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EXPERIMENTAL ANALYSIS OF INCLINED HEAT PIPE THERMAL RESISTANCE

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ABSTRACT

In this research, the effect of filling ratio, heat input and inclination angle on the thermal resistance of a heat pipe under normal operation condition has been investigated, experimentally. The experiments were performed for filling ratio of 50% to 100%. Heat inputs were among 23 W to 142.5 W and inclination angles were 30°, 60° and 90°. The heat pipe was manufactured using an aluminum pipe with an inside and outside diameter of 19.5 and 25.5 mm respectively, and a 600 mm length. Distilled water was used as the working fluid. The thermal resistances of heat pipe were calculated based on measured quantities under different working conditions. Results showed that in higher heat input the thermal resistance is independent of heat input and filling ratio. This means that thermal resistance approaches an asymptotic value. In lower heat input, the effect of filling ratio is intensified by decreasing inclination angle from 90° to 30°. Moreover, as an approximation, it can be said that the least values of thermal resistance belongs to filling ratio around 80%.

Keywords: Heat pipe, Thermosyphon, Thermal resistance, Filling ratio, Inclination angle.

1. INTRODUCTION

Heat pipe is a two-phase heat transfer device with high performance in heat transfer. Requiring small area and temperature difference for heat transfer are the main advantages of heat pipe. In addition, the simplicity, high heat transfer rate, low construction and maintenance cost as well as low weight make it demanding. A typical vertical heat pipe is shown in Figure 1. It consists of a conductive pipe with working fluid sealed inside it. During operation, coming heat from evaporator section is transferred to condenser section by working fluid phase change. Working liquid evaporates in evaporator section and goes outward and condenses in condenser section. The condensed liquid returns back to evaporator section by assistance of gravity and this cycle repeats again.

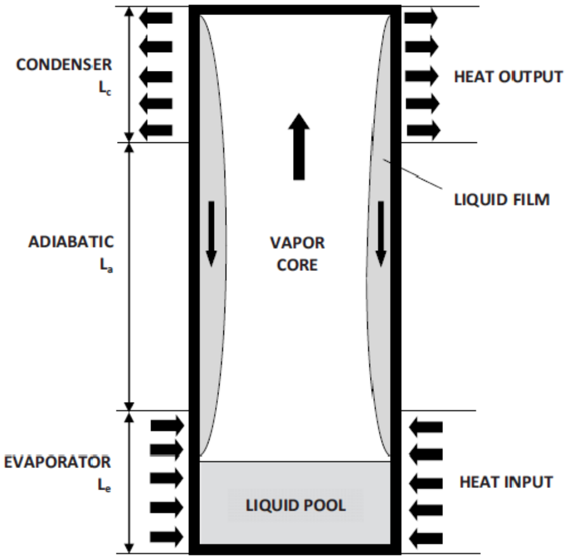


Figure 1. A schematic of heat pipe [1]

As the mechanism of heat transfer in a heat pipe is based on latent heat, its equivalent thermal conductivity may be several hundred times of copper [2]. In a gravity assisted heat pipe, the inclination angle measured form horizon can be varied between near zero for approximately horizontal heat pipe to 90 degrees for vertical one. In spite of its simplicity, the phenomena occur inside it, are so complex that makes it difficult to predict its thermal resistance. So, it seems more experimental data are required yet. Several parameters may affect the heat pipe thermal resistance. Beside the geometry, heat input, filling ratio and inclination angle are the main.

Negishi and Sawada [3] studied experimentally the effect of inclination angle on the performance of heat pipe filled by water and ethanol as working fluids. The inclination angle was between 20 ° and 40 ° for water. They asserted that the highest heat transfer rate was obtained when the filling ratio (ratio of volume of working fluid to volume of evaporator section) is between 25% and 60% for water. Zuo and Gunnerson [4] in their experiments found that the minimum amount of working fluid remains almost constant from 20 ° to 90 ° with respect to the horizontal axis, and then significantly increase by decreasing the inclination angle. Terdtoon *et al.* [5] investigated experimentally the effect of evaporator section length to inside diameter of pipe as well as Bond number on the heat transfer characteristics of an inclined heat pipe. They found that the optimum inclination angle (from horizontal axis) for water is between 70 ° and 80 ° from a horizontal axis. Payakaruk *et al.* [6] performed some experiments on copper heat pipes with inner diameters of 7.5, 11.1 and 25.4 mm and working fluid of water, ethanol, R-22, R- 123, and R-134a. They claimed that the optimum inclination angle for water is between 40 ° and 70 °. Wang and Ma [7] based on their experimental works reported the optimum inclination angle varies with liquid filling from 20 to 50 degrees.

Recently, Qu and Wang [8] studied the role of filling ratio on overall thermal resistance. They claimed that thermosyphon with a filling ratio of 40 to 50 % resulted in lowest thermal resistance. Shabgard et al. [9] investigated the heat pipe thermal performance with various filling ratios. They deduced that thermal resistance of the evaporator section will be decreased by increasing heat flux input. Ong *et al.* [10] studied the performance of water and R410a filled thermosyphon, experimentally. They changed the power inputs between 100 and 830 W and filling ratio between 0.25 and 0.93. Inclination angles in those experiments were between 30 ° to 90 °. They found that vertical heat pipe performance is the highest for R410a filled thermosyphon while for water filled thermosyphon, performance is better in inclined position.

This disagreement in reported optimum working parameters shows the necessity of more studies. In this research, the effect of all heat input, inclination angle and filling ratio have been studied simultaneously on the thermal resistance heat pipe.

2. EXPERIMENTAL SETUP AND PROCEDURE

The heat pipe is constructed of an aluminum 6060 pipe with outside diameter of 25.5 mm and thickness equals to 3 mm. Total lengths is 600 mm which is divided equally into three regions, evaporator region, adiabatic region and condenser region. For filling or draining heat pipe a valve has been considered at the bottom of pipe. On the top of the heat pipe, a valve has been considered to be connected to a vacuum pump. Moreover, a pressure gage and a safety valve have been connected on its top. A schematic of experimental setup is shown in Figure 2.

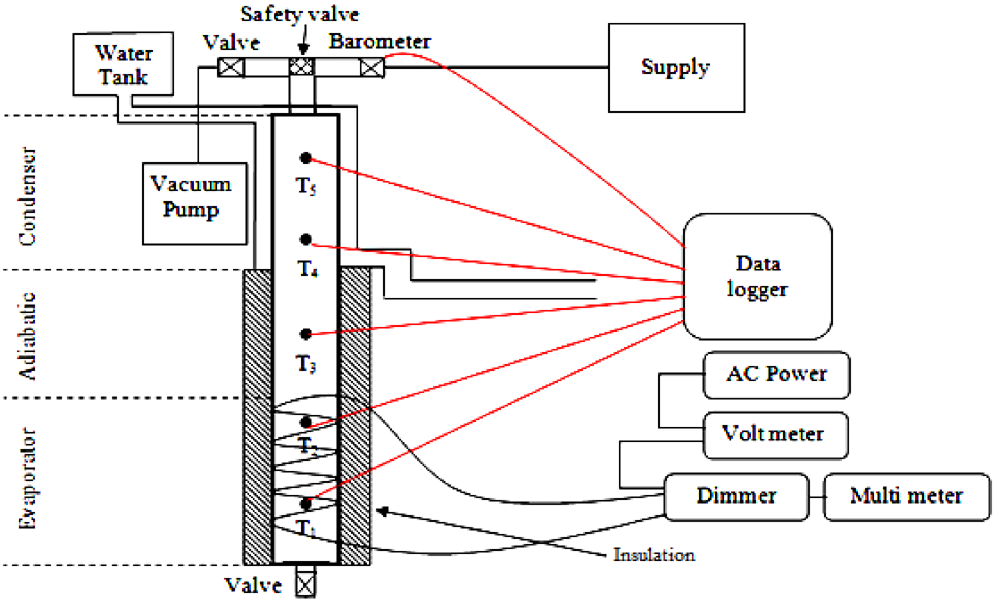


Figure 2. A schematic of experimental setup

Evaporator and adiabatic region is covered by 30 mm glass wool insulation to minimize heat loss from these regions. The insulation surface temperature was monitoring during the experiments by a portable thermometer to get ensured that it is near the ambient temperature. A picture of experimental setup is shown in Figure 3.

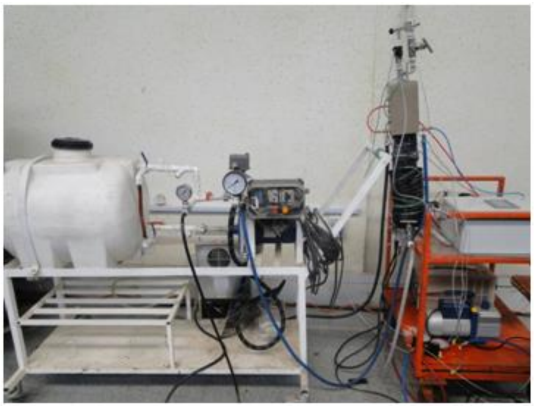


Figure 3. Experimental setup

The condenser is surrounded by a water jacket to extract heat as shown in Figure 4. Cold water flows inside the jacket, from bottom and goes out from its top. Water volumetric flow rate was 88.3 cm^3/s. By this flow rate, the temperature difference between inlet and outlet is negligible. Therefore, the same condition may be expected along the condenser.

Figure 4. Water jacket

Heating source is an electric heater wrapped uniformly around the evaporator section (Figure 5). 220 V AC power is used for electric heater. Voltage and amperage were monitored during the experiments by a multi-meter and a voltmeter.

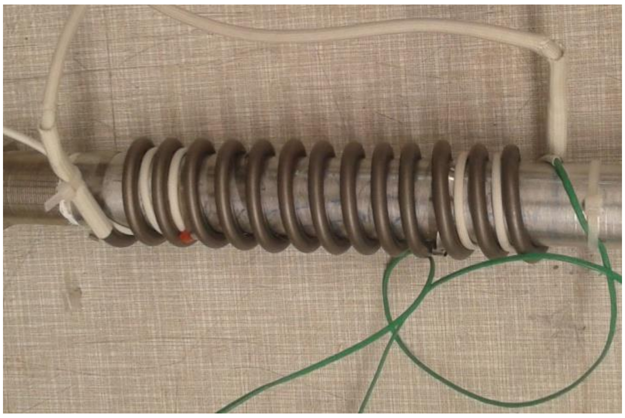


Figure 5. Electrical heater of evaporator region

On the outer surface of heat pipe, five thermocouples of type ‘K’ have been connected. Their locations are shown in Figure 6. All measured temperatures and pressure have been recorded and stored by a data logger.

Before charging the pipe, it was cleaned carefully. To remove any non condensable gas, a pump was used to vacuum heat pipe. Finally the pipe was filled by distilled water. A series of experiments were performed for heat input of 23 W to 142.5 W, inclination angle of 30 °, 60 °and 90 °and filling ratio of 50% to 100%. Filling ratio is defined as the ratio of charged working liquid to volume of evaporator space). The summery of heat pipe geometry and working condition are shown in Table 1.

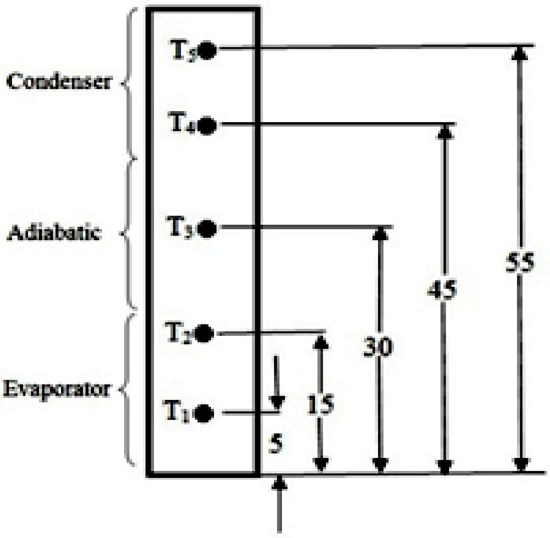


Figure 6. Thermocouples locations

Inner diameter (mm)	19.5
Outer diameter (mm)	25.5
Total length (mm)	600
Evaporator section length (mm)	200
Adiabatic section length (mm)	200
Condenser section length (mm)	200
Inclination angle relative to horizon (°)	30, 60, 90
Filling ratio (%)	50, 60, 70, 80, 100
Heat input (W)	23, 47, 69, 92.5, 116, 142.5

The boiling limit [11] and flooding limit [12] are also presented in table 2. The working condition is sufficiently far from these limits.

Variation of temperature was monitoring to ensure steady condition. Figure 7 shows temperatures variations during the time.

Table 2. Heat pipe working limit

Limits		Value (W)
Boiling	*FR*=50%	1445.8
	FR=60%	1263.3
	FR=70%	1127.1
	FR=80%	1021.1
	FR=100%	856.7
Flooding		8388.3

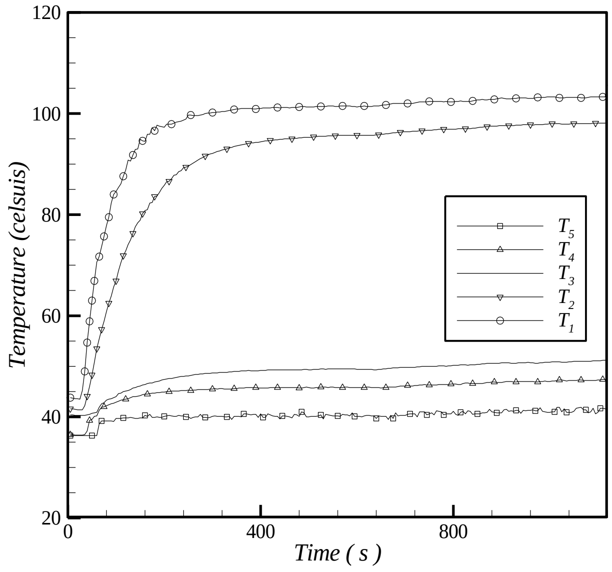
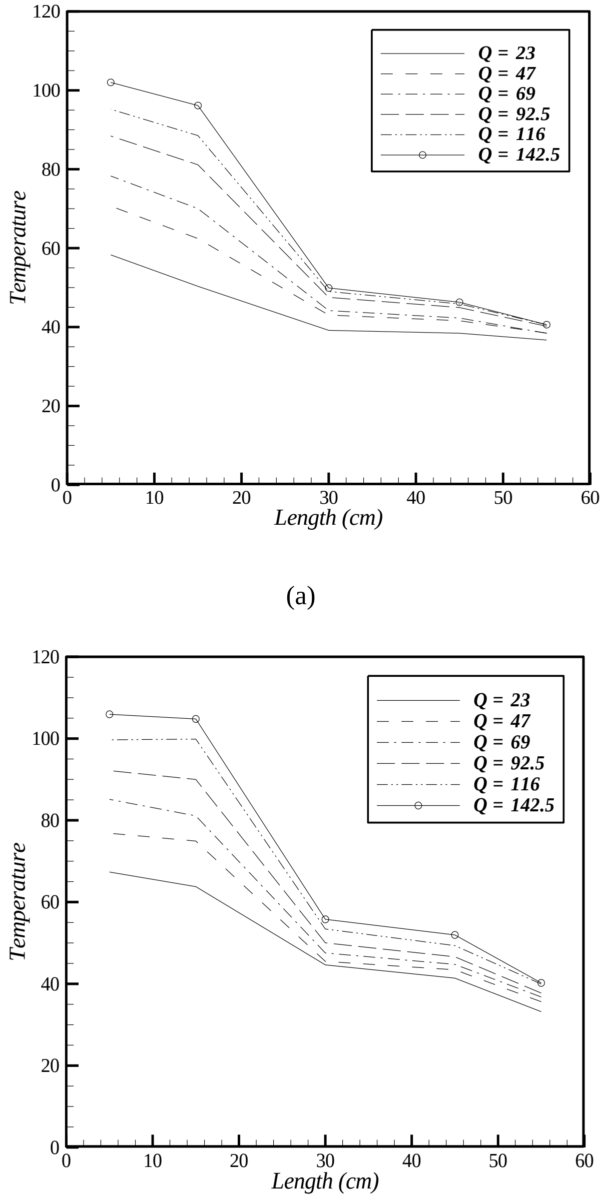


Figure 7. Temperatures variations during the time

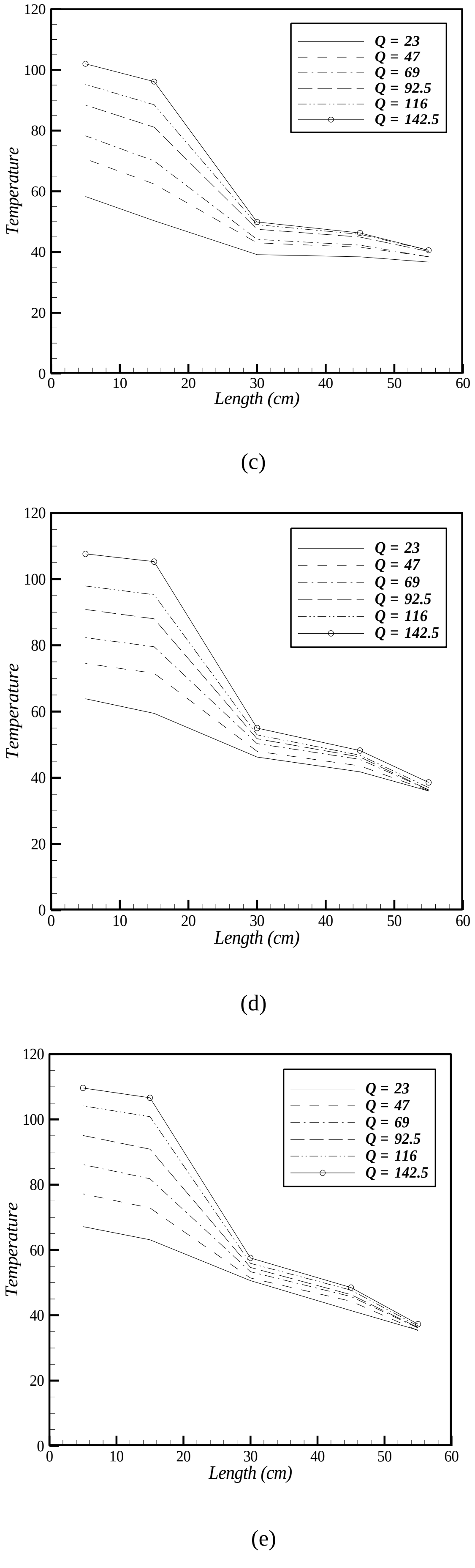
3. EXPERIMENTAL RESULTS

Figure 8 shows temperatures variations along vertical heat pipe for different working conditions. Other inclination angles results are not brought here for brevity sake. However, the behaviors of heat pipe for other angels are the same. As it can be observed, regardless of filling ratio, increasing heat input increases evaporator temperature. However, the effect of filling ratio on evaporator temperature is considerable. Moreover, as it can be observed, the highest evaporator temperature belongs to 100% filling ratio with lowest forced boiling contribution. The differences between evaporator average temperatures and condenser average temperatures are also shown in Figure 9. The lesser temperature difference is more desirable. As it can be observed, the highest temperature differences among all data points belong to filling ratio 100% with inclination angle 30 ° while the least belong to filling ratio around 60% and 80% with inclination angle 30 °. However, it does not mean that the 100% filling ratio is not a good choice, i.e. for the inclination angle of 60 ° with filling ratio 100%; an acceptable temperature difference may be observed.



(a)

(b)



(c)

(d)

(e)

Figure 8. Variations of temperatures along vertical heat pipe for filling ratio a) 50%, b) 60%, c) 70% d) 90% and e) 100%

To have a better judgment about heat pipe performance, the heat pipe thermal resistance is defined as bellow [13]:

$$R = \frac{T_e - T_c}{Q};$$

In which Q, T_e, T_c is heat input, evaporator and condenser average temperature. Results are shown in Figure 10.

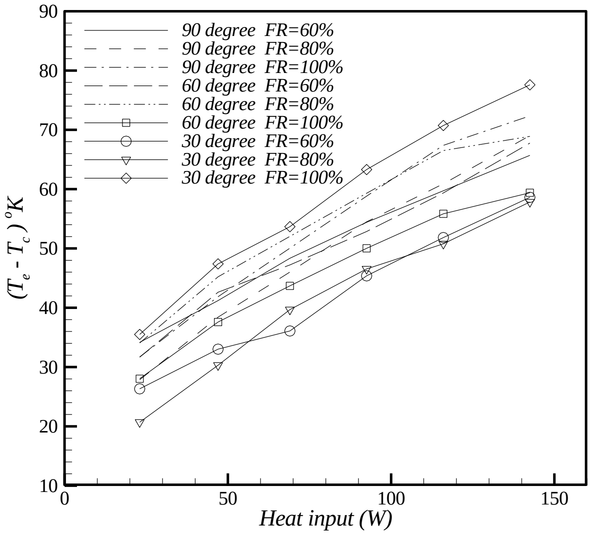


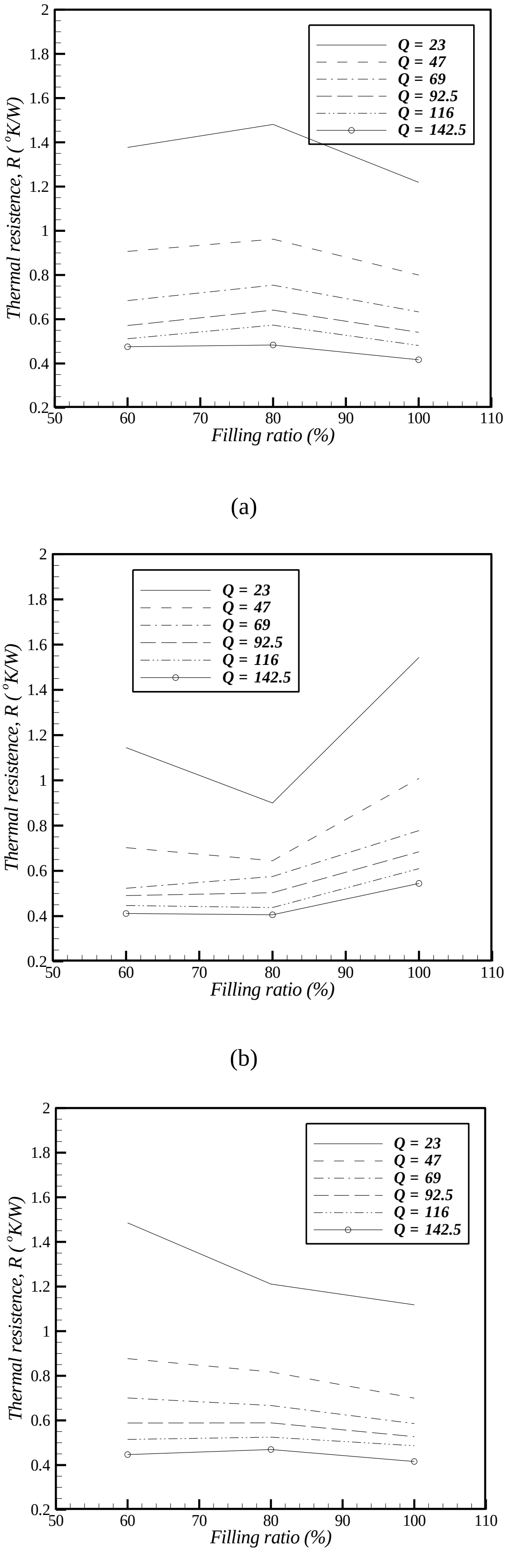
Figure 9. The differences between evaporator and condenser average temperatures

Based on Figure 10, as it was mentioned correctly by Shabgard et al. [9], by increasing the heat flux, the amount of thermal resistance will be decreased. Interestingly, regardless of inclination angle, in higher heat input the amount of thermal resistance is relatively independent of filling ratio. Moreover, by increasing heat input, the distance between constant heat input lines in Figure 9 reduces for example, the difference between lines Q=142.5 W and Q=116W is negligible. This means that in higher heat input the amount of thermal resistance is also independent of heat input. In the other words, by increasing heat input, the amount of thermal resistance approaches an asymptotic value.

By comparing Figure 10 (a) with the others, as a thumb rule, the least values of thermal resistance belong to filling ratio around 80%. However, it is not a general rule, since a weak dependency to inclination angle can also be observed.

3. CONCLUSION

In this study, the performance of a heat pipe was studied. The effect of filling ratio, heat input and inclination angle on thermal resistance were investigated. It was found out that in higher heat input the thermal resistance is independent of heat input and filling ratio. This means that thermal resistance approaches an asymptotic value. In lower heat input, the effect of filling ratio is intensified by decreasing inclination angle from 90° to 30°. Finally, in general, it can be said that the least values of thermal resistance belong to filling ratio around 80%.



(a)

(b)

(c)

Figure 10. Variations of the heat pipe thermal resistance for inclination angle a) 30°, b) 60° and c) 90°

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