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Refrigeration Cycle Exergy-Based Analysis of Hydrocarbon (R600a) Refrigerant for Optimization of Household Refrigerator

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The use of refrigerant specifically Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) in refrigerators greatly contribute to global warming, while the choice of hydrocarbon refrigerant proves to be a better option. This paper shows the results of an exergy-based analysis of the irreversible refrigeration cycle on household refrigerators using hydrocarbon refrigerant (R600a) in accordance with SNI ISO15502: 2008 standard. Through parameters of determinants of exergy such as enthalpy, entropy, mass flow rate, the coefficient of performance (COP), load array types, therefore the optimum use of refrigerant can be obtained. The model analyses used is cycle that include irreversibility of heat transfer across finite temperature differences, heat leakage, and internal dissipation. The approach is done by combining mathematical modelling or simulation cycle in engineering equation solver (EES) software with experiment directly on refrigerator in room chamber where environment has been conditioned according to the prevailing provisions. The obtained results may be able to be used as a reference for other similar research or for optimal utilization of another hydrocarbon refrigerant.

Keywords: EES, Exergy; Taguchi Method, Optimization.

1. Intoduction

Refrigerator plays important role in preserving steadily the foods and daily needs under low temperature. However, since the finding of correlation between refrigerants, such as Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs), and global warming[1,2] also with the accordance to the policy which banning the use of the mentioned refrigerants from the Indonesia's government, manufacturer seek for hydrocarbon refrigerant as the alternative refrigerant for household refrigerator. Furthermore, the pursue towards green and sustainable energy has driven manufacturer to create a more efficient electrical energy usage of refrigerator[3,4]. By associating those reasons, the optimization of household refrigerator becomes a necessary. To achieve the objective, a standardized test SNI ISO 15502:2008 is applied[5]. The test, which is going to be performed, requires a conditioned and controlled environment of temperature 32 ± 0.5 °C, humidity 40% - 70%, and the use of M-Packages, Furthermore, the other study was investigated using CFD simulation method[6].

The tests were conducted by combining variance of 2 variables, M-Package arrangement and R600a refrigerant mass. Current test utilizes various arrangement of M-Package inside freezer compartment which might produce different result, therefore 3 types of M-Package arrangement which highly possible of reaching efficient energy usage were applied. The recommended amount of mass refrigerant from the manufacturer is 48 grams, thus varying the mass from 43 – 53 grams with 5 grams for each variation was decided. Modeling mathematically the acquired pressure and temperature values from the refrigeration system, the exergy destruction can be calculated[7]. Then by analyzing the total exergy destruction as the observed response value of Taguchi method, consequently the optimum working condition of the refrigerator can be achieved which refers to the main purpose of this test.

2. Mathematical Model

Exergy could be defined as the amount of work when material is brought to equilibrium state of thermodynamic with general component from surrounding environmental condition with the purpose of reversible process, involve interaction with the natural component itself[8]. Rashidi et al. define exergy as maximum theoretical useful work (or maximum reversible work) obtained as a system interacts with an equilibrium state[9]. Exergy in every component is analyzed under a steady state process using software EES, a convenient software related to thermo physical properties[10]. Parameter which cannot be obtained while the system running, underwent an approach with an assumption of an ideal refrigeration cycle. Therefore, the equation 1 – 10 as expressed below will help to determine the aimed value:

Exergy balance for control volume

$$\dot{E}x_{dest} = \sum \dot{E}x_{in} - \sum \dot{E}x_{out} + \sum\left[\dot{Q}\left(1-\frac{T_0}{T}\right)\right]_{in} - \sum\left[\dot{Q}\left(1-\frac{T_0}{T}\right)\right]_{out} + \sum \dot{W}_{in} - \sum \dot{W}_{out} \quad (1)$$

Exergy rate destruction to each component:

Compressor:

$$\dot{E}x_{dest,Comp} = \dot{W}_{comp} + \dot{E}x_1 - \dot{E}x_2 \quad (2)$$

Condenser:

$$\dot{E}x_{dest,Cond} = \dot{E}x_2 - \dot{E}x_3 \quad (3)$$

Capillary Tube:

$$\dot{E}x_{dest,Cap} = \dot{E}x_3 - \dot{E}x_4 \quad (4)$$

Evaporator:

$$\dot{E}x_{dest,Evap} = \left(\dot{E}x_4 - \dot{E}x_1\right) + \left[\dot{Q}_{Evap}\left(1-\frac{T_0}{T_L}\right)\right] \quad (5)$$

Refrigerant mass flow rate:

$$\dot{m} = \frac{P_{electric}}{h_2 - h_1} \quad (6)$$

Total exergy destruction:

$$\dot{E}x_{dest,T} = \dot{E}x_{dest,Comp} + \dot{E}x_{dest,Cond} + \dot{E}x_{dest,Cap} + \dot{E}x_{dest,Evap} \quad (7)$$

Relative irreversibility:

$$RI = \frac{\dot{E}x_{dest,i}}{\dot{E}x_{dest,T}} \quad (8)$$

Coefficient of performance:

$$COP = \frac{\dot{Q}_{Evap}}{\dot{W}_{Comp}} \quad (9)$$

Exergetic efficiency:

$$\eta = \frac{COP}{COP_c} \quad (10)$$

Taguchi design, smaller is better:

$$S/N_s = -10\log\left(\frac{1}{n}\sum {y_i}^2\right) \quad (11)$$

3. Setting and Taguchi Method

3.1. Physical model

To analyze exergy destruction of the refrigeration system, it depends on the value of temperature and pressure from the refrigeration system which measured continuously[11,12,13]. Accordingly, it requires accurate placement configuration of the measurement to minimize the error and uncertainty. For this study Thermocouple T-type are used to measure environment temperature in chamber and the refrigeration system temperature shown in Figure 1. 4 pressure transmitters are installed on refrigeration system, close to thermocouple measuring point. While the M-package as the cooling load has 4 types which by dimension and mass can be distinguished individually shown in Figure 2 and Table 2[14]. The refrigeration system schematic diagram, as well as specification of the tested household refrigerator and M-package are as follows:

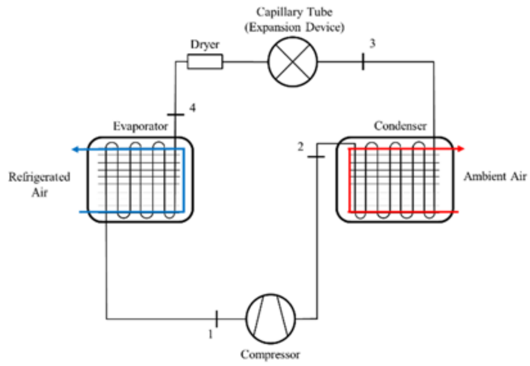


Fig. 1: Schematic diagram of the refrigeration system with the measurement location.

Specifications	Value
Freezer cabin net volume	56 Liter
Fresh food cabin volume	121 Liter
Vegetable compartment volume	28 Liter
Number of doors	2
Voltage	220 V ~50 Hz
Rated current	1.2 A
Refrigerant Type	R-600a, 48 g
Defrost	Auto defrost
Climate class	Tropical

Table 1: Specifications of household refrigerator.

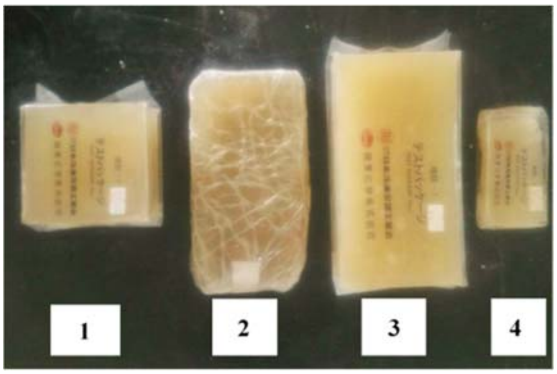


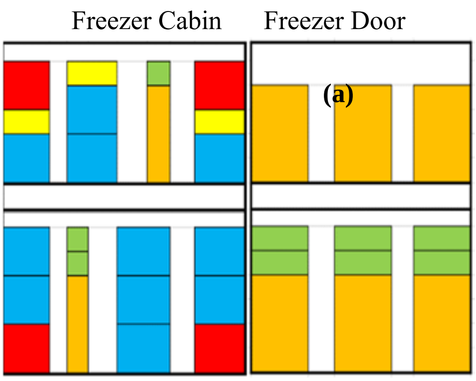
Fig. 2: The four types of M-Packages used.

Type	Dimensions (cm)	Mass (kg)	Color Identification
1	10 (L) x 10 (W) x 5 (H)	0.500	
2	20 (L) x 10 (W) x 2.5 (H)	0.500	
3	20 (L) x 10 (W) x 5 (H)	1.000	
4	10 (L) x 5 (W) x 2.5 (H)	0.125	

Table 2: M-package Specification.

3.2. Variation of Variable

The variation of M-package arrangement is expected to give different result considering the different of air flow inside the freezer cabin. 3 variations are used in this paper as shown in Figure 3. Purple rectangle indicates an arranged backwards of 2 pieces of type 4, while red rectangle indicates an arranged backwards of 2 pieces type of 1. The first variation is obtained from X Test Laboratory for manufacturing purpose. The second and third variation has specially undergone CFD Modelling trial showing possibility of higher exergy efficiency. All of them share the same of total weight as cooling load. Notice tangible distinction of M-package arrangement between variation 2 and 3, while slight modification was made for variation 2 from variation 1.



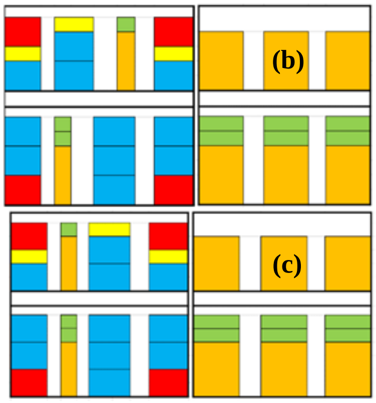


Fig. 3: Variations of M-package arrangement (a) Variation 1 (b) Variation 2 (c) Variation 3.

Equations have shown that mass flow rate plays important role in heat exchanging for this close refrigeration system. Two factors affecting mass flow rate are the compressor power and the refrigerant mass. Since it is more convenient to change the second variable, accordingly mass variation of R600a refrigerant is assigned, consecutively 43-gram, 48-gram, and 53-gram. For this study 5-gram range is set and expected to give apparent difference of the result.

3.3. Taguchi Experimental Design

Taguchi method in experimental design is divided into three sequential stages, they are system design, parameter design, and tolerance design[15)]. It starts with determine the control factor, parameter involved in the study and which we interested to be investigated, which practically divided into several levels shown in Table 3. ANOVA and Orthogonal array are established based on the number of combination shown in Table 4. And lastly signal-to noise (S/N) ratios which is an acceptable range is imposed contingent on the types of loss functions, they are higher is better, nominal is best, and lower is better[16)]. Furthermore, correspond to the objective of finding the least exergy rate for optimum usage of refrigerator work lower is better is chosen, shown in equation 11. Therefore, applying this method throughout the stages will yield the optimum combination with promising reliability.

Factor	Level		
	1	2	3
R600a mass amount (g)	43	48	53
M-package arrangement	Variance 1	Variance 2	Variance 3

Table 3: Selected factors and theirs levels.

Run	R600a mass amount	M-package arrangement	Observed response (total exergy destruction in kW)	
			Attempt 1	Attempt 2
1	1	1	0.09669	0.09998
2	1	2	0.09581	0.09128
3	1	3	0.10410	0.10560
4	2	1	0.14920	0.13320
5	2	2	0.13460	0.15170
6	2	3	0.12950	0.13030
7	3	1	0.17190	0.16150
8	3	2	0.16130	0.15350
9	3	3	0.14940	0.15790

Table 4: Taguchi selected L_9 for total exergy destruction.

Notice that 2 attempts are made to have a better validity of mean value by minimizing the margin of error factor. Whenever another attempt or run is going to be executed, the system is rested until the initial pressure and temperature of the refrigeration system, if it has the same mass amount, have been achieved. Consequently, it can be considered that each conducted experiment undergoes homogenous condition.

4. Setting and Taguchi Method

Data is only acquired exactly after compressor has working and the duration for the acquisition is limited around 30 minutes for every run to have a distinguishable result. The acquired results are then processed and analyzed further by using Minitab 18 software version 18.1. Observation from Figure 4 shows subtle difference within each run that is the first and second attempt. Associating Figure 4 and Figure 5 shows, for the same amount of time, first, second and third run are the optimum condition. Approach by employing Taguchi method is to give a statistical analysis, for it will improve and verify the conclusion.

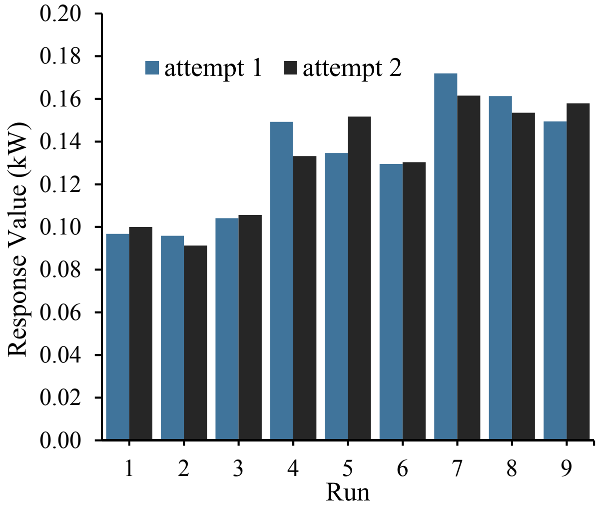


Fig. 4: Variability within and between each run.

4.1. ANOVA Table

It could also be seen from the percent of contribution from Table 5, where the higher the percentage is, therefore, the higher the contribution effect to the efficiency of the system. According to Table 5 R600a mass amount has the highest effect and the most significant, while the M-package arrangement contribute less in the effectiveness of the system. The inconsistency

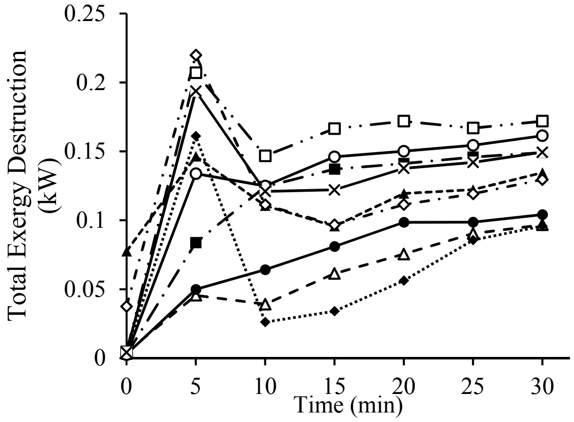


Fig. 5: Total exergy destruction in all run versus time.

of M-Package arrangement to contribute in the system efficiency make it less convincing for optimization of exergy. Run 6 and 9 best the other at their equal mass with significant difference, while run 3, however, yield near identical result. Hence, small value shown either from sum of square or contribution rate is to be expected.

Factor	Degree of freedom (DOF)	Sum of squares (SS)	Mean squares (MS)	F-ratio (F)	Contribution Rate (%)
R600a mass amount (g)	2	27.149	0.005623	52.86	95.8
M-package arrangement	2	0.1622	0.000055	0.32	0.572
Residual Error	4	1.0271	0.000202	-	3.62
Total	8	28.3383	-	-	100

Table 5: Taguchi ANOVA for S/N Ratios.

4.2. Optimum Condition

S/N ratio which compared to its level shown in Figure 6 has a meaning that the larger the differences between control factor the larger the effect on the S/N ratio. Despite the inconsistency of m-package arrangement type, it can be still determined which level is suitable for each factor. Thus, to achieve the most optimum working condition it is more appropriate to employ level 1 for R600a mass amount and level 3 for M-package arrangement type, as shown in Table 6

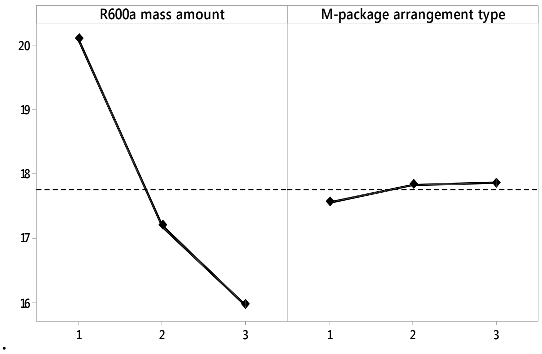


Fig. 6: Factor plot for S/N ratios.

Factor	Optimum Level	Optimum Value
R600a mass amount (g)	1	43
M-package arrangement	3	Variance 3

Table 6: Optimum working condition for the refrigerator.

These clarify the result from Table 4 and previous assumption of the optimum working condition. It can be expected therefore a value of 0.1041 kW for running under the condition. For this condition the exergy destruction and relative irreversibility of the components are plotted and shown consecutively from Figure 7 and Figure 8.

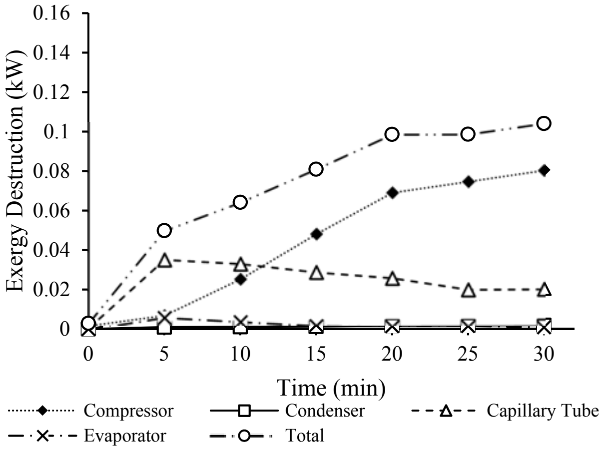


Fig. 7: Exergy destruction of the optimum condition.

In comparison, the manufacturer and reference condition shown in Figure 9 and Figure 10 with 0.1492 kW of exergy destruction rate. Table 7 provides the exergy destruction and relative irreversibility for each component under the optimum working condition. Both conditions have similar characteristics which are exergy destruction in 0 minute is closed to 0 kW because all the components start from equal pressure and temperature, tendency of exergy destruction for capillary tube and evaporator rise in the first 5 minutes and gradually fall to ideal condition for the rest of the time, and compressor exergy destruction rise significantly after the initial 5 minutes as it start to work reaching ideal temperature. RI, the exergy contribution to total exergy destruction, on both conditions also shown similar direction with subtle differences.

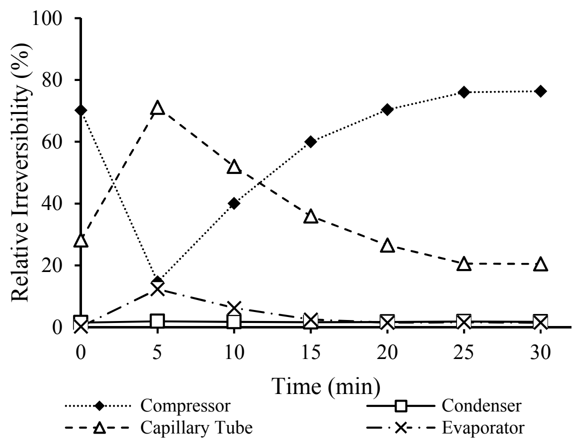


Fig. 8: Relative irreversibility of the optimum condition.

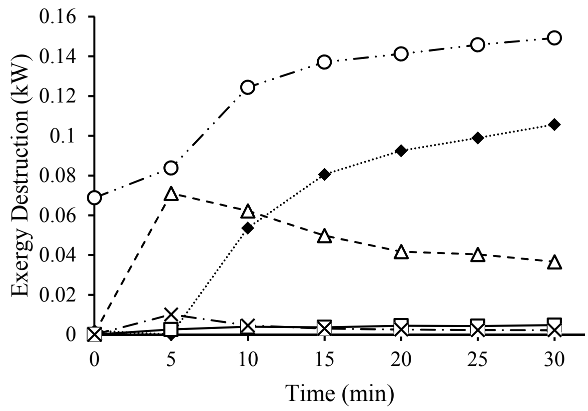


Fig. 9: Exergy destruction of the manufacturer and reference condition.

	Compressor	Condenser	Capillary tube	Evaporator	Total
Exergy destruction (kW)	0.08067	0.001911	0.02061	0.0008818	0.1041
Relative irreversibility (%)	77.52	1.836	19.8	0.8473	100

Table 7: Exergy destruction and RI results at the optimum condition

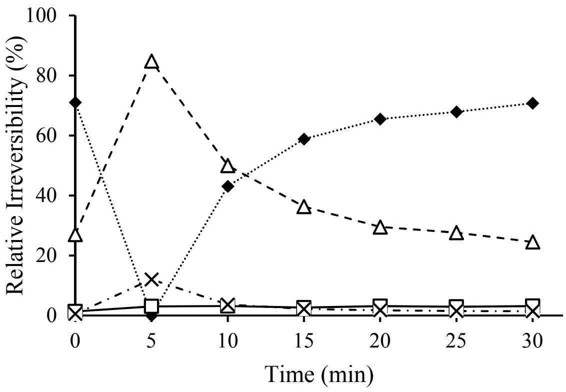


Fig. 10: Relative irreversibility of the manufacturer and reference condition.

5. Conclusion

In this study, an experiment concerning optimum working condition of the household refrigerator based on exergy analysis was conducted. Control factors selection for Taguchi method are R600a mass amount and M-package arrangement type. In conclusion:

- The most optimum mass amount of refrigerant R600a which suitable for the refrigerator's working condition is 43-gram.
- Variation 3 show the most optimum M-Package arrangement type.
- Despite the small value of M-Package arrangement type's contribution rate is low, deeper investigation is necessary to converge simulation and experimental result.
- The combination is highly recommended for household refrigerator and mostly refrigerator testing.

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