

Environmental Heating Effects on the Gas Parameters during the Long-distance Gas Pipelines Leakage Process

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Abstract

Gas pipeline is one of the most economical transportation methods. However, in the long-time operation process, leakage from pipelines may take place due to various effects such as the corrosion, natural or man-made destruction and inherent defects. The leakage may produce unpredictable damage on the human beings, animals, plants and the environment, especially the leakage from the high-pressure gas pipelines. So it is important to predict the influence area of the leakage for making emergency plan. Leakage rate is one of the basic and important parameters used for simulating and predicting the dispersion influence area of the leakage accidents, whose accuracy can improve reliability of the simulation prediction. Taking the heat exchange effect between the pipeline and the environment into consideration, with a reasonable simplification and assumptions, ignoring the influences of fluid flow inside the pipeline, a physical model is proposed. Then with the application of thermodynamics and gas dynamics theory, combining with the ideal gas state equation and the energy conservation equation, the mathematical model is established and solved. Studies and analyses are carried out for the leakage process of high-pressure gas pipelines. A leakage rate formula of the non-adiabatic leakage for both the critical and subcritical leaking process is proposed. And taking CO₂ gas pipeline leakage as an example, the variation of the temperature, the pressure and the leakage rate with the time is presented under different environmental heat transfer conditions. The results show that the environmental heating has a strong influence on the gas temperature in the pipeline, but its effect on the pressure and the leakage rate is very limited compared with the adiabatic leakage process without considering the environmental heating. Therefore, when calculating the leakage of the high pressure gas pipelines, the heating of the environment can be neglected or simplified as a first-order approximation.

Keywords: Gas; Leakage Flow Rate; Environmental Heating; Non-adiabatic Model; Carbon Dioxide

1 INTRODUCTION

Gas pipeline transportation is one of the most economical ways. However, the pipeline leakage is an inevitable and frequent phenomenon due to various factors such as the corrosion, natural elements or man-made destructions and inherent defects in the long-time operation process^[1]. The diffusion in the environment of poisonous and harmful gases such as natural gas with high H₂S content and carbon dioxide after leakage is a very complex dispersion process of atmospheric pollutants. There are many factors directly affecting the validity and reliability of the simulation results, and one of them is the leakage rate. In recent years, as increasing demand for reducing CO₂ emission, extensive and in-depth research work has been carried out, including the impact of CO₂ leakage in the geological on the groundwater^[2-3], the research of CO₂ pipeline transportation technology^[4-5], the CO₂ dispersion^[6-8] and the production of dry ice particles^[9-13] after the leakage. In the study process, CO₂ leakage rate will provide a great guidance for predicting the leakage phenomenon. Qian et al.^[14] summarized three models including small hole model, pipeline model and big hole model for the CO₂ leakage from the pipelines. Brown et al.^[15] developed a

homogeneous relaxation flow model for simulating the discharge following the full bore rupture of the dense phase of CO₂. Martynov et al. ^[16] studied three-phase releases of carbon dioxide from high-pressure pipeline and conducted relative experiment.

Besides, there are also experimental and theoretical investigations about the leakage rate of other gases, especially natural gas ^[17-21]. Liu et al. ^[22] gave the leakage rate calculation formula based on adiabatic condition without considering phase change and heat exchange with the environment during the leakage process and the leakage rate change with time under different leakage hole and pipeline diameter. Wang et al. ^[23-25] conducted a series of studies on the leakage rate of the gas. Morin et al. ^[26] evaluated the leakage rate through a fracture in a pipe with a numerical method and compared with the choked-flow theory. Oke et al. ^[27] developed a highly efficient robust numerical simulation based on the method of characteristics for predicting release rates following the puncture of pipelines containing high pressure hydrocarbon mixtures. Li et al ^[28-29] carried out the experimental study to investigate the thermodynamic and fluid dynamic behaviour in pressurized CO₂ leakage process. As mentioned above, it is very important to investigate and study the influence of the leakage rate clearly. Nevertheless, in the above researches, whether for the CO₂ or the other gases, the environmental heating effect the gas parameter during the long-distance gas pipelines leakage process is not considered.

In this paper, a physical model is established with the application of thermodynamics and gas dynamics, combining with ideal gas state equation and energy conservation equation. For the leakage process of the high-pressure gas transportation pipelines, the calculation formula of the leakage rate considering the environment heating effects is given in the non-adiabatic process of critical and subcritical leakage stage, the environment heating effects on the leakage process of the high-pressure gas pipelines is confirmed by an example.

2 PHYSICAL MODEL

Leakage of high-pressure gas pipeline is an extremely complex unsteady process. The flow of the gas in the pipeline through the leakage hole is a typical compressible gas nozzle flow process, the pressure and temperature of the inlet will change with the leakage process. The gas pressure and temperature in the pipeline will decrease due to the expansion during the leakage, and the leakage will lead to macroscopic flow of the gas. The heat exchange may take place between the gas inside the pipeline and the environment because the large temperature difference may appear during leakage process. In the extreme case, the gas itself of its heavy contents in the pipeline will change from gas to liquid, even into solid with the leakage. Therefore, the flow inside the pipeline may be no longer a single-phase and no-phase-changing process, it is obviously impossible to obtain the analytic formula of the high-pressure gas leakage rate including all the above factors. To simplify the analysis, the following assumptions are made:

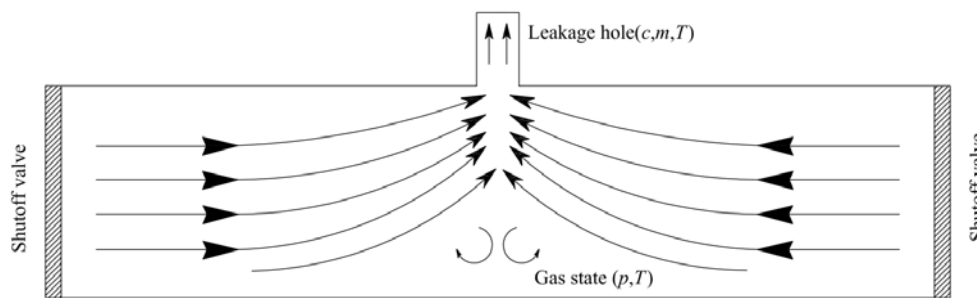


FIG. 1 PHYSICAL MODEL OF GAS PIPELINE LEAKAGE

- (a) The gas in the pipeline can be treated as an ideal gas, ignoring the possible phase change due to temperature variation during the leakage process.
- (b) The emergency shut-off device turns off immediately when the leakage occurs, and then the leakage pipeline is simplified as a rigid container of fixed volume, while the macroscopic flow of the gas in the pipeline can be ignored.
- (c) The volume of the leakage pipe is V and doesn't vary with the pressure and temperature, the initial gas pressure and

temperature in the pipe is p_0 and T_0 when the leakage occurs. The atmospheric pressure and temperature is p_∞ and T_∞ .

(d) There is only one leakage hole and its diameter d or area A is known.

According to the above assumptions, the leakage process of high-pressure gas pipeline is simplified as the non-adiabatic ideal gas leakage problem with the change of the pressure and temperature in a rigid container. Therefore, the physical model of the gathering pipeline leakage is shown in Fig. 1, the calculation formula of long-transportation leakage is given by means of thermodynamic and gas dynamics theory below.

3 BASIC EQUATION

According to the energy conservation equation for open systems^[30], the flow in the pipe can be written as:

$$\frac{dE_{CV}}{d\tau} + \left(h_e + \frac{1}{2}c^2 \right) \dot{m} = UF(T_\infty - T) \quad (1)$$

Here E_{CV} is internal energy of control volume, h_e is specific enthalpy of the flow at the outlet, c is the flow speed of the leakage gas, $\dot{m}$ is gas leakage rate, τ is the leakage time, U is the heat transfer coefficient between the control volume and the environment, F is the heat transfer area between the control volume and the outside, T is the temperature of the gas inside pipe. The gas temperature in the pipeline is generally the same as the ambient temperature when the leakage starts, then it will decrease rapidly and lead to $T_\infty > T$. Therefore, the right term of the equation reflects the heating effect of the environment on the gas. Under the assumption of the ideal gas, the internal energy and enthalpy of the gas in the pipe is only the function of its temperature, which can be expressed by:

$$E_{CV} = mc_v T \quad (2)$$

Where m is the residual mass of the control volume, c_v is the mass specific heat of the gas in the constant volume.

$$h_e = c_p T_e \quad (3)$$

Where c_p is the mass specific heat of the gas in the constant pressure, T_e is the flow temperature of the leakage outlet.

According to the equations (2) and (3), the equation (1) can be simplified as:

$$\frac{d}{d\tau}(mc_v T) + \left(c_p T_e + \frac{1}{2}c^2 \right) \dot{m} = UF(T_\infty - T) \quad (4)$$

The pressure and temperature of the gas will decrease with the leakage process, the state of the leakage flow will become subsonic flow when the ratio of the ambient pressure and the gas pressure p_∞/p is greater than the critical pressure ratio β_{cr} . Therefore, the leakage flow of the whole process in the outlet is divided into the critical leakage stage of the critical state and the subcritical leakage stage of the subsonic state. The critical pressure ratio is given by:

$$\beta_{cr} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \quad (5)$$

4 CRITICAL LEAKAGE

When the leakage begins, the gas pressure in the pipe is far greater than the ambient pressure ($p_\infty/p < \beta_{cr}$), the leakage gas at the outlet is critical state, the flow speed of the leak speed c and the leakage rate of the gas $\dot{m}$ is obtained by:

$$c = c_{cr} = \sqrt{\frac{2k}{k+1} RT} \quad (6)$$

$$\dot{m} = A\varphi \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \frac{p}{RT} \sqrt{\frac{2k}{k+1} RT} \quad (7)$$

Where c_{cr} is the gas velocity of the critical state φ is the velocity coefficient, R is the gas constant.

In the critical leakage period, according to the gas flow theory of the nozzle, the temperature is expressed:

$$T_e = T_{cr} = \frac{2}{k+1} T \quad (8)$$

Applying the equations (6) and (7), and then define:

$$c_1 = k \left(\frac{2}{k+1} \right)^{\frac{1}{k-1}} \phi \frac{A}{V} \sqrt{\frac{2k}{k+1}} R \quad (9)$$

$$c_2 = UF \frac{k-1}{V} \quad (10)$$

The equation (4) can be rewritten as:

$$\frac{1}{p} \frac{dp}{d\tau} = -c_1 \sqrt{T} + c_2 \frac{T_\infty - T}{p} \quad (11)$$

According to the ideal gas state equation:

$$pV = mRT \quad (12)$$

And the mass conservation equation:

$$\dot{m} = -\frac{d}{d\tau} \left(\frac{pV}{RT} \right) \quad (13)$$

Then obtain:

$$\frac{1}{T} \frac{dT}{d\tau} = -\frac{1}{p} \frac{dp}{d\tau} + \dot{m} \frac{RT}{pV} \quad (14)$$

Taking the equations (7) and (11) into the equation (14), then obtain:

$$\frac{1}{T} \frac{dT}{d\tau} = -c_1 \frac{k-1}{k} \sqrt{T} + c_2 \frac{T_\infty - T}{p} \quad (15)$$

By the equation (13), then get:

$$\dot{m} = \frac{pV}{RT} \left(\frac{1}{T} \frac{dT}{d\tau} - \frac{1}{p} \frac{dp}{d\tau} \right) \quad (16)$$

Taking the relative change rate of the pressure and temperature with time obtained by calculating the equations (11) and (15) into the equation (16), the leakage rate can be obtained, and then the pressure and the temperature in the next time can be obtained by solving the equations (11) and (15).

5 SUBCRITICAL LEAKAGE

During the leakage process, the gas pressure inside the pipeline decrease continuously, the leakage outlet will become the subcritical state ($p_{\infty}/p > \beta_{cr}$). Compared with the critical leakage stage, the biggest difference is that the flow of the outlet gas is subcritical state, which is not suitable for the maximum flow condition at the moment, so the velocity is expressed:

$$c = \sqrt{2(h - h_e)} = \sqrt{2c_p(T - T_e)} \quad (17)$$

The equation (1) can be simplified as:

$$\frac{d}{d\tau} (mc_v T) + c_p T \dot{m} = UF(T_\infty - T) \quad (18)$$

In this case, the mass flow of the leakage gas is expressed as:

$$\dot{m} = A\phi \frac{p}{RT} \sqrt{\frac{2k}{k-1} RT \left(\left(\frac{p_{sur}}{p} \right)^{\frac{2}{k}} - \left(\frac{p_{sur}}{p} \right)^{\frac{k+1}{k}} \right)} \quad (19)$$

Taking the equations (19) and (12) into the equation (18), and define:

$$b_1 = k\phi \frac{A}{V} \sqrt{\frac{2k}{k-1}} R \quad (20)$$

$$b_2 = \frac{(k-1)UF}{V} \quad (21)$$

And then obtain:

$$\frac{1}{p} \frac{dp}{d\tau} = b_2 \frac{T_\infty - T}{p} - b_1 \left(\frac{p_{sur}}{p} \right)^{\frac{k+1}{2k}} \sqrt{T} \sqrt{\left(\frac{p}{p_{sut}} \right)^{\frac{k-1}{k}} - 1} \quad (22)$$

By the equations (19), (22) and (14), then obtain:

$$\frac{1}{T} \frac{dT}{d\tau} = b_2 \frac{T_\infty - T}{p} - \frac{k-1}{k} b_1 \sqrt{T} \left(\frac{p_{sur}}{p} \right)^{\frac{k+1}{2k}} \sqrt{\left(\frac{p_{sur}}{p} \right)^{\frac{k-1}{k}} - 1} \quad (23)$$

The leakage rate is still obtained by the equation (16), taking the relative change rate of the pressure and temperature with time obtained by calculating the equations (22) and (23) into the equation (16) to get the leakage rate. And then solving the equations (22) and (23), the pressure and temperature in the next time can be obtained.

6 EXAMPLE

A transformation pipeline of the low pressure gas CO₂ with a pipe diameter D of 400mm is chosen as a calculation case. The distance between two the emergency shut-off valves L is 8000m, the initial pressure in the tube p_0 is 4.5MPa, the gas temperature T_0 is 25°C, the diameter of the leakage hole d is 80mm. Assuming the CO₂ gas is pure without other gases, the molecular mass M is 44, the gas constant R is 189.97 J·(kg·K)⁻¹, the specific heat ratio k is 1.4, the ambient pressure p_∞ and temperature T_∞ is 0.101325MPa and 25°C. Furthermore, assuming that the control valve of the pipe can shut down once the leakage accident happens.

The effects of the pipe diameter and the initial pressure factors on the leakage process is analysed in the literature [24]. The following section mainly focuses on the effect of the heat exchange between the pipe and the environment on the leakage rate. Using the above equations, we obtained the variation of the CO₂ pressure, temperature and the leakage rate inside the pipe with the time during the critical leakage stage and the subcritical leakage stage of the non-adiabatic leakage process at the different heat transfer coefficient between the pipe and the environment. And gives the time of the critical leakage stage at the same time, the results are shown in Fig. 2 to 4.

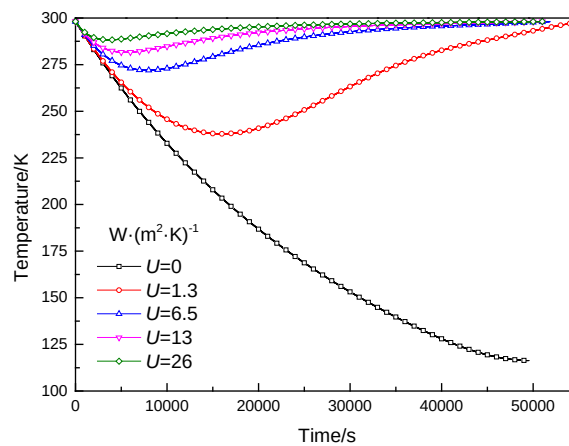


FIG.2 ENVIRONMENTAL HEATING EFFECT ON THE CO₂ TEMPERATURE OF THE HIGH-PRESSURE PIPELINE

Fig. 2 shows the effect of the heat transfer between the pipe and the environment on the gas temperature during the leakage of the CO₂. It is clear to see that the impact of the heat exchange is very obvious. If $U=0$, there is not heat exchange, the leakage is completely an adiabatic process, the temperature of the CO₂ gas reduces quickly with the

leakage time, closing to 116K. If $U \neq 0$ (considering the heating effect of the ambient), the temperature of the gas will decrease rapidly at the beginning of leakage, but the heating effect will produce as the temperature of the gas is below the ambient temperature so that the temperature will reduce slowly. When the heat transfer coefficient U is 26, 13, 6.5 and 1.3 $\text{W} \cdot (\text{m}^2 \cdot \text{K})^{-1}$, the minimum temperature that the gas in the tube can reach is 288.31, 281.63, 271.98 and 237.90K, the time achieving the minimum temperature is increase in order. The heating effect of the environment on the gas is more and more obvious with the enhancement of the environmental heating impact so that the temperature is greater than the reducing temperature caused by the gas expansion, the gas temperature will begin to rise.

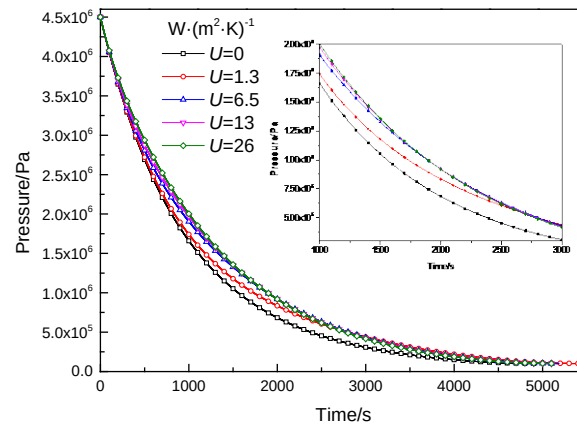


FIG.3: ENVIRONMENTAL HEATING EFFECT ON THE CO₂ PRESSURE OF HIGH-PRESSURE PIPELINE

Although environmental heating effect on the temperature variation of the gas with the time is very obvious, its influence on the gas pressure is relatively weak. Figure 3 shows the pressure variation of the gas in the pipe with the time in the leakage process, it can be seen that the gas pressure is always reduced monotonously whether considering the environmental heating effect on the gas or not, and the pressure is higher than the adiabatic process at the same time. For example, the pressure in the tube is 160604.3, 163218.2, 167751.3 and 188947.9 Pa when the heat transfer coefficient U is 26, 13, 6.5 and 1.3 $\text{W} \cdot (\text{m}^2 \cdot \text{K})^{-1}$ at 4200.0s after the occurrence of the leakage, but the pressure of the adiabatic leakage process is only 131288.5 Pa at this time. At the same time, when the heating effect is relatively small, it should be pointed out that the gas pressure in the pipeline increases as the enhancement of the heat transfer coefficient at first and then it will decrease with the increase of the heat transfer coefficient when the heat transfer coefficient is greater than a certain value.

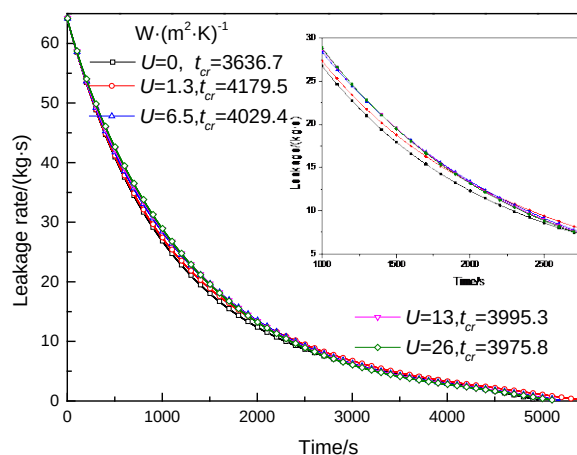


FIG.4 ENVIRONMENT HEATING EFFECT ON THE CO₂ LEAKAGE RATE OF HIGH-PRESSURE PIPELINE

Figure 4 shows the environmental heating effect on the leakage rate of the CO₂ in the leakage process. It is clearly known that the impact of the environmental heating on the leakage rate is relatively small, although the heating

effect on the other state parameters in the pipeline is obvious. The reason is that both the temperature and pressure of the gas are rising due to the environmental heating effect, relative to the condition without the heat transfer, the combined effect makes that the environmental heating effect on the leakage rate can be ignored. Therefore, to simplify the calculation, the leakage rate can be calculated according to the adiabatic without considering the heating effect. Furthermore, figure 4 also provides the time t_{cr} of keeping the critical leakage stage at the different heat transfer coefficient, it can be seen that the time t_{cr} increases because of the heating effect between the pipe and the environment, and is greater than the adiabatic leakage process. The variation of the leakage rate is similar to the pressure, when the heating effect is relatively small, the holding time t_{cr} of the critical leakage state increases as the enhancement of the heat transfer coefficient at first and then it will decrease with the increase of the heat transfer coefficient when the heat transfer coefficient is greater than a certain value.

7 CONCLUSION

Considering the role of the heat exchange between the pipe and the environment in the actual conditions, with the application of thermodynamics and gas dynamics theory, combining with the ideal gas state equation and the energy conservation equation, studies and analyses are carried out for the non-adiabatic leakage process of high-pressure gas pipelines in the critical and subcritical leaking period, and obtain the calculation formula of the leakage rate. Taking CO₂ as an example, the temperature, pressure and leakage rate are obtained under different heat transfer conditions. The main conclusions are obtained and listed as follows:

The heating effect of the environment on the temperature of the gas in the pipeline has a very significant impact. Compared with the adiabatic leakage process, the reducing rate of the gas temperature in the pipe is slow down due to the environmental heating effect after the leakage, and is no longer monotonic: it will begin to increase until closing to the ambient temperature after it reduces to a minimum value. The minimum temperature that the gas of the leakage process can reach is significantly higher than that without environmental heating.

The environmental heating effect on the pressure in the tube is relatively smaller than the influence on the temperature. The gas pressure in the leakage process also declines monotonically with the time even with the consideration of the heating effect of the environment, but the gas pressure is always higher than that without the heat transfer at the same time.

The effect of the environmental heating on the leakage rate is very limited, especially the initial period. Therefore, the gas leakage rate of the leakage process can be calculated according to the adiabatic process and the heating of the environment can be simply neglected as a first-order approximation.

However, as a future extension of this research, some other issues still need to be investigated. Carry out the experimental and simulation research to explore the variable rules of gas parameters and the detailed flow field distribution during the pipeline leakage.

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