

The Influence of Room and Ambient Temperatures of Exergy Loss in Air Conditioning Using Ejector as an Expansion Device with R290 as Working Fluid

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Abstract. This paper presents a numerical approach on exergy loss in an air conditioner (A/C) using ejector as expansion device with R290 (propane) as working fluid. R290 is a natural refrigerant and environmental friendly, recommended by many researchers as a substitute for R22. In the numerical approach, exergy analysis was carried out on an A/C with cooling capacity of 2.4 kW, and the room and the ambient temperatures were varied from 18 °C to 26 °C and 30 °C to 34 °C respectively. The results show that the total exergy loss in an air conditioner using ejector as an expansion device is lower than that of using conventional as an expansion device. In addition, exergy analysis shows that the gradients of increment of total exergy loss due to increase in the ambient temperature are constant, that is 0.003 for the five different room temperatures, namely 18 °C, 20 °C, 22 °C, 24 °C and 26 °C.

Keywords: Natural refrigerant, exergy analysis, efficiency improvement.

1 Introduction

It is well known that the performance of air conditioning system (A/C) is influenced by indoor and outdoor temperatures. The performance of A/C increases when the room temperature setting is increased. Conversely, the performance of A/C will decrease as the ambient temperature increases. This phenomenon can be analyzed using thermodynamic analysis. Energy analysis is able to determine the performance increment or decrement of the A/C. However, the quantity of increment or decrement in each part of the A/C cannot be determined using energy analysis [1].

During operation, not all input energy into the system converted to useful output. Part of input energy is lost due to friction during expansion, friction between refrigerant flow and tube wall, heat transfer to surrounding, etc. To determine the quantity of energy destruction in each part of the component of the A/C, the exergy analysis is utilized. The first law of

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thermodynamic is applied to energy analysis. Meanwhile, to exergy analysis is utilized the first and the second of thermodynamics [1–3]. The systems that have a lower energy loss will have a lower exergy loss. In other words, a system that generates a lower the exergy loss will have better performance.

R22 is a hydro-chlorofluorocarbon (HCFC) that contributes to global warming and ozone depletion. As a result, R22 must be changed with other refrigerants [4–7]. In the market, at least there are two families of refrigerants as a substitute, namely hydro-fluorocarbons (HFCs) and hydrocarbons (HCs). R134a, R407C, R404A and R410A are families of HCFC, whereas R600a and R290 are families of HC. R134a is widely used in many automotive air conditioners and refrigerators. R407C, R404A and R410A are widely used in many residential air conditioners. Although nowadays HCFCs are still widely used in refrigeration and air conditioning system, however, these refrigerants still have a relatively high global warming property, as a result must be phased out in the future and replaced by environmentally friendly, that is HCs. For example, R600a (isobutene) is widely used in refrigerators to replace R134a and R290 (propane) is widely used in residential air conditioners, especially in the South-east countries, such as Malaysia, Singapore and Indonesia.

Traditionally, a small to medium capacity of air conditioner uses a capillary tube as an expansion device. The use of capillary tube as an expansion device results in energy losses during expansion process. To overcome the energy losses during this process, an ejector is introduced as an expansion device. Figure 1(a) shows a schematic diagram of standard cycle (STD) of an air conditioner using a capillary tube as an expansion device. Furthermore, Figure 1(b) shows a schematic diagram of an ejector as expansion device (EED). During throttling process using capillary tube, expansion process experiences enthalpy constants (isenthalpic). This process indicates that there are energy losses during throttling process. An ejector as an expansion device can generate ideal throttling process that is isentropic (constant entropy) process during expansion. As a result, energy losses during expansion can be reduced using an ejector [8–10]. Figure 1(b) shows that a separator is added to the system in the EED. The separator is to separate vapor and liquid phases refrigerant. Vapor phase will be sucked by the compressor, whereas liquid phase flows to the evaporator.

Figure 2 illustrates cycles of STD and EED on the P-h diagram. The STD cycle is 8-2b-3-11-8, whereas the EED is 1-2-3-4-10-5-1 and 7-8-9-10-7. According to Figure 2, the refrigeration effect and compressor work of STD are (h_8-h_{11}) and $(h_{2b}-h_8)$, respectively. Meanwhile, the refrigeration effect and compressor work of EED are (h_7-h_8) and (h_2-h_1) , respectively. It can be seen that the refrigeration effect of EED is higher than that of STD and the compressor work of EED is lower than that of STD. It means that the performance of the EED is higher than that of the STD.

Kornhauser [11] was the first who introduced numerical analysis on the EED in 1990. In his numerical, one-dimensional model was utilized to determine COP of the EED. In his study, the COP improvements of EED using several refrigerants were determined. He found that the highest COP improvement was approximately 21% for R12. His research also reported that the increase in evaporator temperature will decrease the COP improvement. The evaporator temperature represents the room air temperature in the refrigeration system.

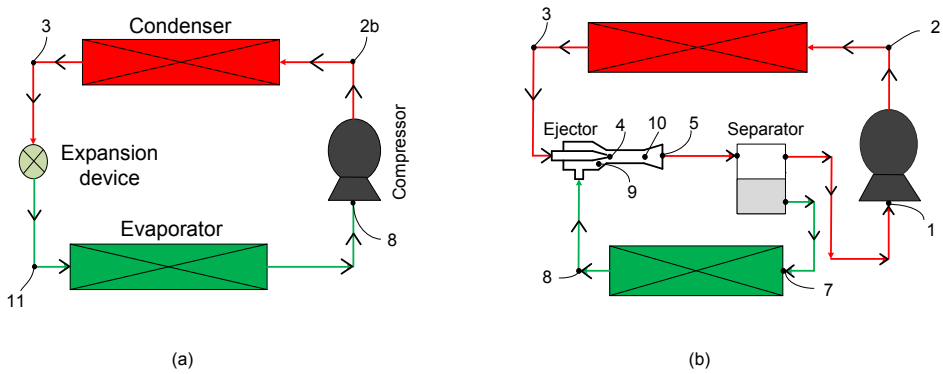


Fig. 1. Schematic diagram of an air conditioner: (a) Standard cycle, (b) EED.

Wongwises and Disawas [12] carried out an experiment to investigate the effect of condenser temperature on the performance of EED. The condenser temperature represents outdoor temperature of the A/C. They found out that the COP improvements were higher for higher ambient temperature. In other words, the EED is better applied for areas which have high outdoor temperatures.

Study of exergy analysis on the EED using R22 was performed by Sumeru et al. [2]. In the study, they utilized compressor capacity of 1 HP. They found that total exergy loss in the STD was higher than that of the EED, namely the total exergy losses in EED and STD were 0.857 kW and 1.442 kW, respectively.

Another exergy analysis on an air conditioner was performed by Vina et al. [3]. They compared exergy loss in the A/C using ejector as an expansion device with R22 and R290 as working fluid. They calculated exergy loss in STD and EDD using R22 and R290 at one condition, namely at 24 °C and 34 °C for the room and the ambient temperatures, respectively. They reported that the total exergy loss using propane was lower than that of R22.

The objective of the present study is to investigate the effect of exergy production in an A/C using ejector as an expansion device with R290 when the indoor and outdoor temperatures are varied.

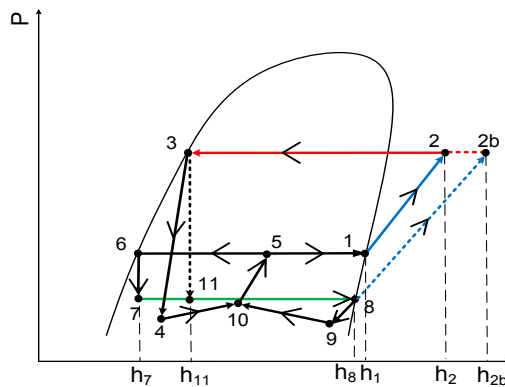


Fig. 2. P-h diagram of STD and EED.

2 Methodology

Before calculating exergy loss in each part of A/C component, the properties of refrigerant in P-h diagram must be determined. There are three conservation equations, i.e., mass, momentum and energy that are utilized to determine refrigerant properties (P, h, s) in each point in Figure 2. There are four sections of ejector: motive and suction nozzles, constant-area and diffuser. Meanwhile, the assumptions are made based on the several researchers [13–15].

Motive nozzle section. In Figure 2, motive nozzle is point 4. Applying energy conservation equation, the enthalpy at motive nozzle exit (point 4) can be determined using Equation 1.

$$u_4 = [2(h_3 - h_4)]^{0.5} \tag{1}$$

Furthermore, the area of the motive nozzle is used mass conservation equation,

$$\alpha_4 = \frac{\dot{m}_{cond}}{\rho_4 u_4} \tag{2}$$

Suction nozzle section. This section is point 9. To determine the area of suction section, the mass conservation equation is applied.

$$h_9 = h_8 - \eta_{sn}(h_8 - h_{9,is}) \tag{3}$$

$$u_9 = [2(h_9 - h_8)]^{0.5} \tag{4}$$

$$\alpha_9 = \frac{\dot{m}_{evap.}}{\rho_9 u_9} \tag{5}$$

Constant-area section. This section is point 10. The mass conservation equation is applied to analyze this section.

$$\dot{m}_T = \dot{m}_{cond} + \dot{m}_{evap.} = \rho_{10} u_{10} \alpha_{10} \tag{6}$$

$$\alpha_{10} = \frac{\dot{m}_{evap.} + \dot{m}_{cond}}{\rho_{10} u_{10}} \tag{7}$$

$$u_{10} = \frac{1}{1 + \omega} u_4 \tag{8}$$

$$(P_{10} - P_4) \alpha_{10} = \dot{m}_{cond} u_4 - (\dot{m}_{evap.} + \dot{m}_{cond}) u_{10} \tag{9}$$

$$h_{10} = \frac{1}{1 + \omega} (h_1 + \omega h_{10}) + \frac{u_{10}^2}{2} \tag{10}$$

Diffuser section. To determine enthalpy at this section (point 5), the conservation of energy equation can be applied.

$$h_5 = h_{10} + \eta_d \frac{u_{10}^2}{2} \tag{11}$$

In the realistic flow, the entrainment ratio (ω) and the refrigerant quality (x) at the point 5 (see Fig. 2) has to fulfill this condition, i.e. $(1 + \omega) = \frac{1}{x_5}$.

Using Equation 1 to Equation 11, the properties of refrigerant can be determined. These properties will be utilized to calculate exergy production in each component of an air conditioner.

The exergy production in a system is defined as,

$$Ex_p = (h - h_0) + T_0(s - s_0) \tag{12}$$

The exergy production represents irreversibility (Ir) in the system. The irreversibility in each component is calculated by equations below.

Compressor:

$$\begin{aligned} Ir_{comp} &= \dot{m}_{pri} (Ex_1 - Ex_2) + W_{comp} \\ &= \dot{m}_{pri} [(h_1 - h_2) - T_o(s_1 - s_2)] + W_{comp} \end{aligned} \tag{13}$$

Condenser:

$$\begin{aligned} Ir_{cond} &= \dot{m}_{pri} (Ex_2 - Ex_3) - Q_{cond} \left(1 - \frac{T_o}{T_{cond}}\right) \\ &= \dot{m}_{pri} [(h_2 - h_3) - T_o(s_2 - s_3)] - Q_{cond} \left(1 - \frac{T_o}{T_{cond}}\right) \end{aligned} \tag{14}$$

Ejector:

$$Ir_{noz} = \dot{m}_{pri} (Ex_3 - Ex_4) = \dot{m}_{pri} [(h_3 - h_4) - T_o(s_3 - s_4)] \tag{15}$$

$$Ir_{suc} = \dot{m}_{sec} (Ex_8 - Ex_9) = \dot{m}_{sec} [(h_8 - h_9) - T_o(s_8 - s_9)] \tag{16}$$

$$Ir_{dif} = (\dot{m}_{pri} + \dot{m}_{sec}) (Ex_{10} - Ex_5) = (\dot{m}_{pri} + \dot{m}_{sec}) [(h_{10} - h_5) - T_o(s_{10} - s_5)] \tag{17}$$

Evaporator:

$$\begin{aligned} Ir_{evap} &= \dot{m}_{sec} (Ex_7 - Ex_8) + Q_{evap} \left(1 - \frac{T_o}{T_{evap}}\right) \\ &= \dot{m}_{sec} [(h_7 - h_8) - T_o(s_7 - s_8)] - Q_{evap} \left(1 - \frac{T_o}{T_{evap}}\right) \end{aligned} \tag{18}$$

Throttling:

$$Ir_{exp} = \dot{m}_{sec} (Ex_6 - Ex_7) = \dot{m}_{sec} [T_o(s_6 - s_7)] \tag{19}$$

Total exergy losses:

$$Ir_{total} = Ir_{comp} + Ir_{cond} + Ir_{ejsec} + Ir_{noz} + Ir_{suc} + Ir_{dif} + Ir_{exp} \tag{20}$$

In this study, the exergy analysis was performed in a residential A/C with cooling capacity of 2.4 kW. Propane or R290 is utilized as refrigerant. The variation of room

temperature is 18 °C, 20 °C, 22 °C, 24 °C and 26 °C. Meanwhile, the variation of ambient temperature is 30 °C, 32 °C and 34 °C.

3 Results and Discussion

3.2 Exergy loss of STD vs. EED

Using Equation 12 to Equation 20, the exergy production or exergy loss in all components of the STD and EED cycles can be determined. Figure 3 depicts the exergy production in four components of the STD and five components of the EED cycles for the room and the ambient temperatures of 24°C and 34°C. The figure shows that the use of ejector as an expansion device reduces exergy loss in the system. In the A/C, the compressor produces the highest exergy loss. Figure 1 shows that exergy loss in the compressor in STD and EED cycles are 0.779 kW and 0.419 kW, respectively. The results shows that the exergy loss in the compressor reduces approximately by 45 % when an ejector is applied as an expansion. The reduction in exergy loss in EED is caused by decreasing the mass flow rate. In addition, the Figure 3 shows that the exergy loss in the expansion device using capillary tube is reduced from 0.078 kW to 0 (zero) kW in EED. The total exergy losses in the STD and EED are 1.22 kW and 0.667 kW. It means that the exergy production decrease in up to 45% when the ejector is applied as an expansion device. As a result, the use of EED cycle will improve the COP of the system as investigated by many researchers [12–15].

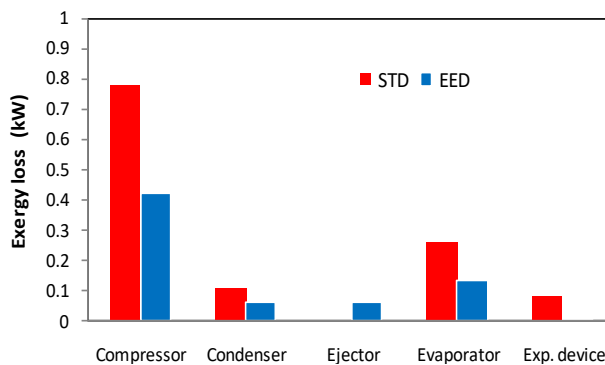


Fig. 3. Exergy loss in each component of STD and EED.

3.2 Effect of room and ambient temperatures

The effect of the room and ambient (outdoor) temperatures on exergy losses in the EED is shown in Fig. 4. It can be seen that for the same room temperature, the exergy loss increases as the ambient temperature increases. It can be seen from Figure 4 that the correlation between the room temperature and the ambient temperature on the exergy loss is linear with equation: $y = 0.003x + C$, where y is total exergy loss, x is ambient temperature and C is constant. In addition, for the same ambient temperature, the increment exergy loss due to decrement the room temperature of 2 °C is approximately 1.1 %. For examples, the exergy loss at ambient temperature of 30 °C for the room temperatures of 24 °C and 26 °C are 0.668 kW and 0.661 kW, respectively.

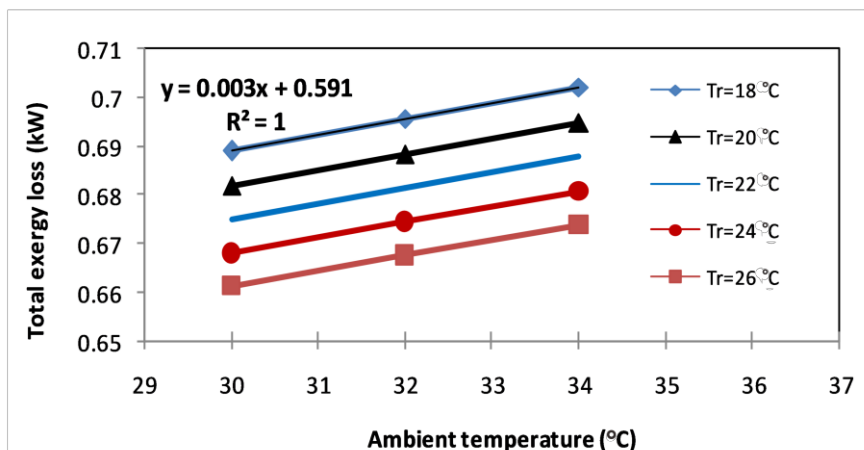


Fig. 4. Effect of room and ambient temperatures in EED.

In the previous section has been mentioned that increase in the room temperature setting will reduce exergy loss. Conversely, the increase in outdoor temperature raises the exergy loss. It was found that, according to Figure 4, the decrement of exergy loss due to increase in the room temperature setting of 2 °C was almost the same to the increment of exergy loss due to the increment of ambient temperature of 2 °C. As a result, in terms of energy savings, it is recommended that when the ambient temperature increase in 2 °C, the room temperature setting also should be raised by 2 °C

4 Conclusions

The numerical approach showed that the EED generated exergy losses lower than that of the STD. It means that the EED cycle has better performance than that of STD cycle for the same room and ambient temperatures. It was found out that the correlation between the room temperature and the ambient temperature on the exergy loss in the air conditioner is linear. It was also found out that for the same increments of room and ambient temperatures will result in almost the same decrement and increment, respectively, of exergy loss in the system. In addition, the thermodynamic analysis showed that the use of R290 in EED would reduce exergy loss in all components of the air conditioning system. It indicates that R290 is able to substitute R22 in the EED cycle.

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