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Effects of Evaporating Temperature on the Flow Pattern of Dimethyl Ether in a Horizontal Evaporator

Windy H. Mitrakusuma[1], Andriyanto Setyawan[1,*], Luga M. Simbolon[1], Muhammad Arman[1], Susilawati[1]

[1] Department of Refrigeration and Air Conditioning Engineering, Politeknik Negeri Bandung, Bandung 40559, Indonesia

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ABSTRACT

Dimethyl ether is one of the derivative products of coal that will be used as a household fuel substitute for LPG in Indonesia. In addition, it can also be used as a working fluid in a refrigeration system. To understand the behavior of this refrigerant, a simulation was carried out to determine the flow pattern of dimethyl ether in a horizontal evaporator. This study was applied in an evaporator of an air conditioner with inside diameter of 6.3 and 7.9 mm and cooling capacity of 2.64 and 5.28 kW. By varying the evaporation temperature from -20 to 5°C it was observed that the flow pattern was dominated by annular flow when the evaporation temperature was set at higher value. Simulation using pipe diameter of 7.9 mm and cooling capacity of 2.64 kW showed that at the evaporator inlet the flow pattern is combination of stratified-wavy and wavy-annular for all range of evaporation temperature. When the pipe diameter was reduced to 6.3 mm, stratified wavy at the evaporator inlet was only found at evaporating temperature of -15 and -20°C. All stratified wavy flow vanishes when the cooling capacity was doubled to 5.28 kW. Annular flow is dominant under this condition.

1. Introduction

Studies on the use of environmentally friendly refrigerants have been carried out for decades since the implementation of Montreal Protocol in 1987. The protocol stipulates the phase out of hydrochlorofluorocarbons (HCFC) and hydrofluorocarbons (HFC). Since then, massive studies on alternative refrigerants have been carried out until the recent decade. Study on the behavior and performance of alternative refrigerants have been conducted. Gil and Kasperski [1] conducted an experiment with alternative refrigerant used for a refrigeration system equipped with ejector. An experiment for finding the best substitutes for R22 has been reported by Antunes and Filho [2], in which R290, R1270, and R32 are the bests in terms of thermal performance and environmental impact. Study on the low global warming potential for medium to high pressure refrigeration applications has been reported by Domanski *et al.,* [3]. It was reported from this study that

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[*] *Corresponding author.*
E-mail address: andriyanto@polban.ac.id

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alternative refrigerants for high pressure applications are limited. An opportunity to use R152a as an alternative for R134 has also been proposed to find the best charge for the substitute [4]. Also, a study on a heat pump water heater has been carried out to find the best substitute for R410a. It was reported that L41b refrigerant offered the best COP improvement relative to R410a [5].

One of the environmentally friendly alternative refrigerants is dimethyl ether (RE170). Even though the studies of alternative refrigerants have been conducted extensively, studies concerning the behavior and performance of RE170 or dimethyl ether (DME) are very limited. Most of them are simulation studies on the thermodynamics properties, such as reported by Bolaji [6], Gil *et al.,* [7], Zharov *et al.,* [8], and Bolaji *et al.,* [9]. To the best of the author's knowledge, there is only one experimental study using dimethyl ether refrigerant in real equipment [10]. In this study, even the DME was not used directly as a single refrigerant but mixed with R290. Promising results were reported when a mixture of DME and R290 was applied to an ice cream refrigerator, i.e., shorter time of ice formation and better coefficient of performance (COP). However, the flammability issue should be seriously anticipated.

Studies on condensation of refrigerant in the condenser and boiling of refrigerant in the evaporator of an air conditioner have also been carried out. Condensation heat transfer and flow pattern of refrigerant HFE-7100 has been investigated in rectangular micro-channels [11]. Suliman *et al.,* [12] studied flow pattern map during condensation for R134a to accurately predict the heat transfer coefficients. Flow pattern visualization during condensation of R410a in a vertical rectangular channel has also been studied [13]. Flow pattern, pressure drop, and performance of R600a in condenser has also been assessed [14]. For boiling of refrigerant, the boiling process and flow pattern of refrigerants with low global warming potential (GWP) and zero ozone depleting potential (ODP) have been investigated [15]. Specific study to investigate the heat transfer and pressure drop of boiling flow of R1234yf has been conducted [16].

The Indonesian government plans to build a large-scale dimethyl ether plant to replace LPG, which is mostly imported from abroad. The groundbreaking was carried out on January 2022. In addition to being a fuel, DME also has a great opportunity to become one of the alternative refrigerants that are environmentally friendly. This study explores the behavior of dimethyl ether as a working fluid in a horizontal evaporator of an air conditioner. The main parameters discussed in this paper are flow quality and void fraction as a function of evaporating temperature. The flow pattern in the evaporator will also be discussed.

2. Methodology

In a room air conditioner that employs vapor compression refrigeration system, two-phase flow can be found in the condenser and evaporator. High-pressure and high-temperature vapor refrigerant from the compressor is cooled and condensed in the condenser. Two-phase flow is formed when vapor and liquid refrigerant flow simultaneously in the condenser pipe. For ideal refrigeration cycle, the refrigerant at the condenser outlet is in saturated liquid. For real refrigeration cycle, however, at the condenser outlet the refrigerant may in subcooled condition [17]. In the evaporator, a mixture of liquid and vapor refrigerant enter the evaporator inlet. Evaporation process takes place in the evaporator until all refrigerant evaporates at the evaporator outlet. Two-phase flow of boiling refrigerant occurs in almost all segment of evaporator pipe, except at the segment near the outlet at which all refrigerant is in the vapor phase [18].

In this study, the behavior of refrigerant in the evaporator pipe is examined, in terms of flow quality, void fraction, and flow pattern. The flow quality, or vapor quality, in a two-phase flow can be determined from the ratio of vapor mass flow rate ($\dot{m}_V$) to the total mass flow rate of refrigerant in the evaporator pipe ($\dot{m}$)

$$x=\frac{\dot{m}_V}{\dot{m}} \tag{1}$$

The total mass flow rate is the sum of the mass flow rate of vapor ($\dot{m}_V$) and mass flow rate of liquid

$$\dot{m}=\dot{m}_V+\dot{m}_L \tag{2}$$

or

$$x=\frac{\dot{m}_V}{\dot{m}_V+\dot{m}_L} \tag{3}$$

The liquid holdup of the refrigerant is the ratio of volume or area of pipe occupied gas and the total volume of pipe, or can be calculated by [19,20]

$$\eta=\frac{V_L}{V_V+V_L} \tag{4}$$

or

$$\eta=\frac{A_L}{A_V+A_L} \tag{5}$$

As the complement of liquid holdup, the void fraction can be calculated using

$$\alpha = 1-\eta \tag{6}$$

or

$$\alpha=\frac{A_V}{A_V+A_L} \tag{7}$$

To calculate the refrigerant volume of vapor and liquid refrigerant in Eq. (4), the flow quality and specific volume (reciprocal of density) for both vapor and liquid are known.

The flow-pattern of refrigerant in the evaporator can be determined by using available flow map from Hatamipour and Akhavan-Behabadi [21]. It depends on the vapor quality and mass velocity (mass flux) of refrigerant, expressed by

$$G=\frac{\dot{m}}{A} \tag{8}$$

3. Results

3.1 Void Fraction

The distribution of void fraction as a function of pipe segment is presented in Figure 1. It can be seen that at the evaporator outlet (s/L=1) flow quality is unity, indicates that all refrigerant is in the vapor state. At the evaporator inlet, the flow quality depends on the evaporating temperature. At evaporating temperature of 5 and 0°C, the refrigerant enters the evaporator at flow quality of 0.20 and 0.23, respectively. As the evaporating temperature decreases to -5 and -10°C, the flow quality at the evaporator inlet increases to 0.25 and 0.27, respectively. The refrigerant enters the evaporator at flow quality of 0.29 and 0.31 when the evaporating temperature decreases to -15 and -20°C, respectively. Therefore, it is clear that the vapor fraction of refrigerant increases with the decrease of evaporating temperature.

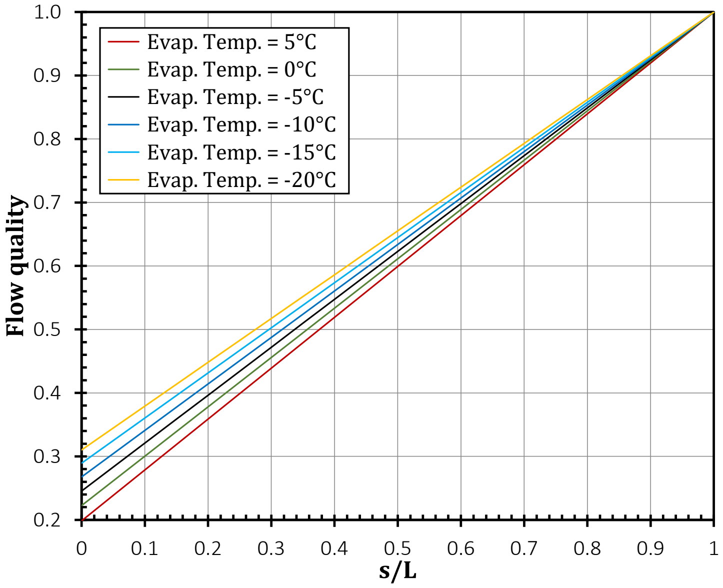

Fig. 1. Plot of flow quality vs pipe segment (s/L) and evaporating temperature for pipe diameter of 7.9 mm

Figure 2 shows the plot of void fraction as a function of pipe segment in the evaporator. The void fraction is smaller than flow quality because it is calculated on the basis of volume fraction. Again, the void fraction increases with the decrease of evaporating temperature because at the lower evaporating temperature, the density of liquid-vapor refrigerant mixture is lower. It means that the refrigerant vapor occupies a larger volume that makes the vapor fraction higher. In this study, the void fraction at the evaporator inlet is in the range of 0.962 to 0.991 (Figure 3), depends on the evaporating temperature. At the outlet of evaporator, the void fraction is unity.

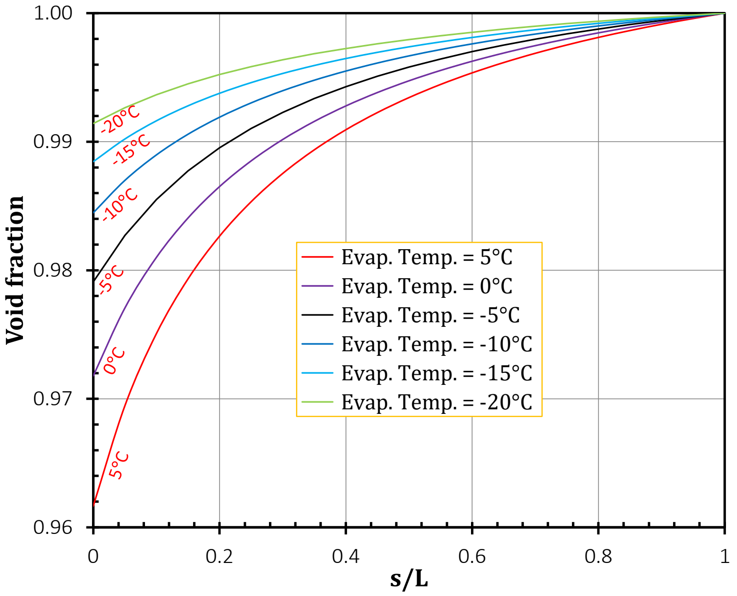

Fig. 2. Plot of void fraction as function of pipe segment (s/L) and evaporating temperature

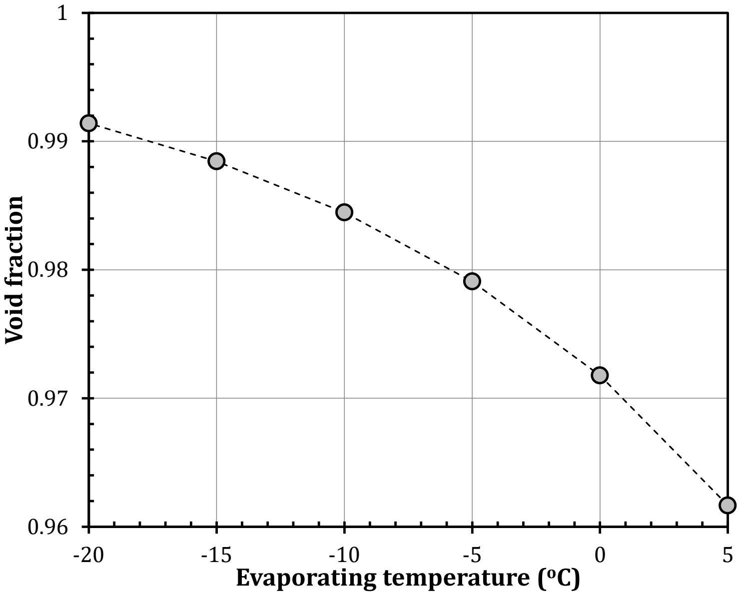

Fig. 3. Void fraction of refrigerant at the inlet of evaporator pipe for various evaporating temperature

3.2 Flow Pattern

The flow pattern of refrigerant DME as function of evaporating temperature and vapor quality for a cooling capacity of 2.64 kW and evaporator pipe diameter of 7.9 mm is presented in Figure 4. As can be seen, the flow pattern for all range of evaporating temperature was dominated by two flow regimes, wavy-annular and annular, indicated by high velocity vapor flow in the core and thin liquid flow in the inner pipe wall [22]. The mass velocity of the refrigerant is calculated to be 156.9 kg $m^{-2}s^{-1}$ at evaporating temperature of 5°C. At the lower evaporating temperature, the density of refrigerant at the evaporator outlet decreases. As the volumetric flow rate or swept volume of the compressor is constant, then mass flow rate and mass velocity decrease. The variations of mass velocity affect the flow pattern.

Detailed examination of Figure 4 shows that the annular flow occupies most of pipe segment when the evaporating temperature is higher. For example, at 5°C of evaporating temperature, 71.4% of flow pattern is identified as annular according to the flow pattern from Hatamipour and Akhavan-Behabadi [21]. When the evaporating temperature was lowered to 0 and -5°C, the portion of annular flow decreases to 61.9% and the remaining is generally wavy-annular. Further decrease of evaporating temperature to -10, -15, and -20°C results in the decrease of annular flow portion to 52.4%, 47.6%, and 38.1%, respectively. For all evaporating temperature, the portion of annular flow is 55.6%, averagely.

It should be noted that the annular flow will be easily formed for high gas superficial velocity [23,24]. Therefore, it can be easily found near the outlet of the evaporator. From Figure 4, it is also clear that at low evaporating temperature (-15 and -20°C), stratified-wavy flow was found at low vapor quality. It was located at the pipe segment near the evaporator inlet.

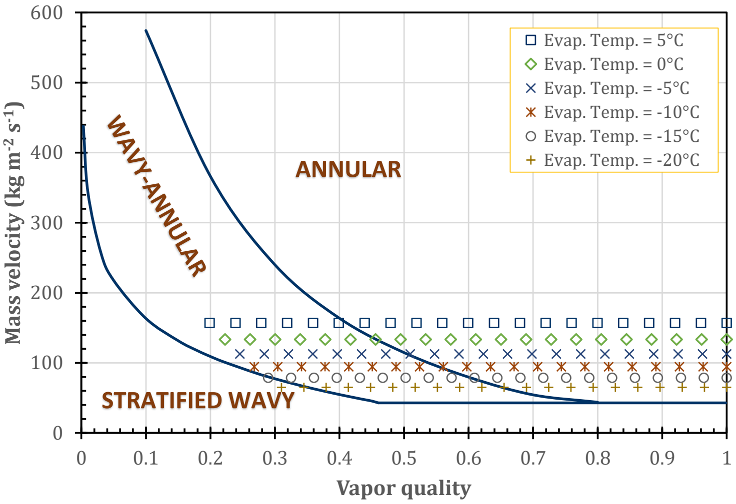

Fig. 4. Plot of mass velocity vs vapor quality in evaporator for 2.64 kW air conditioner with evaporator pipe diameter of 7.9 mm

When the pipe diameter was reduced to 6.3 mm, the velocity of refrigerant in the evaporator pipe increases. As a result, the superficial velocity of both vapor and liquid increase. This situation causes the easier of formation of annular flow. As can be seen in Figure 5, at evaporating temperature of 5°C and 0°C, the portion of annular flow of refrigerant in the evaporator is about 85.7% and annular flow was initiated at pipe segment s/L = 0.2. Decreasing the evaporating temperature to -5 and -10°C results in the decrease of the portion of annular to 81% and 76%, and annular flow was formed at s/L = 0.25 and s/L = 0.3, respectively. For evaporating temperature of -15 and -20°C, the annular flow was formed at s/L = 0.35 and s/L = 0.4 with portion of annular flow 66.7% and 61.9%, respectively. Again, the lower evaporating temperature results in the later formation of annular flow. All range of evaporating temperature gives the average portion of annular flow of 76.2% in evaporator pipe that gives a better heat transfer per unit area of evaporator. However, the higher pressure drop should be considered.

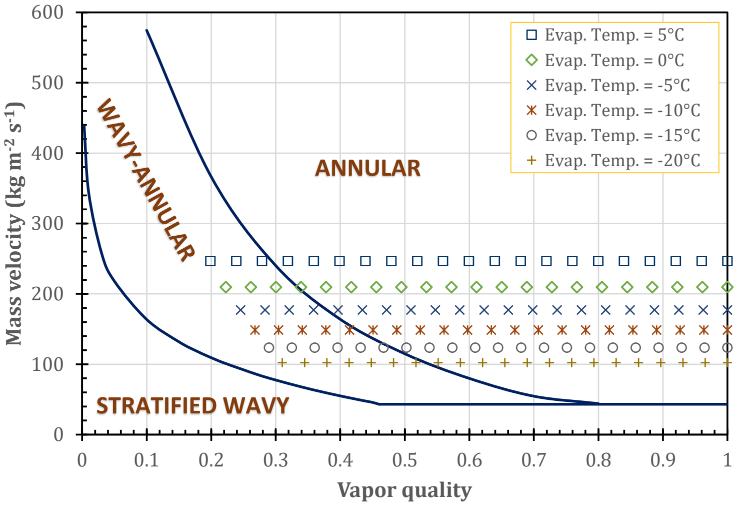

Fig. 5. Plot of mass velocity vs vapor quality in evaporator for 2.64 kW air conditioner with evaporator pipe diameter of 6.3 mm

If the cooling capacity is doubled to 5.28 kW with evaporator pipe diameter of 7.9 mm, the plot of mass velocity as a function of vapor quality is presented in Figure 6. At the evaporating temperature of 5°C and 0°C, the portions of annular flow in evaporator are 95% and 90.5%, respectively. It means that the annular flow was found in almost all segment of pipe. Only a small portion of pipe was occupied by wavy-annular in the evaporator inlet. At evaporating temperature of -5 and -10°C, the portion of annular flow decreases to 90% and 85.7%, respectively, and the remaining is wavy-annular flow. Further decreasing of evaporating temperature to -15 and -20°C results in the decrease of annular flow portion to 81% and 71.4%. By comparing to Figure 4, it is evident that doubling the cooling capacity with constant pipe diameter causes the increase of portion of annular flow, even for low evaporating temperature. Larger portion of annular flow in this condition provides the better heat transfer per unit area along the evaporator [25].

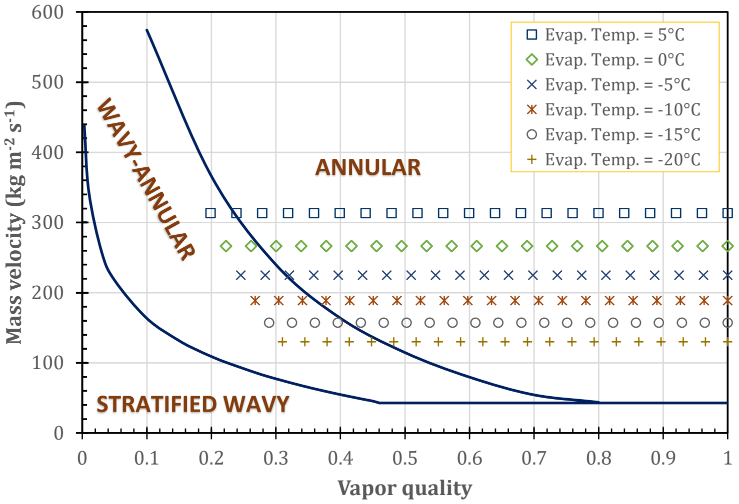

Fig. 6. Plot of mass velocity vs vapor quality in evaporator for 5.28 kW air conditioner with evaporator pipe diameter of 7.9 mm

4. Conclusions

Study on the flow quality, void fraction, and flow pattern of refrigerant in the evaporator has been examined for horizontal orientation and evaporating temperature range of -20 to +5°C. In this study, a range of flow quality from 0.20 to 0.31 has been obtained at the evaporator inlet and unity at the evaporator outlet. The void fraction at the evaporator inlet is in the range of 0.962 to 0.991. The flow quality and void fraction at the evaporator inlet increases with the decrease of evaporating temperature.

The study of flow pattern in the evaporator reveals that the portion of annular flow increases with the decrease of pipe diameter and increase of cooling capacity. This gives the higher heat transfer per unit area of evaporator. However, higher pressure drop should be considered here as a trade-off to the better heat transfer.

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