Influencing factors of flammable refrigerants leaking in building air-conditioning system

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Abstract

This study developed a leakage model of flammable refrigerants in a building air-conditioning system, where the influencing factors of combustible gas distribution are considered including leakage rate, ventilation rate and room size. Propane is selected as refrigerant to study the effects of influencing factors on propane distribution in the room after leakage. The following conclusions are made: 1) increase of leakage rate changes the time when the ratio of dangerous area volume (RODAV) reaches 30% and the lasting time for RODAV exceeds 30%; RODAV is maintained below 30% if the leakage rate is not larger than 2.84 g/s; 2) no apparent effect of room size on concentration distribution was observed; 3) ventilation rate affects the RODAV level and propane distribution in the room, i.e. increase of ventilation rate will reduce the RODAV level and then the hazard in the building.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$V_r$</td>
<td>room size (m$^3$)</td>
</tr>
<tr>
<td>$q$</td>
<td>mass flow rate of flammable refrigerant (g/s)</td>
</tr>
<tr>
<td>$t$</td>
<td>time (s)</td>
</tr>
<tr>
<td>$u$</td>
<td>leaking speed (m/s)</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>ventilation rate (m$^3$/s)</td>
</tr>
<tr>
<td>$C_i$</td>
<td>mass concentration of flammable refrigerant at $t$ s (g/m$^3$)</td>
</tr>
<tr>
<td>$V_d$</td>
<td>volume of mole fraction of propane reaches or exceeds the LEL in the building (m$^3$)</td>
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Greek symbols

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<tr>
<th>Symbol</th>
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<tr>
<td>$\rho_0$</td>
<td>density of gasified flammable refrigerant (kg/m$^3$)</td>
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1. Introduction

Long-term service of Freon refrigerants in heating, ventilation and air conditioning (HVAC) systems has caused a series of environmental problems, such as severe damage to the global ozone layer. Recently Freon refrigerants are being phased out in HVAC industry, while emerging flammable materials such as propane and R32 are selected as potential refrigerant alternatives of Freon for the building air-conditioning system [1-3]. In such case, the safety management of those flammable refrigerants needs to be concern, especially the refrigerant leakage due to pipeline corrosion and sealing materials aging etc.
Since the density of propane or R32 are larger than air, the leaked propane or R32 will accumulate over the floor and mix with air in the room to produce explosive gas. In extreme cases, fire or explosion may be caused [4-7].

Small-scale leakage and related hazards of flammable refrigerant have been studied for small air-conditioning system [8-13], however, the influencing factors of flammable refrigerants used in the building are not clear yet, and safety management of flammable refrigerants in office buildings remains concern. In this paper, propane is selected as a potential refrigerant to examine the influencing factors of flammable refrigerants, together with safety usage of the flammable refrigerants in air-conditioning systems discussed and suggested.

2. Leakage model of flammable refrigerants

The leakage of gas refrigerant into the room from pipe orifice or crack can be regarded as free jet problem. The leakage and diffusion of flammable refrigerants can be simplified as a jet sprayed into a large room under given initial speed, then mixed with the ambient air. When the leaking speed is low, the transfer from high concentration area to low concentration area is dominated by diffusion and/or natural convection.

In order to determine the influencing factors on the concentration distribution of flammable refrigerants, an analytical model is developed with the following assumptions established,

1. The mixing between flammable refrigerant and air is instantaneous;
2. Distribution of flammable refrigerant in the room is uniform;
3. Ventilation is iso-thermal.
4. Mass of flammable refrigerant is finite.

In the following analysis, \( V_r \) (m\(^3\)) is the room size, \( q \) (g/s) is the mass flow rate of flammable refrigerant, \( \Omega \) (m\(^3\)/s) is the ventilation rate, \( C \) (g/m\(^3\)) is the mass concentration of flammable refrigerant and \( t \) (s) is the leaking time. The mass concentration of flammable refrigerant \( C \) after a short time interval \( dt \) (s) leaking can be derived from

\[
V_r dC = qdt - \Omega C dt
\]  
Equation (1) can be deduced to

\[
\frac{dt}{V_r} = \frac{dC}{q - \Omega C} = -\frac{1}{\Omega} \frac{d(q - \Omega C)}{q - \Omega C}
\]  

The concentration of flammable refrigerant can be obtained through integration of the above equation,

\[
C_r = \frac{q}{\Omega} \left[1 - \exp\left(-\frac{\Omega t}{V_r}\right)\right]
\]  
If the leakage hole is a circular orifice, the mass flow rate of flammable refrigerant can be expressed as:

\[
q = 1000 \cdot \rho_0 \cdot \pi r^2 \cdot u
\]  
where \( \rho_0 \) is the density of gasified flammable refrigerant in kg/m\(^3\) and \( u \) is the leaking speed in m/s.

From Equations (3) and (4), it arrives

\[
C_r = \frac{1000 \cdot \rho_0 \cdot \pi r^2 \cdot u}{\Omega} \left[1 - \exp\left(-\frac{\Omega t}{V_r}\right)\right]
\]  
From Equation (5), it is found that the concentration distribution of flammable refrigerant is therefore affected by the leakage rate, ventilation rate, and room size, whose individual effects will be examined in the following.

3. Model development

The building structure considered in this paper is shown in Fig. 1, the room size is 5 m×5 m×3 m. The radius of orifice is located at the top ceiling of the room with a radius of 0.01 m. The 0.5 m × 1.5 m exit door is located on the front and 1 m
away from the left wall. The 0.5 m × 0.5 m square ventilation inlet is located on the right wall.

The commercial CFD package ANSYS Fluent V12 [14] is adopted for the simulation, where SIMPLE [15] algorithm with pressure-based transient solver is used. Meshes are generated by GAMBIT [16], where a size function is established for mesh refinement near the leakage orifice while the default scheme with the fixed size function and T-gird algorithm is used for generating unstructured hybrid meshes for other area.

Velocity inlet condition is set at the leakage orifice and ventilation boundary, and pressure outlet condition is applied at the door boundary. A total mass of 5 kg propane is leaked from the air-conditioning system in all the calculated cases. The leaking speed is fixed until zero when all propane is leaked out.

![Fig. 1. Typical room model (unit: mm).](image)

### 4. Results and discussion

The heavier propane will flow downward from the leakage orifice and accumulate on the floor to reach the flammable or explosion limits. The low flammable or explosion limit (LEL) of 2.1% [17] (volume fraction) is used to determine the ratio of dangerous area volume (RODAV). The equivalent height of dangerous area and the lasting time are also considered as the safety criteria. A RODAV value of 30% is regarded as critical hazardous value. If RODAV reaches 30%, then the lasting time for RODAV over 30% will become the main factor for safety.

RODAV is defined as follows:

\[ RODAV = \frac{V_d}{V_r} \]  

(6)

where \( V_d \) (m³) is the volume of propane reaches or exceeds the LEL in the building, and \( V_r \) (m³) is the volume of the room.

#### 4.1. Baseline case

Given an internal pressure at the leakage orifice 1.2 atm, and the area of leakage orifice 3.14×10⁻⁴ m², the density of propane at the leakage orifice is calculated to be 2.26 g/L. The mass leaking rate is 7.2 g/s in the simulations [18-19]. Assuming a leaking speed of 10m/s, the leakage time is 810 s, after that the leaking speed is set to zero. Only natural ventilation through the door is considered in the baseline case. Fig. 2 shows the propane concentration distribution in the room on the plane of \( Y=2.5 \) m at different times from 30 s to 810 s after leakage. The stratification phenomena are observed apparently from Fig. 2, this is because that propane is heavier than air and it will accumulate over the floor after leakage.

Attenuation trends of propane concentration and jet velocity on the orifice axis from the orifice to the ground are shown in Fig. 3. The RODAV level and propane concentration varying during the simulation are presented in Fig. 4.

It is observed in Fig. 3(a) that the propane concentration attenuates more than 80% at 0.5 m direct below the leakage orifice. Fig. 3(b) shows that jet velocity attenuates approximately 80% at 0.5 m direct below the leakage orifice, and then below this height velocity decay rate decreases.

Figure 4(a) shows that the RODAV level is generally low before 180 s since propane mainly flows downward and accumulates on the floor. The RODAV level increases gradually from below 1% to over 40% around 600 s, and reaches the peak value of 44.76% at 810 s. After that, the RODAV level decreases gradually since no propane released. The analytical solution of time dependence of uniform distributed concentration is presented in Fig.4 (b), where the propane concentration...
increases quickly before 300 s and towards stability after 300 s. Generally, the tendency between numerical solution and analytical solution is similar in less than 900 s.

Fig. 2. Tendency of propane concentration distribution at \( Y = 2.5 \) m plane.

Fig. 3. Trends of (a) propane concentration and (b) jet velocity direct below the leakage orifice.

Fig. 4. Trends of (a) RODAV level and (b) analytical solution of propane concentration in baseline case.
4.2. Effects of leakage rate

Different leakage rates, 2.84 g/s, 3.55 g/s, 5.68 g/s and 8.52 g/s, are modeled to study the effects of leakage rate on concentration distribution in the room. The corresponding leaking speed to those leakage rate on the leakage inlet are 4 m/s, 5 m/s, 8 m/s and 12 m/s respectively. The RODAV levels under different leaking speeds are shown in Fig. 5.

![Fig. 5. RODAV curves for different leakage rates.](image)

Figure 5 shows that the tendency of RODAV level under different leakage rates coincides with that in the baseline case, and the RODAV in the room is increased as the leaking speed increases. For example, the RODAVs at 600 s for cases of 8 m/s, 10 m/s and 12 m/s are 33.68%, 40.35% and 46.97% respectively. The leaking times for the three cases reaching or exceeding 30% are 510 s, 390 s and 240 s respectively. The propane volume in the room increases with the leaking speed. Fig. 5 shows that the maximum RODAV for the case of 4 m/s is always below 30%.

4.3. Effects of room size

Different room sizes 75 m$^3$, 90 m$^3$ and 108 m$^3$ are modeled to study the effects of room size on concentration distribution. Boundary conditions are the same as in the baseline case. Fig. 6 shows the RODAV curves for the three room sizes and the analytical solution for the relationship between propane concentration and room size.

![Fig. 6. Effects of room sizes on propane concentration, (a) RODAV levels for different room sizes, (b) analytical solution for the relationship between concentration and room sizes.](image)

Figure 6(a) shows that the effect of different room sizes on concentration distribution is not as significant as that of leakage rate, although it is effective to reduce the RODAV level and the lasting time for a room with given size. For example, the times for RODAV in three cases to reach or exceed 30% are 390 s, 450 s and 540 s respectively, and the total leaking times are 600 s, 540 s and 450 s respectively. Fig. 6(b) shows that the room size plays a minor role in changing the
concentration if the room volume is less than 150 m$^3$, in consistent with RODAV curve. However, the room size affects the concentration significantly when the room volume is larger than 150 m$^3$.

4.4. Effects of ventilation

The effects of ventilation location on concentration distribution are studied by supplementing fresh air of different ventilation rates 0.025 m$^3$/s, 0.075 m$^3$/s, and 0.125 m$^3$/s into the room, where the corresponding velocities are 0.1 m/s, 0.3 m/s and 0.5 m/s, respectively. Our Group has done some studies on this phenomenon before, however it is focused on different purposes and is based on different parameters [20].

![RODAV curves for different ventilation rates.](image)

Figure 7 shows the RODAV levels under different ventilation conditions. Results show that ventilation can strengthen the mixing process of refrigerant with air. It is found that the ventilation can reduce the harmful consequences and the reduction is in proportion with the ventilation intensity. When the ventilation intensity is 0.5 m/s, the leaking time for RODAV to reach 30% was reduced over 10% and the total leaking time was reduced approximately 20%. Under the ventilation intensity of 0.5 m/s, the propane concentration in the room can be maintained at low level, i.e. RODAV is below 5%, for about 10 minutes. The maximum RODAV when all the propane leaked out was 20%. It can be concluded that ventilation is a key factor for safety management of flammable refrigerant, and the refrigerant concentration can be controlled under the explosive limit with sufficient ventilation intensity.

5. Conclusions

In this study, concentration distribution of flammable refrigerant as a function of the leakage rate, ventilation and room size is derived under assumptions such as instantaneous mixing. Factors affecting the concentration distribution, such as leaking speed and ventilation, are examined in a typical room. The following conclusions can be made:

1) Increase of leaking speed can change the time for RODAV to reach 30% and the total leaking time. Especially, RODAV is maintained below 30% if leakage rate is not larger than 2.84 g/s.

2) For rooms with given sizes in a certain range, no apparent effect of room size on propane distribution in the room was observed, although it is effective to reduce the RODAV level and the lasting time for RODAV over 30% for a room with given size.

3) Ventilation can intensify the mixing, then correspondingly affect RODAV level and concentration distribution of propane significantly. Increase of ventilation rate can slow down the time for RODAV to reach 30% and the lasting time. RODAV can be controlled below 30% when the ventilation rate exceeds 0.125 m$^3$/s.

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