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Heat transfer in an eight-pass oscillating loop heat pipe equipped with cooling tower

An experimental study

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Abstract

In this research, a series of experiments have been performed to study the thermal resistance of an oscillating heat pipe equipped with cooling tower. The effects of filling ratio and input heating power on the thermal resistance of the heat pipe and temperatures of different sections of evaporator and condenser of the heat pipe are investigated and discussed. All tests are taken for input heating power and filling ratio in the ranges of 20–200 W and 10–60%, respectively. A correlation for the thermal resistance is presented, which the effects of input heating power and filling ratio are taken into account in this correlation. The results showed that the heat pipe with filling ratio of 40% and input heating power of 160 W has the minimum value of thermal resistance among all cases considered in this research. Moreover, the thermal resistance decreases about 86% as the input heating power increases in the range of 20–120 W, while this reduction is only 23% by increasing the input heating power in the range of 160–200 W.

List of symbols

f	Filling ratio (%)
C_p	Specific heat at constant pressure (J kg^{-1} K^{-1})
I	Current (A)
$\dot{m}$	Mass flow rate (kg s^{-1})
P	Power (W)
Q	Heat load (W)
R	Thermal resistant (K W^{-1})
T	Temperature (K)
T_{cond}	Mean temperature of the condenser (K)
T_{evp}	Mean temperature of the evaporator (K)
V	Voltage (V)

Subscripts

cond	Condensation
evp	Evaporation
in	Input
out	Output

1–5	Different locations on the evaporator
6–8	Different locations on the condenser

Introduction

Heat transfer and thermal management are very important for many applications [1–3]. Oscillating heat pipes can be used as promising heat transfer equipment in thermal management due to their simple structure, good efficiency, great environmental adaptability, rapid response to large values of thermal loads, and small value of fabrication cost [4–6]. Due to these advantages, they are widely used in electric cooling, heat exchanger, solar water heating systems, thermal control system of spacecraft, cell cryo-reservation, etc. [7–9] Zhang et al. [10] studied the influence of temperature oscillation on start-up characteristics and operating efficiency of a loop heat pipe. They reported that the loop heat pipe with temperature oscillation has an ability to start up at thermal load about 15 W. Moreover, they found that the operating stability of loop heat pipe can be enhanced using a large value of operating temperature. Song et al. [11] investigated the combined

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effects of the primary and secondary wicks on the performance of a loop heat pipe. The heat pipe was equipped by a flat plate evaporator. They reported that the loop heat pipe with combined usage of the primary and secondary wicks has a capability to self-adjust at different thermal loads. Sun et al. [12] and Qu et al. [13] studied the thermal-hydrodynamic characteristics of an oscillating heat pipe. They concluded that the bubble scale, bubble motion, and temperature variation are three important factors, which affect the thermal-hydrodynamic characteristics of an oscillating heat pipe. Moreover, their results indicated that the start-up temperature reduces as the cooling air velocity increases. Note that cooling air was used in condensation sector.

Some researchers used nanofluids in heat pipes to achieve higher thermal performances [14, 15]. Qu and Wu [16] compared the thermal efficiencies of oscillating heat pipes with Silicon dioxide-water and Aluminum oxide-water nanofluids. Their results showed the thermal efficiency of the oscillating heat pipe enhances using Aluminum oxide-water nanofluid as compared with the pure water, while it decays using Silicon dioxide-water nanofluid. Accordingly, the thermal efficiency of oscillating heat pipe is enhanced by nanofluids, which depends on type of nanoparticles. Hung et al. [17] investigated the thermal efficiency of a heat pipe enhanced by Al_2O_3-water nanofluids. They found that the thermal efficiency of a heat pipe enhances using Al_2O_3-water nanofluid in comparison with the case of pure water. Moreover, their results showed that larger values of solid volume fraction of nanoparticles may not be able to enhance thermal efficiency as the larger values of solid volume fraction of nanoparticles cause a larger value of water adsorption. This leads to facilitate formation of the coating substrate due to the sedimentation of nanoparticles on the walls of the evaporation part. Menlik et al. [18] improved the thermal performance of a heat pipe using Magnesium oxide-water nanofluid. They enhanced the efficiency of the heat pipe about 26% using Magnesium oxide-water nanofluid with solid volume fraction of 5%. Moreover, they reported that this enhancement changes with respect to changing thermal loads and changing flow rate in condenser sector.

Yin et al. [19] investigated the limitations occurred during operation of an oscillating heat pipe. They concluded that these limitations are related to working liquid, temperatures of different section, latent heat, filling ratio, and heat pipe sizes. Qu et al. [20] investigated experimentally the design of the hybrid flexible oscillating heat pipe. They reported that the hybrid flexible oscillating heat pipe has a great ability for managing the thermal efficiencies of energy utilization systems.

Valipour et al. [21] studied the influences of magnetic field on the thermal field near a solid obstacle covered with a porous layer. They used the least square technique to present two equations for the average Nusselt number [22–25].

This paper performs an experimental study on thermal resistance of an oscillating heat pipe equipped with cooling tower. The effects of filling ratio and input heating power on the thermal resistance of the heat pipe and temperatures of different sections of evaporator and condenser of the heat pipe are investigated and discussed. A correlation for the thermal resistance is presented, which the effects of input heating power and filling ratio are taken into account in this correlation.

Experiment setup and procedure

Oscillating heat pipe

Generally, the thermal energy can be transferred from the evaporator to condenser using an oscillating heat pipe. A thermal-excited oscillating flow with a phase change heat transfer occurs in this device. The oscillating flow of this device considerably improves the forced convective heat transfer associated with the phase change heat transfer. The oscillating flow has a potential to generate some free surfaces, which considerably improve condensation and evaporation heat transfer. Moreover, the thermal efficiency of an oscillating heat pipe can dramatically enhance by increasing the input heating power.

Experimental setup

The experimental setup apparatus is shown in Fig. 1. The main part of this device is the helix pipes with eight pass, which the fluid is injected into it. As shown in Fig. 1a, some parts of these helix pipes are placed inside the glass chamber, which act as a condenser and the other parts of them are located outside of this chamber. The bottom outer parts of these pipes are covered with the elements, which act as an evaporator. By adjusting a dimmer, these elements begin to give heat to the fluid inside the pipes. This part is covered by insulator to minimize the heat losses. The water after leaving the glass chamber enters the cooling tower. The temperature is reduced inside the cooling tower and after that the water returns to the glass chamber by using a pump. It should be noted that this water passes through the rotameter to measure the mass flow rate before entering the glass chamber. The temperatures of lower helix pipes (evaporator) are measured by three thermocouples, and the temperatures of upper helix pipes (condenser) are measured by three thermocouples. Dimmer is employed to adjust the input voltage. The voltage and current are measured by the multimeter. A vacuum pump is

Fig. 1 Schematic view of experimental setup. **a** Three passes of pipes. **b** The glass chamber. **c** Cooling tower
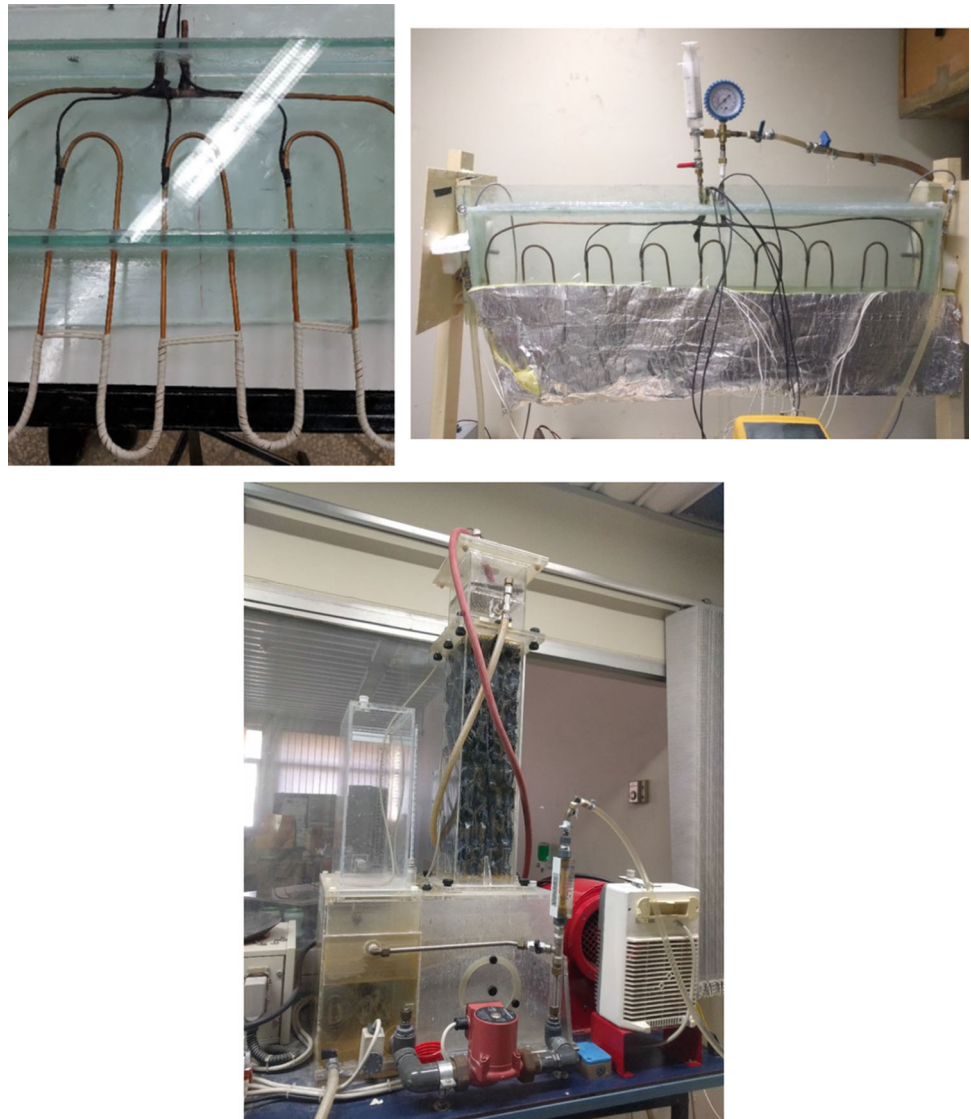
used to provide the vacuum in the pipes and achieve a relative vacuum pressure, and then the working fluid is injected into the pipe by syringe. This pump is shown in Fig. 2. After the test, a compressor is used to drain the fluid from the pipes. Finally, thermometer and rotameter are employed to measure the temperature and mass flow rate. The accuracy and uncertainty of all measurement devices are presented in Table 1.

Experiment procedure

In this experiment, distilled water is used as the working fluid. Seven filling ratios including 10, 20, 30, 40, 50, and 60% are tested. Filling ratio is defined as the total volume of liquid, is injected into the pipes, to the total volume of pipe. Before injecting the fluid, it is necessary to create a vacuum in the pipes. Accordingly, a vacuum pump is used

to evacuate the air inside the pipes. After about 3 min, the pressure inside the pipes decreases from 1 to 0.2 bar. After creation of the vacuum, the valve of the suction pump is closed and the valve of the injection part is opened. The required volume of the fluid is injected into the system by a syringe. Note that after opening the valve of the injection part, the vacuum created inside the pipes causes the fluid to flow into the pipes. After that the condenser chamber fills with water and the cooling tower pump is turned on. The mass flow rate of water is measured by rotameter. Now the electrical system is turned on and each case, different filing ratio, is tested at three input heating powers including 120 W, 160 W, and 200 W. The desired input heating power is adjusted by the dimmer. Note that the multiplication of the applied voltage (V) with the current passing through the wires (I) is equal to the power. The system starts to work with exerting the powers and the
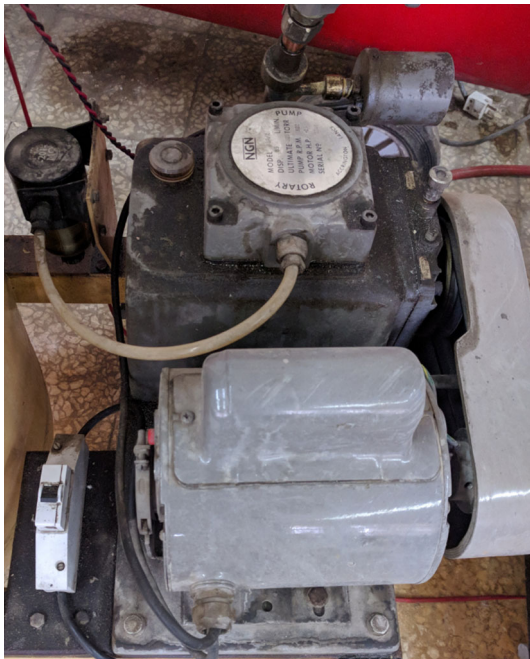
Fig. 2 Vacuum pump

Table 1 Accuracy and uncertainty of all measurement devices

Measurement device	Accuracy	Uncertainty
Voltmeter (V)	± 0.1	$\pm 0.02\#$
Coulomb meter (A)	± 0.01	$\pm 0.002\times$
Thermocouple (°C)	± 0.1	$\pm 0.02\#\times$
Syringe (CC)	± 5	± 1.433
Rotameter (lit h^{-1})	± 25	± 7.217
Thermometer (°C)	± 0.1	$\pm 0.02\#\times$

temperatures read by thermometers begin to change. All temperatures are stored on the memory card of the device within 100 min of each test for further analysis. By applying the heat flux in the evaporator section, the injected fluid, which was accumulated by the gravity force in the evaporator part, began to move upward in the pipes due to the temperature rise and reduction of the density. After evaporating the water, the vapor enters into the condenser. The vapor cools down and condensates by contacting with cold water around the pipes.

Mathematical relationships

In order to obtain the overall efficiency of the oscillating heat pipe, heat transfer in evaporator and condenser should be calculated. The value of heat transfer in the evaporator section can be calculated according to the electrical source used to generate the thermal energy. Accordingly, the value of heat transfer in the evaporator section can be calculated using the following equation:

$$Q_{\text{in-evp}} = VI \tag{1}$$

where Q, V, and I are the heat input to the evaporator, applied voltage, and the intensity of the current passing through the thermal wire, respectively.

The value of heat transfer from the heat pipe to the water tank in the condenser section is calculated using the following equation:

$$Q_{\text{out-cond}} = \dot{m}\, C_{\text{p}}\, (T_{\text{out}} - T_{\text{in}}) \tag{2}$$

where $\dot{m}$, C_{p}, and T_{in} and T_{out} are the mass flow rate of cooling water, which can be shown by the rotameter, the specific heat capacity of the water at constant pressure, and the cold water temperature entering the condenser chamber, and the water output from the condenser chamber, respectively.

In order to compare thermal performance of a heat pipe system in different conditions, the concept of thermal resistance is used, which is defined as follows:

$$R = \frac{T_{\text{evp}} - T_{\text{cond}}}{Q_{\text{in}}} \tag{3}$$

where T_{evp}, T_{cond}, Q_{in} are the mean temperature of the evaporator, the mean temperature of the condenser, and the input power of the system in the evaporator part, respectively. T_{evp} and T_{cond} are obtained from the average temperature of the thermocouples installed in the evaporator and condenser parts. Accordingly, the following relationships are used to calculate T_{evp} and T_{cond}:

$$T_{\text{evp}} = \frac{T_1 + T_2 + T_3 + T_4 + T_5}{5} \tag{4}$$

$$T_{\text{cond}} = \frac{T_6 + T_7 + T_8}{3} \tag{5}$$

Results and discussion

The results of experiments on the oscillating heat pipe equipped with cooling tower are presented and discussed in this section. The effects of filling ratio and input heating power on the thermal resistance of the heat pipe and temperatures of different sections of evaporator and condenser of the heat pipe are investigated. All results are presented for input heating power and filling ratio in the ranges of 20–200 W and 10–60%, respectively.

Figure 3 plots the different temperatures of evaporator and condenser for two values of input heating power and filling ratio. As shown in these figures, the five temperatures at different parts of the evaporator are low at the beginning of the experiment as the available fluid is not

Fig. 3 Different temperatures of evaporator and condenser for two values of input heating power and filling ratio
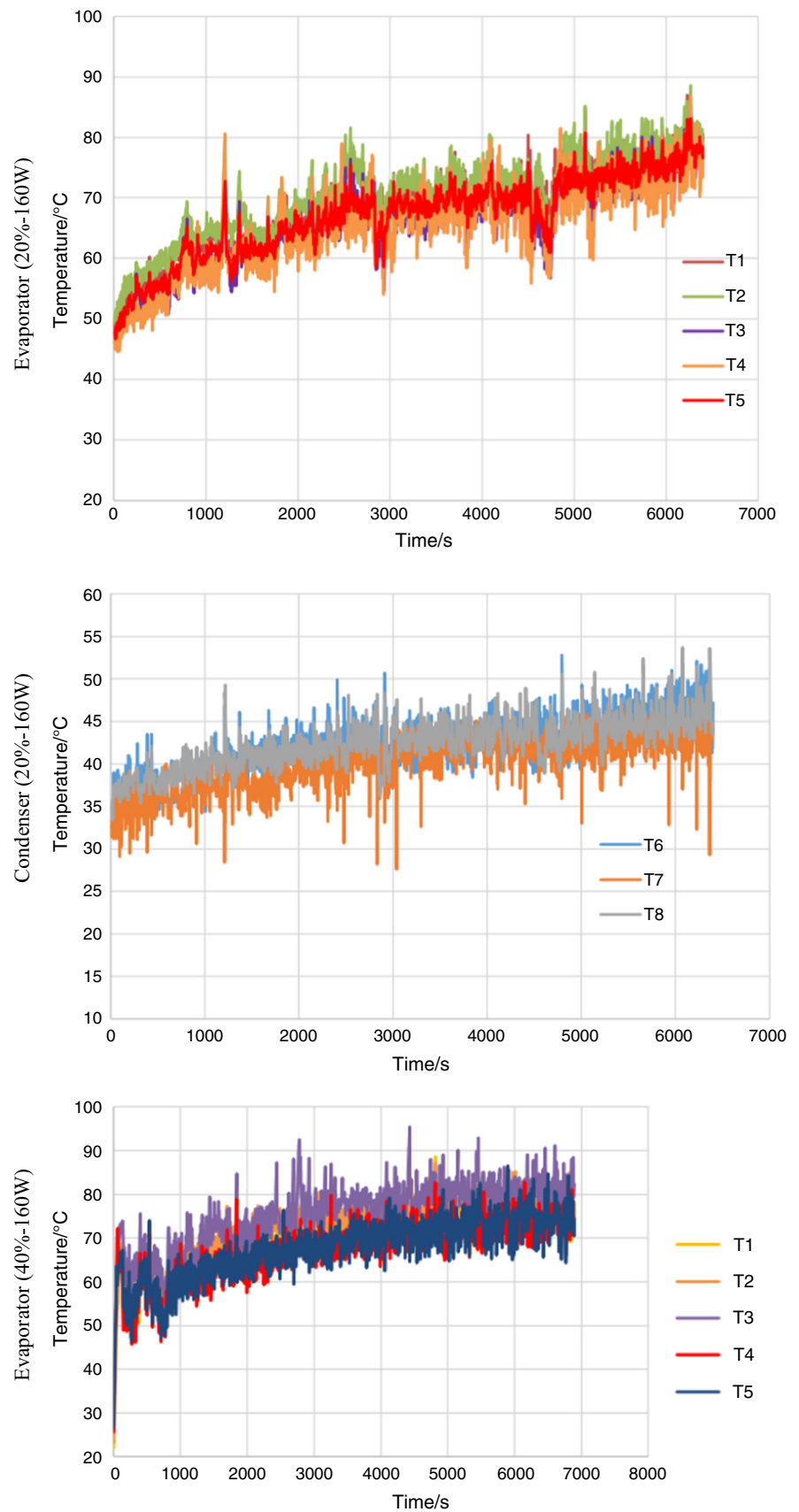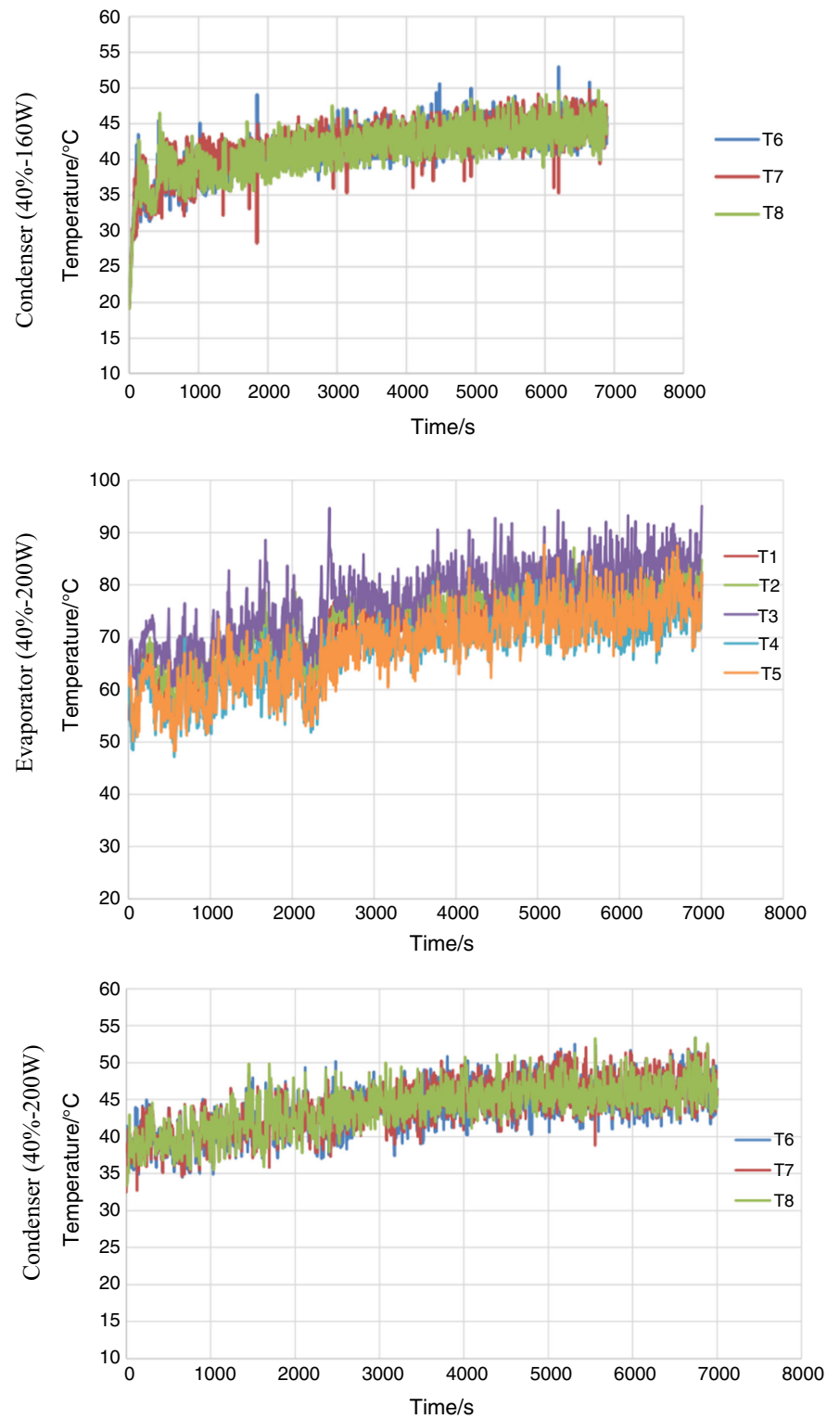
spread inside all the pipes. Over time, changing the fluid state from liquid to gas and vice versa leads to disperse the fluid in all pipes and the temperatures reach to a steady state with stable condition. After reaching the steady state, there are no changes in the graphs over time. For the temperatures of condenser, the thermometers are in contact with the water inside the water chamber and the water is flowing. Accordingly, the temperature changes are tangible at initial times, but after the time and temperature rise, these three temperatures reach a steady state.

The average temperatures of evaporator and condenser at different values of input heating power and filling ratio are presented in Table 2. To reduce the calculating error, these average temperatures are used to calculate the thermal resistance. It can be seen that for most cases, the average temperatures increase with increasing input heating power at a constant filling ratio.

Figure 4 shows the variations of thermal resistance with input heating power at a constant filling ratio of 20%. As shown in this figure, the thermal resistance decreases with increasing the input heating power. It should be stated that this reduction is more significant at lower values of input heating power as compared with the higher one. For example, the thermal resistance decreases about 86% as the input heating power increases in the range of 20–120 W, while this reduction is only 23% by increasing the input heating power in the range of 160–200 W. Note that the
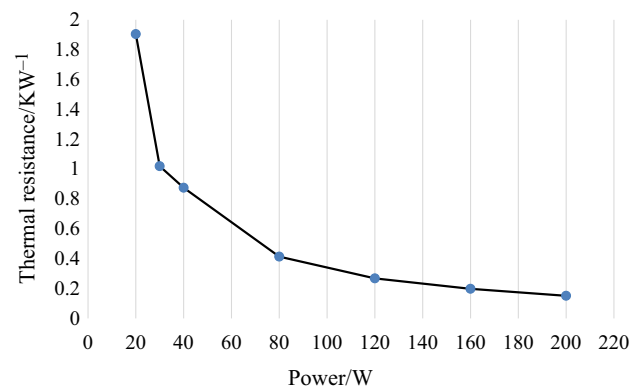

Fig. 4 Variations of thermal resistance with input heating power at a constant filling ratio of 20%

oscillating heat pipe is begun to work and the unsteady oscillation is created when the input heating power is big enough. At this condition, the variations in thermal resistance tend to be negligible. Note that for smaller values of input heating power, isolated bubble regime, around onset of nucleate boiling, at evaporating sectors is occurred leading to a large resistance in pipes. The thermal driving power is not powerful adequately to transfer the bubbles and create a stable oscillation. Accordingly, just intermittent oscillations are created. The thermal driving power enhances with increasing the input heating power and the stable oscillation is begun. Accordingly, a large enough

Table 2 Average temperatures of evaporator and condenser

| No.	Filling ratio (%)	Power (W)	Evaporator						Condenser			
			T_1	T_2	T_3	T_4	T_5	T_{ave}	T_6	T_7	T_8	T_{ave}
1	10	120	76.58	77.12	74.65	74.33	73.69	75.34	37.79	38.41	38.25	38.15
2	10	160	76.88	79.59	76.86	75.61	74.57	76.71	37.03	37.26	40.43	40.28
3	10	200	78.68	82.03	79.01	77.15	75.37	78.45	46.52	43.28	46.98	46.66
4	20	120	73.57	76.75	77.86	73.46	72.62	74.85	43.05	42.69	42.33	42.69
5	20	160	75.71	77.61	79.78	73.84	71.43	75.67	43.63	42.94	45.31	43.96
6	20	200	74.73	77.51	79.87	72.33	71.27	75.14	44.17	44.08	46.19	44.81
7	30	120	69.88	71.07	74.58	68.08	67.55	71.66	41.28	38.83	41.77	40.63
8	30	160	76.62	79.06	86.95	74.64	73.53	75.97	45.79	43.47	45.39	44.89
9	30	200	78.07	80.85	84.89	76.47	75.25	77.65	47.23	46.92	47.23	47.12
10	40	120	75.38	76.94	82.62	74.30	73.26	76.50	43.58	42.86	43.11	43.18
11	40	160	64.24	64.14	67.33	59.31	60.47	63.09	43.12	43.89	42.81	43.28
12	40	200	72.25	74.66	73.52	69.82	68.18	71.69	45.33	46.50	46.11	45.98
13	50	120	74.85	75.52	81.24	70.17	75.04	75.36	45.65	45.82	44.23	45.12
14	50	160	74.99	77.89	82.21	71.95	73.49	76.14	47.01	46.68	45.84	46.51
15	50	200	73.74	77.93	77.59	71.22	72.50	74.95	37.79	45.93	45.24	45.63
16	60	120	76.17	79.21	82.82	74.60.	75.55	76.38	37.03	44.03	43.33	43.74
17	60	160	74.92	79.04	80.86	73.03	73.87	76.34	46.52	44.28	43.61	43.99
18	60	200	77.52	80.27	83.72	73.21	75.55	78.05	43.05	46.58	46.17	46.24
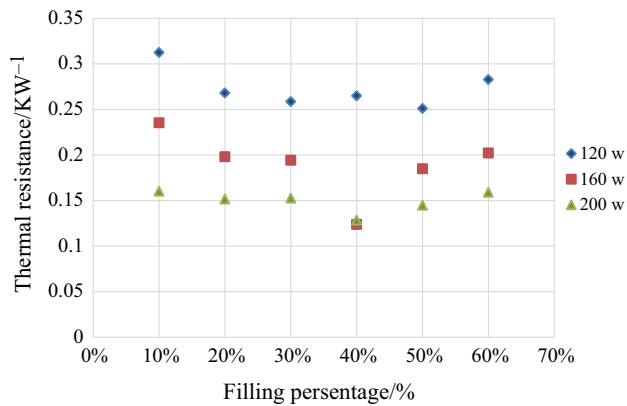
Fig. 5 Variations of thermal resistance with filling ratio at three values of input heating power

input heating power is needed to start up the oscillating heat pipe.

Figure 5 discloses the variations of thermal resistance with filling ratio at three values of input heating power. It should be stated that when the filling ratio inside the pipes is low, there is a little fluid inside the pipes to transfer heat. However, when the filling rate is high, the amount of fluid in the pipes is too large and the fluid inside the pipes can change the state (from liquid to gas and vice versa) hardly. As shown in this figure, the thermal resistance decreases with increasing the filling ratio for all values of input heating power at filling ratio lower than 40%. Note that the filling ratio of 40% is equivalent to the total volume of the evaporator. For example, the thermal resistance decreases about 47% as the filling ratio increases in the range of 10–40% for the input heating power of 160 W. However, the thermal resistance increases with increasing the filling ratio for filling ratio larger than 40%. For example, the thermal resistance increases about 24% as the filling ratio increases in the range of 40–60% for the input heating power of 200 W. As mentioned earlier, the ability of system for changing the state of fluid decreases for higher values of filling ratio. As a result, the heat pipe with filling ratio of 40% and input heating power of 160 W has the minimum value of thermal resistance among all cases considered in this research. In all filling ratio, the input heating power of 200 W has less thermal resistance as compared with other values of input heating power. Also, the dependence of thermal resistance with the filling ratio decreases at 200 W, because the bubble column and jet boiling cause intense turbulent mixing in the liquid.

Based on the experimental data, the following correlation for the thermal resistance is presented:

$$aligned \text{W} \leq P \leq 200 \text{ W} aligned \tag{6}$$

where f and P are filling ratio and input heating power, respectively. It should be stated that the reduction in thermal resistance with increasing the input heating power at a constant filling ratio is due to the changes of the boiling regime and the higher pressure of the thermosyphon pipe.

Conclusions

In this research, a series of experiments were performed to study the thermal resistance of an oscillating heat pipe equipped with cooling tower. The effects of filling ratio and input heating power on the thermal resistance of the heat pipe and temperatures of different sections of evaporator and condenser of the heat pipe were studied. The important results of this study are summarized here:

- The thermal resistance decreases about 86% as the input heating power increases in the range of 20–120 W, while this reduction is only 23% by increasing the input heating power in the range of 160–200 W.

- The reduction in thermal resistance with increasing the input heating power at a constant filling ratio is due to the changes of the boiling regime and the higher pressure of the thermosyphon pipe.

- The thermal resistance decreases with increasing the filling ratio for all values of input heating power at filling ratio lower than 40%. For example, the thermal resistance decreases about 47% as the filling ratio increases in the range of 10–40% for the input heating power of 160 W.

- The thermal resistance increases with increasing the filling ratio for filling ratio larger than 40%. For example, the thermal resistance increases about 24% as the filling ratio increases in the range of 40–60% for the input heating power of 200 W.

- The input heating power of 200 W has less thermal resistance as compared with other values of input heating power.

As a future research work, the authors have planned to develop this problem by considering the nanofluids as the working fluid.

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