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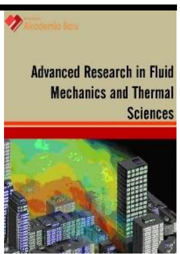

Heat Transfer Performance of Oscillating Heat Pipe with Ethanol and Methanol Working Fluid with Different Inclinations for Heat Recovery Application

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ABSTRACT

In this paper, the experimentally research about the heat transfer characteristic of the OHP using methanol and ethanol working fluid for heat recovery implementation. The OHP was manufactured with l_{eff} of approximately 500 mm, which is not typically used in previous OHP data experimental tests. The results of this experimental data will provide more experimental data for the characteristic behaviour of PHP as heat recovery design. It was found that methanol working fluid has a lower temperature difference between evaporator and condenser which is lower than ethanol. There was no significant difference in changes in methanol inclination and OHP ethanol to the phenomenon of temperature fluctuations that occur in the initial heat supply. The increase in heat supply increases the thermal conductivity of OHP in all working fluids and inclination. In the average initial heat supply, effective thermal conductivity ranged from 844.5 to 1100.43 W/mK. Ethanol in the 60° inclination has the highest thermal conductivity in the initial heat supply. At a maximum heat supply (76 watt), methanol at 90° inclination has a maximum thermal conductivity of 13,586 W/mK or 35.2 times solid thermal copper conductivity. Overall, OHP Methanol has the capability of heat transfer better than ethanol.

Keywords:
oscillating heat pipe, Inclinations, heat recovery, methanol, ethanol

1. Introduction

Pulsating Heat Pipe (PHP) commonly consists of a small diameter meandering copper tube with both ends connected together or not connected. A PHP transfers heat through a consistent motion of the liquid-vapor mixture which pulsates or oscillate between evaporator and condenser. These oscillations are driven by thermally excited of working fluid. Currently, PHP is being heavily studied in many countries, due to their simplicity, flexibility, high performance, compact sizes coupled with

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relatively cheaper costs [1-5]. As one of the promising technologies from heat pipe family, PHP offers reliable operation (no moving parts and free of vibration).

Even that PHP has a simple structure their working fundamental is very complicated compared with conventional cooling device especially wick heat pipe [6,7]. Its working principle strongly affected by various types of two-phase instabilities and thermo-hydrodynamics of working fluid. Similarly, with other heat pipe types, a PHP consists at least of two parts [8-10]. Namely evaporator, condenser and adiabatic, which the last one is optional part. One end of this bundle of tubes serves as evaporator, which absorbs heat from the heat source. The opposite side called condenser sections, which at the same time, release heat to the environment. Those two actions will create non-equilibrium pressure between evaporator and condenser. Thus, these pressure pulsations will act as the driving force for the motions of liquid and vapor slug within the capillary tube. As a result, heat will be transfer for evaporator and condenser with such a unique way.

The heat transfer performance in OHP is predicted to be influenced by various parameters. Han *et al.,* [2] divided this parameter into three general aspects, (i) geometric parameter, among others; inner diameter, shape of cross section, configuration of tubes, evaporator and condenser length, number of turns (ii) physical properties, include thermophysical properties of working fluid, nanofluid, (iii) operational parameter, include, filling ratio, heat flux, orientations, external force [1,2,11,12]. Various PHP performance tests have been carried out on the effect of inclination angles.

Xian *et al.,* conducted an experimental test with OHP, which has evaporator length of 200 mm. The working fluid of OHP was filled with water and ethanol [13]. His results stated that the temperature difference is necessarily important for ensuring the OHP working. Lin *et al.,* [14] investigated the influence of heat transfer length and inner diameter at the heat transport performance of miniature oscillating heat pipes (MOHPs). Their study showed that MOHP has an effective range for normal operation. The performance of MOHP almost equal with sintered heat pipe at horizontal mode for heat heating power. Rittidech *et al.,* examined copper OHP with variations inner diameter, evaporator, working fluid and check valve [15]. They found that OHP with check valve has higher performance with the shorter evaporator. Naik *et al.,* [16] evaluated the performance parameter of PHP for different working fluid, filling ratios, heat supply at horizontal and vertical orientation. They found that Acetone has better performance among the working fluids. Also, the single loop performs better at horizontal inclination during all heat supply, filling ratio and working fluids. Tong *et al.,* [17] conducted a visualization study for methanol OHP and found that the bubble displacement of methanol oscillation versus time is in the form of quasi-sine waves. Their study also stated that high amplitude of oscillation shows up during the start-up stage. Saha *et al.,* [18] stated that methanol and water have better performance for vertical and horizontal inclinations.

Akachi invented OHP at early 1990 to solve the cooling problem at electronic device [19]. Hence, most of the OHP research was designed with an effective length (l_{eff}) of less than 110 mm. Recently, research has been turning to the use of OHP as a heat exchanger and heat recovery device [13,20-22]. Therefore, longer design of OHP with l_{eff} more than 350 mm start to investigated [20,23,24].

The objective of this research is to study experimentally the heat transfer characteristic of the OHP using methanol and ethanol working fluid for heat recovery applications. The experimental research also conducted with different orientations. The OHP was manufactured with l_{eff} of approximately 500 mm, which is rarely used in previous OHP study. The implementation of OHPs in the heat recovery and heat exchanger design areas are became recent trend in the next future. The results of this experimental data will provide more experimental data for the characteristic behavior of PHP as heat recovery design.

2. Methodology

Figure 1(a) show the schematic of the experimental research for OHP. The rig consists of a closed-loop OHP, heating system for evaporator, water-cooling system for condenser, and data acquisition system. The OHP was made from a capillary tube (red copper) with 1.7 mm of inlet diameters. The chosen inlet diameter based on the calculation of maximum diameter equation using Eq. (1). The equation was obtained from Bond Number and calculated using the thermo-physical data of the working fluid [12].

$$d_{max} = \sqrt{\frac{B_o \cdot \sigma}{g(\rho_l - \rho_v)}} \tag{1}$$

$$0.7\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \ll D \ll 1.84\sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} \tag{2}$$

Eq. (1) and (2) is one of the important characteristics that distinguish the OHP from other heat pipes. The minimum and maximum limits of the pipe inner diameter are calculated using Eq. (2). The calculation will ensure the working fluid formation within the pipe as train of liquid slug and vapor plug. For example, using the methanol properties (Table 1) and Eq. (1) and (2), the critical capillary diameter for the temperature range between 20−120 °C is 3.147−2.641 mm (d_{max}). This means the liquid slug and vapor plug should always be formed within the channel. The saturation pressure and the ratio of change in pressure to changes in temperature saturation $(dP/dT)_{sat}$ also computed and plotted for the shake of analyses at the result section (Figure 2).

The evaporator, adiabatic, and condenser have lengths of 260, 240, and 260 mm, respectively. The effective length of this OHP is calculated using the following equation.

$$l_{eff} = \frac{(l_{evaporator} + l_{condenser})}{2} + l_{adiabatik} \tag{3}$$

Based on the Eq. (3), the effective length (l_{eff}) of the OHP is 500 mm. The OHP overall dimensions are 760 mm × 400 mm and 13.66 m in length, which form 18 parallel tubes. The OHP was vacuumed for 30 minutes with a rotary vacuum pump before the working fluid was injected. Methanol was employed as the working fluid with 60% filling ratio. One of the filling tubes was then pinched off using special pinch off tools. To ensure there was no leak again at the OHP tube. For heat supplied, wire electric heater was attached to a copper plate (Figure 1(b)). The copper plate then clamps the evaporator on both sides. The copper plate dimension was 280 × 400 mm, which was based on the area of ducting area of the heat recovery device. The condenser section was inserted into an acrylic cooling box that had an inlet and outlet for cold-water circulation. The cold water supplied to the condenser cooling box was kept constant at 25 °C by using a cooling thermal bath. Rotameter (®Plato) was used to measure the flow rate of cold-water supplies. Thermocouple type K with 0.3 mm of diameter was couple with data acquisition system (NI-9174 and NI 9213) was used to measure the temperature fluctuations at sample rate 1 Hz. The evaporator and condenser were well insulated with glass wool and polyurethane to prevent heat loss to the ambient.

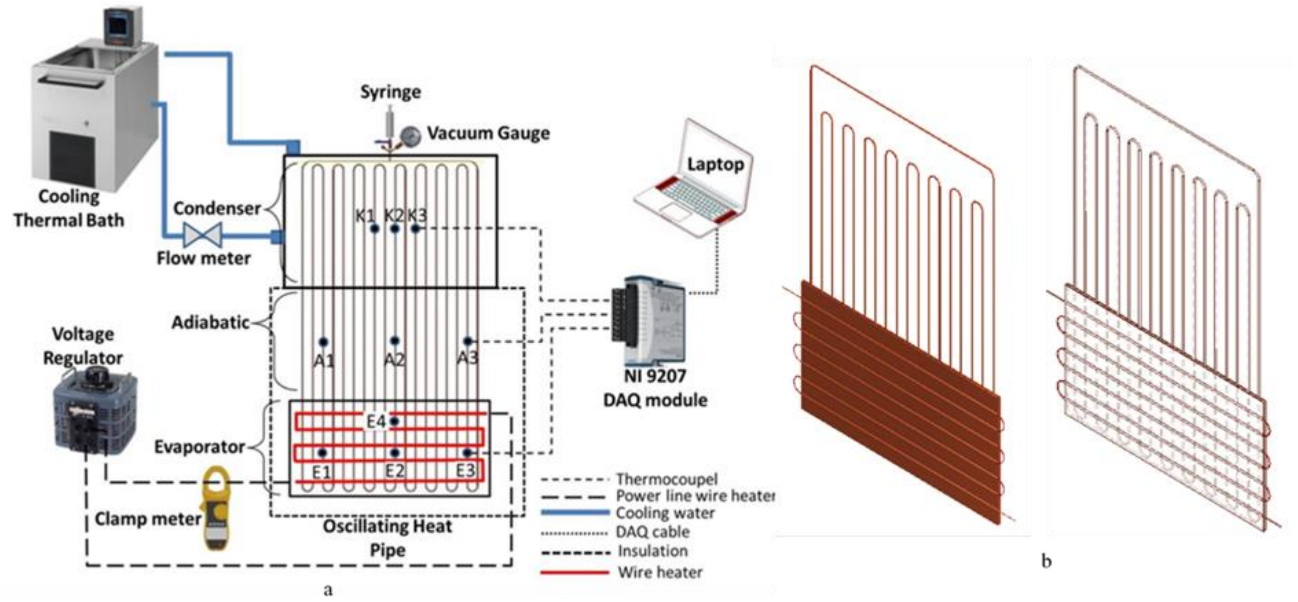
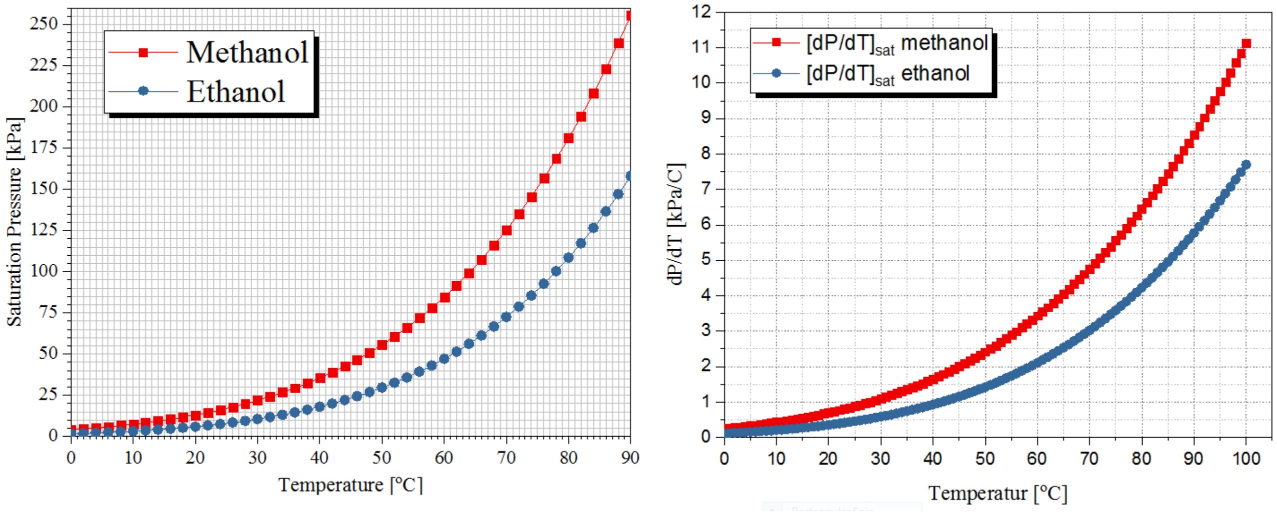


Fig. 1. (a) Schematic of the experimental test of the long OHP, (b) copper plate which attached with wire heater at evaporator OHP



(a) (b)

Fig. 2. Saturation pressure for methanol and ethanol as a function of temperature and ratio of *(dP⁄dT)*$_{sat}$ at working fluid

2.1 Experimental Method

In this test the experimental parameters were the supplied heating power versus the evaporator and the adiabatic and condenser temperatures for each inclination. The OHP was placed on a stand with inclination adjustment (horizontal orientation as reference point 0°). The highest inclination orientation is 90° or vertical orientation, and the lowest inclination is 0° or horizontal position. The inclination angles varied among 30°, 60° and 90° from the horizontal reference.

Although quite simple, overall thermal resistance (R_{th}) is a convenient method to analyze the thermal performance of a heat pipe and can be obtained by Eq. (2).

$$R_{th} = \frac{\bar{T}_e - \bar{T}_c}{Q} \tag{4}$$

$$k_{eff} = \frac{L_{eff}}{A_{cr} \cdot R_{th}} \tag{5}$$

where R_{th} is the thermal resistance, Q is the thermal power supplied from a Ni-Chrome wire heater measured by a power meter, $\bar{T}_e$ is the average temperature at the evaporator, and $\bar{T}_c$ is the average temperature at the condenser.

The heating power is measured by a digital power meter with an accuracy in the range of ±0.1% The minimum heat supply was 10.19 watt; hence, the maximum relative error of power input was 5.9%. The thermal resistance error was calculated using Eq. (5) with a minimum temperature difference between the evaporator and the condenser of 8.19 °C. The thermocouple of K type (±0.1 °C after calibration) and NI 9213 (±0.02 °C for temperature) results in a relative error of 6.34%.

$$\frac{\Delta R}{R} = \left[\left(\frac{\Delta(\Delta T)}{\Delta T}\right)^2 + \left(\frac{\Delta Q}{Q}\right)^2\right]^{1/2} \tag{6}$$

Table 1

The properties of methanol and ethanol

No	Properties	Ethanol	Methanol	unit
1	Boiling point	96.93	83.189	°C
2	Latent heat (h_{fg})	815.93	1062.20	kJ mol^{-1}
3	*Cv* (liquid)	2.7771	2.4691	kJ/kg K
4	*Cv* (vapor)	1.6683	3.6330	kJ/kg K
5	*Cp* (liquid)	3.3747	2.9964	kJ/kg K
6	*Cp* (vapor)	1.9120	4.7838	kJ/kg K
7	Viscosity (liquid)	0.33664	0.26502	m Pa s
8	Surface Tension	0.013063	0.017285	N/m
9	Density of liquid	716.57	729.24	kJ/kg
10	Density of vapor	3.1869	2.3639	kJ/kg
11	Thermal conductivity (liquid)	0.14907	0.18580	W/mK
12	Thermal Conductivity (vapor)	0.0238	0.02290	W/mK

3. Results

3.1 Temperature Characteristic at Evaporator

The temperature at evaporator is one of the influence parameters which results in amplitude level of working fluid oscillations. The oscillation of working fluid is one of the mechanisms of heat transport at OHP. Better performance usually obtained from higher frequency of oscillation. Also, the lower minimum temperature the higher the percentage of latent heat absorption that occurs within the heat pipe [13]. Even though, temperature difference is still important for ensuring the movement of working fluid within OHP. Figure 3(a) shows that OHP methanol has fluctuated at maximum temperature difference at inclinations of 90°. Meanwhile, other inclinations stay flat and decrease at the end. At highest heat supplied, methanol OHP has tendency to absorb the heat at evaporator much better. Reduce the inclinations result in lower amplitude of oscillations. Figure 3(b) shows the inverse trend of maximum and minimum temperature from the previous graph. Reduce the inclination increase the difference between maximum and minimum temperature. High level of oscillation amplitude happened at Ethanol OHP.

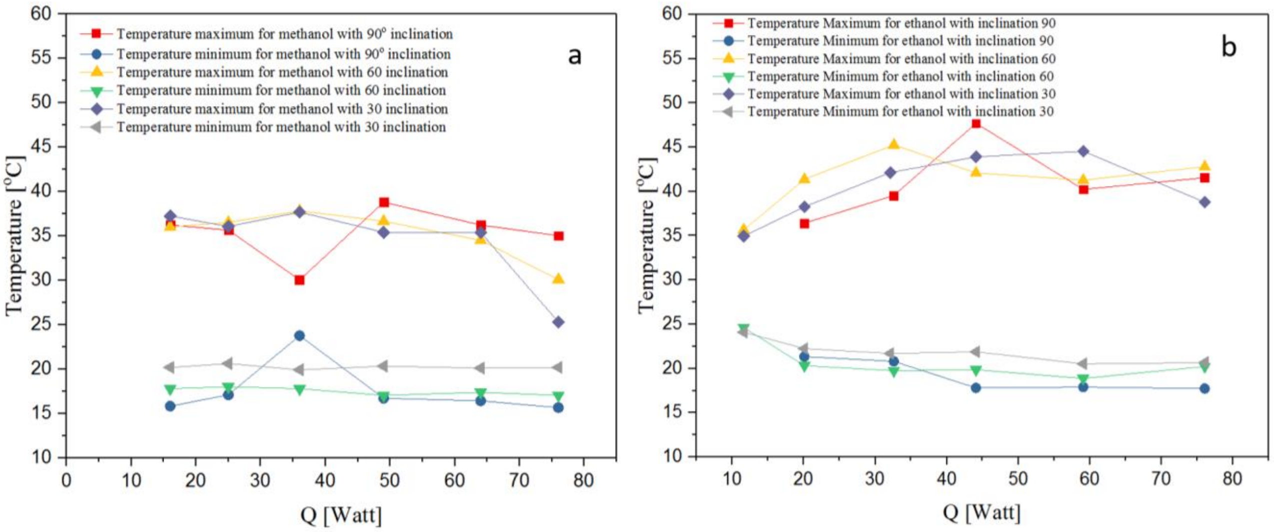


Fig. 3. Maximum and minimum temperature at OHP for (a) methanol and (b) ethanol

Methanol OHP has lower minimum temperature than ethanol for all heat supplied and inclinations. Although, there was a tendency that the temperature difference was nearly stagnant at low heat and high heat supplied. These might happen due to lower boiling point for methanol (Table 1). Whereas the minimum and maximum temperature of ethanol seem decreasing and increasing, respectively for the increase of heat supplied. Higher amplitude was generated by heat supplied increment. Ethanol OHP has lower motion of working fluid, which then result in lower heat transport capability than methanol. These could be affected by lower latent heat and thermal conductivity of working fluid.

3.2 Effect of Inclination Angle

Figure 4 shows the variation of heat supply and inclinations angle to the temperature difference of evaporator and condenser for both working fluids. The graph shows that at 20-50 watt of heat supplied the highest average temperature difference exist. Based on the visualization study, the flow pattern of working fluid is slug flow for low and nearly medium of heat supplied. This slug flow generally creates high amplitude of temperature oscillations. The heat transport process was dominated by forced convection due to the working fluid movement produced by the "driving force" of different pressure at both ends. Further increase of heat supplied decreases the dominance of one-phase heat transport. There will be an increase in the two-phase heat transport component due to the transition of flow patterns from slug flow to semi-annular flow. Increase the heat supply cause an increase in the speed of the working fluid and the operational temperature of the OHP. The latter causes the working fluid to decrease viscosity. Thus, the vapor plug will have higher speed and result in multiple mergers of vapor plugs. Then, semi annular flow would be generated. Finally, the liquid would be pushed much stronger to the channel wall which then will evaporates and produce higher coefficient heat transfer (two phase heat transport). The data shows that methanol with an inclination of 60° has the lowest temperature difference at the maximum heat supply. Methanol working fluid has a lower temperature difference between evaporator and condenser than ethanol. This is probably one indication that methanol has a lower sensible heat ratio (SHR) component than ethanol. SHR is the ratio of sensible heat to total heat (sensible and latent).

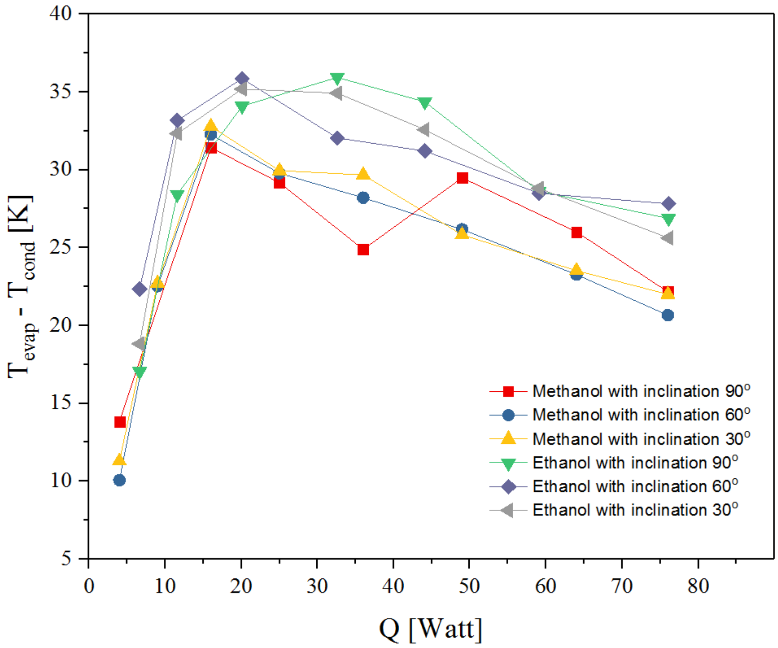
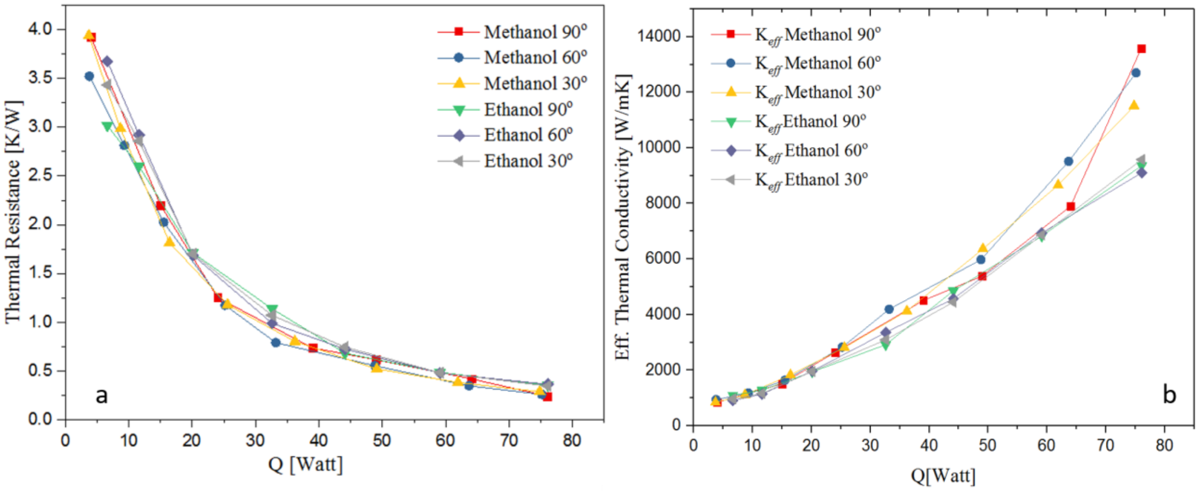


Fig. 4. Temperature different at evaporator and condenser at different heat supplied and inclinations

The lower thermal resistance indicates higher and more effective heat transfer capability of heat pipe. Figure 5 shows the thermal resistance and thermal conductivity of methanol and ethanol OHP. The thermal resistance was calculated using Eq. (4). Meanwhile the effective thermal conductivity of OHP was computed using Eq. (5). Figure 5(a) shows the thermal resistance for both working fluids was relatively high (close to 4 °C/W) at the initial heat supply. It can be concluded that the oscillation movement (fluid movement) has not existed yet. Heat transport only occurs through the mass of copper and creates the rising of heat pipe temperature. The working fluid was stagnant until start-up occurred at next level of heat supplied (11.6 watt on ethanol and 15 watt on methanol). Significant drop of evaporator temperature takes place shortly after that. Thus, the thermal resistance decreases almost 91.25%. The existence of oscillation of working fluid causes heat transfer from evaporator to condenser exist. Further, the increase in heat supply raising the oscillation frequency which causes the thermal resistance to decrease again. At a maximum heat of 76 watt, the lowest thermal resistance was 0.36 °C/W. The effect of inclination angle at thermal resistance was relatively insignificant for both working fluids. Also, the comparison of the thermal resistance produced tends to similar to each other. This could be happened by various factors including the embedded structure model of heat supplied at evaporator, the length of the evaporator, level of heat flux and the thermal properties of working fluids.

Figure 5(b) shows the thermal conductivity of OHP for both heat supplied and inclinations. The thermal conductivity of OHP increases with heat supplied for all working fluids and inclination. The effective thermal conductivity ranged from 844.5 to 1100.43 W/mK at initial heat supplied. Ethanol with 60° inclination has the highest thermal conductivity at low heat supply. While methanol at 90° inclination has a maximum thermal conductivity of 13,586 W/mK at maximum heat supplied (76 watt). This thermal conductivity was equivalent to 35.2 times of solid copper. This is very possible because methanol has a 30% higher latent heat and higher ratio of $(dP/dT)_{sat}$ than ethanol.



(a) (b)

Fig. 5. Thermal resistance and thermal conductivity for different heat supplied and inclinations

3.3 Effect of Working Fluid

Figure 6 shows the thermal oscillation of OHP ethanol and methanol at highest heat supplied (76 watt) and 90° inclination angle. The graph shows the thermal oscillation frequency produced by both working fluids has a significant difference. In ethanol some of the periods produced by the thermal oscillation are wider, for example as show in A for about 700 seconds, B for 508 seconds and C for 400 seconds. While in methanol the period ranges from 158 to 187 seconds. The period length produced by ethanol oscillation was almost 3.7 times the methanol OHP. These could be concluded that the velocity of ethanol OHP within the channel was far much lower than the methanol methanol one. This result was inline with previous first subsection about effect of minimum and maximum temperature of evaporator. There was some heat loss due to lower motions of working fluid. These phenomena would be indicated by higher evaporator temperature at ethanol OHP. This lower speed was influenced by higher viscosity and the lower $[dP/dT]_{sat}$ property for ethanol as shown previously in Table 1 and Figure 2(b). The higher speed of movement of OHP methanol is also confirmed by the higher frequency of thermal oscillations.

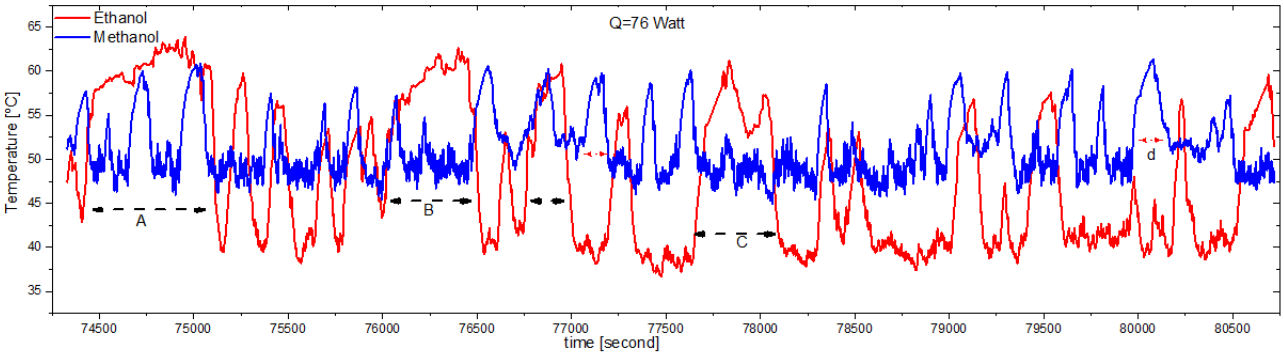


Fig. 6. Comparation of temperature oscillation between methanol and ethanol at highest heat supplied (76 watt) and 90° inclination

4. Conclusions

The heat transfer characteristic of large scale OHP for the heat recovery application was design and tested. The conclusion obtained from the experimental data are summarized as follows.

i. There is no significant difference in changes in methanol inclination and OHP ethanol to the phenomenon of temperature fluctuations that occur in the initial heat supply.
ii. The data shows that methanol with an inclination of 60° has the lowest temperature difference in the maximum heat supply. Methanol working fluid has a lower temperature difference between evaporator and condenser which is lower than ethanol.
iii. Ethanol with 60° inclination has the highest thermal conductivity in the initial heat supply. While, methanol at 90° inclination has maximum thermal conductivity of 13,586 W/mK at maximum heat supplied (76 watt).
iv. This thermal conductivity was equivalent with 35.2 times of solid copper. Overall the OHP Methanol has the capability of heat transfer better than ethanol.

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