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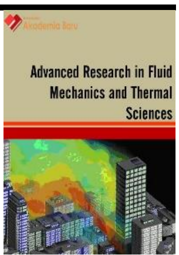
Akademia Baru

Journal of Advanced Research in Fluid
Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Parametric Study and Multi-Objective Optimization of Vapor Compression Heat Pump System by Using Environmental Friendly Refrigerant

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ARTICLE INFO

Article history:
Received 21 August 2018
Received in revised form 25 October 2018
Accepted 1 December 2018
Available online 5 February 2019

Keywords:
Environmental Friendly Refrigerant, Heat Pump, Multi-objective Optimization, Parameter Study

ABSTRACT

This study proposes the parameter study and multi-objective optimization of a vapor compression heat pump system using environmentally friendly refrigerant, R1224yd(Z). The effect of three design parameters including refrigerant mass flow rate, evaporation temperature, and condensation temperature on compressor work, cooling load in the evaporator, heat rejected by the condenser, and exergy of the system are investigated through parameter studies. A multi-objective optimization was then performed. Exergy efficiency and exergoenvironmental value are the objectives of this optimization scenario. The purpose of the optimization is to obtain the optimum value of three design parameters in terms of exergy and environmental point of views so that the heat pump system has maximum exergy efficiency and minimum effect to the environment. The result showed that the system will be in the optimum condition at Te = 287.98 K, Tc= 315.56 K and refrigerant mass flow rate = 0.0321 kg/s with the exergy efficiency of 38.48% and exergoenvironmental value of 200.98 mPts/h.

1. Introduction

Over the past years, the increase in energy consumption is associated with an increase in environmental issues including the hot discussion topics of ozone depletion and global warming [1]-[5]. Recent reports estimate that Asia is responsible for 27% of the world's energy-related emissions and in 2030 it will increase to 40% [6]. In Addition, the use of high ODP and GWP refrigerant, such as R22 has contribute to environmental problem [7].

Scientists have endeavored to tackle these problems. The solutions offered include designing efficient technology and using environmentally friendly energy sources [8] or nanorefrigerants [9]. It

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has been shown that heat pumps can be a solution for energy and environmental problems [4], [10] and [11].

Several earlier studies have conducted research on the heat pump system and have analyzed the energy and exergy balances in the performance of the heat pump system. Bi, Y *et al.,* [12] conducted a comprehensive energy analysis for the heat pump system including energy destruction, energy efficiency, and energy loss ratio. The result indicated that more attention must be paid to a comprehensive energy analysis because it may help engineers to design and optimize heat pump systems [12]. The same analysis has also been discussed in many other papers such as, Energy and Energy Evaluation in Building by Nasruddin [2] Abdullah Yildiz [13], Lohani and Schmidt [14], Amiri L Amiri L *et al.,* [15], and Alhamid [16].

To date, there is still a lack of research that analyses the environment or correlates the exergy or energy analysis to the effect on the environment. Therefore, this paper presents the parameter study of the heat pump system by conducting energy, exergy, and exergoenvironmental analysis. The effect of evaporation temperature, condensation temperature and refrigerant mass flow rate to system performance and to the environment are investigated. Furthermore, this paper also includes multi-objective optimization to identify the optimum operating condition of the heat pump system by using the latest environmental friendly refrigerant, R1224yd. The reason for selecting R1224yd as the working fluid is because of its low GWP value and zero ODP [17]. Furthermore, R1224yd is a non-flammable refrigerant [17,18]. In addition, this refrigerant has never yet been studied for its effect on a heat pump system, thus it is a unique work.

2. Methodology

2.1 Working Fluid Properties

Selecting the working fluid for heat pump systems takes into account some criteria such as thermo-physical properties, safety issues (toxicity and flammability) and environmental factors [19]. Thermo-physical properties such as critical temperature and pressure, as well as the important aspects of environmental factors, Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) are described in Table 1.

Table 1
Properties of discussed refrigerants
Source: [20, 21]

Parameter	R1224yd
Critical Temp (°C)	156
Critical Pressure (MPa)	3.33
GWP	<1
Safety Group	A1
Glide Temperature (°C)	0

According to the research by [17] R1224yd has a high critical temperature, it is non-flammable, non-toxic, suitable for heat pump systems and is expected to be a substitute for high GWP refrigerant such as R245fa and R123 [17].

2.2 Cycle Description

A heat pump is a device that conveys heat from low-temperature region to a higher temperature region [22]. The vapor compression air to air heat pump is widely used nowadays for air conditioning and heating, producing hot water and as a preheater [21, 23]. In this work, an air conditioning heat pump is discussed with cooling load is about 4 kW. The configuration of the system is illustrated in Figure 1.

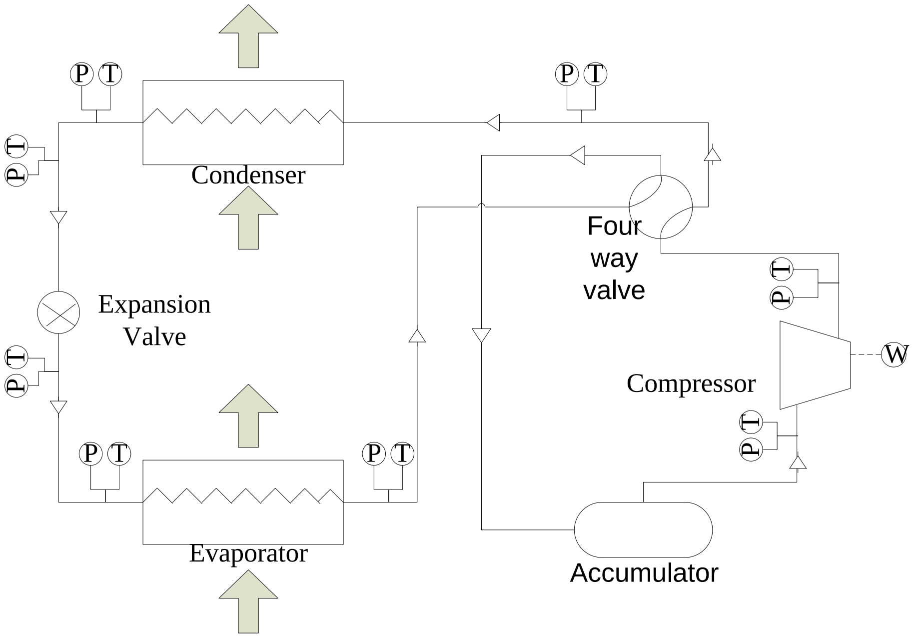

Fig. 1. Heat pump system configuration

A heat pump system configuration is shown in Figure 1. The system consists of Four main components, including a compressor, condenser, expansion valve and evaporator. The work is done by the refrigerant. The refrigerant that is used is R1224yd which discussed in the previous section. The refrigerant enters the evaporator and absorbs heat from ambient air. Then, compressed in a compressor, the temperature and pressure of the refrigerant increase and move into the superheated phase. After that, the refrigerant enters the condenser and releases the heat. Finally, the refrigerant expands in the expansion valve and flows through the evaporator again as a closed cycle.

2.3 Thermodynamic Modeling

The following assumptions are made during thermodynamic modeling of the heat pump system.

i. The system is in a steady stable condition.
ii. The pressure and heat loss in the pipelines of the system are not considered in the calculation.
iii. Saturated refrigerant occurs at the outlet of the evaporator and condenser.
iv. The kinetic and potential energies are negligible.

Once all components of the cycles have been determined, the simulations were performed by using software MATLAB 2017b which also integrated with REFPROP ver 10.0.

2.3.1 Energy and exergy analysis

The mass, energy and exergy balances for each component of the heat pump system are determined as [22]

For compressor,

$$\mathrm{m_1} = \mathrm{m_2} \tag{1}$$

$$\mathrm{W}_{comp} = \mathrm{m}_{ref}(\mathrm{h_2} - \mathrm{h_1}) \tag{2}$$

$$\mathrm{Ex}_{D,comp} = \mathrm{m}_{ref}(\mathrm{ex_2} - \mathrm{ex_1}) + \mathrm{W}_{comp} \tag{3}$$

For condenser,

$$\mathrm{m_2} = \mathrm{m_3} \tag{4}$$

$$\mathrm{Q}_{cond} = \mathrm{m}_{ref}(\mathrm{h_3} - \mathrm{h_2}) \tag{5}$$

$$\mathrm{Ex}_{D,cond} = \mathrm{m}_{ref}(\mathrm{ex_2} - \mathrm{ex_1}) - \mathrm{Ex}_{Q} \tag{6}$$

Expansion Valve,

$$\mathrm{m_3} = \mathrm{m_4} \tag{7}$$

$$\mathrm{h_3} = \mathrm{h_4} \tag{8}$$

$$\mathrm{Ex}_{D,exvalve} = \mathrm{m}_{ref}(\mathrm{ex_3} - \mathrm{ex_4}) \tag{9}$$

Evaporator,

$$\mathrm{m_4} = \mathrm{m_1} \tag{10}$$

$$\mathrm{Q}_{evap} = \mathrm{m}_{ref}(\mathrm{h_4} - \mathrm{h_1}) \tag{11}$$

$$\mathrm{Ex}_{D,evap} = \mathrm{m}_{ref}(\mathrm{ex_4} - \mathrm{ex_1}) + \mathrm{Q}_{cond}(1 - \frac{\mathrm{T_0}}{\mathrm{T}_L}) \tag{12}$$

Finally, the exergy destruction and efficiency are evaluated as

$$Ex_{D;tot} = Ex_{D,evap} + Ex_{D,comp} + Ex_{D,cond} + Ex_{D,exvalve} \tag{13}$$

$$Ex_{in} = W_{co} \tag{14}$$

$$Ex_{eff} = 1 - \frac{Ex_{D;tot}}{Ex_{in}} \tag{15}$$

2.3.2 Exergoenvironmental analysis

The exergo-environmental analysis is one of the most appropriate methods for evaluating the energy conversion process of a system based on environmental aspects [24]. The exergo-environmental analysis consists of exergy analysis and life cycle assessment (LCA) [25]. Exergy analysis is useful for evaluating the performance of a system as well as determining inefficiency in thermodynamic processes that may occur in the system [25]. Exergy is closely related to the system and environment, so it can be said that exergy loss will have an impact on the environment. LCA is a way to evaluate the environmental impact of the system directly [26]. By using this combination analysis, the environmental impacts obtained from analysis and LCA calculations will be correlated with the exergy flow analysis of the system. This exergy flow will show which components in the system contribute most environmental damage, so system optimization can be undertaken to reduce the impact of damage to the environment.

In the evaluation of the environmental performance of each component of the system used exergo-environmental variables. One is the comparison of the environmental impact associated with exergy destruction on each component and can be calculated by the equation

$$\dot{B}_{D,k} = b_{F,k}\dot{E}_{D,k} \tag{16}$$

Where $B_{D,k,}$ and $E_{D,k}$ is the ratio of environmental effects to the amount of exergy associated with exergy destruction. To identify the most important components of environmental impacts, the total environmental impact of Btot, k can be obtained by the equation

$$\dot{B}_{tot,k} = \dot{B}_{D,k} + \dot{Y}_k \tag{17}$$

Yk is an environmental impact related to the life cycle of each component, consisting of the construction process (production, transportation, and installation), operation Yk^{CO} and maintenance Yk^{OM} and disposal and unloading Yk^{DI} as indicated by the equation

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{18}$$

2.4 Multi-objective Optimization Genetic Algorithm (MOGA)

Multi-objective Genetic Algorithms (MOGA) is a type of optimization commonly used nowadays. It is a simple extension of a single objective GA and helps the user to solve two or more objective optimization problems [27]. In the real engineering problems, the objectives are generally conflicting such as when the performance of the system is at its maximum value, the cost needed will also be maximum and vice versa. By using MOGA, engineers can gain the optimum condition both in performance and from an economic aspect [27-28]. The problem of multi-objective optimization can be expressed as follows

$$\text{Min/max } F(x) = \{f_1(x), f_2(x), \ldots\ldots, f_k(x)\} \tag{19}$$

$$G(x) \leq 0\ ;\ h(x) = 0 \tag{20}$$

$$x_l < x < x_u \tag{21}$$

In optimization procedure, it is necessary to limit the constraints ($x_l < x < x_u$) written in each objective function. The limits are entered in the "bounds" column in the "optimtool" toolbox which is listed in Table 2.

Table 2
Constraints in Optimization Procedure

Parameter	Unit	From	To
Evaporation Temperature	K	278	288
Condensation Temperature	K	313	323
Refrigerant Mass Flow Rate	Kg/s	0.03	0.1

3. Results

3.1 Parameter Study and Performance Evaluation of Heat Pump

3.1.1 Effect of varying refrigerant mass flow rate

Figure 2 illustrated the effect of varying the refrigerant mass flow rate on compressor work. It revealed that an increase in refrigerant mass flow rate increases the compressor work. When the refrigerant mass flow rate fluctuates from 0.025 kg/s to 0.035 kg/s, the compressor work increases from 700 Watt to 1000 Watt. This occurs due to the increasing the refrigerant mass flow rate results in more refrigerant needs to be compressed, and it affected the energy to drive the compressor to become higher.

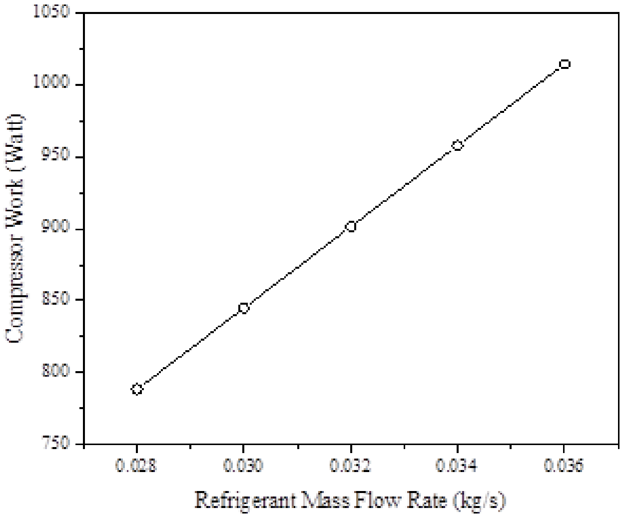

Fig. 2. Effect of varying refrigerant mass flow rate on compressor work

The effect refrigerant mass flow rate on cooling load and condenser load is also discussed and presents in Figure 3. As the refrigerant mass flow rate increases, both evaporator cooling load and the condenser load also increase. This phenomenon occurred because the increase of compressed refrigerant entering the condenser makes the ability of the condenser to reject heat increases, so the cooling load becomes higher. And it also happened on the evaporator side.

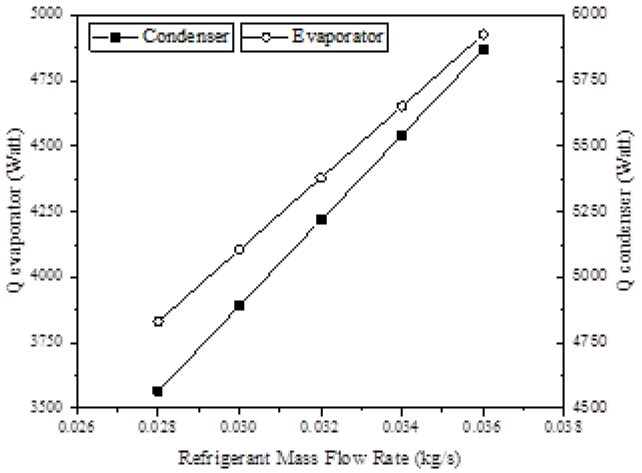

Fig. 3. Comparison Q evaporator and Q condenser at various refrigerant mass flow rate

3.1.2 *Effect of varying evaporation temperature*

Figure 4 shows the effect of evaporating temperature on COP heat pump, the cooling load and work of the compressor at a condensing temperature of 42°C. It can be seen that increasing the evaporating temperature affected an increase at the outlet specific enthalpy of the evaporator which results in an increase in cooling load. The compressor work decreases from 1050 Watt to 650 Watt as the evaporating temperature increases from 278 K to 288 K and it implies in the suction temperature of the compressor, which also increases. When the suction temperature becomes high, the vaporizing pressure is also high and it results in the decreasing of pressure ratio and in the end, the work of compressor decreases. As the compressor work decreases and the cooling load increases, the COP of the heat pump becomes higher.

The parametric study results showed that the evaporation temperature has a positive effect on both parameter performances, namely, COP and exergy efficiency. As the evaporation temperature increased from 281 K to 289 K, the performance of the system also increased; COP increased from 4.2 to 6.7 and exergy efficiency from 0.22 to 0.29 as illustrated in Figures 4, 5 and 6. This is due to the fact that when evaporation temperature increases, the cooling capacity increases, while when compressor work decreases it leads to an increase in COP and exergy efficiency.

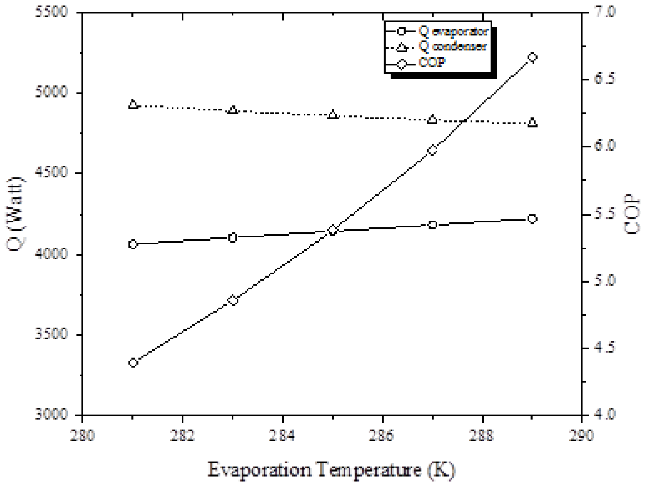

Fig. 4. Comparison of cop and q evaporator at various evaporation temperature

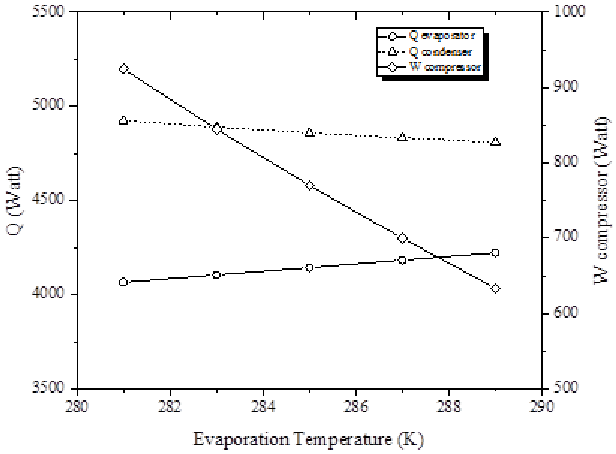

Fig. 5. Comparison of compressor work and q evaporator at various evaporation temperatures

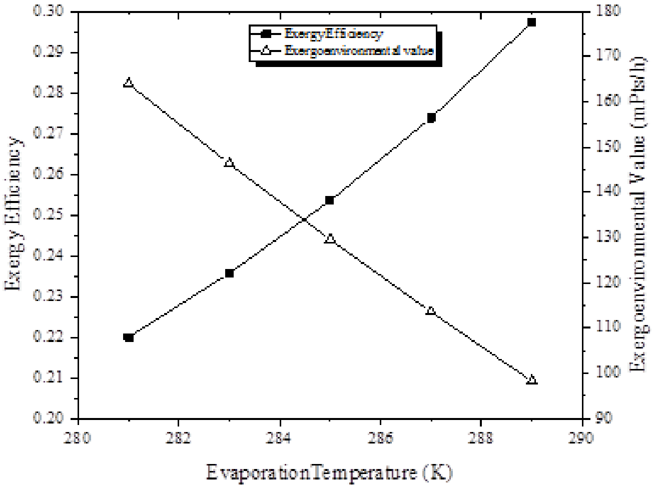

Fig. 6. Effect of varying evaporation temperature on exergy efficiency and exergoenvironmental value

3.1.3 Effect of varying condensation temperature

Another important parameter to be investigated is the condensation temperature. The effect of increasing the condensation temperature on the performance of the system can be seen in Figures 7, 8 and 9.

Figure 7 shows the effect of condensing temperature on COP, the cooling load and compressor work at a constant evaporating temperature of 283 K. It can be observed that an increase in condensing temperature from 313 K to 323 K leads to an increase in compressor work from 775 Watt to 1100 Watt. When the compressor work increases, the COP of the heat pump decreases from 5.2 to 3.2. While from Figure 9, it can be observed that an increase in condensation temperature increased the work of the compressor and decreased the condenser load. This is because increases of condensation temperature from 313 K to 321 K resulted in an increase of energy content of the stream leaving the condenser and entering the evaporator. When the stream temperature increases for a constant input temperature to the condenser, heat rejection decreases.

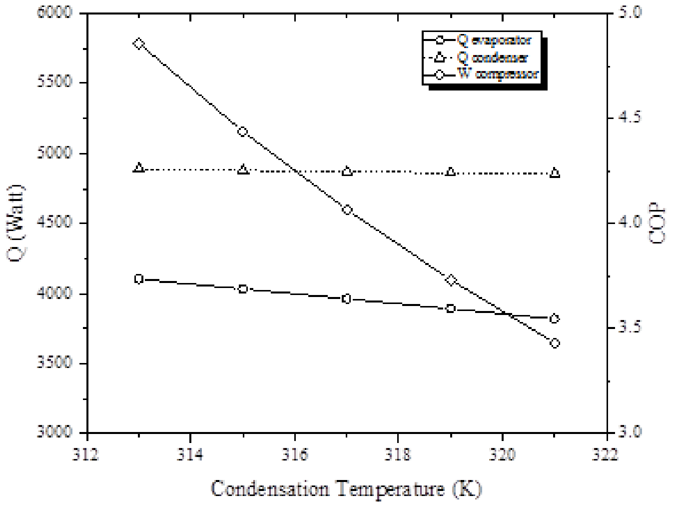

Fig. 7. Comparison of compressor work, q evaporator and q condenser in various condensation temperature

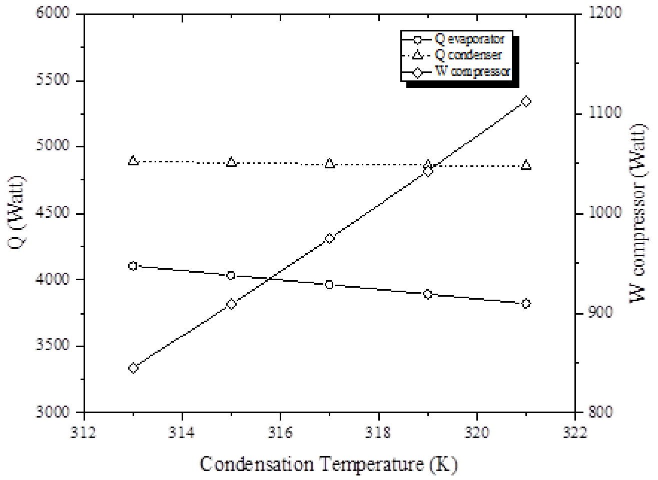

Fig. 8. Effect of Varying Condensation Temperature on Q and Work of Compressor

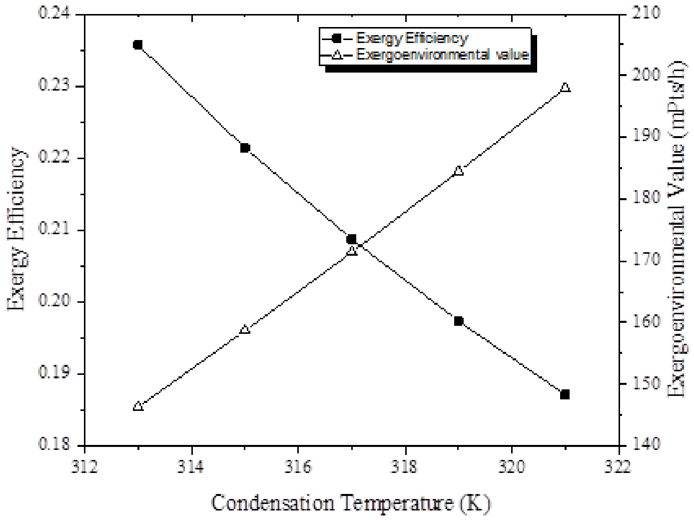

Fig. 9. Effect of Varying Condensation Temperature on Exergy Efficiency and Exergoenvironmental Value

3.2 Optimization Result

After conducting parameter studies, to identify the effect of three parameters including refrigerant mass flow rate, evaporation temperature and condensation temperature to the performance of the system, it is known that three design parameters have the different effect on performance parameter, so that optimization scenario will be beneficial. Multi-objective optimization produces optimum results for several objective functions. The results obtained through multi-objective optimization offer several optimum solutions in range form. These solutions are known as Pareto-optimal solutions or Pareto frontier as illustrated in Fig 10.

Figure 10 shows the correlation between exergy efficiency and exergo-environmental value of the system, it represents Pareto Front Optimal as the multi-objective optimization result. Exergy efficiency represents the performance of the system while exergo-environmental value expresses the effect of the system on the environment. From Fig 10, it can be seen that there are 3 points namely A, B and C. Point A is the optimum point in terms of exergy efficiency, while point C is the optimum point in the exergo-environmental point of view and point B is the optimum point both in exergy efficiency and exergo-environmental point of view. Table 3 listed the operating condition on each point.

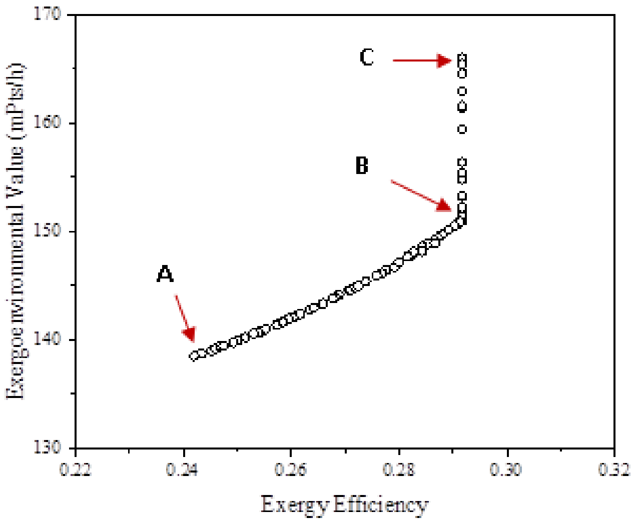

Fig. 10. Pareto Front Optimal Multi-objective Optimization Result

Table 3
Optimization Result

Parameter	Exergy Eff, (C)	Optimum, (B)	Exergoenv, (A)
Tevap (K)	288	287.98	287.97
Tcond (K)	323	315.56	313.90
mref (kg/s)	0.0341	0.0321	0.0320
Exergy Eff	0.4068	0.3848	0.3752
Exergoenv (mPts/h)	268.2151	200.9875	190.6816

The variables distribution for the optimal solution on the Pareto optimization result is shown in Figure 11-13. It can be deduced that condensation temperature and refrigerant mass flow rate distributed all over its domain, while the evaporation temperature selected its maximum level.

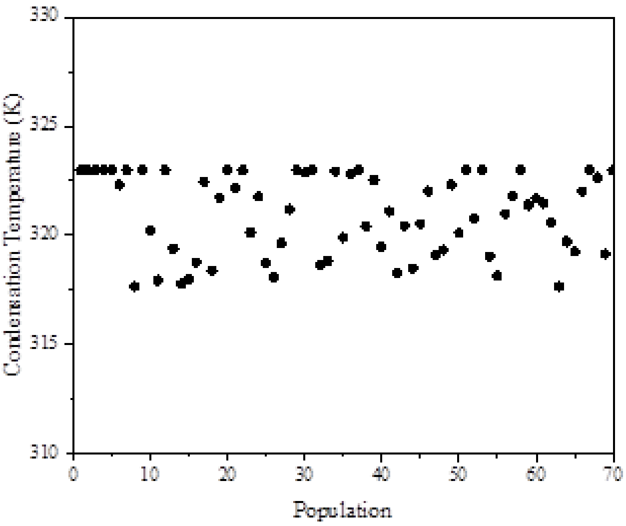

Fig. 11. Optimum values distribution of condensation temperature

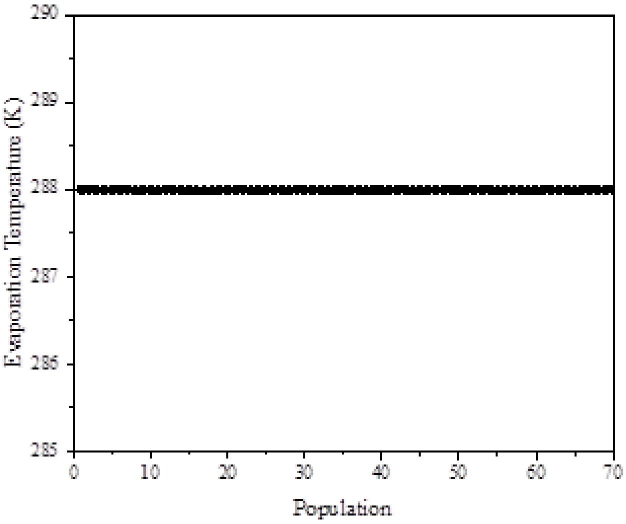

Fig. 12. Optimum values distribution of evaporation temperature

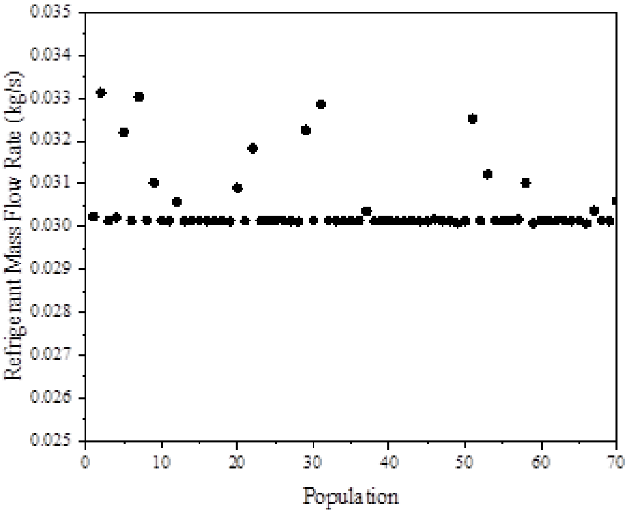

Fig. 13. Optimum values distribution of refrigerant mass flow rate in pareto optimization result

Since the optimum values of condensation temperature and refrigerant mass flow rate have scattered distribution in their lower and upper bound values, it can be predicted that both condensation temperature and refrigerant mass flow rate have important effects on both objective functions, exergy efficiency, and exergo-environmental value.

4. Conclusions

The parameter study and multi-objective optimization of heat pump system using R1224yd as the latest environmental friendly refrigerant has been discussed in this paper. The aim of this research is the first to identify the effect of the operating parameters such as evaporation and condensation temperature and refrigerant mass flow rate on the performance of the system and the second is to determine the optimum operating conditions. The results showed that three design parameters have the different effect on performance parameter and the optimization scenario is the best way to predict the optimum condition of design parameters. Optimization result showed that the system will be in the optimum condition at Te = 287.98 K, Tc= 315.56 K and refrigerant mass flow rate = 0.0321 kg/s with the exergy efficiency of 38.48% and exergoenvironmental value of 200.98 mPts/h.

Acknowledgment

This research was funded by a grant from Ministry of Higher Education of Indonesia with the Master Program to Doctorate for Scholar Excellent (PMDSU) Grant 561/UN2.R3.1/HKP05.00/2018, including Scheme for Academic Mobility and Exchange (SAME) with contract number 3557 / D3 / PG / 2017 and The Authors also gratefully acknowledge Prof Kiyoshi Saito and Saito Lab members in Waseda University, Japan, for introducing new environmental friendly refrigerant.

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