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MECHANICAL ENGINEERING | RESEARCH ARTICLE

Exergy analysis of refrigerator for a three steps freezing process

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Abstract: Temperature difference between the evaporator and the product during a freezing process is one of the sources of irreversibility. Application of three-steps evaporator temperature during the freezing course is expected to lower the irreversibility and improve energy efficiency of the system. The purpose of this research is to analyze the energy and exergy efficiency of a refrigeration system with three-steps temperature for freezing process. The experiment was conducted using laboratory scale freezer equipped with three expansion valves to provide the required temperature level at each step. Thermodynamic properties of the refrigerant during the process were obtained by using Engineering Equation Solver (EES). The results show that freezing with three temperature steps gave total COP of 2.66, higher than COP of the fixed temperature process, which was 2.40. Exergy analysis shows that average irreversibility of the compressor with stepping temperature operation was higher than that of fixed temperature operation, which was mainly affected by the higher irreversibility during the first step of the stepping temperature operation. It is concluded that compressor work needs to be adjusted to the real work requirement by using an



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PUBLIC STATEMENT INTEREST

Freezing is the best method for maintaining food quality for a long time, compared with other technologies such as drying and canning. However, freezing technologies require more energy, so energy-saving efforts are needed. On conducting steps-temperature experiments on a freezer, the results show that COP increases. Exergy analysis shows that the average irreversibility of compressors with steps temperature operations is higher and exergy efficiency is low. Therefore, the compressor work needs to be adjusted to the real load in order to take advantage of this operation, which is lower compressor power and more efficient. Rotation or compressor power can be adjusted using an inverter.

equipment such as inverter in order to take advantage of the stepping temperature operation in terms of more efficient use of power by the compressor.

Subjects: Food Engineering; Preservation; Product Design; Heat Transfer; Thermodynamics

Keywords: Stepping temperature; freezer; energy; exergy; COP

1. Introduction

Food preservation by freezing is preferred when compared to other methods, such as curing and canning. Most of the freezers used in food freezing industry are vapor-compression system (Yumrutas, Kunduz, & Kanoglu, 2002). However, such a freezing system is an energy-intensive process (Barbosa-Cánovas, Altunakar, & Mejía-Lorio, 2005). Due to the increasing price of energy, methods to increase the energy efficiency of a freezing system are indispensable. A number of studies have been conducted by researchers to increase the energy efficiency of the refrigeration system. Fang, Xing, Yang, and Li (2005) analyzed energy loss in the components of the refrigeration system such as compressor, condenser, evaporator and expansion valve. Luo and Wang (2010) recommended a model of low-temperature freezer which is able to save energy in the freezing process. Freezer or refrigerator-freezers is a household appliance that is most commonly used, and is a device which consumes considerable energy. Therefore, it is a necessary effort to improve energy efficiency. For this purpose, Chen, Yan, and Yu (2017) and Belman-Flores, Barroso-Maldonado, Rodríguez-Muñoz, and Camacho-Vázquez (2015,) during the past decades, have developed a variety of energy-saving methods for freezer.

Utilizing natural refrigerants such as hydrocarbons is one method to improve performance and reduce global warming and ozone depletion. Arora (2008), Bolaji and Huan (2013), Chopra (2014) and Shilliday (2009) have performed energy analysis on R404A with vapor-compression cycle refrigeration and have stated that R404A is well used as a cooling fluid. R404A is a coolant pressure and low-temperature-type BLP (back low pressure).

Analysis energy and exergy of the refrigeration system is a way to determine the amount of freezing energy consumption (Belman-Flores, Rangel-Hernández, Usón, & Rubio-Maya, 2017). The vapor-compression cooling system uses several evaporators and compressors with several expansion valves better than using one expansion valve stated by Chopra, Sahni, and Mishra (2015). An irreversible analysis observed by Chopra, Sahni, and Mishra (2014) states that a refrigeration system that uses R404A refrigerant produces COP and exergetic efficiency higher compared to systems using R152. Performance efficiency (COP), exergy destruction and exergy efficiency for R502, R 404A and R507A have been developed with computational models by Arora and Kaushik (2008). The simple thermodynamic model may not be enough to predict the actual working characteristics (Megdoui et al., 2017), suggesting that to explore and evaluate the feasibility of this cycle requires some experiment.

Tambunan, Sihalo, and Kamal (2012) utilized energy and exergy analysis on freezing process. The study assumed that the process can be divided into three consecutive steps. Step 1 is temperature reduction from the product's initial temperature to its freezing temperature, Step 2 is phase change at the freezing temperature and Step 3 is temperature reduction to the product's final temperature. Controlling temperature of the freezing medium at different level for each of the step was found to improve the energy and exergy efficiency. The findings are reasonable since irreversibility of the process was reduced by reducing temperature difference between the product and the freezing medium, especially during the first step. It is well understood that temperature difference is one of source for irreversibility in a heat transfer process. However, the study was focused only on the freezing process of the product and did not analyze the energy and exergy of the refrigerator. Kamal (2008) developed a beef-freezing model in three steps of the process in one system,

and on the model examined energy and exergy efficiency. The result is that model exergetic freezing system can reduce exergy loss compared to a fixed temperature freezing system.

The objective of this research is to perform an exergy analysis on a vapor-compression refrigerator when it is used in a three-step temperature of freezing process. The exergy analysis can be used as an indicator performance in order to increase the coefficient of performance and determine the exergy efficiency to get a more efficient freezing machine for further research.

The importance of this study is to conduct a three-step temperature experiment (varied load) in freezing process and fixed temperature experiment as a comparison. In the initial stage (low load), increase in irreversibility and decrease in exergy efficiency happens, which indicates an excess of power entering the system. The application of real power at low loads requires a device that can reduce electrical power or reduce the rotating speed compressor (for example, with an inverter), so as to get a energy-saving freezing machine. This study can be used as a basis for further research.

2. Research methodology

The energy and exergy analysis was conducted using experimental data obtained from a laboratory scale freezer as shown schematically in Figure 1. Research equipments and details of measuring instruments are arranged as shown in Figure 2. The freezer used is R-404A refrigerant and has specification as presented in Table 1. The freezer is equipped with three expansion valves to provide the required temperature level at each step. Temperature of the evaporator was set into three steps, as shown in Table 2, during the course of the freezing process. The freezing load was 1 kg of water. Using a thermal load 1 kg of water is intended to facilitate the experiments and measurements according to the condition of the cooling plate in the evaporator. The thermal load has a condition (temperature, mass and position). The condition of the initial temperature of each test is the same, which is the initial temperature of water (27°C). Experiment on fixed temperature, where the temperature of the evaporator was set constantly at -24°C, was conducted as a standard to compare the effect of the stepping temperature. The data were collected

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Figure 1. Schematic diagram of the refrigerator and point of measurement.

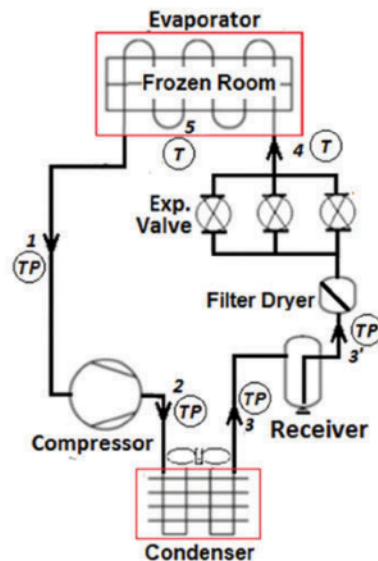


Figure 2. Photo research equipment; (a) view from the side, (b) view from the front.

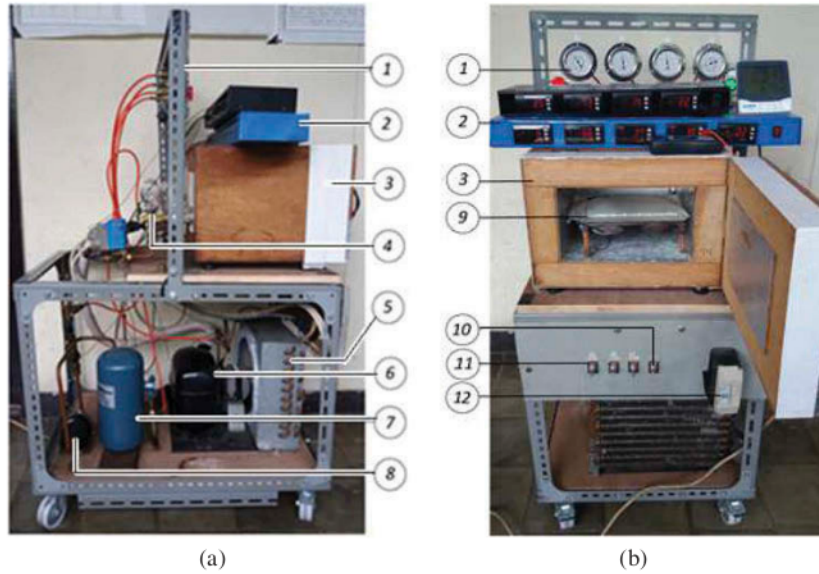


Table 1. Specification of the freezer

Component	Specification
Compressor	Type; SC12CL, Code; 104L2623, 220-240V/50Hz, Ve 12 cm ³ /rev
Evaporator	Type; plate touch 210 x 210 x 3) mm ³ , d pipe 5/8", Inner space (148 x 251 x 251) mm ³
Condenser	Type; Tinned tube n 30, d 3/8", L 10.080 mm, air conditioner
Exp. valve	Danfoss TS2
Refrigerants	R 404A
Receiver	Merk; Airmender, A 127 mm, L 240 mm, Vol. 3 dm ³
Pressure gauge	Bourdon Barometer Type analog
Thermometer	Thermocouple digital type TC4Y Accuracy $\pm 2^{\circ}\text{C}$
Wattmeter	Multifunction Mini Ammeter D02A, Accuracy $\pm 1\%$

Table 2. Stepping of the evaporator's temperature during the experiment

Experiment	First step (°C)	Second step (°C)	Third step (°C)
Stepping	-10	-15	-24
Fixed temperature	-24	-24	-24

every 5 minutes. Parameters used for the energy and exergy analysis were COP, entropy generation and exergy efficiency of the refrigeration system.

The energy and exergy analysis were performed at each of the refrigerator's main components, i.e. compressor, condenser, expansion valve and evaporator. COP of the refrigerator was calculated with Equation (1), where the subscripts 1, 2, 3 and 4 are the point of measurements as shown in

Figure 1. The expansion valve was assumed to work adiabatically (isenthalpic), where enthalpy of the refrigerant entering and exiting the expansion valve is equal ($h_3 = h_4$).

$$COP = \frac{q_{RE}}{W_k} = \frac{(h_1 - h_4)}{(h_2 - h_1)} \quad (1)$$

Exergy of a two-stage vapor-compression refrigeration system is based on ambient temperature as stated by Chopra et al. (2015), and is shown in Equation (2). Irreversibility at compressor, condenser, expansion valve, evaporator and receiver is given in Equations (3)–(7), respectively, as derived by Tambunan and Abdullah (2017). Total irreversibility of the system is the sum of irreversibility of each component, as shown in Equation (8). Total irreversibility is regarded as a loss of work. Reversible work can be calculated by using Equation (9). Accordingly, exergetic efficiency of the system can be calculated by using Equation (10), as stated by Yumrutas et al. (2002).

Equations (3–11) are clarified by references from Tambunan and Abdullah (2017).

Energy balance on a closed system work is generally defined in terms of rate change, like the following equation $\frac{dE}{dt} = \dot{Q} - W + \sum_0 \dot{m}_0 h_0 - \sum_1 \dot{m}_1 h_1$.

The compressor's real work generally generates heat (Q_{comp}) and releases around, so energy balance on compressor is as in the following equation: $0 = \dot{Q}_{comp} - W + \dot{m}_2 h_2 - \dot{m}_1 h_1$. The compressor works is modeled as open system, so the entropy generation process (σ) as shown in the equation: $0 = \frac{\dot{Q}_{comp}}{T_{comp}} + \dot{m}(s_2 - s_1) + \sigma_{comp}$. Ambient temperature is the dead-state temperature (T_0); then, the entropy generation process at compressor is based on the dead-state temperature (T_0 , σ_{comp}) same as exergy destroyed during the compression process and stated as irreversibility process (I_{comp}), or $I_{comp} = T_0 \sigma_{comp}$.

The isentropic process takes place and is assumed to have no heat transfer (adiabatic), so that $Q = 0$.

Then, the exergy balance of compressor is calculated using the following equation:

$0 = \dot{Q}_{comp} \left(1 - \frac{T_0}{T_{comp}}\right) - W + \dot{m}\{(h_2 - h_1) - T_0(s_2 - s_1)\} - T_0 \sigma_{comp}$. So that the exergy balance of each component can be obtained by the equation:

Exergy at any point

$$Exergy = (h - h_0) - T_0(s - s_0) \quad (2)$$

Compressor entropy generation

$$T_0 \sigma_{comp} = I_{comp} = \dot{Q}_{comp} \left(1 - \frac{T_0}{T_{comp}}\right) - W + \dot{m}\{(h_2 - h_1) - T_0(s_2 - s_1)\} \quad (3)$$

Condenser entropy generation

$$T_0 \sigma_{cond} = I_{cond} = \dot{m}\{(h_3 - h_2) - T_0(s_3 - s_2)\} + \dot{Q}_{cond} \left(1 - \frac{T_0}{T_{cond}}\right) \quad (4)$$

Expansion valve entropy generation

$$T_0 \sigma_{exp} = I_{exp} = \dot{m}\{(h_4 - h_3) - T_0(s_4 - s_3)\} \quad (5)$$

Evaporator entropy generation

$$T_0 \sigma_{evap} = I_{evap} = \dot{m}\{(h_1 - h_4) - T_0(s_1 - s_4)\} + \dot{Q}_{evap} \left(1 - \frac{T_0}{T_{evap}}\right) \quad (6)$$

Receiver entropy generation

$$T_0 \sigma_{rec} = I_{rec} = \dot{m} \{ (h_3 - h_3) - T_0 (s_3 - s_3) \} \quad (7)$$

Total irreversibility process

$$I_{tot} = I_{comp} + I_{cond} + I_{rec} + I_{exp} + I_{evap} \quad (8)$$

Compressor reversible work

$$W_{Rev} = \dot{Q}_{evap} \left(\frac{T_{cond}}{T_{evap}} - 1 \right) \quad (9)$$

where T_{comp} is refrigerant temperature at compressor outlet, T_{cond} is refrigerant temperature at condenser inlet, T_{evap} is refrigerant temperature in the evaporator plate and T_0 is the temperature of surrounding air.

2.1. Exergy efficiency

The efficiency of thermodynamic law known as exergy efficiency or effectiveness can be defined as the ratio of minimum/reversible work (W_{Rev}) against real work (W_{ac}) and the amount of compressor work loss equal to the amount of irreversibility ($W_L = I_{tot}$). So, exergy efficiency can be calculated as in Equation (10).

$$\eta_{ex} = \frac{W_{Rev}}{W_{Rev} + W_L} \quad (10)$$

The total irreversibility can be accounted as loss of work, while the sum of loss of work and reversible work can be regarded as the measured work consumption by the compressor. Accordingly, the exergy efficiency can be calculated using Equation (11).

$$\eta_{ex} = \left(1 - \frac{W_L}{W} \right) \quad (11)$$

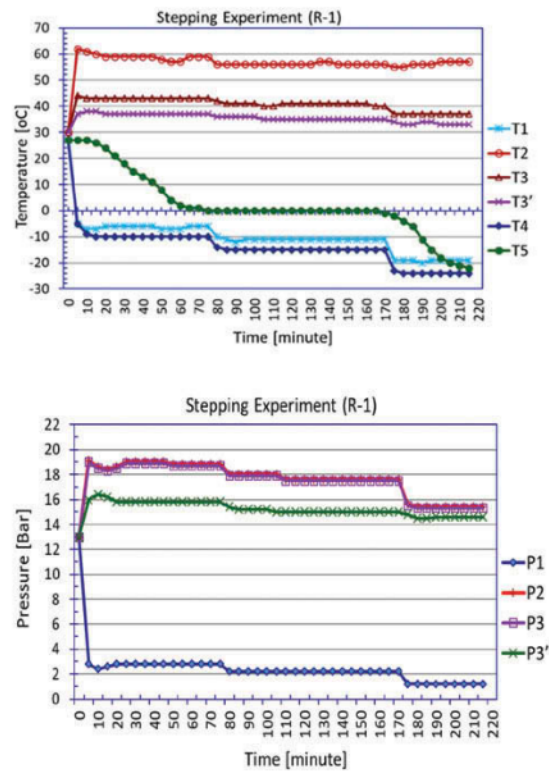
3. Result and discussion

3.1. Temperature and pressure profile

Figure 3 shows temperature (T) profiles and pressure (P) profiles at specific points of measurement during the process of three-step temperature. The points numbering is the same as the numbering in Figure 1. As shown in the figure, temperature entering the evaporator (T_4) was changing to follow the set temperature as expected at each step. Changing of the set evaporator's temperature was occurring in accordance with the product's temperature (T_5), as mentioned above. It can also be seen that temperature at the receiver's outlet (T_3) was lower than the inlet (T_3).

The change in pressure at the suction part of the compressor or the outlet of the evaporator (P_1) was changing in accordance with set temperature of the evaporator. Inlet pressure of the evaporator was not measured and was assumed to be the same as its outlet pressure, i.e. pressure drop was assumed to be negligible. Peculiarly, there was a significant pressure difference between the inlet (P_3) and outlet (P_3) of the receiver. This pressure difference was also indicated by its temperature difference (T_3 and T_3). The refrigerant from condenser flows out through the pipe. It enters the receiver that has a greater volume. The result is the pressure and temperature drop that can be seen in point 3 moving to point 3' as shown in Figure 5, since refrigerant in the receiver should be in saturated state. Pressure at the discharge side of the compressor was changing with the same pattern as the suction pressure. Temperature and pressure profiles during the fixed temperature experiment is shown in Figure 4. It can be seen that the evaporator's temperature was constant during the freezing process despite the change in the product's temperature (T_5). Pressure and temperature difference between inlet and outlet of the receiver also raised as in the stepping temperature experiment.

Figure 3. Temperature and pressure profiles during experiment on three-step temperature of the evaporator (R-1).



Summary of the data at steady-state condition is given in Table 3. Plot of the data on stepping experiment during steady-state process at pressure-enthalpy (p-h) diagram is given in Figure 5. There exist three cycles according to the three steps which occurred during the process, where the blue line is for Step 1, the green line is for Step 2 and the red line is for Step 3. It also shows that the refrigeration temperature in the evaporator gets lower so that the graph of the refrigeration system shifts down and also the distance between P1 and P2 becomes wider. The temperature in the evaporator is getting lower, resulting in greater compressor work so that the COP gets lower.

3.2. COP and exergy analysis

Enthalpy of the refrigerant at each point of measurement for the stepping experiment and fixed temperature experiment is shown in Table 4. The enthalpy was determined by using the measured temperature and pressure during steady state process. The enthalpy was then used to calculate the equivalent of the compressor work (w_k) and refrigeration capacity (q_{RE}) as well as the coefficient of performance (COP), which are also presented in the table. COP of the refrigerator operating with stepping temperature was decreasing according to the decreasing temperature of the steps. The results of data analysis in each measurement from three steps and fixed temperature experiments are calculated using Equation (1). The results are plotted as shown in Figure 6. The graph shows that COP for Step 1 is greater than COP for Step 2 and COP for Step 2 is greater than COP for Step 3; efforts to improve COP are achieved. The table shows that total COP of the stepping process was 2.66, which is higher than COP of the fixed temperature process, i.e. 2.40. The results indicate that freezing with three temperature steps is better than with fixed temperature in terms of COP.

Figure 4. Temperature and pressure profiles during experiment on fixed temperature of evaporator (R-2).

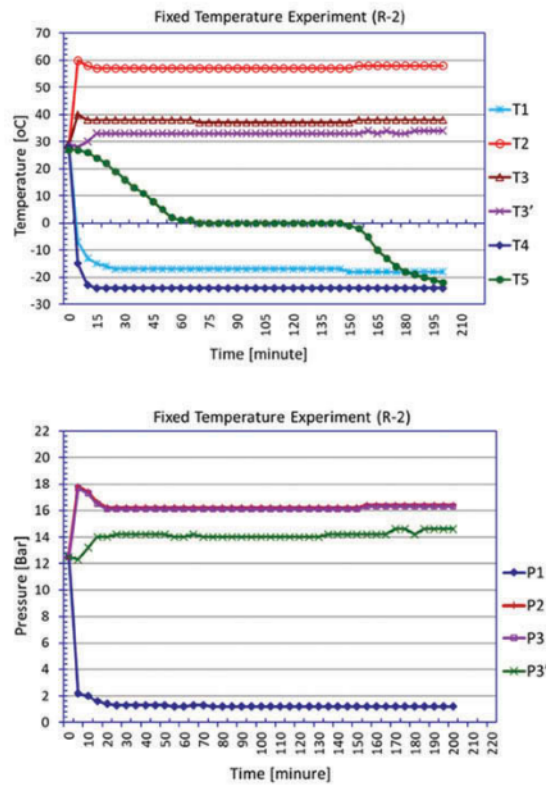


Figure 5. Three cycles of the stepping experiment on p-h diagram.

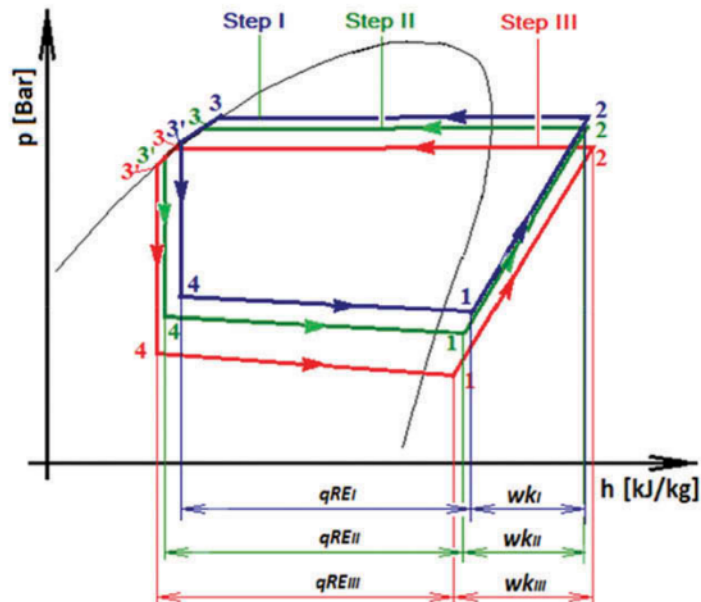


Table 3. Summary of measured data during steady-state process

	Evap.		P ₁ (Bar)	P ₂ (Bar)	P ₃ (Bar)	P _{3'} (Bar)	T ₁ (°C)	T ₂ (°C)	T ₃ (°C)	T _{3'} (°C)	T ₄ (°C)
	[°C]	[°C]									
Temp. stepping	-10		3.8	19.8	19.7	16.8	-7	58	43	37	-10
	-15		3.2	18.6	18.5	16.0	-11	57	41	35	-15
	-24		2.2	16.4	16.3	15.5	-19	55	37	33	-24
Fixed temp.	-24		2.4	17.2	17.1	15.0	-16	57	38	33	-24

Table 4. Result of Energy and COP analysis from research sample and process steps with analysis of refrigeration diagram

Description	Evap [°C]	Enthalpy						W _k	Q _{RE}	COP
		h ₁	h ₂	h ₃	h _{3'}	h ₄				
Research		kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	–
Temp. stepping	-10	366.0	402.71	270.24	257.29	257.29	36.63	108.79	2.97	
	-15	363.49	403.82	265.06	254.33	254.33	40.33	109.16	2.71	
	-24	358.68	405.30	255.81	252.11	252.11	46.62	106.57	2.29	
Total		1088.25	1211.83	791.11	763.73	763.73	123.58	324.52	2.66	
Fixed temp.	-24	360.90	406.78	259.14	250.63	250.63	45.88	110.27	2.40	

Figure 6. Graph of COP from data analysis in each measurement.

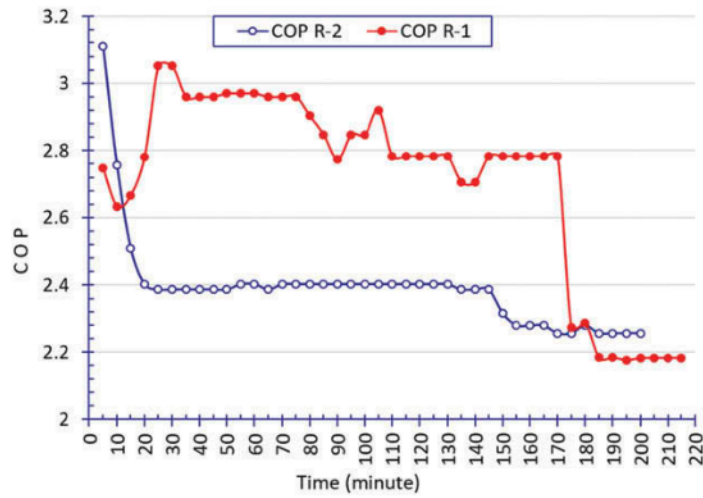


Table 5. Entropy of the refrigerant at each point of measurements during steady state

Description		Refrigeration entropy [kJ/kg.K]				
	Evap. [°C]	s ₁	s ₂	s ₃	s _{3'}	s ₄
Step temp.	-10	1.65	1.65	1.23	1.20	1.22
	-15	1.64	1.65	1.22	1.18	1.21
	-24	1.64	1.67	1.19	1.18	1.22
Fixed temp.	-24	1.66	1.67	1.20	1.17	1.21

Table 6. Irreversibility of each component analyzed during steady state of the process

Description		Refrigeration entropy [kJ/kgK]						Comp. power (W)	η _{ex} [%]
	Evap. [°C]	I _{comp}	I _{cond}	I _{exp}	I _{evap}	I _{rec}	I _{tot}		
Step temp.	-10	331.45	3.77	55.58	131.53	17.92	459.21	595.13	10.67
	-15	312.10	2,85	61.33	110.01	3.88	419.27	547.39	11.79
	-24	167.29	1.51	79.69	129.73	0.74	295.51	432.22	21.02
	Aver.	270.28	2.71	65.54	123.76	7.51	391.33	524.91	14.49
Fixed temp.	-24	149.17	1.75	79.84	160.93	4.30	308.35	457.30	20.27

In order to analyze the exergy of the process, entropy of the refrigerant at each point of measurement during steady state was found based on the measured temperature and pressure, using Engineering Equation Solver (EES), as shown in Table 5. Irreversibility of the process at each of the components was calculated using Equations (3)–(7). The results, as well as the total irreversibility and exergy efficiency, are shown in Table 6. It is clear that irreversibility of the compressor was the highest among the components, followed by evaporator and condenser.

Figure 7. Graph of irreversibility from data analysis in each measurement.

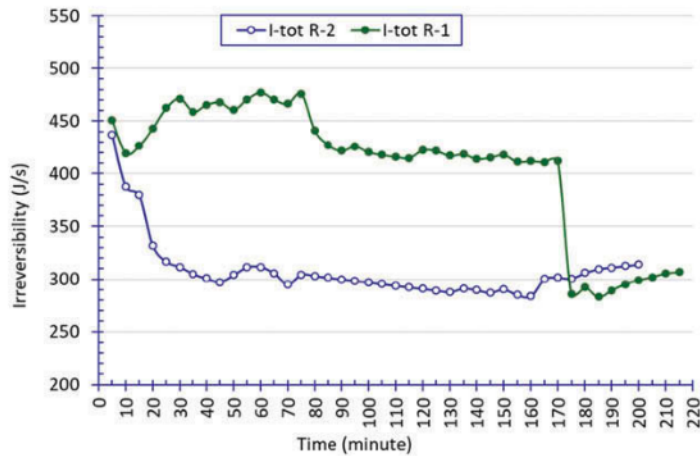
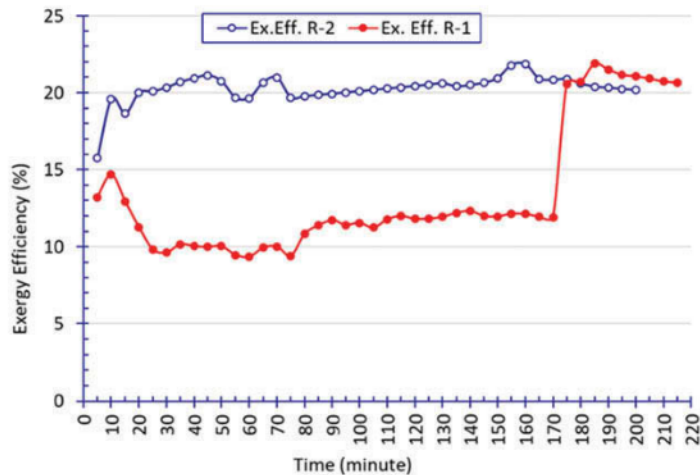


Figure 8. Graph of exergy efficiency from data analysis in each measurement.



Average irreversibility of the compressor with stepping temperature operation was higher than that of fixed temperature operation. The higher irreversibility of the compressor was mainly affected by the higher irreversibility during the first step of the stepping temperature operation. From Table 4, it was found that the heat equivalent of the compression work (w_c) at the first step was lower than the second and third steps due to the adjustment of evaporator temperature step-wise. On the other hand, Table 6 shows that the average power consumed by the compressor was relatively equal for each of the step. This result indicated that compressor work needs to be adjusted to the real work requirement by using an equipment such as inverter.

Figure 7 shows the irreversibility graph as a result of data analysis in each measurement from three-steps and fixed temperature experiments which is calculated using Equations (3)–(8). The graph can show that irreversibility Step 1 is greater than irreversibility Step 2 and irreversibility Step 2 is greater than irreversibility Step 3. High irreversibility occurs in Step 1 (low load); this is because the compressor is constant (excess power), and thus to save energy, a tool is needed that can reduce compressor power.

Figure 8 shows a graph of exergy efficiency as a result of data analysis in each measurement of the three-step and fixed temperature experiments, calculated using Equation (10). The graph shows that exergy efficiency Step 1 is lower than exergy efficiency Step 2, and exergy efficiency Step 2 is lower than exergy efficiency Step 3.

However, the exergetic efficiency of the stepping temperature operation was found to be higher than that of fixed temperature operation, as shown in the table. Higher exergetic efficiency is expected if the compressor work is controlled and justified to the real refrigeration load in the freezing room. Its implementation will lead to more efficient use of power by the compressor.

4. Conclusion

The results show that freezing with three-temperature step performed better than with fixed temperature in terms of COP, where total COP of the stepping process was 2.66 and COP of the fixed temperature process was 2.40. Exergy analysis shows that average irreversibility of the compressor with stepping temperature operation was higher than that of fixed temperature operation, which was mainly affected by the higher irreversibility during the first step of the stepping temperature operation. It is concluded that compressor work needs to be adjusted to the real work requirement by using an equipment such as inverter in order to take advantage of the stepping temperature operation in terms of more efficient use of power by the compressor.

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Nomenclature

Symbols

h	Specific enthalpy (kJ/kg)
I	Irreversibility (kJ/kg)
m	Refrigeration mass flow rate (kg/s)
P	Refrigerant pressure (Bar)
R-1	Stepping temperature experiment
R-2	Fixed temperature experiment
s	Specific entropy (kJ/kgK)
T	Temperature (°C, K)
W	Compressor power (W)
W_K	Compressor work (kJ/kg)
q_{RE}	Cooling capacity (kJ/kg)
Q̇	Thermal capacity (W)

Evap	Evaporator
Exp	Expansion valve
H	High temperature
L	Low temperature
L	Energy losses
o	Ambient
rec	Receiver
Rev	Reversible
tot	Total

Greek Symbols

η_{ex}	Exergetic efficiency (%)
σ	Entropy generation (kJ/kgK)

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Subscripts

1	At compressor inlet
2	At compressor outlet
3	At condenser outlet
3'	At receiver outlet
4	At evaporator inlet
5	In product (water-ice)
Comp	Compressor
Cond	Condensor

RESEARCH HIGHLIGHT

- The results show that freezing with three temperature steps performed better than with fixed temperature, especially on the COP.
- In Step 1 (low load), high irreversibility occurs; this is because the compressor is constant (excess power), and thus to save energy, a tool is needed that can reduce compressor power.
- Compressor work needs to be adjusted to the real work requirement by using an equipment such as inverter in order to take advantage of the stepping, so that electricity consumption is more efficient.

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