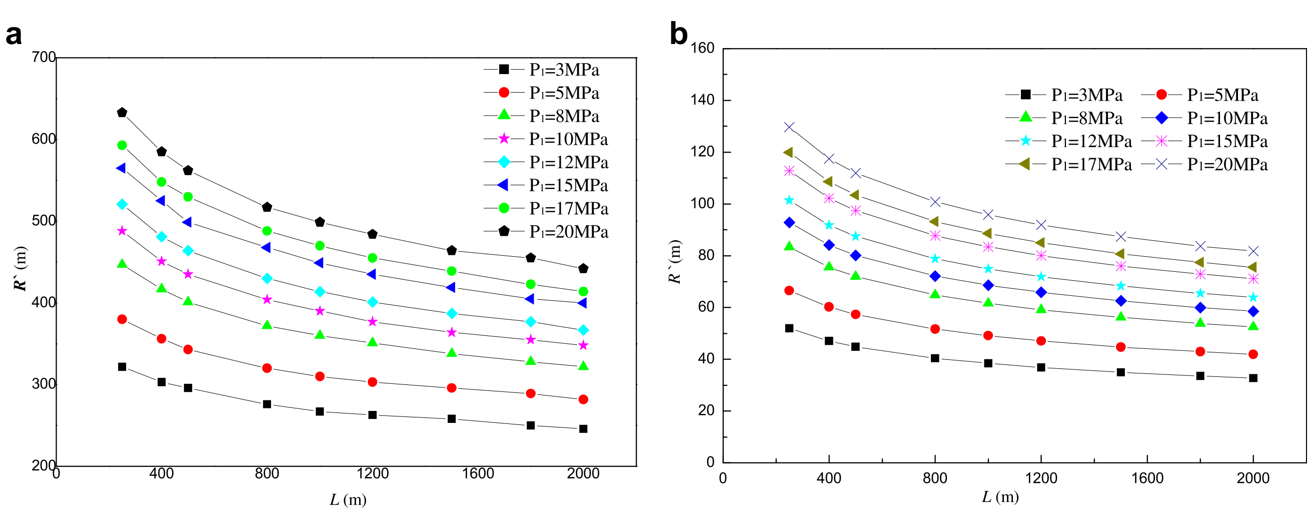

Fig. 5. Hazard distances of (a) fireball; (b) jet fire as a function of operating pressure and pipeline length ($D = 0.216$ m).

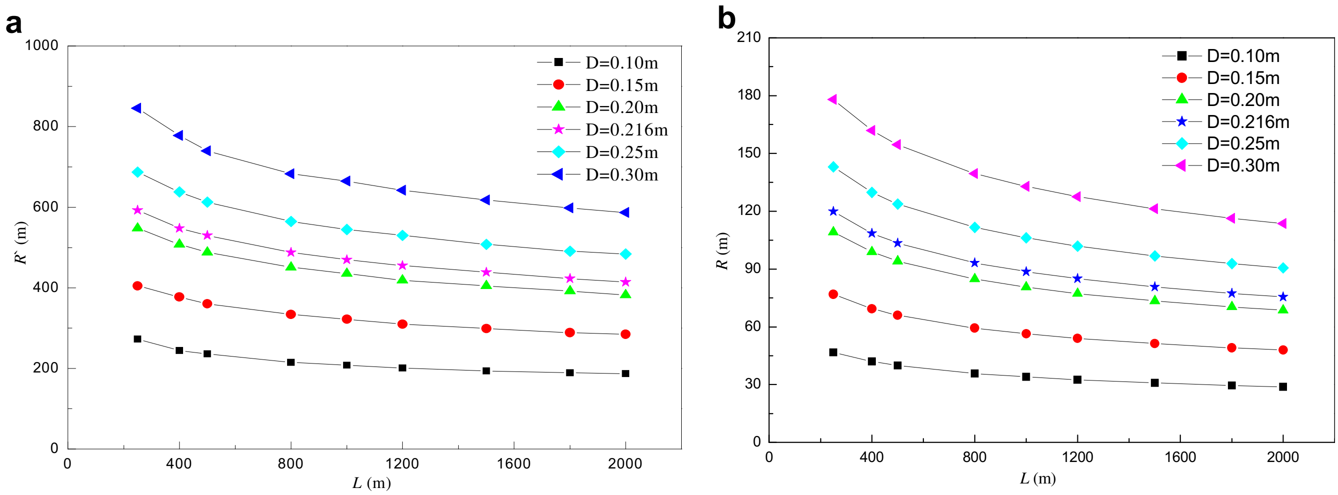

Fig. 6. Hazard distances of (a) fireball; (b) jet fire as a function of pipeline diameter and pipeline length ($P_1 = 17$ MPa).

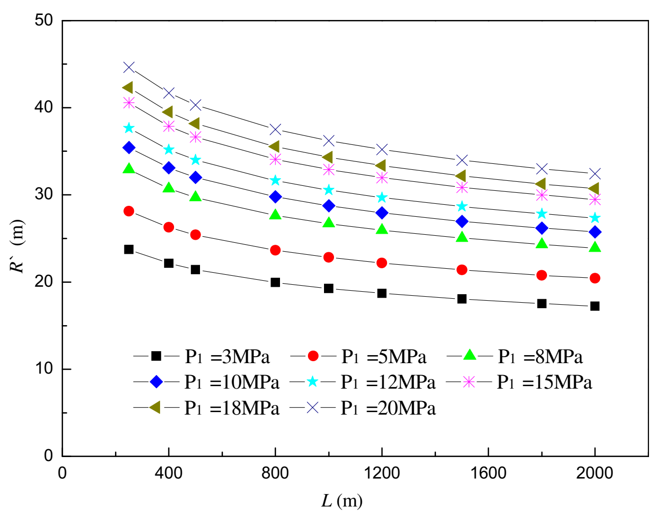

Fig. 7. Hazard distances of vapor cloud explosion as a function of operating pressure and pipeline length ($D = 0.216$ m).

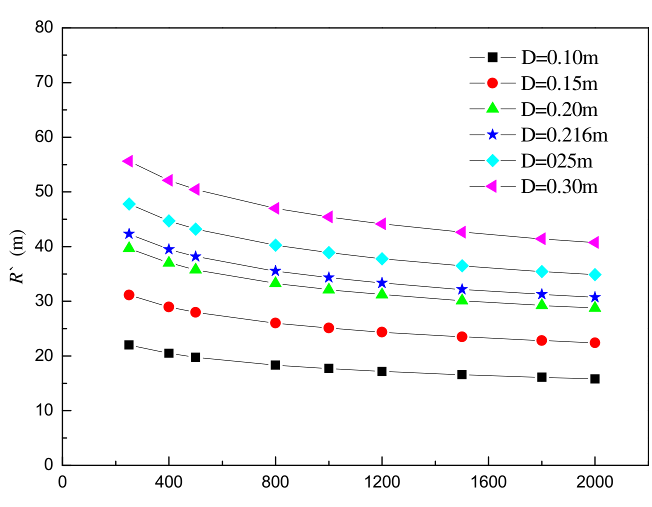

Fig. 8. Hazard distances of vapor cloud explosion as a function of pipeline diameter and pipeline length ($P_1 = 17$ MPa).

as long as several kilometers, the predicted hazard distance will be constant. And the hazard distance increases with increasing the operating pressure and pipeline diameter.

3.3. VCE

Based on the parameters listed in Table 1, the hazard distance of VCE for the natural gas storage caverns was calculated, and the results are listed in Figs. 7 and 8.

Similarly, the hazard distance from production casing of underground natural gas storage cavern in salt rock diminishes with prolonging length. The predicted hazard distance will be also constant when the pipeline gets as long as several kilometers. And the hazard distance also increases with increasing operating pressure and pipeline diameter.

From the above hazard analysis of the sample natural gas storage cavern in salt rock, the proposed integrated quantitative method for hazard analysis on natural gas storage cavern can be used in practical applications. It should be also noted that future work should be concentrated on the adoption of domino failure models and the computation of interactional effects of heat and overpressure, because explosions in chemical process industries are either caused by fire or lead to fire in various situations (Khan & Abbasi, 1999).

4. Conclusion

An integrated quantitative method for hazard analysis on natural gas eruption from storage caverns in salt rock was discussed, and the corresponding framework and needed models were described. Revised calculation model of gas leaking rate, consequences analysis and probability assessment of harm are consisted in this method. For the consequence analysis of natural gas eruption, heat and overpressure were considered for calculating the hazard range on people and properties.

In the present study, the effects of source release parameters (i.e., the pipeline length, the operating pressure of cavern, the release hole diameter and the pipe diameter) on the NG eruption process were investigated for the first time. The results showed that the rate and hazard range of gas release increased with reducing pipeline length or increasing operating pressure, leaking hole diameter or pipe diameter.

It is believed that the obtained results not only provide a useful database for evaluating the hazard range of NG eruption from a natural gas storage cavern in salt rock, but also provide a foundation of decision-making for further fire and/or explosion evaluation and evacuation.

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