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THERMODYNAMIC AND ENVIRONMENTAL ANALYSIS OF A HIGH-TEMPERATURE HEAT PUMP USING HCFO-1224YD(Z) AND HCFO-1233ZD(E)

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ABSTRACT

This paper investigates the use of two low global warming potential working fluids, HCFO-1224yd(Z) and HCFO-1233zd(E), in high-temperature heat pump systems. A simulation was performed at evaporating temperatures ranging from 50–70°C and a condensing temperature of 110°C. A solar thermal collector was used to supply the energy needs on the evaporator side. Energy, exergy, and environmental analyses were performed to evaluate both environmentally friendly refrigerants and compare them to HFC-245fa. The coefficient of performance (COP) and total exergy destruction represented the performance of the system, while the total equivalent warming impact was used to evaluate the environmental effect of each refrigerant. At an evaporation temperature of 50°C, HCFO-1224yd(Z) and HCFO-1233zd(E) showed comparable performance to R245fa, with COP values of about 2.74 and 2.69, respectively (R245fa had a COP value of about 2.66). The same results were also obtained at evaporation temperatures of 60°C and 70°C, at which R1224yd showed good performance compared to R1233zd and R245fa with COP values of 3.6 for 50$^{\mathrm{o}}$C evaporation temperature and 4.75 for 70$^{\mathrm{o}}$C evaporation temperature. Additionally, both suggested refrigerants had low direct emission compared to R245fa based on the results from the environmental analysis.

Keywords: COP; Energy; Exergy; Heat pump; Low global warming potential; Total equivalent warming impact

1. INTRODUCTION

The world demand for energy is constantly increasing (Yabase et al., 2016), and according to the Ministry of Indonesia, fossil energy is still the primary energy consumed, with a growth rate of 7% per year (Fuadi et al., 2019). The need for cooling and air conditioning systems also continues to increase (Beshr et al., 2016); based on research studies, 40% of the total energy used comes from HVAC systems (Omer, 2008). These systems have a negative impact on the environment, as refrigerants used in the system usually contain hydrochlorofluorocarbon (HCFC) and chlorofluorocarbon (CFC; Djubaedah et al., 2018), both of which cause global warming and can damage the ozone layer (Fukuda et al., 2014). The UNEP Ozone Secretariat banned the use of CFCs and HCFCs as refrigerants because of this damage to the ozone layer and recommended hydrofluorocarbon (HFC) refrigerants instead. However, research has shown that HFC refrigerants have a high global warming potential, so the Kyoto Protocol regulations were issued to prohibit the use of HFC refrigerants (Beshr et al., 2016).

As seen above, energy and the environment are interrelated, so environmental aspects must be

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considered when meeting energy needs (Nasruddin et al., 2019). One technology that could solve energy and environmental problems is the heat pump system. Based on data from the IEA Heat Pump Center, about 6% of the world's CO_2 emissions could be reduced using heat pump technology (Curtis et al., 2005). Using heat pump technology with a high coefficient of performance (COP) value could reduce the energy used by a system while decreasing CO_2, NO_x, and SO_x emissions in the air (Omer, 2008). However, research on the heat pump system is still developing. The challenge for this research is making a system as efficient as possible while impacting the environment as little as possible (Nasruddin et al., 2017).

The used of low global warming potential (GWP) refrigerant could be an option to minimize the effect of the system on the environment (Nasruddin et al., 2017; Aisyah et al., 2018; Aisyah et al., 2019). Mastrullo et al. (2016) conducted a simple model for the thermal cabin system to compare the energy consumption and total equivalent warming impact (TEWI) value of R134a to the new environmentally friendly refrigerants R1234yf and R1234ze. The results showed that the R1234ze refrigerant has a smaller impact on the environment than R1234yf and is the best alternative refrigerant for R134a (Mastrullo et al., 2016). Aisyah et al. (2019) evaluated the use of low GWP refrigerants, including R1234ze and R1234yf, in a vapor compression heat pump system. The results showed that both refrigerants have a comparable performance to R410a (Aisyah et al., 2018). Beshr et al. (2016) investigated the potential of two low GWP refrigerants, N-40 and L-41a, as alternatives to R410A. Using the Life Cycle Cost Plan (LCCP) method, they found that both refrigerants have low environmental impact values and are environmentally friendly refrigerants suitable for replacing R410A (Beshr et al., 2016).

This study performed an evaluation of the use of R1224yd and R1233zd in a high-temperature heat pump system. Both refrigerants were considered to meet all aspects required for the next generation of refrigerant. R1224yd refrigerants have been referred as one of the candidates to replace current refrigerants with high GWP values (Watanabe et al., 2017). However, very few studies have introduced the use of R1224yd and R1233zd as working fluids in refrigeration systems. Thus, examining this refrigerant for the heat pump system was the novelty of this study. In this study, the heat pump system was modeled using MATLAB 2017a software and REFPROP ver. 10. Energy, exergy, and environmental analyses were carried out to determine the feasibility of both refrigerants to replace R245fa in a high-temperature heat pump system.

2. SYSTEM DESCRIPTION AND MODELING

2.1. Description of the High-temperature Heat Pump System

Molés et al. (2014) identified several criteria for selecting the working fluid in heat pump systems: thermo-physical properties, critical temperature and pressure, and the important environmental aspects of ozone depletion potential (ODP) and GWP. Table 1 and Figure 1 describe some refrigerants discussed in this study.

A schematic diagram of the high-temperature heat pump system discussed in this paper is demonstrated in Figure 1. The system consisted of a solar thermal collector and heat pump system. The solar collector helped the heat pump system absorb energy from the sun to raise the temperature of the refrigerant in the evaporator. The heat pump system consisted of an evaporator, two compressors, a high-temperature compressor and low-temperature compressor, a condenser, and two expansion valves. The evaporator absorbed heat from the solar thermal collector at the evaporating temperature T_E. The condenser delivered heat to raise the temperature of the water up to 105°C at condensing temperature T_C. The heat rejected from the condenser was equal to the sum of the heat absorbed by the evaporator and the heat issued by the two compressors. HCFO-1224yd and HCFO-1233zd were used as working fluids in this system. The reason for using these refrigerants is presented in the next section

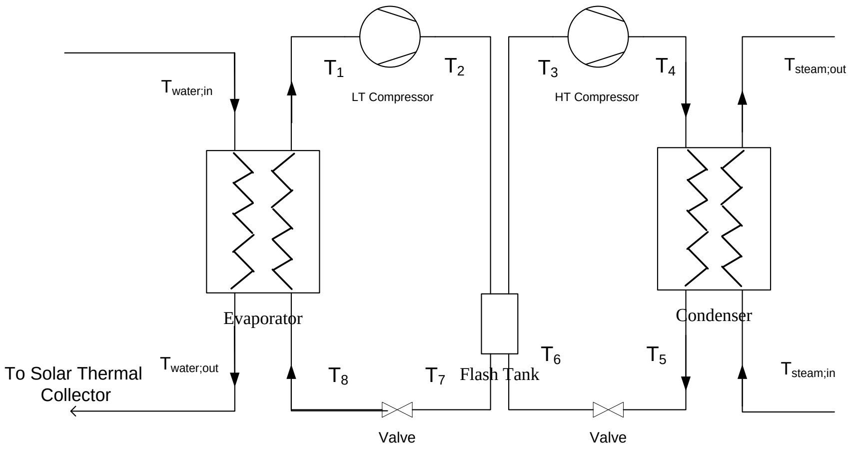

Figure 1 High-temperature heat pump diagram

2.2. Working Fluids Properties

Some criteria were considered when selecting the working fluid for the high-temperature heat pump. They included thermo-physical properties, such as critical temperature and pressure, environmental aspect, GWP, and ODP, as well as the safety aspects of refrigerant such as flammability and toxicity. Table 1 provides information about the discussed working fluids.

Table 1 Properties of discussed refrigerants

Parameter	R1233zd	R1224yd	R245fa
Critical temp (°C)	165.6	156	154
Critical pressure (MPa)	3.57	3.33	3.65
GWP	1	<1	1030
Safety group	A1	A1	B1
ODP	0.00034	0	0

Sources: Watanabe et al., 2017; Yang et al., 2018; Higashi, 2016

According to the research by Fukushima et al. (2016), R1224yd has a high critical temperature and is non-flammable, non-toxic, and suitable for heat pump systems. Furthermore, it is expected to be a substitute for high GWP refrigerants, such as R245fa and R123 (Fukushima et al., 2016).

2.3. Modeling of the System

Thermal modeling included mass, energy, and exergy balance for all components of the solar-assisted heat pump with the following assumptions:

1. The system operates under a steady-state condition.
2. The pressure and heat loss in the pipelines of the system are neglected.
3. Saturated refrigerant occurs at the exit of the evaporator and condenser.
4. The process in the expansion valves is isenthalpic.
5. The kinetic and potential energies are not considered for exergy analysis.

The set of equations shown in Table 2 was applied for the heat pump modeling (Dincer & Rosen, 2012).

Table 2 Energy and exergy balance

Component	Energy	Exergy destruction
Evaporator/	$Q_{evap} = m_{ref;LT} (h_1 – h_8)$	$Ex_{D;evap} = [m_{ref;LT} (Ex_8 - Ex_1)] + [m_w(Ex_{win} - Ex_{w;out})]$
Compressor		
LT	$W_{LT;c} = m_{ref;LT} (h_2 – h_1)$	$Ex_{D;LTc} = [m_{ref;LT} (Ex_1 - Ex_2)] + [W_{LT;c})]$
HT	$W_{HT;c} = m_{ref;HT} (h_4 – h_3)$	$Ex_{D;HTc} = [m_{ref;HT} (Ex_3 - Ex_4)] + [W_{HT;c}]$
Condenser	$Q_{cond} = m_{ref;HT} (h_4 – h_5)$	$Ex_{D;cond} = [m_{ref;HT} (Ex_4 - Ex_5)] + [1- T_w/T_e]$
Ex.Valve		
LT	$h_5 = h_6$	$Ex_{D;LTv} = [m_{ref;LT} (Ex_5 - Ex_6)]$
HT	$h_7 = h_8$	$Ex_{D;HTv} = [m_{ref;HT} (Ex_7 - Ex_8)]$

Finally, the exergy destruction and efficiency were evaluated as follows:

$$Ex_{D;tot} = Ex_{D,evap} + Ex_{D,comp} + Ex_{D,cond} + Ex_{D,exvalve} \tag{1}$$

$$Ex_{in} = W_{co} \tag{2}$$

$$Ex_{eff} = 1 - \frac{Ex_{D;tot}}{Ex_{in}} \tag{3}$$

2.4. Total Equivalent Warming Impact Analysis

After determining which refrigerants to use, an analysis of the environmental aspects, namely TEWI, was performed. The TEWI in this study was determined as follows (Islam et al., 2017):

$$\begin{aligned} TEWI &= \text{direct emissions} + \text{indirect emissions} \\ &= (GWP \times L \times N) + (Ea \times \beta \times n) \end{aligned} \tag{4}$$

where TEWI is the total equivalent warming impact, L is the leakage rate in kg (estimated 3% of charge), N is the system life span (years), Ea is the energy consumption (KWh/year), β is the CO_2 emission factor (0.483 kg CO_2/kWh), and n is the system running time in one year.

3. RESULTS AND DISCUSSION

3.1. Performance Analysis

The performance of the system was evaluated by compressor work, COP, and total exergy destruction. Figure 2 shows the effect of evaporation temperature on the compressor work for each refrigerant, including the low GWP refrigerants R1224yd and R1233zd.

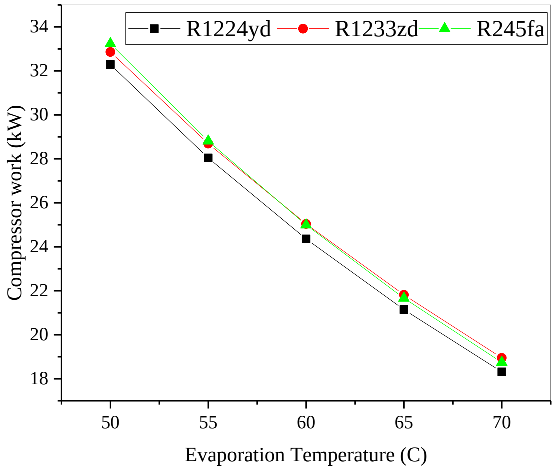

Figure 2 The effect of evaporation temperature on the compressor work

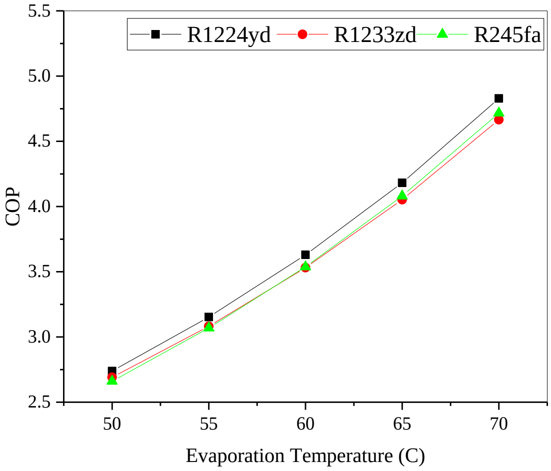

Figure 3 The effect of evaporation temperature on COP

Compared to R245fa, R1224yd showed lower compressor work. At the evaporation temperature of 50°C, R1224yd had compressor work of 32.3 kW, R1233zd had compressor work of 32.8 kW, and R245fa had compressor work of 33.2 kW. At the evaporation temperature of 70°C, R1224yd, R1233zd, and R245fa had compressor work of 18 kW, 19.5 kW, and 19 kW, respectively.

Figure 3 presents the COP of the system while evaporation temperature increased. R1224yd had the highest COP value when compared to R1233zd and R245fa. At an evaporation temperature of 50°C, the COP value of R1224yd was about 2.74 while R1233zd and R245fa had COP values of 2.69 and 2.66, respectively. At the evaporation temperature of 70°C, R1224yd had a COP value of 4.75, while R1233zd and R245fa had COP values of 4.5 and 4.6, respectively.

The total exergy destruction on each component of the system is presented in Figure 4. As seen in the figure, increasing evaporation temperature caused a decrease of total exergy destruction. When exergy destruction decreased, exergy efficiency increased.

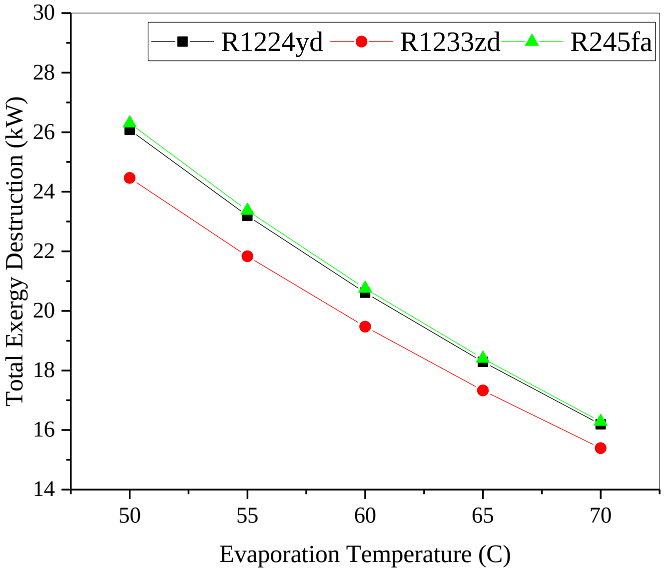

Figure 4 The effect of evaporation temperature on total exergy destruction

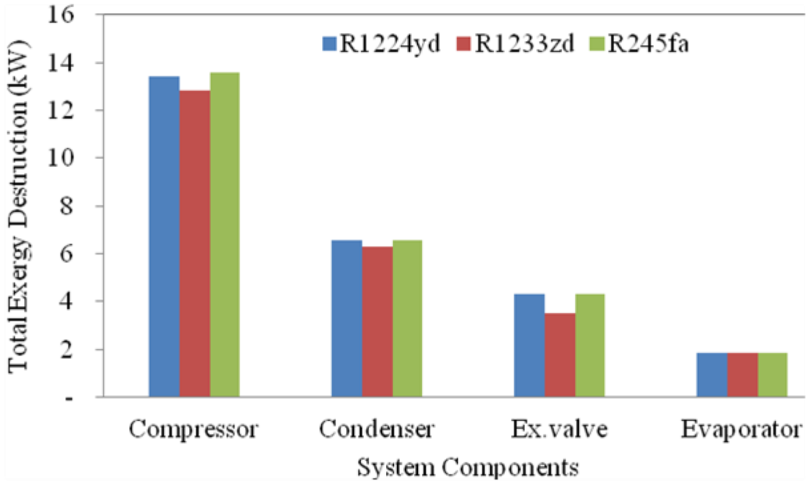

Figure 5 Exergy destruction on each component of the system at 50°C evaporation temperature

The compressor was most responsible for the high total exergy destruction, followed by the condenser, expansion valve, and evaporator (Figure 5). At an evaporation temperature of 50°C, the total exergy destruction for R1224yd was about 13.8 kW, while the condenser, expansion valve, and evaporator had total energy destructions of 6.0 kW, 4.3 kW, and 2 kW, respectively.

3.2. Total Equivalent Warming Impact Analysis

To evaluate the environmental impact of both alternative refrigerants, TEWI analysis was performed. TEWI analysis provided the value of equivalent CO_2 emissions from both the energy consumption of the system (indirect emission) and the refrigerant leakage (direct emission). This method of analysis is considered one of the best for real environmental impact approximation of vapor compression systems (Makhnatch & Khodabandeh, 2014; Juhasz & Simoni, 2015).

Based on the TEWI analysis of each refrigerant at different evaporation temperatures, the amount of ton equivalent CO_2 decreased as the evaporation temperature increased (Figure 6). R1224yd had the lowest TEWI value when compared to R1233zd and R245fa. At an evaporation temperature of 50°C, R1224yd had an indirect emission of 79.58 ton CO_2 eq, while R1233zd and R245fa had indirection emissions of 80.96 ton CO_2 eq and 81.88 ton CO_2 eq, respectively. For direct emissions, both alternative refrigerants had nearly the same amount: 0.2 ton CO_2 eq. R245fa had direct emissions of 206 ton CO_2 eq.

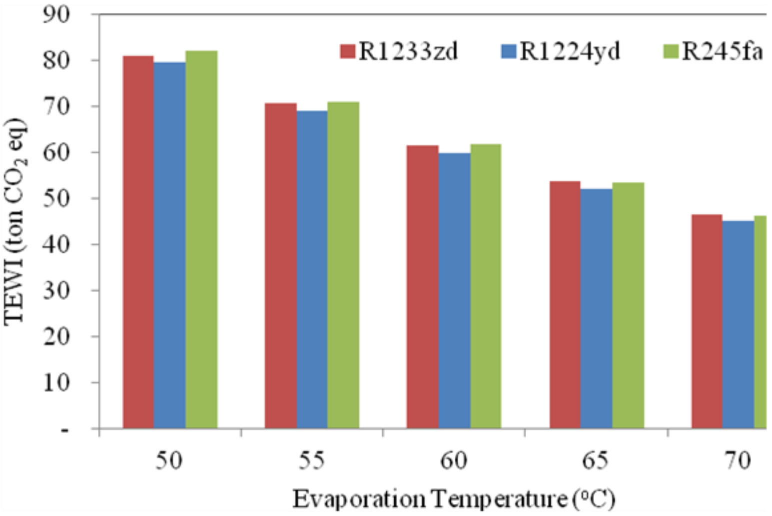

Figure 6 The effect of evaporation temperature on TEWI analysis

Based on the results of the analysis, the two alternative refrigerants, R1224yd and R1233zd, could significantly reduce the amount of CO_2 indirect emissions compared to the existing refrigerant, R245fa. Therefore, using these alternative refrigerants can be considered as one way to protect the environment.

4. CONCLUSION

This study modeled a solar-assisted heat pump system to recover waste heat. Two alternative refrigerants, R1224yd and R1233zd, were evaluated through energy, exergy, and environmental analysis. The results showed that both alternative refrigerants performed comparably to R245fa in terms of COP and total exergy destruction. At an evaporation temperature of 50°C, R1224yd and R1233zd showed comparable performance to R245fa, with COP values of about 2.74 and 2.69, respectively (R245fa had a COP of about 2.66). The same results were also obtained at evaporation temperatures of 60°C and 70°C; R1224yd showed better performance compared to R1233zd and R245fa with COP values of 3.6 for 50^{o}C evaporation temperature and 4.75 for 70^{o}C evaporation temperature. An environmental analysis was also performed. Based on the TEWI analysis, both R1224yd and R1233zd had lower CO_2 emission compared to R245fa. Therefore, from both a performance and environmental perspective, R1224yd and R1233zd could substitute for R245fa as working fluids for heat pump systems.

5. ACKNOWLEDGEMENT

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