Evaluation of performance of dimethyl ether and high-pressure refrigerants under varied evaporating temperature

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Abstract. Dimethyl ether is an organic compound that has the potential to be used as an environmentally friendly refrigerant. In this study, the performance of dimethyl ether refrigerant was tested and compared with other refrigerants having high working pressure, namely R410A, R410B, and R32. The study results show that dimethyl ether has a lower cooling capacity compared to R410A, R410B, and R32, in the order of 37% to 40%. However, the compression work of the cooling system with dimethyl ether is much lower, i.e., in the order of 30.7% to 36.9%. As a result, the coefficient of performance (COP) of the cooling machine with dimethyl ether is 7.4% to 10.6% higher than that of the three high-pressure refrigerants. The COP increases with the increase of evaporating temperature.

1 Introduction

To address the issues of global warming and ozone depletion, the use of environmentally friendly refrigerants is highly encouraged. One of the environmentally friendly refrigerants that has not been widely used is dimethyl ether (DME). This refrigerant with the chemical formula CH3OCH3 has a zero ozone depletion potential (ODP) and very low global warming potential (GWP) [1]. In the early stage of the development of mechanical refrigeration, this refrigerant was commonly used [2]. However, due to the issues of flammability and explosivity, its popularity has declined. Now, this compound is more popular as an aerosol propellant [3], fuel for compression ignition diesel engines, and an alternative substitute for liquified petroleum gas (LPG) [4].

With its relatively low normal boiling point (-24.8°C), this refrigerant is suitable for applications of air conditioning and refrigeration which does not require a very low working temperature. This compound has a low saturation pressure, very close to R134a and slightly higher than that of isobutane.

Studies concerning the performance of DME as a working fluid of a refrigeration system are generally conducted by simulation or thermodynamics studies. A comparative study of the thermodynamics properties of DME, R22, and R407C has been carried out and it was reported that DME was superior over R22 and R407C in terms of coefficient of performance

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[5]. A study on alternative refrigerant for R134a using DME, R1234yf, and R1234ze showed that DME has the best overall performance among all tested refrigerant [6]. A mixture of R134a + DME + R600a has also been tested as a substitute for R134a. The test showed that this mixture has higher cooling capacity and coefficient of performance that those of R134a [7]. In heat pump applications, R744 mixed with DME has a higher energy efficiency ratio (EER) at a mole fraction of 0.3:0.7 [8]. Subsequently, by adjusting the superheat and sub-cool levels of an air conditioner using R134a and DME, it was found that DME performed optimally at lower superheat and sub-cool settings.

So far, there have only been two publications on the use of DME as a refrigerant directly in refrigeration machines. The first study was conducted on an ice cream maker to substitute R404A with a mixture of DME and R290. As a result, this mixture of environmentally friendly refrigerant has a better performance, indicated by reduced time of ice formation [9]. The second study was carried out on a chest freezer which originally using R134a as a working fluid. The substitution of refrigerant using DME resulted in the lower energy consumption.

Almost all previous comparative studies on DME refrigerants were conducted by comparing the performance of DME which has low working pressure with other refrigerants which also have low working pressure. In this study, the performance of DME refrigerant is examined and compared to other refrigerants with high working pressure, i.e., R32, R410A, and R410B. This study was performed by simulation at varied evaporating temperature from -15°C to +5°C using constant condensing temperature of 15°C.

2 Methods

A room air conditioner with a 1 hp compressor and nominal cooling capacity of 2.64 kW was used in this simulation study. Four different refrigerants, i.e., DME, R32, R410A, and 410B were used as working fluids for the air conditioner. The study was carried out at a constant condensing temperature of 45°C and varied evaporating temperature from -15°C to 5°C. REFPROP Software from National Institute of Standards and Technology (NIST) was employed in this study as a simulation tool.

The refrigeration system used in the AC used in this simulation is sketched as in Figure 1. Four main components of a refrigeration system are presented here: compressor, condenser, expansion device, and evaporator. In this system, low pressure refrigerant from the evaporator (1) is sucked by the compressor and then compressed to produce a high-pressure and high-temperature vapor refrigerant (2). The refrigerant is then cooled and condensed in the condenser. At the condenser outlet (3), refrigerant is in a liquid phase at high pressure. The liquid refrigerant is then passed through expansion device to decrease the pressure and temperature, resulting in low-pressure and low-temperature refrigerant mixture of liquid and vapor (4).

The simulation was started by setting the evaporation temperature, condensation temperature, subcool, and superheat. These parameters were used to calculate suction pressure, discharge pressure, and discharge temperature. Once the last three parameters are known, the refrigerant enthalpy at the compressor suction (h_1), compressor discharge (h_2), condenser outlet (h_3), and expansion device outlet (h_4) can be determined. The enthalpies can be used to determine the refrigeration effect, specific work of compression, and specific heat rejection. The refrigeration effect can be expressed as

$$q_e = h_1 - h_4 \tag{1}$$

Where q_e is refrigeration effect [kJ/kg], h_1 is the enthalpy of refrigerant at evaporator outlet [kJ/kg], and $h_4$is the enthalpy of refrigerant at evaporator inlet [kJ/kg]

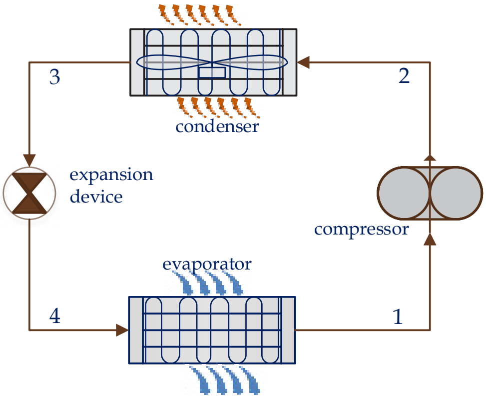

Fig. 1. Sketch of refrigeration system used in room air conditioner.

The specific work of compression is the difference of refrigerant enthalpy between the outlet and inlet of the compressor and can be written as

$$w = h_2 - h_1 \tag{2}$$

Here, w represents the specific work of compression [kJ/kg] and h_2 denotes the enthalpy of refrigerant at compressor outlet [kJ/kg].

Meanwhile, the specific heat rejection (q_c) is defined as the amount of heat rejected through the condenser per unit mass of refrigerant, or

$$q_c = h_2 - h_3 \tag{3}$$

where h_2 is the enthalpy of refrigerant at condenser outlet [kJ/kg]

The ratio of refrigeration effect and specific work of compression is called coefficient of performance (COP) of the refrigeration system and can be expressed as

$$COP = \frac{h_1 - h_4}{h_2 - h_1} \tag{4}$$

All parameters in equations (1) to (3) are expressed in energy content per mass of refrigerant. To calculate the cooling capacity, work of compression, and heat rejection, the mass flow rate of refrigerant should be determined first. In this study, refrigerant mass flow rate ($\dot{m}$) can be determined by using the data of specific volume, compressor clearance, swept volume, superheat, and suction pressure. Once the parameter is obtained, cooling capacity can be determined by

$$Q_e = \dot{m}(h_1 - h_4) \tag{5}$$

where Q_e and $\dot{m}$ are cooling capacity [kW] and refrigerant mass flow rate [kg/s]. The work of compression (W) to compress the refrigerant to its discharge pressure can be determined using

$$W = \dot{m}(h_2 - h_1) \tag{6}$$

The heat rejection from the condenser can be determined using

$$Q_c = \dot{m}(h_2 - h_3) \tag{7}$$

As the mass flow rate of refrigerant is equal along the refrigeration pipeline, the heat rejection can be approximated by

$$Q_c = Q_e + W \tag{8}$$

Finally, the COP can be expressed as

$$COP = \frac{Q_e}{W} \tag{9}$$

The simulations and calculations using equations (1) to (9) are carried out for all refrigerants employed in this study. The results are then compared to evaluate the performance of all refrigerants in terms of cooling capacity, work of compression, and coefficient of performance.

3 Results and Discussion

This section discusses the operating conditions and the performance of the air conditioner using the different refrigerants under varied evaporating temperature. Parameters discussed in this section include the refrigeration effect, refrigerant mass flow rate, cooling capacity, compression work, and coefficient of performance.

3.1 Refrigeration effect

This parameter can be determined by calculating the difference of refrigerant enthalpy at the outlet and inlet of evaporator. It represents the amount of heat removed by the evaporator per unit mass of refrigerant. The profile of refrigeration effect for all refrigerants used in this study is depicted in Figure 2. As can be seen, the refrigeration effect of DME is higher than that of R32, R410A, and R410B. For all range of evaporating temperature, the refrigeration effect of DME is in the range of 329.6 kJ/kg to 351.1 kJ/kg. This refrigeration effect is 39%, 114%, and 126% higher than that of R32, R410A, and R410B, respectively. The higher refrigeration effect of DME is mainly caused by its high latent heat compared to R32 and R410A [10].

3.2 Refrigeration mass flow rate

Figure 3 depicts the refrigeration mass flow rate of R32, R410A, R410B, and DME as a function of evaporating temperature at constant condensing temperature of 45°C. DME has the lowest refrigerant mass flow rate as it has the lowest density (735.59 kg/m^3) compared to the other three refrigerants used in this study. R410A has a liquid density of 1365.26 kg/m^3, while the density of R410B and R32 are 1350.50 kg/m^3 and 1213.65 kg/m^3, respectively. As can be seen in Figure 3, the order of mass flow rate from the smallest is DME, R32, R410A, and R410B. This is in accordance with the order of the density of the four refrigerants in order from the smallest. The small difference of density of R410A and R410B is also reflected in the small difference in mass flow rate between the two refrigerants.

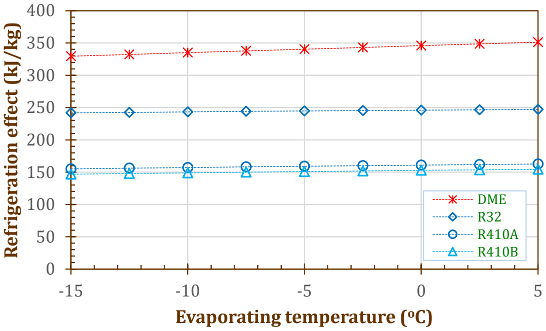

Fig. 2. Refrigeration effect of DME, R32, R410A, and R410B vs evaporating temperature.

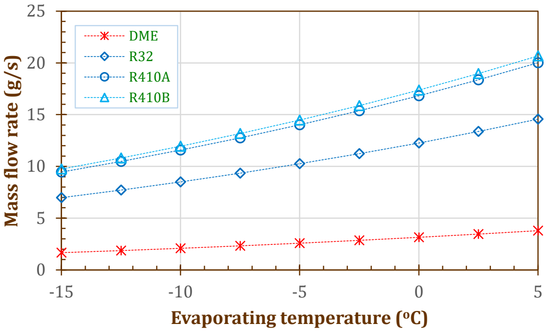

Fig. 3. Refrigerant mass flow rate of DME, R32, R410A, and R410B vs evaporating temperature.

3.3 Cooling capacity

Measured at the evaporator, this parameter represents the ability of the air conditioner to remove heat from the surrounding. To calculate the cooling capacity, the mass flow rate and the refrigerating effect of the AC should be calculated first. At condensing temperature of 45°C, the profiles of cooling capacity of all refrigerants as a function of evaporating temperature are presented in Figure 4.

From a glance, two important facts can be noted. First, it can be seen that DME refrigerant has the lowest cooling capacity, ranging from 0.55 to 1.33 kW. Second, the cooling capacities for all refrigerants increase with the increase of evaporating temperature.

Detailed observation of Figure 2 reveals that R32 has the highest cooling capacity, ranging from 1.68 kW to 3.60 kW. R410A and R410B have similar cooling capacities, ranging from 1.47 kW to 3.25 kW. For comparisons, experiments using R32 at varied outdoor air temperature results in the range of cooling capacity of 2.59 to 2.63 kW at outdoor temperature of 30 to 32°C.

Compared to the cooling capacity of high-pressure refrigerants, the cooling capacity of DME is about 35.2% of R32 cooling capacity, 38.5% of R410A, and 39.1% of R410B. Therefore, in terms of cooling capacity, DME is inferior to the other three refrigerants. From the study using evaporating temperature of 2.5°C, DME has a slightly higher cooling capacity. This is caused by the use of lower condensing temperature than the present study.

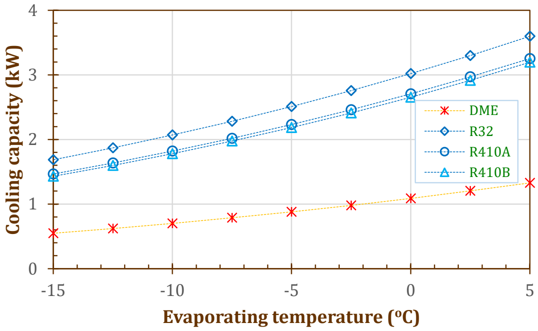

Fig. 4. Cooling capacity of systems with DME, R32, R410A, and R410B vs evaporating temperature.

3.4 Work of compression

The profiles of cooling capacity of all refrigerants as a function of evaporating temperature at condensing temperature of 45°C are presented in Figure 5. As can be seen, DME has the lowest work of compression, thus the lowest input power needed to operate the air conditioner. As in cooling capacity, the work of compression also increases with the increase of evaporating temperature.

The work of compression of AC system with DME is in the range of 0.26 kW to 0.36 kW. R32 has the highest work of compression, i.e., in the range of 0.89 kW to 1.08 kW. R410A and R410B have a similar range of work of compression, ranging from 0.79 to 1.01 kW. The range of work of compression of R32 system is comparable to previous study conducted in varied outdoor dry-bulb temperature and constant wet-bulb temperature. In percentage, the work of compression of DME refrigerant is about 32.6% of that of R32, 35.1% of R410A, and 35.6% of R410B. In terms of the work of compression, DME is superior to the other refrigerants as it needs a low power to compress the refrigerant.

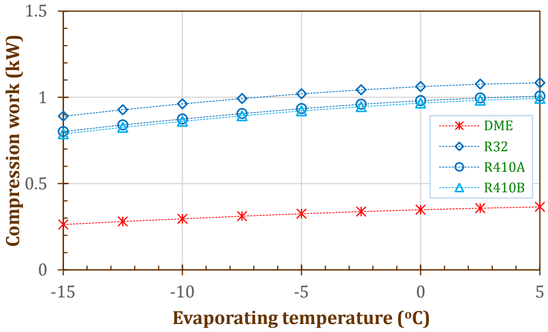

Fig. 5. Work of compression of systems with DME, R32, R410A, and R410B vs evaporating temperature.

3.5 Coefficient of performance

Although it has a low cooling capacity, because DME has a much lower compression work, the coefficient of performance (COP) of DME refrigerant is higher than that of three high-pressure refrigerants. Detailed examination of Figure 6 reveals that the COP of DME refrigerant is in the range of 2.09 to 3.65 for evaporating temperature of -15°C to 5°C. This is higher than that of R32 (1.89 to 3.32), R410A (1.83 to 3.23), and R410B (1.70 to 2.96).

For a comparison, the COP of previous study using R32 is in a range of 2.8 to 3.0 for outdoor air temperature of 30 to 32°C. Another experiment at constant outdoor temperature of 35°C and varied relative humidity resulted in COP of about 3.07.

As in cooling capacity, the COP increases with the increase of evaporating temperature. In percentage, the COP of DME system is 9.2%, 11.9%, and 12.4% higher than that of R32, R410A, and R410B, respectively. The COP of DME refrigerant in this study is slightly lower than that of resulted from previous study using dimethyl ether as a working fluid. This is mainly caused by the higher condensing temperature used in this study. The higher COP of DME system reflects its advantage in energy efficiency and lower impact on the global warming and climate change.

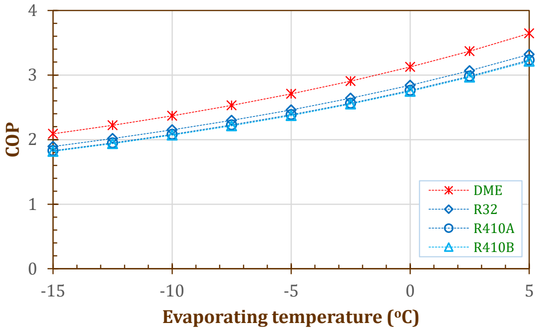

Fig. 6. Coefficient of performance of systems with DME, R32, R410A, and R410B vs evaporating temperature.

4 Conclusion

Performance comparison of DME refrigerant and three high-pressure refrigerants using simulation study has been conducted at various evaporating temperatures. The cooling capacity, work of compression, and COP of all refrigerants increase with the increase of evaporating temperature. Due to its lowest density, the system with DME has the lowest mass flow rate of refrigerant, resulting in the lowest cooling capacity and work of compression. However, with the even lower work of compression, DME system provides the highest COP among all refrigerants tested in this study. From this study, the COP of DME system is 9.2%, 11.9%, and 12.4% higher than that of R32, R410A, and R410B, respectively. With its higher energy efficiency, DME has a lower impact on global warming and climate change.

The authors would thank the Ministry of Education, Culture, Research and Technology, Politeknik Negeri Bandung, and PT Bumi Tangerang Gas Industry for the kind supports during the research and article preparation.

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