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EXPERIMENTAL INVESTIGATION OF A LARGE SCALE-OSCILLATING HEAT PIPE AT DIFFERENT INCLINATIONS

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ABSTRACT

As a family of heat pipes, oscillating heat pipes have many additional unique operating parameters. This paper examined the heat transfer characteristics of an oscillating heat pipe that has an effective length (l_{eff}) of 500 mm and uses methanol as the working fluid. The effective length of 500 mm is not typically used in previous experimental setups. This structural dimension of the oscillating heat pipe is widely used as a heat recovery device. The heat pipe was tested with various heat supplies and inclinations. The results show that the inclination makes a substantial contribution to the heat transfer capability for large scale heat pipes. Decreasing the degree of inclination reduces the capability of the heat pipe in handling the heat load. Reducing the inclination also decreases the oscillatory motion, which is an obvious "heat carrier" from the evaporator to the condenser.

Keywords: Heat transfer characteristics; Inclinations; Methanol; Oscillating heat pipe

1. INTRODUCTION

The oscillating heat pipe (OHP) is an up-and-coming passive thermal transfer device that transports heat through the thermally excited oscillating motions of a working fluid. OHP has become one of the popular research topics since its discovery by Akachi in 1990 (Akachi, 1990). Although more than two decades have passed since its invention, lots of information regarding the OHP, such as information on the hydrodynamic and thermodynamic coupling leading to complex combinations of two-phase instabilities and a metastable fluid state, remains unknown (Khandekar & Groll, 2004; Lips et al., 2010).

The OHP is built from a small-diameter tube formed into a meandering snake shape tube and joined end to end. First, the tube is evacuated and then filled partially with a working fluid, which distributes itself naturally in the form of liquid-vapor plugs and slugs inside the capillary tube. The device essentially works with two main different pressures between the evaporator and the condenser. These two main different pressures generate the driving force for the oscillatory motion of the working fluid.

The OHP structure typically consists of the following three parts: the evaporator, adiabatic, and condenser sections. Heat transfer occurs in the evaporator and condenser sections, while the

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adiabatic section connects both of them. The evaporator absorbs heat from an object, heat which is then transferred to the condenser by the oscillating motion of the working fluid. If the evaporator is in contact with the thermal load, then the working fluid inside will evaporate and increase the local vapor pressure. Due to bubble formation, local high pressure will expel the liquid and form vapor towards the condenser section. In the condenser section, the vapor plugs will collapse and condense because of the low saturation pressure. The growth and collapse of bubbles in the two different sections leads to the oscillating or pulsating motions inside the tube. As a result, a pressure imbalance is generated inside the OHP tube. As a result, working fluid oscillations appear and deliver heat from the evaporator to the condenser. Latent heat transfer processes are involved during OHP operation, mainly as a driving force of the working fluid motions. These working fluid motions will continue as long as the temperature difference exists. Although the heat transfer phase change does not dominate the total heat transfer rate, as in a conventional heat pipe, the oscillating heat pipe has the potential for better heat transfer capability, especially at high heat flux (Mameli et al., 2012).

A PHP is essentially a nonequilibrium heat transfer device whose performance success depends primarily on the continuous maintenance of these nonequilibrium conditions within the system. Because the length of each liquid slug and vapor plug are different, it is not surprising that this working fluid flow both undergoes complex oscillatory displacements and displays circulatory characteristics (Tong et al., 2001). Ma stated that the OHP motion is a mechanical vibration system with a vapor plug acting as a constant spring (Ma, 2015). Contrary to conventional heat pipes, OHP has a wickless structure inside. Avionics and extraterrestrial applications need more lightweight cooling devices, thus OHP is more preferable than conventional heat pipes with wick structures.

Cui et al. studied OHP with distilled water, methanol, acetone, and ethanol as working fluids (Cui et al., 2014). They found that dry-out appeared locally on some individual pipes in the evaporator. Elevating the power input would cause the dry-out to spread to several other locations. Naik et al. examined acetone, methanol, and ethanol as working fluids at various filling ratios (Naik et al., 2013). They found that acetone with a 60% filling ratio had the lowest thermal resistance and the highest heat transfer coefficient. Verma et al. demonstrated that methanol worked efficiently in a variety of orientations compared with distilled water (Verma et al., 2013). Tong et al. conducted a study of OHP visualization with methanol as the working fluid (Tong et al., 2001). The visual study showed a high amplitude of oscillation during the start-up stage. They also discovered that the bubble displacement of methanol oscillation versus time is in the form of quasi-sine waves. The water OHP had periodic "stationary–fast movement" oscillation motion behavior. Xu et al. observed a difference in the advancing and receding angles of water when traveling inside the channel due to high surface tension (Xu et al., 2005). An experimental study by Saha et al. showed that methanol and water should be the first consideration when choosing a working fluid for an open loop OHP with vertical and horizontal orientations (Saha et al., 2012). Senjaya and Inoue conducted an OHP simulation considering the dry-out phenomenon (Senjaya & Inoue, 2014). These research studies stated that dry-out occurs because there is not a sufficient supply of liquid to the evaporator. The performance of the heat pipe seriously deteriorates if dry-out occurs. Xian et al. tested an OHP with an evaporator length of 200 mm with water and ethanol as the working fluids (Xian et al., 2010). They found that the maximum thermal conductivity for the water OHP and the ethanol OHP peaks at 295 kW/m·K and 111 kW/m·K, respectively. Based on their results, there is a potential high thermal transfer capability over long distances using an OHP design with the longest effective length (l_{eff}). Lin et al. conducted an experiment with different heat transfer lengths and inner OHP diameters (Lin et al., 2011). In their study, all the OHPs used water as the working fluid. They showed that the inner diameter of the OHP should be greater than 0.8 mm in vertical bottom heating mode. At high heating power, the performance of MOHP is at almost the same level when compared with a sintered heat pipe in the horizontal orientation. Yang et al. conducted an experimental work with an OHP length of approximately 600 mm for a solar collector application (Yang et al., 2009). They found that the OHP could be applied properly as a solar collector. The relative importance of testing the OHP under high heat flux to prove that OHP could withstand a higher heat flux, as stated by Akachi et al. that could operate as passive cooling up to 30 W/cm^2 (Mameli et al., 2012).

Varying the effects of gravity on the OHP orientation has become one of the popular topics in the recent investigations (Mameli et al., 2014; Mameli et al., 2015; Ayel et al., 2015; Mangini et al. 2017). The results of such studies show that both gravity and heat input level influence the device operation. One of the recent popular topics of experimental OHP research is varying the effect of gravity. The change of performance of OHP due to gravitation is still growing as a hot topic in many publications. Even though, there are still rare data about these topics.

At the beginning, the OHP was designed with an effective length (l_{eff}) of no more than 20 mm. There is a lack of data on the thermal characteristics of OHPs with effective lengths more than 200 mm. This scarcity makes sense because the OHP was originally developed to provide thermal management solutions for small electronic devices, especially electronic devices that have strict requirements for space limitations and high heat flux rejection. However, OHPs are starting to be investigated in heat exchange or heat recovery applications using an l_{eff} exceeding 350 mm (Supirattanakul et al., 2011; Arab et al., 2012; Mahajan et al., 2017; Winarta et al., 2017).

The objective of this research is to experimentally study the heat transfer characteristics of an OHP using methanol as the working fluid for different orientations and higher heat flux. The OHP was manufactured with an l_{eff} of approximately 500 mm, which is not typically used in previous OHP data experimental tests. Most of the heat transfer performance for OHPs was designed for electronic thermal management. However, recent trends include the implementation of OHPs in heat recovery and heat exchanger design areas. The results of this experimental data will also provide more experimental data for improving the characteristic behavior of the thermal process in an OHP.

2. EXPERIMENTAL APPARATUS AND METHOD

2.1. Experimental Setup

Figure 1 shows the schematic of the experimental setup. It consists of a closed-loop OHP, an electrical heating system, a water-cooling system, a data acquisition system and an inclination table. The OHP was made from a copper capillary tube with inlet and outlet diameters of 1.7 mm and 3.2 mm, respectively. The choice of these diameters are based on the calculations from equation (1) below, which is calculated using the fluid properties used (Taft et al., 2012):

$$0.7\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}} \ll D \ll 1.84\sqrt{\frac{\sigma}{g(\rho_l-\rho_v)}} \tag{1}$$

The Equation 1 is the important characteristics that distinguish OHP from other heat pipes. In addition, the minimum and maximum limits of the pipe's inner diameter will ensure the characteristic of the working fluid formed within the pipe. Using methanol's properties and Equations 1, 2, the critical capillary diameter for the temperature range between 20−120°C is 3.147−2.641 mm (d_{max}). This means that the slug and plug should always be formed at the temperature range of the evaporator temperature.

The evaporator, adiabatic, and condenser have lengths of 200, 280, and 240 mm, respectively. The effective length of this OHP is calculated using the following Equation 2:

$$l_{eff} = \frac{(l_{evap}+l_{cond})}{2} + l_{adiab} \tag{2}$$

Based on Equation 2, the effective length of the OHP is 480 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 (up to 250 mTorr) with a rotary vacuum pump before the working fluid is injected. Methanol was employed as the working fluid with a 60% filling ratio. One of the filling tubes was then pinched off using special pinch-off tools. To explore the effect of different heat input levels on the evaporator section of the closed-loop OHP, a wire electric heater was connected to a regulated power supply. The power input to the evaporator was measured by a Yokogawa WT310 power meter. The condenser section was inserted into an acrylic cooling box that had an inlet and outlet for cold-water circulation. The temperature of the cold water supplied to the condenser cooling box was kept constant at 25°C by using a cooling thermal bath. The flow rate of the cold-water supply was measured by a rotameter. Temperatures were measured using a data acquisition system (NI-9174 and NI 9213) connected with a 0.3 mm type K thermocouple. The temperature data were obtained at a sample rate of 1 Hz. The evaporator and condenser were well insulated with glass wool and polyurethane to prevent heat loss to the ambient environment.

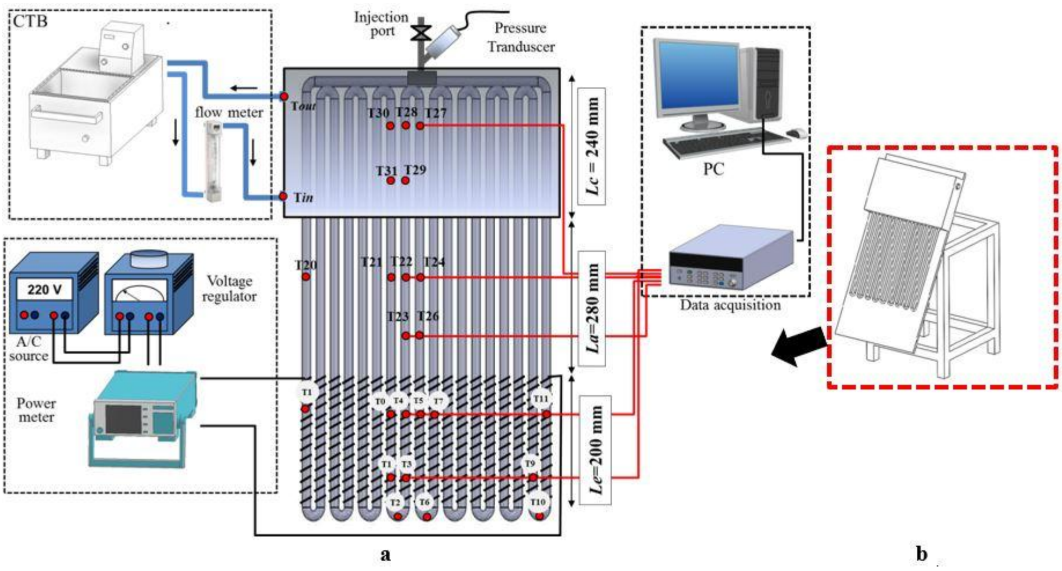

Figure 1 (a) Schematic of the experimental test of the large scale OHP; (b) Inclination table apparatus

2.2. 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 table with inclination adjustments (with the horizontal orientation as a reference point of 0°). The inclination angles varied among 0º, 30º, 45º, 60º and 90º from the horizontal reference. During the test, the power supply was increased from 10 watts (6,91 W/cm^2) to 220 watts (152,05 W/cm^2) for the vertical inclination.

Although quite simple, the overall thermal resistance is a convenient method to analyze the thermal performance of a heat pipe and can be obtained by Equation 3 as follows:

$$R_{th} = \frac{\bar{T}_e - \bar{T}_c}{Q} \tag{3}$$

where R_{th} is the overall thermal resistance, Q is the thermal power supplied from an 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.

A power meter unit (Yokogawa WT210) was used to measure the heating power with an accuracy of ±0.1% of the reading +0.1% of range. If the minimum heat supply (reading) and selected range are 10 and 300 W, respectively, then the maximum relative error is 3.04%. The thermal resistance error was calculated using Equation 4 with a minimum temperature difference between the evaporator and the condenser of 8.19°C. The K-type thermocouple (±0.1°C after calibration) and NI 9213 (±0.02°C for temperature) result in a relative error of 4.5% using Equation 4.

$$\frac{\delta R_{th}}{R_{th}} = \sqrt{\left(\frac{\delta T}{T_e - T_c}\right)^2 + \left(\frac{\delta Q}{Q_{in}}\right)^2} \tag{4}$$

3. RESULTS AND DISCUSSION

3.1. Effect of Power Supply (Q_{in}) at Different Inclinations

Figure 2 shows the typical temperature response (evaporator, adiabatic and condenser) for various heat supplies and inclinations. As shown in Fig. 2a, the evaporator temperature (T11) rises rapidly until 41 °C after the power was turned on at 10 W. After that, the evaporator temperature stayed steady at approximately 42 °C for almost 1421 seconds. Then, it slightly drops by approximately 3 °C and started to fluctuate, which indicated that start-up had already begun. At the 60° inclination, the evaporator temperature had a sharper increase than in the vertical position, as shown in Fig. 2b. A higher heat supply (20 W) was needed to initiate oscillation at 60° inclination. Therefore, our result showed that at 10 and 20 W the movement of hot vapor and liquid slug from evaporator to condenser was successfully initiated for vertical and 60° inclinations, respectively.

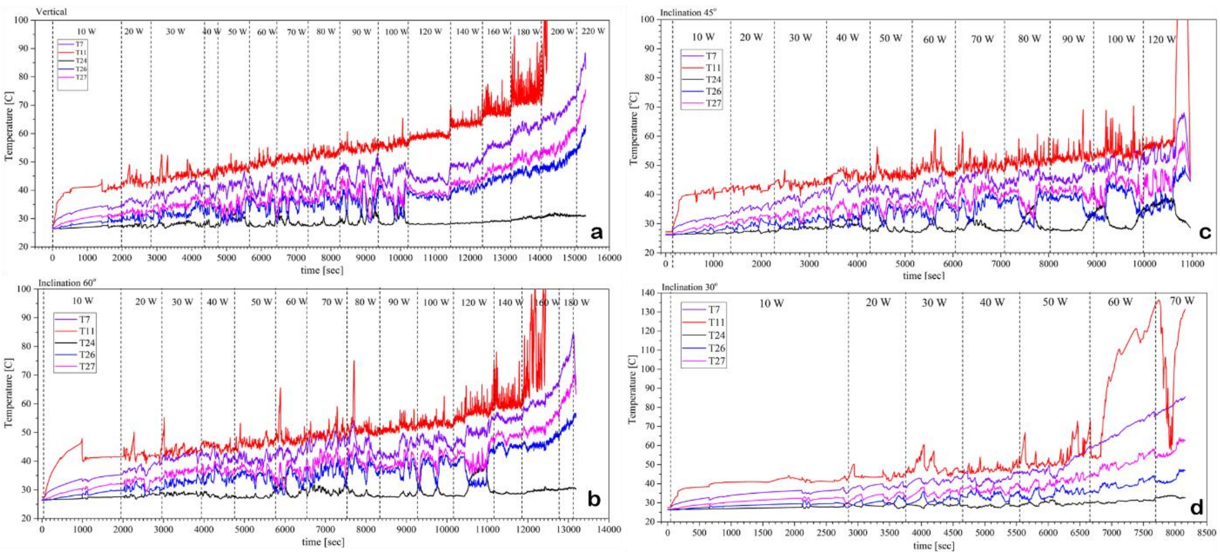

Figure 2 Effect of inclination for temperature fluctuations at: (a) Inclination of 90°; (b) Inclination of 60°; (c) Inclination of 45°; and (d) Inclination of 60°

The amplitude of the oscillation temperatures only show a large increase at the 90° and 60° inclination with high heat fluxes. Particularly at 160 W (90°), which is higher than at the 60° inclination. No significant increase of oscillation frequency was shown at low heat flux (20–50 W). At the 60° inclination, as the level of heat supply increased, then a higher amplitude occurred and peaked at 120 W. A higher temperature amplitude also occurred at 160 W in the vertical orientation. Dry-out also occurred faster at the 60° orientation than in the vertical position. The unbalanced pressure due to gravitation was reduced when the orientation changed (vertical to near horizontal), which then reduced the motions of hot slug and directly decreased the heat transfer capability.

Figures 2c and 2d shows the OHP temperature fluctuations at the 45° and 30° orientations, respectively. The heat supply range at which OHP can absorb properly becomes smaller for both inclinations compared with the previous stage. Especially at 30°, the temperature evaporator increases rapidly with a medium heat supply (60 watt). Moreover, the oscillation frequency also decreased significantly at 30°. Decreases of the fluid velocity might be responsible for the temperature spikes and dry-out at lower heat fluxes. While several temperature spikes have already occurred at the 45° orientation, the oscillation frequency is still higher than at the 30° orientation. This indicated that heat transfer was still better at the 45° orientation. It seems that the OHP experienced intermittent flow or that the working fluid movement started and stopped more frequently at lower inclinations. These intermittent flows were also described earlier by Cui et al. (Cui et al., 2014).

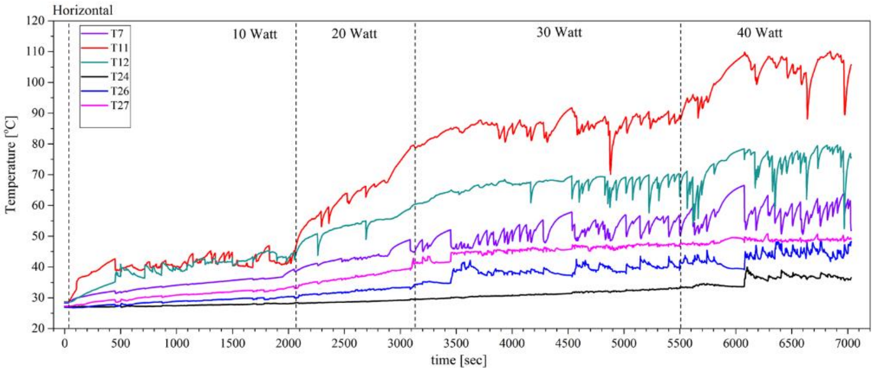

Figure 3 Effect of inclination for temperature fluctuations at horizontal position (0°)

Figure 3 gives the typical temperature fluctuations at the horizontal position (0°). The OHP temperature fluctuated at the lowest frequency among all orientations. There was a sharp increase in the evaporator temperature when the heat supply was increased to 20 W. Meanwhile, the temperature of the condenser (T24) tends to be flat along the same heat supply. The heat transfer coefficient at the condenser section seems to be at a sufficiently low level. Soponpongpipat et al. stated that if the vapor inside the condenser could not collapse properly, then the vapor flow would be stagnant at the evaporator sections (Soponpongpipat et al., 2009). Thus, the temperature of the evaporator (T7, T11) increases, because of the stagnant working fluid. Continued supply of heat (Q_{in}) will merely increase the evaporator temperature until dry-out occurs.

The frequency of the temperature fluctuations increased after the heat supplied raised to 30 W. Further, the average evaporator temperature reaches 86.5°C, which is the highest of all inclinations. At this orientation, the working fluid simply flows with the lowest velocity and stops periodically. The effect seems very clear at this OHP effective length. The evaporator temperature then increases rapidly due to the stagnant motions of the working fluid. The static pressure distribution between the vertical and horizontal orientations are quite different (Khandekar, 2004). At the horizontal position, the gravitation and buoyancy do not assist the movement of the working fluid. The slug and bubble movements are only assisted by pressure difference force created by the temperature differences between the evaporator and condenser. In this experiment, it failed to create sufficient frequency of oscillation in the horizontal position. Gravity acceleration clearly shows its influence in this OHP. Gravitational acceleration assists the returning condensates, which formed at the condenser due to vapor condensation. Decreasing the inclination reduces the oscillation frequency significantly. The effect of gravitational acceleration decreases as the inclination changes from vertical to horizontal. The heat pipe work capability decreased by almost 83.33% when the inclination changed from a vertical to horizontal.

Interestingly, the inclination significantly affects the operational range of OHP with long effective length. Reduced the inclinations will lower the operational range of the heat absorption.

3.2. Start-up Characteristics

Table 1 displays the start-up temperatures for various inclinations. The table shows that the increase in the orientation angle slows down the start-up or two-phase heat transfer. In the vertical position, the working fluid at the evaporator section experienced higher pressure due to its bottom position. Conversely, in the horizontal position, the pressure force from the working fluid reaches its lowest point. However, this benefit does not have much effect on the working fluid movement and heat transfer capability.

Table 1 Start-up time and temperature at different orientations

Inclination	90°	60°	45°	30°	0°
Start-up Temp	43.83	47.28	41.54	38.43	42.65
Start-up Time	1421	983	615	653.9	448.54

At start-up, the working fluid regime is generally in the form of slug flow (Borkar & Pachghare, 2014). Thus, the effect of gravitational potential is much more dominant than other patterns, such as annular/semi annular patterns. The center of gravity of the slug flow would be located in the middle of channel. Additionally, liquid slug has higher density. Therefore, it would have a greater tendency to move downward. This benefit will sustain the circulation of the working fluid within the OHP tubes. These forces also help unbalance the working fluid pressure, which then generated the oscillations.

In the vertical orientation, the gravitational acceleration has a substantial impact on maintaining the working fluid movement as a result of the dynamics of the driving and restoring forces of the working fluid. Gravitation also helps the condensed working fluid to flow more easily to the evaporator, whereas in a horizontal position, the gravitational potential does not have a positive impact on the working fluid movement. Similarly, the buoyancy force also does not have a significant effect on fluid movement. These parameters are the reason why performance at horizontal orientation gets worst significantly.

3.3. Temperature and Performance Characteristics

The OHP heat transfer characteristics depend on multivariate factors, such as gravitational force, the thermophysical properties of the working fluid, operational parameters, heat supply, geometry and there may be other reasons that remain unknown. Among these factors, the driving forces caused by the phase change and gravity play the most crucial roles.

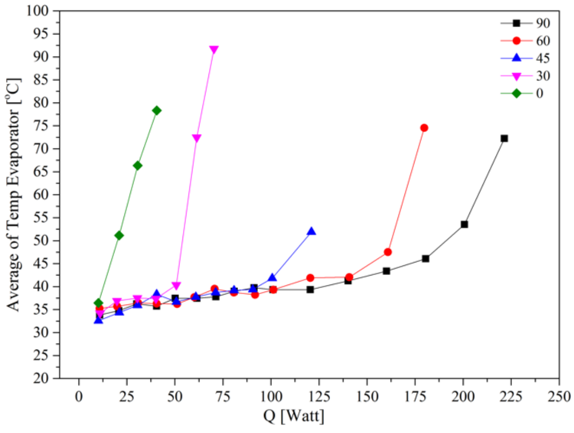

Figure 4 Effect of inclination angle on the range of OHP working temperature

Additionally, the proper evaporator temperature is a substantial and major requirement for the good performance of the heat pipe as a heat exchanger device. Thus, it is very important to design the evaporator temperature within the range of the thermal device's operations.

Figure 4 shows the effect of inclination angle on the average temperature of the evaporator. At 10 and up to 90 W, almost all inclinations have evaporator temperatures in the range of 32.5ºC to 40ºC, except for the horizontal position. Reducing the inclination at maximum heat load increases the temperature of the evaporator. This finding shows that reducing the inclination angle results in poor heat transport ability in the OHP. Axial heat transfer changes to radial heat transfer, which results in significant temperature increases at the evaporator.

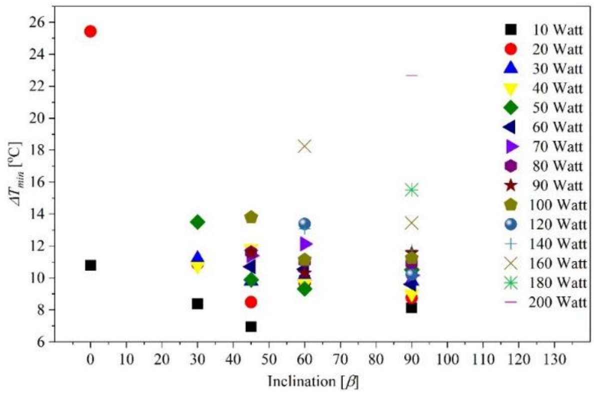

Figure 5 Effect of inclination and heat supply to minimum temperature difference between evaporator and condenser

Figure 5 shows a graph of the minimum temperature difference (ΔT_{min}) between the evaporator and condenser for various inclinations and heat supplies. The data shows the trend in the temperature differences was not linear (chaotic) with respect to variations in the inclination. The minimum temperature difference was gathered at an adjacent area at almost all heat load in a vertical orientation. This indicates that inclination might be affected by the proportion of latent and sensible heat of heat transfer. The liquid supplied from the condenser move downward due to gravitation and fed the evaporator sections with liquid. Thus, the temperature of the evaporator decreases more quickly and frequently. Low temperature differences indicated the dominance of latent heat, meanwhile, high temperature differences indicated the dominance of the sensible heat. The influence of latent and sensible heat on heat transfer in the OHP was also described by Yuan et al. (Yuan et al., 2010). Higher latent heat results in better heat performance (Xian et al., 2010).

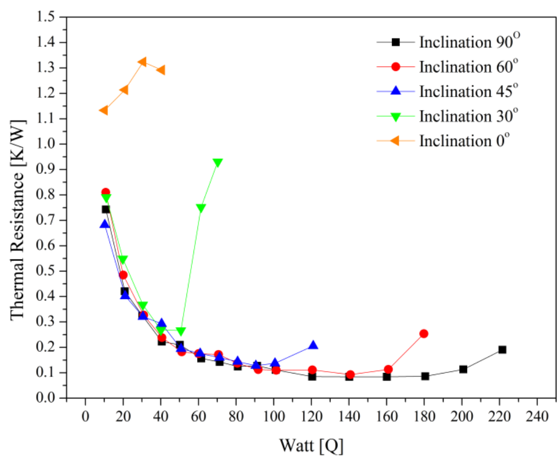

Figure 6 Thermal Resistance at different inclinations

To discuss the relationship between inclinations and OHP performance, the thermal resistance of each heat load was computed using Equation 4. The overall thermal resistance is generally used as the indicator of the heat transfer capability an OHP. Figure 6 shows the thermal resistance of the OHP at various inclination angles and heat supplies. At 10−50 W nearly all variations of inclination have similar tendencies, except for the horizontal orientation, which has a thermal resistance higher than 1 K/W. At 60 W, the thermal resistance at the 30° inclination increased from 0.266 K/W to 0.75 K/W. For the inclination of 45°, the thermal resistance increased from 0.13 K/W to 0.20 K/W with a 125 W heat supply. At an inclination of 60°, the thermal resistance increased from 0.11 K/W to 0.25 K/W with a 180 W heat supply. The inclination of 90° has an effective heat supply until 180 watts, which shows a decreasing trend in thermal resistance. Reducing the inclination results in increases in the thermal resistance and a shorter effective heat supplier range. Increasing the heat supplied beyond the operational range might drastically raise the evaporator temperature and result in worse performance. The decreases in inclination angle from 90° to 0° directly affects the OHP thermal resistance, which became worse.

4. CONCLUSION

In this paper, experimental studies were performed to achieve better understanding of the heat transfer characteristics of an OHP with a 500 mm effective length (l_{eff}) using 60% FR of methanol for different inclinations.

The conclusions obtained in the experiment are summarized as follows: (1) The heat pipe work capability was decreased by almost 83.33% from a vertical to horizontal inclination. Inclinations affected the temperature fluctuations, operational range and heat transfer capability to absorb heat at the evaporator. Thus, it is found that specific inclination angles reduce the capability of the OHP in handling a heat load; (2) The performance of the OHP with l_{eff} 500 mm decreased by 5.6 times when the orientation was changed from vertical to horizontal. The inclination reduced the oscillatory motion, which acts as the “heat carrier” from the evaporator to the condenser. Certain inclinations also reduce the gravitational acceleration, which occurred at the highest level in the vertical orientation. Hence, the restoring effects of the working fluid decrease at reduced inclinations, in turn affecting the performance of the OHP.

5. ACKNOWLEDGEMENT

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Nomenclature		**Greek letter**	
D	diameter inlet	ρ	density (kg/m^3)
d_{max}	maximum diameter	σ	surface tension (N/m)
g	gravitational acceleration (m/s^2)	δ	delta
l_{eff}	effective lenght	**Subscripts**	
l_{evap}	evaporator length	*adiab*	adiabatic
l_{cond}	condenser lenth	*cond*	condenser
l_{adiab}	adiabatic lenth	*eff*	effective
Q	heat energy (W]	*evap*	evaporator
R_{th}	thermal resistance (K/W)	*e*	evaporator
T	temperature (^{o}C)	*c*	condenser
T_e	evaporator temperature (^{o}C)	*in*	in
T_c	condenser temperature (^{o}C)		
$\bar{T}$	mean temperature (^{o}C)		

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