Numerical Simulation of Gas-Liquid Two-Phase Leakage of R-290 Refrigerant in Split Air Conditioner

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Abstract: R290 as a refrigerant has significant advantages of low cost, high energy efficiency, and more environmental protection, but the leakage will form a hazardous area inside the indoor unit and the room where the concentration exceeds the lower flammable limit of propane. In this paper, we focus on the gas-liquid two-phase leakage of R-290 indoor air conditioner at the evaporator, and use Computational Fluid Dynamics (CFD) method to numerically simulate the refrigerant leakage dispersion at three air conditioning supply volumes of 178.2 m^3/h, 342 m^3/h and 576 m^3/h, and analyze the indoor velocity distribution and concentration distribution. The results show that the trajectory of the refrigerant jet changes under different air supply volumes, and the simulation results show that the spatial extent of the combustion explosion limit is mainly distributed at the air conditioning leak and the air conditioning outlet. Vortices were formed in the local area above the propane leakage port and then spread.

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1 Introduction

Hydrocarbon refrigerants represented by R290 are popular research targets for replacing HCFs due to their good thermodynamic properties and environmentally friendly characteristics. However, R290 is an A3 refrigerant, which is a highly flammable gas, so the market progress of R290 for domestic air-conditioner split units is relatively slow.

The leakage characteristics of R290 air conditioning systems have been actively studied by scholars both at home and abroad. Hu et al[1]. investigated the concentration distribution of different masses of R-290 leaking from the interior and exterior of split air conditioning indoor units into the room. The effect of indoor unit installation height and air volume on the leakage concentration was analyzed through numerical simulations.Li et al[2]. conducted safety tests on indoor air conditioner R-290 leakage to determine the safety impact of refrigerant concentration leaking into the room by evaluating variables such as leakage volume, fan on/off, and air conditioner operation or shutdown.Colbourne[3]by studying the dispersion of CO2 simulated refrigerant (R-290) leakage, mainly analyzing the effect of flow rate and the risk of flammability of air conditioners using R-290 under a range of conditions.Zhang and Yang[4] studied the R-290 leakage from split air conditioner indoor units and outdoor units with fire and explosion characteristics and showed that deflagration overpressure does not cause significant damage to indoor or outdoor units throughout the leak. liu[5] established and simulated vertical downward leakage of flammable refrigerant from the exterior of an air conditioner and found that ventilation exacerbates the mixing of refrigerant volume ratios in the hazardous area.

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The current safety tests on R290 are mainly focused on the leakage state of the gas, but there is no literature on the study of R290 gas-liquid two-phase. Therefore, in this paper, CFD technology is used to numerically simulate the leakage of R290 household air conditioners to explore the trajectory of the jet, the internal velocity and concentration changes of the jet in the gas-liquid two-phase state, and to provide an effective basis for the risk assessment of R290 leakage.

2 Thermodynamic analysis of the R290 leakage process

For the calculation of the outlet flow and parameters such as pressure and temperature for two-phase flow the "ω-method"[6] is used in this paper. This method is widely used and has been extensively tested.

The "ω-method" is based on a one-parameter approximation of the P versus v relationship using:

$$\frac{v}{v_0} - 1 = \omega\left(\frac{P_0}{P} - 1\right) \tag{1}$$

And

$$\omega = \alpha_0\left(1 - 2\frac{P_0 v_{fg0}}{h_{fg0}}\right) + \frac{T_0 C_{p0} P_0}{v_0}\left(\frac{v_{fg0}}{h_{fg0}}\right)^2 \tag{2}$$

$$v_0 = v_{f0} + x_0 v_{fg0} \tag{3}$$

The critical mass flow rate and critical pressure of the two-phase flow at the leak point are obtained from the following:

✧ According to equation 2 to get ω=1.04;

✧ Query by design figure 1 η_c=0.605 、G_c^*=0.59;

✧ According to Equation 5 and Equation 6, the outlet flow rate and pressure are calculated, and the Tc corresponding to Pc is found from Figure 2 to obtain the outlet temperature.

$$P_c = \eta_c P_0 \qquad (4)$$

$$G_c = G_c^* \sqrt{\frac{P_0}{V_0}} \qquad (5)$$

Calculated:P_c=355KPa, G_c=0.0014kg/s, Tc=276.89K.

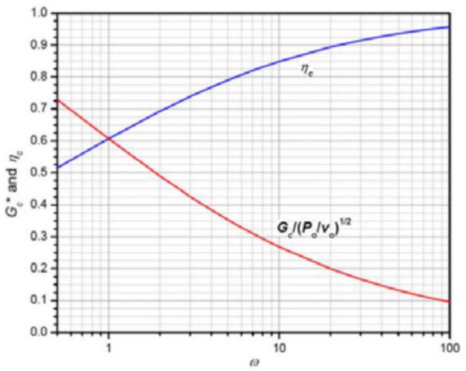

Fig 1. Design chart for critical flow parameters of a two-phase mixture[7]

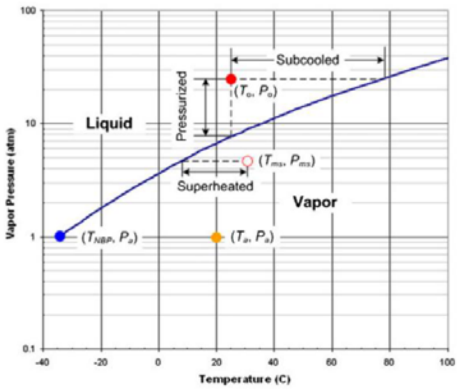

Fig 2. The saturation curve of pressure against temperature for chlorine[7];

3 Numerical simulation

3.1 Geometric model

In this paper, CFD software FLUENT is used to simulate the concentration field and velocity field of the diffusion process of R290 gas-liquid two-phase leakage. The room model size is 4.4m×5.4m×2.6m as shown in Figure 3, and the R290 refrigerant air conditioner is installed in the middle of the wall with the installation height of 1.8m.

ANSYS ICEM was used to mesh the room model, and the mesh refinement was performed at the leakage port and the internal area of the air conditioner. The entire computational model was meshed with a tetrahedral unstructured mesh with good adaptability, and the total number of meshes was about 3.41 million.

The indoor unit of the split type air conditioner is simplified as shown in Figure 4. The leakage port is located above the center of the evaporator coil of the air conditioner, the size of the leakage surface is 0.9mm × 0.9mm, and the leakage direction is vertically downward. The heat exchanger inside the indoor unit is simplified to a porous-jump plane (porous-jump) for calculation, and the simplified model of the fan is referred to Papas et al. [8], where the pressure jump of the cross-flow fan is represented by the internal flow path of the indoor unit and adjusted to achieve different air volumes.

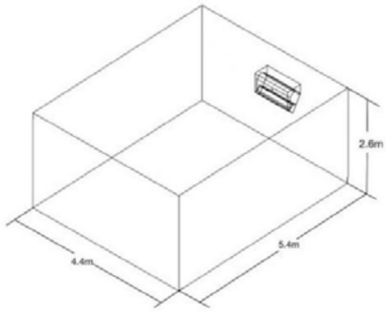

Fig 3. Simulation model

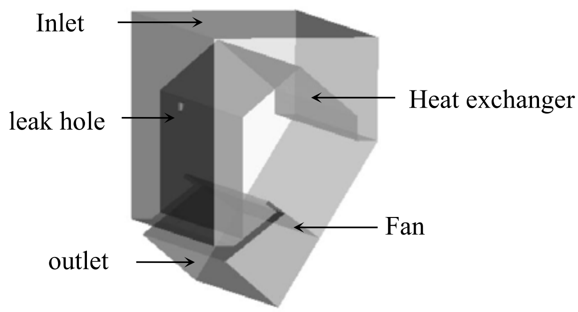

Fig 4. Indoor unit model

3.2 Two-phase flow simulation method

At present, the simulation methods for gas-liquid two-phase flow can be divided into two main types: a two-fluid model (i.e., Eulerian-Eulerian), in which both gas-liquid phases are treated as continuous media, so that the calculation of the liquid phase can be done in the same way as the meteorological calculation.The other is the particle orbit model (i.e., Eulerian-Lagrangian), where the gas phase is still treated as a continuous medium and the liquid phase as a discrete phase, and the Lagrangian method is used to track the motion of particles or particle populations. According to this paper, the discrete phase model (Eulerian-Lagrangian DPM) method is used to perform numerical simulations more accurately. The continuous phase is solved by solving the Navier-Stokes equations, while the discrete phase is described by a random particle orbit model. The propane droplet temperature of 276.89 K, the initial velocity of 1.68 m/s and the flow rate of 0.0007 kg/s were set in the simulation.

3.3 Simulation conditions

In this paper, we simulate the leakage and diffusion of R290 in the range of 3 to 10 air changes/h at 178.2 m3/h, 342 m^3/h and 576 m^3/h during the operation of air conditioners, and analyze the safety of R290 after leakage in the room with the simulation results.

In simulating the diffusion of R290 leakage in a room, the following assumptions were made:

(1) The temperature field in the room is stable, and there is no obstacle to the spread of leakage inside the room;

(2) air-conditioning system in addition to the leak, the rest of the wall is set to adiabatic wall,.

(3) the diffusion process is a non-stationary process, the leakage time is 4min, the initial temperature of the room is set to 300K, the reference pressure is set to 101325Pa, and the refrigerant charge in the air conditioner is 342.9g.

(4) The leaking R290 is gas-liquid two-phase, the gas-liquid ratio is 1:1, and the leakage direction is vertical downward.

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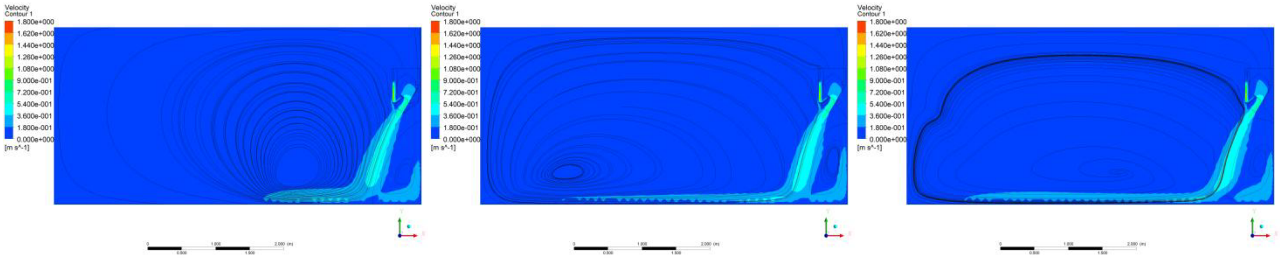


Fig.5. Velocity contour of the Y = 0.5 m plane and the airflow rate is 178.2 m^3/h

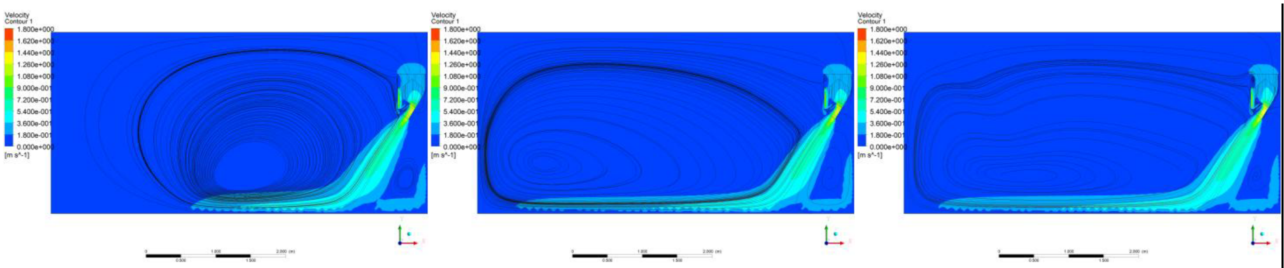
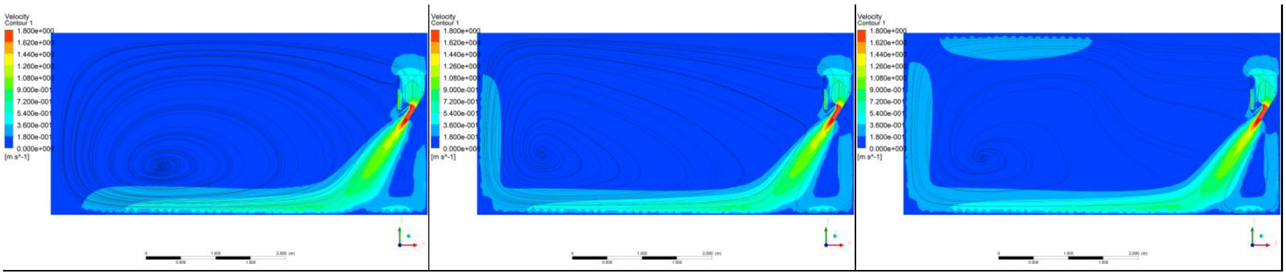


Fig.6. Velocity contour of the Y = 0.5 m plane and the airflow rate is 342 m^3/h



20s 40s 60s

Fig.7. Velocity contour of the Y = 0.5 m plane and the airflow rate is 576 m^3/h

4 Results and discussion

4.1 Velocity field

The velocity clouds and flow lines in the Y=0.5m plane when propane leaks at air volumes of 178.2 m3/h, 342 m^3/h, and 576 m^3/h are given in Figures 5 to 7

By comparing the velocity field clouds for the three working conditions, it can be seen that the angles of the jets are close when the airflow is larger (342 m3/h and 576 m3/h), while when the airflow is smaller (178.2 m3/h), the jets start to favor the vertical direction after some distance from the exit. The velocity field moves upward against the wall after 40 s for the airflow of 576 m3/h. And with the increase of air volume appears in the jet trajectory behind the vortex gradually becomes smaller, the flow line in the room towards clear, which is due to the joint action of gravity and large air volume fan, resulting in the airflow blown out after the velocity fast become uniform. From Figure 5 - Figure 7 can be seen with the increase in time the vortex in the room gradually move backward becomes smaller and smaller, and the leak point above the formation of a new vortex, the greater the air volume vortex is more likely to produce.

4.2 Concentration field

By varying the airflow velocity of the indoor unit and studying its effect on the concentration distribution in the room, Figure 8 shows that the spatial extent of R290 gas at the combustion explosion limit increases gradually with time, and is mainly distributed at the air conditioning leak and the air conditioning outlet. Figure 10 shows that the spatial extent of R290 gas concentration at the explosion limit decreases from working condition one (178.2 m^3/h) to 60 s. The reason for this is that after a certain time of leakage, the disturbance near the source of leakage is enhanced and the dilution increases. Therefore, when a leak occurs in the indoor unit, only in its vicinity

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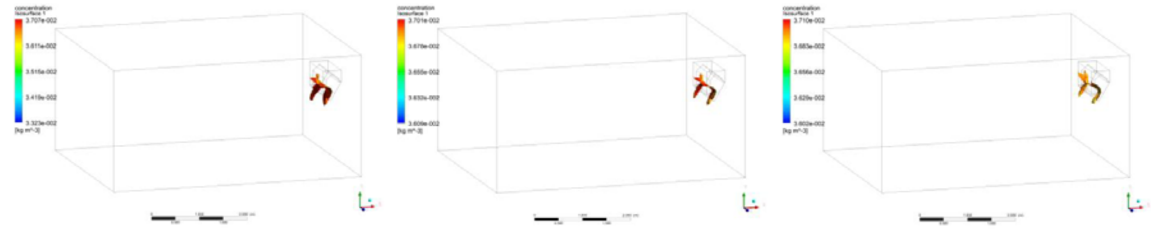
may form an area of combustion and explosion.



178.2 m^3/h 342 m^3/h 576 m^3/h

Fig 8. Three working conditions 60s when R290 is in the space range of the explosion limit

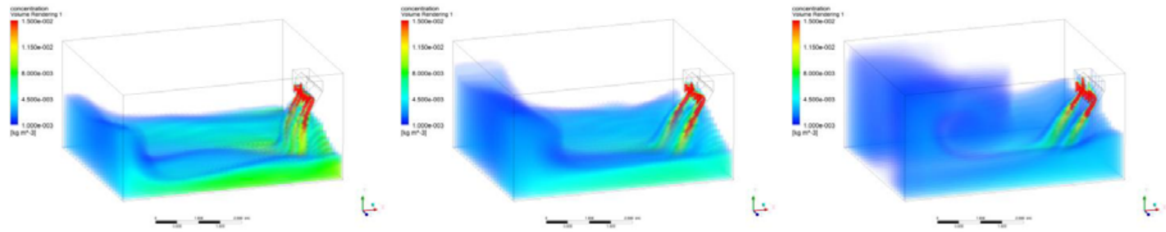


Fig 9. Indoor concentration field distribution of R290 leak for 60s under three working conditions

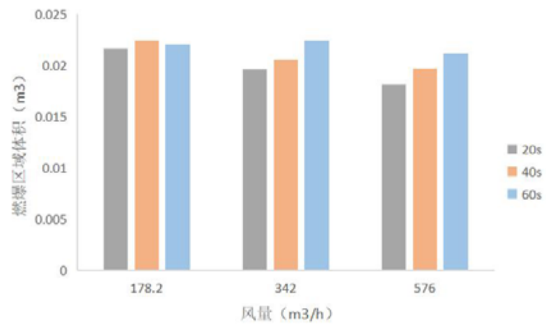


Fig 10. Volume of space exceeding the lower limit of ignition and explosion for the three operating conditions

5 Conclusion

Since different air supply angles will have an impact on the maximum concentration of indoor refrigerant and the maximum concentration point, but as long as the airflow speed is large enough, the impact of air supply angle on refrigerant dispersion can be negligible, so this paper only considers the indoor concentration distribution when the blow-out angle is -70° for the time being.

The study of the velocity flow line distribution law of the propane diffusion process and the area where the explosive concentration range exists in the room after the propane leak. The following conclusions can be drawn.

1) Vortices are formed in a very small localized area of the propane leak port, with diffusion. As the air volume becomes larger the jet velocity increases and a new vortex is formed behind the jet trajectory. As the air volume becomes larger, the velocity field in the room is more uniformly distributed.

(2) the explosion hazard area in the room is mainly concentrated in the interior of the indoor unit and near the exit, and when the diffusion of a period of time, the room exceeds the lower limit of the propane explosion of the region gradually decreases, has been located above the space.According to the above phenomenon in order to avoid disaster, the gas alarm can be installed in the leak port below the location.

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