Correlations for estimating natural gas leakage from above-ground and buried urban distribution pipelines

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A numerical method is developed to investigate leakage in above-ground and buried urban distribution natural gas pipelines. The main aim is to develop a few equations to estimate leakage form above-ground and buried urban natural gas pipelines. The equations are developed by considering the impact of various parameters such as the pipeline and hole diameters. A computational model for steady, compressible turbulent flow is built to model leakage. The natural gas as working fluid is treated as an ideal gas and soi considered as a porous zone. The results indicate that for holes with small diameters, discharge speed reaches to the sound speed and at the so-called, choking occurs in the flow. Also based on the result, the volumetric flow rate of leaked gas have a linear relation, second order relation and fourth order relation with pressure of initial point, diameter of hole and ratio of the hole diameter to the pipe diameter, respectively. In the case of buried pipes, permeation depth of gas into soil at the small diameter holes is more than large holes but volumetric rate of leaked gas is lower. Also after permeation of natural gas into the soil, and hitting the soil particles and the air moving through soil, a pair of vortex is created inside the soil. Finally two new correlations have been proposed to calculate the natural gas leakage from a small hole located on the lateral surface of the above-ground and buried distribution gas pipelines. Results show that, the percentage of relative error between simulation results and correlation values is below 5% which implies high accuracy of the presented correlations.

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1. Introduction

Pipelines are the common and comfortable method of transporting and distributing fuels and dangerous gases such as natural gas (NG) (Parvini and Gharagouzlou, 2015). Pipelines are often subjected to various damages such as third party activities, corrosion, mechanical or material failure and natural hazards (Sklavounos and Rigas, 2006). Annually, a significant amount of gases are wasted under the title of Unaccounted for Gas (UAG) and it’s one of the main issues in the management and control of NG transmission networks (Costello, 2014). The UAG is defined as difference between the volume of gas injected into a distribution system and the gas measured at customers’ meters (Arpino et al., 2014).

The factors which affect UAG can be identified as the gas leakages from pipes and fittings, measurement errors, third party damage and theft of the gas (Haydell, 2011). Due to the major share of leakage among these factors, it is one of the most important factors in UAG. Leakage is the action of unmeasured gas that release from a transmission or distribution pipeline to the surroundings. Gas leakages can be occurred on pipe walls, at welded and flanged connections, valves and other gas equipment. Leakage can be arising by various ingredients such as internal friction, corrosion and external accidents (such as underground work, dealing with bulldozer, etc.) (Montiel et al., 1996).

When a hole is created on the pipe surface, an expansion wave moves into the pipe and it makes the gas flow toward the damaged section (Nouri-Borujerdi, 2011). Due to the high gas flow velocity in the damaged pipe, common measurements are not able to calculate the amount of released gas; therefore the laws of gas dynamics should be used to calculate the amount of released gas.

There are many researches which studied gas leakage. These researches can be categorized into two main groups: leakage detection location and calculation its amount. In the case of leakage detection, some methods and studies for gas pipeline leak detection have been developed in recent studies (Buerck et al., 2003;
In the case of leakage calculation, there are many published books and manuscripts about the viscous compressible flow inside the pipe around two adiabatic and isothermal flow states (Churchill, 1980; Crowl and Louvar, 2002; Levenspiel, 1984; Crane, 1988; Farina, 1997).

One of the first studies about natural gas leakage modeling was done by Olorunmaiye and Imide (Olorunmiaye and Imide, 1993). In their study, a mathematical model of natural gas leakage from broken end of a pipe was developed based on unsteady isothermal flow. The results of their study predicted that gas release rate is lower than that of adiabatic flow theory by about 18%. It agrees quite well with the results of research that done by Lang and Fannelop (1987) in the isothermal flow state. Woodward and Mudan (1991) developed a model for computing liquid and gas discharge rates through holes in process vessels, that takes into calculate the decrease in pressure with changing in the time.

Montiel et al. (1998), developed a mathematical model of accidental gas release. They developed one dimension model for gas distribution system operating at medium and low pressure with ideal gas assumption ($c_p = c_t e$). A mathematical modeling of gas release through holes in high-pressure pipelines was developed by Yuhu et al. (2003), based on constant compressibility factor ($Z = 0.9$). They concluded that gas leaks from small holes can be considered as a steady state process. Lu et al. (2014), analyzed the theory of the one-dimensional natural gas leakage in urban medium pressure pipelines, and examined their proposed model for both steady and transient (unstable) states. In another investigation Jo and Ahn (2003) developed a simple and definite model to calculate leaked gas from a hole in a pipe containing dangerous high-pressure gas using the ideal gas equation.

Some researches were done by using numerical method of characteristics to solve governing equations, such as investigation which done by Oke et al. (2003). They introduced a transient outflow model for pipeline puncture for real natural gas flow consists of several hydrocarbons. They concluded that because of the returned gas flow from downstream, modeling of the pipe like a reservoir that gas flow discharge from end of it, is not a suitable model.

Kostowski and Skorek, (2012) investigated the flow in the damaged pipes in the natural gas distribution network. They considered the damaged pipe as open side wall in their proposed model. They simulated the flow for two isothermal and adiabatic flow states and checked both of these states for ideal gas and real gas. They also analyzed the discharge coefficient effect in flow of the gas output.

In the case of buried pipe, a model based on finite element method was provided for a leaking species migration from a heat source buried into a fluid saturated porous medium by Nithiarasu, (1999) The results of this research showed that, the size of the leaking hole has a great effect on the discharged mass in addition to the Rayleigh number.

Almost in all previous researches, flow modeling has been done as one-dimensional and in most of them the pipe modeled as a closed reservoir. In other word, the length of the pipe after the hole has not been considered. The models, which not considered the length of the pipe after the hole, are inappropriate and causes unreal results for cases with larger holes. Also most of researches have been done on the field of leakage calculation for above-ground pipelines and reliable investigations are very limited in the field of buried pipelines. Consequently, the purpose of this study is to investigate the natural gas leakage for both above-ground and buried pipes cases in the urban distribution gas pipelines. The investigation is carried out by using numerical simulation of a two-dimension turbulent flow. Also the length of the pipe after the hole is considered and pipe divided into two down-stream and up-stream parts. Finally two simple, useful and comprehensive correlations have been presented to estimate the amount of natural gas leakage from a small hole located on the lateral surface of the above-ground and buried distribution gas pipelines.

2. Theoretical analysis

As it motioned, to calculate the amount of pipelines leakage, two models can be identified as:

a) Hole model
b) Pipe model

In the situation of (a), there is a hole on the lateral surface of the pipe, hole diameter is smaller than pipe diameter ($d < D$) and gas discharges from the hole. But situation of (b) is a case that the diameter of the hole is equal or larger than pipe ($d \geq D$). In the other words, the pipe model is used when rupture occurs in the pipe.

Fig. 1 shows schematic of the hole and pipe models that used in the investigation is carried out by using numerical simulation of a two-

\[
\text{CPR} = \frac{p_a}{p_{2cr}} = \left( \frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}} \tag{1}
\]

where $p_a$ and $p_{2cr}$ indicate the atmosphere pressure and critical pressure of the point 2, respectively (the indexes in this equation are according to the Fig. 1). According to Eq. (1), when the pressure at point 2 is larger than critical pressure ($p_2 > p_{2cr}$), choked flow occurs and the discharge speed of the gas reaches the sound speed ($Ma = 1$). But when $p_2 < p_{2cr}$, a subsonic flow in the discharge section is occurred (Montiel et al., 1998; Yuhu et al., 2003; Lu et al., 2014; Jo and Ahn, 2003).

Fig. 2 is a schematic of the model considered in this work. As it can be seen, the length of pipe before and after the hole are considered as $l_1$ and $l_2$ respectively.

In the handbook of the gas engineering (GPSA) (Engineering Data Book and Tw, 2004), there is an equation to calculate the amount of the gas leakage based on the law of the orifice. In this way, an orifice is installed between a pair of flanges at the outlet of a vertical pipe nipple which calculates the amount of gas discharged into the atmosphere. An approximate flow rate of gas which discharged from the small orifice into the atmosphere can be calculated from Eq. (2) (Engineering Data Book and Tw, 2004).

\[
Q_d = 16330 (1 + \beta^4) \rho_{eff} \sqrt{(29.32 + 0.3H)} F_{eff} C_g \tag{2}
\]

\[
\beta = \frac{d_{eff}}{D} \tag{3}
\]

\[
F_{eff} = \sqrt{\frac{520}{460 + \frac{T_m}{m}}} \tag{4}
\]

\[
C_g = \sqrt{\frac{0.6}{C}} \tag{5}
\]

where $Q_d$ is the approximate volumetric rate of the discharged gas.
(ft³/day), \(d_{off}\) is orifice diameter (in), \(D_p\) is pipe diameter (in), \(H\) is pressure (in Hg) and \(T_m\) is the average temperature of the gas (°F).

### 3. Simulation analysis

In this section, firstly, the attention has been paid to introduce the physical model. Then, the numerical simulation which used to calculate the amount of leakage is presented.

A two dimensional, steady, compressible turbulent flow has been built to calculate the amount of natural gas leakage from urban distribution pipelines. Since the flow equations in the pipe and soil are different, the equations are divided into two distinct parts.

### 3.1. Governing equations of above-ground pipe

The governing equations for natural gas flow inside the pipe are expressed as follows:

Conservation of mass (continuity) (Versteeg and Malalasekera, 2007; Lu et al., 2016)

\[
\frac{\partial}{\partial x_i}(\rho u_i) = 0
\]  

Conservation of momentum (Versteeg and Malalasekera, 2007; Lu et al., 2016)

\[
\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} - \rho u_i u_j + \rho g_i + F_i
\]

Conservation of energy (Versteeg and Malalasekera, 2007; Lu et al., 2016)

\[
\frac{\partial}{\partial x_j} \left[ u_i (\rho E + p) \right] = \frac{\partial}{\partial x_j} \left[ k_{eff} \frac{\partial T}{\partial x_j} + u_i \left( \bar{v}_j \right)_{eff} \right]
\]

Equation of state (EOS) (Moean et al., 2011)

\[ p\rho = RT \]  

### 3.2. Governing equations of buried pipe

Since the flow equations in the pipe and soil are different, the equations are divided into two distinct parts:

a) Equations of flow inside the pipe: equations (6)–(9);
b) Equations of flow within the soil: equation (10)–(12).

To simulate the soil above the pipe, the definition of a porous

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Fig. 1. Schematic diagram of the studied model used in most previous studies, (A) hole model, (B) pipe model (Montiel et al., 1998; Yuhu et al., 2003; Lu et al., 2014; Jo and Ahn, 2003).

Fig. 2. Schematic diagram of the considered model.

Fig. 3. Solution domain (above-ground pipe).
Equations of the flow in the porous zone are defined and solved independently from the flow inside the pipe. Accordingly, the governing equations for this case are containing Eqs. (6)–(12) (Ewing et al., 1999).

\[
\frac{\partial}{\partial t}(\rho U_i) = 0
\]  

(10)

The effect of the computational cells number on the mass flow rate of leaked gas is shown in Table 1.

Table 1
Effect of the computational cells number on the mass flow rate of leaked gas.

<table>
<thead>
<tr>
<th>Number of the cells (cells)</th>
<th>Mass flow rate of leaked gas (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>240,000</td>
<td>0.175</td>
</tr>
<tr>
<td>530,000</td>
<td>0.172</td>
</tr>
<tr>
<td>1,070,000</td>
<td>0.159</td>
</tr>
<tr>
<td>1,260,000</td>
<td>0.158</td>
</tr>
</tbody>
</table>

Table 2
Thermal properties of the soil (Itoh, 1981).

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>(m²/s)</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>Conductivity</td>
<td>(W/mK)</td>
<td>2.9</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>(J/kgK)</td>
<td>732.69</td>
</tr>
<tr>
<td>Density</td>
<td>(kg/m³)</td>
<td>2650</td>
</tr>
</tbody>
</table>

Table 3
Type of the boundary conditions.

<table>
<thead>
<tr>
<th>Boundary location</th>
<th>Boundary type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial of the pipe</td>
<td>Pressure inlet</td>
</tr>
<tr>
<td>End of the pipe</td>
<td>Pressure outlet</td>
</tr>
<tr>
<td>Hole</td>
<td>In above-ground pipe</td>
</tr>
<tr>
<td></td>
<td>In buried pipe</td>
</tr>
<tr>
<td></td>
<td>On pipe: pressure outlet</td>
</tr>
<tr>
<td></td>
<td>On soil: interface</td>
</tr>
<tr>
<td>Lateral surface of the pipe</td>
<td>Wall (adiabatic)</td>
</tr>
<tr>
<td>Ground surface</td>
<td>Pressure outlet</td>
</tr>
</tbody>
</table>
The effect of buoyancy on turbulence appears as so-called "turbulence kinetic energy generation due to buoyancy" and is defined as Eq. (18). With ideal gas assumption, Eq. (18) reduces to Eq. (19) (Jianwen et al., 2015).

$$G_b = \frac{\rho g \mu_t \partial T}{\rho_{\text{Pr}} \partial x_i}$$  \hspace{1cm} (18)

$$G_b = -\frac{\rho g \mu_t \partial \mu}{\rho_{\text{Pr}} \partial x_i}$$  \hspace{1cm} (19)

In the flow with high Mach number value, compressibility affects turbulence through dilatation dissipation, which is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate ($Y_M$). This effect is normally neglected for incompressible flow modeling (Wilcox, 1998). Also in compressible flow, this parameter is modeled according Sarkar (Sarkar and Balakrishnan, 1990) proposal as Eq. (20).

$$Y_M = 2 \rho e \frac{\kappa}{\gamma R T}$$  \hspace{1cm} (20)

In Equations (14)–(19), $C_{1\kappa} = 1.44$ and $C_{2\kappa} = 1.92$ are constants; $\sigma_s = 1.0$, $\sigma_e = 1.3$ and $\text{Pr}_t = 0.85$ are the turbulent Prandtl numbers for $k$, $\epsilon$ and energy, respectively. Also $\mu_t$ is the eddy viscosity coefficient which is calculated from Eq. (21).

$$\mu_t = \rho C_{\mu} \frac{\kappa^2}{\epsilon}$$  \hspace{1cm} (21)

where $C_{\mu}$ is a constant and its value for standard $\kappa$–$\epsilon$ method is $C_{\mu} = 0.09$.

### 3.4. Geometry and grid generation

The geometry under investigation is a pipe with 500 m long in which a hole has been made in the first 300 m from initial point of pipeline. The leakage will be investigated for various amounts of the hole diameter and initial point pressure. Since the walls are a major source of the vortex and turbulence and near the walls quantities such as speed has a severe gradient, modeling the flow

![Fig. 7. Comparison of normalized release flow rate from hole between this study and others.](image-url)
near the wall properly has a very important effect on the success of the solution. Therefore to achieve this, the solution domain is divided to 9 zones in the above-ground pipe state and in the buried case is divided to 18 zones. Figs. 3 and 4 show the solution domain divided to 9 zones in the above-ground and buried pipe state, respectively.

The grid structure employed for computation is shown in Fig. 5. The structured mesh (Square cells) is used for computation. The fine grid is utilized near the walls as well as hole, where the highest change is expected.

Table 1 shows the validity and independence of the number of cells used in the computational domain (this table is as an example for a model with \( D = 163.6 \text{ mm}, d = 15 \text{ mm} \) and \( p_1 = 3 \text{ bar} \)). Because of the small size of the holes, the investigations show that the models can be extended to other diameter holes, too. The mass flow rate of leaked gas difference between model with 530,000 cells and 1,070,000 is about 7.5% while this difference for the models with 1,070,000 and 1,260,000 cells is about 0.6%. Finally, based on the results, the computational domain for all samples is considered almost 1.5 million computational cells.

3.5. Numerical simulation of flow inside the soil

Coefficients required for modeling porous medium resistance to fluid flow are defined in two ways of experimental or porous material properties. Viscous resistance and inertial resistance are coefficients that are obtained from the properties of the porous material used. In this research, soil is considered as a porous material with an isotropic porosity (same resistances in all directions). Viscous resistance is defined as the inverse of the permeability of porous material (1/\( \mu \)).

Another way to determine the coefficients of viscous and inertial resistances is the use of experimental formulas; for example, an experimental formula provided by Ergun, (1952) to calculating the coefficients. In this formula, viscous and inertial resistances are as functions of porous particle diameter and the porosity amount. Also, the properties of the soil which used in this research are as Table 2.

3.6. Boundary conditions and fluid properties

The boundary conditions which are used in the computational domain contain pressure inlet, pressure outlet and wall boundaries. Type of the boundary conditions, which used for each of the selected boundaries, is shown in Table 3. Also for buried gas pipe, hole is a subscriber boundary between pipe and the soil and this boundary should be disconnected between pipe and soil; after disconnecting, two boundaries are created and type of these boundaries is according to Table 3. The pipe under investigation is located in the urban distribution gas pipelines with low pressure level and relatively small pipe diameter and this means that natural gas can be treated as an ideal gas (Montiel et al., 1998; Yuhu et al., 2003; Lu et al., 2014; Luo et al., 2006). Therefore there is a different between current study and other models that investigated leakage for high-pressure gas pipelines (Olorunmeyi and Ismede, 1993; Flatt, 1986), in which it should be take into account dispersion of the pressure along the pipe. Natural gas is mainly composed of methane, ethane and propane (Jarrahian and Heidaryan, 2014a). Since the major component of natural gas is methane (approximately 75%–98% of natural gas is methane) (Jarrahian et al., 2015; Jarrahian and Heidaryan, 2014b), natural gas is assumed to contain only methane.

3.7. Numerical procedure

The governing equations are discrete by Upwind method. The coupling of the velocity and pressure phrases is done by using SIMPLE algorithm. The Fluent software in pressure based solver mode is used for the current study.

Fig. 6 shows the convergence of the outlet mass flow rate from the hole (this figure is as an example for a model with \( D = 163.6 \text{ mm}, d = 30 \text{ mm} \) and \( p_1 = 4.5 \text{ bar} \) in above-ground state). Our experience shows that for flow with compressibility importance or high working pressure, for better convergence and the correct answer, it is suggested to discretize the governing equations with first order firstly. After the solution reached convergence, the second order method of discretization can be employed.

In this study, the governing equations are discretized and solved for 8000 iterations by the first order Upwind method. As it can be realized from Fig. 6, after 8000 iterations, the solution is converged but the results are not accurate enough. Therefore, the terms including density phrases are discretized and solved with the second order Upwind method for a repeat of 8000–10,500 iterates; and then a repeat of 10,500–15,000, momentum equation discretized and solved with the second order method too. According to Fig. 6 after performing each of these steps, it is observed that a leap occurs in the amount of mass flow rate. Finally a repeat of 15,000–16,000, the energy equation discretized by second order Upwind method and it is observed that it has no effects on the solution.

![Fig. 8. Contour of the Mach number around the (as sample for \( d = 20 \text{ mm} \) and \( p_1 = 4.5 \text{ bar} \).](image)
4. Results and discussion

4.1. Model validation

This section presents the validation of the numerical simulation. Due to the limited researches in the field of natural gas leakage from buried pipes and also lack of similar reference to current study, for validate results and simulation method of this study, the results have been compared with above-ground pipe state. To validate the results of the simulation, numerical results of this research have been compared with results of Montiel et al. (1998).

Montiel et al. (1998) modeled a pipe with a length of 1000 m and an inner diameter of 163.6 mm in distribution pipelines which has a hole in one end (the pipe is intended to be a closed reservoir) and methane with assumption of ideal gas was considered as natural gas. Modeling of ref Montiel et al. (1998) was assumed by a one-dimensional and the flow in the pipe adiabatic. In addition, the finite difference method (the Secant iterative algorithm) is used to solve the governing equations on the problem.

The model used for validation in the present study is divided into two cases. The first case contains a pipe with a length of 1000 m that a hole is created at the end of it (it means that in first case, similar to ref Montiel et al. (1998), the length of the pipe after the hole isn’t considered); the second case contains a pipe with a length of 1500 m that a hole is created at the distance of 1000 m from beginning point. In second case the hole divided the pipe into downstream and upstream sections. Boundary conditions and solution assumptions for this simulation have been considered similar to the reference Montiel et al. (1998). Then, numerical results have been compared with Montiel’s results.

Fig. 7 compares the results of the normalized volumetric discharge rate from hole between this research and the other researches. As it can be seen, there is a good agreement between the results of ref Montiel et al. (1998) model and first case of current model that shows the validity of the current modeling. The reason of larger numbers in results of second case than Montiel research, can be considering due to the movement of the reversal flows from downstream section toward the hole. Also as it seen, by increasing the hole diameter the flow reversal becomes more and the result
differences of the two researches gets more. This indicates that ignoring the pipe length after the hole caused some errors in the amount of leakage, compared to the actual state. Also the percentage of relative difference between second case of present study (with L after the hole) and Montiel’s (Montiel et al., 1998) model is about 7.11%, 3.8% and 5.53% for holes with 20 mm, 25 mm and 30 mm diameter, respectively.

In Fig. 8, contour of Mach number is presented. As it may be observed, in the investigated range of hole diameters, the average of Mach number at the hole is approximately unity which indicates the existence of a sonic flow. This issue is another reason showing the accuracy of this simulation and its related results.

4.2. The effect of pipe diameter, hole diameter and pressure on leakage

In this section, the effects of various parameters on natural gas release for both above-ground and buried pipe states are presented. Effective parameters on the amount of leakage for low-pressure gas pipelines can be identified as: pressure of initial section \( p_1 \), pipe length \( L \), pipe diameter \( D \), hole diameter \( d \) and mean temperature of the pipeline \( T_f \). The effect of pipe length appears in the pressure drop along the pipe and as it motioned in previous sections, the current model is developed for urban gas distribution pipelines operating at low pressure with relatively small pipe diameter; therefore due to these, the pressure drop along the pipe is negligible. Also, due to adiabatic flow assumption temperature changes along the pipe is very low. Based on the foregoing, effective parameters of this study are as \( p_1, d \) and \( D \).

The model of this investigation is a polyethylene pipe (pipe roughness 1.5 µm) (Handbook of Polyethylene (2007)) with a length of 500 m which is located at the urban gas distribution system. A hole 300 m from the initial point of the pipe is created on the lateral surface of it and the flow has a developed state before reaching the hole.

The inlet temperature is 288 K and the problem is investigated with the different amounts of beginning point pressure in the range of 3 bar—5 bar absolute. Hole diameter is investigated in the range of 5 mm—80 mm and pipe diameter investigated for three most common pipe sizes (with nominal diameters: 114.6 mm, 163.6 mm and 204.6 mm) with used in urban gas distribution systems. In the case of buried pipes, the soil above the pipe is considered 1.5 m high.

Analysis of the results indicates that, per a specified amount for input pressure, the larger amount of the hole diameter, causes increasing in the pressure difference between the initial point and hole \( p_1 - p_3 \) which results in increasing the volumetric flow rate output.

Fig. 9 provides volumetric flow changes in terms of the hole diameter in different amounts of inlet pressure for gas pipeline
states including above-ground and buried pipes (because the overall behavior of charts for different values of the pipe diameter is the same, this chart is given as a sample for a case with $D = 204.6$ mm). The result of curve fitting for leakage flow changes depending on hole diameter, showed that the leakage flow with hole diameter ($d$) and ratio of the diameters ($d/D$) varies as a second order and fourth order function, respectively. Also, by comparing Fig. 9(A) and (B), as expected, the volumetric flow rate of leakage in the buried pipe state is less than the one in the above-ground state, because of the resistance of the soil column on top of the hole.

In Fig. 10, the volumetric flow rate change is shown according to the inlet pressure for different diameters of the holes. As shown in this figure, the volumetric flow rate has an approximate linear function with inlet pressure. Also by increasing the initial point pressure, the pressure difference of initial point and the hole gets more and as a result the leaked gas flow from the hole increases. By comparing Fig. 10(A) and (B) it can see that, the volumetric flow rate of released gas from the hole in the buried pipe state is less than above-ground pipe, which is due to soil resistance.

Due to compressibility of investigated fluid in this study, all the quantities have various values in different points of the hole. Therefore in order to quantify at the hole, mass-weighted average have be taken into account.

Figs. 11 and 12 respectively show the absolute pressure contour in the pipe and around the damaged section for the above-ground and buried pipelines. As seen in the Fig. 11(A), the pressure drop along the pipe is very small but sudden pressure changes is significant around the damaged section, due to the sudden change in the sectional area in damaged area (small hole diameter in ratio to the pipe diameter). In other words, when the hole is too small, it causes the pressure at the damaged section to be greater than the ambient pressure. Also, a survey of results shows that by increasing the hole diameter, the pressure difference between the ambient pressure and the damaged section decreases.

The achievement of noted cases, creating an expansion wave into the pipe that makes the gas flow moves toward the hole. As shown in Fig. 13(A), the consequent of the velocity at the damaged section of above-ground pipe equals to the sound speed.

In case of buried pipes, the damaged section is a common section between the pipe and the soil. According to the Fig. 13(B), in the case of buried pipe, we also have a sonic flow; but just in the proximity of the hole and inside the soil (immediately after the entry of gas flow into the soil), we see a subsonic flow. The reason for this matter is the resistance of the soil that reduces the gas flow speed when entering the soil. In addition, the pressure caused by the soil above the damaged section makes the input and output pressures in the damaged section different.

Entering natural gas flow into the soil and its hit with soil particles and also passing air through the soil particles causes the natural gas emission into the soil and creates two vortices on the right and left sides of the gas flow in the soil. Fig. 14 shows the velocity vectors inside the pipe and soil around the hole. By magnifying and increasing the size of the velocity vectors, the created vortices are observed in the Fig. 14(C).
Fig. 14. Velocity vectors around the hole for buried pipe.
By analysis of the results of this simulation and using curve fitting method, it is observed that volumetric flow rate of leaked gas has a second, fourth and linear relation with the hole diameter, ratio of the hole diameter to the pipe diameter and initial point pressure respectively. According to this, normalized volumetric flow rate of natural gas leakage from urban distribution gas pipes, can be respectively calculated by Eqs. (22) and (23) for above-ground and buried pipes.

\[
Q = 0.748 \left(1 + \beta^4\right) d^2 p_1 \quad (22)
\]

\[
Q = 0.44 \left(1 + \beta^4\right) d^2 p_1 \quad (23)
\]

As it can be seen, these equations have an agreement with Eq. (2). In Eq. (2) the amount of leaked gas calculated from an orifice which installed at the end of a vertical pipe. The orifice located at the outlet of a pipe and between two flanges. This equation can only be used for an approximate estimation of discharged gas from an orifice into the atmosphere. In the other word, this case is different with the real accident of gas leakage and gives approximate and unreal results. Therefore based on the results of this research, Eq. (2) modified into the Eq. (22).

Comparison between Montiel’s model (Montiel et al., 1998) and results of Eq. (22) are presented in Fig. 15. As it could be seen, general behavior of both charts is similar. As it mentioned before, the leakage value obtained by Eq. (22) is higher than Montiel’s model (due to reversal flow from downstream side toward hole). A significant increase in outflow from the hole can be seen for larger hole diameters. Also by increasing hole diameter, difference of the hole pressure and downstream pressure get more and we could see more reversal flow from downstream side toward the hole. Therefore, considering the length of pipe after the hole have an impact on large diameter holes. In other words, disregarding length of downstream in previous studies causes unrealistic prediction for leakage. According to the figure, the percentage of relative difference between the results is 2%, 4.5%, 11%, 12.43% and 12.3% for 10 mm, 15 mm, 20 mm, 25 mm and 30 mm holes, respectively. Fig. 16 compares numerical values and results of Eq. (22). Data analysis shows that the minimum percentage of relative error between these results is about 1.276% (which is for a case with \(d = 5\) mm and \(p_1 = 5\) bar) and the maximum of it is about 6.625% (which is for a case with \(d = 30\) mm and \(p_1 = 3\) bar).

5. Conclusion

In this investigation, a two-dimensional, turbulent and compressible gas flow model has been built to predict leakage from above and underground natural gas pipeline. Based on the numerical results, the following points could be made:

- By increasing the hole diameter, the pressure of damaged section is reduced and consequently the pressure difference increases between the damaged section and initial section, which results in the increase in the leaked flow. In this investigation, small diameter holes are examined and it makes the pressure difference between the damaged section and the ambient pressure to be low and have a sonic flow in the damaged section.
- For larger hole diameters, taking into account the length of pipe after the hole will have a significant impact on results due to the increase of the reversal flow from the downstream toward the hole. In the other word, considering the length of pipe after the hole show an impact on large diameter holes. The reversal flow from downstream part toward the hole causes higher amounts in prediction of the gas leakage. For example in a case with \(D = 163.6\) mm and \(p_1 = 5\) bar, considering the pipe length after the hole causes 2–15% increasing in the amounts of leakage for various hole diameters.
- In case of buried pipes, the damaged section is a common section between the pipe and the soil and similar to the above-ground pipe status in this case, we also have a sonic flow, but just in the proximity of the hole and inside the soil, we see a subsonic flow. The reason for this matter is the resistance of the soil that reduces the gas flow speed when entering the soil. In addition, after entering natural gas flow into the soil and hitting with soil particles and also passing air through the soil particles, a pair of the vortices created on both sides of the gas jet which penetrated into the soil.
- By analysis of the results of this simulation paid to provide a simple and useful correlation to calculate the amount of natural gas leakage from urban distribution pipelines for both above-
ground and buried gas pipes. According to this correlations, the volumetric flow rate of natural gas leakage, changes as ascending functions approximately into the second, fourth and first orders with hole diameter, ratio of the hole diameter to the pipe diameter and initial point pressure, respectively. Also in most of the investigated cases, the percentage of relative error between simulation results and correlation results is below 5% which implies high accuracy of the presented correlation.

- This model is therefore a step forward in the effort to develop more precise and powerful calculation tools to foresee the effects and consequences of potential accidents caused by the loss of containment of hazardous materials.

References


Nomenclature

$C_p$: correction factor of the gas specific weight

$CR$: critical pressure ratio

$d$: hole diameter (mm)

$D$: pipe diameter (mm)

$E$: total energy (J)

$F$: external body forces (N/m^3)

$F_g$: correction factor of the gas temperature

$G$: gravitational acceleration (m/s^2)

$K$: conductivity factor (W/mK)

$m$: mass flow rate (kg/s)

$n$: pressure (bar)

$p$: Mach number

$q$: volumetric rate of leaked gas (Nm^3/hr)

$R$: gas constant (kg/kg)

$t$: temperature (K)

$u$: velocity (m/s)

$v$: specific volume (m^3/kg)

$x$: displacement (m)

$Z$: compressibility factor of gas

Subscript

$i$: initial point of the pipe

$cr$: critical

$eff$: effective

$f$: fluid passing through porous media

$i, j, l$: directions

$s$: solid material of the porous media

$t$: turbulent

Greek letters

$\alpha$: permeability of the porous material (m^2)

$\beta$: orifice ratio

$\delta$: Kolmogorov delta

$\varepsilon$: turbulence dissipation rate (J/kgs)

$\gamma$: $c_p$/c; heat capacity ratio

$\delta$: porosity of the porous media

$\zeta$: turbulence kinetic energy (J/kg)

$\mu$: viscosity (kg/ms)

$\rho$: density (kg/m^3)

$\tau$: stress tensor (Pa)