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Energy and Environmental Science Division
Building Equipment Research Group

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NOMENCLATURE

v	Velocity (m/s)
C_d	Coefficient of discharge
ρ	Density (kg/m^3)
ΔP	Pressure difference (Pa)
m_c	Charge amount (kg)
LFL	Lower Flammability Limit
UFL	Upper Flammability Limit

ABSTRACT

With the effort to find alternative refrigerants with lower global warming potential (GWP), challenges have arisen due to the flammability risk for many of the alternatives. One of the new alternatives is R-452B, which is recommended as a replacement for R410A. R-452B is classified as a mildly flammable refrigerant (A2L) by ANSI/ASHRAE Standard 34. This paper summarizes a computational fluid dynamic (CFD) simulation study of a leak incident of R-452B from a 3-ton packaged unit which serves a 167 m^2 residence. The R-452B leak is assumed to be downstream of the evaporator coil. The simulated residence has four rooms and a hallway. The packaged unit distributes the conditioned air through a supply duct system delivering the air through registers. The dispersion of R-452B is characterized for two scenarios: one with underfloor supply air ducts and another with ceiling supply air ducts. The mass flow rate of R-452B exiting the duct outlets is quantified and the refrigerant volume fraction is monitored inside the residential space.

1. INTRODUCTION

As the world is facing the risks of global warming, research efforts are taking place to mitigate this harmful effect. Replacing conventional high global warming potential (GWP) refrigerants with new, lower GWP alternative refrigerants is among the efforts. However, we are challenged with the fact that almost all the alternatives are either mildly flammable and categorized as A2L or A2, or flammable and categorized as A3 according to ISO Standard 817 (2014) and ANSI/ASHRAE Standard 34 (2013). The flammability of any refrigerant is determined by two quantities which are defined in terms of the volume fraction of refrigerant in air: lower flammability limit (LFL) and upper flammability limit (UFL). If the refrigerant volume concentration is between these two limits, it can ignite under certain pressure and temperature in the presence of an ignition source. There has been considerable effort to investigate the flammability risk during leaks of alternative refrigerants for different leak scenarios (i.e. leak height, leak duration, leak flow rate, etc..).

Okamoto et al. (2014) investigated numerically and experimentally a leak from a wall-mounted indoor room air conditioner (RAC) unit for different refrigerants (R1234ze(E), R1234yf, R32, and R290). They found that for indoor units, combustion did not occur in a wall-mounted unit in the case where there was no ignition source inside the unit. They also found that for a leak from a floor-mounted indoor RAC unit, the risk of combustion was higher for R1234yf than for R32. Imamura et al. (2015) studied leak of A2L refrigerants (R-1234yf, R-1234ze and R-32) from a pinhole in a pipe into collection device used for service maintenance. Leak rate varied from 5 to 847 g/min. They found that the possibility of ignition is very small because only a small zone of flammability is formed in the vicinity of the leak point. In addition, they concluded that the flame propagation would be small since the burning velocity of the refrigerants studied was lower than the velocity of the refrigerant leak stream.

Papas et al. (2016) investigated a numerically choked refrigerant leak from a 750ton chiller with R-1234ze(E), R-32 and R-290 (propane) inside a machine room. The leak rate was from 1.24 to 40 kg/min. Forced ventilation was included in the simulation as a flammability mitigation technique. They found that the current ventilation requirement for nonflammable refrigerants can mitigate flammability risks for leak rates up to 10 Kg/min with 50% probability. Elatar et al. (2018a) numerically studied an R-32 leak from a 17.58 kW (5-ton) package unit into a conference room. The unit charge was 6.8 kg and the whole charge was leaked in 31.5 seconds. They found that the leaked refrigerant overshoots the closest duct outlet and exits from the three other outlets. They also observed that the leaked refrigerant was falling vertically into the room while dispersion was negligible. Elatar et al. (2018b) also published a similar study for the same conference room with smaller package unit (3 ton) and two charges of 1.81 kg and 3.62 kg.

Another low GWP refrigerant which holds strong potential as a replacement for R-410A is R-452B which is classified as mildly flammable refrigerant (i.e. A2L). It is a blend of 67% R-32, 26% R-1234yf and 7% R-125 by mass (ISO 817 (2014) and ASHRAE 34 (2013)). It has a GWP of 676 and no ozone depletion potential (ODP). This blend has an LFL and UFL of 11.9% and 22% by volume and a laminar burning velocity of less than 0.04 m/s. As a continuation on the effort to investigate the flammability of low GWP refrigerants, we are investigating in this paper the flammability risk of R-452B leak from a 3-ton package unit which serves a 167 m^2 residential space. The refrigerant volume fraction is monitored, and the total flammable volume is quantified.

2. NUMERICAL MODELING

A 3-ton package air-conditioning unit serving a 167 m^2 residential space which has four rooms and a hallway as shown in Figure (1) was numerically simulated. The unit is charged with 3.175 kg of R-452B. Two cases were considered, one for underfloor ducts where the air is being supplied from air grills fixed in the room floor as seen in Figure. (1) while for the other case, a ceiling duct was considered with air supply grills in the middle of the room ceiling. A return air grill of 0.6 x 0.6 m is located in the hallway. The room's doors are open in the simulated cases. The floor duct design and dimensions are shown in Figure 2. The ceiling duct is identical except for the length of the branches from the main duct to the outlets. For the ceiling duct the branch length is 2.25 m. The numerical models were built using CONVERGE 2.3.18 to run the CFD simulations.

A catastrophic (i.e. full rupture) of a ¼ inch (0.635 cm) pipe downstream of the evaporator coil was assumed. The incident was assumed to take place right after the unit stopped operating (i.e. the indoor air circulation fan is off). The leaked refrigerant temperature was assumed 280 K. Orifice equation was used to calculate the leaked refrigerant mass flow rate assuming a coefficient of discharge of 0.8 as follows (Richard, 2015),

$$v = C_d \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

Where C_d is the coefficient of discharge equals to 0.8, ΔP is the pressure difference across the rupture and ρ is the refrigerant density. The leaked refrigerant velocity was 187 m/s and the mass flow rate was 0.173 kg/s. The total charge was leaked in 18.36 seconds assuming that the refrigerant pressure inside the pipe remained constant. The leaked refrigerant was entering the duct from the duct end side and the flow was horizontal (i.e. parallel to the duct side walls). The room temperature was 297 K and the initial temperature of the air inside the duct was 288 K. The Navier-Stokes equations with continuity equation and energy equations were solved and a standard k-ε turbulence model was used to simulate the flow turbulence; gravity force was included in the momentum equation. The refrigerant was assumed to be an ideal gas. A pressure implicit with splitting of operators (PISO) scheme was used for pressure-velocity coupling. The time step was variable, ranging from 10^{-5} to 3×10^{-3} seconds.

The simulations were divided into two stages for each of the two cases studied in this paper. The first stage was to simulate the leak into the duct and measure the refrigerant mass flow rate at each of the duct outlets. The second stage was to simulate the leaked refrigerant into the residential space using the refrigerant mass flow rates from the first stage as a boundary condition. Half the duct and the room were simulated due to symmetry to reduce the computational time. Cut cell is used for meshing with basic size of 0.1 m. Adaptive mesh refinement which automatically changes the grid size based on the fluctuation and moving condition for both the velocity and species was used during the simulation.

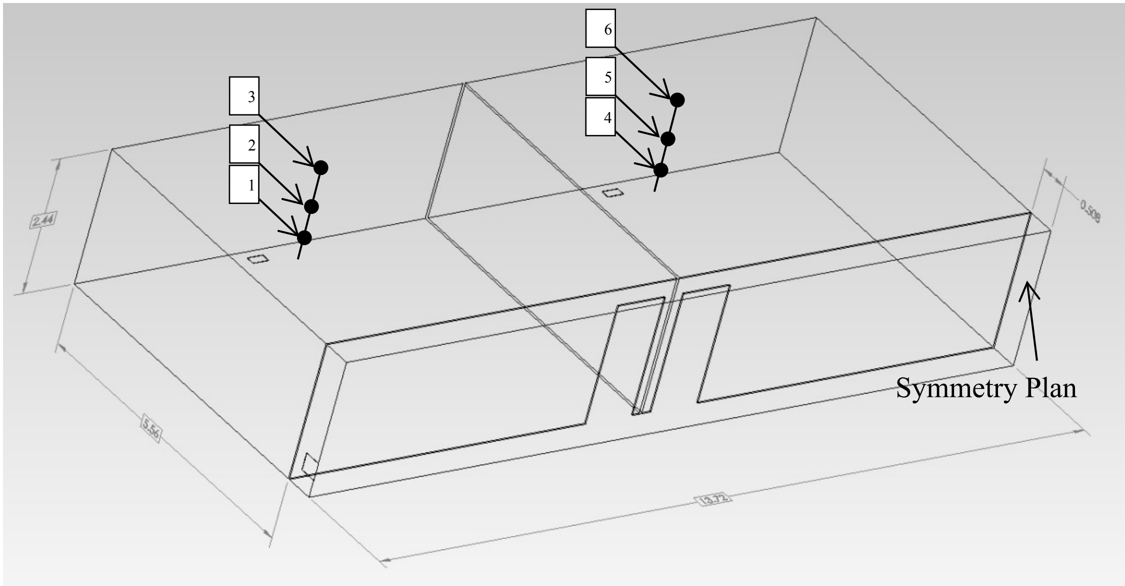
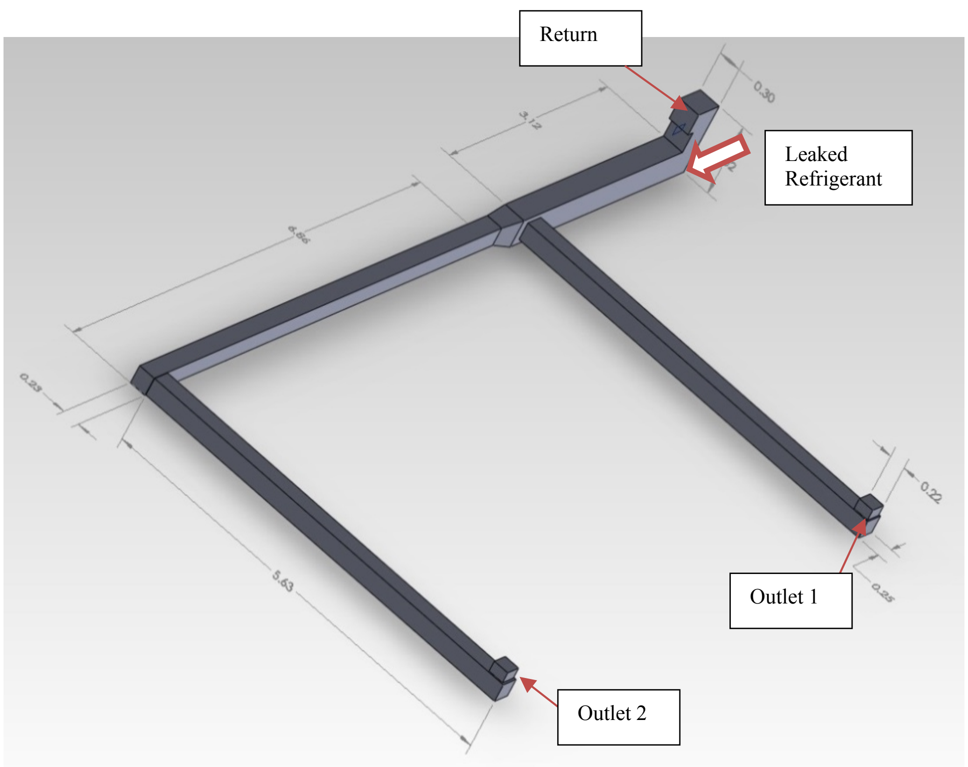


Figure 1. Schematic of half the residential space (floor air diffusers are shown).

(a)



(b)

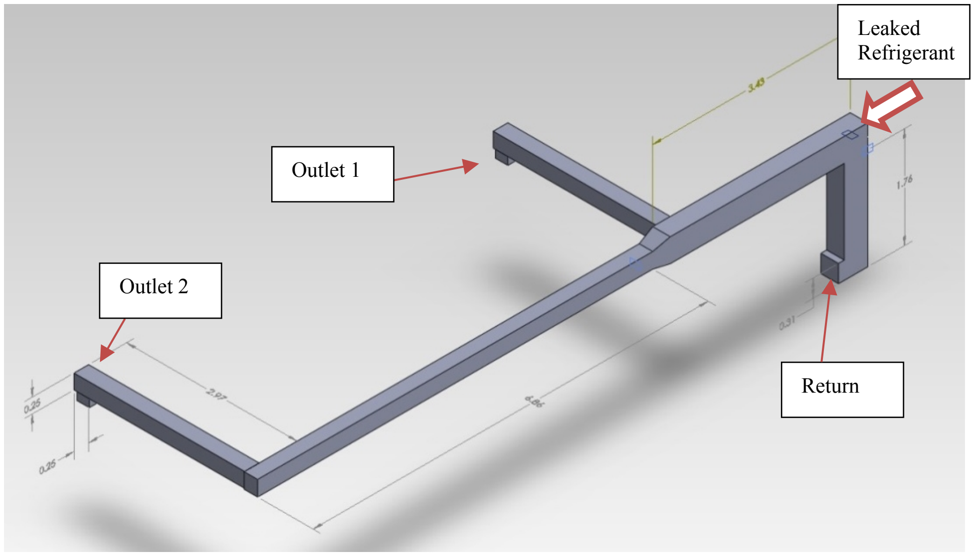


Figure 2. Duct design for (a) floor duct and (b) ceiling duct (dimensions are in meters and half duct is shown).

2.1 NUMERICAL VALIDATION

The authors were not able to find any experimental results in the literature for leak from package unit into duct system to validate the numerical method with. Therefore, an experimental case for a leak from a RAC unit into a single room by Okamota et al. (2014) was chosen to validate the numerical approach with. For further details about the case setup, please see the paper by Okamota et al. (2014). The base grid size was 2.54 cm and the total number of cells in the model was about 1 million. The time step for the simulation was 0.02 second. The inlet velocity was about 0.055 m/s. A transient pressure-based solver with gravity ($g = 9.81\ m/s^2$) was employed. The energy equation was turned on. A standard k-ε model with enhanced wall treatment and buoyancy effects was used. The species model was used to simulate the species transport. In the mixture, the employed models included ideal gas for density, mixing law for specific heat, ideal gas mixing law for thermal conductivity and viscosity, and a constant mass diffusivity value of $2.88e^{-5}\ m^2/s$.

The inlet was set as a mass flow inlet with a mass flow rate of 0.00417 kg/s and 100% R32 leakage, and the pressure outlet was 100% air with zero-gauge pressure. The PISO scheme was used as the pressure-velocity coupling. Six monitor points were stacked vertically, starting with point 1 at the floor level. Figure 3 shows the refrigerant volume fraction as a function of time at the monitoring points. It can be seen that the simulations successfully predicted the volume concentration compared to the experimental data. Although the comparisons show some over prediction of the R32 volume concentration at lower sampling points (i.e., points 1 to 4) based on the present modeling, it did capture the concentration at points 5 and 6 well. All numerically predicted data were within the error bar of the experimental data. This showed that the adapted numerical model was able to simulate and capture the refrigerant leak dispersion inside the room with acceptable accuracy.

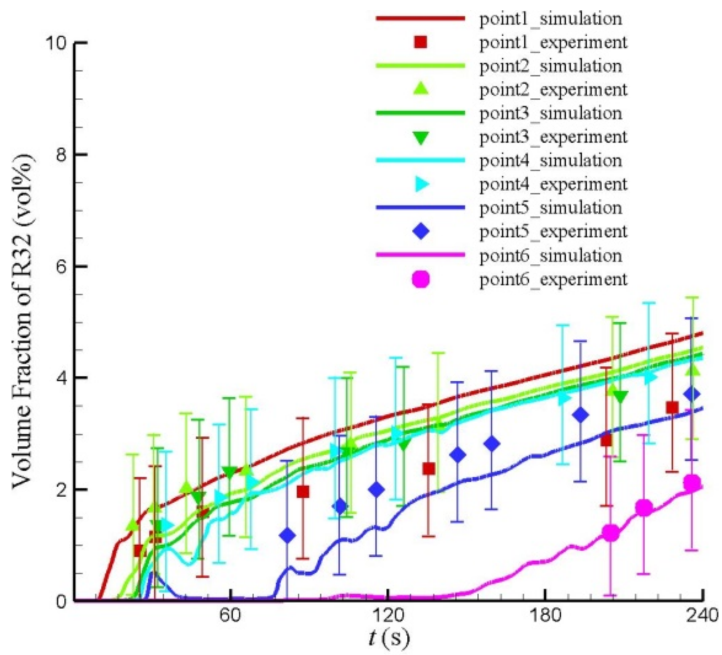


Figure 3. R-32 volume fraction of the numerical prediction against the results from Okamota et al. (2014).

To find the optimal grid size which accurately predicts the leaked refrigerant volume fraction with the shortest time to solution, a grid convergence test was conducted for the duct and room simulations. The grid convergence test was conducted for base grid sizes of 0.04 m (2 million (M) cells), 0.035 m (3 M cells), and 0.032 m (4 M cells) for half the domain (i.e., the residential space). It was observed that convergence is achieved at the 3M size grid for both monitored points. This grid was adopted to conduct the numerical simulations.

3. RESULTS

3.1 DUCT SIMULATION

The first part of the simulation predicted the leaked refrigerant dynamics inside the duct for both ceiling and floor ducts. Figure 4 shows a contour plot of R-452B volume fraction at 5 and 60 seconds from the leak onset. It is observed from the plots that the highest concentration is seen close to the leaked refrigerant jet with a maximum volume fraction of about 60%. The volume fraction of the leaked refrigerant drops significantly at a given instant in the streamwise direction as seen in Figure 4a. The volume fraction inside the duct is maintained around 5% away from the refrigerant jet and that is observed in Figure 4a and 4b. This refrigerant volume fraction distribution maintained the same distribution during the leak incident (i.e. 18.36 seconds from the leak onset). After 60 seconds from the incident onset, the refrigerant volume fraction distribution inside the ducts stayed unchanged for both ceiling and floor ducts. This was also observed for the rest of the simulation time (600 seconds). The leaked refrigerant jet created a lower pressure zone compared to the pressure at the return grill, therefore, air was driven into the return duct during the leak incident for both ducts systems. Only for the ceiling duct, after the leaked jet perished, the remaining refrigerant inside the duct started to descend through the return duct and exit at the return grill. This resulted in the generation of a reversed flow stream at outlet 1 and 2 entering the duct. The contour plots show that the average volume fraction for the ceiling duct was slightly higher than that for the floor duct as seen in Figure 4c and 4d. This could be due to the larger volume of the floor duct. It can be seen that the refrigerant volume fraction between LFL and UFL is occupying a very small volume downstream of the leaked refrigerant jet and it exists only during the refrigerant leak (i.e. 18.36 seconds).

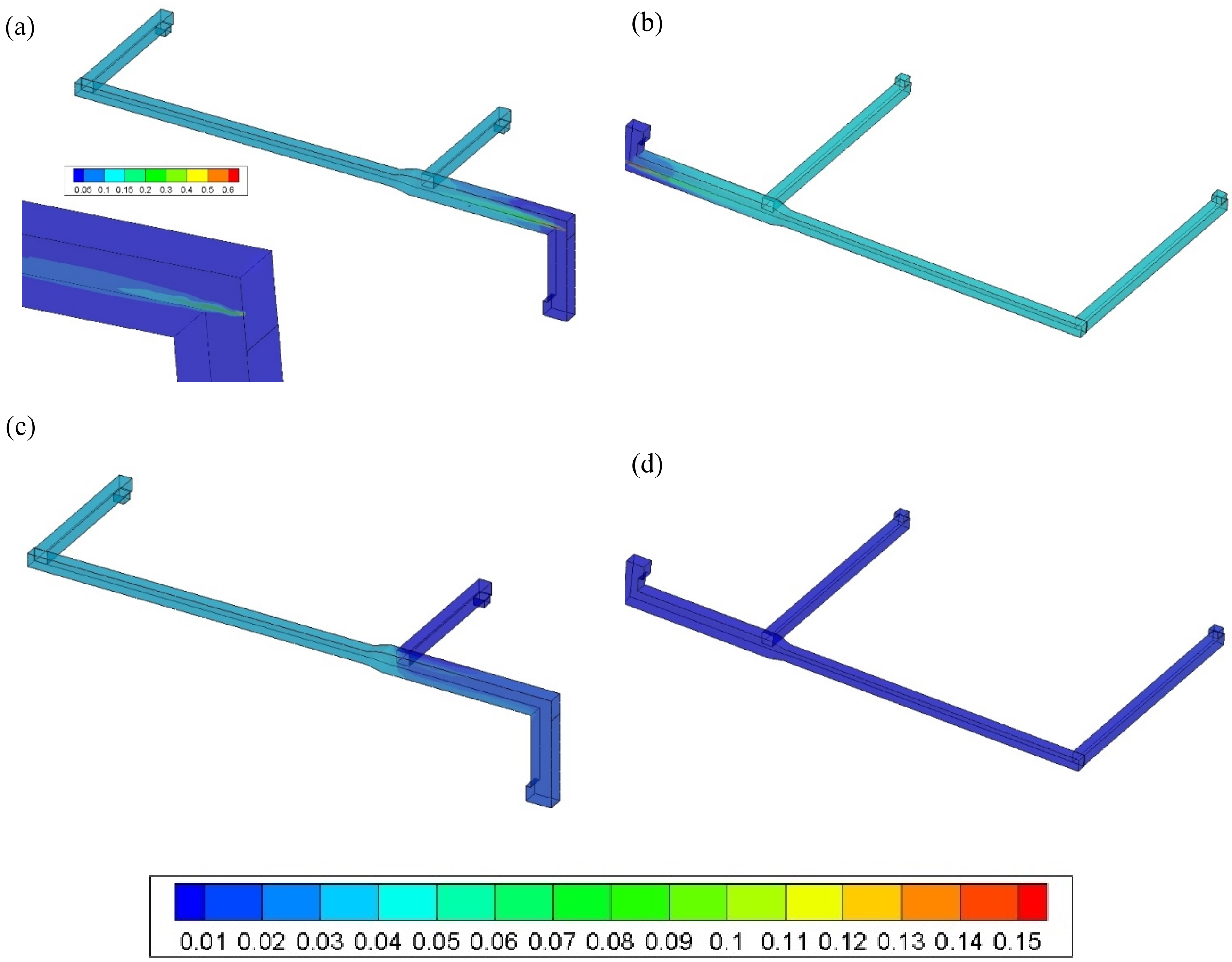


Figure 4. Contours of R-452B volume fraction inside the ceiling duct (left) and floor duct (right) at 5 seconds (top row) and 60 seconds (bottom row) from leak onset. Note: the color bar for the zoomed in image in (a) has different scale than the color b.

(a)

(b)

(c)

(d)

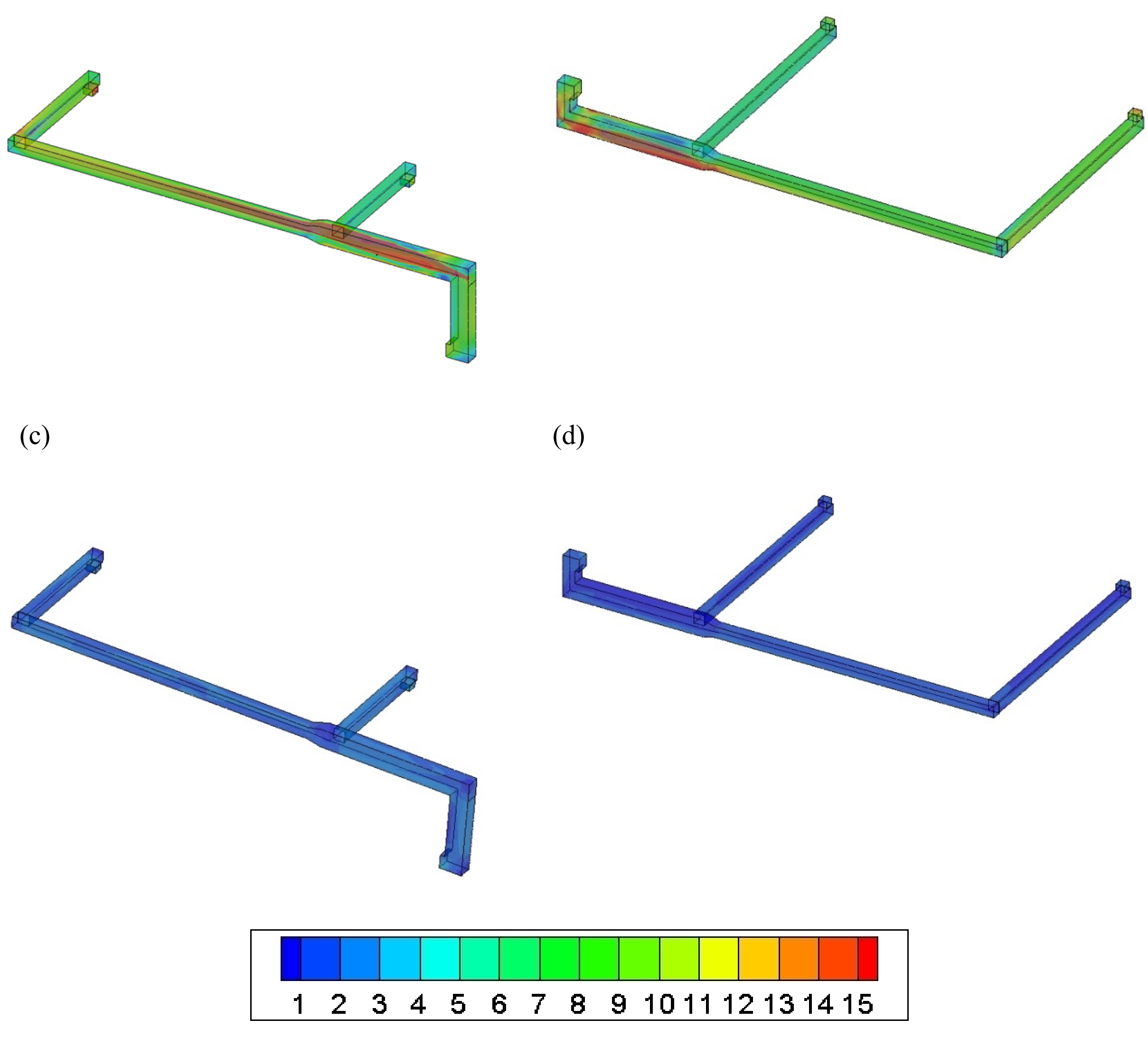


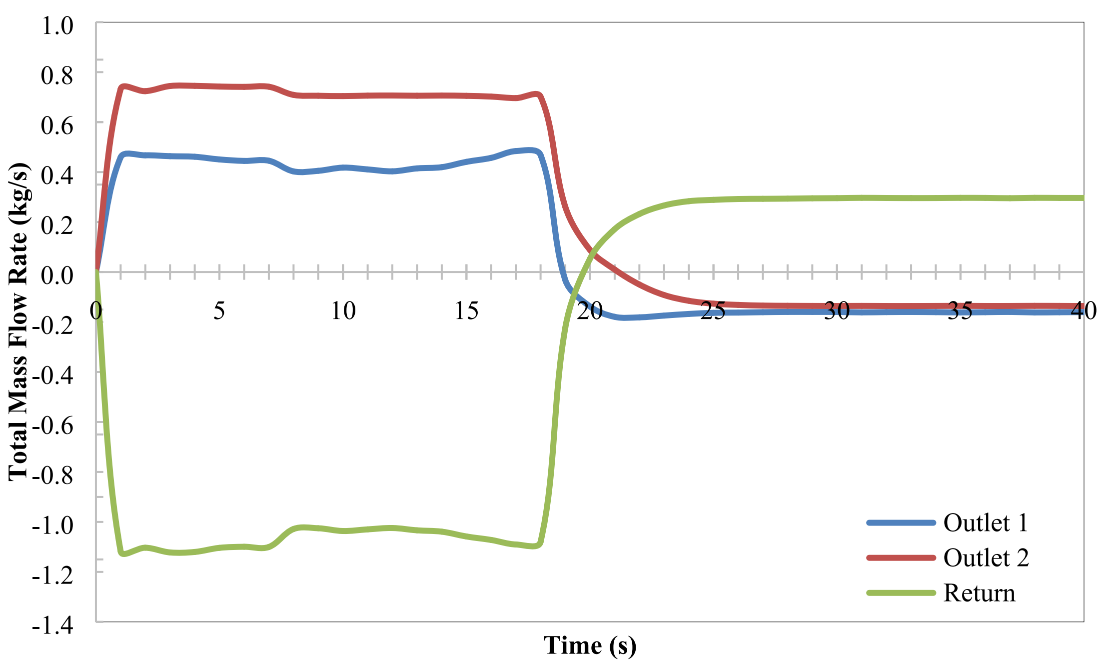
Figure 5. Velocity contours in m/s of R-452B inside the ceiling duct (left column) and floor duct (right column) at 5 seconds (top row) and 60 seconds (bottom row) from leak onset.

Figure 5 presents the contour plots of the refrigerant velocity inside the ducts at 5 and 60 seconds form the leak incident onset. One can see that the refrigerant velocity downstream of the leak refrigerant jet is around 14 m/s and this velocity magnitude was maintained only during the leak incident as seen in Figure 5a and 5b. The laminar burning velocity for R-452B is less than 0.04 m/s which is very small compared to the leaked refrigerant velocity inside the duct. Particularly, in the jet downstream zone where the volume fraction of R-452B is within the flammability limit during the leak incident period. After the whole refrigerant charge is leaked, the flow starts to lose its momentum and the average refrigerant velocity inside the ducts drops to less than 1 m/s after 60 seconds from the leak start as seen in Figure 5c and 5d.

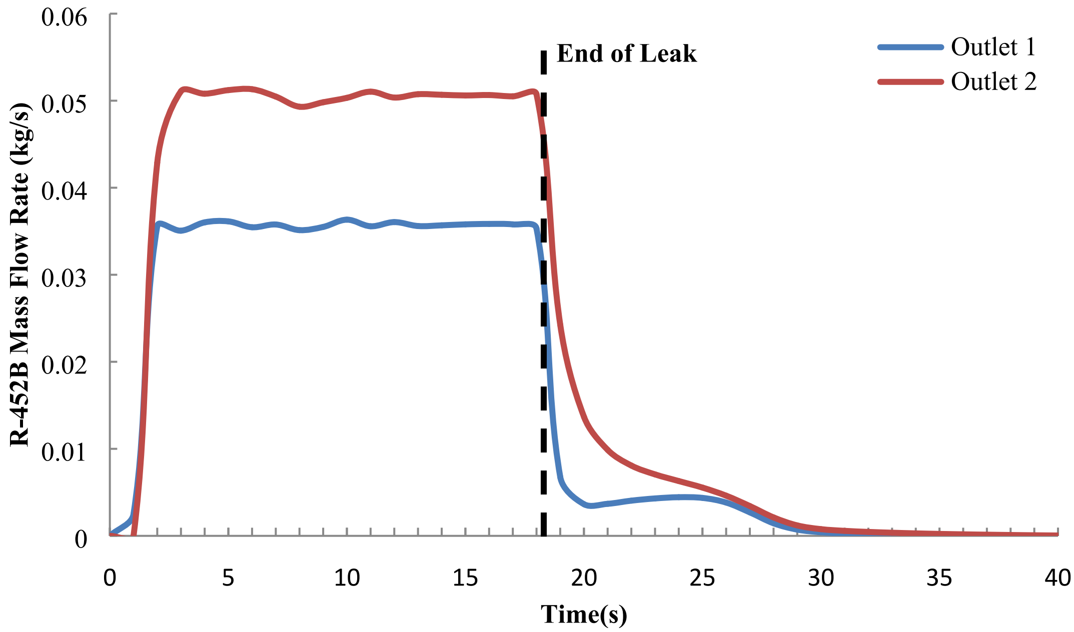
The flow which exits or enter the ducts is a mixture of air and refrigerant as the leaked refrigerant entrains and mix with air inside the duct before it dispersed into the residential space. Figure 6a shows the mixture flow rate for the ceiling ducts at the three duct openings. Please note that these flow rates are for half the duct and residential space. The Figure shows that during the leak incident (mixture of air and refrigerant exits at outlet 1 and 2) a reversed flow is generated at the return grill. After all the entire charge is leaked, the flow direction of both flow streams is reversed. This is due to the gravitational effect which drives the refrigerant inside the duct to downfall into the return duct which creates a lower pressure zone that reverse the flow direction at outlet 1 and 2. Figure 6b and 6c shows the mass flow rate of R-452B exiting from the duct outlets for both cases. For the floor duct as seen in Figure 6b, the refrigerant mass flow rate rapidly increased to a peak value of around 0.036 and 0.05 kg/s for outlet 1 and 2 respectively then maintained this mass flow rate until the leak stopped. Then, a sharp decrease in the mass flow rate was observed. There was no refrigerant coming out from the return outlet as the leaked refrigerant jet was horizontal and the refrigerant (heavier than air) remained in the duct.

For the ceiling duct, the refrigerant mass flow rate behavior at outlets 1 and 2 as seen in Figure 6c was similar to the floor duct case during the leak incident. When the leak incident ends, the flow rate at the two air outlets rapidly decreases, and the remaining refrigerant in the duct begins to exit from the return air grill at a relatively smaller mass flow rate. The total leaked refrigerant entering the residential space during the first 30 seconds of leak incident is 1.518 kg and 1.583 kg for the floor and roof ducts respectively.

(a)



(b)



(c)

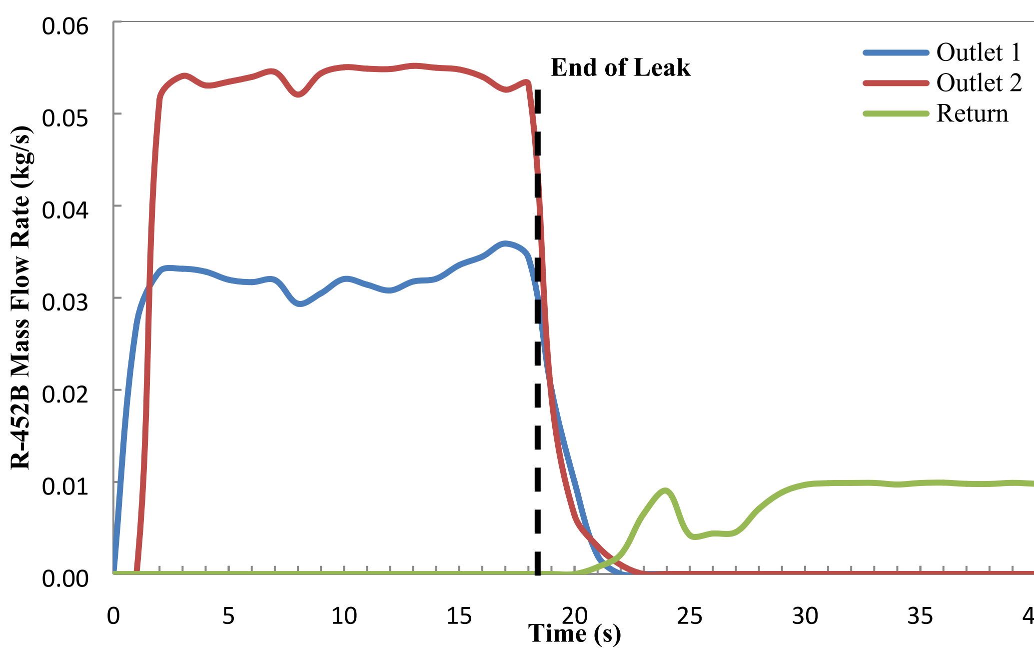


Figure 6. Mass flow rate for (a) air and refrigerant from the ceiling duct, (b) refrigerant from the floor duct and (c) refrigerant from the ceiling duct

3.2 RESIDENTIAL SPACE SIMULATION

For the residential space simulations, the volume fraction of R-452B was monitored using six monitoring points located along the centerline of the duct air outlets for both duct cases as described in table 1. Figure 1 shows the monitor point locations for the floor duct case.

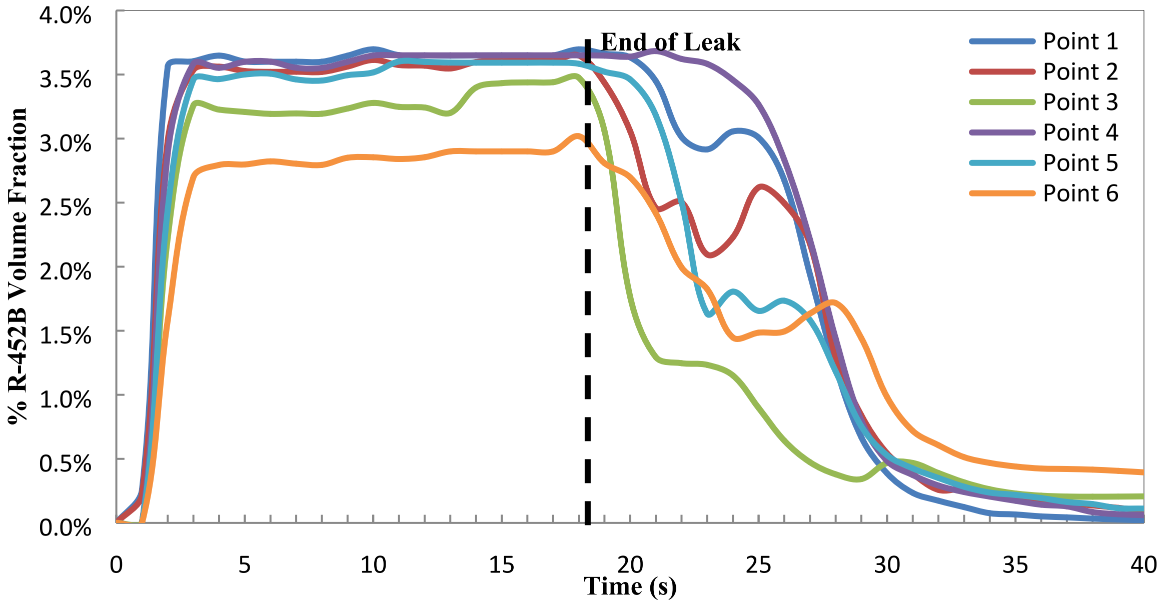
Table 1. Monitor Points

Outlet	Monitor Point	Elevation (m)
1	1	0.3
	2	0.9
	3	1.5
2	4	0.3
	5	0.9
	6	1.5

The %volume fraction of R-452B is shown in Figure 7 at the six monitoring points as a function of time. The highest volume fraction is always located close to the outlets (i.e. point 1 and 4 for the floor duct and point 3 and 6 for the ceiling duct). One can see that the volume fraction at all monitoring points for both cases is lower than 4%. As mentioned earlier, LFL of R-452B is 11.9% which indicates that the leaked refrigerant inside the residential space was below LFL. Therefore, there was no flammability risk associated with this leak scenario. Moreover, to make sure that there are no locations inside the residential space within the flammability limit, post processing of the numerical results showed that the volume fraction did not pass the LFL value during the first minute of the leak at any location inside the residential space. To explain the similarity of the refrigerant volume fraction at the monitor points for both ceiling duct (refrigerant is descending) and floor duct (refrigerant is ascending), the average refrigerant exit velocity at the outlets was calculated. It was found that the average exit velocity magnitude is around 9 m/s for both ducts which shows

how the flow momentum overcome the gravitational force for the floor duct leak case.

(a)



(b)

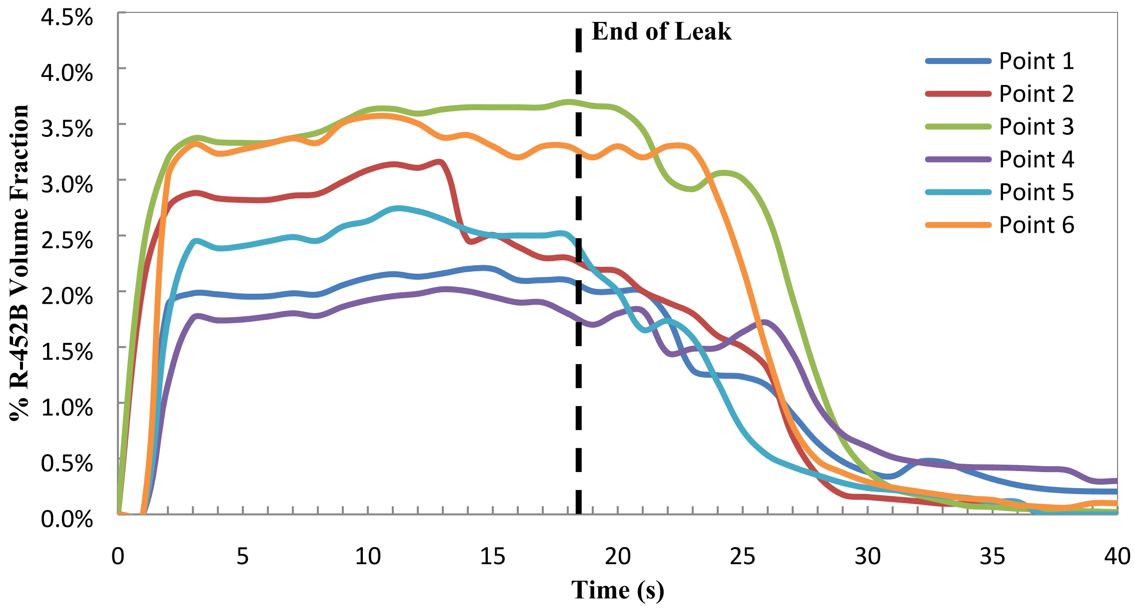


Figure 7. R-452B % volume fraction at the monitor points for (a) floor duct and (b) ceiling duct.

4. DISCUSSION

A catastrophic leak of R-452B from a 3ton unit connected to a floor or ceiling ducts was simulated computationally. The total charge of 0.173 kg/s was leaked in 18.36 seconds. The results showed that for catastrophic leaks where the refrigerant flow maintains a high momentum during the leak incident, the orientation of the duct outlets (i.e. facing upwards or downwards) will not make a significant change in the discharged refrigerant into the room. This was evident in the refrigerant flow rates from outlet 1 and 2 for both duct systems. The total amount of leaked refrigerant into the room was about 50% of the total unit charge, however, the maximum volume fraction of R-452B at the monitoring point was below 4% for both ducts. This is due to the fact that the leaked refrigerant with high momentum represents a small fraction compared to the air exiting the duct outlets. For the first 20 second, the average outlet air mass fraction was around 92% at each outlet. The increase in the refrigerant mass flow rate at outlet 2 compared to outlet 1 is due to the duct design. Due to the leaked refrigerant high momentum, the flow partially overshoots the first branch of the duct and continue flowing to the second outlet. One can see that the flammable volume is only located inside the duct close to the leak source and that the refrigerant volume fraction inside the duct slowly reach an equilibrium with the air inside the duct.

The dispersed refrigerant inside the residential space did not reach a flammable concentration value which shows that even with catastrophic leak from package unit, there was no associated flammability risk found inside the residential space. However, the flammability risk is mainly existing inside the duct system. Flammability risk mitigation efforts for similar types of leaks incidents for which a unit is connected to duct, should mainly focus on the duct and not the residential space. Similar observation was also seen by Elatar et al. (2018b) for a catastrophic leak of R-32 from a package unit into a conference room.

The simulations presented are considered as the worst-case scenario. On the other hand, for slower leak durations of the same charge amount as shown by Baxter et al. (2018), most of the refrigerant stayed inside the duct and did not disperse to the residential space. This imposed longer flammable volume inside the duct. This further confirms the suggestion of directing the effort of flammability risk mitigating of leaks from package systems to mainly the ducts. Several questions need to be answered in that particular matter, for example: is there an ideal duct design to mitigate the flammability risk in case of a leak incident?, What are the appropriate mitigation techniques which can be used to reduce the flammability risk inside the ducts?, Can a circulating fan be used for reducing the flammability risk inside the duct or this will have a detrimental effect on the residential space ?. We believe that for the sake of proper addressing the flammability risk associated with leaks from package units, a comprehensive investigation needs to be conducted to determine the followings:

- Duct design considerations
- Proper flammability mitigation techniques

5. CONCLUSIONS

A catastrophic leak incident of R-452B from a 3-ton package unit which serves a 167 m^2 residential space was numerically simulated for two supply duct cases, one mounted under the floor and the other mounted in the ceiling. A 3.175 kg charge was leaked in 18.36 seconds at a flow rate of 0.173 kg/s. Half the space was simulated due to symmetry. The leaked refrigerant exits from the duct air outlets in the first 20 to 30 seconds from the leak onset. Outlet 2 always showed higher mass flow rate compared to outlet 1. For the ceiling duct, the gravitational force drove the leaked refrigerant inside the duct to exit from the return outlet and that is after all the refrigerant was leaked. This resulted in a reverse flow at the air outlets. The volume fraction of R-452B was monitored inside the residential space and it was found that its value was always lower than 4.0%. The results showed that the leaked R-452B volume fraction did not reach the flammability limit (i.e. between LFL and UFL) inside the residential space and there was no flammability risk associated. On the other hand, the flammability risk was evident inside the ducts due to the refrigerant volume fraction.

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