Analysis of the performance of air blast freezer by using hydrofluorocarbon and hydrocarbon refrigerants

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Abstract. The air blast freezer has been used as a freezing method in the fish processing units before being frozen for a long time in cold storage. For this reason, the use of hydrocarbon refrigerants that are more environmental friendly has become a demand and a central issue in the future. This paper presents a performance analysis of using R290 and R600a as a drop-in replacement to R404A and R507A. The system performance analysis is based on the evaporation temperature variation using CYCLE_D-HX software with the condensation temperature maintained constant. The important quantities analyzed are mass flow rate, pressure ratio, temperature discharge, heat released, power consumption, coefficient of performance and refrigeration efficiency. The results show that at minimum evaporation temperature, system performance using R290 and R600a is on average ±14% higher compared to R404A and R507A. R290 has characteristics that are closer to R404A and R507A so it is more suitable to replace the two refrigerants compared to R600a. However, this is a performance analysis that can lead to higher performance than normal conditions.

1. Introduction
The integrated cold storage of DKP Kupang is a place for fish processing activities that is equipped with a refrigerator to produce frozen and fresh fish processing products, so it must be equipped with processing, freezing and cold storage facilities with room temperature of -25 °C. The fish to be kept in cold storage for a long period of time must first be frozen in a quickfreezing room so that the fish center temperature reaches -18 °C in the shortest time. The fast freezing method commonly used is the air blast freezer (ABF) [1-3]. In ABF fish products are frozen by rapid cooling for a vulnerable time of 8 hours/shift [4].

ABF uses vapor compression refrigeration to achieve the freezing process with the working fluid is R404A or R507A which is a refrigerant from the hydrofluorocarbon group. This refrigerant does not contain chlorine so it does not damage the ozone layer but still has a high global warming potential. Therefore, in the future it is necessary to use refrigerants that have a much lower GWP, namely from the hydrocarbons such as R290 and R600a. Currently, these two types of refrigerants are used in household refrigeration systems and air conditioning. Table 1 presents the properties and environmental effects of R404A, R507A, R290 and R600a [5,6].
Table 1. Environmental effects of refrigerant.

| Refrigerant Number | ODP | GWP  | Safety group (ASHRAE) |
|--------------------|-----|------|-----------------------|
| R404A              | 0   | 3922 | A1                    |
| R507A              | 0   | 3985 | A1                    |
| R290               | 0   | 3    | A3                    |
| R600a              | 0   | 3    | A3                    |

The thermodynamic performance of ABF is strongly influenced by the refrigerant used as the working fluid because there is a limited temperature difference between the system and its environment, which is the main source of irreversibility of the refrigeration system. A decrease in evaporation temperature will result in a decrease in system performance and efficiency, and vice versa [7,8]. This has prompted several researchers to conduct theoretical studies and experiments on the use of hydrocarbon refrigerants on the performance of the refrigeration system, including comparing the energy and exergy performance of the vapor compression refrigeration cycle using R404A, R290 and R744. The results of this study indicate that at various evaporation and condensation temperatures, R290 has better performance than R404A and R744 [9].

The use of R290, R600a and R1270 as an alternative to R22 in refrigeration systems that use subcooling heat exchangers for theoretical performance has also been carried out. The results of this study indicate that the thermodynamic properties of R290 and R1270 match those of R22, and show better performance than R22. The R600a performed slightly better in terms of lower power per ton of refrigeration, and higher COP but its saturation pressure and specific volume deviated significantly from R22, thus requiring a system redesign before being used as a replacement for R22 [10]. Experimental studies using R600a and R436A (mixture of 45% R600a and 56% R290) as substitutes for R134a in household refrigerators have also been carried out to compare the energy efficiency of the three refrigerants. The results show that R600a has the greatest energy efficiency compared to the other two refrigerants under various operating conditions [11].

2. Methods

In a simple vapour compression refrigerator, the refrigerant vapour is assumed to enter the compressor as saturated vapour, and the refrigerant liquid before entering the expansion valve is assumed to be saturated liquid. If the dimensions of the evaporator are slightly enlarged, saturated steam will usually continue to absorb heat, and therefore superheated steam before reaching the compressor. In practice, this is controlled by an expansion valve. If the condenser dimensions are slightly enlarged, the saturated liquid will continue to release heat, and becomes a subcooled liquid before entering the expansion valve. Superheating and subcooling are applied to increase system efficiency [12].
Figures 2 provide comparative P-h and T-s diagrams for the vapour compression cycle with subcooling and superheating (1'-2-3'-4'-1) and a saturated vapour compression cycle (1-2-3-4-1). The cooling capacity per unit mass is greater for the subcooled and superheated cycles so the refrigerant mass flow rate per unit capacity is smaller for that cycle than the saturation cycle. In addition, the increase in cooling capacity is proportionately greater than the increase in compression heat, so the COP of the subcooled and superheated cycles is higher than the saturation cycle.

Figure 2. P–h and T–s diagrams of the cycle.

From Figures 2, the mass flow rate of the refrigerant can be determined using the equation:

$$m_{ref} = \frac{Q_{evap}}{h_1 - h_4}$$

(1)

where $Q_e$ is the cooling capacity. The heat released during the condensation process is:

$$Q_{cond} = \dot{m}(h_2 - h_3)$$

(2)

then the compression work can be determined from:

$$W_{comp} = Q_e - Q_{cond}$$

(3)

The subcooling and superheating capacities can be determined from the equation:

$$Q_{SC} = \dot{m}(h_1 - h_3)$$

(4)

$$Q_{SH} = \dot{m}(h_r - h_1)$$

(5)

The coefficient of performance is the ratio of cooling capacity to compressor work, which is calculated using the equation:

$$COP = \frac{h_1 - h_4}{h_2 - h_1}$$

(6)

and by applying the second law of thermodynamics to the system under study, the refrigeration efficiency is:

$$\eta_R = \frac{COP}{(COP)_{rev}} = \frac{COP(T_x - T_1)}{T_1}$$

(7)

Several parameters and assumptions in this study are presented in table 2 which were selected based on the work range of BABF in ICS DKP Kupang.
Table 2. Research parameters and assumptions.

| Parameter                  | Unit  | Score |
|----------------------------|-------|-------|
| Cooling capacity           | kW    | 26.79 |
| Evaporation temperature    | °C    | -30 – 0 |
| Condensation temperature   | °C    | 40    |
| Subcooling temperature     | °C    | 2     |
| Superheating temperature   | °C    | 8     |
| Isentropic Efficiency      | %     | 0.8   |
| Volumetric Efficiency      | %     | 0.8   |
| Compressor heat loss       | %     | 10    |

3. Results and discussion

Figure 3 presents the relationship between the evaporation temperature and the mass flow rate of the refrigerant for cooling capacity and the condensation temperature is kept constant. It can be seen that the mass flow rate of the refrigerant using R290 and R600a is much lower than the use of R404A and R507A. This is because the densities of R290 and R600a are much lower. However, low density will result in a higher volume flow rate of refrigerant which results in an increase in the size of the heat exchanger (condenser and evaporator) to limit the pressure drop.

![Figure 3. Evaporation temperature vs mass flow rate of refrigerant.](image1)

![Figure 4. Evaporation temperature vs compressor pressure ratio.](image2)

During the cooling process, a decrease in the evaporation temperature will cause the pressure ratio on the compressor to increase, and vice versa. This is shown in Figure 4 and occurs for all of the refrigerants reviewed. The pressure ratio for use with R290 is the lowest which at the minimum evaporation is lower than ±28.8% of R600a, ±8.6% of R404A and ±6.41% of R507A, respectively.
The temperature of the refrigerant gas out of the compressor is an important parameter in choosing an alternative refrigerant. Lower out temperature increases compressor life time due to better refrigerant stability and lubrication. In Figure 5, the compressor out temperature for the system with R600a is much lower than that of R290, R404A, and R507A. R290 has out temperature that is not much different from R404A and R507A.

![Figure 5](image_url)

**Figure 5.** Evaporation temperature vs compressor refrigerant gas exit temperature.

Increasing the pressure ratio in the compressor will have an impact on the increase in compressor power for each decrease in evaporation temperature, and vice versa, and this is shown in Figure 6. At the minimum evaporation temperature, the compressor power of the system using R404A and R507A is relatively equal. However, the use of R290 was ± 10.97% smaller than that using R404A and R507A, and the use of R600a was ± 12.61% smaller. Compressor power is the largest energy input required to circulate a certain amount of refrigerant mass so that the process of heat absorption in the evaporator and heat release in the condenser can take place in the system.

![Figure 6](image_url)

**Figure 6.** Evaporation temperature vs compressor power.

Figure 7 presents the relationship between the evaporation temperature and the rate of heat released in the condenser. The heat release value is needed to design the condenser, and calculate the amount of condenser cooling fluid flow. The figure shows that increasing the evaporation temperature will decrease the rate of heat release in the condenser, and vice versa. At the minimum evaporation temperature, the heat released for systems using R600a and R290 was smaller than ±4.6% on average, respectively.
Figure 7. Evaporation temperature vs heat released in the condenser.

Figure 8. Evaporation temperature vs coefficient of performance.

Figure 9. Evaporation temperature vs refrigeration efficiency.

Figure 8 presents the relationship between evaporation temperature and the coefficient of performance (COP). In this figure, it can be seen that by decreasing the evaporation temperature, the system
performance coefficient will also decrease, and vice versa. Systems using R404A and R507A at minimum evaporation temperature have the same COP, and the values are smaller than ±12.31% of R290 and ±14.39% of R600a, respectively. The evaporation temperature has a strong influence on the performance of the refrigeration system. Similar to the coefficient of performance, the refrigeration efficiency will also decrease as the evaporation temperature decreases, as shown in Figure 9. At minimum temperature, the refrigeration efficiency of the system using R404A and R507A has the same value, and less than ±12.31% of R290 and ±14.39% of R600a, respectively. The evaporation temperature has a strong influence on refrigeration efficiency.

4. Conclusion
This analysis shows that the use of hydrocarbon refrigerants (R290 and R600a) will result in better system performance compared to the use of hydrofluorocarbon refrigerants (R404A and R507A). At the minimum evaporator temperature, systems using hydrocarbon refrigerants have refrigeration efficiency higher than hydrofluorocarbon refrigerants. R290 has closer characteristics to R404A and R507A so it is more suitable to replace the two refrigerants compared to R600a. In addition, hydrocarbon refrigerants are more environmentally friendly than hydrofluorocarbon refrigerants so their use in the future is more recommended, even though they are more flammable.

References
[1] Wasan T, Kitrichai T 2008 American Journal of Engineering and Applied Sciences 1 (1) p 33
[2] Patrick D, Pradeep B 2012 Applied Thermal Engineering 42 p 71-83
[3] Guiqiang W, Pinghua Z 2014 International Journal of Materials, Mechanics and Manufacturing 2 (4) p 278
[4] Anonim, Buku Manual Cold Storage Kapasitas 100T DKP Kupang, Kementerian Kelautan dan Perikanan, Republik Indonesia 2017, pp. 11-12, 27.
[5] El-Sayed A R, El-Morsi M, Mahmoud N A 2018 International Journal of Air-Conditioning and Refrigeration 26 (3) p 4
[6] Bhatkar V W, Kriplani V M, Awari, G K 2013 International Journal of Environmental Science and Technology 10 p 872
[7] Matheus M D, Verdy A K, Josef M M 2015 Prosiding SEMNASTEK pp. 1-17.
[8] Matheus M D, Suhanan, Prajito 2017 AIP Conf Proc 1788, pp. 030011:1–8.
[9] Shiliday, J A, Tassou, S A, Shiliday, N 2009 International Journal of Low-Carbon Technologies pp. 1–8.
[10] Bukola O B, Zhongjie H 2012 Journal of Power and Energy 226 (7) pp. 882–891
[11] Rasti M, Aghamirî S F, Hatamipour M S 2013 International Journal of Thermal Sciences (74) pp. 86–94.
[12] Sencan A, Selbas R, Kizilkan O, Kalogiru S A 2006 International Journal of Energy Research (30) pp. 323–347.