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Heat Pipe Thermal Performance Analysis by Using Different Working Fluids

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HIGHLIGHTS

- The heat pipe charged with Methanol has a thermal resistance of (0.7666 °C/W), which is the lowest value of thermal resistance.
- The lowest thermal resistance of using mixtures is (0.7466 °C/W) for (70 % methanol: 30% ethanol).
- The highest value of heat transfer coefficient when using water as a working fluid is (519.1073 W/m^2. °C).

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Heat Pipe; Binary Mixture Fluids; Thermal Resistance; Heat transfer coefficient.

ABSTRACT

This study investigated the thermal performance of the heat pipe and conducted on the effects of working fluids with wick and vertical position. The experiments were conducted using a copper heat pipe with (a 20.8) mm inner diameter, and the length of the evaporator, the condenser, and the adiabatic regions were 300 mm, 350 mm, and 300 mm, respectively. The working fluids selected were water, Methanol, Ethanol, and different binary mixtures (50: 50) %, (30:70) %, and (70:30) % mixing ratios. The filling ratio for all working fluids remained constant with the value of 50% of the evaporator volume, and the heat input values were 20, 30, 40, and 50 watts. The results show that the heat pipe charged with Methanol has a thermal resistance of (0.7666 °C/W) which is the lowest value of thermal resistance. The lowest thermal resistance of using mixtures is (0.7466 °C/W) for (70 % methanol: 30% ethanol). Both are achieved at 50 W heat input. Also, the highest value of heat transfer coefficient when using water as a working fluid is (519.1073 W/m^2. °C), and for using a mixture (70 % water: 30% methanol) is (805.89 W/m^2. °C). Both are achieved at 50 W heat input.

1. Introduction

The consumption of energy in numerous states has been raised all over the world. An increase in energy consumption has been realized due to the significant evolutions in various sectors [1]. It can be anticipated that energy consumption has even quicker progress in the hot and equatorial states than in other states. Energy and global warming are primary issues currently and the main challenge for scientists and policymakers. Applying a heat recovery system to enhance energy-consumption expression systems performance is essential for reducing emissions. Heat pipes are the best heat transfer equipment with minimum thermal resistance, becoming an extremely effective heat transfer device. Even with small temperature variations between the evaporator and condenser regions, large heat input at the evaporator section could be gained in a heat pipe due to the two-phase flow of the working fluid inside it [2, 3, 4]. All heat pipes consist of sealed tubes partially filled with the working fluid. The heat pipes can be classified into three types: a gravity-assist heat pipe or two-phase closed thermosyphon (TPCT), a pulsating or oscillating heat pipe (OHP), and a traditional or conventional heat pipe (CHP). In operation, the heat supplied to the evaporator section, the equilibrium is perturbed and generates a vapor at a slightly higher pressure and temperature. Due to the increased saturation pressure, the vapor flows along the pipe to the condenser section. A lower temperature causes the vapor to condense and reject its latent heat of evaporation. The condensed vapor backs to the evaporator side due to the capillary effect of the wick in the CHP at different orientations or the gravity asset force in the TPCT.

TPCTs are heat pipes that eliminate the wick structure. The variation between a CHP and a TPCT is that the TPCT uses a gravity asset to transfer heat energy from a heat supply located below the cold region. As a result, the evaporator section is situated below the condenser section. The working fluid evaporates, condenses in the condenser section, and flows back to the

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evaporator section under the influence of gravity. When gravity can be utilized, TPCTs are preferred to CHPs because the wicks in the heat pipes produce additional resistance to the flow of condensate [2].

The thermosyphon Heat Pipe is a simple two-phase closed loop heat pipe and a useful heat transfer apparatus. It's no more than a wickless heat pipe having a liquid reservoir at the bottom. The best depiction of Thermosyphon is divided into three sections, as revealed in Figure 1. The heat input throughout the evaporator section converts the working fluid into a vapour that rises and flows across the adiabatic section to the condenser section. This vapour condenses and releases its latent heat into the condenser section. Then, the condensate is forced back to the evaporator section in the form of a liquid film via the force of gravity. [5]. A thermosyphon device is a wickless heat pipe. Thus, gravity is the main driving force for the condensate to return to the evaporator section.

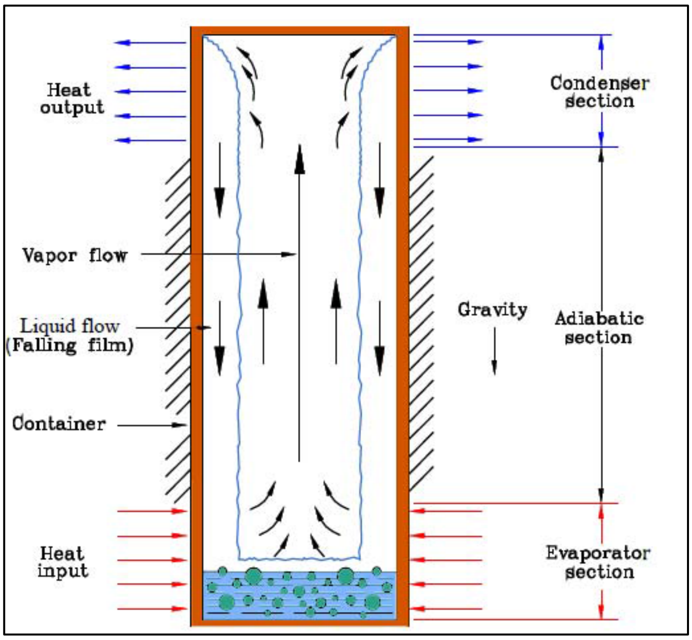

Figure 1: The schematic process of the Thermosyphon device [2]

Ashok et al. [6] studied the performance of the thermosyphon by using a copper tube of 1000 mm in length with inside and outside diameters of 24 mm and 26 mm, respectively. Also, the inclination angles were 40, 50, 60, 70, 80, and 90^o. The length of the evaporator, the condenser, and the adiabatic section were 300 mm, 450 mm, and 250 mm, respectively, and using (60% ethanol and 40% methanol) mixture as a working fluid by filling ratio of the 60% of evaporator volume. The heat inputs were (25, 45, 80, 120, and 190 W), and the coolant flow rates of water were (3.6, 7.2, 14.4, and 21.6 kg/h). The results showed that the highest heat transfer efficiency is 86.39% at 190 W, at a 3.6 kg/h coolant flow rate and 80^o inclination angle. The binary mixture manifested better thermal conductance for the thermosyphon heat pipe. Raghuram et al. [7] studied experimentally the performance of a copper heat pipe having (12 mm) dia., (300 mm) length, and (1 mm) thickness with a (7.29 W) heat input. Experiments were performed without and with working fluid for various inclinations to assess heat pipe thermal efficiency. The selected working fluids for the investigation were distilled water and acetone. The heat pipe thermal efficiency was quantified in the thermal resistance and the general coefficient of heat transfer via the temperature distribution measurement across the heat pipe. The optimum tilt angle was experimentally obtained and confirmed, similar to the simulation outcome determined via the analysis of CFD. The heat pipe made of Cu was obtained to be influential if acetone was utilized as a working fluid. The optimal angle of inclination of the heat pipe for the ultimate heat transfer rate was obtained to be (60°) for the two tested working fluids. Yeonghwan et al. [8] experimented using a thermosiphon made of copper, with an inner diameter of 25 mm, a total length of 925 mm, the length of each evaporator, condenser, and adiabatic section 300 mm, 325 mm, and 300 mm, respectively. The evaporator was heated using a DC source (Eight cartridge heaters). Each part of the thermosiphon contains 9 thermocouples, 3 on the upper surface, 3 on the lower surface, and 3 inside. The condenser was cooled with water through the jacket. The water temperature entering the condenser was fixed at 15 ^{o}C, and the flow rate was 5.6 l/min. The thermosiphon was insulated to reduce the heat losses from the system to the environment. The water was selected as the working fluid, with a fill ratio of (25, 35, 40, 50, 60, 75, and 100%). The inclination angle rates were (5, 15, 30, 45, 60, 75, and 90^o). The input power to the evaporator varied within (10 -300 kW/m^2). It was found that at a 25% filling ratio, the liquid fluctuation increased. The thermosyphon performance agrees well with the correlation at stable condensate film formed on the surface. The present two-phase closed thermosyphon shows the best thermal performance at the inclination angle of 30º and the filling ratio of 50%. Charoensawan and Prait [9] investigated the thermal performance of a horizontal closed loop OHP. Copper OHP was used in the experimental work with various inner diameters (1, 1.5, and 2 mm), evaporator lengths (50 and 150 mm), working fluid (distilled water and ethanol), and filling ratios (30, 50, and 80%), number of turns (5, 11, 16, and 26), and evaporator temperature (40 – 90) ^{o}C. The condenser section was cooled by air at 25 ^{o}C and 0.4 m/s. The results showed that the operation of OHP in a horizontal position is related to the number of turns. The thermal performance enhances by decreasing the length of the evaporator, the high number of turns, and increasing the pipe diameter. Kuo et al. [10] used two 8 turns of OHP made from copper and glass for flow visualization. The first one had uniform square tubes with a cross-sectional area of 2x2 mm^2. The non-uniform second OHP had 8 tubes with a cross-sectional area of 2x2 mm2 and 8 tubes with a cross-sectional area of 1x2 mm^2. The distilled water was used as working fluid at filling ratios (40, 50, 60, and 70) % for both types. The effect of inclination angles was examined by conducting (0, 30, 60, and 90) degrees, respectively. The results showed that the inclination angles clearly affected the thermal resistance of uniform OHP. While for non-uniform OHP, the thermal resistance was somehow less sensitive to the orientation angles. At a horizontal configuration, the uniform OHP had poor heat transfer and large thermal resistance (2.2 $^oC/W$ at 40 W& 60% filling ratio), which led to the OHP not operating in all test cases. In comparison, the non-uniform OHP can be operated at a horizontal orientation (1 $^oC/W$ at 40 W& 60% filling ratio). However, it is still sensitive to filling ratio (above 50%) and heat input power. Chih et al. [11] investigated the thermal performance of a 4 turns OHP made from copper tube, and the length of the evaporator, adiabatic, and condenser sections are 70, 60, and 70 mm, respectively. A uniform and alternating tube OHP was used in this study. The inner diameter of uniform channels OHP was 2.4 mm. The alternating OHP had 4 uniform tubes (each turn had a uniform and alternative channels) with an inner diameter of 2.4 mm, and the other 4 alternative tubes consisted of two halves; one half with an inner diameter of 2.4 mm and the other half with major diameter 3.9 mm and miner diameter 1.5 mm for each alternating channel. The effect of alternative tube diameter in one OHP, working fluid (water, Methanol, and HFE-7100), and variable heat input (20 to 140) W were examined in both horizontal and vertical modes. The results showed that the thermal resistance for both types (alternative and uniform) OHP has the same trend, but the alternative one is lower than the uniform type. Also, CLPHP with HFE-7100 gave the lowest thermal resistance at low heat input, and distilled water had the lowest thermal resistance at high heat input (more than 60W).

The effects of inserting fins in OHP were studied by Rahman et al. [12], expediting a finned and un finned structure of OHP made from copper tube meandering in 8 turns with an inner diameter of 2.5 mm and outer diameter of 3 mm. The length of the evaporator, adiabatic, and condenser sections were 50, 120, and 80 mm, respectively. The copper wires with 1 mm diameter were used as fins inserted only in the condenser section at an equal distance between fins. Methanol and Ethanol fluids were used as working fluids with a 50% filling ratio. The heat input was at three inclination angles (0, 30, and 45) degrees. The evaporator section was insulated and heated by a heater at (10 – 80) W, while the condenser section was cooled by forced air. The results demonstrated that Methanol had 0.4 $^oC/W$ lower thermal resistance than Ethanol 0.75 ^oC /W at 80W, and the finned–inserted structure showed higher thermal resistance (0.33 and 0.7) ^oC /W than the normal structure (0.3 and 0.6) ^oC /W at 80W for Methanol and Ethanol respectively.

The conventional heat pipe is a passive device transporting an amount of heat between two different temperature zones. It has no moving parts and does not require electricity input. The heat pipe is constructed of three sections: the first end of the pipe is the evaporator section where the heat is received from the heat source, the other end of the pipe is the condenser section where the heat is rejected, and in between, the adiabatic section where the working fluid and heat transported inside the heat pipe, as depicted in the Figure 2.

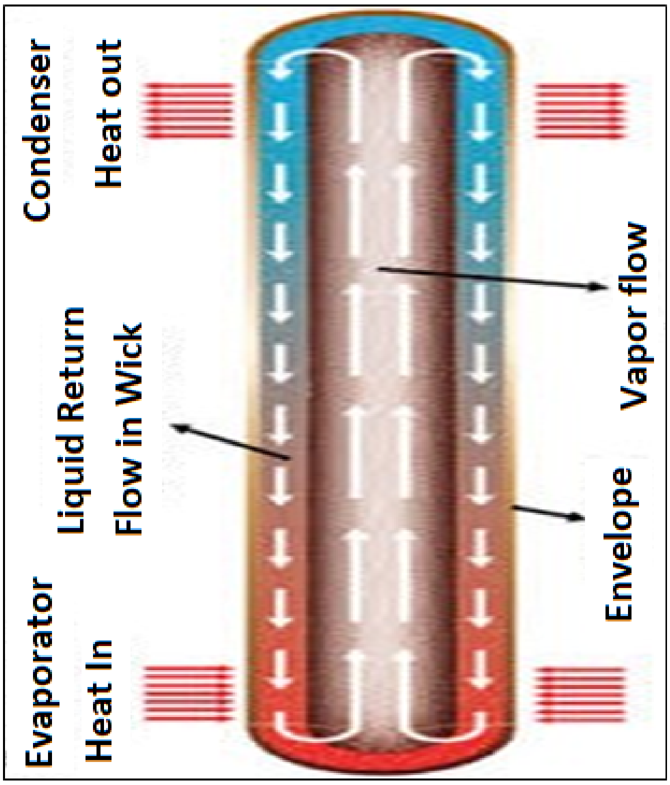

Figure 2: Conventional heat pipe [2]

If the heat energy is supplied to the evaporator, this heat will transfer from the heat source throughout the wall and the internal wick to reach the working fluid (liquid). The resulting heat input vaporizes the liquid, and the vapor moves by pressure difference driving force through the adiabatic section to reach the condenser. In the condenser section, the working fluid changes its phase (vapor to liquid) due to the temperature cooling down and rejecting its latent heat of vaporization to the heat sink. The liquid is pumped back to the evaporator section by the wick's capillary pressure. The heat pipe continuously transfers the latent vaporization heat from the heat source to the heat sink as long as the heat input at the evaporator section is supplied.

Fadhil [1] tested the performance of a copper heat pipe of 300 mm in length. The length of the evaporator, the condenser, and the adiabatic section were 75mm, 75mm, and 150 mm, respectively, the inner and outer diameters were 14 mm, and 16 mm, respectively, and the heat pipe was at a horizontal position. The water and ethanol were used as a working fluid, and the heat flux changed in a range (of 2.8 -13.13) kW/m^2. The results showed that thermal resistance was lower when the water was used as a working fluid. Manimaran et al. [5] used a copper tube with 20.8 mm inner diameter and 22 mm outer diameter to form a heat pipe with the length of the evaporator, adiabatic, and condenser sections 50 mm, 300 mm, and 250 mm, respectively. They used distilled water as a working fluid with different filling ratios of 25%, 50%, 75%, and 100% of the evaporator volume. The evaporator section was heated using an electrical heater (30 – 70) W. The water was used to cool the condenser section. It was found that the lowest value of thermal resistance at vertical position (90^o) and filling ratio of 70%. The performance of heat transfer in the heat pipe with screen mesh wick was studied by Peyghambarzadeh et al. [13]. A copper heat pipe of 400 mm in length with an evaporator diameter of 26.4 mm and adiabatic and condenser diameters of 20 mm was fabricated and used water, methanol, and ethanol as working fluids with a constant volume filling ratio of 50% and in a horizontal position. The evaporator section was heated by low heat input of 20.7 W. The condenser section was cooled by constant water bath temperatures (15, 25, and 35 ^{o}C). It was found that the heat pipe charged by methanol produces the lowest heat transfer coefficient value. H. Ahmad et al. [14] manufactured two heat pipes from copper with a 32 mm inner diameter, and the lengths of the evaporator, adiabatic, and condenser sections were 370, 230, and 400 mm, respectively. The first heat pipe (Thermosyphone) circulates the working fluid by gravity, and the other heat pipe works by capillary force due to wick use. The ethanol was used as a working fluid with a filling ratio (35 and 85 %). The heat input was varied by (200 – 700 W). The results were at aspect ratio of 7.8 and an 85% filling ratio. The best performance of the heat pipe was obtained at 500 W, with a maximum heat transfer coefficient of 9950 W/m^2.^{o}C. In contrast, the best performance of the two-phase thermosyphon was obtained at aspect ratio 4 for a 35% filling ratio and power input 600W, with a maximum heat transfer coefficient of 4590 W/ m^2.^{o}C. The performance of the heat pipe is better than that of the two-phase thermosyphon. As the overall comparison between the two pipes. Sachin et al. 15] A copper thermosyphone with a 25.4 mm inner diameter and the working fluids used were a binary of methanol and ethanol with mixing ratios (50:50%), (30:70%), and (60:40%) at four tilt angles (0, 30, 60, and 90^o). The analysis results of experiments showed that the best thermal performance was for the binary fluid with a (60:40%) mixing ratio and at a 30^o tilt angle.Chandrasekaran et al. [16] investigated the operation of a copper heat pipe with a 9.25 mm inner diameter. The total length of the heat pipe was 450 mm, and the wick was made of stainless steel with mesh sizes 100 and 200 pore /in. The distilled water was used as a working fluid, and the heat pipe was positioned at three orientations, horizontal, inclined, and vertical. The results showed that the heat transfer coefficient and thermal resistance decreased using a wick with a 200 pore/mesh size. Mozumder [17] studied heat pipe performance with 150 mm length and 5 mm diameter. The filling ratios are 35, 55, 85, and 100%. The heat inputs were 2, 4, 6, 8, and 10 W. Experiments were done with and without working fluid (dry run) under various thermal loads to evaluate the heat pipe's performance. The working fluids chosen for the study were water, methanol, and acetone. Compared to a dry run, the system reaches a steady state early in the wet run. The functioning heat pipe with a wet run has a lower overall thermal resistance than a dry run. The thermal resistance obtained in the dry test for a 2 W heat input capacity was 10.5 ^{o}C/W, while it was 7.25oC/W in the wet run. Working fluid filling ratios of more than 85% evaporator volume produce the best results in increased heat transfer coefficient and decreased thermal resistance. Bogarrasa and Khalifa [18] conducted a comparative study on the performance of a conventional heat pipe with various working fluids. The working fluids selected for the research were water and ethanol. The mixing ratio of ethanol in water varied between 25% and 95%. The heat pipe material was copper with a stainless steel wick structure. The results reported that the temperature of the evaporator section charged by water was lower than other working fluids at high heating input. Though, the water transferred more significant heat than ethanol and binary fluids. Review previous research and identify the types of tubes used, working fluids, how researchers worked, and the results they reached. We found that most researchers used mixtures with thermosiphon and pulsating heat tubes. And some of them used the separator, a piece of tube with a diameter less than the inner diameter of the heat pipe, which is fixed inside the tube in the adiabatic section. Some used the separator in the thermosiphon, others used it in the traditional heat pipe, but they used a wick only in the evaporator section. In this work, we manufactured a heat pipe. It contains a separator piece with a fuse installed along the heat pipe. A small camera (resistant to heat, pressure, and moisture) with a diameter of 6 mm was installed. It was fixed at the end of the pipe from the side of the condenser part, with the special fixing paste placed to close the gap between the camera wire and the edge of its hole. The camera's benefit is ensuring that the wick structure is fixed in contact with the inner surface of the heat pipe and knowing when and how the evaporation and condensation process of the working fluids occurs inside the heat pipe.

The study aims to conduct a practical study to verify the effect of experimentally using binary mixtures of working fluids, water, ethanol, and methanol, and their mixing ratios. On the thermal performance of the heat pipe under the influence of the heat input variables, the degree of inclination of the heat pipe, and the evaporator and condenser sizes, to get the best performance.

2. The Experimental Setup

A model of heat pipe used in the present work was manufactured from a copper pipe provided with stainless steel wick with (350) pore/in. The heat pipe assembly specifications and dimensions are shown in Table1.

Table 1: Heat Pipe specifications and Dimensions

Heat pipe material	Copper
Jacket material	Copper
Total length of the heat pipe, Lt	950 mm
Outer diameter of the heat pipe, Do	22 mm
Inner diameter of the heat pipe, Di	20.8 mm
Adiabatic section length, (La)	300 mm
Evaporator section length, (Le)	300 mm
Condenser section length, (Lc)	350 mm
Wick	stainless steel with d_w (22.8 μm) & N (350 pore /in)

The working fluids used were water, methanol, ethanol, and binary mixture. Table.2 show the working fluids used with their properties. The heat supplies are done by a flexible heater wrapped around the evaporator section—the heat input is controlled by a voltage regulator device. A multimeter was used to measure the amount of supplying electrical power. The value of heat input was simply calculated as the product of the current and voltage as;

$$Q_{in} = I \times V \tag{1}$$

Where, I = electrical current, and V = voltage difference

The adiabatic section was isolated by a 25 mm glass wool layer to ensure no heat transfer in or out of the heat pipe. The heat rejected from the condenser section occurs by using a water jacket. Where the cooled water circulated at a constant mass flow rate. The value of heat rejected was calculated as:

$$Q_w = \dot{m}_w \times C_w \times \Delta T_w \tag{2}$$

Thermocouples (K–Type) were fixed at different positions to measure the external surface, inside heat pipe, and inlet and outlet water temperatures and connected with data acquisition and PC interface to record data. Figure 3 and Figure 4, show a schematic diagram and photograph of the test rig.

Experimental tests were conducted using different pure and binary working fluids at a 50 % filling ratio and for different heat inputs (20, 30, 40, and 50 W). At a specific heat input, the temperatures were recorded at evaporator, adiabatic, and condenser sections after reaching a steady state.

The merit number provides the approach for comparing the thermal performance of working fluids used in heat pipes, as shown in Table 2.

Table 2: Working fluids properties

Working Fluid	Tbo (ºC)	Density (kg/m3)	Hfg (kJ/kg)	μ × 106 (N.s/m2)	Σ (N/m)	M.N (W/m2)
Water	100	959	2251	8.92	0.0589	45.56×10^7
Ethanol	78	758	962	445	0.0173	2.83×10^7
Methanol	64.7	789	1120	329	0.0188	5.04×10^7
Water50%& Ethanol 50%	94.708	910.605	1944.545	317.897	0.049023	27.3×10^7
Water 50% &Methanol 50%	88.623	904.6093	1887.321	294	0.04622	30.96×10^7
Ethanol 50% &Methanol 50%	70.029	830.307	1056.498	375.506	0.018196	4.25×10^7
Water 30% & Ethanol 70%	90.775	874.6019	1710.622	348.5738	0.04146	17.79×10^7
Water 30% & Methanol 70%	81.686	870.662	1664.351	304.897	0.038102	18.1×10^7
Water 70% & Ethanol 30%	97.416	935.21	2099.861	298.394	0.0540269	35.55×10^7
Water 70% & Methanol 30%	94.1658	930.717	2064.114	287.246	0.052274	34.96×10^7
Ethanol 70% & Methanol 30 %	72.81	770.0855	1023.626	399.743	0.017884	3.52×10^7
Ethanol 30 % & Methanol 70 %	67.666	782.0763	1084.74	354.875	0.018465	4.41×10^7

A high merit number is not the only factor in choosing a working fluid. Many important factors are taken into consideration in choosing the working fluid, including:

- Compatibility with wick and wall material.
- Stabile thermal properties.
- Wettability wick and wall material.
- Vapor pressure is not too high or low over the operating temperature range.
- High thermal conductivity.

The properties of the user working fluids, whether pure or mixtures, were extracted and calculated according to their properties table, the equations and laws of mixtures, and the merit number law application.

$$M.N = \rho\sigma\, h_{fg} / \mu \tag{3}$$

It was found that the highest value of merit number is (45.56×10^7 W/m^2) for water [19].

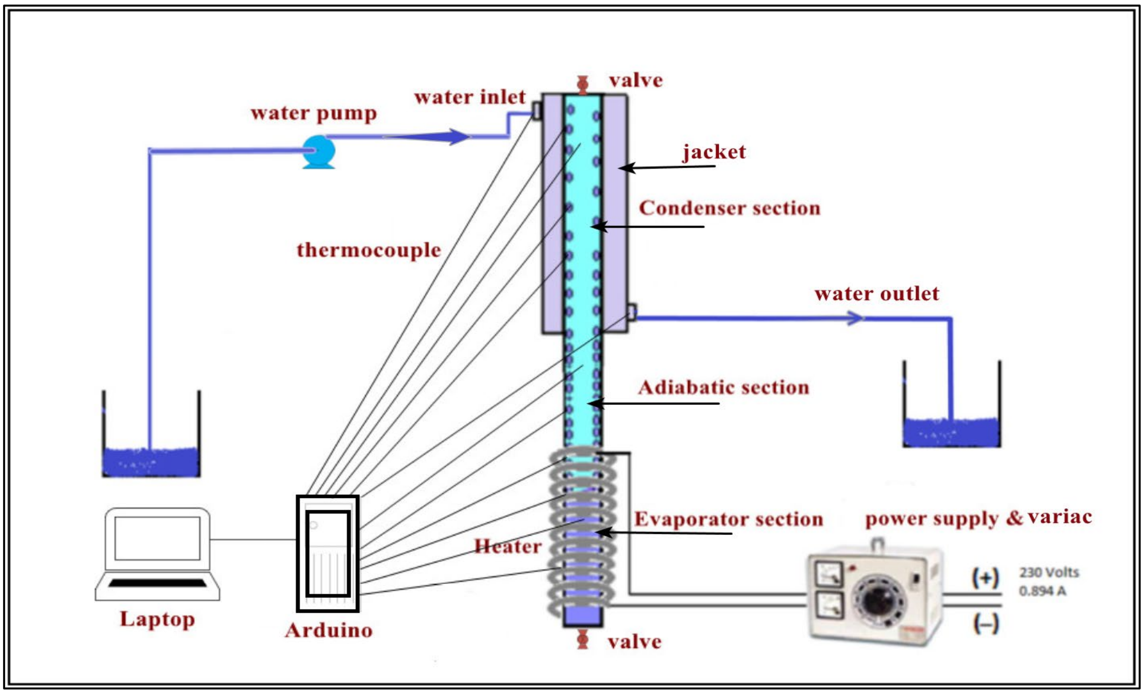

Figure 3: A schematic diagram of the test rig

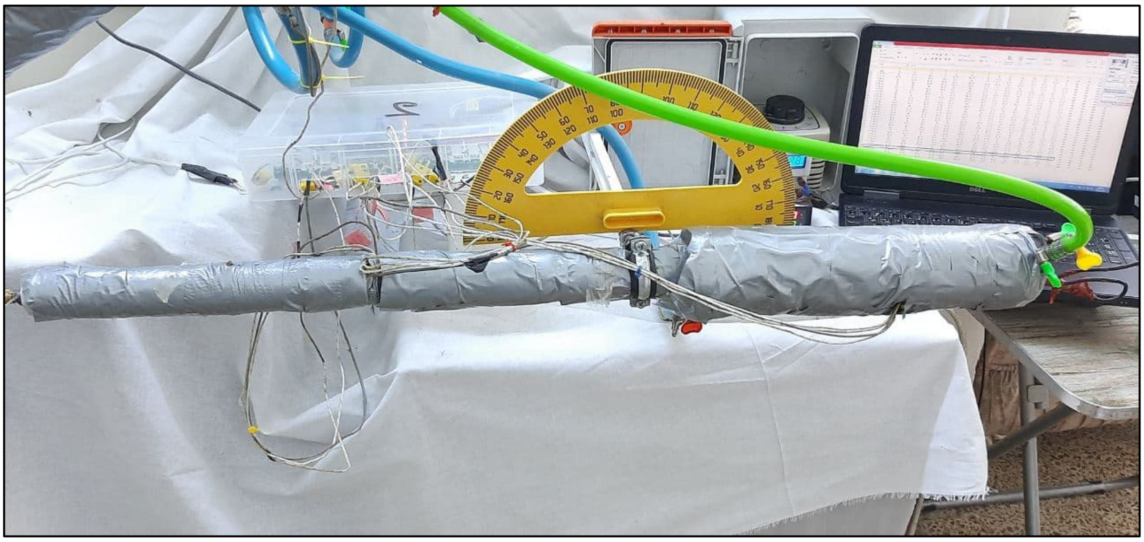

Figure 4: A photograph of the test rig

3. The Experimental Calculation

3.1 Thermal Resistance Calculation

The thermal resistance measured in °C/W could be determined from [5] [13]:

$$R_{th} = (\overline{T}_e - \overline{T}_c)\ /Q_{in} \tag{4}$$

Where $\overline{T}e$ & $\overline{T}c$ are the average evaporator and condenser temperatures, respectively, measured at three different locations around them.

The experimental results show that the input power (Qin) calculated from eq.1 is almost equal to the heat rejected from the condenser (Qw) at steady state conditions. Therefore, the small difference can be neglected.

3.2 The Heat Transfer Coefficient Calculation

The heat transfer coefficient in the evaporator can be evaluated by using the following Equation [13]:

$$h = Q_{in}\, /\, A_s\, (\overline{T}_e - \overline{T}_v) \tag{5}$$

Where: (A_s): The evaporator surface area equals ($\pi\ D_i\ L_e$).
$\overline{T}_v$: The HP inside average vapor temperature at the evaporator

4. Uncertainty Analysis

The least count of the respective measurement devices can be used to represent the uncertainty associated with measuring parameters, such as voltage and current. For example, a few options in Table 3 regarding temperature measuring exist. It may be deduced from the calibration that the temperature value is ±0.42°C; accuracy is guaranteed. However, the derived quantity power, which is a product of the voltage and current, requires an uncertainty calculation; the uncertainty in power (50 W) can be calculated as:

$$\sigma p = \pm \sqrt{(\frac{\partial p}{\partial V}\sigma V\ )^2 + (\ \frac{\partial p}{\partial I}\ \sigma I)^2}$$

$$= \pm \sqrt{(0.75 \times 3.09\ )^2 + (\ 68 \times 0.01)^2}$$

$$= \pm\ 2.415$$

$$\frac{\sigma p}{p} = \pm \frac{2.415}{50}$$

$$= \pm\ 0 \tag{8}$$

Table 3: Summary of the uncertainty related to the used devices

No.	Quantity measured	Uncertainty	Unit
1	Temperature	± 0.42	°C
2	Voltage	± 3.09	V
3	Current	± 0.01	A
4	Power	± 0.048	

5. Results and Discussion

The performance of the heat pipe is determined indirectly in terms of thermal resistance and heat transfer coefficient. The thermal resistance values were determined at the different heat input values of 20, 30, 40, and 50 W.

Figure 5 shows the thermal resistance values plotted as a function of heat input. In general, the thermal resistance decreases with increasing the heat input for all working fluids.

Thermal resistance values for methanol, water, and ethanol decreased as heat input increased, as observed in Figure 5.a. The thermal resistance of the fluid depends on the working fluid's properties. When the surface tension decreases, the vapor bubble forms a smaller bubble instead of a long vapor plug since the smaller bubble has a lower vapor mass than the longer bubble. This causes the buoyancy force to be higher, the vapor plug can flow from the evaporator to the condenser section, and the methanol has a lower boiling temperature than the other working fluids. For that reason, methanol has the lowest thermal resistance values at all heat inputs compared to the other working fluids. Also, it was observed from the obtained results that the temperature difference between the evaporator and the condenser reduces as the values of heat input increase, and the minimum value of thermal resistance of methanol was recorded as (0.7666 °C/W) at 50 W heat input value. Figure 5.b. illustrates that the thermal resistance values for (water: methanol), (ethanol: methanol), and (Water: ethanol) binary mixtures (50:50) % are decreased as the heat input increases. The thermal resistances of (ethanol: methanol) result in lowest value than other binary mixtures (0.7476 °C /W). Figure 5.c. illustrates that the thermal resistance values decreased as the heat input increased for (50% water: 50% methanol), (30% water: 70% methanol), and (70% Water: 30% methanol) binary mixture. The lowest value of thermal resistances was (0.79334 °C /W) for (30% water: 70% methanol). Figure 5d illustrates that the thermal resistance values decreased for (50% water: 50% ethanol), (30% water: 70% ethanol) and (70% Water: 30% ethanol) binary mixture as the heat input increased and the lowest value of thermal resistances is (0.83666 °C /W) for (30% water: 70% ethanol). Figure 5.e. illustrates that the thermal resistance values decreased for (50% ethanol: 50% methanol), (30% ethanol:

70% methanol), and (70% ethanol: 30% methanol) binary mixtures as the heat input increased and the lowest value of thermal resistances is (0.7466 ^{o}C /W) for (30% ethanol: 70% methanol). From the summary results, the HP charged with methanol has thermal resistance (0.7666 oC /W), which is the lowest thermal resistance value and achieved at 50 W. Also, the thermal resistance value of the mixing at a mixture of (70 % methanol: 30% ethanol) at a value of (0.7466 ^{o}C /W). The lowest value at all mixing ratios was achieved at 50 W. This is because, at low heat input, the effective thermal resistance increases. After all, the increase in the evaporator boiling temperature is at a higher rate than that in the condenser. This is usually because of nucleate boiling at high heat inputs. Moreover, the surface tension of the working fluid is significant at low heat input, and its amount decreases with increasing heat input. Also, in the evaporator section, the thickness of the film of the liquid layer is high at a low heat supply. So this leads to an excessive thermal resistance, but the film thickness tends to reduce with increasing the heat supply. A similar result obtained by [20,21].

The relationship of the fluid's effective thermal conductivity with the heat input is the opposite of the thermal resistance relationship.

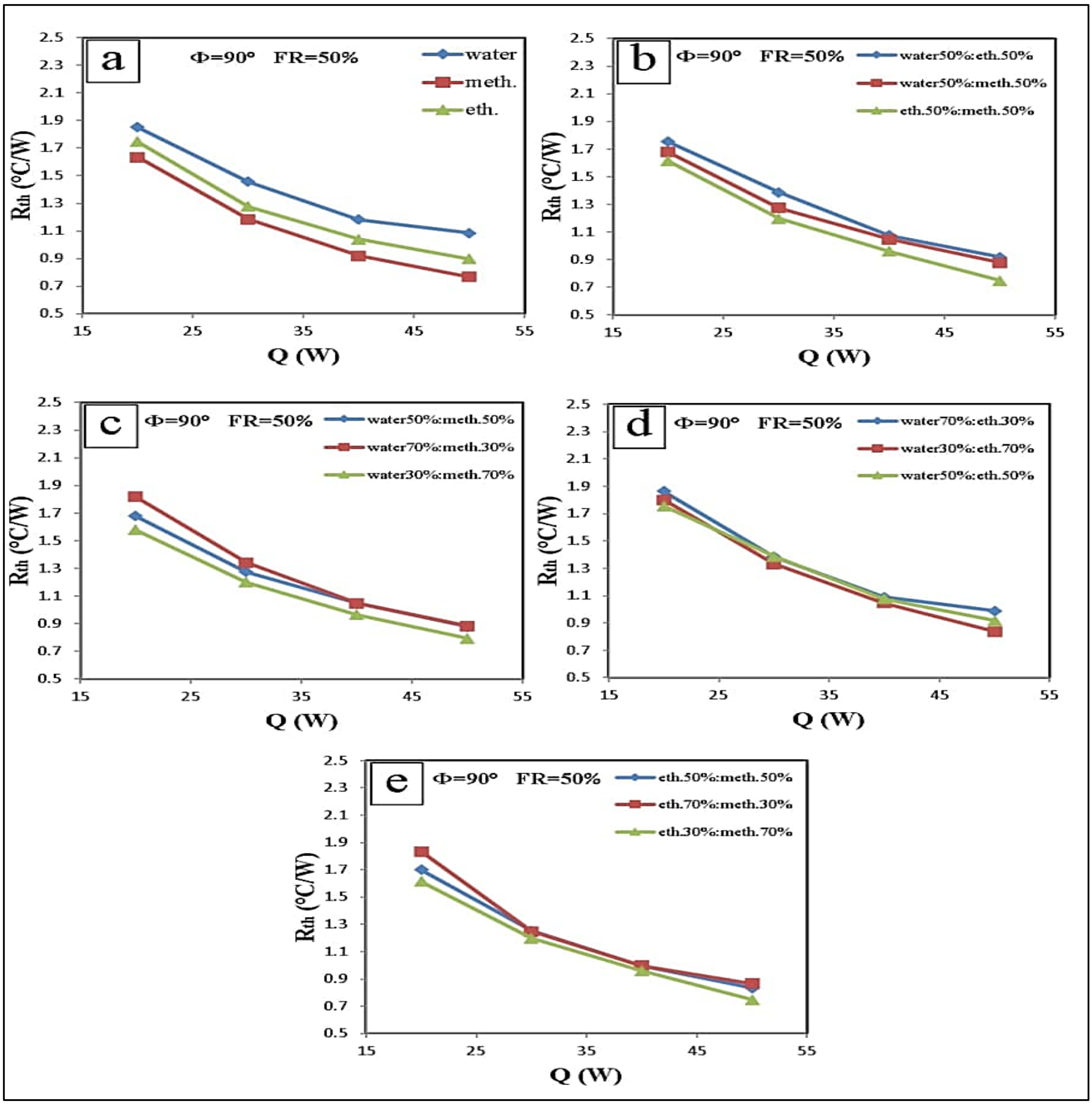

Figure 5: Thermal resistance vs. heat input using: (a) pure working fluids, (b) binary fluids with (50%: 50%) mixing ratio, (c) binary fluids water& methanol, (d) binary fluids water & ethanol and (e) binary fluid ethanol & methanol

Figure 6 illustrates the variation of the heat transfer coefficient under the Influence of using water, ethanol, and methanol pure and their mixtures as the working fluids. As observed, there are increases in the heat transfer coefficient values with increasing the heat input values for all working pure fluids and mixtures. Figure 6.a. illustrates that the heat transfer coefficient values for methanol, water, and ethanol increased as heat input increased. The water produces a higher heat transfer coefficient (519.1073 W/m^{2}.^{o}C) at 50 W heat input. From Figure 6.a, the increase in the value of the heat transfer coefficient at 50 W is greater compared to the increase between the heat inputs from 20 to 40 W. This is because, at high heat inputs, the thermal conductivity is high and fast, so the difference between the surface temperature of the evaporator and the temperature of the vapor inside the evaporator. It is small compared to the lower heat inputs, and according to Equation (5), the value of the heat transfer coefficient is greater. Figure 6.b. illustrates that the heat transfer coefficient values for (water& methanol), (ethanol & methanol), and (Water & ethanol) binary mixtures (50%: 50%) increased as the heat input increased. The heat transfer coefficient of using (water: methanol) is higher than other binary mixtures (729.123 W/m^2. ^{o}C). Figure 6.c. illustrate that the heat transfer coefficient values for (50% water: 50% methanol), (30% water: 70% methanol), and (70% Water: 30% methanol) binary mixtures are increased as the heat input increases. The heat transfer coefficient of using (70% water: 30% methanol) is higher than other binary mixtures (805.89 W/m^2. ^{o}C). Figure 6.d. illustrate that the heat transfer coefficient values for (50% water: 50% ethanol), (30% water: 70% ethanol), and (70% Water: 30% ethanol) binary mixtures are increased as the heat input increases. The heat transfer coefficient of using (70% water: and 30% ethanol) is higher than other binary mixtures (588.952 W/m^2. ^{o}C). Figure 6.e. illustrate that the heat transfer coefficient values for (50% ethanol: 50% methanol), (30% ethanol: 70% methanol), and (70% ethanol: 30% methanol) binary mixtures are increased as the heat input increases. The heat transfer coefficient of using (30%ethanol: 70% methanol) is higher than other binary mixtures (732.543 W/m^2. ^{o}C).

From the results summary, the water-charged HP has a higher heat transfer coefficient at a value of (519.1073 W/m^2.^{o}C) achieved at 50 W. Also, the heat transfer coefficient of the mixing at a mixture of (70 % water: and 30% methanol) is (805.89 W/m^2. ^{o}C) the highest value at all mixing ratios achieved at 50 W. This occurs because the increase in heat input results in an increase in the active temperature rate and heat transfer rate, and a high heat input can also explain that the working fluid temperature of the evaporator section will be high enough to make the liquid boiling rate increases and the working fluid flows smoothly in one direction. The heat transfer coefficient depends primarily on the working fluid's latent heat, surface tension, and viscosity.

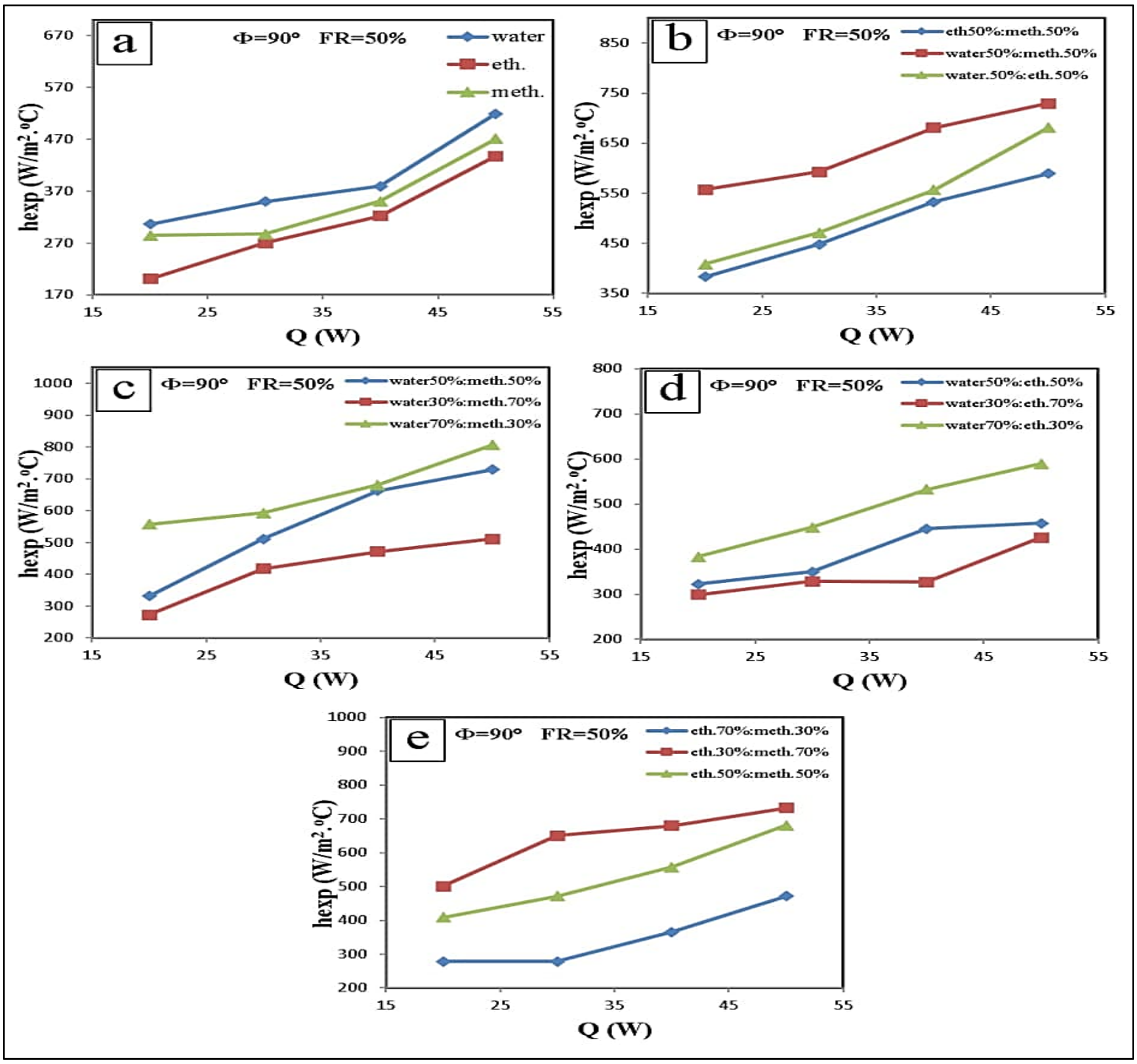

Figure 6: Heat transfer coefficient vs. heat input using: (a) pure working fluids, (b) binary fluids with (50: 50) % mixing ratio, (c) binary fluids water& methanol, (d) binary fluids water & ethanol and (e) binary fluid ethanol & methanol

6. Comparison with the Available Literature

Figure 7 compares the present experimental results with those reported by R. Manimaran [5] in the case of using pure water as a working fluid with FR equal to 50%. It can be observed that the thermal resistances as a function of heat input have the same trends with lower values. The difference between both results when using pure water may be attributed to the difference in heat pipe geometry and the used separator in the present work.

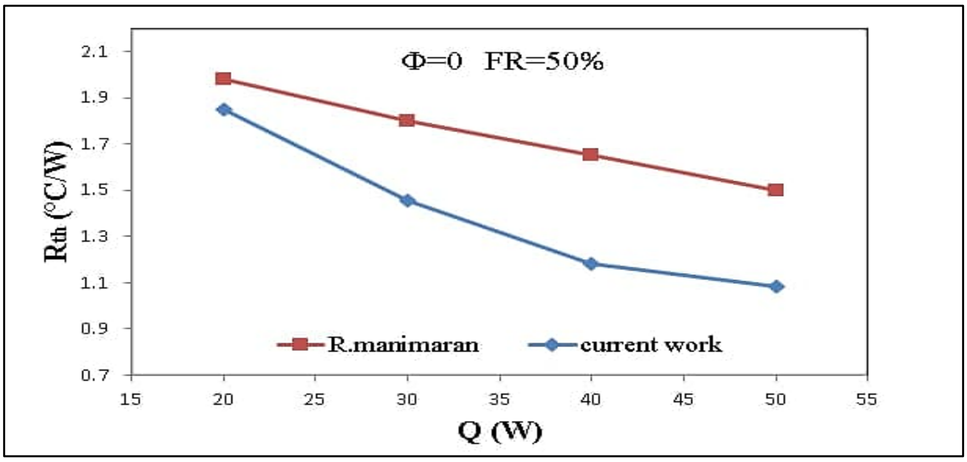

Figure 7: The present work's thermal resistance vs. heat inputs and R. Manimaran [5]

7. Conclusions

The heat pipe performance has been experimentally obtained using pure and binary mixtures as working fluids. The following main conclusions can be drawn from the experiment:

The thermal resistance decreases with the increasing heat inputs for heat pipes charged with pure and binary mixtures of working fluids. Methanol has the lowest thermal resistance values for all heat inputs when using pure fluids compared to water and ethanol. For example, using a (50:50 %) mixture of methanol and ethanol produces the lowest value of thermal resistance (0.7466 ^{o}C/W) compared with the other working fluids (pure and mixture). Thus, the percentage of thermal resistance improvement when using mixtures is 2.8%.

The heat transfer coefficient increased as the heat inputs increased for all working fluids. The heat transfer coefficient of water was found to have the highest value when using pure working fluids. The heat transfer coefficient of a mixture of (70% water: and 30% methanol) is (805.89 W/m^2. ^{o}C), which is the highest value at all mixing ratios. Thus, the percentage of improvement in the heat transfer coefficient when using mixtures is 35.58 %.

The overall experimental results show that the thermal resistance and heat transfer coefficient values for using binary mixtures as the working fluid are better than that for single fluids.

Nomenclature

Symbol	Definition	Units
c	Specific heat	J/kg.ºC
D_{in}	Inner diameter	m
d_w	Mesh wire diameter	µm
h_{fg}	Latent heat of vaporization	J/kg
h_{exp}	heat transfer coefficient	W/m^2.ºC
L	heat Pipe length	m
M.N	Merit number	W/m^2
$\dot{m}$	Mass flow rate	kg/s
N	Mesh number	pore/in
Q	Heat transfer rate	W
R_{th}	Thermal resistance	ºC/W
$\overline{T}$	Average temperatures	ºC
As	Surface area of the evaporator	m^2
ρ	Density	kg/m^3
σ	Surface tension	N/m^2
µ	Viscosity	kg /m.s
T_{bo}	Boiling temperature	ºC
FR	Filling Ratio	%
Φ	Tilt angle	degree
P	power	Watt

Subscripts

Symbol	Definition
a	Adiabatic
c	Condenser
e	Evaporator
w	Water
in	Inlet
v	Vapor

Abbreviations

Symbol	Definition
eth	ethanol
meth	methanol

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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