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Natural gas emission incidents simulation and calculation of vent in distribution networks (Case study: Fars Gas Company)

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Abstract

This research study aimed at conducting the numerical simulation of accident consequences of natural gas release. Failure of the pipeline can lead to various outcomes, some of which can pose a significant threat of irretrievable damage to people in the immediate vicinity of the failure location. The area of hazard associated with the damage depends on the mode of pipeline failure, time to ignition, environmental conditions at the failure point, and the meteorological conditions. To make the solution and results more similar to the actual scenario, gas leakage rate from the pipeline fracture was investigated in the steady state flow and transient flow modes were assessed. The numerical results revealed that, as the pressure at the fracture point was equal to the atmospheric pressure, the Mach number was smaller than one. In the pipe model, as the length of the pipe was long and the pressure difference between the inside and outside of the pipe was high, the Mach number tended to one and the gas leak rate to the sound speed. The main source of gas emission was divided into four main sections including, the pressure reducing stations, piping and branching and users' instruments. In this study, the findings were calculated using PHAST software.

Keywords: Distribution networks; gas leakage; numerical simulation; pipeline fracture; vent emission; wind speed.

Introduction

The natural gas industry has been found to be responsible for the production, processing, transportation, and distribution of the natural gas to different kinds of customers including, industrial, commercial, and domestic. The distribution section receives a high-pressure gas from transportation section, reduces the pressure, injects the odorant into the gas and then delivers it to customers. In distribution section, pipelines have different responsibilities such as receiving the gas, transferring the gas to pressure reducing stations, transferring the gas between stations (making a loop) and transferring the gas from stations to consumptions points [1, 2].

Leaks are created stochastically, drawing from the current understanding

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of the frequency and size distributions at production facilities.

Keith and Crowl investigated about pipeline leakage and puncture. They reported that, increasing the velocity head-losses caused the rate of the outlet mass to reach a constant value [3]. A new approach was developed by Moloudi and Abolfazli Esfahani, estimating the amount of gas release from a straight pipe in transient compressible flow [4]. They investigated some dimensionless gas release parameters to derive the equations from Euler equations [5].

Natural gas (NG) is discharged from the pipeline for two purposes. Pipeline discharge for general cleaning operations or maintenance. In this case, the gas inside the pipeline is completely discharged by injecting an inert gas into the pipeline. In this way, the beginning and the end of the pipeline is blocked. Then, from one side, the inert gas is injected and from the other side the NG is discharged into the atmosphere. The second form of the gas discharge is done by suddenly opening the discharge valves for a limited time. By opening the valve due to the high pressure difference between the pipeline and environment, NG is released into the atmosphere at a high velocity (approaching the speed of sound) and draws out impurities with it. In this study, the purging process is refereed to this action (the second form) [4,6].

Montiel and Partners developed one-dimensional mathematical modeling of natural gas leakage. They numerically solved the governing equations using Secant iterative method [4,7].

Lu and Partners solved Montiel's model for different amount of the whole diameter and pipeline pressure [4,8].

A numerical model of isothermal and adiabatic gas flow conditions was simulated by Kostowski and Skorek for investigating one- dimensional steady-state leakage flow. They applied both of the ideal gas and real gas assumptions to analyze the discharge coefficient effect on the output flow rate [4,9].

They proposed a new numerical simulation of pressurized pipeline puncture. They considered natural gas as a mixture of various hydrocarbons and concluded that the conventional gas leakage models, treating the pipeline as a closed reservoir, are inappropriate especially during the early stages of depressurization [4,10].

A definite and simple model was developed by Jo and Ahn based on Fanning equation to calculate the amount of gas leakage from a hole in high-pressure gas pipelines. They concluded that their proposed model revealed a little more gas discharge rate compared with that of the theoretical model [4,11].

Although the natural gas transmission pipe lines usually buried underground, the probability of the damage still exists. As an example, 67% of 185 accidents reported by Motil and co. [12] are related to natural gas pipelines networks. The most common accidents are caused by mechanical wreckage, human errors, wreckages resulted from hitting objects or heavy drilling machines. Pipelines damages can make a hole in the pipeline or cause the pipeline ruins apart completely. The diameter and pressure of the pipeline are used to determine the rate of exit gas.

The danger zone area can be determined by pipeline wreckage, combustion time, atmospheric and surrounding conditions. Design, manufacturing and maintenance conditions will impact the pipeline wreckage rate due to external damages.

The problem of natural gas pipeline leakage has become the focus of scholars in various fields [13].

Natural gas may exit continuously from the created hole in the pipeline and causes pressure loss and cooling the exit point, the tiny holes growth will occur and finally the pipe breaks apart. British gas [14] researches showed that if the ratio of working stress to yield stress is bigger than 0.3, a hole may end up pipe fracture.

When the gas exits from a hole with high speed, the gas flow is spread as a cone jet in surrounding (Figure1). Speed profile will be higher than the wind speed (high turbulence stream) and sucks the air into the cone and causes the more distribution in comparison to gas without the initial speed. The range of Reynolds number for fully developed turbulence cone will be Re >2.5*104 [15].

When gas exits from a hole with low velocity and distribution to the surrounding may happen by density difference, dispersion to the low stream will be occurred as plume (Figure 2). Plume path theory that suggested by Omez [16], is used in calculating the flow path of low specific gravity and air of equal density gases which exit from a chimney in atmospheric pressure and temperature.

Figure 1. The flow of a high-speed gas jet and spreading it in surrounding [15]

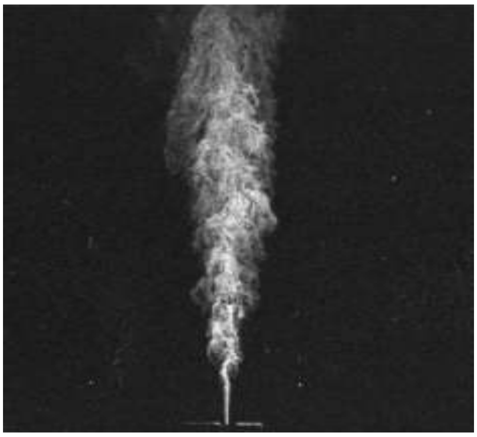

Figure 2. The Flow of a low velocity plume and spreading it in the environment [15]

Project implementation

The estimation of greenhouse emission resulted from operations and installations of Fars Gas Company was done using the activity and emission coefficients. Activity coefficients and number of sources, instruments and activities were calculated based on data, documents which are available in Fars Gas Company, while the emission coefficients or emission intensity from different sources were done using experimental measurements, software simulations or engineering calculations. The proper methodology for estimating the emission amount in the base year (2018-2019) was conducted by taking into consideration the statistical society from the point of quantity, nature, the number and the correctness and the accuracy. It should be noted that, the data collection was done by field investigation and using inquiries. The fugitive emission from all instruments was measured using the Hi-Flow Sampler and the emission from accidents was calculated using PHAST software.

Experimental measurement using Hi-Flow TM sampler

The emission rate of natural gas was determined using the Equation 1.

$$Leak=Flow\times(Gas_{sample}-Gas_{background})10^{-2} \quad (1)$$

Leak: methane emission from definite source (lit/min)

Flow: the rate of sampling (lit/min)

Gas_{sample}=methane concentration in sampling flow (%)

$Gas_{background}$=methane concentration in air (%)

Figure 3. Methane emission measuring device (Hi-Flow Sampler)

Calculating fugitive emission (leakage) using PHAST simulation software

This software uses the release models and the data from vent modeling to predict the behavior of gas bulk depending on geographical and ambient situations (Figure 3).

Theory

Natural gas transmission pipelines structure stresses

Pipelines as a cylindrical object has axial symmetry and most of the incoming stresses may have side effects, causing pressure and temperature gradient along the pipeline.

Tensile stress from internal pressure:

$$\sigma_\tau=\frac{PR}{t} \quad (2)$$

R: Pipe radius

t: pipe wall thickness

Temperature stress is arising from internal and external differentiation changes happen to pipe wall. In a hollow cylinder with internal diameter of R_i and external diameter of R_o and steady temperature gradient ΔT, the highest stress in internal (tensile stress) and external (pressure stress) surfaces will happen. [17]

$$\sigma_\tau=\frac{\Delta T\beta E}{2(1-\nu)\log(\frac{R_o}{R_i})}\left(1-\frac{2R_i^2}{R_o^2-R_i^2}\log\frac{R_o}{R_i}\right) \quad (3)$$

$$\sigma_\tau=\frac{\Delta T\beta E}{2(1-\nu)\log(\frac{R_o}{R_i})}\left(1-\frac{2R_o^2}{R_o^2-R_i^2}\log\frac{R_o}{R_i}\right) \quad (4)$$

β: Thermal Expansion Coefficient

ν: Poason Coefficient

Gas leakage rate from pipeline fracture

Gas leakage rate from pipeline fracture is a function of different parameters such as temperature, pressure, fracture size, pipe diameter, and length and friction factor. In the following sections, gas leakage rate in different situations will be explained.

Gas leakage rate in steady state flow

Energy, momentum and continuity equations was considered for natural gas in a pipeline as a compressible fluid.

Hole model

In this model, the dimensions of the hole are small compared to the diameter of the pipe (Figure 4).

In calculating the gas leakage rate from a hole which may occurred from an accident, Figures 1 and 2 will be considered.

Point 2 is in inside the pipe.

Point 3 is exactly at the hole cross section and right before the gas exit.

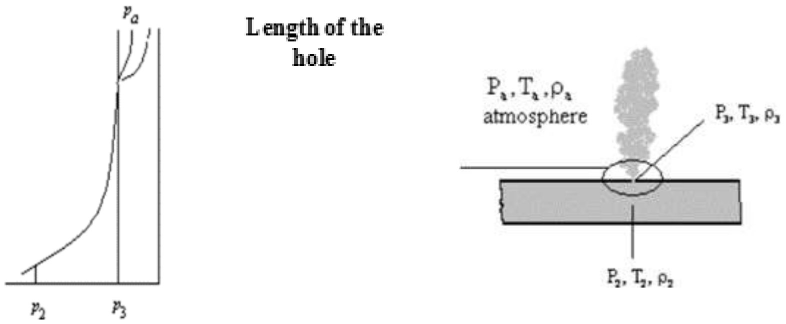

Figure 4. A schematic of gas leakage from a hole on pipeline and pressure distribution across the hole

The mass flow rate of gas leakage from the hol: $\dot{m}_3 = C_D A_3 \sqrt{k\rho_2 p_2 (\frac{2}{k+1})^{\frac{k+1}{k-1}}}$ (5)

C_D: Hole discharge coefficient

Pipeline model

In this model, the fracture dimensions was large and about the diameter of the pipe.

Figure 5 is showing this model.

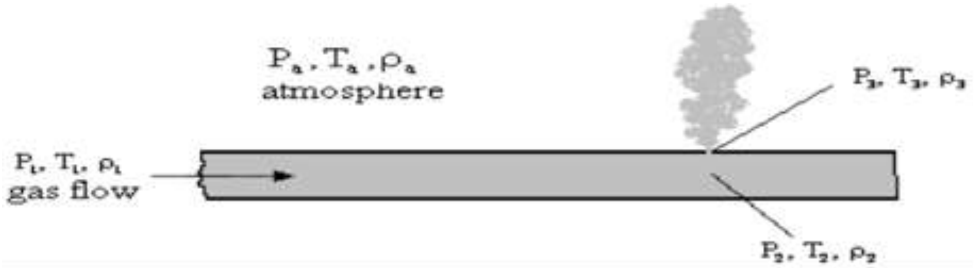

Figure 5. A schematic for gas leakage from a hole on a long pipeline

Point 1 is the point for injecting the gas into the pipeline with pressure P_1.

Point 2 is inside the pipeline and in front of the fracture location.

Point 3 is at fracture cross section and just before the point that gas will enter into the air.

A) Developed Flow: When gas pressure is low and density change across the pipeline is small, we can eliminate momentum in comparison to friction force and pressure loss [18].

$$\dot{m}_1 = A_1 \sqrt{\frac{d}{f_D * L} * \frac{2K}{K+1} \rho_1 p_1} \left[1 - (\frac{P_2}{P_1})^{\frac{k+1}{k}}\right] \quad (6)$$

B) Developing Flow: If density variation along the pipeline is high, we should take into consideration the effect of momentum force in comparison to friction force and pressure loss.

In this case, it assumes that the pipeline is buried underground in depth of H_{soil} and heat transfer is happening between gas and the ground surface.

$$\dot{m} = \rho A u = const \quad (7)$$

$$\rho u = \frac{du}{dx} + \frac{dp}{dx} + \frac{f_D}{2d}\rho u^2 = 0 \quad (8)$$

$$\frac{1}{U} = \frac{1}{h_i} + \frac{d\ln(1+\frac{2\delta}{d})}{2K_W} + \frac{d\cosh^{-1}(1+\frac{2H_{soil}}{d+2\delta})}{2k_{soil}} + \frac{d\cosh^{-1}(1+\frac{2H_{soil}}{d+2\delta})}{2h_o(h_{soil}-0.5d-\delta)} \quad (9)$$

K_W: Thermal conductivity of the pipeline

u: Average speed of gas inside the pipeline

$G=\rho u$

U: Overall Heat Transfer coefficient

$St=U/GC_p$

Gas leakage rate in transient flow

gas leakage rate in transient flow with short pipeline length

For a short length of the pipeline and the closed feeding valve, the gas inside the pipeline will be assumed as a system and therefore the pressure inside the pipeline will be constant.

Leakage Rate Equation:

$$\frac{dM}{dt} = -m_3^{\cdot} \qquad (10)$$

M: Mass of the gas inside the pipeline

$m_3^{\cdot}$: Gas leakage rate from the fracture point

A) The pressure inside the pipeline is greater than critical pressure. Also the leakage speed will be greater than sound speed and gas properties will be a function of time ($t \leq t_{cr}$)

$$M(t) = \rho(t)\forall = M(0)\left(1 + \frac{k-1}{2}t^*\right)^{-\frac{2}{k-1}}$$

(11)

t_{cr}: Critical Time

$\rho(0)\forall = M(0)$: Initial gas mass inside the pipeline.

B) Gas leakage in time period $t > t_{cr}$: In this case gas leakage will be done with the speed less than sound speed and as the feeding valve is closed, the gas pressure inside the pipeline will decrease.

$$\frac{d}{dt}\left(\frac{\rho}{\rho_a}\right) = -\frac{C_D A_3 C_a}{\forall}\sqrt{\frac{2}{k-1}\left[\left(\frac{\rho}{\rho_a}\right)^{k-1} - 1\right]}$$

(12)

C_a: Sound speed at surrounding temperature

The numerical solution of the above equation can be done using the Ronge Kuta method [19].

Gas leakage rate in transient flow with long pipeline length

The continuity equation:

$$\frac{\partial\rho}{\partial t} + \frac{\partial\rho u}{\partial x} = 0 \qquad (13)$$

$$\frac{\partial\rho u}{\partial t} + \frac{\partial\rho u^2}{\partial x} + \frac{dp}{dx} + \frac{f_D}{2d}\rho u^2 = 0 \qquad (14)$$

The momentum equation:

d: pipeline diameter p: pressure *ρ: density u: gas velocity* f_D*: Darci friction coefficient*

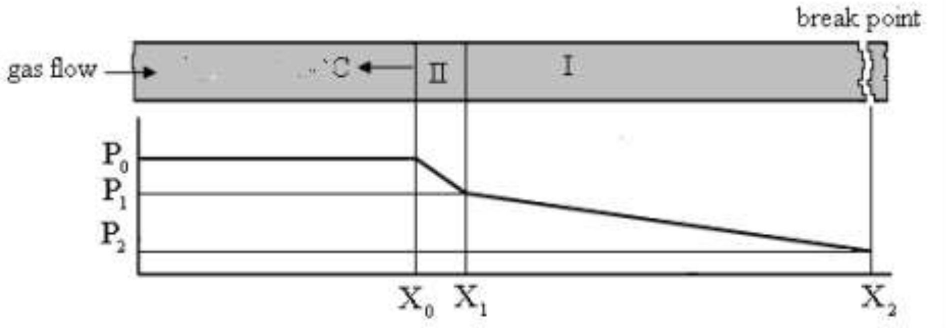

Figure 6. Showing a gas pipeline which has a fracture in point X_2

Region I: The flow will be steady and adiabatic and we use pressure gradient and friction force (Figure 6). These two equations will be summarized as below:

$$\frac{\partial G}{\partial X} = \frac{\partial\rho u}{\partial x} = 0 \qquad (15)$$

Mass velocity: G= ρu

These equations will be summarized as below:

$$\frac{\partial\rho u^2}{\partial x} + \frac{dp}{dx} + \frac{f_D}{2d}\rho u^2 = 0 \qquad (16)$$

$$\frac{f_D\,(x_2 - x_0)}{2d} = \frac{1}{k+1}\left[ln\left(\frac{pr_2}{pr_1}\right)^{\frac{k+1}{k}} + \left(\frac{pr_2}{pr_1}\right)^{\frac{-(k+1)}{k}} - 1\right]$$

(17)

$$G_{max} = \sqrt{k\rho_0 p_0 pr_2^{\frac{k+1}{k}}}$$

(18)

Region II: This region is defined by a forehead expansion wave, waiving the friction force and introducing a correction factor (Figure 7).

With variable $\varepsilon = x/t$ we will have:

$$-\varepsilon\frac{\partial\rho}{\partial\varepsilon} + \frac{\partial\rho u}{\partial\varepsilon} = 0 \qquad (19)$$

$$\frac{\partial\rho u^2}{\partial\varepsilon} + \frac{dp}{d\varepsilon} - \varepsilon\frac{\delta\rho u}{\delta\varepsilon}\rho u^2 = 0 \qquad (20)$$

Mass flux passing through X_1:

$$G_1 = -\rho_1 u_1 = \frac{2}{k-1}\left[(p_{rI})^{\frac{1}{k}} - (p_{rI})^{\frac{(k+1)}{2k}}\right]\sqrt{k\rho_0 p_0}$$

(21)

$$G_{max} = \left[1 + \frac{k-1}{2}\left(\frac{p_{r2}}{p_{r1}}\right)^{\frac{k+1}{2k}}\right]\sqrt{k\rho_0 p_0\left(\frac{p_{r2}}{p_{r1}}\right)^{\frac{k+1}{k}}}$$

(22)

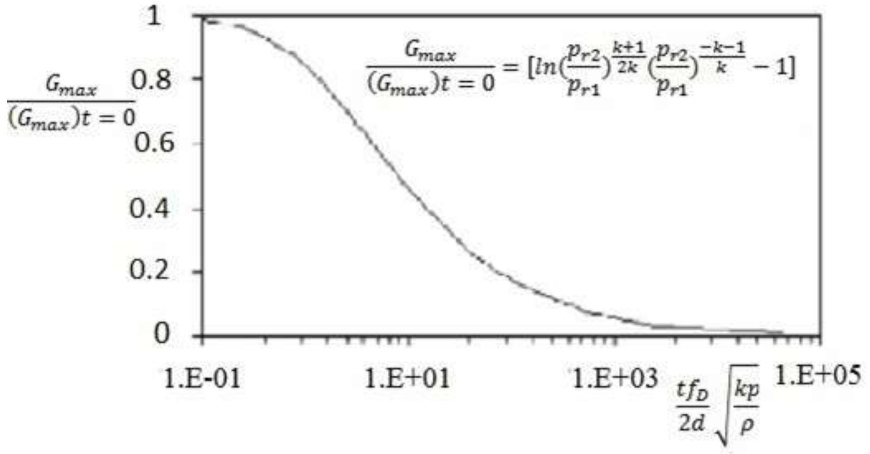

Figure 7. Outlet gas mass fluxes in terms of the friction parameter

Methods and scenarios in estimating emission

calculating fugitive emission using PHAST

PHAST software used the release models and the data from vent modeling, predicting the behavior of the gas bulk depending on geographical and ambient situations. This software is a comprehensive tool for analysing the processes sequences. This software was used to investigate the incident from the start of substance release to creation of cloud or pool and the emission at the end and is capable of calculating the substance concentration, fire radiation and the increase in pressure due to explosions in different distances.

Some of the results from substances emission modelling using the PHAST software will be as:

- The distance the gas cloud will travel from the release point
- The height of cloud central line from the ground
- The mass dimensions in desired concentrations (including height and width)
- The concentration profile

Results

The amount of gas released in each incident was categorized as below.

1- The high pressure gas emission from leakage to the environment (from the beginning up to the gas cut off by emergency units)

2- The release of remaining gas in pipeline to the atmospheric pressure (from the gas cut off time up to the end of maintenance). Table 1 is showing the number of incidents happened from 2018 to 2019 in Fars Province.

Table 1. Number of incidents was happened from 2018 to 2019 in Fars province (Shiraz city with pressure working at 60 psi)

Row	Pipe diameter (mm, in)	Hole diameter (mm, in)	the arrival time of emergency units and cut off the gas flow (min)	Row	Pipe diameter (mm, in)	Hole diameter (mm, in)	the arrival time of emergency units and cut off the gas flow (min)
1	63mm	50mm	20	15	2in	Cut off completely	8
2	2in	80mm	30	16	2in	Cut off completely	10
3	8in	50mm	20	17	2in	Cut off completely	8
4	63mm	30mm	30	18	2in	20mm	10
5	125mm	50mm	20	19	2in	20mm	10
6	160mm	100mm	10	20	63mm	8mm	15
7	90mm	50mm	10	21	63mm	63mm	10
8	63mm	Pipeline rupture	7	22	63mm	63mm	10
9	63mm	Pipeline rupture	10	23	63mm	63mm	15
10	63mm	Pipeline rupture	10	24	63mm	63mm	15
11	63mm	Pipeline rupture	7	25	63mm	63mm	15
12	63mm	Pipeline rupture	8	26	160mm	160mm	10
13	63mm	Pipeline rupture	8	27	2in	1.5mm	20
14	2in	Cut off completely	7				

Calculating high pressure gas vent emission form leak point to environment
Scenarios in PHAST Software: Different incidents used in consequences evaluation were divided as below. In every investigation consequences evaluation, the substance and the incident forecasted and one or more incidents were determined.

Catastrophic Rupture: This scenario is related to sudden release of substances in the environment. Catastrophic rupture scenario was designed for the scenarios in which a vessel may rupture due to a hard strike, a crack that will expand so fast. It was assumed that, the substances release created a homogeny mass without any restriction from the vessel. If the release is done at the ground surface, a semi-sphere cloud will be created, and if it is done in upper levels of the ground a spherical cloud will be created.

Leak: The leak scenario was used in situations in which a hole is created in the body of the vessel or a small hole in a big pipe. In this model, the orifice calculation method was used and assumed that there was no friction inside the vessel or the pipe when the fluid moved toward the hole.

Fixed duration release: In this scenario, a leakage was modeled in which the orifice size is such a big one that lets the whole inventory leaves the line in a definite time. This model was used as the “worst situation” release and usually the time for the release was 10 min.

Long pipeline: This scenario modeled a time based release from long pipeline. In this model the effect of unit shutdown was taken into consideration. These effects were determined by closing the pipeline valves. Depending on the situation in the pipeline, the release can be in gas or two phase modes .This scenario can be used when the pipeline length is so big (length>> diameter*300) or when the hole size is assumed to be so much smaller than full rupture. For full ruptures in shorter pipelines, the pipeline scenario should be used. Release can be taken anywhere along the pipeline with any size (from leakage to full rupture). In this case the pipeline features, valves and the location of the leakage should be determined.

The parameters affecting the gas vent emission flow rate from the incident point are: leak point diameter, the pressure and temperature inside the pipeline. It is obvious that with longer incident time, much more amount of gas will be released (with constant flow rate). Therefore PHAST software is mow using for estimating the amount of gas vent emission from the incident point.

Since the simulation result measure the emission intensity of methane over time, the duration of each event is needed to calculate the emission. Depending on the start time of the accident until relief and gas cut off, the duration of the emission time can be calculated for each incident.

Regarding all point up to now, the total incidents emission can be calculated as below:

$$E_{\mathrm{Ac}} = \sum_{i=1}^{n} (\mathrm{EFi} \times \mathrm{ti}) \qquad (23)$$

In which the ti and EFi are incident time and the methane emission rate and n is the total number of incidents. Table 2 reveals different incidents scenarios and methane emission rate as the standard m^3 (Sm^3).

Table 2. The simulation result for release gas up to emergency units and cut off the gas flow (min)

Row	The vent gas flow rate (kg/s)	Vent Gas flow rate (LPM)	Vent Methane flow rate (LPM)	The whole amount of methane released (Sm3)
1	1.573	128090.549	115563.293	2311.266
2	4.028	327911.805	295842.030	8875.261
3	1.573	128090.549	115563.293	2311.266
4	0.566	46112.598	41602.785	1248.084
5	1.573	128090.549	115563.293	2311.266
6	6.294	512362.195	462253.172	9245.063
7	1.573	128090.549	115563.293	1155.633
8	2.498	203356.555	183468.284	1284.278
9	2.498	203356.555	183468.284	1834.683
10	2.498	203356.555	183468.284	1834.683
11	2.498	203356.555	183468.284	1284.278
12	2.498	203356.555	183468.284	1467. 746
13	2.498	203356.555	183468.2	1467.746
14	1.624	132222.252	119290.916	835.036
15	1.624	132222.252	119290.916	835.036
16	1.624	132222.252	119290.916	954.327
17	1.624	132222.252	119290.916	1192.909
18	0.252	20494.488	18490.127	184.901
19	0.252	20494.488	18490.127	184.901
20	0.04	3279.118	2958.420	44.376
21	2.498	203356.555	183468.284	1834.683
22	2.498	203356.555	183468.284	1834.683
23	2.498	203356.555	183468.284	2752.024
24	2.498	203356.555	183468.284	2752.024
25	2.498	203356.555	183468.284	2752.024
26	16.11	1311647.218	1183368.120	11833.681
27	0.001	115.281	104.007	2.080

Calculating Remaining Gas in Vent Emission in Pipeline

The amount of emission for each incident was constant and not depending on the emission time and leak hole diameter. The parameters that affect the emission are including, diameter and the length of pipeline, the pressure, and temperature of the inside gas (Table 3). Diameter and the gas pressure for every incident were recorded and the length of the pipeline as reported by the Fars Gas Company will be assumed by average as 200 m.

Therefore the pipeline dimension can be calculated as below.

$$V_{pipeline} = \frac{\pi D^2}{4} L \tag{24}$$

$$V_2 = V_1 \frac{P_1}{P_2} \frac{Z_2}{Z_1} \frac{T_2}{T_1} y_{CH_4} = v_1 \frac{60+14.696}{14.696} * \frac{1}{0.9881} * \frac{298.15}{288.65} * 0.9 = V_1 * 4.7818$$

Subscript 1: Pipeline conditions

Subscript 2: Gas standard conditions

Table 3. The remaining vent gas volume after emergency units

Row	The vent methane volume up to emergency units be in the incident location (Sm3)	The vent methane volume after emergency units be in the incident location up to the end of maintenance (Sm3)	The whole amount of methane released (Sm3)
1	2311.266	2980	2314.246
2	8875.261	0.019	8875.280
3	2311.266	0.310	2311.576
4	1248.084	2.980	1251.063
5	2311.266	11.730	2322.966
6	9245.063	19.219	9246.282
7	1155.633	6.081	1161.714
8	1284.278	2.980	1287.258
9	1834.683	2.980	1837.663
10	1834.683	2.980	1837.663
11	1284.278	2.980	1287.258
12	1467.746	2.980	1470.726
13	1467.746	2.980	1470.726
14	835.036	0.019	835.056
15	954.327	0.019	954.347
16	1192.909	0.019	1192.929
17	954.327	0.019	954.347
18	184.901	0.019	184.921
19	184.901	0.019	184.921
20	44.376	2.980	47.356
21	1834.683	2.980	1837.663
22	1834.683	2.980	1837.663
23	2752.024	2.980	2755.004
24	2752.024	2.980	2755.004
25	2752.024	2.980	2755.004
26	11833.681	19.219	11852.90
27	2.080	0.019	2.100

Conclusion

This research study aimed at conducting the numerical simulation of accident consequences of natural gas release. Due to the high pressure of the pipeline, the gas leakage velocity may occur at the velocity when leaving the fracture site. During this time the leakage rate is constant and the gas flow is constant. Its rate varies with time.

Non-permanent flow occurs when the dimensions of the fracture are large compared to the diameter of the pipe or the short length of the pipe and the blockage of the gas flow to the pipeline coincides with the fracture. Since the natural gas transmission behavior of the pipelines is between the isothermal and adiabatic states, while the pipelines are long, the results of both processes are the same.

In the whole model, when the gas pressure inside the pipe exceeds the critical pressure of the gas in the pipe, the gas leaks at the speed of sound and we have the maximum leakage rate. The gas flow rate in the pipe relative to its velocity from the fracture site can occur in one of the following three situations.
1) Infrared gas flow through the fracture site and the tube
2) Gas flow at the speed of sound passing through the fracture site and infrared in the tube.
3) Gas flow at the speed of sound passing through the fracture site and the tube If the pressure at the fracture site is equal to the atmospheric pressure, the Mach number is smaller than one In the pipe model, it was found that, if the length of the pipe is long and the pressure difference between the inside and outside of the pipe is high, the Mach number will tend to one and the gas leak rate to the sound speed.

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