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ABSTRACT

Although hydrocarbons and lower GWP HFCs are flammable, they are preferable to high GWP HFCs from the perspective of mitigating climate change. Appropriate standards are necessary to utilize these refrigerants so that their flammability risks are minimized. Although standards for the use of flammable refrigerants exist, some reports indicate that the refrigerants can sometimes be ignited even at levels which satisfy the standards. In addition, the theoretical background of these standards is unclear. To promote the development of a more appropriate standard, a more scientific method for calculating the allowable refrigerant charge was established. Because the calculation method was proposed as the foundation for a new international standard, a relatively simple formula was developed, based on experimental and numerical (CFD) analyses.

NOMENCLATURE

CFD; Computational Fluid Dynamics
GWP; Global Warming Potential
HFC; Hydrofluorocarbons
HCs; Hydrocarbons
UFL; Upper Flammable Limit
LFL; Lower Flammable limit
A; Floor area [m^2]
h; Effective Height [m]
h_o; Leak height (Installation Height) [m]
h_7; Effective height in 7 m^2 room [m]
K; Coefficient for adjusting charge amount other than propane
LFL; LFL in weight [kg/m^3]
m_{max}; Allowable charge [kg]
t; Leak duration [minutes]
x; Height from the floor [m]
y; Concentration of refrigerant [kg/m^3]

1. INTRODUCTION

This study was conducted to prepare a foundation for an amendment to IEC 335-2-40; "Particular Requirements for Electrical Heat Pumps, Air Conditioners and Dehumidifiers," in order to incorporate requirements for flammable refrigerants. Selection of the most appropriate refrigerant technology from a range of alternatives, taking into account environmental, safety, and other relevant factors, requires consideration of flammable refrigerants. In order to reduce the risks due to refrigerant flammability, an appropriate safety standard is necessary. Conventional safety standards employ simple safety factors such as four [1] to calculate the allowable charge in a room. However, several reports indicate that flammable refrigerants which are heavier than air can stagnate near the floor and ignite if an ignition source is present, even if the charge quantity complies with the conventional safety standard [2][3]. Therefore, quantitative calculation methods which consider this stagnation phenomena should be developed.

Propane and HFC-32 are the most important refrigerants to consider, since they have the most attractive thermophysical properties for air conditioning. The basic concept for the calculation method was first developed for propane. Then, CFD (Computational Fluid Dynamics) analysis was conducted on a supercomputer to confirm that the method yielded a sufficient level of safety for propane, butane, HFC-152a and HFC-32 and that the approach was neither too restrictive nor too relaxed. Finally, based on the results of the CFD analysis, some modifications to the basic formula were made.

If a flammable refrigerant which is heavier than air leaks into a room and stagnates near the floor, it can be ignited, resulting in a fire or explosion. This seems to be the most critical potential hazard arising from the use of flammable refrigerants. Therefore, a calculation method was developed which limits the refrigerant charge so that even in the case of catastrophic leak, the flammable space is very small.

It is impossible to eliminate the flammable space completely when a flammable refrigerant leaks, because the concentration of the leaking refrigerant is almost 100% at the leak point, while the concentration reaches zero at some distant location. The concentration varies continuously between these points. Therefore, at some location, the concentration is between the lower flammable limit (LFL) and the upper flammable limit (UFL). It is obviously better to have no flammable space at all, but some finite flammability risk from refrigeration oil and electric circuits has been accepted in air conditioning systems, so it should be acceptable to have a very low but non-zero flammability risk from the refrigerant.

2. LEAK CONDITIONS AND REFRIGERANT CONCENTRATION

Before the new calculation method was developed, refrigerant dispersion phenomena were evaluated experimentally and numerically. Major results of these investigations have already been reported in another paper [3], so they have not been repeated here.

Numerous parameters affect refrigerant dispersion behavior. Since it is impossible to evaluate every parameter in detail, only the most significant parameters were evaluated. The evaluation was done under conservative conditions, meaning that parameters other than the one under evaluation were fixed at their worst case condition. Table 1 shows these parameters and conditions. In the following analysis, the results under these conservative conditions were employed.

Both vertical and horizontal refrigerant concentration gradients exist. However, the horizontal concentration gradient is much smaller than the vertical one, except in the vicinity of leak port. The reason for this phenomenon is that if a horizontal concentration difference is present, airflow due to natural convection occurs, which reduces the horizontal gradient. This airflow velocity can reach approximately 1 meter per second. On the other hand, vertical dispersion occurs due to molecular movement if there is no airflow, at a velocity of a few centimeters per minute. Therefore, the horizontal gradient of refrigerant concentration was first neglected. Later, the horizontal gradient of refrigerant concentration in large rooms was evaluated through CFD analysis.

Table 1. Leak Parameters

	Parameter	Evaluated Condition	Reason
Refrigerant	Molecular Mass	Evaluated	
	Charge Amount	Evaluated	
	Temperature	Neglected	Effect does not seem significant. Evaporation of refrigerant has a more significant effect.
	Pressure	Neglected	Evaluated through leak rate analysis.
	Interaction with Oil	Neglected	Oil reduces the leak amount, so it is neglected for conservatism.
Leak	Velocity	Low velocity	Conservative.
	Rate	Leak takes 4 minutes	As leak rate increases, concentration increases. An appropriate conservative assumption is necessary.
	Direction	Downward	Conservative.
	Height	Evaluated	
	Location	Middle of the room	A wall close to the leak inhibits mixing, but not greatly, so the location was chosen to reduce calculation time.
Room	Temperature	Neglected (Used approximately 25° C)	Lower temperature will generate worse results, but the effect is not significant.
	Pressure	Neglected (Used 1 bar)	Lower ambient pressure will generate worse results, but the effect is adjusted by calculation.
	Tightness	Tight room except door gap	Conservative, but the smallest opening (30 cm^2) is used.
	Ventilation	No ventilation except the door gap effect	Conservative but smallest opening (30 cm^2) is used.
	Air Flow	None.	Conservative.
	Shape	Rectangular	Negligible effect.
	Obstacles	None	Negligible effect.

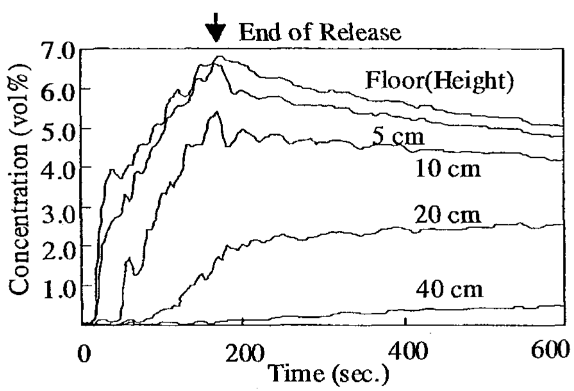

Figure 1. Concentration Variation

Refrigerant concentration at the floor level increases as the leak proceeds, until the leak stops. Except for the area directly surrounding the leak port, the highest refrigerant concentration occurs on the floor. As shown in Figure 1, the concentration at the floor level peaks just after the end of release and then starts to decrease. If the refrigerant charge is limited to a reasonable amount so that this highest concentration on the floor does not reach the LFL, no other location will ever reach the LFL, except directly adjacent to the leak port. The refrigerant concentration at higher elevations continues to increase for some time after the release ends. However, the concentration at these points will remain below that at the floor level because the dilution of the high concentration on the floor is the cause of this increment.

3. LEAK RATE

As the refrigerant leak rate increases, the concentration also increases. The leak rate must be fixed in order to calculate the refrigerant concentration. Most leaks occur very slowly, but rapid leaks have also been reported [4]. In this analysis, a leak duration of four minutes was chosen to represent a catastrophic leak, since it takes about 4 minutes to leak 150g of CO_2 through the capillary tube defined in IEC335-2-24 [5]. In addition, refrigerant recovery from a room air-conditioner generally takes five minutes or more. Therefore, the 4 minutes assumption is believed to be sufficiently conservative.

4. ASSUMPTION OF VERTICAL CONCENTRATION PROFILE

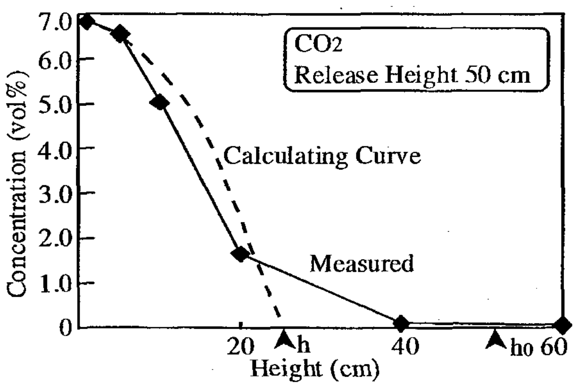

Figure 2. Concentration Profile

Integrating the vertical concentration (by mass) profile curve gives the refrigerant mass at a particular height, per unit area. Therefore, the total refrigerant amount in a room can be calculated as the product of the floor area and the integrated profile curve.

The vertical concentration profile was assumed to be parabolic, as indicated in Figure 2. When refrigerant is released from a height substantially above the floor, such as 2 m, the refrigerant concentration profiles can be approximated as functions of the 4th power of height. If the release point is low, such as 0.1 m, the concentration profiles can be approximated as linear functions of height, or functions of the 1.5 power of height. However, the parabolic (power 2) function of height was employed for the representative profile curve, since it can approximate the profile curve most cases. In addition, it is more restrictive for large charges at elevated leak conditions and gives some allowance for small charges at low leak elevations.

The parabolic curve when the floor concentration reaches LFL is specified by following three conditions:

- Concentration equals zero at the effective height.
- Concentration on the floor is LFL.
- Concentration profile curve is symmetric with respect to the floor.

$$y = LFL - a \cdot x^2 \tag{4.1}$$

When $x = h, y = 0$

$$y = LFL - \frac{LFL}{h^2} \cdot x^2 \tag{4.2}$$

$$m_{max} = \int_0^h (LFL - \frac{LFL}{h^2} \cdot x^2) \cdot A \cdot dx = \frac{2}{3} \cdot LFL \cdot A \cdot h \tag{4.3}$$

The low concentration above the effective height and the high concentration near the leak port are neglected. Then, if y is the concentration at a given height x, the allowable refrigerant charge can be calculated using the (4.1)-(4.3):

5. EFFECTIVE HEIGHT

At a certain height, the concentration becomes zero. The estimated height where the concentration profile curve crosses the axis is called the "effective height". This effective height is affected by most of the parameters in Table 1. However, only the effects of molecular mass, LFL, leak height and floor area were evaluated in this analysis. Other parameters such as leak velocity and duration were set at conservative levels.

5.1 Effect of Leak Duration and Velocity on Effective Height

As discussed in section 3, the leak duration has a significant impact on the concentration profile. As the release duration becomes shorter, the highest concentration on the floor increases. In this analysis, as indicated in section 3, it was assumed that all the refrigerant was released in four minutes, in order to avoid variation in effective height due to a difference in leak duration.

The leak velocity was chosen to avoid any dynamic effects. Generally, a catastrophic leak occurs at sonic velocities at the leak port. However, if the leak port is surrounded by walls with a opening, the velocity can decrease quickly, so a minimum velocity was employed in the analysis.

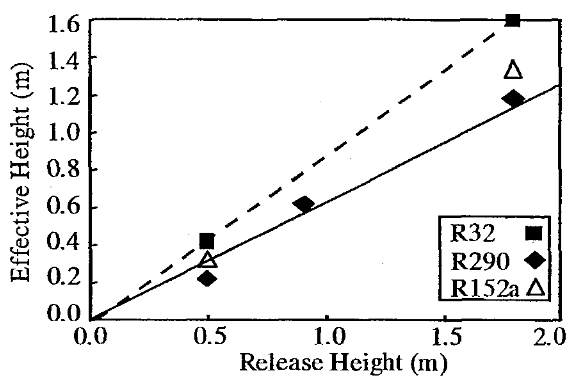

Figure 3. Height Effect on h

5.2 Effect of Release Height

As the leak height becomes higher, the effective height also increases. Since the velocity of down flow increases as the height increases, the concentration of refrigerant is diluted due to larger airflow. In addition, release at an elevated position generates mixing through turbulence, while mixing from a low release is caused mainly by air and refrigerant acceleration. Therefore, a large volume of the air and refrigerant mixture reaches the floor due to dilution, resulting in a higher effective height. This relationship is shown in figure 3.

The effective height of propane in a 7 m^2 room is approximately expressed by formula 5.1 when the floor concentration is at approximately LFL. As the actual floor area of the test room where most tests were conducted is approximately 7 m^2, the area 7m^2 was chosen. HFC-32 has a higher effective height than propane due to its higher LFL. However, effective heights of hydrocarbons are explained here to simplify the formula of the standard. The effective height of HFC-32 is discussed in section 6, along with other effects.

$$h_7 = 0.63 \cdot h_0 \qquad (5.1)$$

5.3 Effect of Molecular Mass and LFL

For a given amount of refrigerant released, a variation in the molecular mass of the refrigerant has a minor effect on the effective height. However, the refrigerant LFL has a substantial impact on effective height when floor concentrations are close to LFL. Figure 4 shows this phenomenon. In this figure, the accurate formula with adjustment includes effects of door gap. As the LFL by weight increases, the effective height becomes higher. This effect is discussed in section 6.

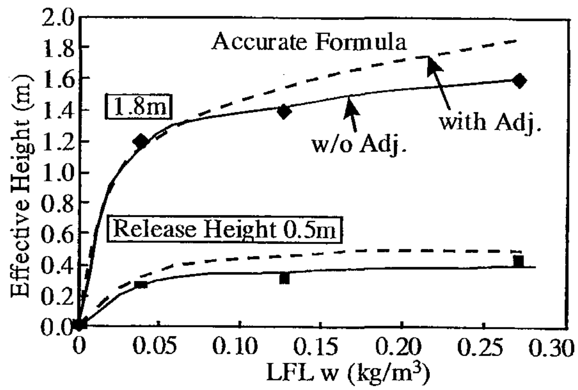

Figure 4. LFL Effect on h

5.4 Effect of Floor Area

As the floor area increases, the effective height decreases, because the refrigerant and air mixture volume to reach the floor from the unit is almost constant. The floor area and effective height appear to have a linear relationship on a log-log scale, as shown in Figure 5. For hydrocarbons, this relationship is approximated by equation 5.2.

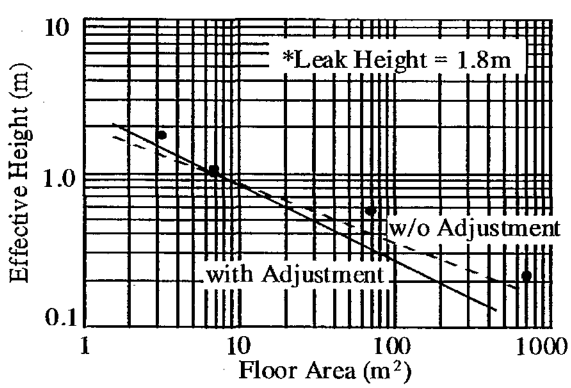

Figure 5. Floor Area Effect on h

$$\log\left(\frac{h}{h_7}\right) = -0.37 \cdot \log\left(\frac{A}{7}\right) \quad (5.2)$$

This formula gives a constant refrigerant concentration at the proportional distance point from the leak port. However, if this formula is used, the flammable volume and time integration become large as the floor area increases, since the distance between the leak port and the representative point increases. Therefore, the use of an adjustment coefficient is necessary. Many CFD analyses were conducted to confirm that the flammable space is reasonably small. Finally, equation 5.3 was employed to obtain a conservative value using a simple calculation method for hydrocarbons.

$$\log\left(\frac{h}{h_7}\right) = -0.5 \cdot \log\left(\frac{A}{7}\right)$$

$$h = 2.6 \cdot A^{-0.5} \cdot h_7 \quad (5.3)$$

This relationship is also affected by LFL, as discussed in section 6. The allowable charge for hydrocarbons can therefore be calculated as shown in equation 5.4.

$$m_{max} = \frac{2 \cdot LFL \cdot A \cdot h}{3}$$

$$h = 2.6 \cdot A^{-0.5} \cdot h_7 = 2.6 \cdot A^{-0.5} \cdot 0.63 \cdot h_0$$

$$m_{max} = \frac{2}{3} \cdot LFL \cdot A \cdot 2.6 \cdot A^{-0.5} \cdot 0.63 \cdot h_0 \cong 1.1 \cdot LFL \cdot h_0 \cdot \sqrt{A} \qquad (5.4)$$

6. COEFFICIENT FOR OTHER REFRIGERANTS

As mentioned previously, since a simplified calculation formula was established to calculate the allowable charge for propane, a correction factor for other refrigerants is necessary to adjust for the effect of their different LFL and molecular weight. In addition, the expected ignition probability is lower for class 2 refrigerants than for class 3, which is categorized by ASHRAE 34 [6] or ISO 5149 [7], due to the higher minimum ignition energy and lower flame speed of the class 2 refrigerants. Therefore, another correction factor is needed to address the lower safety risks of equipment using class 2, rather than class 3, refrigerants. Besides of these factors, for an equal flammable volume, the consequence of igniting class 2 refrigerants is different from that of class 3 substances. To adjust for these differences, a coefficient is necessary.

$$h = 1.45 \cdot h_o \cdot LFL^{\frac{1}{4}} \cdot \left(\frac{7}{A}\right)^{\left(\frac{0.00061}{LFL}\right)^{\frac{1}{6}}} \qquad (6.1)$$

$$m_{max} = \frac{2 \cdot LFL \cdot A \cdot h_0}{3} \cdot 1.45 \cdot LFL^{\frac{1}{4}} \cdot \left(\frac{7}{A}\right)^{\left(\frac{0.00061}{LFL}\right)^{\frac{1}{6}}} \qquad (6.2)$$

$$\cong 1.1 \cdot K \cdot LFL \cdot h_0 \cdot \sqrt{A} \qquad (6.3)$$

Based on the results of the CFD analysis, equation 6.1 was derived to maintain the flammable volume and time integration at a level less than 15-m^3·minutes for refrigerants other than propane. Equation 6.2 then gives the allowable charge calculation. However, equation 6.2 is too complicated to be used as a standard. Therefore, a simplified equation and correction coefficient was proposed, as shown in equation 6.3 that is derived from equation 5.4.

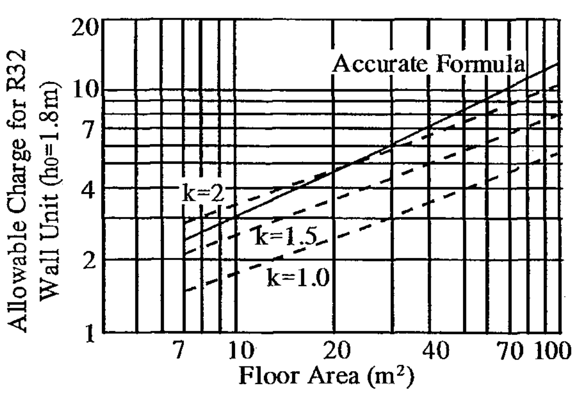

Figure 6. Detailed Calculation and K

Figure 6 shows the results of this detailed calculation and simplified formula with some coefficients for HFC-32. In order to maintain the allowable charge of HFC-32 using the simplified formula to be equivalent to or less than that derived from detailed calculations, a conservative value of K=1.7 is appropriate, as shown in Figure 6. To compensate for the different probability and consequence of ignition for HFC-32, larger value of K seems to be appropriate, but this most conservative approach was chosen for all refrigerants other than propane. If the K is fixed by this minimum value, K can be calculated by following formula because most critical condition appears when the room size is the minimum. Finally, formula 6.5 is obtained by using this K value.

$$K = 2.33 \cdot \sqrt[4]{LFL} \qquad (6.4)$$

$$\begin{aligned} h &= K \cdot h_0 \\ &= 2.33 \cdot \sqrt[4]{LFL} \cdot \frac{1.64 \cdot h_0}{\sqrt{A}} = 3.82 \cdot \frac{\sqrt[4]{LFL}}{\sqrt{A}} \cdot h_0 \end{aligned}$$

$$m_{\max} = \frac{2 \cdot LFL \cdot A \cdot h_0}{3} \cdot 3.82 \cdot \frac{\sqrt[4]{LFL}}{\sqrt{A}} \cong 2.5 \cdot LFL^{\frac{5}{4}} \cdot h_0 \cdot \sqrt{A} \qquad (6.5)$$

Since this formula 6.5 is obtained by evaluation of propane, butane, R152a and R32, this is applicable to HCs and fluorocarbons that has larger molecular weight than 44 because larger molecular weight gives higher effective height than this calculation.

7. CONCLUSION

A new method for calculating allowable charge for flammable refrigerants has been developed based on experimentation and numerical analysis. This formula was proposed to the IEC SC 61D and ISO TC86 SC1 WG1 joint working group to assist in establishing a standard for using flammable refrigerants in electrical heat pumps, air conditioners and dehumidifiers. Although the key coefficient (K value) is still under discussion at the time of writing this paper, the basic concept was accepted in the working group.

8. ACKNOWLEDGEMENT

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