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A System Analysis of Cold Storage using the New Non-Freon Refrigerant "GF-08"

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The equipment for chilling or freezing food consumes much energy. Therefore, there is a need to reduce the energy consumption. Also, to contribute to reduce the greenhouse gas (GHG) emissions, it is necessary to replace conventional refrigerants which affect Global Warming because of high Global Warming Potential (GWP). Hence, there is a need for the use of alternative refrigerants with lower GWPs. Therefore, in this study, the potential of the non-freon refrigerant GF-08, which consists of hydro-carbons, as an alternative refrigerant was evaluated. The use of GF-08 for chilling and freezing storage systems was evaluated. The eco-benefits of GF-08 in comparison to the conventional refrigerant (R404A) was evaluated by developing a theoretical simulation model. A demo-test using a refrigerator in a restaurant was conducted to validate the simulated result. This result showed that performance differences depend on different operating conditions of temperature. Based on the simulation model, the benefits considering the energy reduction was evaluated. The reduction of the annual energy consumption, and the environmental impact of GF-08 using the life cycle assessment (LCA) methodology were estimated. The use of GF-08 reduced the annual energy consumption by 28.6% and the GHG emissions by 27.1 % in comparison to the R404A.

1. Introduction

An approximately 90 % of food loss in Southeast Asian Countries occurs during the manufacturing and/or transportation stages in the supply chain (MLIT, 2017). this is due to that the quality of foods can't be maintained. To preserve the quality of food, there are several ways. In previous study, it was found that the quality of mozzarella can be maintained by using a new liquid formulation containing antimicrobials (Falcone, G.,2017). But it doesn't reveal that the new liquid formulation can maintain the quality of various foods or not. Likewise, as another way to preserve the quality of food, there is countermeasure for chilling or freezing.

Refrigeration, food safety and food waste are inter-connected, and most of the food we consume need to be stored in chilled and/or frozen states along the entire supply chain. The quality of food can be compromised by degradation, which includes rotting that occurs as a result of enzymic and microorganic activities. Additionally, the taste of some food is impaired due to oxidation and drying, and its nutritional value can also be reduced. Fruits and vegetables continue to undergo respiration releasing moisture even after harvest. As the energy and moisture are lost over time, the nutritional value of food decreases, thereby altering its appearance. Hence, storing food in a chilled and/or frozen state can minimize these changes.

Thus, the cold chain must be improved. The cold chain is a temperature-controlled supply chain that stores food in a chilled and/or frozen state during manufacturing, transportation and consumption. Storing food in a chilled and/or frozen state slows down respiration and the subsequent heat. This allows for the quality of food to be maintained in comparison to storage at normal temperature. Hence, the cold chain may be more beneficial in Southeast Asian countries because the cold chain is not part of all the food supply chains. Hence, food loss can be reduced, and the quality of food can be maintained using chilling or freezing facilities. The disadvantage of the chilling and freezing is that it is not environmentally friendly because the equipment used consumes a lot of energy, and the energy consumed is linked to GHG emissions through the combustion of fossil fuels (Mylona et al., 2017). Therefore, there is a need for more environmentally friendly systems which consume less energy and lower operating costs. On the other hand, the total GHG emissions in Japan has been decreasing from 2005 to 2017 and CO_2, CH_4 and N_2O are also decreasing (Ministry of the Environment,

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2018). But, the only alternative CFCs emissions has been increasing. The cause of this increasing is the increasing of HFCs, and approximately 90 % of HFCs emissions is from refrigerants which have extremely higher value of Global Warming Potential (GWP). Hence, to solve the environmental problem, it is necessary to alternate conventional refrigerants to non-freon refrigerant. Traditionally, refrigerants such as R404A and R410A which consists of R-125/R-134a/R-143a (44/4/52) and R-32/R-125 (50/50) were used in refrigerators. In this study, a natural refrigerant, GF-08 which consists of C_3H_8 and C_3H_6 (Maruhachi-Kucho-Kogyo Inc.), was focused. The GWP of GF-08 is 3 compared to CO_2 that has a GWP is 1, and R404A and R410A that have GWP's of 3,920 and 2,090.
Hence, the purpose in this study was to evaluate the amount of energy required to maintain the quality of food under refrigeration whilst reducing GHG emissions. Based on the refrigeration cycle, the simulation model which can estimate the energy consumption considering operating condition was developed. By using this simulation model, the energy consumption in case of R404A and GF-08 was compared. In the life cycle assessment (LCA), the environmental impact in case of R404A and Gf-08 was compared by using simulated result and LCA.

2. Evaluation of performance

2.1 Vapor compression refrigeration cycle

To evaluate the performance of each refrigerant under operating conditions, a theoretical simulation model was developed based on the vapor compression refrigeration cycle. The vapor compression refrigeration cycle is most commonly adopted in refrigerators and is divided into two-types depending on the evaporator temperature. A single-stage compression cycle is adopted when the evaporator temperature is -30 °C and above, and if it is lower than -30 °C a two-stage compression cycle is adopted. The main difference between a single-stage and a two-stage compression cycle is the number of compressors used i.e. the single stage has one compressor and the two-stage has two compressors. Theoretically, dividing the compression stages into two-stages can reduce the energy consumption. In the single-stage compression cycle, the COP is expressed as Eq(1), and it is necessary to reduce the compressor work whilst increasing the refrigerating effect.

$$COP = \frac{\varphi}{W_{comp}} \tag{1}$$

The compressor work depends on the pressure ratio between outlet and inlet of the compressor and is determined using Eq (2).

$$W_{comp} = \frac{\gamma}{\gamma - 1} \times P_{low} \times V \times \left\{ \left(\frac{P_{high}}{P_{low}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right\} \tag{2}$$

In the above equation, $\mathrm{W_{comp}(kW)}, \gamma, \mathrm{P_{low}(kPa)}, \mathrm{P_{hi}(kPa)}$ and $\mathrm{V}(m^3/\mathrm{kg})$ are the compressor work, specific heat ratio at the inlet of compressor, suction pressure of compressor, discharge pressure of compressor, and specific volume at the inlet of compressor.
In this paper, the refrigerating effect was defined as φ and determined using Eq(3).

$$\varphi = h_1 - h_4 \tag{3}$$

In the above equation, $\varphi\mathrm{(kJ/kg)}$, $\mathrm{h_1(kJ/kg)}$ and $\mathrm{h_4(kJ/kg)}$ are the refrigerating effect, specific enthalpy of refrigerant at the outlet of evaporator, and specific enthalpy of refrigerant at the inlet of evaporator.
The refrigerating effect and low pressure are dependent on the preset temperature. A low preset temperature requires high compressor work input resulting in a low refrigerating effect and COP. In the two-stage compression cycle, the COP was determined using Eq(1), and the total compressor work was defined as the sum of the low-pressure compressor work and the high-pressure compressor work.

2.2 Heat penetration of the refrigerator

Heat penetration, difference between the outside and inside temperatures, heat transfer area and overall heat transfer coefficient were determined for the developed model refrigerator. The dimensions and specifications of the refrigerator is shown in Figure 1. The overall heat transfer coefficient was determined using Eq(4). In this paper, it is assumed that the heat transfer of air outside the refrigerator was as a result of free convention heat transfer, and the heat transfer of air inside the refrigerator was as a result of forced convention heat transfer driven by a fan. The thermal conductivity and the thickness of heat transfer areas at chilling and freezing were determined for the model of refrigerator with rigid polyurethane foam material (Table 1).

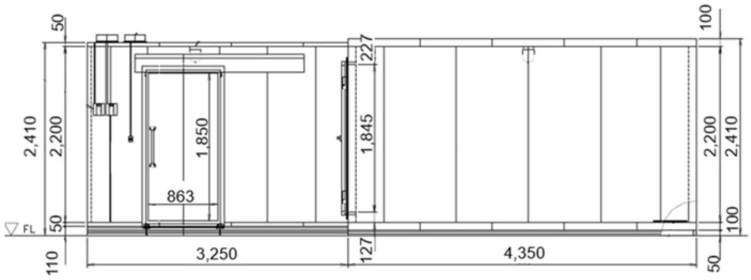

Figure 1: Dimensions and specifications of the model refrigerator (unit in mm)

Table 1: Thermal conductivity and thickness at chilling and freezing of the different components

Place	Area(m^2)		Thickness(m)		Thermal conductivity(W/m/K)	
	Chilling	Freezing	Chilling	Freezing	Chilling	Freezing
Front	7.83	10.70	0.05	0.1	0.024	0.024
Back	7.83	10.70	0.05	0.1	0.024	0.024
Ceiling	4.88	6.53	0.05	0.1	0.024	0.024
Bottom	4.88	6.53	0.05	0.1	0.024	0.024
Side(of outside)	3.62	3.69	0.05	0.1	0.024	0.024
Side(of Freezing)	3.62	3.69	0.05	0.1	0.024	0.024

The overall heat transfer coefficients for the components of the refrigerator at the chilling and freezing temperatures were determined using Eq(4), and is presented in Table 2. Finally, the heat penetration was estimated using Eq(5).

$$K_n = \frac{1}{\frac{1}{\alpha} + \frac{d}{\lambda} + \frac{1}{\beta}} \tag{4}$$

$$Q_{into} = \sum (K_n \times A_n) \times \Delta T = \sum (K_n \times A_n) \times (T_{out} \times T_{in}) \tag{5}$$

In the above equation, $K_n(W/K/s/m^2), \alpha\ (W/m^2/K), \beta\ (W/m^2/K), d(m), \lambda(W/m/K), Q_{into}(W/s), A_n(m^2), T_{out}(K)$ and $T_{in}(K)$ are the overall heat transfer coefficient, the heat transfer of air outside the refrigerator, the heat transfer of air inside the refrigerator, the thickness of heat transfer areas, the thermal conductivity, the heat penetration, the heat transfer areas, the outside temperature and the inside temperature.

Table 2: Overall transfer coefficients and transfer areas at chilling and freezing of the different components

Place	Heat overall transfer coefficient($W/m^2/K/s$)		Area(m^2)	
	Chilling	Freezing	Chilling	Freezing
Front	0.465	0.236	7.83	10.70
Back	0.465	0.236	7.83	10.70
Ceiling	0.465	0.236	4.88	6.53
Bottom	0.465	0.236	4.88	6.53
Side(of outside)	0.465	0.236	3.62	3.69
Side(of freezing)	0.465	0.236	3.62	3.69

2.3 COP of GF-08 in comparison to conventional refrigerant

A simulation was conducted under the following conditions i.e. an outside temperature of 25 °C, a freezing temperature range of between -25 and -20 °C, and a chilling temperature range of between 0 to 5 °C. The results showed that the COP of GF-08 was higher for each cycle and each range of temperature in comparison to R404A and R410A. The COP at the chilling temperatures for the single-stage compressor was higher than that of the two-stage compressor. But, at freezing temperatures the COP of the two-stage compressor was higher than that of the single-stage. This result suggest that the single-stage compressor should be adopted at chilling temperature and the two-stage compressor should be adopted at freezing temperature.

2.4 Validation of simulation model

The simulation model was validated by comparing the estimated temperature change at chilling and freezing to the temperatures measured. The validation was conducted at a restaurant using one of their refrigerators. A simulation was conducted using the specifications of the refrigerator at the restaurant. Temperature outside the refrigerator, inside the refrigerator at chilling and freezing, and the preset temperature of the refrigerator were measured. The simulated temperature changes and test data (actual physical measurements) are compared (Figure 2). The average temperature difference between the measured and estimated temperature for chilling and freezing were 1.44 °C and 0.82 °C. The changes overtime of the simulated and test temperatures inside the refrigerator were comparable. The results suggest that the simulation model can be used to predict the inside temperature of refrigerators.

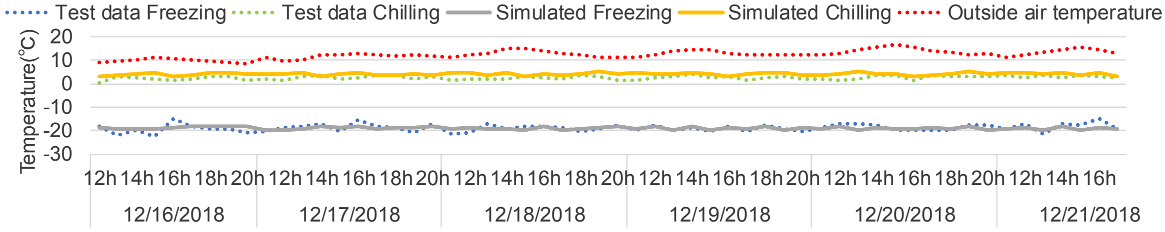

Figure 2: Comparison of the simulated and test temperatures at freezing and chilling

2.5 Estimation of the energy reduction when using GF-08 as refrigerant

In the winter, the potential energy reduction when GF-08 is used as a refrigerant instead of a traditional refrigerant such as R404A was determined as 21.6 %. The validation of simulation in this study was performed during winter. But, to determine the estimated energy saving throughout the year we assumed that the simulation model had a high validity throughout the year. The result of the estimated energy savings is presented in Figure 3 as the ratio of energy consumption at chilling, freezing and the total of chilling and freezing, for GF-08 in comparison to R404A (Eq(6)).

$$Ratio\ of\ energy\ consumption_{x,y}\ [\%] = \frac{Energy\ consumption_{x,y}(GF-08)[kWh]}{Energy\ consumption_{x,y}(R404A)[kWh]} \times 100 \tag{6}$$

In the above equation, x is freezing, chilling or total (sum of freezing and chilling), y is each season. The results show that the total energy consumption of the refrigerator can be reduced by using GF-08. The ratio in summer is the lowest in comparison to the other seasons, and this is when the highest energy saving can be achieved. In addition, the annual energy reduction was estimated. The days of each season were defined differently. The days in Spring and Autumn were defined using the average seasonal temperatures. The days in summer were all defined as having the temperature of the highest summer day, and winter days were all defined as having the lowest winter day temperature. The temperatures were used to determine the energy consumption of each day as per the definition. The seasonal consumption was determined by multiplying daily energy consumption by the number of days of each season as defined by the meteorological agency (spring:92, summer:92, autumn:91, winter:90). The annual energy consumption was a summation of the seasonal energy consumption. The average annual estimated reduction in energy consumption was 28.6 %.

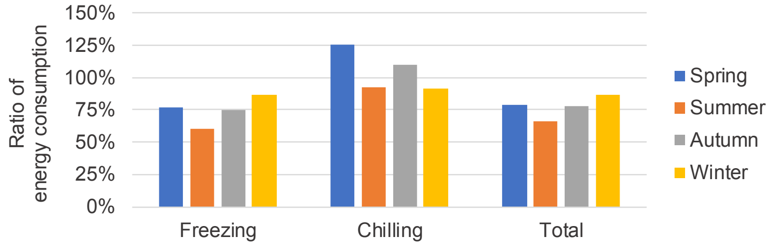

Figure 3: Ratio of energy consumption

2.6 Life cycle assessment (LCA) and goal

LCA was used to evaluate the annual environmental impact of the refrigerants during their life cycle using the emission of GHGs. A comparison of the GHG emissions of R404A and GF-08 was conducted for the model refrigerator.

2.7 Functional unit, system boundaries and inventory analysis

The performance of refrigerator depends upon the specific kind of refrigerant. That is, due to the replacement of R404A by GF-08, the energy consumption of refrigerator is affected including the GHG emissions. The purpose of LCA in this study is to evaluate the annual environmental impact during refrigerants life cycle. Thus, the functional unit in this LCA is set as for as one year of use. The system boundaries are shown in Figure 4. The replacement of the refrigerant includes only the system boundary of GF-08 on the grounds that R404A was disposed of when it was replaced. At the inventory analysis, the total GHG emissions were estimated using Eq(7) (International Institute of Refrigeration, 2015).

$$CO_{2_{eq}} = C \times (1 + ALR) \times RFM + AEC \times EM + C \times GWP \times ALR + C \times (1 - ALR) \times GWP + C \times GWP \quad (7)$$

In the above equation, C(kg), ALR(%), RFM(kg CO_2-eq/kg), AEC(kWh) and EM(kg CO_2-eq/kWh) are Refrigerant charge, Annual leakage rate, Refrigerant Manufacturing Emissions, Annual energy consumption and GHG emissions per kWh of energy.

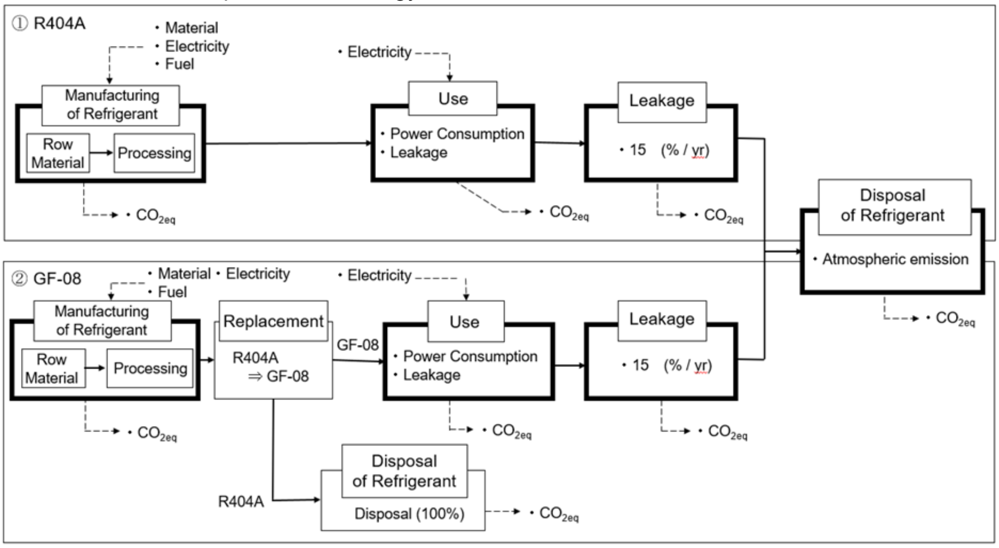

Figure 4: The system boundary (In Japan Case)

Table 3 shows the parameters used in inventory analysis. The refrigerant charge for R404A was estimated as 2.1 kg based on the compressor size as per the product specifications.

Table 3: The parameters

Name	Unit	R404A	GF-08
C	kg	2.10	0.80
ALR	% / year	15.0	15.0
RFM	kg CO_2-eq/kg	1.36×10^2	1.00
AEC	kWh	2.88×10^5	2.06×10^5
EM	kg CO_2-eq/kWh	0.462	0.462
GWP	kg CO_2-eq /kg	3.92×10^3	3.00

The reduction ratio of refrigerant charge of GF-08 in comparison to R404A was estimated by using the simulation model which is developed in this research. Here, note that the reduction ratio of refrigerant charge of GF-08 was defined as the ratio of the circulating volume of R404A and the circulating volume of GF-08 which is able to obtain the same cooling capacity to R404A. The GF-08 charge was estimated by multiplying the amount of R404A charge by the reduction ratio. Annual leakage rate (Center for Global Environmental Research, 2019), the refrigerant manufacturing emissions for R404A (Johnson, 2011) and the GHG emissions per kWh of energy (Tokyo Electric Power Company, 2018) were shown in Table 5. The manufacturing emissions of GF-08 were determined as 1.00 kg CO_2-eq/kg using SimaPro ver. 8.5.0.0 software (SimaPro). Annual energy consumption was estimated using the theoretical model developed in this study.

2.8 Result of environmental impact

The results of the total GHG emissions in the whole life cycle of R404A and GF-08 are presented in Figure 5. The use of GF-08 instead of R404A can potentially reduce the GHG emissions by approximately 27.1% which is due to the replacement R404A to GF-08 and the reduction of energy consumption by introducing GF-08. The highest GHG emissions are estimated to occur during use for both R404A and GF-08 in their life cycles. The results suggest that the reduction in the amount of energy consumed resulting from the use of GF-08 in a conventional refrigerator can reduce its environmental impact.

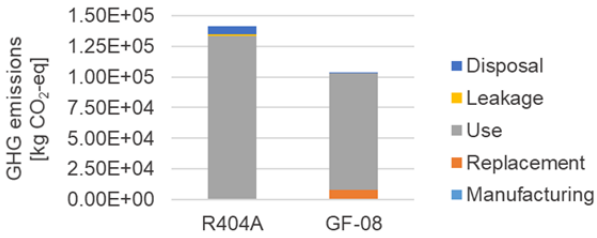

Figure 5: Result of the estimated GHG emissions

3. Conclusions

In this paper, the advantages of using GF-08 as a refrigerant was determined. The replacement of R404A with GF-08 has the potential to reduce the power consumption of a refrigerator required to maintain the quality of food. A simulation model was developed based on the vapor compression refrigeration cycle and the heat penetration. A comparison of the simulated results to test data (actual measurements) showed that they were comparable and validated the model. The results suggested that the simulation model had a high validity. The estimated annual energy reduction when GF-08 was used instead of R404A was at 28.6 %. The use of GF-08 as an alternative to R404A could potentially reduce GHG emissions by 27.1 % which is due to the replacement R404A to GF-08 and the reduction of energy consumption by introducing GF-08.

Note that the GHG emissions in Japan case was estimated. That is, in case of Vietnam which has a higher value of grid emission factor of electricity (0.815 kg CO_2-eq/kWh) than that of Japan, the reduction of GHG emissions was estimated as 34.2 % (Japan:27.1 %). Hence, by introducing GF-08 into Southeast Asian countries, the quality of food can be maintained with lower energy consumption and eco-friendly than the conventional ones.

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