Simulation of Gas Pipelines Leakage Using Modified Characteristics Method

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The process of pressure reduction and gas leakage rate (discharge characteristics) of a hole has so far been accomplished by utilizing some zero-dimensional models. In these models, the effects of complex boundaries are ignored. The major aim of this study is simulating the process of pipeline gas leakage by the aid of a modified one-dimensional characteristics model. This model, beside the possibility of modeling the impact of leakage on one-dimensional compressible flow, benefits from introducing a variety of boundary conditions to flow zone. In this approach, hole is considered as an orifice, which makes a path for gas to release in a lower pressure ambient. Also, in this study, the effects of four kinds of boundary conditions at the ends of the pipeline on gas discharge characteristics are investigated. [DOI: 10.1115/1.4005697]

Keywords: leakage, gas pipeline, characteristics method

1 Introduction

The natural gas is considered as a clean source of energy worldwide. One of the usual problems is finding methods for prevention of wasting natural gas during transportation and distribution. Fannelap and Ryhming [1] studied the unsteady flow in a natural gas pipeline in which a break occurred at the high pressure end. They divided the flow into three time regimes. The "early time regime" following the sudden break is dominated by wave processes, and the pressure at the open end approaches the ambient value. This is followed by the "intermediate time regime" in which an internal pressure peak occurs, the location of which corresponds approximately with the location of flow reversal where the velocity is zero. By the time the pressure peak gets to the low pressure end of the pipe (the closed end), the "late time regime" starts. In this time regime, the pressure in the pipeline decreases monotonically from the closed end of the pipe to the open end. Lang and Fannelap [2] improved on this work by using some approximation procedures in the family of weighted residuals. The flow profiles were not specified a priori as in the work of Fannelap and Ryhming but were found as part of the solution. They were able to obtain more accurate results, but their methods produced oscillations in the dependent variables predicted during the early time regime. Ryhming [3] used the method of matched asymptotic expansion to study unsteady isothermal flow in a long pipeline ruptured suddenly. He showed that wall friction caused the velocity derivative along the pipe to become singular at the broken end exit when the flow was critical. Flatt [4] developed a method of characteristics to compute unsteady adiabatic flow of natural gas in a long pipeline following a sudden break. His method could handle flows in the three time regimes because he used the full set of hyperbolic partial differential equations.

The quantitative risk assessment of the pipelines consists of estimation of failure probability and failure consequences. As a failure consequence, first of all, the gas release rate through the damaged pipeline must be studied. There are two ordinary models to calculate the gas release rate [5–7]. One is the hole or tank model, which is only suitable for calculation of gas release through small holes in which the pipeline is considered as a tank. The second one is the pipe model, which is especially efficient when the pipeline is ruptured. In order to eliminate the gap between these two models, a relevant model was proposed by Helena et al. [8]. In their model, gas is considered as a perfect gas, but this assumption would bring a large error when the pressure is high. Yuhua et al. [9] also investigated the gas release rate at different holes diameter by the aid of a compound model, which merges two models of tank and pipe in the range of their applicability.

In this study, presented somewhat differently by Nourollahi [10], the process of gas release through the hole is simulated by a modified one-dimensional characteristic method. In this method, the impact of hole on flow characteristics is accomplished by using orifice model. Also, it is now possible to introduce boundary conditions to compressible flow. Therefore, the effects of four specific cases of boundary conditions (open end, closed end, reservoir, and nozzle) on discharge characteristics are investigated.

2 Problem Description

The pipe surface leakage or the pipe section dismissal can be created because of various reasons, such as corrosion, earthquake, and mechanical stroke, which may be implemented by overload compressors. When this leakage is created, the flat expansion pressure waves propagate in two converse sides. These waves have the sonic speed and, after clashing to the upstream and downstream boundaries, return in the form of compression or expansion wave depending on the edge type conditions (Fig. 1). In the leaking location, the flow will be subsonic or sonic depending on the ratio of pressure to ambient pressure to be more or less than CPR (critical pressure ratio) quantity, which is

$$\mathrm{CPR} = \frac{P_{\mathrm{out}}}{P_{1\mathrm{cr}}} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{1}$$

In the above equation, $P_{1\mathrm{cr}}$ is the critical pressure of point 1 and k is thermal capacity ratio. Therefore, the problem physics changes to one of the following cases: If the leaking flow is sonic and supersonic, the pressure wave cannot inter back to the pipe practically. Hence, the changes in the flow field are accomplished due to the flat pressure waves and the real boundary conditions on the start and end of the pipe. Also, mass flow outlet of the hole depends only on the stagnation pressure in the leaking location and on the area of the hole and is not related to the shape of the orifice cross section. But, if the flow in the leaking location is subsonic, the hole could be the source of production of compression or expansion sonic wave and will affect the flow field. In this situation, the pipe and leakage spot act as a T junction, and the mass outflow of the leaking location would depend on the ambient pressure and a coefficient known as empirical discharge coefficient, in addition to the stagnation pressure and the orifice area.

Since the pressure with respect to the ambient pressure in gas transmission pipelines is great and its ratio is more than CPR and also the gas flow is provided permanently from the sources like gas refineries, in this paper, the problem physics is considered like the sonic flow, and therefore, a modified one-dimensional characteristics method would be suitable. The assumption is that the pipe inner flow is homentropic, hence the solution of the mass and

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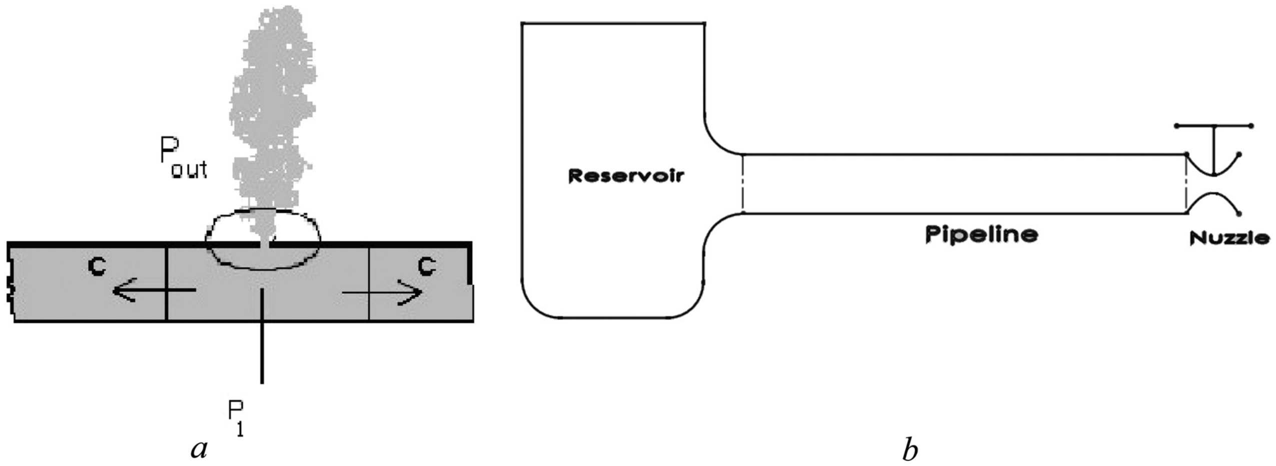

Fig. 1 **(*a*) Leakage display and waves that produced. (*b*) The implementation of the leakage effect.**

momentum conservations in addition to the constant entropy flow assumption are sufficient for flow simulation. In Sec. 3, the modified characteristics method is introduced, which considers the necessary corrections for the leakage effects in order to determine the leakage flow and the pressure distribution in the pipe line.

3 Modified Characteristics Method

Some authors [11,12] have developed many features of characteristics method in order to calculate different cases of one-dimensional compressible flows. Homentropic flow (a flow which has a same entropy level in the whole field) is a special case of the compressible flow problem, and its solution is fairly straightforward compared to the more complicated general flow problems. The physical process of gas release through a hole for a high pressure pipeline is a complicated one and is difficult to be simulated by high order numerical methods. In Sec. 3.1, a modified characteristics method for evaluating the impact of hole on flow parameters will be introduced. It is assumed that flow is homentropic and gas discharge through hole is calculated using orifice model.

3.1 Method Explanation. Calculation of one-dimensional compressible flow using characteristics method is equivalent to determination of two characteristic values, which are named Reimann variables. These variables are functions of two parameters: dimensionless sound speed and dimensionless particle velocity and are defined as

$$\lambda = A + \frac{k-1}{2}U; \quad \beta = A - \frac{k-1}{2}U \tag{2}$$

where

$$U = \frac{u}{a_{\mathrm{ref}}}; \quad A = \frac{a}{a_{\mathrm{ref}}} \tag{3}$$

Therefore, determination of two parameters β and λ in any point of solution field is going to bring about the speed and pressure at that point. In order to estimate the variations of flow parameters by time, there are explicit relations between Reimann variables in inner points of the solution field. These relations are presented as

$$\lambda_i^{n+1} = \lambda_i^n \frac{\Delta t}{\Delta x}\left[b\lambda_{i-1}^n - a\beta_{i-1}^n\right].\left[\lambda_{i-1}^n - \lambda_i^n\right] \tag{4}$$

$$\beta_i^{n+1} = \beta_i^n \frac{\Delta t}{\Delta x}\left[b\beta_{i+1}^n - a\lambda_{i+1}^n\right].\left[\beta_{i+1}^n - \beta_i^n\right] \tag{5}$$

For each end, based on governing equation of state, there is a relation between Reimann variables. Therefore, at a boundary, new value of one characteristic will be determined from the old value of the other characteristic [11]. Boundary conditions can be open end, closed end, valve with the special opening percentage, exit nozzle with special opening percentage, orifice, reservoir, the end without the changes with respect to the location, etc. An example of the configuration of the boundaries is shown in Fig. 2.

For implementation of the leakage effect on the flow field, the mesh is chosen in such a way that the hole location would be situated between two nodes, as shown in Fig. 2.

When $P_{1\mathrm{cr}}$ is the critical pressure of point 1 (in Fig. 1) and $P_1 > P_{1\mathrm{cr}}$, the gas release is a sonic flow at the orifice, and its rate is described by the following equation [11]:

$$Q = A_{\mathrm{or}}P_l \cdot \sqrt{\frac{M}{ZRT_l}\cdot k \cdot \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{6}$$

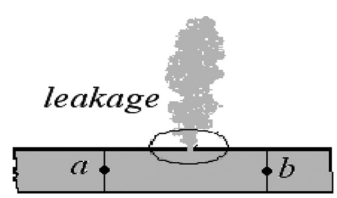

Fig. 2 **Location of hole between two nodes**

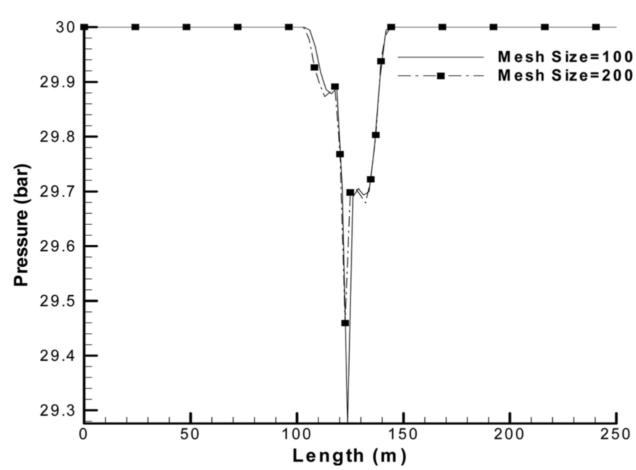

Fig. 3 **Grid independency**

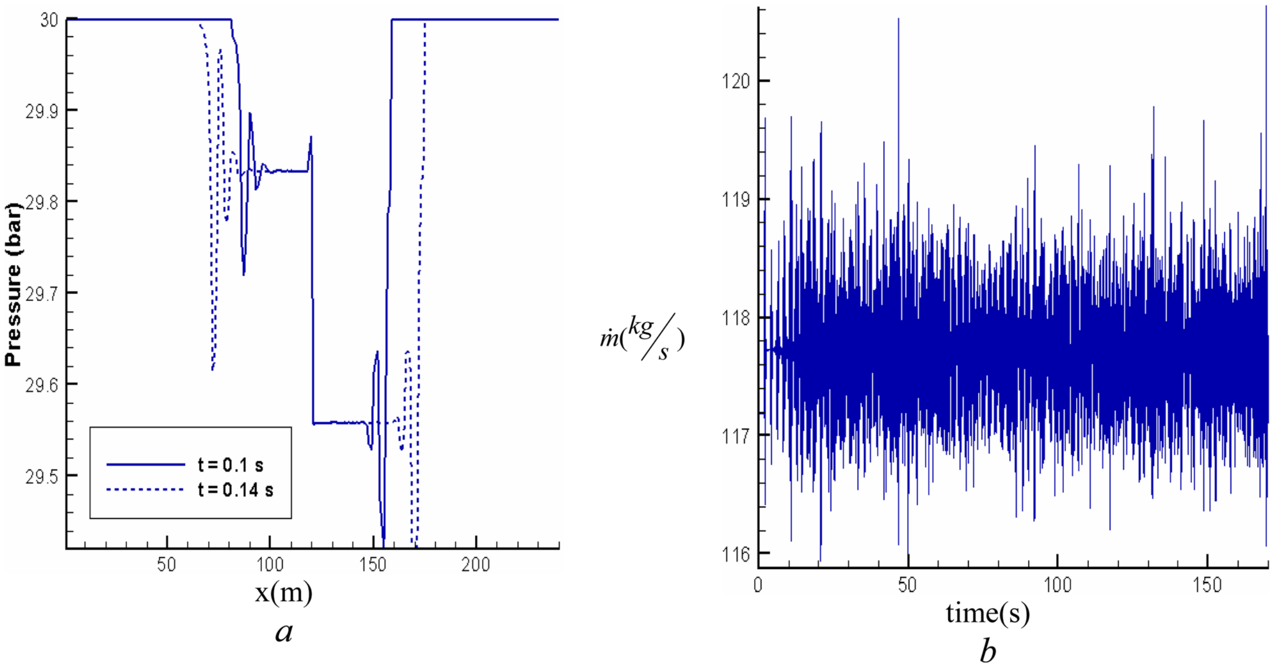

Fig. 4 State (1) of the boundary conditions: (*a*) Pressure changes as function of the pipe length at primary times. (*b*) Changes of the exit mass flux by time.

The leakage point in any time-step acts as a boundary and the two expansion waves would reach to the points a and b with a little time difference and make changes in nondimensional speed as

$$U_a = U_a - \frac{Q}{\dot{m}_a} \cdot U_a$$
$$U_b = U_b + \frac{Q}{\dot{m}_b} \cdot U_b \tag{7}$$

Therefore, two known characteristics (λ_a and β_b) based on the definition of the positive direction (toward boundary) for the particle velocity will be as

$$\lambda_a = \frac{(2 * A_a + (k-1) * U_a)}{2}$$
$$\beta_b = \frac{(2 * A_b - (k-1) * U_b)}{2} \tag{8}$$

Then, the unknown parameters λ_b and β_a are calculated as

$$\beta_a = \lambda_a - (k-1) * U_a$$
$$\lambda_b = \beta_b - (k-1) * U_b \tag{9}$$

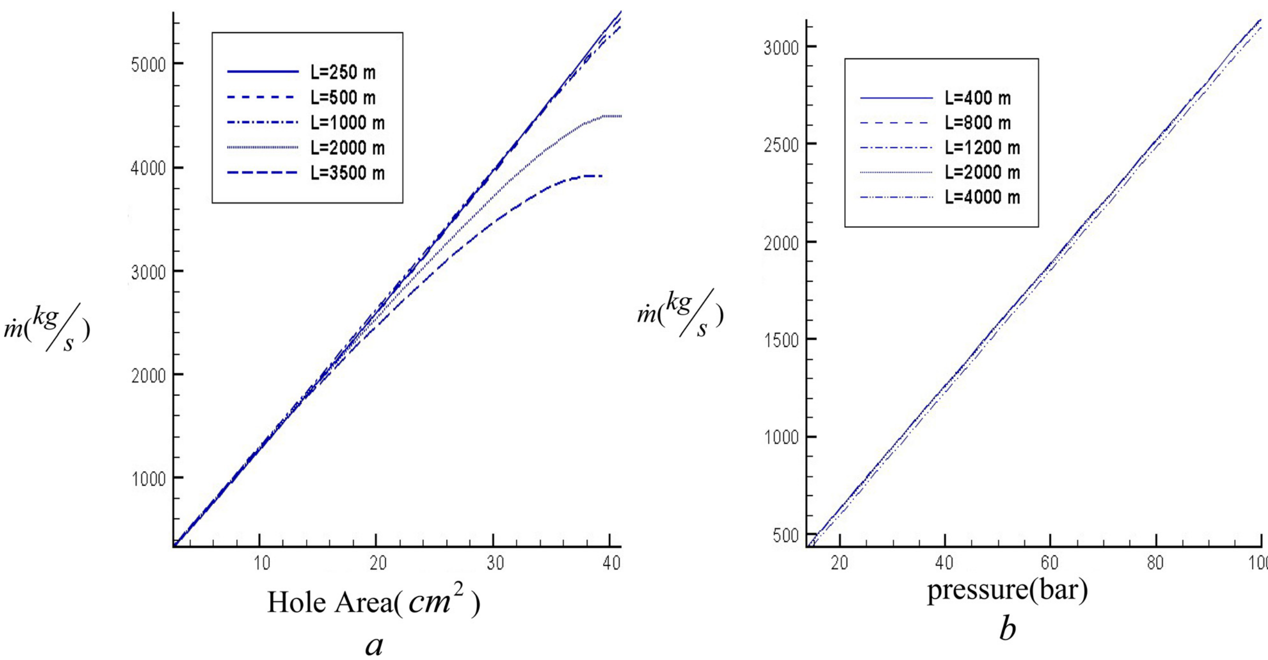

Fig. 5 State (1) of the boundary conditions: (*a*) Exit mass flux change as a function of hole area and pipe length. (*b*) Exit mass flux change as a function of pipe pressure and pipe length.

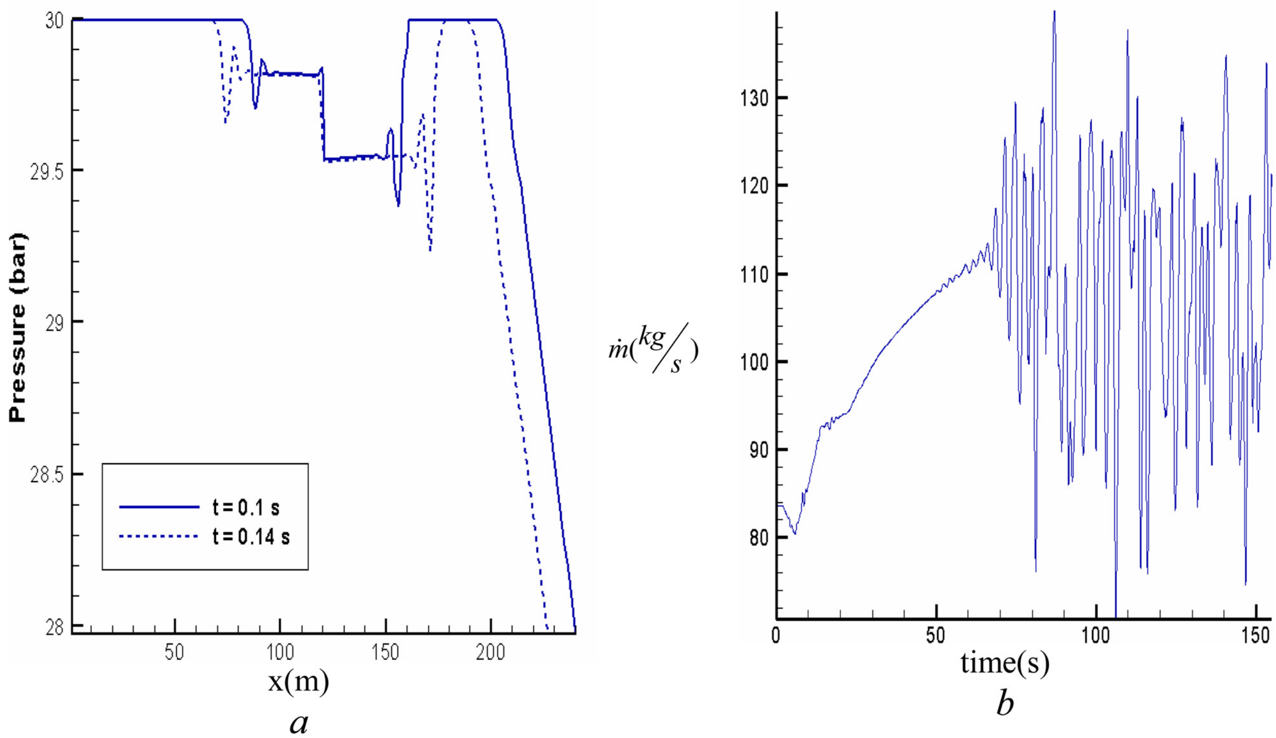

Fig. 6 State (2) of the boundary conditions: (*a*) Pressure changes as function of pipe length at primary times. (*b*) Changes of the exit mass flux by time.

Consequently, gas release through the hole will modify Riemann characteristics of all points and then makes change in flow velocity and pressure of any points.

4 Results and Discussion

In this section, the results of the simulation of the leakage are presented for a pipe with the length of 250 m, and there is a hole (orifice) with 1 cm^2 area on its surface, by using a grid system with 100 nodes. Also, it is considered that the hole is in the middle of the pipe length and the initial gas pressure and initial gas speed are assumed to be 30 bar and 12.5 m/s, respectively [13]. It is considered that the upstream boundary condition is the reservoir with constant pressure and the downstream boundary condition is stated with the following three forms:

- the boundary with no changes with respect to the location
- the valve with constant coefficient of pressure drop
- closed end

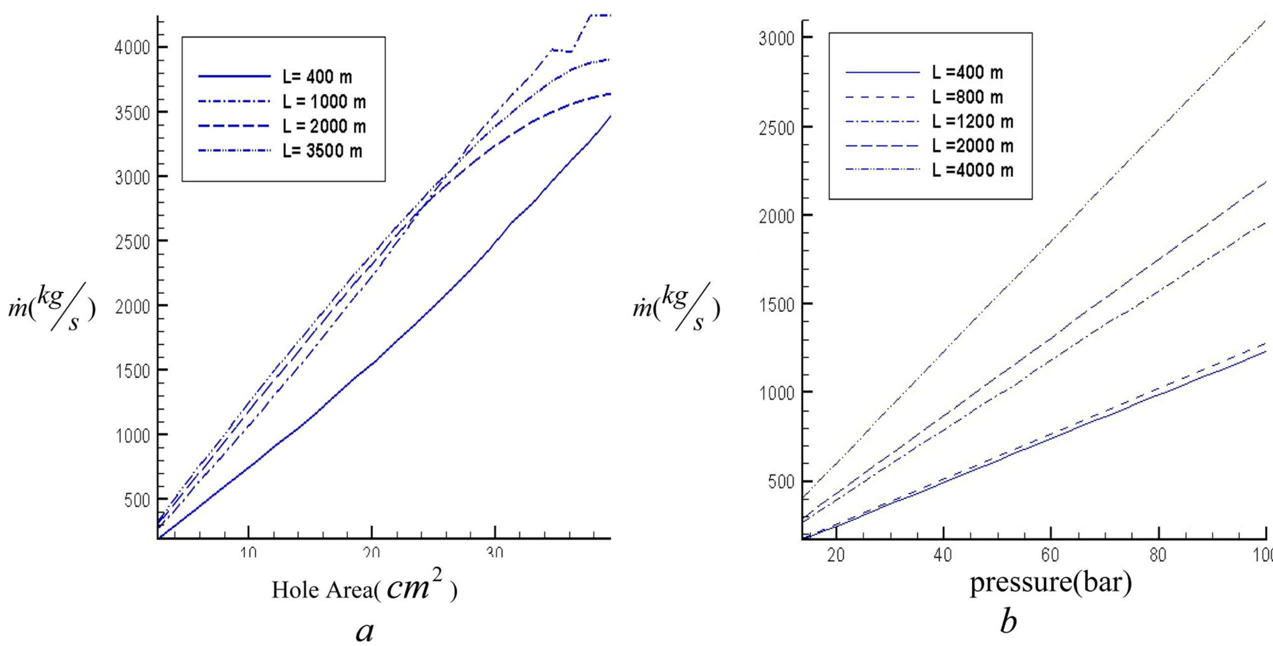

Fig. 7 State (2) of the boundary conditions: (*a*) Exit mass flux changes as a function of hole area and pipe length. (*b*) Exit mass flux changes as a function of pipe pressure and pipe length.

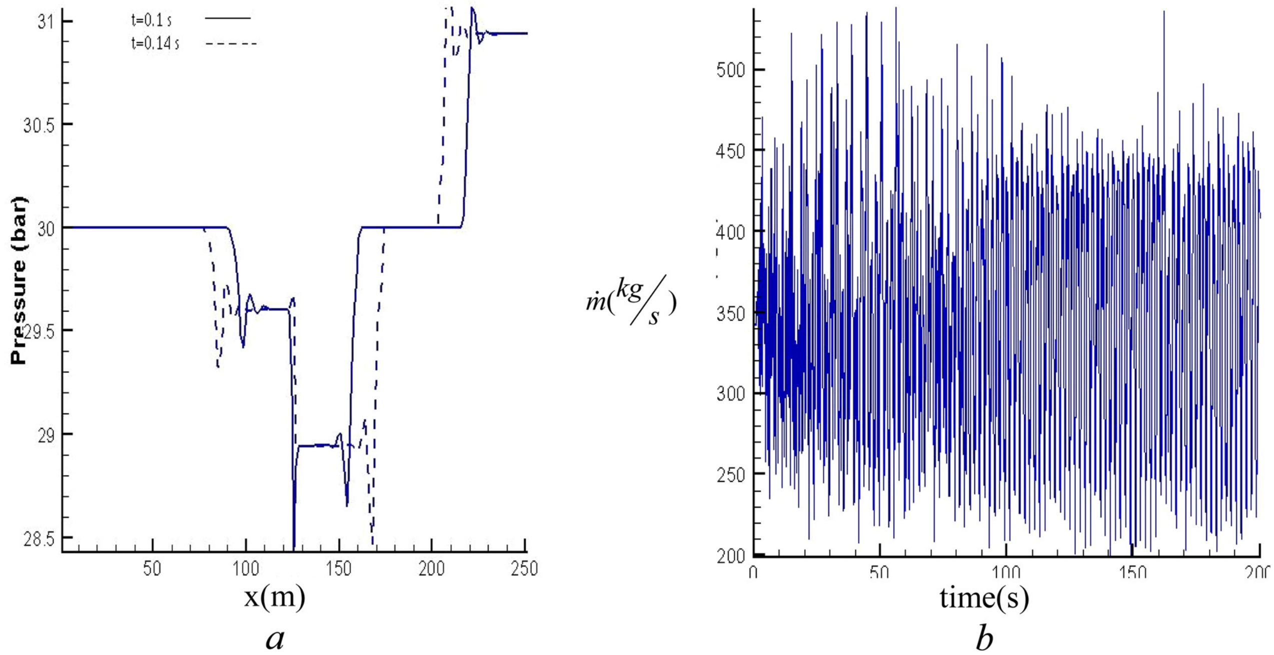

Fig. 8 state (3) of the boundary conditions: (*a*) Pressure changes as function of pipe length at primary times. (*b*) Changes of the exit mass flux against time.

The first situation is when the pipe length is very long compared to the hole, where gas pipelines are like this in the most of the cases. The second situation is when the leakage occurs before a valve with the constant pressure drop in a part of the pipe. The third situation is when the pipe end is closed (e.g., when the exit valve is closed completely). In the following paragraphs, the respective results and discussions for the pressure changes in the initial times (to see how the expansion waves from the leakage location propagate) and changes of mass flux against time are presented. First, grid independency of the method used is shown in Fig. 3, which is for the first 0.05 s of the leakage process.

Figures 4 and 5 are for the no gradient boundary (with respect to the location), and Figs. 6 and 7 are for the downstream boundary related to the valve with the constant pressure drop, and also, Figs. 8 and 9 are for the closed downstream boundary. By studying these situations, the following conclusions can be inferred: Figures 4(*a*), 6(*a*), and 8(*a*) depict the history of pressure wave progress in the one-dimensional medium of pipeline in earlier stages. As it can be seen, the hole produces expansion pressure waves, which, based on the flow direction in pipe, are weaker or stronger in magnitude. But, the oscillations in profiles of pressure waves are because of second order accuracy of characteristics method in space. From Figs. 4(*b*), 6(*b*), and 8(*b*), it can be seen that the leaking mass flux has an intense fluctuant behavior. These oscillations are not exactly the consequences of physical behavior of gas release to atmosphere and are mainly produced because of

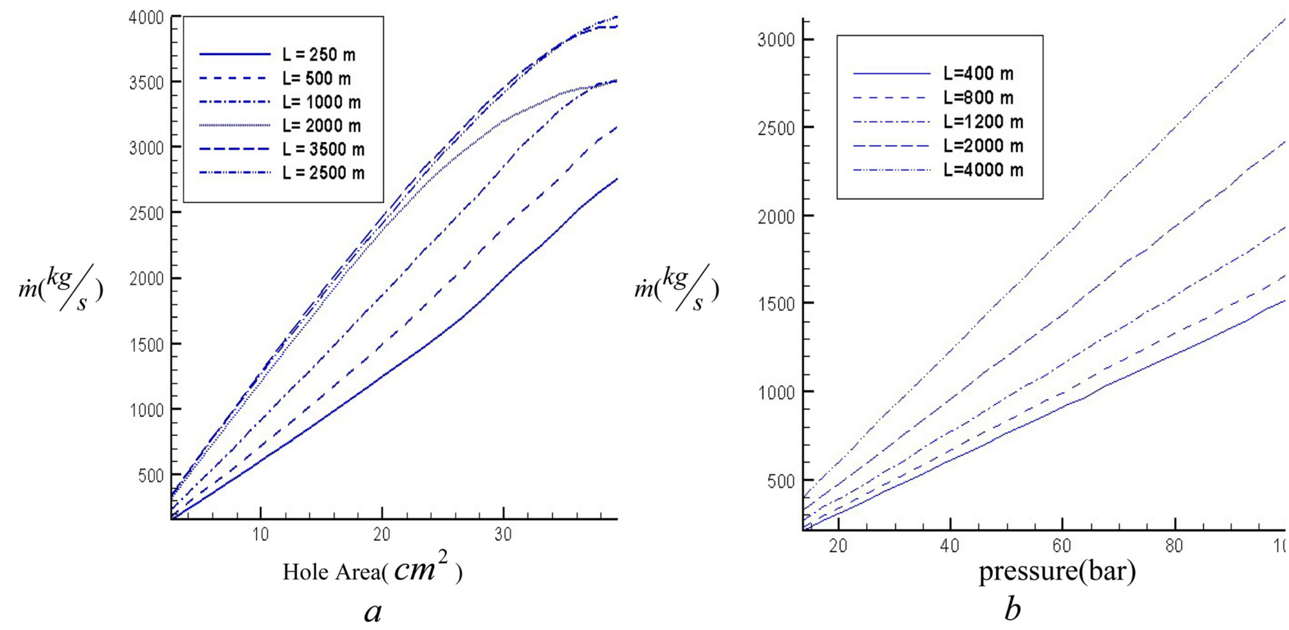

Fig. 9 State (2) of the boundary conditions: (*a*) Changes of the exit mass flux as function of hole area and pipe length. (*b*) Changes of the exit mass flux as function of pipe pressure and pipe length.

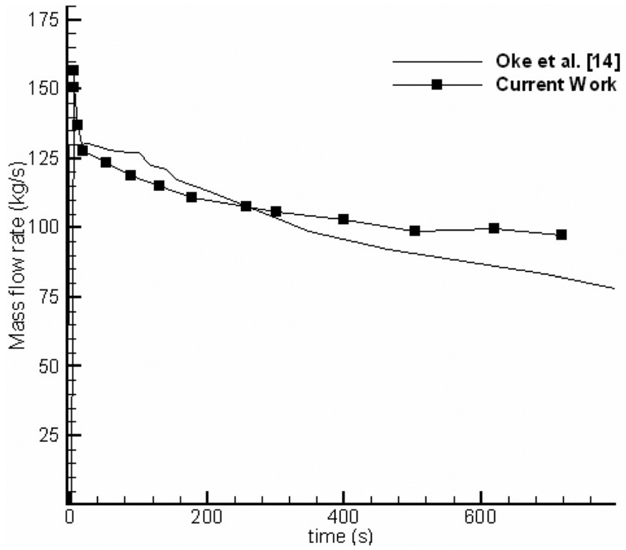

Fig. 10 Comparison of mass flow rate with the result of Oke et al. [15]

the fact that orifice model cannot predict gas flow rate, which depends on older time step values of mass flow rate. On the other hand, mass flow rate through an orifice in each time step is independent of its previous or next time step values. Therefore, the mean value of the calculated leaking flow rate is of importance. From these figures, it is obvious that the boundary conditions in upstream and downstream affect the average and amplitude values of fluctuations. Also, boundary conditions can affect frequency of the outlet mass flux. Then, because of dependency of fluctuations frequency to states of boundary conditions, it can be concluded that there are physical oscillations, which are mixed with numerical unreal fluctuations. Therefore, these physical frequencies cannot be easily estimated. In Figs. 5(*a*), 7(*a*), and 9(*a*), the quantity of the outlet mass flux changes are shown against increasing the hole area and the various lengths of the pipe. It is clear that by increasing the area of the hole, the quantity of outlet mass flux is increased for all the lengths, and this fact is true for all three states. Also, by paying attention to these figures, it is observed that the gradient of the pressure is zero at right-end. In other words, the increase of the hole area does not have any effects on the outlet mass flux, which is more obvious in diagram 5(*a*). In diagrams 5(*b*), 7(*b*), and 9(*b*), the outlet mass flux changes are shown against pressure and for the various pipe lengths. It is seen that the exit flux quantity is increased for all lengths by increasing the pressure of the pipeline, but the manner of its increase with respect to the various lengths depends on its boundary conditions. So, for the first boundary condition [Fig. 5(*b*)], the increase of the pipe length does not have any effect on it, and the gradient of all the diagrams are rather equal. But, in the second and third states [Figs. 7(*b*) and 9(*b*)], the quantity of the exit mass flux is raised by increasing the pipe length.

Since there is no experimental results for leakage through a gas pipeline to compare and validate the results of the modified method, mass flow rate through leakage of a pipeline is calculated for an incompressible flow. For this purpose, instead of using real gas equation of state, the equation of state of Tait [14] is used, and the obtained result for mass flow rate is compared with the corresponding results of Ref. [15], which is for petroleum. This comparison has been shown in Fig. 10, which relatively proves well considering the fluid flow in Ref. [14] is water.

5 Conclusions

In this study, by using modified characteristic method, the impact of leakage on flow characteristics has been investigated. This method is simple and can simulate the leaking process when pipeline pressure is high. Also, it has the advantages of introducing various kinds of boundary conditions to the flow field. Results for leaking mass flux are intense fluctuant, but only the average values have physical meaning. There is numerical noise in the flow field data like pressure that may result in some instability difficulties. Therefore, utilizing a noise removal method can be beneficial. The numerical model used here can be improved by using a one-dimensional element, which has negligible thickness instead of orifice model.

Nomenclature

A = area of cross-section (m^2)
u = velocity of gas (m/s)
M = molecular weight (kg/kmol)
T = temperature (K)
P = pressure (Pa)
ρ = density of gas (kg/m^3)
R = constant of gas (Pa m^3/mol K)
d = pipeline diameter (m)
C_D = coefficient of discharge for leak orifice
$\dot{m}$ = mass flow rate (kg/s)
t = time (s)
a = sonic speed of gas (m/s)
L = length of pipeline (m)
a_{ref} = sonic speed of gas in start point (m/s)

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