บทความวิจัย

การใช้ฟิกเกอร์ออฟเมอริทในการทำนายสมรรถนะของปั๊มความร้อนเมื่อใช้สารผสมชนิดซีโอทรอปิค

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บทคัดย่อ

ในปัจจุบันมีการใช้ปั๊มความร้อนอย่างแพร่หลายเนื่องจากเป็นเทคโนโลยีที่ใช้พลังงานต่ำและเป็นมิตรต่อสิ่งแวดล้อม ปัจจัยสำคัญที่มีผลต่อสมรรถนะของปั๊มความร้อนคือสารทำงาน ส่วนมากเป็นสารทำงานชนิดสารเดี่ยว ซึ่งพบว่า ก่อให้เกิดสภาพการย้อนกลับไม่ได้สูง จึงได้มีการใช้สารทำงานชนิดสารผสมเพื่อช่วยลดสภาพการย้อนกลับไม่ได้ เนื่องจากสารผสมจะมีการเปลี่ยนอุณหภูมิระหว่างที่เปลี่ยนสถานะ (Gliding Temperature) ทำให้งานที่ใช้ในวัฏจักรลดลง ส่งผลให้สมรรถนะของระบบสูงขึ้น แม้ว่าปัจจุบันจะมีซอฟต์แวร์ต่างๆ ช่วยในการหาสมรรถนะของระบบ แต่สำหรับการใช้สารผสมในปั๊มความร้อน การใช้ซอฟต์แวร์ยังคงซับซ้อนและใช้เวลานาน งานวิจัยนี้ได้พัฒนาการใช้วิธีฟิกเกอร์ออฟเมอริท (Figure of Merit; FOM) ซึ่งเป็นการรวมคุณสมบัติต่างๆ ให้อยู่ในเทอมไร้หน่วย เพื่อใช้สำหรับทำนายสมรรถนะของระบบได้อย่างรวดเร็ว โดยที่ไม่ต้องใช้การคำนวณด้วยวิธีทางเอนทัลปี โดยนำสารเดี่ยว 8 ชนิด ซึ่งพิจารณาจากคุณสมบัติทางเทอร์โมไดนามิกส์ ความเป็นมิตรต่อสิ่งแวดล้อม และความปลอดภัยในการใช้งาน มาผสมเป็นสารผสมแบบซีโอทรอปิค 12 ชนิด ในสัดส่วนที่ทำให้เกิดสมรรถนะการทำความร้อน (COP_H) และสมรรถนะการทำความเย็น (COP_L) สูงสุด ผลการวิจัยพบว่า การใช้สารผสมทำให้ระบบมีสมรรถนะสูงกว่าการใช้สารเดี่ยว และสัดส่วนของสารผสมที่ทำให้เกิดสมรรถนะสูงสุด อยู่บริเวณเดียวกับสัดส่วนที่ทำให้เกิดอุณหภูมิระหว่างที่เปลี่ยนสถานะสูงสุด นอกจากนี้ เมื่อหาสมรรถนะของปั๊มความร้อนด้วยวิธี FOM พบว่า ได้ผลลัพธ์สอดคล้องกับวิธีทางเอนทัลปีและการทดสอบกับระบบจริง โดยมีความแตกต่างเฉลี่ยไม่เกิน 3%

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Research Article

Use of Figure of Merit as a Quick Method for Finding Performance of Heat Pump with Zeotropic Mixtures

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Abstract

Heat pumps have been widely used because of their low energy consumption and environmental friendliness. Working fluid has a strong influence on the system thermal efficiency. Most working fluids used in heat pumps are single refrigerants, which are found to cause high irreversibility rates, resulting in high electricity costs. This problem could be alleviated by using zeotropic mixtures. There are various software programs for monitoring the system performance; however, using software for best performing refrigerant fluid selection is still complex and time consuming. This paper proposes a quick method to evaluate the COP and capacity of heat pumps using zeotropes, precisely Figure of Merit (FOM) which combines thermodynamic and thermal properties in dimensionless term instead of enthalpy calculation. Eight single-substance refrigerants, considered from thermodynamic properties, environmental properties and safety were selected and blended into twelve zeotropic mixtures at various compositions. The simulations were carried out with a standard heat pump cycle to find out the ideal composition for the highest COP for heating (COP_h) or cooling (COP_l). The results showed that the mixtures gave higher COP than the single refrigerant; meanwhile the highest COP occurred with the composition having highest gliding temperature. Moreover, the COPs for both heating and cooling calculated by FOM agreed very well with those calculated by enthalpy method from the literatures, whereby the average difference remained no greater than 3 percent.

Keywords: Heat Pump, Coefficient of Performance, Zeotropic Mixture, Figure of Merit, Heating and Cooling

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1. Introduction

Heating and cooling have been used in many applications especially food industry for drying and cooling to control quality of products. The processes consume a lot of energy consumption in terms of electricity and fuels which also generate environmental impact. Therefore, heat pump is a prospective technique to solve these problems due to its ability to generate both heating and cooling with high energy efficiency and environmentally friendly [1]. Generally, the heat pump working fluid is single refrigerant of which the temperatures at the evaporator and the condenser are constant during the phase change and the cycle COP or the EER depends on these temperatures and refrigerant types. Arpagaus *et al.* [2] simulated COP of a heat pump using various single refrigerants at evaporating temperature of 60°C and condensing temperature of 130°C. It was found that the use of R245fa and R1233zd gave high COP at 2.82 and 3.07 respectively. Shuxue *et al.* [3] tested R32 in a heat pump for cooling at evaporating temperature of 5°C and condensing temperature of 40°C. It was found that the EER of system was 3.80. Anyhow, for single refrigerant, high irreversibilities during heat exchanges were found at evaporator and condenser due to temperature differences between the refrigerant and the external fluids resulting in high compression work. To solve this problem, zeotropic mixture having gliding temperature during phase change could be used to replace the single refrigerant [4]. Yilmaz [5] used R12, R22, R114 and R12/R22, R12/R114 mixture in a heat pump and found that the mixtures gave higher COP than those of the single refrigerants. Zhang *et al.* [6] compared performance of a heat pump having R245fa and R245fa/R152a mixture with various compositions. It was found that all mixture compositions gave higher

COP than R245fa. Khalifa *et al.* [7] studied performance of a cascade heat pump having R134a and R410a/R134a mixture for cooling. It was found that the mixture gave 24% higher COP than that of the single refrigerant. Venzik *et al.* [8] tested R1270, R600a and R1270/R600a mixture in a heat pump. The result also showed that the mixtures gave 5–7% COP improvement compared with single refrigerant.

From the literatures, it could be seen that the uses of zeotropic mixtures give higher COP compared with single refrigerant. However, evaluation of heat pump performance with these mixtures is rather complicated and the thermodynamic properties could be calculated by trial and error. Therefore, a quick method for calculating the system performance is needed which is the aim of this study. Kuo *et al.* [9] gave a technique to evaluate performance of organic Rankine cycle which was a reversed cycle of heat pump. A dimensionless term, Figure of Merit (FOM) consisted of specific heat, latent heat, condensing temperature and evaporating temperature was correlated with cycle efficiency. With the information of working fluid properties and operating conditions, the FOM could be calculated and also the cycle efficiency. Deethayat *et al.* [10] applied the FOM technique to the ORC having zeotropic mixture for evaluating the cycle performance.

In this paper, the FOM concept was developed for quick calculation of heating and cooling COPs of heat pump having zeotropic refrigerant. This is a new method for quick calculation of heat pump performance. In addition, this approach could be used to classify the zeotropic refrigerants those give high heat pump performance.

2. Materials and Methods

2.1 Working cycle

Heat pump consists of four main components which are compressor, condenser, expansion valve and evaporator as shown in Figure 1. The refrigerant flows into evaporator to absorb heat from heat source. Then it was compressed through the compressor to get high temperature and pressure. After that, it flows into condenser to transfer heat to heat sink. Afterward, the refrigerant exits condenser to expansion valve to reduce pressure and temperature and flows to the evaporator to start a new cycle.

The working cycle of the heat pump can be given in T-s diagram when using single and zeotropic refrigerants as shown in Figure 2(a) and 2(b) respectively. It could be seen that at the same operating condensing and the evaporating temperatures, the zeotropic refrigerant has less temperature differences between the external fluids and the refrigerant compared with those of single refrigerant since the mixture has gliding temperature during phase change. Smaller temperature difference means that less irreversibility is obtained which results in less cycle work input and higher cycle COP.

2.2 System performance

To find COP of a heat pump cycle, the thermodynamic properties at each state (1–5) in the diagram in Figure 2 are needed with these following assumptions:

- System operates under steady condition.

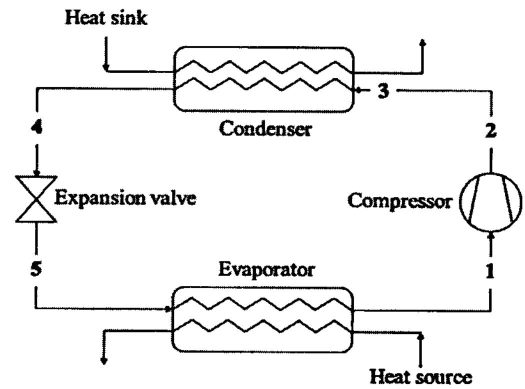

Figure 1: Schematic diagram of a standard heat pump cycle.

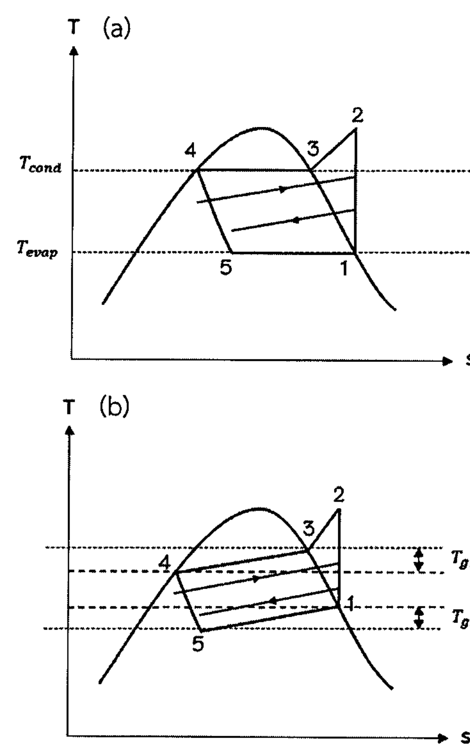

Figure 2: T-s diagram of standard heat pump cycle using (a) single refrigerant and (b) zeotropic refrigerant.

- Efficiency at compressed process is isentropic.
- The expansion process is throttling process.
- Pressure drop and heat loss are negligible.

• Refrigerant at outlets of evaporator and condenser are saturated

Then, heat and work at each component could be calculated as follows

Work used by compressor:

$$\dot{W}_{comp}=\dot{m}_R(h_2\text{-}h_1) \tag{1}$$

Heat transferred from condenser:

$$\dot{Q}_{cond}=\dot{m}_R(h_2-h_4) \tag{2}$$

Heat absorbed by evaporator:

$$\dot{Q}_{evap}=\dot{m}_R(h_1\text{-}h_5) \tag{3}$$

COP for heating:

$$COP_{heating}=\frac{\dot{Q}_{cond}}{\dot{W}_{comp}} \tag{4}$$

COP for cooling:

$$COP_{cooling}=\frac{\dot{Q}_{evap}}{\dot{W}_{comp}} \tag{5}$$

Where "$\dot{m}_R$" is the mass flow rate of refrigerant in kg/s and "h_1 *to* h_5" are specific enthalpies of state points in kJ/kg.

In case of zeotropic mixture, since the temperatures during phase change at a given pressure are not constant. The calculations of the enthalpy at each state and the cycle COP are rather complicated and the trial and error approach is needed. The steps of calculation are given in Figure 3. The calculation starts with the trials of the saturated temperatures leaving the evaporator (T_1) and the condenser (T_4) and the process finishes when the convergences of these values are lower than 0.1%.

Following the FOM technique of ORC developed by Kuo *et al.* [9] and Deethayat *et al.* [10]. A dimensionless term called FOM is defined as to Equation (6)

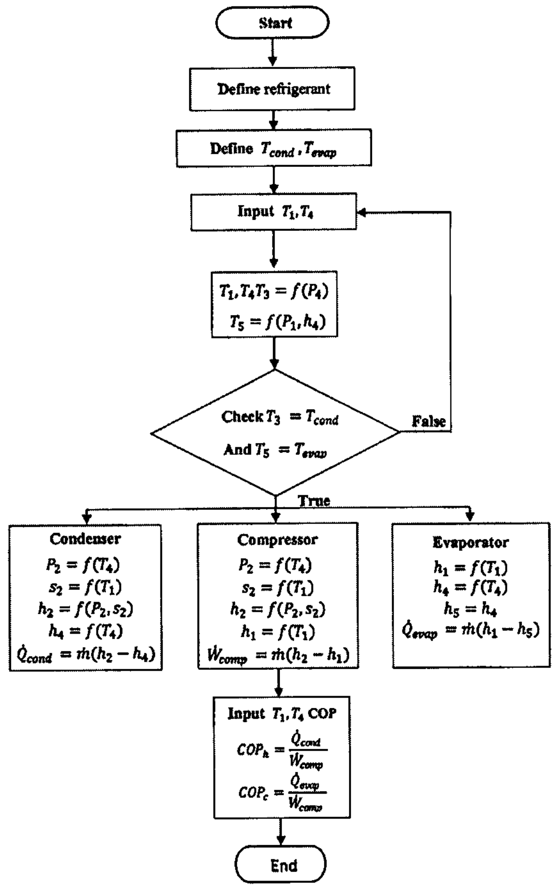

Figure 3: Flow chart for calculating the heat pump performance using zeotropic mixture by enthalpy method.

$$FOM=Ja^{0.1}\left(\frac{T_{cond}}{T_{evap}}\right)^{0.8} \tag{6}$$

However, in case of heat pump with zeotropic mixtures, this FOM could not be used. So, this paper modified the previous FOM which can be defined as:

$$FOM=Ja^{0.1}\left(\frac{\bar{T}_{cond}\text{-}\bar{T}_{evap}}{\bar{T}_{cond}}\right) \tag{7}$$

Where:

$$\bar{T}_{cond}=T_{cond}\text{-}\frac{T_{g1}}{2} \tag{8}$$

$$\bar{T}_{evap}=T_{evap}+\frac{T_{g2}}{2} \tag{9}$$

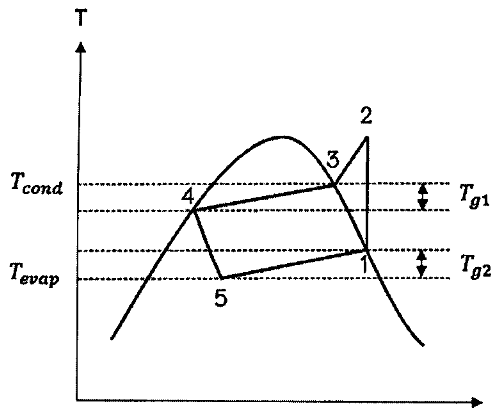

Figure 4: Gliding temperature in condensing and evaporating process.

Jacob number *(Ja)* can be defined as to Equation (10)

$$Ja = \frac{C_p \Delta T}{h_{fg}}. \tag{10}$$

Where "C_p" is the specific heat in kJ/kg K, "ΔT" is the temperature difference between condensing and evaporating in K, "hfg" is the latent heat at condensing temperature in kJ/kg, "T_{g1}" and "T_{g2}" are the gliding temperatures at the condenser and the evaporator, respectively in K as shown in Figure 4.

A correlation of FOM with the standard cycle COP for zeotropic mixture could be developed as described in Figure 5. The detail on the correlation is described in the following part. With the given operating conditions, the FOM could be calculated and this one is used to indicate the COP immediately

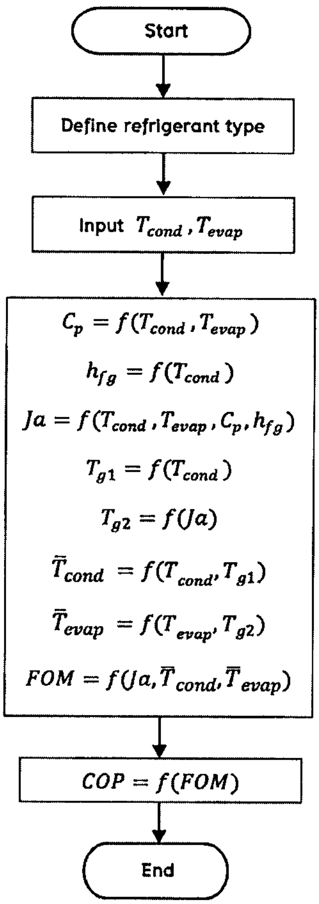

Figure 5: Flow chart for calculating the heat pump performance using zeotropic mixture by FOM technique.

2.3 Working fluids

Zeotropic mixtures in this paper are blended from eight single refrigerants – R245fa, R1233zd, R245ca, R152a, R134a, R32, R125, and R143a at various compositions. The properties of these single refrigerants are given in Table 1. The high boiling point refrigerants are used for heating and the low boiling point refrigerants are used for cooling.

3. Results and Discussion

3.1 Zeotropic mixtures

Figure 6 shows the COPs for heating (COPh) and cooling (COPl) and gliding temperature of selected zeotropic mixtures blended from the single refrigerants. The properties of zeotropic mixtures were calculated by REFPROP 9.1. It could be seen that the COPs and

Table 1: The thermodynamic properties, environmental properties and safety of selected single refrigerants [11]

Refrigerant	M (kg/kmol)	T_{nbp} (°C)	P_{cr} (Mpa)	T_{cr} (°C)	ᵃODP	ᵇGWP	Safety Group
R245fa	134.05	15.1	3.651	154.0	0	1050	B1
R1233zd	130.5	27.7	3.5709	165.6	0	20	A1
R245ca	134.05	25.1	3.9407	174.4	0	726	n.a
R152a	66.05	-24	4.5168	113.3	0	133	A2
R134a	102.03	-26.1	4.0593	101.1	0	1370	A1
R32	52.02	-51.7	5.782	78.1	0	716	A2L
R143a	84.04	-47.2	3.761	72.7	0	4180	A2L
R125	120.02	-48.1	3.6177	66	0	3420	A1

[a]ODP: Ozone depletion potential relative to R11.

[b]GWP: Global Warming Potential relative to CO_2.

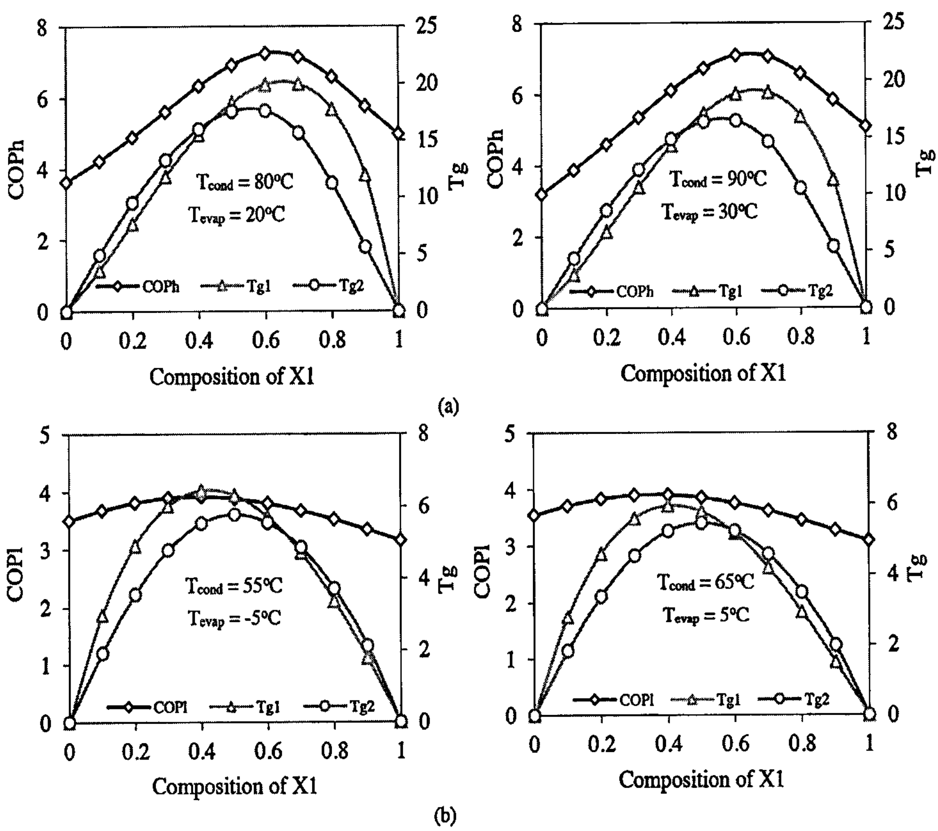

Figure 6: The system COP and gliding temperature v.s. refrigerant compositions of (a) R245ca/R134a and (b) R32/R152a.

Table 2: The thermodynamic properties of the zeotropic mixtures [12]

Refrigerant	Mass fraction	M (kg/kmol)	Pcr (Mpa)	Tcr (°C)
R245fa/R152a	80/20	111.16	4.0767	141.68
R245fa/R134a	60/40	119.1	4.1331	131.15
R1233zd/R152a	70/30	100.95	4.2382	142.10
R1233zd/R134a	50/50	114.52	4.227	130.24
R245ca/R152a	70/30	122.51	4.5024	152.54
R245ca/R134a	60/40	119.1	4.545	144.97
R32/R152a	70/30	55.564	5.6236	88.93
R134a/R32	70/30	79.194	4.8586	91.58
R143a/R152a	70/30	77.693	4.0865	86.03
R143a/R134a	40/60	93.984	3.9952	89.48
R125/R152a	70/30	96.393	4.1111	85.89
R125/R134a	40/60	108.54	3.9937	89.00

gliding temperature are changing with the refrigerant compositions. The maximum COPs could be found around the composition that give highest gliding temperature. The optimum compositions of each zeotropic mixture are shown in Table 2. It could be noted that the composition of R152a must not exceed 30% because of flammability.

Figure 7 shows the gliding temperatures, T_{g1} at the condenser and T_{g2} at the evaporator, of the refrigerant mixtures given in Table 2. The operating minimum evaporating temperature of 20–40°C and the maximum condensing temperature of 75–90°C were taken for heating. The minimum evaporating temperature of -10–5°C and the maximum condensing temperature of 40–70°C were also defined for cooling. The results are shown in Figure 7.

Figure 7 shows that T_{g1}, the temperature difference between state 3 and 4 in Figure 4, depended on the condensing temperature only. For T_{g2}, the temperature difference between state 1 and 5 in Figure 4, the value depended not only on the evaporating temperature but it was varying with Ja.

With these gliding temperatures, the average values of condensing temperature and evaporating temperature in Equation (8) and (9) could be taken and the FOM in Equation (7) could be evaluated for the zeotropic mixtures at various operating temperatures.

Figure 8 shows the correlation between the COP and FOM of the selected zeotropic mixtures working at the minimum evaporating temperature of 20–40°C and the maximum condensing temperature of 75–90°C for heating; the minimum evaporating temperature of -10–5°C and the maximum condensing temperature of 40–70°C for cooling. The correlation between COP*h* and FOM could be written as to Equation (11)

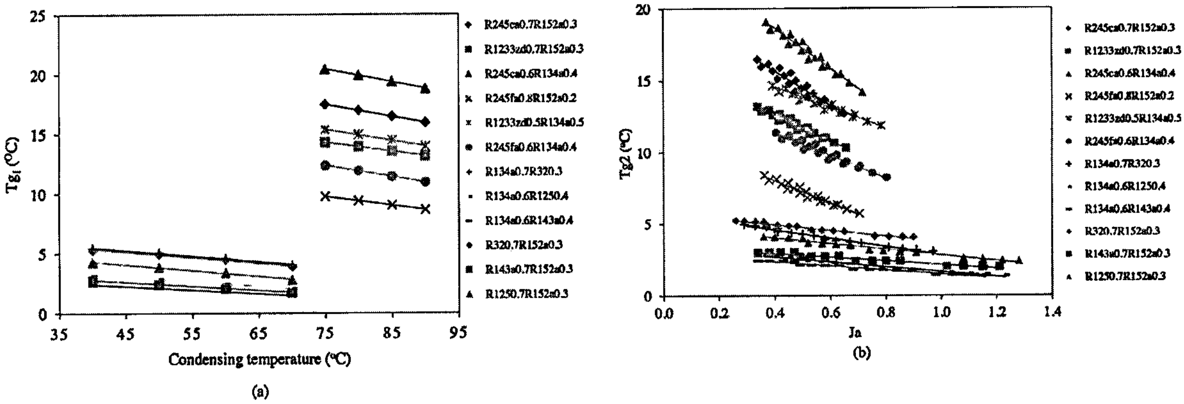

Figure 7: (a) The correlation between T_{g1} and condensing temperature, (b) The correlation between T_{g2} and Jacob number.

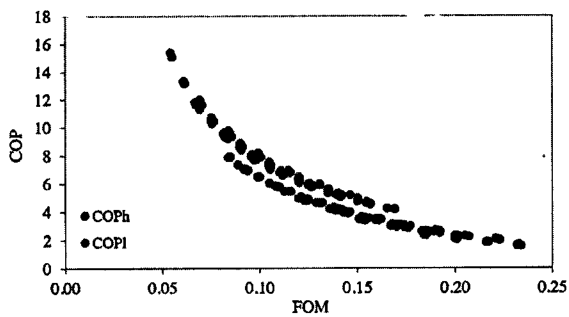

Figure 8: The correlation between the COP and FOM of heat pump using zeotropic mixture.

$$COP_h = 826.87FOM^2 - 264.72FOM + 26.012 \quad (11)$$

and the correlation between COP_l and FOM could be written as to Equation (12)

$$COP_l = 233.29FOM^2 - 112.41FOM + 15.362 \quad (12)$$

All refrigerant mixtures have the same trend of COPs varying with FOM. Lower the FOM resulting in higher the COPs for both heating and cooling. These FOM could also be used to select the refrigerant that gave high cycle COP.

3.2 Experimental cycle

The FOM in this paper is used for standard cycle. But in actual cycle, there is isentropic efficiency at the compressor. So, the COP from the FOM can be applied by multiply the isentropic efficiency into the standard COP. An experimental data of heat pump with zeotropic mixture were taken to validate the calculation results from the FOM technique. The specification of the heat pump with zeotropic mixture was given in Table 3.

The results from FOM technique were used to compare the cycle COP studied by Zhang *et al.* [6] and Sagia and Rakopoulos [13] as shown in Table 4.

From Table 4, it could be seen that the COP from the FOM agreed very well with the enthalpy method and experiments of which the average error was less than 3%.

Nomenclature

T_{cond}	condensing temperature	K
T_{evap}	evaporating temperature	K
h	enthalpy	kJ/kg
s	entropy	kJ/kgK
M	molecular weight	kg/kmol
T	temperature	K

Table 3: The specification of the heat pump with zeotropic mixture

Heat pump type	Water source heat pump
Refrigerant	R245fa/R152a
Compressor	1.2 kW hermetic reciprocating compressor
Evaporator	Coaxial pipe evaporator with inner and outer diameters of 19 mm and 25 mm, respectively
Condenser	Coaxial pipe condenser with inner and outer diameters of 19 mm and 25 mm, respectively
Expansion valve	Thermostatic expansion valve

Table 4: The performance comparison of FOM, enthalpy method and experiments

Refrigerant	T_{cond} (°c)	T_{evap} (°c)	η_{isen}	COP_{FOM}	$COP_{enthalpy}$	$COP_{experimental}$	Error (%)
R245fa0.8/R152a0.2	75	30	0.4	3.29	3.22	3.17	2.89
R245fa0.8/R152a0.2	80	35	0.4	3.29	3.20	3.21	2.58
R245fa0.8/R152a0.2	85	40	0.4	3.29	3.18	3.27	1.98
R134a0.7/R320.3	40	0	0.7	4.50	4.55	4.58	1.45

P	pressure	kPa
COP	coefficient of performance	
EER	Energy Efficiency Ratio	
η_{isen}	isentropic efficiency	

Subscript

comp	compressor
cond	condenser
evap	evaporator
h	heating
l	cooling
nbp	normal boiling point
cr	critical

4. Conclusions

This paper proposed a quick method to find the COP of system by dimensionless term called FOM. There are important points which could be concluded as

Use of zeotropic mixture gave higher COP than single refrigerant for both heating and cooling. The COP was highest around the composition that gave highest gliding temperature.

T_{g1} depends only on the condensing temperature but T_{g2} strongly depend on Ja.

A correlation between COP and FOM could be performed for the selected refrigerant mixtures for heating and cooling. With a given refrigerant composition, when the operating conditions were defined, the FOM could be calculated and the COP could be pointed out immediately.

FOM could be used to classify the refrigerant blend that gave high COP. Lower the FOM resulted in higher the COP.

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