SIMULATION AND ANALYSIS OF INDOOR GAS LEAKAGE

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ABSTRACT

The indoor fire induced by gas leakages can cause a lot of property losses and fatalities. One of the primary fire reasons is the explosion caused by the leaked gas concentrated within the explosive limits and an ignition source offered. In the paper, the characteristics of indoor gas leakages are disscussed and the theoretical models of the release rate and diffusion of gas are presented firstly. And then, the gas leakage in a room of a residential building is numerically simulated based on the application of computational fluid dynamics (CFD) techniques. Under different boundary conditions, the regions of concentrations within the explosive limits in the room are displayed and analyzed. Finally, the influences by the release rate of gas leakages and the velocity of outdoor air flows are studied. The analysis theoretically contributes a lot to fire prevention and control.

KEYWORDS

Indoor gas leakage, Explosive limits, CFD, Numerical simulation

INTRODUCTION

With the development of gas networks, more and more residents use piping gas as family fuel. However, the gas leakage accidents, which result from the improper use of gas stoves, privately moving or changing the indoor pipeline and the corrosion of gas pipes, have increased sharply in the past years (Junpu Wei 2004).The indoor fire induced by gas leakages causes a lot of property losses and fatalities. One of the primary fire reasons is the explosion caused by the leaked gas concentrated within the explosive limits and an ignition source offered. So simulations and analyses of indoor gas leakage and concentration fields are helpful for preventing from gas fire accidents and decreasing property losses.

At present, there are just a few research achivements on the indoor gas leakage. Zhihu Fang and Hong Lin (2006) performed the model experiment and the numerical simulation of the gas leakage in utility tunnels. Young-Do Jo and Bum Jong Ahn (2003) presented a simple model for the release rate of hazardous gas from a hole on a high-pressure pipeline. Xinwei Ding (1999) summarized the computing models and experiments of flammable or toxic gas dispersion in the atmosphere. Jinxiang Wu (2005) studied experimentally the concentration distribution of leaked gas in a room with a ventilation window.

In the paper, the gas leakage in a room of a residential building is numerically simulated based on the application of computational fluid dynamics techniques. Under different boundary conditions, the region of concentrations within the explosive limits and the concentrations field in the room are analyzed. The influences by the release rate of gas leakage and the velocity of outdoor air flows are also studied. The analysis theoretically contributes a lot to fire prevention and control.

CHARACTERISTICS OF INDOOR GAS LEAKAGE

In view of the leakage formation, gas leakage sources are divided into two kinds: instantaneous source and continuous source. The instantaneous source can form the gas agglomerate of the flammable or toxic gas within specified radius and height at the moment of gas containers or attachments breaking. The continuous source, which is caused by the corrosion of containers or pipelines, the damage of valves and the hosepipe falloff at joints, can make the gas release continuously. Generally speaking, the instantaneous source is of large and instantaneous gas release. And the continuous source is of small, steady and durative gas release. The gas leakages with instantaneous sources seldom occur indoors because the pressure of indoor gas pipes is usually low. So it is reasonable to regard gas leakages indoors as continuous sources. When leakages occur, the flammable gas will not be full of the whole room at once, and the release of gas is a long-playing and time-variable process. The purpose of the study is to simulate numerically the process and to analyze the distributions of gas concentration.

GAS LEAKAGE MODEL

It is supposed that the temperatures of gas and air in the room are same, and the heat transform caused by the difference in temperatures is neglected. The whole process of the gas leakage and diffusion is divided into two phases: the buoyant jet near a release orifice and the turbulent diffusion far away from the orifice.

Buoyant Jet Model

When a leakage occurs, the gas injectes into the air through a leakage orifice at a specified rate according to a jet flow model. The model influenced by the air buoyancy is a buoyant jet model since the densities of gas and air are usually different. The mixing process of gas and air satisfies momentum and mass conservation equations.

Turbulent Diffusion Model

In the region far away from a release orifice, the effect of the buoyant jet becomes less and less. The gas turbulent diffusion operates at this time. The diffusive process is made up of molecular diffusion, turbulent diffusion and dispersion. The Euler turbulent diffusion equation (Changzhao Yu 1992) is given as:

$$\frac{\partial \bar{c}}{\partial t}+\frac{\partial}{\partial x_i}\left(\bar{c}\,\bar{u}_i\right)=D_{ij}\frac{\partial^2 \bar{c}}{\partial x_i \partial x_j}+D_m\frac{\partial^2 \bar{c}}{\partial x_i \partial x_i} \qquad (1)$$

where $\bar{c}$ is the time-average concentration of gas; $\bar{u}$ is the time-average velocity of indoor air; D_{ij} is the turbulent diffusive coefficient; D_m is molecular diffusive coefficient. The numerical solution is usually obtained since it is difficult to solve the equations analytically.

Release Rate of Gas Leakages

Several assumptions are given firstly: (1) The leakage orifice is circle; (2) Gas is the perfect gas; (3) Gas flows adiabatically through the release orifice; (4) Gas release at a leakage point is considered as one dimensional model. The gas release is usually considered as the compressible fluid flow due to the significant changes of gas density before and after a leakage. The Euler motion differential equation of one dimensional flow is written as follows:

$$\frac{dp}{\rho}+vdv=0 \qquad (2)$$

Define two states at the inlet and the outlet of a leakage orifice as state 0 and state 1. Eq. (2) can be integrated from state 0 to state 1. Then

$$\int_{p_0}^{p_1}\frac{dp}{\rho}+\int_{v_0}^{v_1}vdv=0 \qquad (3)$$

where v_0 is the release rate before the leakage occurs ($v_0=0$); p_0 is the absolute pressure in pipes; ρ_0 is the gas density in pipes; v_1 is the release rate at a leakage point; p_1 is the local air pressure; ρ_1 is the gas density at p_1.

The following equation is given in terms of the adiabatic process.

$$\frac{p_0}{\rho_0^{\kappa}}=\frac{p_1}{\rho_1^{\kappa}}=const \qquad (4)$$

By substituting Eq. (4) into Eq. (3), the expression of the gas release rate at a leakage point is as follows:

$$v_1=\sqrt{\frac{2\kappa}{\kappa}\frac{p_0}{\rho_0}\left[1-\left(\frac{p_1}{p_0}\right)^{\frac{\kappa-1}{\kappa}}\right]} \qquad (5)$$

Where κ is the adiabatic index, theoretically depending on the gas temperature. The adiabatic index of the perfect gas can be regarded as a constant at the normal temperature. For natural gas, LPG, water gas and blast furnace gas $\kappa=1.3$.

SIMULATION AND RESULT ANALYSIS

In China, the natural gas has become the main family fuel instead of the coal gas. Therefore, the leakage and the diffusion of indoor natural gas are simulated by using CFD software in the paper.

Boundary Conditions and Source Terms

The geometric model of the simulated room is shown in Figure 1.

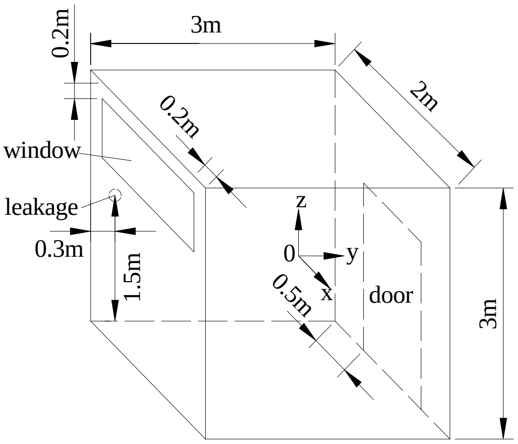

Figure 1 Geometric model of the room

The dimension of the room is $3m\times 2m\times 3m$. The study takes the hosepipe falloff at a joint as the leakage source. Set the orifice diameter of the leakage to be 0.01m. The dimensions of the window and the door are $1.6m\times 1m$ and $1m\times 2m$ respectively. Assume that the temperature in the room is $27°C$ and the air pressure is $1\,atm$ indoors. Eq. (5) makes clear that the pressure in pipes influences the release rate at the leakage point significantly. The pressure of indoor natural gas is usually less than $3\,kPa$. And the pressure variation caused by gas leakages is neglected. It is assumed that the pressure in pipes and the release rate at the leakage point are constant during the whole process of the gas leakage.

However, the change of gas load will cause the fluctuation of pressure in pipes. With the occurrence of leakages at different time of a day, the pressure in pipes can change consequently and the release rate is different. Obviously, the gas release rate at a leakage point is small at the consumed peak with a relatively low pressure in pipes, whereas it becomes large at night with a relatively high pressure. Thus, the gas leakages at the different release rates are simulated respectively. In addition, the air flow influences greatly the gas diffusion, so simulations and analyses are performed with and without air flow respectively.

Leakage without Air Flow

Supposing that both of the window and the door are closed and no air flows in the room with the air seepage neglected. The leakage processes at the release rates of $3m/s$ and $6m/s$ are simulated respectively. Using the method of unsteady calculation, the profile of gas concentration fields at different time can be obtained. The explosive limits of natural gas are from 5% to 15%, and within the concentrations, the explosion can occur if an ignition source is offered.

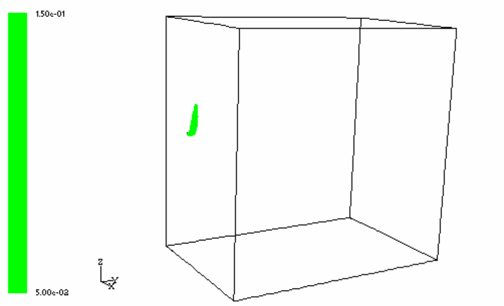

Figure 2 Distribution of concentrations within explosive limits at t=60s, $v = 3m/s$

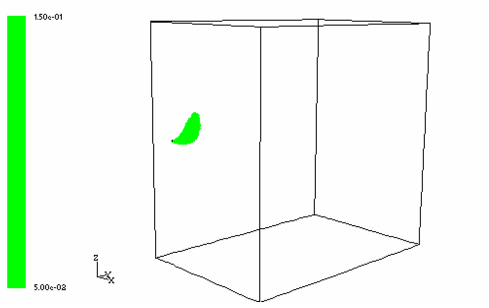

Figure 3 Distribution of concentrations within explosive limits at t=60s, $v = 6m/s$

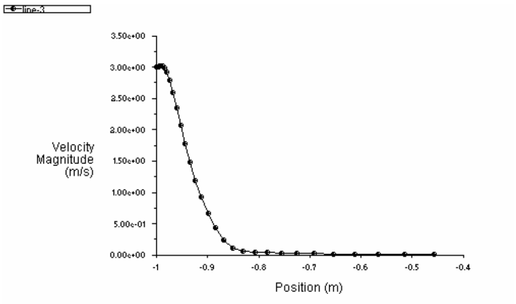

Figure 4 Velocity along the orifice axis at t=60s, $v = 3m/s$

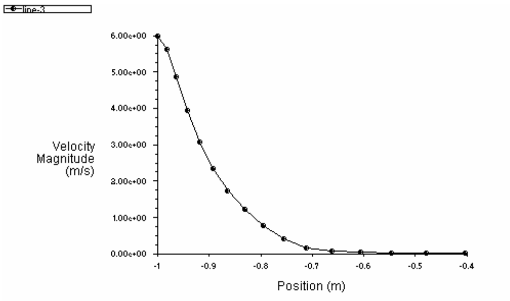

Figure 5 Velocity along the orifice axis t=60s, $v = 6m/s$

Figure 2 and Figure 3 exhibit that the buoyant jet of natural gas dominates the diffusion near the release orifice at the beginning of the leakage. Figure 4 and Figure 5 show that the gas release rate decreases sharply along the axis of the orifice.

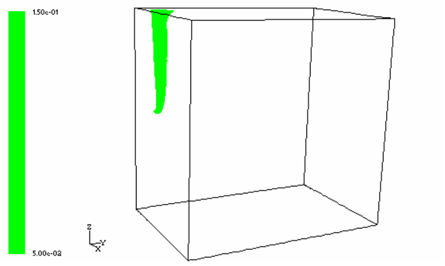

Figure 6 Distribution of gas concentrations within explosive limits at t=1800s, $v = 3m/s$

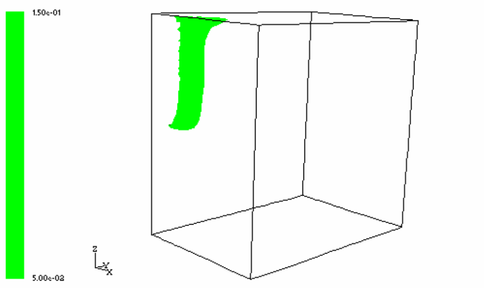

Figure 7 Distribution of gas concentrations within explosive limits at t=900s, $v = 6m/s$

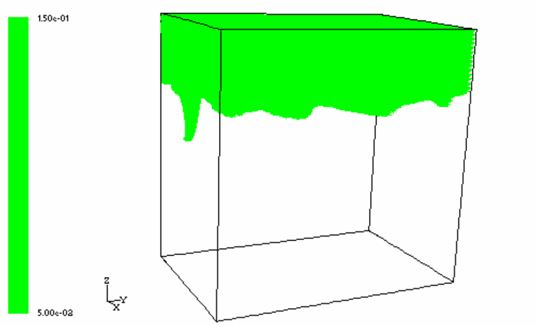

Figure 8 Distribution of gas concentrations within explosive limits at t=2400s, $v = 3m/s$

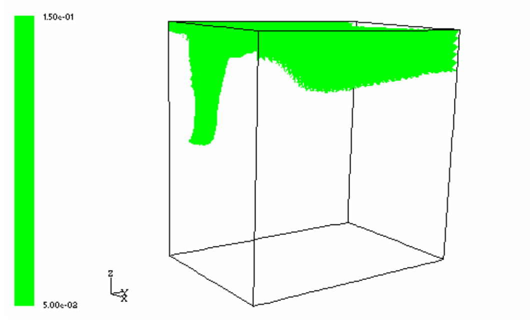

Figure 9 Distribution of gas concentrations within explosive limits at t=1080s, $v = 6m/s$

Figure 6 to Figure 9 display that with the time increases, the region of gas concentrations within the explosive limits becomes larger. Under the function of the turbulent diffusion and the buoyant jet, gas diffuses upwards to fill the ceiling. And the gas concentrations close to the ceiling in the upper part of the room reach the explosive limits firstly. Finally the whole room will be full of gas from the top down.

The study also discloses that the release rate at the leakage point influences greatly the region of concentrations within the explosive limits. When the release rate is 3m/s, at 1800s the gas with concentrations within the explosive limits reaches the ceiling and at 2400s it fills the ceiling. In the case of 6m/s, the time to reach the ceiling is 900s and to fill the ceiling is 1080s.

Leakage with Air Flow

It is supposed that the door and the window in the room are all open, and the outdoor air flows into the room from the window at the rate of 0.05m/s and out of the door. The gas leakage and the diffusion at the release rate of 3m/s are numerically simulated. The distribution of the gas concentration in the vertical plane along the axis of the leakage orifice is displayed in Figure10 and Figure11.

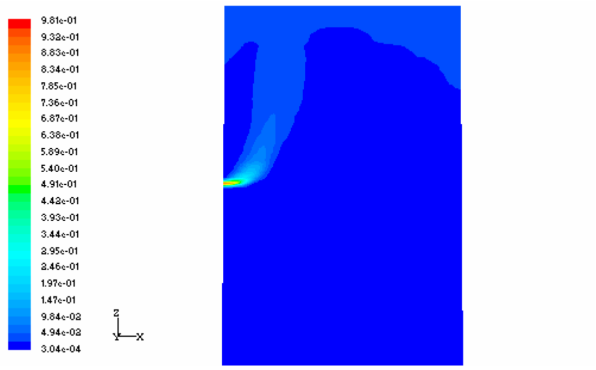

Figure 10 Concentration distribution in vertical plane at t=600s

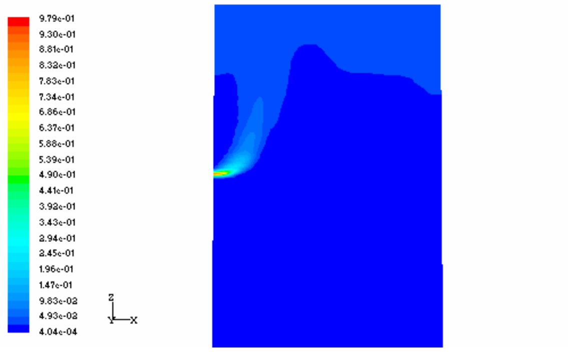

Figure 11 Concentration distribution in vertical plane at t=1800s

The study has disclosed that the air flow influences the buoyant jet of natural gas near the release point little. But it can reinforce the turbulent diffusion of gas far away from the leakage point in the room.

In comparison with no air flow, it has shown that the air flow can dilute the leaked gas in the room. The region of the concentrations within the explosive limits just distributes around the release point and hardly increases with time. About at 1800s after the leakage, the potential explosion region reaches the maximum and keeps invariable.

CONCLUSIONS

In the study, the gas leakage in a room is numerically simulated under different boundary conditions. The conclusions are summed up in the following.

(1) When a leakage occurs, the natural gas diffuses upwards and the gas concentration in the upper part of a room reaches the explosive limits firstly. So we need pay more attentions to the existence of potential ignition sources over the gas pipelines.

(2)The pressure in pipes influences the occurrence of a leakage and the release rate of the leakage greatly. So the pressure in pipes indoors should be controlled below a specified safe value.

(3)The air flow can dilute the leaked gas indoors and decrease the region of the high concentrations. So keeping ventilations smoothly in a room is favorable for the prevention of fire and explosion.

NOMENCLATURE

$\overline{c}$	time-average concentration of gas
D_{ij}	turbulent diffusive coefficient
D_m	molecular diffusive coefficient
p_0	absolute pressure in pipelines
p_1	local air pressure
$\overline{u}$	time-average velocity of indoor air
v_0	release rate before leakages happen ($v_0 = 0$)
v_1	release rate at leakage points
ρ_0	gas density in pipeline
ρ_1	gas density at p_1

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