Experimental study of working fluids in thermosyphon heat exchanger with annular fins for thermal performance enhancement

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Abstract

This research study aims to investigate the effect of working fluids on thermal performance in a thermosyphon heat exchanger with and without annular fins. The thermosyphon heat exchangers were formed from the evaporator, adiabatic and condenser sections in which the lengths were 20, 10 and 20 cm respectively, made from steel, the tube had an outside diameter of 20 mm and a thickness of 3 mm. Distilled water, ethanol and R134a were used as the working fluids with a filling ratio of 50% by total volume of the evaporator section. The temperature of the hot air in the evaporator section was controlled at 60 70 and 80 ° C The results show that when the variable temperature increased from 60, 70 to 80°C the heat transfer rate and thermal effectiveness also increased. In addition, it was found that at all operating temperatures, the highest heat transfer rate and thermal effectiveness were with R134a as the working fluid. Moreover, the thermosyphon heat exchanger with annular fins had a higher heat transfer rate and thermal effectiveness than the thermosyphon heat exchanger without fins under all variables.

Keywords: Annular fins, Heat exchanger, Thermosyphon, Thermal performance, Working fluid

Introduction

For quite a few years, thermosyphon heat exchangers (TPHEx) have become an important subject for energy conservation. Due to it being a passive device with high efficiency thermal conductivity, low cost and easy construction. They make use of the highly efficient thermal transport process of evaporation and condensation to maximize the thermal conductance between a heat source and a heat sink. They have a range of applications in thermal engineering, such as air preheater, air conditioning systems, waste heat recovery and water heater[1-3]. A schematic of the working principle of the TPHEx is show in Fig. 1. An operating TPHEx may be divided into three distinct sections, namely the evaporator, adiabatic and condenser sections. Energy is added into the evaporator section where the working fluid reaches its boiling temperature and begins to boil. The buoyant vapor of the working fluid rises through the adiabatic section to the condenser, where it condenses. The condensate then drains back into the evaporator section by gravitation. This process of evaporation and condensation of the working fluid repeats itself continuously as long as heat is supplied to the evaporator and an opportunity for its removal from the condenser exists[4-5].

Due to the operating principle of a TPHEx, the main factors that affect the thermal performance of a thermosyphon are inclination angle, operating temperature and pressure, filling ratio, aspect ratio and working fluid. In this research, the experiments were related to the working fluid and operation in a low temperature range (200 to 550 K). Most thermosyphon applications fall within this range[5]. There were many studies that have attempted to

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investigate the thermal performance of thermosyphons [3, 6-9]. Such as Pipatpaiboon et al.[6] that presents a case study for the design, construction and testing of a thermosyphon heat exchanger (TPHE) in a Thai bio-diesel factory to reduce the temperature of the bio-diesel after the drying process under actual operating conditions. The temperature of the bio-diesel passing though the evaporator section was 120 °C and the mass flow rates of the bio-diesel were set at 0.07, 0.15 and 0.21 kg/s. They found that the maximum heat transfer rate was12.48 kW/m^2 and the experimental effectiveness was 0.38 at a mass flowrate for bio-diesel at 0.21 kg/s with R134a as the working fluid. The TPHE could reduce the temperature of the bio-diesel from 120 to 81°C. Nimmol and Ritthong [7] studied the development of a paddy drying system using thermosyphon heat pipes (THPs). In this study, R-134a was used as the working fluid and the temperatures of the energy sources were 60, 70 and 80 °C, and the characteristics of the themosyphon heat pipes (finned and unfinned) on the change in moisture content and quality of paddy were then investigated and discussed. Paddy with an initial moisture content of around 26% (d.b.) was used as the test material. The experiments were performed until a paddy moisture content of 14% (d.b.) was obtained under each drying condition. The results obtained from the experiments showed that, compared with hot air and unfinned thermosyphon heat pipes, the rate of moisture reduction in the paddy was higher when hot water and finned thermosyphon heat pipes were employed.

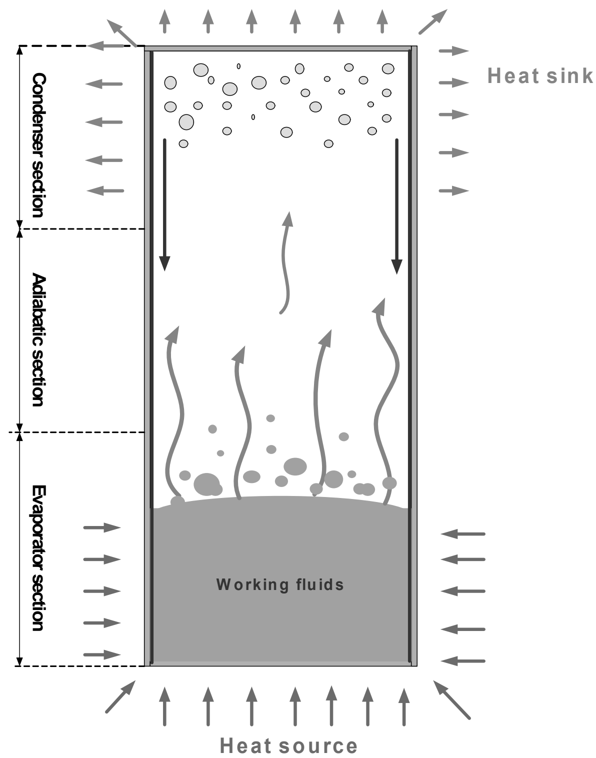

Figure 1 Schematic of the working principle of the TPHEx[19].

There have been some publications related to the experimental work on the performance of thermosyphon with different working fluids. Li et al[10]studied the heat transfer characteristics of a TPCT at low temperature differences with R11, R22 and water as the working fluids. Nuntaphan et al[11] selected R123, methanol and acetone as the working fluids for use in an experiment about using the oscillating heat pipe technique as an extended surface in wire on a tube heat exchanger for heat transfer enhancement. The most common thermosyphon working fluid at a low operating temperature range is water, due to its good thermo physical properties, availability, low cost, non-toxic and environmentally neutral properties, as well as having the added benefit of being safe to use during handling[12]. Moreover, earlier work also studied possible working fluids for low to intermediate operating temperatures that included R-11, R-12, R-22 and R113[13-16]. However, with these there were negative environmental impacts and/or toxicity. Most of them have been prohibited and replaced by more environmentally friendly and low to non-toxic fluids, such as R134a and 3 M Fluorinert™ liquids[17].

Thus, the objectives of this research were to investigate a passive heat transfer enhancement technique with annular fins on a thermosyphon wall and the effect of working fluids on the thermal performance of the TPHEx with anular fins. R134a, ethanol and distilled water were selected as working fluids. The results are compared with the heat transfer rate and thermal effectiveness of a thermosyphon heat exchanger with and without fins and using all working fluids.

Thermosyphon heat exchanger analysis

Heat transfer rate of thermosyphon heat exchanger

The heat transfer rate of thermosyphon heat exchanger is as follows:

$$Q_c = \dot{m}_c C_{p,c}\left(T_{c,out} - T_{c,in}\right) \quad (1)$$

$$Q_e = \dot{m}_h C_{p,h}\left(T_{h,in} - T_{h,out}\right) \quad (2)$$

Where

Q_c is heat transfer rate of condenser section

Q_e is heat transfer rate of evaporator section

c refer to cold fluids and condenser section

h refer to hot fluids

Thus, the heat transfer rate at the air side of the evaporator and condenser sections, respectively. In this study, the mathematical average of the heat transfer rate can be calculated from:

$$Q_{ava} = 0.5\left(Q_e + Q_c\right) \quad (3)$$

When:

$\dot{m}_c = (\rho v A)_c$ and $\dot{m}_h = (\rho v A)_h$

Where: A is the total surface area that can be represented by the following equation:

$$A_f = 2\pi n\left(\left(D_f^2 - D_o^2\right) + D_f f_t\right) \quad (4)$$

$$A_b = n\pi D_o L \quad (5)$$

Thus: $A_{eo} = \eta_e A_f + A_b$ (6a)

and: $A_{co} = \eta_c A_f + A_b$ (6b)

Where:

$$\eta = \frac{\tan\left(\varphi\sqrt{\dfrac{2h_o}{f_t k_f}}\right)}{\varphi\sqrt{\dfrac{2h_o}{f_t k_t}}}, \quad (7)$$

Then:

$$\varphi = \frac{D_o}{2}\left(\frac{D_f}{D_o} - 1\right)\left(1 + 0.35\ln\left(\frac{D_f}{D_o}\right)\right) \quad (8)$$

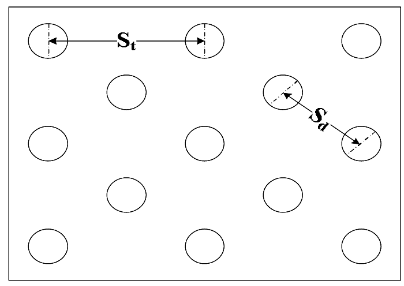

Figure 2 Staggered arrangement

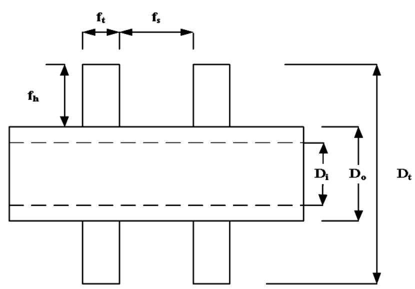

Figure 3 The geometrical parameters for annular fins[18].

Effectiveness of thermosyphon heat exchanger with fins

The effectiveness (Q_{act}) of the heat exchanger can be defined as the ratio of the actual heat transfer rate (Q_{max}) for a heat exchanger to the maximum possible heat transfer rate $\varepsilon = \frac{Q_{act}}{Q_{max}}$ [21]. This can be represented by the following equation:

$$\varepsilon = \frac{Q_{act}}{Q_{max}} \quad (9)$$

When:

$$Q_{act} = \dot{m}_h C_{p,h}\left(T_{e,in} - T_{e,out}\right) = \dot{m}_c C_{p,c}(T_{c,out} - T_{c,in}) \quad (10)$$

As:

$$\varepsilon_e = \frac{\dot{m}_h C_{p,h}(T_{e,in} - T_{e.out})}{\left(\dot{m} C_p\right)_{\min} (T_{e,in} - T_{c.in})} \quad (11)$$

$$\varepsilon_c = \frac{\dot{m}_c C_{p,c}(T_{c,out} - T_{c.in})}{\left(\dot{m} C_p\right)_{\min} (T_{e,in} - T_{c.in})} \quad (12)$$

From which it follows:

$$\varepsilon = Q_e / Q_{\max} = Q_c / Q_{\max} = Q_{ave} / Q_{\max} \quad (13)$$

Where the maximum possible heat transfer rate $(Q_{\max})$ can be represented by the following equation:

In case $C_c < C_h$

$$Q_{\max} = C_c\left(T_{e,in} - T_{c,in}\right) \quad (14)$$

In case $C_c > C_h$

$$Q_{\max} = C_h\left(T_{e,in} - T_{c,in}\right) \quad (15)$$

When $C_c = \dot{m}_c C_{p,c}$ and $C_h = \dot{m}_h C_{p,h}$

Equation 14 and 15 can be rewritten to the general expression[6]:

$$Q_{\max} = C_{\min}\left(T_{hi} - T_{ci}\right) \quad (16)$$

$$Q_{ave} = (Q_e + Q_c)/2 \quad (17)$$

By definition the effectiveness, which is dimensionless, must be in the range $0 \le \varepsilon \le 1$.

Experimental details

The experimental setup used in this study and the thermocouple locations are shown in fig.4. The specifications of the thermosyphon heat exchanger are given in table 1. The test consists of three main sections: the TPHEx section, the heating loop the cooling section. This was measured using thermocouples (K-type) with an uncertainty of ±0.1°C at a total of 25 points. The thermocouples were attached to a Data Logger (Agilent Technologies 34970A and the 34970A features 61/2 digits (22bits) of resolution, 0.004% basic DCV accuracy). The device used in the experiment was completely insulated with the glass wool. The amount of heat loss from the evaporator and condenser surfaces was negligible.

The heating loop region is the evaporator section of the TPHEx. This was heated by a voltage regulated heater that controlled the temperature of hot air in the evaporator section at 60 70 and 80 °C. A blower was used to control the heating loop with an inverter (Siemens sinamics g110, output frequency 0 Hz-650 Hz and Cos j ³ 0.95) to controller the speed motor. The air inlet and outlet temperatures of the experimental setup were measured when the system reached a steady state condition.

The cooling loop is in the region of the condenser section of the TPHEx. This caused cooling by refrigeration and the velocity was controlled at 0.5 m/s by use an inverter. The cooling air was allowed to flow through the condenser to cool the TPHEx. The air inlet and outlet temperatures in the condenser zone were measured.

The TPHEx section, for the adiabatic section of the heat exchanger was completely insulated with **poly-ethylene**, in fig.5. R134a, ethanol and distilled water were selected as the working fluids with a filling ratio of 50% by total volume of the evaporator section.

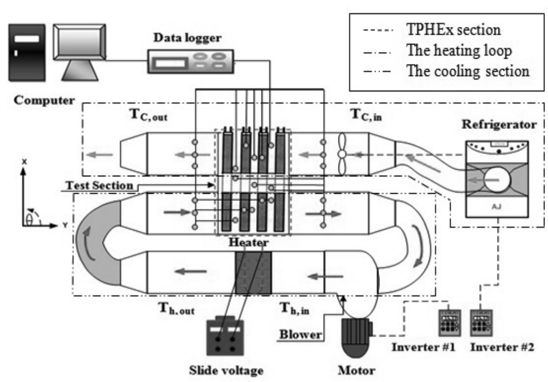

Figure 4 Schematic view of the experimental setup

Table 1 Specification of thermosyphon heat exchanger and testing condition

Description	Value
Dimension of thermosyphon heat exchanger (m)	0.2(W)x0.22(L) x 0.5(H)
Total number of tubes in heat exchanger	13 tube
Tube outside diameter	20 mm
Tube thickness	3 mm
Tube material	Stainless steel
Type and dimensions of fins	Stainless steel annular fin, thickness =2 mm number of fins per tube =16, spacing f_s=2 cm and radius of fin=0.5 cm
	Staggered, S_t= 6.3 cm, S_d=4cm
Thermosyphon arrangement	Distilled Water, Ethanol and R134a
Working fluid	50% of total volume evaporator section
Filling ratio	60 70 and 80°C
Inlet temperature of hot air	25 °C
Inlet temperature of cool air	0.5 m/s
Velocity of air	

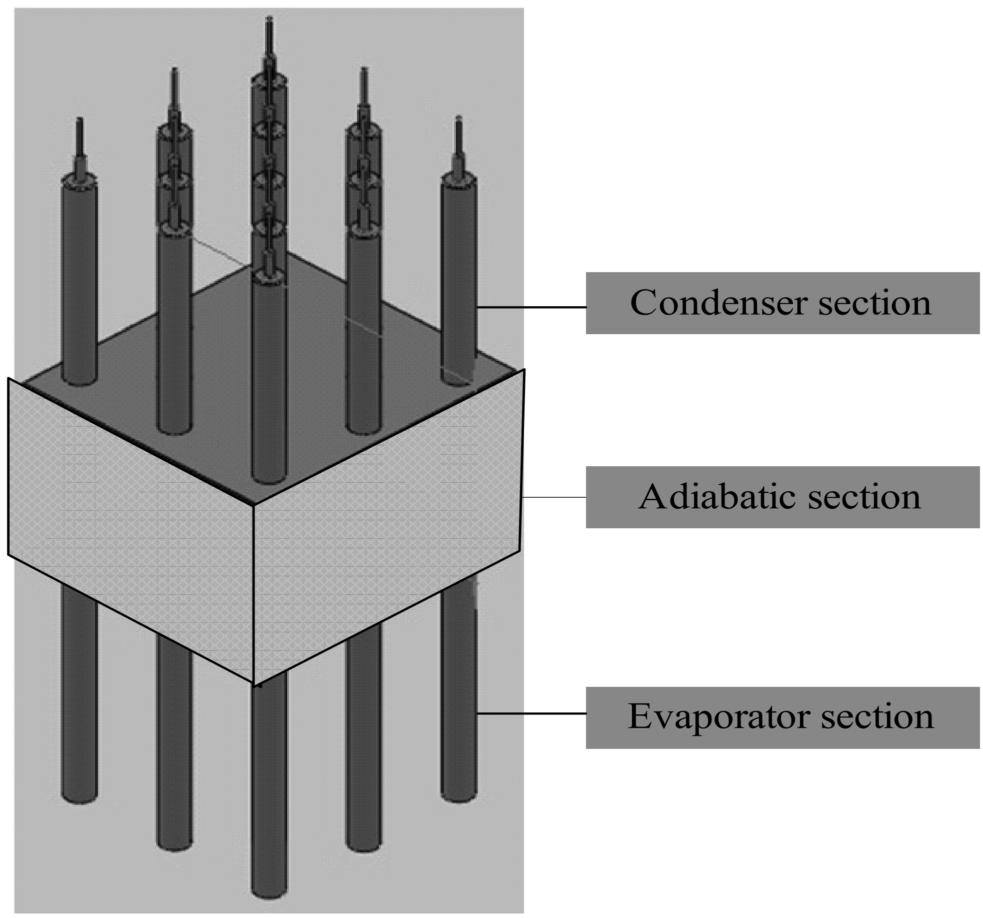

Figure 5 Thermosyphon heat exchanger.

Results and discussion

Effect of working fluids on heat transfer rate of thermosyphon heat exchanger

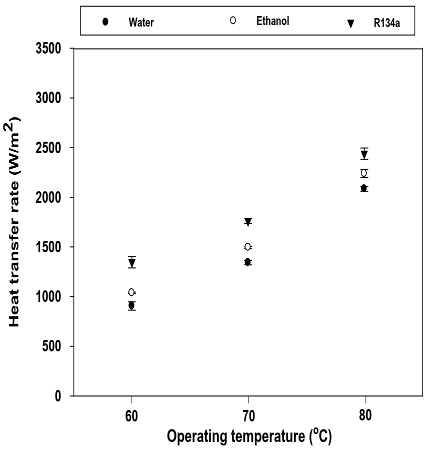

Figure 6 Effect of working fluids on heat transfer rate at different operating temperatures for thermosyphon heat exchanger without fins.

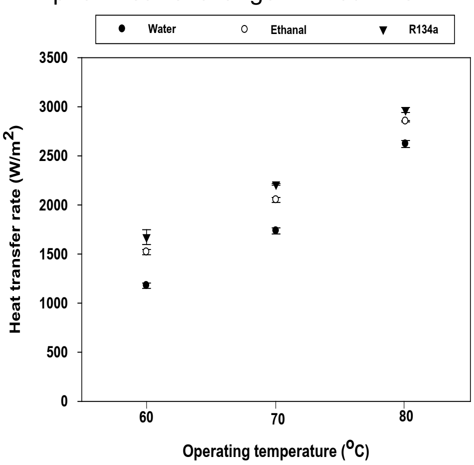

Figure 7 Effect of working fluids on heat transfer rate at different operating temperatures for thermosyphon heat exchanger with fins.

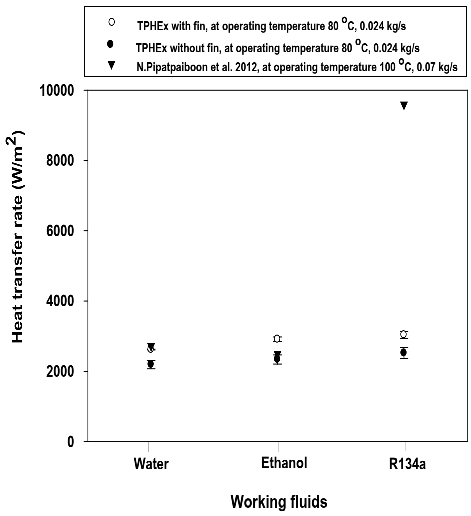

Figure 8 Effect of working fluids on heat transfer rate at an operating temperature of 80 oC for thermosyphon heat exchanger when comparing result with Pipatpaiboon et al.[6].

Figs. 6-7 show the effect of working fluid on heat transfer rates at different operating temperature for the thermosyphon heat exchanger with and without fins (radius of fin is 0.5 cm.). In the experiment, R134a, ethanol and distilled water were selected as the working fluids with a filling ratio of 50% by total volume of the evaporator section. The temperature of hot air in the evaporator section was controlled at 60 70 and 80 °C. The velocity of the cool air in the condenser section was at 0.5 m/s. The experimental results clearly present the effect of the working fluid on the heat transfer rate. Comparing working fluids found that when the working fluid was changed from distilled water to ethanol and to R134a the heat transfer rate increases. In addition, it was found that when the operating temperature increased from 60 70 to 80 °C the thermal efficiency increased under all working fluids. This was due to it increasing the ease of phase change to vapor in the working fluids. In this experiment, R134a showed the maximum heat transfer rate because the boiling point of R134a is lower when compared with distilled water and ethanol. The thermosyphon heat exchangers with fins had heat transfer rates that were higher than the thermosyphon heat exchangers without fins. The fins increased the surface area that enhanced heat transfer.

Pipatpaiboon et al. studied the design, construction and testing of a TPHE in a Thai bio-diesel factory to reduce the temperature of the bio-diesel after the drying process under actual operating conditions. The thermosyphon was made of 17 steel tubes with an outside diameter of 32 mm and a 1 mm wall thickness. Three working fluids were tested in the thermosyphon: distilled water, methanol and R134a. This experiment found results that were similar, and the heat transfer rate of Pipatpaiboon's experiment higher this experiment because it is heat exchanger in liquid to liquid which liquid will has specific heat value more than air, see fig. 8.

Effect of working fluids on thermal effectiveness of thermosyphon heat exchanger

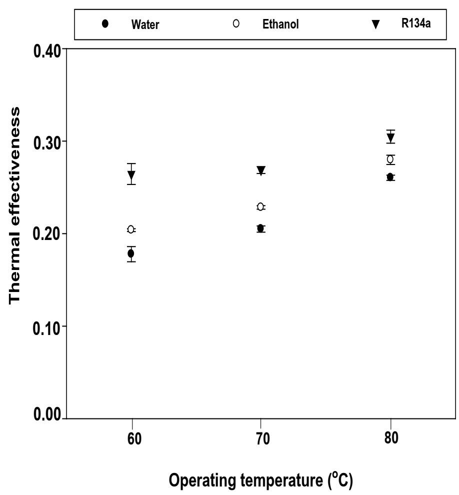

Figure 9 Effect of working fluids on thermal effectiveness at different operating temperatures for thermosyphon heat exchanger without fins.

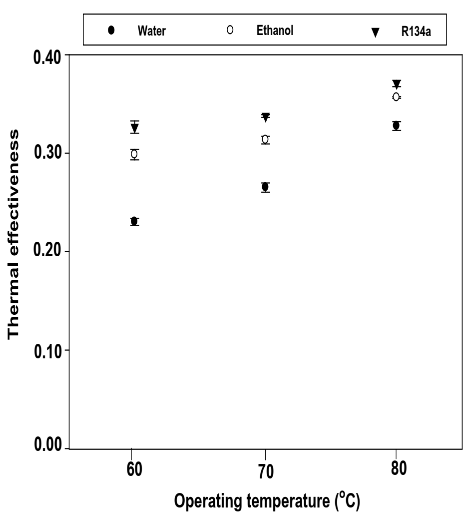

Figure 10 Effect of working fluids on thermal effectiveness at different operating temperatures for thermosyphon heat exchanger with fins.

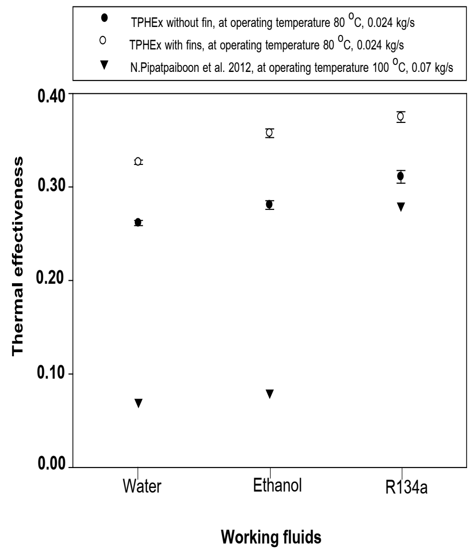

Figure 11 Effect of working fluids on thermal effectiveness at an operating temperature of 80 oC for thermosyphon heat exchanger when comparing the result with Pipatpaiboon et al.[6].

Figs. 9-10 show the effect of working fluid on thermal effectiveness at different operating temperatures for a thermosyphon heat exchanger with and without fins (radius of fin is 0.5 cm.). The experimental results present the effect of working fluid on thermal effectiveness. When changing the working fluid from distilled water to ethanol and to R134a it was found that the heat transfer rate increases. In addition, it was found that when the operating temperature increased from 60 70 to 80 °C, the thermal efficiency for all working fluid increased. Thus, the thermal effectiveness also increases. In this experiment, R134a showed maximum thermal effectiveness because it had the highest actual heat transfer rate. The thermal effectiveness may be determined from equation (9), which will mean the thermal effectiveness also increases. Comparing the thermosyphon heat exchangers with and without fins found that the TPHEx with fins has a higher heat transfer rate; the thermal effectiveness was also higher than the TPHEx without fins.

When comparing the result with Pipatpaiboon et al. it was found that this result was similar, as shown in fig. 11. When changing the working fluids from distilled water to ethanol and to R134a the thermal effectiveness increases.

Conclusion

The experiments investigated a passive heat transfer enhancement technique with annular fins on the thermosyphon wall and the effect of working fluid on the thermal performance of the TPHEx with anular fins. R134a, ethanol and distilled water were selected as the working fluids. Based on the analysis of the experimental investigations presented in this paper, the following conclusions can be drawn:

1. The working fluid had an effect on heat transfer rate and thermal effectiveness for both thermosyphon heat exchangers, when changing the working fluids from distilled water to ethanol and to R134a, the heat transfer rate and thermal effectiveness increased, at all operating temperatures.

2. The operating temperature had an effect on the heat transfer rate and thermal effectiveness for both thermosyphon heat exchangers using all working fluids.

3. The heat transfer rate and the thermal effectiveness of the thermosyphon heat exchanger with fins under all working fluids and all operating temperatures were higher than the thermosyphon heat exchanger without fins.

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