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Study of Refrigerant Leakage in Refrigeration System

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ABSTRACT: In this paper, a method to calculate the leakage of the flammable refrigerants in the refrigeration system by simplifying the leaking process using hydromechanics is put forward. Based on the efflux theory, it also calculates the velocity and concentration fields of the refrigerant, and points out the existance of FOECA.

KEY WORDS: flammable refrigerants, leakage, concentration fields, FOECA.

INTRODUCTION

PAST STUDIES HAVE proved that most of the alternatives of CFCs and HCFCs, except R125 (CHF_2CF_3), R134a (CH_2CF_4), etc., are flammable or slightly flammable [1,2]. The flammable refrigerants will easily leak out of the refrigeration system through holes, cracks or breakpoints caused by corrosion of pipelines, aging of sealing materials in joints or valves, imperfect installation, mechanical vibration, thermal expansion and cold contraction of pipelines, etc. It will produce flammable mixtures in environment and cause a fire or an explosion. Therefore, it is necessary to study the leakage process of gaseous refrigerants in the refrigeration system and evaluate its hazard.

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CALCULATION OF LEAKAGE QUANTITY

Generally, two kinds of leakage, from a hole or from a crack, are common in refrigeration systems. The leakage may be considered as a flow of the compressible gas from a hole of the containing vessel. The mass flow rate can be calculated by the following equation:

$$Q_0 = 1000 \times wF_0\rho_1 \tag{1}$$

where Q_0 is the mass flow rate (g/s) from the hole, w is the initial velocity of leakage (m/s), ρ_1 is the density of gaseous refrigerant inside the leakage point (kg/m^3), and F_0 is the orifice area of the hole (m^2).

Considering the leakage from hole as an adiabatic process, it will have the following standard expressions:

$$w^2/2 + \int_{p_1}^{p_0} dP/\rho = 0 \tag{2}$$

$$P/\rho^k = P_1/\rho_1^k \tag{3}$$

where k is the adiabatic index, P_0 is the environmental pressure (Pa) and P_1 is the refrigerant pressure inside the leakage point (Pa).

Substituting Equation (3) into Equation (2) yields

$$w = \{2k/(k-1)P_1/\rho_1[1-(P_0/P_1)^{(k-1)/k}]\}^{0.5} \tag{4}$$

When the calculated value w according to Equation (4) is greater than the sonic speed of the refrigerant gas (ν_c), it is called super criticality. But in fact the velocity w will never exceed ν_c for any diffuser in the process. If this case happens, the w should be calculated according to the following equation:

$$w = \{2k/(k-1)P_1/\rho_1[1-(P_0/P_1)_c^{(k-1)/k}]\}^{0.5} \tag{5}$$

Considering the real process, the velocity of leakage is less than the theoretical calculative value for the local friction loss, so w should be modified by a, the coefficient of flow rate. By experiments, a is generally 0.6–0.82 [3], then

$$w_0 = aw \tag{6}$$

The calculated leakage of three flammable refrigerants – R290 ($CH_3CH_2CH_3$), R600 ($CH_3CH_2CH_2CH_3$), and R600a ($CH(CH_3)_3$) – are shown in Figures 1 and 2. The evaporating temperature and the condensing temperature of the three refrigerants are 270 and 325 K separately. And the pressures are shown in Table 1.

From these figures, it can be found that the leakage increases both with the area of the hole and the leakage pressure, but decreases with the increasing of density of the refrigerants.

Figure 3 shows the flow circuit of the refrigerant in a refrigeration system.

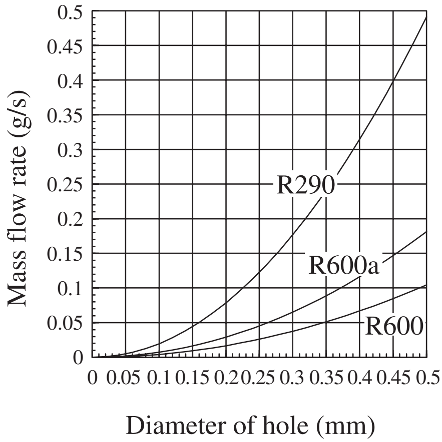

Figure 1. Leakage at evaporating temperature 270 K.

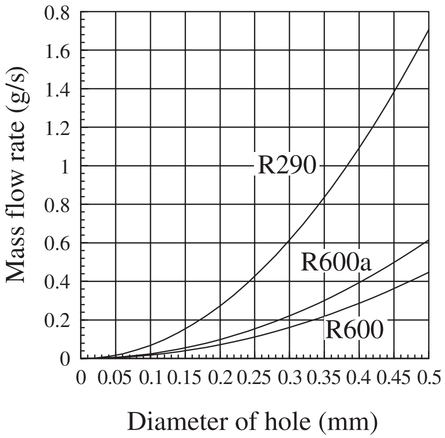

Figure 2. Leakage at condensing temperature 325 K.

Table 1. The evaporating pressure and condensing pressure of studied refrigerants [4].

Temperature (K)	R290 (MPa)	R600 (MPa)	R600a (MPa)
270	0.431	0.091	0.140
325	1.787	0.521	0.722

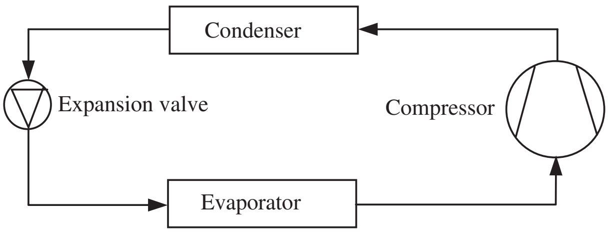

Figure 3. The scheme of flow circuit of refrigerant.

During operation, pressure from compressor outlet to expansion valve in the refrigeration system is much higher than the pressure from expansion valve to compressor inlet. Thus the leak rates are correspondingly higher if they occur. When the system is not operating, the pressure and the leak rate are intermediate.

The leak rate from a crack or holes with different shapes can be calculated with above expressions by using equivalent diameter, which is the diameter of a round hole that has the same area, and pulsing the appreciative coefficient.

SIMULATION OF THE LEAKAGE PROCESS OF REFRIGERANTS

Leak of gaseous refrigerants in refrigeration system through a hole or crack may be considered as a free jet. In fact, it is a process of exchanging momentum and mass between the ejecting refrigerants and the surrounding air [5]. When the temperature and density of the surrounding air are different from those of the leaking gaseous refrigerants, the jet may be regarded as a non-isopycnic one. The track of the non-isopycnic jet is very complex because of the bending caused by the gravity difference between the refrigerants.

Simulation of the Jet Velocity Field

The change of the jet axis velocity (w_m) depends on the diameter of the hole and the initial jet axis velocity (w_0). In the initial zone, the w_m is constant as w_0, and in the principle zone, it gradually decreases as the jet goes forward. In the turbulent jet, the molecules or their micelle of the gaseous refrigerants collide freely with the surrounding working fluids, thus it will cause the loss of the jet fluid momentum. But at the same time, the surrounding working fluids will obtain momentum and begin to move. So the total momentum of the two fluids is constant [6], and the pressure along the jet axis is also constant. According to the law of conservation of momentum in any section, it can derive the following equation:

$$w_m/w_0 = 0.96/(\varepsilon \times s/r + 0.29) \tag{7}$$

where r is the radius of the orifice (mm), s is the distance from the outlet to the section (mm), ε is a turbulent coefficient, which represents the turbulent degree of the efflux in the hole, such as $\varepsilon = 0.066$ for $w_0/w_{\mathrm{ave}} = 1$ and $\varepsilon = 0.076$ for $w_0/w_{\mathrm{ave}} = 1.25$ [3], w_{ave} is the average velocity of the efflux in the outlet section of the hole.

Figure 4 shows the reduction of the non-dimensional axis velocity along the jet axis from Equation (7) for five holes from 0.1 mm diameter to 0.5 mm diameter. It can be found that the velocity of the flammable refrigerant efflux attenuates very rapidly despite its high initial velocity for its small mass flow rate. For example, the hole with 0.5 mm diameter, the w_m/w_0 is less than 0.04 at a distance of 100 mm

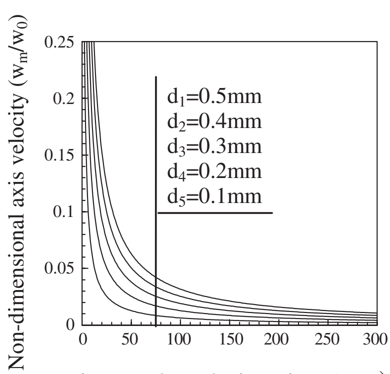

Figure 4. Non-dimensional axial velocity.

from the hole. This shows that the leak refrigerants diffuse very rapidly in air.

Simulation of the Leakage Concentration Field

The outer boundary of the leakage jet is the diffusive boundary of refrigerant. The leakage cannot cross the boundary. And the boundary of the jet core is the inner diffusive boundary of air. Therefore, in the inner of the core it is pure flammable refrigerant, and out of the outer boundary it is pure air. Between the two boundaries it is the moving mixture of flammable refrigerant and air. Under the steady conditions, the concentration at every point in the jet does not change with time. Apparently, any ray educed from the pole (center of the hole) has the following characteristic: the concentration of the refrigerant decreases with the increasing of distance from the pole along the ray. It keeps its maximum concentration ($C_g = 100\%$) from the outlet to the inner boundary of the jet, and decreases to zero concentration ($C_g = 0\%$) at an enough distance. Thus, three points can be found on every ray: the first one is the upper flammability limit (UFL) (or upper explosion limit) of the refrigerant in the mixture, the second one is the stoichiometric concentration (C_{st}), and the third one is the lower flammability limit (LFL) (or lower explosion limit).

The changing law of the non dimensional concentration along axis is the same as non dimensional velocity for turbulent jet. So the non dimensional concentration on the jet axis can be calculated by following equation [3]:

$$c_m/c_0 = 0.7/(as/r + 0.29) \tag{8}$$

The non dimensional concentration in a cross-section of the jet can be calculated by the following equation:

$$c/c_m = \exp[-57.5(R/s)^2] \tag{9}$$

Substituting Equation (8) into Equation (9) yields:

$$R = s\{\ln[c(as + 0.29r)/(0.7c_0 r)]/(-57.5)\}^{0.5} \tag{10}$$

where c_0 is the concentration of the gaseous refrigerant in the core of the jet, c_m is the gaseous refrigerant concentration of the jet axis in the principle zone, and c is the refrigerant concentration of the point at the radial distance R from the axis.

If the UFL and LFL of the refrigerant are known, the iso-concentration line of UFL or LFL can be calculated from the Equation (10).

Figures 5 and 6 show the iso-concentration lines of UFL and LFL of R290 from a 0.1 mm diameter hole and a 0.5 mm diameter hole respectively. The LFL (volumetric ratio) of R290 is 2.37% [4]. The area between the two iso-concentration lines of UFL and LFL is called a flammable or explosive concentration area (FOECA). As the LFL

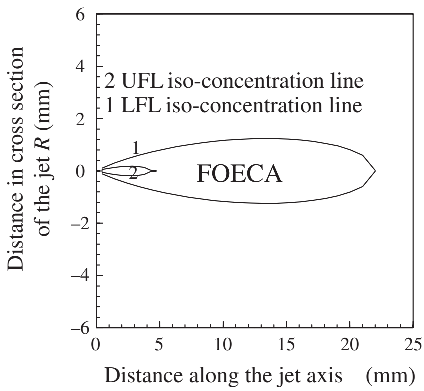

Figure 5. The range of flammable concentration area of R290 from a 0.1 mm diameter hole.

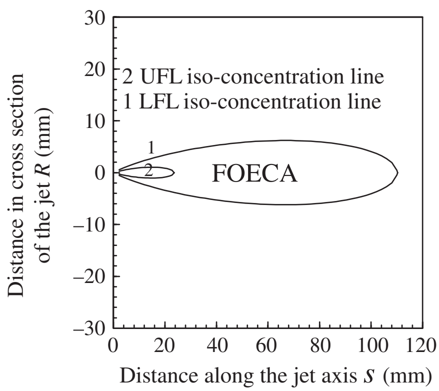

Figure 6. The range of flammable concentration area of R290 from a 0.5 mm diameter hole.

increases or the UFL decreases, the FOECA will increase, and as a result the danger is greater. Equation (10) also indicates that the FOECA is relative to the diameter of the hole r and the distance s. The bigger the diameter is, the larger the FOECA is. As for s, from Equation (7), it has a direct ratio with w_0, so the FOECA has a relation with w_0. When w_0 is less than v_c, the FOECA increases with increasing w_0. But when w_0 is bigger than v_c, it has no influence on the FOECA.

From the above discussion, it shows that when the leak happens, there must exist a FOECA. It means that though the refrigerant concentration of the whole leakage zone does not reach the LFL, it is still flammable for the existing of FOECA. So in practice, more attention should be paid to the FOECA, otherwise it will burn and cause a fire disaster.

CONCLUSIONS

1. The leakage flow rate of the refrigerant from a hole increases both with the rising of area of the hole and the increasing of the leakage pressure, but decreases with the increasing of density of the leakage refrigerants. The part from compressor outlet to expansion valve in the refrigeration system has the biggest leaking ability for the highest pressure in it, so it is the most dangerous part in the system. It should be paid more attention.
2. There exists FOECA in the leak area. Although the refrigerant concentration in the environment does not reach the LFL, there still has the possible danger of flaming in the area for the FOECA. It is needed to pay more attention to FOECA.

NOMENCLATURE

a = coefficient of flow rate
c = refrigerant concentration of the point at the radial distance R from the axis
c_m = gaseous refrigerant concentration of the jet axis in the principle zone
c_0 = concentration of the gaseous refrigerant in the core of the jet
C_{st} = stoichiometric concentration
FOECA = flammable or explosive concentration area
F_0 = orifice area of the hole (m^2)

k = adiabatic index
LFL = lower flammability limit
P_0 = environmental pressure (Pa)
P_1 = refrigerant pressure inside the leakage point (Pa)
Q_0 = mass flow rate (g/s) from the hole
r = radius of the orifice (mm)
R = radial distance from the axis
s = distance from the outlet to the section (mm)
UFL = upper flammability limit
v_c = sonic speed of the refrigerant gas
w = initial velocity of leakage (m/s)
w_m = jet axis velocity
ρ_1 = density of gaseous refrigerant inside the leakage point (kg/m^3)
ε = turbulent coefficient

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