Performance comparison of cooling systems using R410a and RE170 as working fluids at various condensing temperature

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Abstract. In addition to being used as a fuel and propellant, dimethyl ether (RE170) can also be used as an environmentally friendly refrigerant. Apart from having zero ozone depletion potential (ODP), this compound also has a very low global warming potential (GWP), making it safe for the environment. This study aims to compare the performance of refrigeration machines using RE170 and R410, which has long been used as a refrigerant in air conditioning systems. The study was conducted at various evaporation and condensation temperatures. The results showed that RE170 does have a lower cooling capacity, about 41.5% of the cooling capacity of R410A. However, the power required on the system with RE170 is very low, which is only about 35.5% compared to the power required by the system with R410. As a result, the system with RE170 has 16.9% better energy efficiency. Thus, RE170 is not only environmentally friendly but also energy efficient. Another important finding of this study is that RE170 is superior to R410A in terms of energy efficiency at high condensing temperature.

1 Introduction

Dimethyl ether (DME) is a type of ether with the chemical formula C2H6O. At room temperature, it is a colorless gas commonly used as a propellant in aerosol products and as a possible alternative fuel. DME has a high energy density and combusts cleanly, emitting only water and carbon dioxide, which makes it an appealing choice for lowering emissions in transportation and energy production.

DME can also be used as a refrigerant and is designated as RE170. From a thermodynamic perspective, DME has a 46.07 kg/mol molecular weight, 24.78°C normal boiling point, 400.38 K critical temperature, and 5.336 MPa critical pressure. with an ozone depletion potential (ODP) of zero and a global warming potential (GWP) of approximately 1, it has a minimal environmental impact [1]. Additionally, in terms of latent heat of evaporation, RE170 demonstrates a higher value compared to other refrigerants.

Earlier theoretical studies have emphasized the opportunity of the use of DME and its mixtures in different refrigeration applications. It was reported that that R510A (a mixture of

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88% DME and 12% R600a) exhibited better thermal conductivity, volumetric cooling capacity, and coefficient of performance when compared to R134a [2]. A simulation study indicated that RE170 outperforms R134a, R1234yf, and R1234ze in terms of coefficient of performance (COP), refrigeration effect, and refrigeration capacity [3]. A study on a DME mixture with R134a and R600a demonstrated improved performance and reduced environmental impact in comparison to R134a [4]. Later, a simulation on the effect of subcool and superheat on the performance of DME refrigerant and R134a has been conducted. It was reported that DME has a best performance at low subcool and superheat.

Experimental studies of the use of DME are limited. Examination of the heat transfer properties and miscibility of mixtures of refrigerants R227ea/DME and R1234ze(E)/DME showed favorable performance and compatibility of DME with mineral oils [5]. The direct use of DME as a refrigerant in an ice cream maker was conducted by Kim [6] and it was reported that the use of natural refrigerant mixture R-290/DME could improve the performance of the machines. An experiment on the use of DME in a mini freezer has been performed and it was reported that DME could improve the freezer performance. Another experiment was conducted on a heat pump tumble dryer using R-290/DME mixture [7]. As a result, the mixture could work well with a 40% reduction in refrigerant charge, maintaining a capacity similar to R134a while offering an elevated temperature level.

In this study, a performance comparison of R410A and DME was carried out at varied condensing temperature. This study is aimed to find out the influence of condensing temperature on the input compression work, capacity, and coefficient of performance (COP) of an air conditioner.

2 Method

A split room air conditioner with a rated cooling capacity of 9000 Btu/hr (2.64 kW) was employed in this study. This type of air conditioner was chosen as it is the most popular AC with the largest market share. This air conditioner uses a 1 hp compressor to raise the pressure and temperature of the refrigerant and circulate the refrigerant along the refrigeration components and piping. The work of compression, cooling capacity, heat rejection, and coefficient of performance were evaluated.

Refrigeration cycle in a room air conditioner can be described using pressure-enthalpy diagram as shown in Fig. 1. Four processes are involved in this cycle: compression (1-2), condensation (2-3), expansion (3-4), and evaporation (4-1). The compression process takes places in the compressor. Here, low-pressure, low-temperature refrigerant is compressed to high-pressure and high-temperature vapor refrigerant. In the condenser, hot vapor refrigerant is cooled and condensed so that its phase changes to high pressure liquid. During the expansion process, the liquid refrigerant is expanded into a low-pressure liquid-vapor refrigerant mixture. The remaining liquid refrigerant evaporates in the evaporator. During evaporation process, the refrigerant absorbs heat from the room air to cool the room air.

In this study, the refrigeration cycle of the air conditioner was simulated using REFPROP software. The study was carried out by varying the condensing temperature at a constant evaporation temperature of 0°C. With the nominal capacity of 2.64 kW, the compressor of the air conditioner has a swept volume of 2.22 m^3/h or 0.62 liter per second. Other initial parameters for this study include the type of refrigerant, degree of subcool, degree of superheat, and isentropic efficiency.

By using the initial parameters, the suction pressure, discharge pressure, and discharge temperature can be determined. The combination of suction pressure and suction temperature can be used to determine the enthalpy of refrigerant leaving the evaporator (point 1 in Fig. 1). Combination of discharge pressure and discharge temperature can be used to determine the enthalpy of refrigerant at discharge line of the compressor (point 2). The enthalpy of

refrigerant at the condenser outlet (point 3) can be determined if the discharge pressure and the degree of subcool are known. Next, the enthalpy of refrigerant at the outlet of expansion device (point 4) can be determined by assuming adiabatic process along this device.

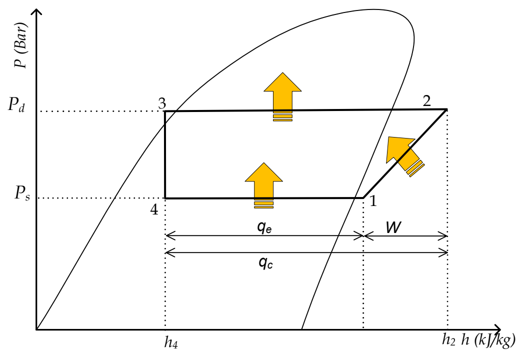

Fig. 1. Refrigeration cycle in pressure-enthalpy chart.

If the four enthalpy parameters are known, then the specific work of compression, refrigeration effect, and specific heat rejection can be determined. The performance of the air conditioner, in terms of work of compression, cooling capacity, and heat rejection can be determined by multiplying the last parameters with the mass flowrate of refrigerant. The mass flowrate can be determined by inputting the suction pressure, suction temperature, and suction enthalpy. The coefficient of performance of the air conditioner can be calculated from the ratio of cooling capacity and heat rejection to the work of compression.

3 Results and Discussion

3.1 Work of compression

The profiles of work of compression for both refrigerants are presented in Figure 2. R410A system has a range of work of compression of 0.80 kW to 1.14 kW for condensing temperature range of 35°C to 55°C. For a comparison, the similar test under varied range of condensing temperature resulted in a power consumption range of 0.81 kW to 1.0 kW [10,11]. Meanwhile, for the same range of condensing temperature, RE170 system has a range of compression work from 0.29 kW to 0.40 kW. It means that the work of RE170 system is about 35.5% of that of R410A.

Using linear approximation, the effect of condensing temperature on the work of compression for R410A system can be expressed as

$$W_{R410A} = 0.0172t_c + 0.2024 \quad (1)$$

For system with RE170, the correlation between the work of compression and condensing temperature can be written as

$$W_{RE170} = 0.0057t_c + 0.0919 \quad (2)$$

W_{R410A} and W_{RE170} represent the work of compression of system with R410A and RE170, respectively, in kilowatt. Meanwhile, t_c denotes the condensing temperature in °C.

From equation (1) and (2), it is clear that condensing temperature has a more significant effect on the work of compression of R410A system than that of RE170. According to equation (1), each 1°C of increase in condensing temperature results in the increase of work

of compression of R410A system by 17.2 Watt. Whereas, according to equation (2) each 1°C increase in condensing temperature causes an increase of compression work of 5.7 Watt.

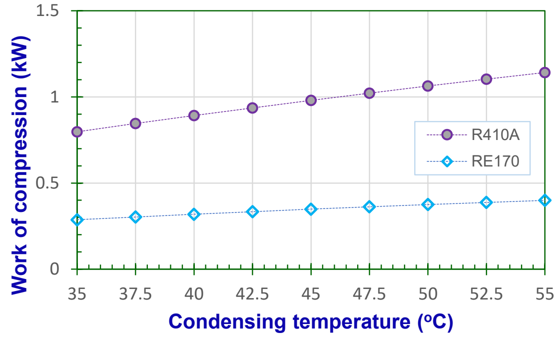

Fig. 2. Work of compression vs condensing temperature.

3.2 Cooling capacity

The cooling capacity of R410A and RE170 systems are depicted in Fig. 3. R410A system has a range of cooling capacity of 2.13 to 2.93 kW. This is higher than that of RE170 with a range of 0.93 to 1.17 kW. It indicates that the average cooling capacity of RE170 system is about 41.5% compared to that of R410A. Previous experiment with varied outdoor temperature at constant moisture content and wet-bulb temperature provided a range of cooling capacity in a range of 2.4 to 2.8 kW.

The effect of condensing temperature on the cooling capacity of R410A can be expressed using

$$Q_{e,R410A} = -0.04t_c + 4.333 \quad (3)$$

where $Q_{e,R410A}$ denotes the cooling capacity of R410A system in kW. The similar expression for RE170 is

$$Q_{e,RE170} = -0.0119t_c + 1.5843 \quad (4)$$

Equation (3) indicates that every 1°C increase in condensing temperature causes a decrease in cooling capacity of R410A system by 0.04 kW or 40 Watt. For RE170 system, each 1°C increase in condensing capacity causes a decrease in cooling capacity by 11.9 Watt. In other words, condensing temperature has a more significant effect on cooling capacity of R410A than that of RE170.

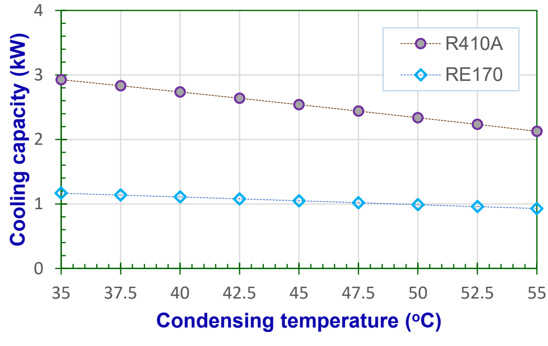

Fig. 3. Cooling capacity vs condensing temperature.

3.3 Heat rejection

Heat rejection represents the amount of heat rejected by the condenser. In a simple refrigeration cycle, the total heat rejection is the sum of work of compression and cooling capacity. The profile of total heat rejection for both refrigerants is depicted in Fig. 4. System with R410A has a range of heat rejection from 3.27 to 3.72 kW and RE170 system has a range of 1.33 to 1.45 kW. From these figures, the heat rejection of RE170 system is about 39.8% of that of R410A.

The influence of condensing temperature on the heat rejection of R410A and RE170 can be expressed as

$$Q_{c,R410A} = -0.023t_c + 4.535 \tag{5}$$

and

$$Q_{c,RE170} = -0.006t_c + 1.676 \tag{6}$$

where $Q_{c,R410A}$ and $Q_{c,RE170}$ represent the heat rejection of system with R410A and RE170, respectively. From both equations, it is apparent that condensing temperature has a more significant effect on heat rejection for R410A system, in which each 1°C increase in condensing temperature causes a decrease in heat rejection by 23 Watt. In the RE170 system, every 1°C rise in condensing temperature results in a reduction of heat rejection by 6 watts.

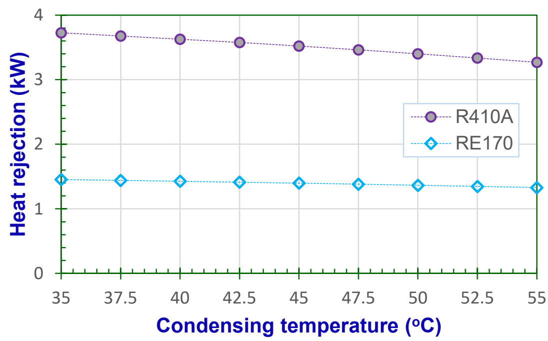

Fig. 4. Heat rejection vs condensing temperature.

3.4 COP (cooling)

Even though the cooling capacity of system with RE170 is lower, its energy efficiency or COP is higher than that of R410A. It is because RE170 system has an even lower work of compression, so that the ratio between the cooling capacity and work of compression is higher. A range of COP from 1.86 to 3.67 was achieved by R410A system. RE170 system has a higher COP with a range of 2.32 to 4.07. The profile of COP for cooling process is presented in Figure 5. For a comparison, an experiment by varying outdoor air temperature (24 to 38°C) resulted in the COP range of 2.4 to 3.46. Another experiment using outdoor temperature of 35°C at varied relative humidity resulted in the average COP of 3.07.

As can be seen in Figure 5, the COP of both refrigerants decrease with the increase in condensing temperature. By using a linear approximation, the correlation between COP and condensing temperature can be expressed as

$$COP_{cooling,R410A} = -0.089t_c + 6.674 \tag{7}$$

and

$$COP_{cooling,RE170} = -0.086t_c + 6.966 \tag{8}$$

The correlation for COP is valid for the range of condensing temperature of 35 to 55°C. From equation (7) and (8), it is apparent that the effect of condensing temperature on the COP for

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both refrigerants is almost the same. Each increase 1°C in condensing temperature causes a decrease in COP by about 0.09.

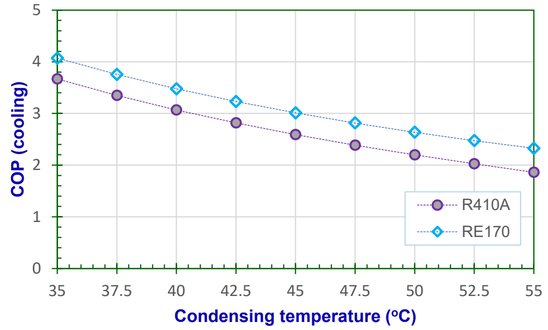

Fig. 5. COP for cooling vs condensing temperature.

3.5 COP (heating)

If the air conditioner is operated for heating purpose, the COP can be calculated from the ratio of heat rejection and work of compression. Figure 6 shows the profile of heating COP of both refrigerants as a function of condensing temperature. Again, RE170 is superior to R410A in terms of heating COP with a range of 3.32 to 5.07. The heating COP of R410A is 12% lower that RE170, i.e., in the range of 2.86 to 4.67.

A linear correlation between the COP and condensing temperature can be expressed as

$$COP_{heating,R410A} = -0.089t_c + 7.674 \quad (9)$$

and

$$COP_{heating,RE170} = -0.086t_c + 7.966 \quad (10)$$

The heating COP decrease by about 0.09 per 1°C increase in condensing temperature.

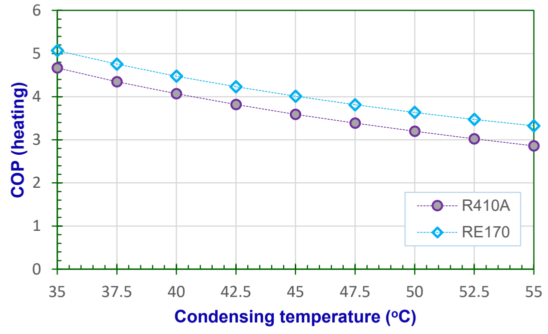

Fig. 6. COP for heating vs condensing temperature.

4. Conclusion

A simulation study on the use of RE170 and R410A as refrigerants in a 2.64 kW air conditioner has been accomplished. The results showed that generally DME system has a lower work of compression, i.e., only 35.5% of that of R410A. As in work of compression, the cooling capacity of RE170 is 41.5% lower than that of R410A. The cooling COP of RE170, however, is 16.6% higher than R410 system due its even lower work of compression. For heating purpose, the COP of RE170 is still 12% better than R410A system. As the condensing temperature increases, the cooling capacity of both DME and R410A systems

decrease. In addition, in terms of energy efficiency RE 170 is superior to R410A at high condensing temperature. It implies that RE170 has a lower impact on the global warming and climate change. However, the flammability issue of RE170 should be anticipated if it is used as a refrigerant for a safe operation.

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