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A Risk Assessment for Leakages of Flammable Refrigerants into a Closed Space

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ABSTRACT

This study proposes a procedure for a risk analysis for leakages of flammable refrigerants into a poorly ventilated three-dimensional space. It also presents several test cases of risk analyses on flammability and ignitions to a leaked refrigerant. Concentration of a leaked flammable refrigerant at a leakage window, \(C_{in}\), is determined by mass balance, providing information on the capacity of an air-refrigerant mixture, and the leakage rate. Five flammable refrigerants, 2,3,3,3-tetrafluoropropene (R-1234yf), difluoromethane (R-32), 1,1-difluoroethane (R-152a), propane (R-290), and ammonia (R-717) have been used to analyze risk of ignitions and flammability. A computational fluid mechanics (CFD) technique has been applied to the present risk analyses, and temporal development of velocity, concentration, and temperature profiles of an air-refrigerant mixture in a three-dimensional space are computed. The obtained concentration profiles are compared with the lower flammability limits to analyze detailed risk of ignitions and flammability. The results of this study demonstrate that risk of ignitions can be investigated successfully based on the current CFD technique. This study furthermore shows that risk of ignitions and flammability is different depending on the flammability characteristics of each refrigerant. This study proposes an indicator, the Safety Index, to evaluate risk of ignitions in individual cases easily as screening of flammability without performing three-dimensional calculations based on a CFD technique.

1. INTRODUCTION

Since the Montreal Protocol (Montreal Protocol, 1987) and its successor agreement, ozone-depleting refrigerants such as chlorofluorocarbons (CFCs) have been phased out. Technologies in the field of heating, ventilating, and air-conditioning (HVAC) have switched to alternative substances, such as hydrofluorocarbons (HFCs), to meet the demand. More than 20 years after the Montreal Protocol agreement, another environmental issue concerning alternative substances, HFCs, has been highlighted. Alternative refrigerants, and ones previously used, such as CFCs and hydrochlorofluorocarbons (HCFCs), have been found to have extensive global warming impacts. It has been found that their global- warning potentials (GWPs) are typically larger than 1000. The Kyoto Protocol specifies qualitative targets of emissions of greenhouse gases (GHGs) of six substances, including HFCs, based on their impacts on global warming by calculating their equivalent emissions of carbon dioxide (Kyoto Protocol, 1997). A recent study by Velders et al. (2009) predicted future HFC emissions and their impacts on future climate changes under several emission scenarios. Their conclusions indicate that global HFC emissions in 2050 will be equivalent to 9-19% of projected global CO2 emissions under the business-as-usual scenario, increasing the radiative forcing up to 0.4 W·m⁻² in 2050, compared with the baseline at 2000. Many countries have prohibited intentional releases of HFCs into the atmosphere to control the contributions of HFC emissions to environmental impacts, following the agreement based on the Kyoto Protocol. In 2008, the Ministry of Economy, Technology, and Industry of Japan (METI) disclosed an estimation of annual emissions of HFCs from 1997 to 2007 (METI, 2008), which indicate that 0.0024 GtCO₂-eq of HFCs were emitted from domestic mobile air conditioners (MACs) in 2007. Total amounts of emissions of HFCs from the whole of HVAC industries were also estimated as 0.0047 GtCO₂-eq in 2007, which is equivalent to about 0.34% of the total amount of domestic emissions of GHGs, about 1.36 GtCO₂-eq in 2007 (ME,
Future emissions of HFCs are predicted to increase, especially in the next few decades, since numerous air-conditioning systems using HFCs will be abandoned and a significant amount of emissions of HFCs is inevitable. In view of global warming due to emissions of traditional refrigerants, a search for a ‘next generation refrigerant’ has been launched worldwide. Many countries, regional unions, and business organizations including the HVAC industries are following the trend to reduce the environmental impact posed by emissions of HFCs. One of the most well-known examples is a directive referred to as “F-Gas Regulation” in the EU, which prohibits the use of refrigerants whose GWPs exceed 150 in new model automobiles effective from 2011, and for all models of automobiles starting from 2017 (Lindley and McCulloch, 2005; Calm, 2008). Based on this scientific and political background, many engineers and scientists working in the field of HVAC industries have to consider the practical applications of refrigerants whose GWPs are small enough. In the mobile air conditioning industries, 2,3,3,3-tetrafluoropropene (hereafter, R-1234yf is used to refer to this substance, based on the designation system specified by the International Organization for Standardization (ISO, 2010)) has been proposed as a new replacement which promises significant reduction of environmental impacts while maintaining sufficient energy efficiency. The GWP of this new refrigerant is 4 (Nielsen et al, 2007), which is about three-order smaller than that of traditional refrigerant, 1,1,1,2-tetrafluoroethane (R-22) of 1430, in 100-year time horizon specified in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC, 2007). Isobutane (R-600a), whose GWP is 3.3 (UL, 2011), has already been used as a refrigerant for home-use refrigerators, as an alternative to previous HCFC-based refrigerants such as chlorodifluoromethane (R-22). Difluoromethane (R-32), which has also been used in several mixed refrigerants such as R-410A is also one of the candidates for a new refrigerant, although its GWP is not surprisingly small, 675 (IPCC, 2007).

Figure 1 indicates the relationship between GWP and lower and upper flammability limits (LFL/UFL) for several refrigerants. The GWP values used in this figure are gathered from the IPCC AR4 (IPCC, 2007). Several references are used to collect the data on LFL and UFL, such as ASHRAE 34 (ASHRAE, 2010), ISO/DIS 817 (ISO, 2010), a technical report by Underwriters Laboratory Inc. (UL 2011), and Kondo et al. (2008). This figure indicates that traditional refrigerants such as CFCs, HCFCs, and HFCs, are non-flammable, however, their GWPs are categorized into “high-GWP,” 1000<GWP<3000, based on a new classification proposed by UNEP/TEAP (UNEP, 2010). On the other hand, several candidates such as R-1234yf have low GWPs, which are categorized into “low-GWP,” (100<GWP<300), or “very low-GWP,” (GWP<100), although these substances are flammable (ASHRAE, 2010; ISO, 2010). It is clear from this figure that only a few candidates are available to meet the demand required by the F-Gas Regulation, in which GWP of a new refrigerant of the next generation should be less than 150. This figure also implies that concentrated efforts to overcome the risk trade-off between environmental impacts and flammability should be made to develop environmentally-friendly HVAC systems (UL, 2011; UNEP, 2010), since all the refrigerants whose GWPs are less than 150 are flammable, except carbon dioxide (R-744).

The development of a systematic procedure of a risk assessment on the flammability of leaked refrigerants will assist efforts to overcome the risk trade-off and to use weak or moderately flammable refrigerants in the field of HVAC in a more extensive and efficient manner. Several risk assessments on discharges of flammable, and/or, toxic substances have been proposed and carried by several researchers. Colbourne and Suen (2004) proposed a systematic concept and model for the flammability of hydrocarbons. They presented conceptual models of the...
spread of flammable refrigerants whose concentration is within its LFL and UFL. Dharmavaram et al. (2005) performed several computational fluid dynamics (CFD) analyses on leakages of chemical substances in industrial sites, and indicated significant possibilities of CFD analysis to predict risk caused by the leakages of chemical substances. Venetsanos et al. (2009) carried out short and long-terms distributions and turbulent mixing of hydrogen in a garage based on a CFD technique. Minor et al. (2010) performed flammability assessments of several refrigerants, including R-1234yf, and ignition tests using several ignition sources to assess safety of flammable refrigerants for a fixed air conditioner. Several advantageous aspects of CFD analysis for risk assessments of leakages of chemical substances have been summarized by Hermann (2007), and Hansen and Middha (2008).

The purpose of this study is to propose a systematic procedure and numerical details to perform a risk analysis on flammability of refrigerants in a poorly ventilated space, as a preliminary stage for a complete risk assessment on ignitions and flammability, and possible hazards caused by ignitions. A CFD technique has been introduced to predict temporal development of concentration distribution of leaked refrigerants into a three-dimensional space, together with the velocity and temperature profiles. An initial concentration of a leaked refrigerant is predicted by a simple formulation based on mass balance. Only a few parameters are necessary in this formulation to determine the initial concentration of a leaked refrigerant. Five flammable refrigerants, R-1234yf, R-32, 1,1-difluoroethane (R-152a), propane (R-290), and ammonia (R-717), have been used in the present risk analyses to compare relative risk of flammability among these five refrigerants. Examples of risk analyses for these refrigerants are given to show a practical procedure to analyze risk and chance of ignitions.

2. NUMERICAL PROCEDURES FOR RISK ASSESSMENT

2.1 Prediction of Concentration of Leaked Refrigerant

It is assumed that the size of a window of refrigerant leakage is \( A_{in} \), and a refrigerant is discharged into a three-dimensional space through this window. Leakage velocity of refrigerant at the window, and its concentration and temperature are \( U_{in} \), \( C_{in} \), and \( T_{in} \), respectively. Total amount of refrigerant charged in an air-conditioning system is \( S \), and all the refrigerant is considered leaked during \( 0 \leq t \leq t_L \).

By considering mass balance of leaked refrigerant, the following equation is obtained,

\[
S = A_{in} \int_0^{t_L} U_{in}(t) C_{in}(t) \, dt. \tag{1}
\]

If \( U_{in}(t) \) and \( C_{in}(t) \) are constant in time, respectively, Equation (1) can be reduced to the following relation,

\[
C_{in} = \frac{S/t_L}{A_{in} U_{in}} = \frac{W}{Q}, \tag{2}
\]

where \( W \) is the leakage rate of refrigerant, and \( Q (=A_{in} U_{in}) \) is the capacity. Steadiness of both \( U_{in}(t) \) and \( C_{in}(t) \) to derive Equation (2) from Equation (1) means that the leakage rate of refrigerant is constant in time, \( W = dS/dt = S/t_L \).

Equation (2) indicates that concentration of leaked refrigerant is determined by only the two parameters, \( W \) and \( Q \). If the two parameters are given appropriately, comparisons of the results from several risk analyses can be performed in a systematic fashion.

2.2 Numerical Procedure

Temporal development of velocity, concentration, and temperature fields of an air-refrigerant mixture can be predicted by a CFD technique. Leakage velocity, \( U_{in} \), temperature, \( T_{in} \), and concentration, \( C_{in} \), are given as boundary conditions at the window. Viscosity of an air-refrigerant mixture is assumed constant, \( \nu \), without respect to its mixture ratio. Also, thermal diffusivity, \( \alpha \), and molecular diffusivity of a refrigerant, \( D \), are considered constant in this study. Both air and refrigerant satisfy the assumption of an ideal gas, and \( R \) is the gas constant.

Under the assumption that an air-refrigerant mixture is incompressible Newtonian fluid of constant density, \( \rho \), the governing equations of advection-diffusion problem of the mixture with heat transport in a three-dimensional space are expressed as follows,

\[
\frac{\partial U_i}{\partial t} + \nabla_j \left( -p \delta_{ij} + \frac{\partial U_i}{\partial x_j} - U_j U_i \right) + \left( \frac{C_{RT} \rho_0}{\rho_0} (r - 1) - \beta T_0 \left( \frac{T}{T_0} - 1 \right) \right) g_i = 0, \tag{3}
\]

\[
\frac{\partial}{\partial t} \frac{C_{in}}{\rho} + \nabla_j \left( -p \delta_{ij} + \frac{\partial U_i}{\partial x_j} - U_j U_i \right) = \left( \frac{C_{RT} \rho_0}{\rho_0} (r - 1) - \beta T_0 \left( \frac{T}{T_0} - 1 \right) \right) g_i, \tag{4}
\]
where $U_j$ ($j=1,2,3$) is the velocity, $p$ is the pressure, $C$ is the concentration of a leaked refrigerant in air, $T$ is the temperature, $g$ is the gravitational acceleration, $r$ is the specific gravity of refrigerant, $\beta$ is the volume expansion coefficient, $D$ is the molecular diffusivity of a refrigerant in air, and $\alpha$ is the thermal diffusivity, and $\delta_{ij}$ in Equation (4) is the Kronecker delta. $T_0$ and $p_0$ are the temperature and pressure of the ambient air, respectively. The subscripts 1, 2, and 3 indicate the $x$, $y$, and $z$ directions, and the gravitational force is acted only in the $y$ direction. Hence, $g_1=g_3=0$, and $g_2=g$ are given in Equation (4), where $g$ is the gravitational acceleration. The last two terms in the right-hand-side of Equation (4) express the effect of buoyancy caused by the density difference between the air and a refrigerant, and temperature, respectively.

These governing equations are solved by utilizing a non-commercial CFD package, OpenFOAM®, by developing a new solver for the governing equations. The current version of our solver does not implement turbulent subgrid-scale (SGS) models for a large-eddy simulation (LES) so far, since any SGS models available at this stage are not satisfactory in the sense of numerical accuracy to predict advection-diffusion of fluid under the presence of temperature and density differences. A sufficiently resolved computational domain using an enormous amount of meshes is necessary to carry out an exact computation of transient behavior of an air-refrigerant mixture in a three-dimensional closed space in current risk analyses.

### 2.3 Refrigerants Used in the Present Risk Assessments

Five flammable refrigerants, 1-1234yf, R-32, R-152a, R-290, and R-717, have been considered in the present risk analyses to compare risk of flammability, and to explore the possibilities of reducing and managing risk. Figure 2 shows the relation between LFL and the maximum burning velocity (BV) for the five flammable refrigerants. The dashed line of LFL of 3.5 vol% at 296.15 K and 101.3 kPa in this figure is the border of volume-based concentration to distinguish between flammability classification of Class 2 and 3 in the standard specified by ISO/DIS 817 (ISO, 2010). A refrigerant categorized into Class 2 whose BV is less than or equal to 0.1 m·s⁻¹ should be considered as Class 2L refrigerant, as shown by the chain-dotted line in Figure 2.

Risk analyses performed in this study consider leakage of a refrigerant from a wall-mounted air conditioner. The size of the space this study considers is a 3-meter cubic, and the area of the six walls of the room is $A=9$ m². The room is filled with the air of temperature of $T_0=303.15$ K, and the pressure of $p_0=101.3$ kPa at the time refrigerant leakage begins $(t=0)$, and these temperature and pressure are used to convert between volume-based and mass-based concentrations. These walls are assumed non-slip, non-permeable, and insulated, therefore, zero-velocity, and zero-gradient concentration and temperature are given at these boundaries. The leakage window is located 2.4 m above the floor in the center of one of the walls. The size of the leakage window is 0.45-meter in width and 0.15-meter in height. An artificial outflow of an air-refrigerant mixture is assumed at the opposite side of
the wall, and the outflow velocity is expressed by $U_{out} = U_{in} \frac{A_n}{A} = 3.75 \times 10^{-3} \text{ m s}^{-1}$. A total of $1.728 \times 10^8 (=120^3)$ non-equidistant mesh points is used to discretize the governing equations.

The leakage scenarios and parameters for five refrigerants considered in the current risk analyses are summarized in Table 1. Parameters required for performing the current risk analyses are listed in Table 2. This study deals with a leakage scenario of a low-temperature refrigerant, and temperature difference between at the window and in the ambient is set to be 6 K, which is a typical temperature difference when an air conditioning system is operated in the summer season. The present study considers the initial charge of refrigerant of 1.2 kg for R-1234yf, R-32, and R-152a, and 0.6 kg for R-290, and R-717. The different initial charge of refrigerants for R-290 and R-717 is prepared for the reasons below. For R-290, LFL is very low, and poses an extremely high risk if it is discharged into a poorly ventilated space. For R-717, the initial concentration should be very high because of its small molecular weight.

This study assumes that all the initial charge of refrigerants is discharged during 600 seconds with a constant leakage rate. The leakage rate of refrigerants is assumed $W = 2.0 \times 10^{-3} \text{ kg s}^{-1}$ for R-1234yf, R-32, and R-152a, and $W = 1.0 \times 10^{-3} \text{ kg s}^{-1}$ for R-290, and R-717 in this study. The capacity assumed here, $Q = 3.38 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} (=7.15 \text{ cfm})$, corresponds to about 6% of that of a home-use air conditioner operated in “silent” mode (Habara et al., 2008).

The governing equations are integrated in time from the time leakages begin ($t=0$) to the time all the initial charges are leaked ($t=t_L$) using a fixed time step of $5 \times 10^{-3}$ seconds to maintain the Courant number of approximately 0.5 or less during computations. About 7 CPU seconds per time step are necessary to integrate a set of the governing equations when 4-CPU parallel processing is applied on the Intel® Core™ i7-2960XM Processors which are used.

### Table 1: Leakage scenarios in individual refrigerant

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>$r$ (g mol$^{-1}$)</th>
<th>$M$ (g mol$^{-1}$)</th>
<th>LFL (vol%)</th>
<th>UFL (vol%)</th>
<th>BY (m s$^{-1}$)</th>
<th>$S$ (kg)</th>
<th>$C_m$ (mol)</th>
<th>$W$ (mol m$^{-3}$)</th>
<th>$H$ (kg s$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1234yf</td>
<td>4.0</td>
<td>116.0</td>
<td>6.70</td>
<td>11.7</td>
<td>0.016</td>
<td>1.2</td>
<td>10.34</td>
<td>5.11</td>
<td>12.7</td>
</tr>
<tr>
<td>R-32</td>
<td>1.8</td>
<td>52.2</td>
<td>13.5</td>
<td>27.5</td>
<td>0.065</td>
<td>1.2</td>
<td>22.99</td>
<td>11.3</td>
<td>28.2</td>
</tr>
<tr>
<td>R-152a</td>
<td>2.3</td>
<td>66.7</td>
<td>4.32</td>
<td>17.3</td>
<td>0.236</td>
<td>1.2</td>
<td>17.99</td>
<td>8.88</td>
<td>22.1</td>
</tr>
<tr>
<td>R-290</td>
<td>1.5</td>
<td>43.5</td>
<td>2.03</td>
<td>10.0</td>
<td>0.387</td>
<td>0.6</td>
<td>13.79</td>
<td>6.81</td>
<td>16.9</td>
</tr>
<tr>
<td>R-717</td>
<td>0.6</td>
<td>17.4</td>
<td>15.2</td>
<td>30.0</td>
<td>0.072</td>
<td>0.6</td>
<td>34.48</td>
<td>17.0</td>
<td>42.4</td>
</tr>
</tbody>
</table>

### Table 2: Parameters used in the present risk analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nomenclature and Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of walls of the room</td>
<td>$A$ (m$^2$)</td>
<td>9</td>
</tr>
<tr>
<td>Area of leakage window</td>
<td>$A_n$ (m$^2$)</td>
<td>0.0675 (=0.45×0.15)</td>
</tr>
<tr>
<td>Leakage velocity</td>
<td>$U_{in}$ (m s$^{-1}$)</td>
<td>0.05</td>
</tr>
<tr>
<td>Artificial outflow velocity</td>
<td>$U_{out}$ (m s$^{-1}$)</td>
<td>$3.75 \times 10^4$</td>
</tr>
<tr>
<td>Leakage temperature</td>
<td>$T_w$ (K)</td>
<td>297.15 (=24°C)</td>
</tr>
<tr>
<td>Time duration of leakage</td>
<td>$t_L$ (s)</td>
<td>600 (=10 min)</td>
</tr>
<tr>
<td>Ambient pressure</td>
<td>$p_0$ (Pa)</td>
<td>1.013x10$^5$</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>$T_0$ (K)</td>
<td>303.15 (=30°C)</td>
</tr>
<tr>
<td>Capacity</td>
<td>$Q$ (m$^3$s$^{-1}$)</td>
<td>$3.375 \times 10^3$</td>
</tr>
</tbody>
</table>

### 3. RESULTS AND DISCUSSIONS

#### 3.1 Individual Risk Assessment for Leaked Refrigerants

This subsection provides results from individual risk analysis for the five flammable refrigerants based on predictions by the present CFD technique. Figure 3 shows the concentration distributions of R-1234yf, and R-32 after 600 seconds from leakage. Blue surfaces in this figure indicate isosurfaces of concentration at individual LFL, suggesting presence of flammable gas (hereafter we refer to an air-refrigerant mixture whose concentration of refrigerant is beyond its LFL as “potentially flammable refrigerant/gas”). Hence, larger occupancy of such potentially flammable gas in the space could be one of the reasons for high risk of ignitions and flammability in the leaked refrigerants.

In the cases of leakages of R-1234yf and R-32, potentially flammable gases occupy only extremely limited volume of the room, even if all the refrigerants are discharged. The flammable gases are concentrated only in a region close
to the wall below the leakage window. These concentration profiles suggest that risk of ignitions and flammability is extremely limited for both R-1234yf, and R-32. Velocity distributions of potentially flammable refrigerants obtained in this study indicate that the velocity magnitude of the two flammable gases is large, from 0.2 up to 1 m·s⁻¹, at 0.01 m from the wall. It is clear that these potentially flammable gases of R-1234yf, and R-32 do not stagnate, and are continuing to flow downward along the wall. It should also be mentioned here that the minimum ignition energies (MIEs) for both the two refrigerants are two- to three-order larger than that of R-290, which is one of the typical flammable and explosive gases, as shown in Table 3. This suggests that igniting these leaked refrigerants is difficult, since large energy should be supplied to ignite these refrigerants. The present risk analysis concludes that risk of ignitions and flammability posed by the leakage of R-1234yf, and R-32 is thought manageable.

Figures 4(a) and 4(b) show the concentration profiles of leaked R-152a at 200, 400, and 600 seconds after its leakage, respectively. The values of concentrations for drawing these isosurfaces are 1.736, 1.527, and 1.326 mol·m⁻³, corresponding to 4.32 (LFL), 3.80, and 3.30 vol% at 303.15 K, and 101.3 kPa. This figure demonstrates that presence of potentially flammable refrigerant of R-152a is observed only in the region close to the wall below the leakage window. These concentration profiles however suggest that the floor of the room is covered by leaked R-152a whose concentration is only about 1.0 vol% below its LFL after 600 seconds from leakage. It is confirmed from the present CFD analyses that such concentration profiles are not observed in the cases of leakages of R-1234yf, and R-32. In addition, velocity profiles of leaked R-152a after 600 seconds from leakage exhibit that the leaked gas is stagnant, especially near the corner of the opposite side of the leaked window. Considering very small value of MIE of R-152a as shown in Table 3, risk of ignitions and flammability of R-152a should be evaluated carefully. Results from ignition experiments will be helpful to evaluate details of risk posed by R-152a leakage. Unlike the previous three refrigerants, risk of ignitions and flammability is difficult to manage if R-290 is discharged into a poorly ventilated space. One of the reasons for the difficulties is significant accumulation of potentially flammable R-290 at the floor, as found in Figure 5. It is understood from the observation that accumulation of leaked R-290 above the floor begins after about 300 seconds from its leakage. The results of the present risk analysis also show that a region about 1.0 m above the floor is occupied by potentially flammable R-290 after 600 seconds from leakage. The velocity and concentration distributions of leaked R-290 suggest that the accumulated refrigerant have very slow flow velocity, and the gas forms “clouds,” as one of the risky behavior of flammable gases (Colbourne and Suen, 2004). The small value of MIE for R-290, 0.28 mJ, could also be another reason for the difficulty of managing risk posed by leaked R-290.

Table 3: Minimum ignition energies for flammable refrigerants (Clodic, 2010)

<table>
<thead>
<tr>
<th>Refrigerant</th>
<th>Minimum Ignition Energy (MIE) (mJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1234yf</td>
<td>5000</td>
</tr>
<tr>
<td>R-32</td>
<td>30</td>
</tr>
<tr>
<td>R-152a</td>
<td>0.38</td>
</tr>
<tr>
<td>R-290</td>
<td>0.25</td>
</tr>
<tr>
<td>R-717</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 3: Three-dimensional concentration profiles of leaked refrigerants after 600 seconds from leakage: (a) R-1234yf; (b) R-32.
The four refrigerants discussed above have specific gravities of larger than 1, meaning that they are heavier than the air. These refrigerants hence accumulate in the lower part of the space once they leak, unless the leaked gases have much higher temperature than the ambient. In contrast, the specific gravity of R-717 is \( r \approx 0.58 \), and physical behavior of the refrigerant after leakage is different with those of other gases. Indeed, leaked R-717 into the space from the window rises toward the ceiling, as shown in Figure 6. The results of the present risk analysis indicate that significant accumulation of leaked R-717 is observed between 3 to 4 minutes after leakage, as illustrated in Figure 6, and the thickness of the stagnant gas at the ceiling becomes about 0.3 m after 600 seconds from leakage. Risk of ignitions and flammability of R-717 is also difficult to manage, as observed in the case of R-290 leakage. It should be mentioned here that R-717 has acute toxicity, and risk management of R-717 is difficult on this point.

The conclusions of the present risk analyses are summarized based on the above discussions. Risk of ignitions and flammability of R-1234yf, and R-32 is manageable under the current leakage scenario, since accumulations of

**Figure 4:** Concentration profiles of leaked R-152a at: (a) 200 seconds; (b) 400 seconds; and (c) 600 seconds from leakage. Red, blue, and grey isosurfaces indicate concentrations of 1.736, 1.527, and 1.326 mol·m\(^{-3}\), respectively. These concentrations correspond to 4.32, 3.80, and 3.30 vol% at 303.15 K, and 101.3 kPa.

**Figure 5:** Temporal development of concentration field of leaked R-290 after: (a) 60 seconds; (b) 120 seconds; (c) 180 seconds; (d) 240 seconds; (e) 300 seconds; and (f) 360 seconds from leakage. Gray isosurfaces show LFL of R-290.
potentially flammable refrigerants are not observed. Their larger MIEs do not pose an immediate risk of ignitions and flammability if these refrigerants are leaked into a poorly ventilated space. Detailed assessment of risk posed by leaked R-152a is necessary, since the floor of the space is covered by leaked gas whose concentration is only 1.0 vol% smaller than its LFL after 600 seconds from its leakage. It should also be stressed here that igniting R-152a is easier than R-1234yf, and R-32, because of its small value of MIE. Risk posed by leakages of R-290 and R-717 will be difficult to manage, since the floor of the space is occupied by potentially flammable refrigerants after about 300 seconds from leakage.

3.2 An Indicator for Screening of Risk of Ignitions and Flammability

A new indicator to screen risk of ignitions and flammability is proposed. The new indicator, the Preliminary Safety Index, is defined by

\[
SI = \frac{C_m}{r \times LFL} = \frac{W/Q}{r \times LFL}. \quad \text{(7)}
\]

The index can easily be calculated by the parameters this study uses, as shown in Table 2. It is worth to mention here that the index is obviously a function of leakage rate of refrigerant, \(W\). Our explorations based on concentration fields of leaked refrigerants exhibit that risk of ignitions and flammability is manageable if the index is less than approximately 1.5. Using the parameters this study assumes as shown in Table 2, \(SI\) is about 0.94 for R-1234yf, 1.16 for R-32, 2.22 for R-152a, 5.56 for R-290, and 4.64 for R-717 after 600 seconds from their leakages. The results indicate that R-152a, R-290 and R-717 pose risk of ignitions and flammability under the current leakage scenario. An initial charge of flammable refrigerant without posing risk of ignitions and flammability can be determined by using this index. Reducing the initial charges to 0.8 kg for R-152a, 0.15 kg for R-290 and 0.2 kg for R-717 can lower the safety index to about 1.5, suggesting more manageable risk of ignitions and flammability, if time duration of leakage is the same.

4. CONCLUSIONS AND FUTURE DIRECTIONS

This study proposed a systematic procedure for a risk analysis of flammable refrigerants leaked into a poorly

![Figure 6: Temporal development of concentration field of leaked R-717 after: (a) 60 seconds; (b) 120 seconds; and (c) 180 seconds; (d) 240 seconds; (e) 300 seconds; and (f) 360 seconds from leakage. Gray isosurfaces show LFL of R-717.](image)
ventilated three-dimensional space. A leakage scenario proposed in this study requires only a few parameters on leakage to perform risk analysis. A CFD technique for predicting temporal development of concentration, velocity, and temperature fields in the space was developed, with the aid of a non-commercial CFD package. Five refrigerants were used to exhibit examples of risk analyses. The initial charge of 1.2 kg was assumed for R-1234yf, R-32, and R-152a, and 0.6 kg for R-290, and R-717. This study analyzed successfully risk of ignitions and flammability when these refrigerants were leaked into a poorly ventilated space. This study also proposed a new indicator, the Safety Index, for screening risk posed by leakages of flammable gases without performing CFD calculations. It is found that the index should be less than approximately 1.5 under the current leakage scenario for avoiding risk of ignitions and flammability.

This new index has not been examined in a satisfactory manner in various kinds of leakage scenarios, and generalization of this index should be carried out in the near future for easy screening of risk posed by leakages of flammable refrigerants. In particular, the current index does not involve the effect of room size, and installation height of the appliance. Both factors will be important to analyze risk of ignitions and flammability posed by leakages of refrigerants. Indeed, International Electrotechnical Committee regulates permitted charge of a flammable refrigerant, which is determined by room size, installation height of air conditioning system, and LFL of refrigerant (IEC, 2005). An introduction of a coefficient for calibrating the effects of room size, and installation height of the appliance should be considered to generalize the results of this study in the near future.

It should be stresses finally that determining a new refrigerant of the next generation requires more comprehensive assessments, including LCCP (Life Cycle Climate Performance) analysis, to evaluate overall impacts of a refrigerant to the environment. The current risk analyses on ignition and flammability should be involved in the comprehensive assessments for choosing a suitable refrigerant to satisfy both the environmentally friendliness and the safety.

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