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Risk assessment of built-in refrigerated display cabinet using A3 refrigerant

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Abstract

In Japan, from 2011 to 2016, risk assessment of each type of equipment using A2L refrigerants was carried out and JRAIA standards which prescribed safe operating method were created, resulting in the relaxation of law was realized. In order to respond to demand in recent years to further lower GWP, risk assessment of built-in refrigerated display cabinet using A3 refrigerants was carried out. CFD analyses on refrigerant leakage from inside or outside the refrigerated space of each refrigerated display cabinet was carried out, the flammable volume was calculated, the ignition sources were investigated, and the ignition probability was calculated. Risk assessments were carried out at each stage of transportation, storage, installation, usage, service, and disposal. In this paper, the contents of the study and safe operating method created as a result are summarized.

Keywords: CFD analysis; Flammable volume; Ignition source; Risk assessment; Display Cabinet

1. Introduction

The use of A2L refrigerants for HVAC&R products was investigated in Japan from 2011 to 2016. Risk assessments of the products have been carried out[1], to establish methods for ensuring the safe use of the products using A2L refrigerants, resulting in the relaxation of relevant regulation and followed by product launches in Japanese market. However, further reduction of GWP are expected in response to the Kigali Amendment to the Montreal Protocol, and the Japan Refrigeration and Air Conditioning Industry Association (JRAIA) has been carrying out the risk assessment for built-in refrigerated display cabinets using A3 refrigerants.

In this paper, the duration and the mean volume of flammable region obtained by CFD analysis for each refrigerated display cabinet were formulated. The investigative findings on the characteristic ignition sources in the stages of usage and working are shown, and the methods for ensuring safe operation are explained.

2. Method of Risk assessment

Ignition probability is calculated by multiplying the temporal encounter probability representing the time rate of contacting between the ignition source and the flammable region, the spatial encounter probability representing the spatial distribution of the flammable region and the refrigerant leakage probability. Flammable region is the area where refrigerant concentration is between the lower flammability limit (LFL) and the upper flammability limit (UFL). Flammable volume is the volume of the flammable region, the time when flammable region exists is the duration of the flammable region, and the flammable volume-time integration is obtained by multiplying the duration of the flammable region and the mean flammable volume. Temporal encounter probability is calculated by using the duration of the flammable region, the duration of the ignition source and the frequency of occurrence of ignition source. Spatial encounter probability is calculated by dividing the mean

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flammable volume by the volume of the target space. The duration of the flammable region and the mean flammable volume are obtained by CFD analyses. The ignition probability is obtained by calculating the average of the ignition probabilities weighted by operating rate for both the operation and stoppage (e.g. due to system failure) of the air circulating fan.

3. CFD Analysis of Refrigerant Leakage

CFD analysis was carried out with STAR CCM+ using the Realizable k-ε model. The subject refrigerant is R290, and the values at 25 °C in atmospheric pressure calculated by REFPROP Ver. 8.0 are used as its physical properties. The value 1.12×10^{-5} (m^2/s) calculated from the molecular diffusion equation is used as the diffusion coefficient of R290, 2.1 (vol%) and 9.5 (vol%) are used as LFL and UFL values, respectively. Leakage analysis was carried out for reach-in, horizontal and vertical open refrigerated display cabinets. Analysis models and calculation results of the reach-in refrigerated display cabinet and the horizontal refrigerated display cabinet are shown below. Validity of the results of CFD analysis has been verified by simulation of R32 leak from an indoor unit of the residential air conditioner. In addition, CFD analysis when the refrigerant was R170 (molecular weight is 30.0, LFL is 3.1 (vol%)), R1270 (molecular weight is 42.1, LFL is 2.7 (vol%)) or R600a (molecular weight is 58.1, LFL is 1.8 (vol%)) was carried out. When the refrigerant is R170 or R1270, the duration of the flammable region and the mean flammable volume are smaller than the value of R290. As a result, when the refrigerant is R600a, the mean flammable volume was almost the same as the value of R290 and the duration of the flammable region was 10 to 20 % longer than the value of R290.

3.1. Analysis of refrigerant leakage from the reach-in refrigerated display cabinet

3.1.1. Analysis model of refrigerant leakage

Because the flammable region in the shop becomes the largest when the door is fully opened rapidly after refrigerant leakage inside the refrigerated space of the reach-in refrigerated display cabinet, CFD analyses were carried out for this case. The CFD model of the reach-in refrigerated display cabinet installed in the shop with an area of 24.01 m^2 is shown in Fig. 1. The display cabinet has 1.08 m^3 of refrigerated volume, and its external dimensions are 2.0 m in height, 1.542 m in width, 0.7 m in depth. The condensing unit consists of a compressor, a condenser and a fan installed in the lower part of the display cabinet. The air is sucked from the front of the condensing unit, passes through the rear side and is exhausted from the top of the display cabinet. Area of the

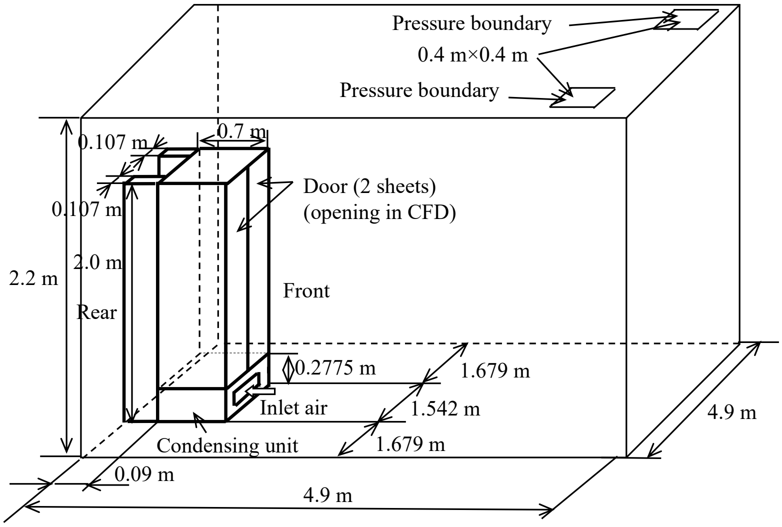


Fig. 1. CFD model of reach-in refrigerated display cabinet installed in the shop area with an area of 24.01 m^2

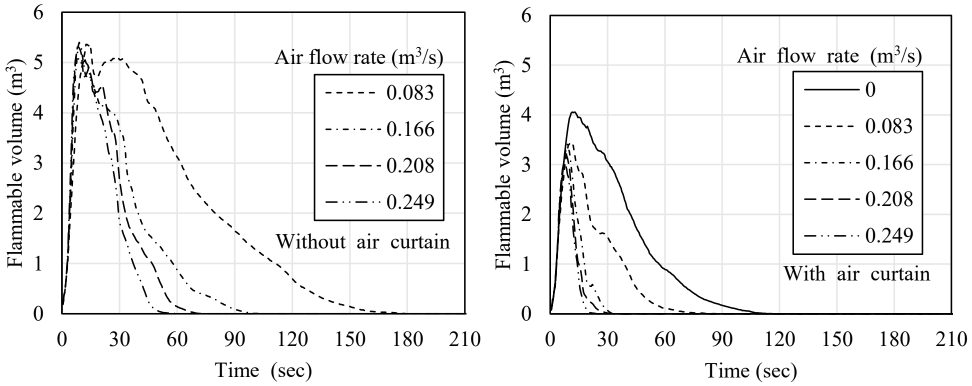
air inlet opening is set to 8.3×10^{-2} m^2 and the air flow rate is varied from 0 to 0.249 m^3/s, which corresponds to air velocity of 0 to 3 m/s. The display cabinet is assumed to be installed at the center of a wall of a shop with square-shaped floor, and the both corners of the ceiling opposite the display cabinet has the pressure boundaries with a size of 0.4 m × 0.4 m. Both with and without the down flow air curtain from the top-front of the refrigerated space have been considered in this study. As an initial condition, the refrigerant concentration was set to be uniform in the refrigerated space. Then, the calculation was started from the state, and the refrigerant was assumed to fall naturally from the front of the display cabinet assuming that there was no door. These analyses assume the situation of the display cabinet with sliding doors. The air velocity of the air curtain is set to 2.08 m/s and the air flow rate is 0.137 m^3/s. CFD analyses were carried out for cases with the floor area of 17.14 m^2, 24.01 m^2, 36.00 m^2, 64.00 m^2 and 100.00 m^2 while the refrigerant amount was set to 0.358 kg and 0.5 kg. The dimensions of the shop were set to 4.14 m×4.14 m, 4.9 m×4.9 m, 6.0 m×6.0 m, 8.0 m×8.0 m and 10.0 m×10.0 m, respectively. The ceiling height of the shop was set to 2.2 m.

3.1.2. Calculation results of refrigerant leakage from inside of the refrigerated space

Fig. 2 shows the change with time in the flammable volume when the air flow rate of the condensing unit is varied when the floor area is 24.01 m^2 and the refrigerant amount is 0.5 kg. Fig. 2 (a) is the calculation results without the air curtain, (b) is the results with the air curtain. With the air curtain, the duration of the flammable region is shortened and the flammable volume is reduced, but the difference in values with and without the air curtain is not so great. In addition, when the air flow rate of the condensing unit is increased, the duration of the flammable region is reduced both with and without the air curtain, but the maximum value of the flammable volume is hardly reduced. Therefore, it is found when the door of the reach-in refrigerated display cabinet is suddenly opened that the large flammable volume is always generated outside the refrigerated space, although for a short time.

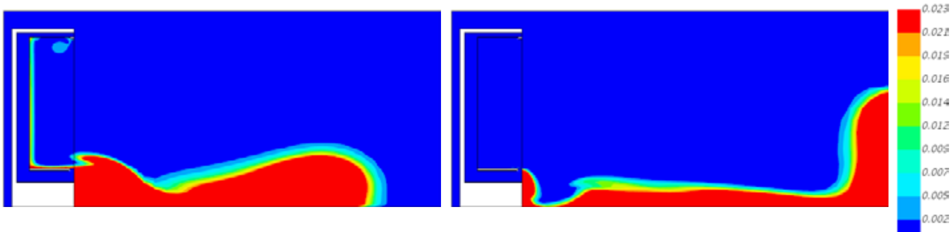
Next, the refrigerant concentration distribution at the center of the display cabinet in the store after 5 sec. and 10 sec. from opening the door are shown. Fig. 3 and Fig. 4 are figures when the floor area is 24.01 m^2, refrigerant amount is 0.5 kg, without the air curtain and the air flow rate of the condensing unit is 0 m^3/s and 0.166 m^3/s, respectively. In both cases, flammable region spreads over the entire floor surface or entire ceiling surface in a short time. As for A3 refrigerant, a relay or a thermostat of electrical equipment in the shop, a lighting switch, plugging/unplugging of power outlet and hot surfaces such as heaters are also ignition sources, and there is a risk of ignition even if the flammable region is generated for several seconds. The calculation results with the air curtain were almost the same as those without the air curtain

Since there are several types of the reach-in refrigerated display cabinet with different air flow pattern in the refrigerated space, e.g. top-face-forward discharge and bottom-front suction type refrigerated cabinet (air curtain type system), and top-rear discharge and upper-front suction type refrigerated cabinet, risk assessment by JRAIA is based on the worst-case scenario of having no air curtain, and the values with and without the air flow rate of the condensing unit are used as operating and stopping value, respectively. Fig. 5 and Fig. 6 show the calculation results of the mean flammable volume and the duration of the flammable region without the air curtain. The figures show the case with the air flow rates of 0 m^3/s and 0.166 m^3/s (air velocity of 2.0 m/s), respectively. In the figures, the horizontal axis shows the value obtained by dividing the refrigerant amount (M) by the floor area (A) inside the shop. Both the mean flammable volume (V_v) and the duration of the



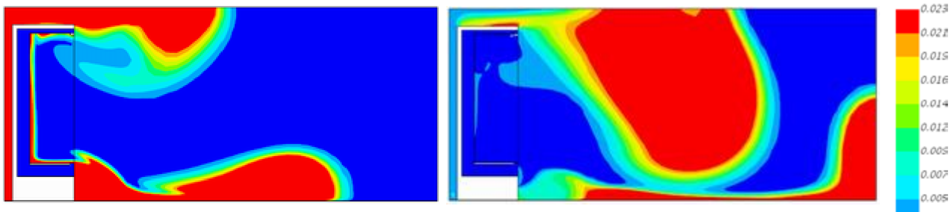
(a) Flammable volume without the air curtain (b) Flammable volume with the air curtain

Fig. 2. Change of flammable volume with time when the air flow rate of the condensing unit is varied



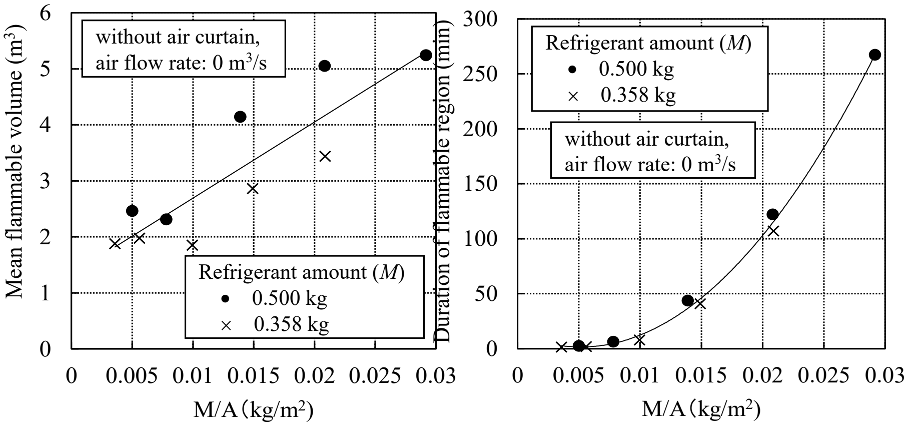
(a) After 5 sec. from opening the door (b) After 10 sec. from opening the door

Fig. 3. Concentration distribution of air velocity 0 m^3/s without the air curtain



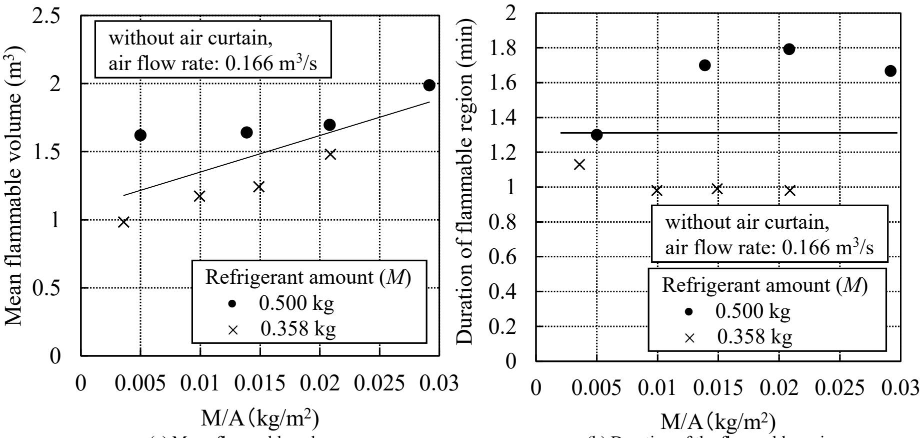
(a) After 5 sec. from opening the door (b) After 10 sec. from opening the door

Fig. 4. Concentration distribution of air velocity 0.166 m^3/s without the air curtain



(a) Mean flammable volume (b) Duration of the flammable region

Fig. 5. Duration and volume of flammable region of air flow rate 0 m^3/s without the air curtain



(a) Mean flammable volume (b) Duration of the flammable region

Fig. 6. Duration and volume of flammable region of air flow rate 0.166 m^3/s without the air curtain

flammable region (T_v) can be expressed as a function of the value M/A. The obtained least squares approximate equations are expressed by Eq. (1) to Eq. (3), and at the air flow rate of 0.166 m³/s, the duration of the flammable region does not change so much and is expressed as an average value as shown in Eq. (4). These equations are shown as solid lines in Fig. 5 and Fig. 6, respectively. In the case of leakage inside the reach-in refrigerated display cabinet, the flammable region outside the refrigerated space did not disappear even when the air flow rate of the condensing unit was increased. This is the same even when there is the air curtain in front of the refrigerated space.

$$V_v=1.36\times10^2\times(M/A)+1.34 \quad \text{(air flow rate ; 0 m}^3\text{/s)} \quad (1)$$
$$T_v=4.61\times10^5\times(M/A)^2-4.76\times10^3\times(M/A)+1.38\times10^1 \quad \text{(air flow rate ; 0 m}^3\text{/s)} \quad (2)$$
$$V_v=2.68\times10^1\times(M/A)+1.08 \quad \text{(air flow rate ; 0.166 m}^3\text{/s)} \quad (3)$$
$$T_v=1.32 \quad \text{(air flow rate ; 0.166 m}^3\text{/s)} \quad (4)$$

3.1.3. Refrigerant leakage from the condensing unit

As a result of CFD analyses of refrigerant leakage from the condensing unit at the bottom of reach-in refrigerated display cabinet, the duration of the flammable region was almost the same as the value of the horizontal refrigerated display cabinet described in section 3.2.2 and the mean flammable volume was about half of the value of horizontal refrigerated display cabinet, when the air flow rate of the condensing unit was 0 m³/s. CFD analysis showed that the influence of the difference in the leak rate on the generation of the flammable region was small when the refrigerant leaked from the condensing unit at the bottom of the refrigerated display cabinet. Since the lower opening area of the condensing unit of the reach-in refrigerated display cabinet was half of that of the horizontal refrigerated display cabinet, the mean flammable volume was likewise halved. And, regardless of the kind of refrigerant, if the airflow rate of the condensing unit was increased, the flammable region was not generated outside the refrigerated display cabinet in the case of refrigerant leakage from the condensing unit.

3.2. Analysis of refrigerant leakage of the open refrigerated display cabinet

3.2.1. Analysis model of refrigerant leakage from the condensing unit of the horizontal display cabinet

CFD analyses were carried out for refrigerant leakage from the condensing unit at the bottom of the horizontal refrigerated display cabinet. The CFD model is shown in Fig. 7. The external dimensions of the display cabinet are 0.81 m in height, 1.8 m in width and 1.09 m in depth. The condensing unit consists of a compressor, a condenser and a fan installed in the lower part of the display cabinet. Air is sucked from one side of the condensing unit and exhausted from another side. Area for both air inlet and outlet openings were set to 6.89×10^{-2} m² (0.733 m×0.094 m), and the air flow rate was varied from 0 to 0.207 m³/s, which corresponds to air velocity of 0 to 3 m/s. The display cabinet is assumed to be installed at the center of a square-shaped shop floor. At the opening of the condensing unit, the value k and ε were set to 1×10^{-4}, the refrigerant concentration was set to 100% when the air flow rate was 0 m³/s, and the concentration when the air flow rate exceeded 0 m³/s was set to calculated value. When the air flow rate was 0 m³/s, the refrigerant was leaked evenly from both air inlet opening and air outlet opening. The refrigerant was leaked from the air outlet opening when the air flow rate was over 0 m³/s. CFD analyses were carried out for the cases with the floor area of 15.21

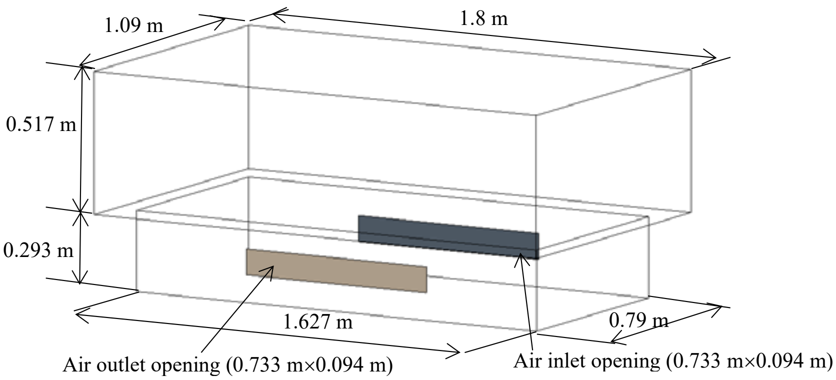


Fig. 7. CFD model of horizontal refrigerated display cabinet

m^2, 24.01 m^2, 36.00 m^2, 64.00 m^2 and 100.00 m^2 while refrigerant amount was 0.5 kg. The dimensions of the shop were set to 3.9 m×3.9 m, 4.9 m×4.9 m, 6.0 m×6.0 m, 8.0 m×8.0 m and 10.0 m×10.0 m, respectively. The ceiling height of the shop was set to 2.2 m.

3.2.2. Calculation results of refrigerant leakage from the condensing unit of the horizontal display cabinet

At the first, the calculations were performed when the leak rate was set to the value at which the total refrigerant amount was leaked in 4 minutes. The leak rate was 7.5 kg/h for 0.5 kg, and 5.37 kg/h for 0.357 kg. Fig. 8 shows the calculation results of the mean flammable volume and the duration of the flammable region when air flow rate of the condensing unit of the horizontal refrigerated display cabinet is 0 m^3/s. Its horizontal axis shows the value obtained by dividing the refrigerant amount (M) by the area (A) inside the shop. Both the mean flammable volume (V_v) and the duration of the flammable region (T_v) can be expressed as a function of the value M/A. The obtained least squares approximate equations are expressed by Eq. (5) and Eq. (6) and as solid lines in Fig. 8, respectively. If the airflow rate of the condensing unit was increased, flammable region was not generated outside of the refrigerated display cabinet at the time of refrigerant leakage from the condensing unit.

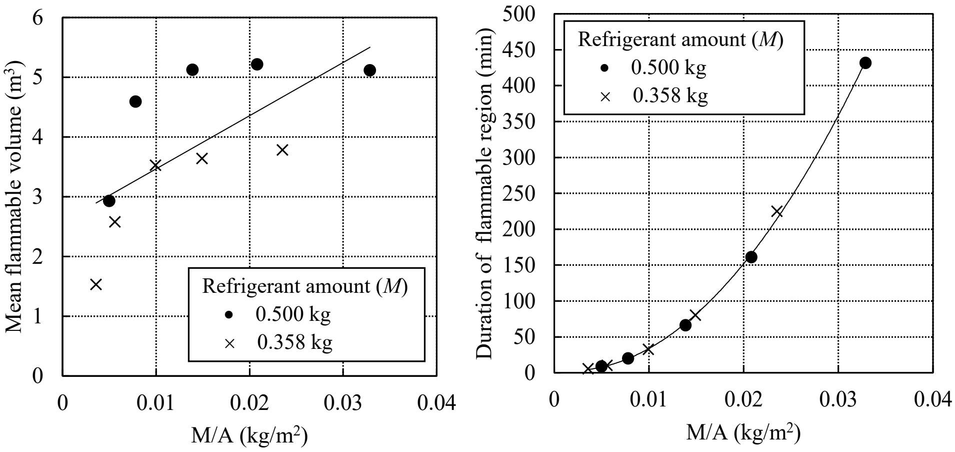
$$V_v=8.90\times10^1\times(M/A)+2.58 \quad \text{(air flow rate ; 0 m}^3\text{/s)} \quad (5)$$

$$T_v=4.41\times10^5\times(M/A)^2-1.42\times10^3\times(M/A)+3.94 \quad \text{(air flow rate ; 0 m}^3\text{/s)} \quad (6)$$

As for the leakage from the condensing unit, when the air flow rate of the condensing unit was set to 0.150 m^3/s calculated by Eq. (7) proposed by Colbourne et al. [2], no flammable region was generated outside the display cabinet. Similar results were obtained when the refrigerant was changed to R170, R1270, or R600a.

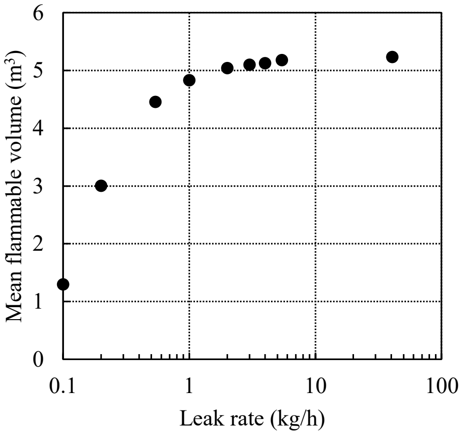
$$Q \geqq \frac{5\times\sqrt{A_0}\times w^{3/4}}{h_0^{\,1/8}\times\{G\times(1-F)\}^{5/8}} \quad (7)$$

Next, the calculations were performed when the leak rate was varied from 40.71 to 0.1 kg/h when the shop area of 24.01 m^2, the refrigerant amount of 0.5 kg, and the condenser air flow rate of 0 m^3/s. The calculation results of the mean flammable volume, the duration of the flammable region and the flammable volume-time integration are shown in Fig. 9. The mean flammable volume is almost the same when the leak rate is 2 kg/h or faster, and begins to decrease when the leak rate becomes slower than that, and the value at the leak rate of 0.2 kg/h was about 60% of that at 2 kg/h and the value at 0.1 kg/h was about 25%. The duration of the flammable region increases when the leak rate is decreased because the time from the start to the end of the refrigerant leakage becomes long. The flammable volume-time integration was almost the same at leak rate of 0.54 kg/h or faster, and begins to decrease when the leak rate becomes slower than that, but the value at 0.1 kg/h is about 50% of that at 0.54 kg/h. Therefore, the refrigerant leak from the condensing unit at the bottom of the display cabinet generates a sufficiently large flammable region even of the slow leak rate, and it is necessary to calculate the ignition probability considering all leaks including slow leak in the risk assessment. The slow leak rate is 1 kg/h for R32 and 0.54 kg/h when converted to R290.

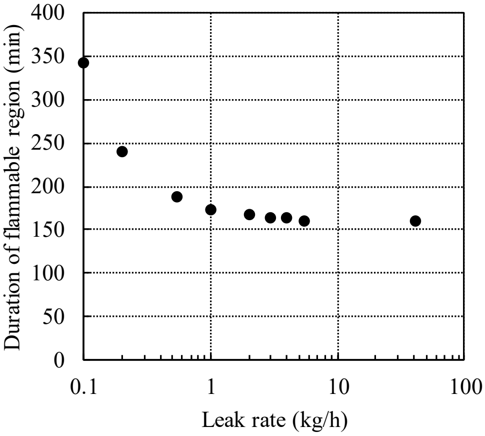


(a) Mean flammable volume (b) Duration of the flammable region

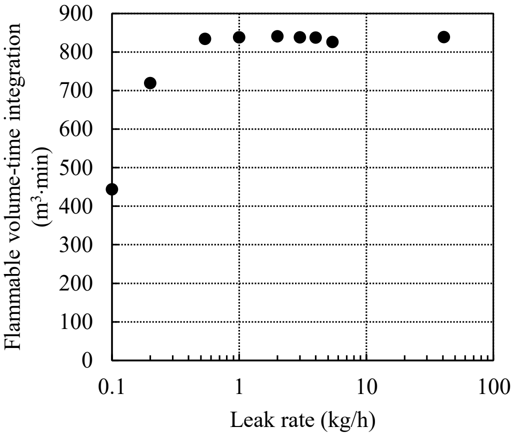
Fig. 8. Calculation results for a horizontal refrigerated display cabinet at air flow rate of 0 m^3/s



(a) Mean flammable volume



(b) Duration of the flammable region



(c) Flammable volume-time integration

Fig. 9. Calculation results when leak rate varies

3.2.3. Refrigerant leakage from inside the refrigerated space of the open refrigerated display cabinet

Since the air curtain is formed in the upper opening of the horizontal refrigerated display cabinet and built-in refrigerated display cabinet has a small refrigerant amount, almost of the refrigerant leaked inside of the refrigerated space does not leak outside the refrigerated space.

As a result of CFD analysis for refrigerant leakage from inside of the vertical refrigerated display cabinet, a slight flammable region was generated outside the refrigerated display cabinet when there was no airflow outside the refrigerated display cabinet. However, there was nearly no generation of the flammable region outside the display cabinet, even with little airflow, when there was the condensing unit at the bottom.

3.2.4. Refrigerant leakage from the condensing unit of the vertical refrigerated display cabinet

Behavior at the time of refrigerant leakage from the condensing unit at the bottom of the vertical refrigerated display cabinet is the same as the condensing unit of the reach-in refrigerated display cabinet.

4. Calculation of Ignition Probability and Safety Measures

4.1. Equations for calculating ignition probability

Temporal encounter probability (P_t) representing the time rate of contacting between the ignition source and the flammable region is calculated by using Eq. (8), based on the theory of geometric probability[3], using the total time of the target stage (T_a), the duration of the flammable region (T_v), the duration of the ignition source (T_I) and the frequency of occurrence of ignition source (n). Here, the frequency of occurrence of ignition source (n) is the number of times that the ignition source is ignited within the total time of the target stage (T_a). The coefficient k is a coefficient representing the abundance ratio of the ignition source, dissemination rate of the electric equipment, or the degree of concentration when operation of the ignition source concentrates in a certain time zone. Spatial encounter probability (P_s) is calculated by Eq. (9), using the mean flammable volume (V_v) and the volume of the target space (V_a). Ignition probability (P) is calculated by Eq. (10), using the temporal encounter probability (P_t), the spatial encounter probability (P_s) and the refrigerant leak probability (P_R).

$$P_t = k \times [1 - \{1 - (T_I + T_v)/T_a\}^n] \tag{8}$$

$$P_s = V_v / V_a \tag{9}$$

$$P = P_t \times P_s \times P_R \tag{10}$$

Assuming the allowable value of ignition probability is on the level of a serious accident occurring once every 100 years, the allowable value was set to 5.26×10^{-9} by using 1.9 million units which is the number in operation in the market. Also, since the work is carried out by experts, the allowable value at the time of work was set to 5.26×10^{-8} which is 10 times the value for usage.

4.2. Calculation of ignition probability at usage stage and safety measures

Ignition probability for convenience stores in Tokyo, Japan was investigated. Table 1 shows the main ignition sources assumed at the usage stage. Static electricity is assumed to occur at a humidity of 30% or less, the occurrence probability was set to 18.7 % at the shop temperature and the discharge time was set to 1 μsec. It is assumed that ignition does not occur if air is flowing around the brush motor at velocity sufficiently higher than the burning velocity of the refrigerant, and ignition occur only when the brush motor turns on. The electric spark discharge time was set to 5 msec. Additionally, ignition accidents involving electrical equipment were also taken into consideration, based on survey data of the National Institute of Technology and Evaluation (NITE). The air flow rate of the condensing unit of the display cabinet was assumed to be set at the air flow rate at which flammable region does not generate. Regarding leakage from the condensing unit, it is assumed

Table 1 Ignition sources assumed at the usage stage

Name	Type	T_i (sec.)	n	k	Note
Coffee machine	Electric spark	5×10^{-3}	186	1	Relay operates when selling
Switch of deep frying machine	Electric spark	5×10^{-3}	10	1	Cooking every 4 hrs in a span of 20 hrs
Chinese-style buns steamer	Electric spark	5×10^{-3}	10	1	Cooking every 4 hrs in a span of 20 hrs
Heating appliance for "Oden"	Electric spark	5×10^{-3}	10	1	Cooking every 4 hts in a span of 20 hrs
Power outlet	Electric spark	5×10^{-3}	4	0.5	Unplugging twice a day for cleaning; occurrence ratio: 50 %
Light switch	Electric spark	5×10^{-3}	4	1	Switch on/off twice a day
Copier	Electric spark	180	50	1	50 times in a day, usage time 3 min. per time
Brush motors of other equipment	Electric spark	5×10^{-3}	144	0.01	Turn on 6 times in a hour. dissemination rate: 1 %
Static electricity (door of reach-in refrigerated display cabinet)	Electrostatic spark	1×10^{-6}	434	0.187	Taking out iced coffee
Static electricity (exterior of open refrigerated display cabinet)	Electrostatic spark	1×10^{-6}	22	0.187	Shoppers touch metallic parts
Static electricity (other doors)	Electrostatic spark	1×10^{-6}	22	0.187	Assumed to share the same value as above
Electronic lighter	Open flame	5	5	1	Five people trying ignition in a day
Combustion type boiler	Open flame	3.6×10^{4}	1	0.0001	Use 10 hrs in a day, Dissemination rate: 0.01%

Table 2 Safety measures for usage stage

Safety measures
1. The fan of the condensing unit is operating even while defrosting.
2. The air flow rate of the condensing unit is set to a specified value or higher
3. Equipped with the function of detecting refrigerant leakage into the refrigerated space of reach-in refrigerated display cabinet, and function of shutting off the refrigerant leakage into the refrigerated space in case of refrigerant leakage.

that no flammable region is generated during operation, but flammable region is generated during stoppage such as defrosting or system failure. The mean flammable volume and the duration of the flammable region were calculated by Eq. (5) and Eq. (6), respectively. As for the refrigerant leakage from inside the refrigerated space of the reach-in refrigerated display cabinet, Eq. (3) and Eq. (4) were used to calculate the mean flammable volume and the duration of the flammable region at operation, and Eq. (1) and Eq. (2) were used for cases of stoppage. The effective area in the shop where the leaked refrigerant can diffuse is set to 84.7 m^2, and the refrigerant amount of each refrigerated display cabinet is set to 0.5 kg. M/A was set to 0.0059 in Eq. (1) through Eq. (6). It is assumed that no flammable region is generated outside the refrigerated space at the time of refrigerant leakage from inside of the refrigerated space of the open refrigerated display cabinet. It is necessary to also consider the slow leak rate in the risk assessment for A3 refrigerants, shown in Fig. 9, though only the rapid leak rate, 10 kg/h for R32 (5.4 kg/h when converted to R290), or higher was considered in the risk assessment for A2L refrigerants. Refrigerant leakage probability in usage was calculated based on the survey results of refrigerant leak accidents in the market involving built-in refrigerated display cabinets manufactured by JRAIA member companies. The refrigerant leak probability was set to 1.00×10^{-3}.
As a result, the ignition probability exceeded the allowable value, and fell to the allowable value or less by taking the safety measures shown in Table 2. In the reach-in refrigerated display cabinet, the ignition probability exceeds the allowable value even if only a slight flammable region is generated outside the refrigerated space when the door is suddenly opened after the refrigerant leak in the refrigerated space. It was possible to prevent the generation of the flammable region outside the refrigerated space at the time of opening the door suddenly by detecting the refrigerant leakage in the refrigerated space in the reach-in refrigerated display cabinet and shutting off the refrigerant circuit. As a result, the ignition probability was reduced to be not higher than the allowable value. It was also confirmed that the ignition probability became not more than the allowable value even if the duration of flammable region was set to the value of R600a.

4.3. Calculation of ignition probability at various working stage and safety measures

In the various working stages, such as transportation, storage, installation, repair and disposal, ignition sources were assumed and the ignition probabilities were calculated. Table 3 shows the main ignition sources assumed at each stage. Transportation on a minivan with an internal volume of 2.9 m^3 was assumed as the transportation stage. Storage was assumed to be in a medium-sized warehouse of 1000 m^2 or a small-sized warehouse of 15 m^2 in storage stage. For installation, repair and disposal, ignition sources described in Table 1 were considered in addition to the ignition sources at the time of work since such work is carried out while using the equipment in the shop. Static electricity is assumed to occur at a humidity of 30% or less, and the occurrence probability was set to 18.7 % annually at shop temperature, 54.5% in winter at shop temperature, 3.2% at outdoor temperature, and the discharge time was set to 1 μsec. As for the refrigerant leakage probability, the value was calculated for each stage by using the value of human error or similar value. The mean flammable volume and the duration of the flammable region were calculated by Eq. (3) and Eq. (4) for the value at the

Table 3 Ignition sources assumed at each working stage

Name	Type	T_i (s)	n	k	Note
Common; Smoking by workers	Open flame	4.5×10^1	1/hour	0.282	Cigarette smoked: 1 stick/person/hrs; ignition time with lighter: 5 sec.; duration of high cigarette temperature: 40 sec.; smoking rate: 28.2%
Transportation (minivan)					2 hrs, 2 workers
Static electricity when the key contacts	Electrostatic spark	1.0×10^{-6}	2	0.04675	2 times, discharge ration: 25 %
Static electricity when undressing	Electrostatic spark	1.0×10^{-6}	1/person	0.1362	Acrylic sweater: 1 time per person; discharge ratio: 12.5 %
Storage (small-sized warehouse)					2 hrs, 2 workers, 15 m^2
Static electricity	Electrostatic spark	1.0×10^{-6}	1/person	0.064	Contact with worker (reuse, without cover)
Heater	Open flame	7.2×10^2	1	0.082	Usage of 120 days per year; usage rate: 25%
Install, repair or disposal					1 to 4 hrs, 1 to 2 workers
Ignition source in usage-					See Table 1
Power outlet	Electric spark	5.0×10^{-3}	2	0.25	Unplugging; occurrence rate: 25%
Electric screwdriver	Brush motor	3.0	10	0.05	Opening/closing screws; occurrence rate: 5%
Static electricity	Electrostatic spark	1.0×10^{-6}	10	0.187 /person	Contact with display cabinet
Burner for brazing	Open flame	1.2×10^2	4	1	2 min × 2 places

Table 4 Safety measures for working stage

Stage	Safety measures
Transportation (for minivan transportation only)	1. Marking of warning of risk of fire on the product 2. Using a portable leak detector and ventilating after detection of leakage
Storage	1. Use of work gloves to prevent electrostatic discharge 2. Marking of warning of risk of fire on the product and packing
Installation	1. Use of work gloves to prevent electrostatic discharge 2. Marking of warning of risk of fire on the product 3. Using a portable leak detector and stopping the working at the time of leakage
Repair	1. Use of work gloves to prevent electrostatic discharge 2. Using a portable leak detector and diffusing refrigerant to the surroundings at the time of leakage (e.g. electric fan, paper fan)
Disposal	1. Use of work gloves to prevent electrostatic discharge 2. Using a portable leak detector and stopping the working at the time of leakage

time of leakage inside the refrigerated space, and Eq. (5) and Eq. (6) for the value at the time of leakage from the condensing unit.

As a result, the ignition probability exceeded the allowable value at all stages, and fell to the allowable value or less by taking the safety measures for each stage shown in Table 4. It was also confirmed that the ignition probability became not more than the allowable value even if the duration of flammable region was set to the value of R600a.

5. Conclusion

For built-in refrigerated display cabinet using A3 refrigerant, CFD analysis of refrigerant leakage from inside the refrigerated space and from the condensing unit of each display cabinet were carried out, and risk assessments at the stages of usage and working were carried out by using the CFD results. This led to the clarification of methods to ensure safe operation of the equipment.

(1) Flammable region was generated outside of the refrigerated space when the door was opened suddenly after all refrigerant leaked in the reach-in refrigerated display cabinet. Approximate equations using R290 were introduced to calculate the mean flammable volume and the duration of the flammable region without the air curtain and with or without the airflow of the condensing unit.

(2) Equations were introduced to calculate the mean flammable volume and the duration of the flammable region with or without the airflow of the condensing unit in case of refrigerant leakage of R290 from the condensing unit of the horizontal refrigerated display cabinet.

(3) Flammable region was not generated when the air flow rate was set to a specified value or higher at the time of refrigerant leakage from condensing unit.

(4) Risk assessments were carried out by identifying the ignition sources at the stages of usage and working for a convenience store. The ignition probability using A3 refrigerants such as R290 or R600a at the usage stage did not exceed the allowable value by taking safety measures, such as the product function enabling the fan of the condensing unit to keep operating even while defrosting, the function of detecting refrigerant leakage into the refrigerated space of reach-in refrigerated display cabinet and the function of shutting off the refrigerant leakage into the refrigerated space at the time of refrigerant leakage. The safety measures at each stage of working were also clarified.

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Nomenclature

A	shop area (m^2)
A_0	area of air outlet (m^2)
F	coefficient (safety factor), equal to 0.25
G	LFL (kg/m^3)
h_0	height of centerline of air outlet (m)
k	coefficient
M	refrigerant amount (kg)
n	frequency of occurrence of ignition source
P	ignition probability
P_R	refrigerant leak probability
P_s	spatial encounter probability
P_t	temporal encounter probability
Q	air flow rate of outlet air (m^3/s)
T_a	total time of target stage (s)
T_i	duration of the ignition source (s)
T_v	duration of the flammable region (s)
V_a	volume of target space (m^3)
V_v	mean flammable volume (m^3)
w	refrigerant leak rate (kg/s)

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