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Comparative Study on the Performance of Wickless Heat Pipes with Self Rewetting Fluids for Different Orientations

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ABSTRACT

Background: Wickless heat pipe is a simple but effective heat transfer device working on two phase change of working fluid inside. In such device, the heat transport efficiency increases due to the occurrence of phase change of working fluid. Self rewetting fluids which are diluted aqueous alcoholic solutions having more than four numbers of carbon atoms are used because they have positive surface tension gradient with the temperature in the operating temperature region. Anomalous increase in the surface tension with rise in temperature is observed in the wickless heat pipe filled with self rewetting fluids. **Objective:** To study and compare the performance of two copper wickless heat pipes filled with self rewetting fluids namely aqueous solution of n-Butanol and aqueous solution of n-Pentanol with the wickless heat pipe of copper material filled with De Ionised (DI) water. The self rewetting fluids are prepared by adding n-Butanol and n-Pentanol at a concentration of 0.001 moles per litre to the DI water. **Results:** The performance of wickless heat pipe filled with self rewetting fluids is compared with the heat pipe filled with DI water for the thermal efficiency, resistance, overall heat transfer coefficient. From the experimental results it has been found that the maximum thermal efficiency is obtained for wickless heat pipe filled with aqueous solution of n-Pentanol for 90° orientation. On the other hand, the thermal resistance is high for low heat input but the overall heat transfer coefficient of wickless heat pipe increases with increase of heat input. **Conclusion:** Best performance is obtained for the wickless heat pipe filled with aqueous solution of n-Pentanol.

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INTRODUCTION

Wickless heat pipe also referred to as two-phase closed thermosyphon is a gravity assisted heat transfer device with very high thermal conductance and thermal performance. It is a closed container filled with little amount of working fluid. The working principle of the wickless heat pipe is as follows: the heat is applied to the evaporator section located at the lower end of the wickless heat pipe causes the working fluid inside the wickless heat pipe to vapourize and evaporate. The vapour generated then moves upwards to the condenser section located at the upper end of the wickless heat pipe. Because of the gravitational force, the condensed liquid now goes down along the surface of the tube wall. The foremost benefit of using wickless heat pipe is that it is cheaper and reliable as it doesn't need further additional mechanical pumping power. Wickless heat pipe transfers a large amount of heat at a higher rate with a small temperature difference.

Due to the simplicity in nature, two-phase closed thermosyphon is widely used in many applications compared to other heat pipe types. Dunn and Reay (1994) elucidated that the thermal conductivity of thermosyphon is effective and exceeds nearly 200–500 times than that of copper. So they are widely used in many applications such as heat exchangers, cooling of electronic components, solar energy conversion systems, spacecraft thermal control, cooling of gas turbine rotor blades, etc.

Faghri *et al*. (1991) conducted tests on high temperature sodium / stainless steel heat pipe for various heat sources and sinks under vacuum and air. Their result explained that the startup behaviour of a liquid metal heat pipe from the frozen state is greatly dependent on the heat injection rate at the condenser. In the condenser section supersonic vapour velocities occurred and in the evaporator section two way vapour flow was observed. For single or multiple evaporator section, evaporator dryout failure did not take place either in air or vacuum but

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sonic limit occurred in air during the startup processes. The steady state showed a significant effect on the operating temperature of the heat pipe as there was a change in the emissivity of the heat pipe wall. The final steady state operating temperature of the heat pipe is independent of the startup power levels and the size of the subsequent power increases. The annular gaps enhanced the maximum heat transport capability of the heat pipe. However, this created inconvenience in calculating the capillary limit and optimal heat pipe fluid charge. The numerical model presented will be in need in the design of heat pipe.

Gross (1992) reviewed the data published by various researchers on condensation heat transfer inside two phase thermosyphon for various parameters like working fluids, inside tube diameter, saturation temperature, pressure, inclination angle and suggested a correlation for the prediction of condensation heat transfer. Harley and Faghri (1994) presented a transient two dimensional thermosyphon model for conjugating heat transfer through the wall and falling condensate film using quasi - steady Nusselt analysis . This model stimulates the entire low temperature thermosyphon with the experimental data .

Hirashima *et al.* (1994) examined the heat transfer characteristics of the evaporator section for a different type of thermosyphon with inbuilt internal heater. From the result we inferred that the attributes like type of the heater, diameter of the pipe, heat flux, working fluid and its level affect the thermal performance of the thermosyphon. The heat transfer coefficient decreases with filling ratio and is higher for U type heater than the spiral type heater for the same liquid level. Bezrodnyl and Alekseenko. (1977) experimentally investigated the heat transfer capacity of closed two phase thermosyphons for the effect of heat supply, adiabatic region, pressure inside the cavity, degree of filling ratio, and working fluids (water, methanol, Freon - 11, Freon – 113, Freon – 12). They gave a generalized report for determining the maximum heat flux.

Kanji Negishi *et al.* (1983) studied the heat transfer performance of an inclined two phase closed thermosyphon with water and ethanol as working fluids. The chaotic striking motion of liquid associated with the boiling and scattering of liquid drops enhanced the amount of heat transfer. Also the thermal diode characteristics depend upon the fill ratio of working fluid. Imura *et al.* (1983) made an experimental study on the effects of inside diameter, heated length, working fluid (water, ethanol, Freon 113), fill charge and inside temperature on critical heat flux in a two phase closed thermosyphon and derived correlations.

Abou-Ziyan *et al.* (2001) designed a two phase closed themosyphon to foresee the performance characteristics under stationary and vibrated conditions. The experiments were carried out for a wide range of fill ratio (0.4, 0.5, 0.6, 0.8), various length of adiabatic section (275 mm, 325 mm, 350 mm), vibration frequency (0.0 – 4.33 Hz) and heat flux (160 – 2800 kW/m^2) for water and R134a working fluids. Finally it was observed that the above factors had impact on the performance of thermosyphon. Also the vibration weakened the thermosyphon performance below the limit, whereas above the limit, it improved the performance. Azouni *et al.* (2001) studied the velocities of surface tension driven flows caused by gradients in temperature and concentration for water – n-Heptanol solutions. They succeeded in their experiment and showed that even when the surface tension decreases with temperature, the flow will be directed from cold to hot which shows the predominating effect of the concentration gradient on the surface tension.

Abe *et al.* (2005) performed thermal performance of wickless heat pipes using dilute aqueous solutions of high carbon alcohols called self rewetting fluids as working fluids in low gravity provided by parabolic flights. The self-rewetting fluids show an increase in the surface tension with increasing temperature. This peculiar character allows a spontaneous liquid supply to the hotter region by thermocapillary flow. Because of the concentration gradient in the aqueous solution, additional Marangoni effect occurs when liquid / vapour phase change takes place. As the condensate spontaneously returns to the evaporation section by additional Marangoni effect, self rewetting fluids are assured in the space applications. Their result gave an idea that wickless heat pipes has better thermal resistance and higher dry out limit than conventional heat pipes with wick. Raffaele Savino *et al.* (2009) conducted experiments with binary solutions of water and long chain alcohols. The effects of surface tension in wickless heat pipes were investigated. It was found that evaporator region contains more liquid than water for self - rewetting fluid which means supply of liquid is spontaneous in the higher temperature region. Also vapour slug behaviour is observed near the heating region which shows a strong shear stress between the vapour and liquid film. The heat pipes with self rewetting fluids reveal better thermal performance is also inferred from the above study.

Faghri and Thomas. (1989) described the design, testing and capillary limit prediction of the concentric annular heat pipe made up of two concentric pipes of unequal size which created an annular vapour space. The testing results showed that as the cross sectional area of the wick and the surface area for heating and cooling increased, the heat capacity per unit length also increased. Also as temperature is uniform in the inner and outer walls, it can be used as simplified temperature control device for furnace applications. Oron and Rosenau. (1994) studied such impact in thin liquid layers. It was noted that only a small amount of the long-chain alcohols, order of 10^{-3} mole per litre, was needed to change the surface tension characteristics of water without affecting other bulk properties of water. Hussain (2012) studied the effect of working fluid and mixture ratio of two fluids water and acetone on the performance of wickless heat pipe. From the experiments it was inherited that performance of thermosyphon is more effective when pure liquid is used than mixture. Noie *et al.* (2005) probed the heat transfer characteristics of a two phase closed thermosyphon for a range of heat transfer rates, system pressure, aspect ratios and filling ratios. The experimental results of boiling and condensation heat transfer coefficients were compared to the existing correlations. A new correlation was used to predict the boiling heat transfer coefficient.

Wickless heat pipe made of copper material of three numbers is taken into consideration for the current study. The experiments are performed for various orientations namely 15^o, 30^o, 45^o, 60^o, 75^o, 90^o and series of heat inputs such as 40W, 80W and 120W. The main purpose of the study is to compare the performance of wickless heat pipe filled with De Ionized water, aqueous solution of n-Butanol and aqueous solution of n-Pentanol for their thermal efficiency, thermal resistance, overall heat transfer coefficient and temperature distribution.

Experimental Setup:

The schematic view of the experimental setup and the locations of the thermocouple are depicted in the fig. 1 (a) and fig. 1 (b) respectively. The experiment is carried out by taking three numbers of wickless heat pipes. Three identical wickless heat pipes of 1000 mm total length and made up of copper container are taken. Each has 19 mm outer diameter, 17 mm inner diameter and a wall thickness of 1 mm. One of the wickless heat pipes is charged with De Ionized water, second with aqueous solution of n-Butanol and the third with aqueous solution of n-Pentanol of 60 ml each. The working fluid charged approximately corresponds to the amount required to fill the evaporator section.

The length of the evaporator section is 400 mm at the bottom; the adiabatic section is 150 mm in the middle and the condenser section is 450 mm at the top of the wickless heat pipe. The evaporator section is heated by the electric heater. This is provided by the wattmeter of required power range along with the variac. The necessary heat to be supplied by the electric heater is calculated with an uncertainty of ± 1 W. Six copper constantan (T type) thermocouples with an uncertainty of ± 0.1 °C are used to measure the wall temperature distribution of the wickless heat pipe. In addition to this, three more thermocouples are located in the condenser section and one in the adiabatic section. The condenser section has an additional concentric tube which is of 34 mm outer diameter and 30 mm inner diameter. This is used as a cooling water jacket to remove the heat from the wickless heat pipe. The wickless heat pipe has the ability to transfer more amount of heat. As a result of it, a sudden rise in the wall temperature would damage the wickless heat pipe when the heat is not released properly at the condenser section. Therefore, cooling water is dispersed first through the water jacket before supplying heat to the evaporator section.

Flow rate of cooling water from the water tank to the water jacket in the condenser section is measured by using a rotameter with ± 1% accuracy. The mass flow rate is kept constant at 0.08 kg/min. The inlet and outlet temperatures of the cooling water are measured by using two more copper constantan thermocouples. The wickless heat pipe is completely insulated with the glass wool. The amount of heat loss from the evaporator section and condenser section is negligible. The vacuum pump model BABA – 1- 25 and 0.25 HP is used for evacuating the wickless heat pipe.

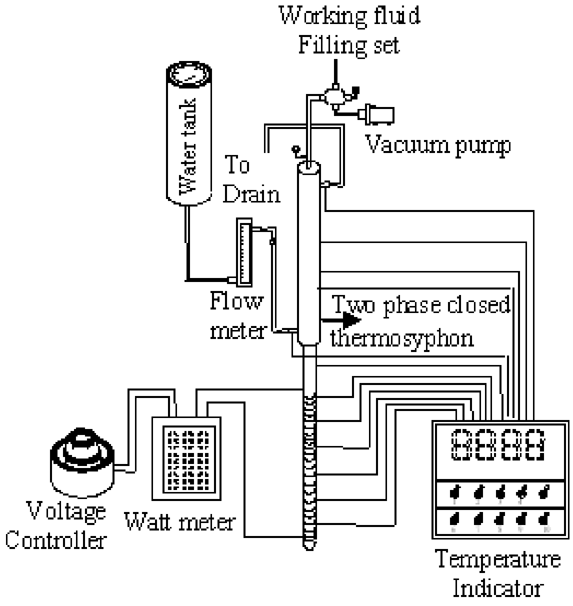

Fig. 1(a): Schematic diagram of experimental setup.

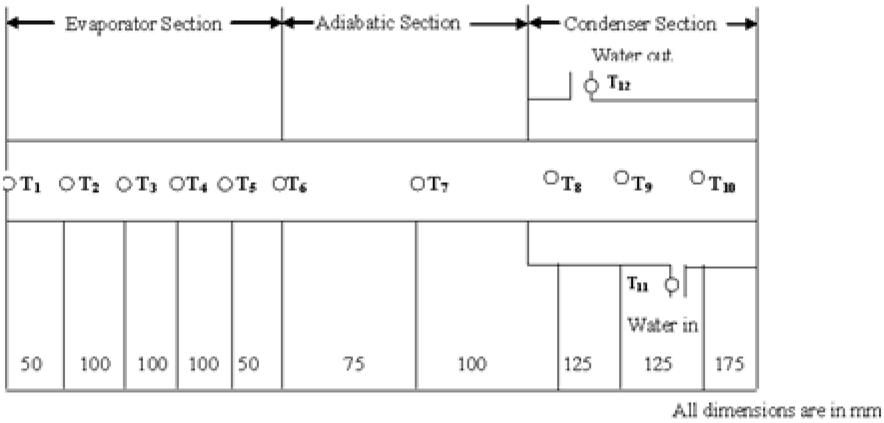

Fig. 1(b): Thermocouple locations.

Experimental Procedure:

The experiment is carried out using three identical wickless heat pipes of same dimensions mentioned above. One of the wickless heat pipe is charged with de-ionized water, second with aqueous solution of n-Butanol and the third with aqueous solution of n-Pentanol. The wickless heat pipe is evacuated using the vacuum pump to remove the dissolved gases within it before filling up with the working fluid. After evacuation, the wickless heat pipe is filled with 60 ml of the working fluid. The evaporator section is heated using the required power supply with the help of auto transformer. The power input to the wickless heat pipe is gradually raised to the desired power level. The surface temperatures at six different locations along the evaporator section of wickless heat pipe are measured at regular time intervals until the wickless heat pipe reaches the steady state condition. Similarly, adiabatic wall temperatures, water inlet and outlet temperatures in the condenser region are measured. Once the steady state is reached, the input power is turned off and cooling water is allowed to flow through the condenser inorder to cool the wickless heat pipe and to make it ready for further experimental purpose. Again, the power is increased to the next level and the wickless heat pipe is tested for its performance. This experimental procedure is repeated for different heat inputs namely 40 W, 80 W and 120 W and for various orientations likely 15°, 30°, 45°, 60°, 75° and 90° with respect to horizontal direction. The output heat transfer rate from the condenser is calculated by applying an energy balance to the condenser flow. The vacuum pressure in the inner side of the wickless heat pipe is monitored by vacuum gauge which is attached to the condenser end of the wickless heat pipe.

RESULTS AND DISCUSSION

Thermal Efficiency:

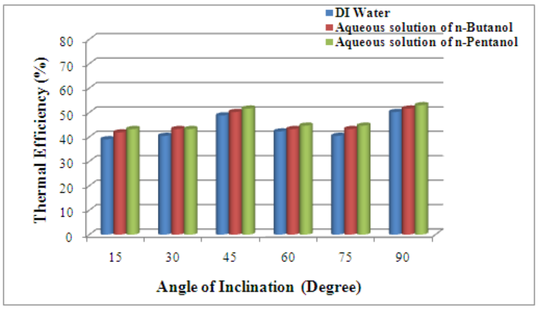

Fig. 2: Thermal efficiency for various orientations at 40 W heat input.

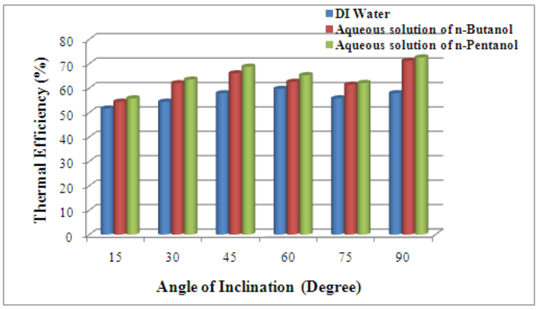

Fig. 3: Thermal efficiency for various orientations at 80 W heat input.

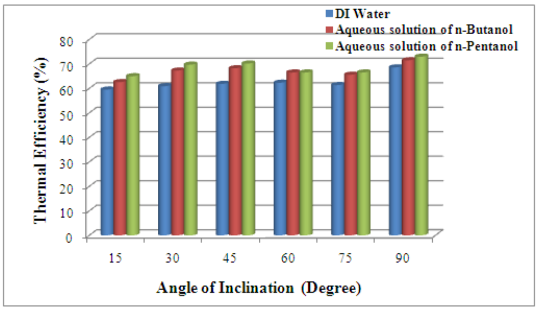

Fig. 4: Thermal efficiency for various orientations at 120 W heat input.

The thermal efficiency of wickless heat pipe is calculated as the ratio of heat output in the condenser section to the heat input in the evaporator section Masoud Rahimi *et al*. (2010). The wickless heat pipe was tested for its efficiency and performance with various working fluids namely DI water, aqueous solution of n-Butanol and aqueous solution of n- Pentanol. Figs. 2 – 4 represents the variation of the thermal efficiency of wickless heat pipe for different orientations (15°, 30°, 45°, 60°, 75° and 90°) and heat inputs (40 W, 80 W and 120 W). From the figures it is clear that the thermal efficiency increases with increase of orientation up to certain degree, then decreases and again increases. The thermal efficiency attains a maximum level at 90° orientation. This is because of the higher gravity forces acting on the working fluid at these orientations. At the lower orientations, the thermal efficiency is reduced due to the obstruction of vapour with condensate return from the condenser section. As the temperature gradient between the evaporator and condenser section increases, the thermal efficiency of the wickless heat pipe also increases with increase in heat flux. So it is clear from the analysis that the thermal efficiency of aqueous solution of n-Pentanol is higher when compared to that of other working fluids.

Thermal Resistance:

The thermal resistance of wickless heat pipe for the working fluids against heat input for different orientations are plotted and shown in the figs. 5 - 10.

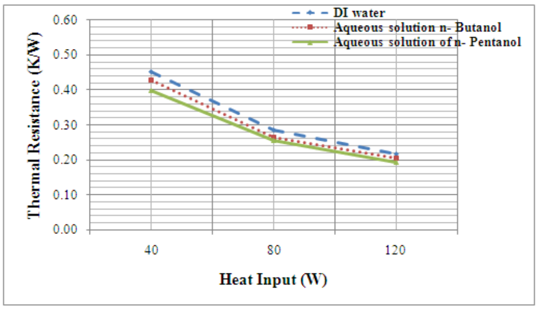

Fig. 5: Thermal resistance for various heat inputs at 15° orientation.

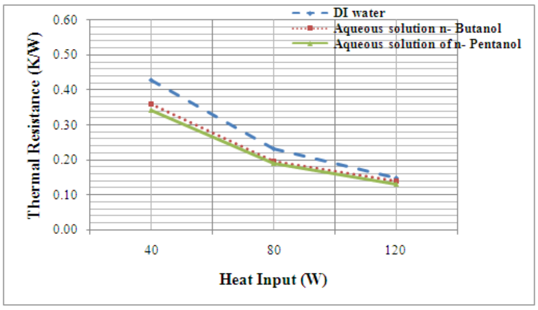

Fig. 6: Thermal resistance for various heat inputs at 30° orientation.

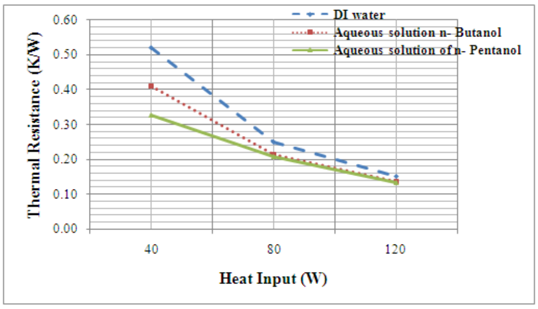

Fig. 7: Thermal resistance for various heat inputs at 45° orientation.

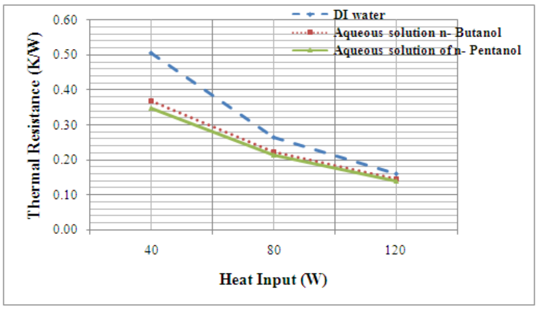

Fig. 8: Thermal resistance for various heat inputs at 60° orientation.

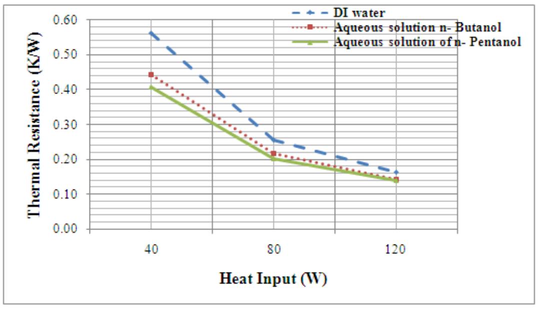

Fig. 9: Thermal resistance for various heat inputs at 75° orientation.

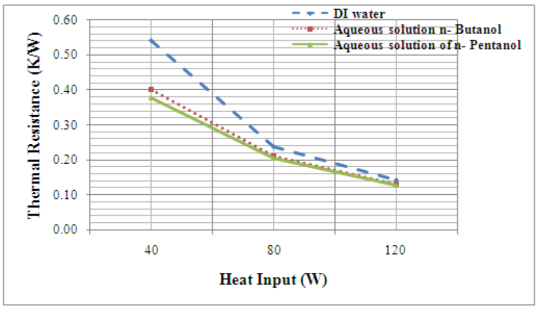

Fig. 10: Thermal resistance for various heat inputs at 90° orientation.

The thermal resistance (TR) of the wickless heat pipe is calculated as

$$TR = \left[\frac{T_e - T_c)}{Q_1}\right] \tag{1}$$

where T_e and T_c are the average surface temperature of wickless heat pipe at evaporator section and the condenser section respectively and Q_1 is the heat input applied to the wickless heat pipe. The thermal resistance is analyzed for various orientations and heat inputs. From the figures it is made known that when heat input increases, the thermal resistance decreases for all the working fluids. The thermal resistance is high for low heat input for all the working fluids. This is the typical characteristic of wickless heat pipe where evaporation takes place in the surface of a liquid pool in low heat flux and nucleate boiling in a higher heat flux. As a result of it, thermal resistance drastically reduces with higher heat input Abe *et al* (2005). The thermal resistance of aqueous solution of n-Pentanol is low compared to that of other working fluids.

Overall Heat Transfer Coefficient:

The overall heat transfer coefficient of the wickless heat pipe is calculated by the following expression

$$U = \left[\frac{Q_1}{A(T_{we} - T_{wc})} \right] \qquad (2)$$

The overall heat transfer coefficients for various heat inputs are computed for all the orientations. Figs. 11 - 16 portray the overall heat transfer coefficient of wickless heat pipe for the working fluids against the heat input applied 40 W, 80 W and 120 W for the orientations 15°, 30°, 45°, 60°, 75° and 90°.

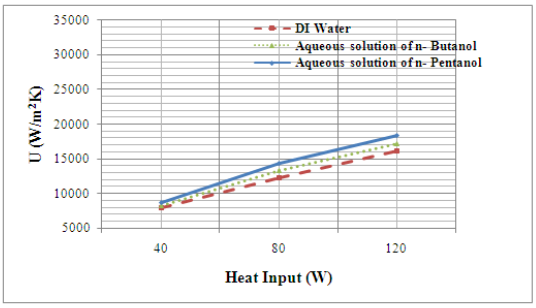

Fig. 11: Overall heat transfer coefficient for various heat input at 15°orientation.

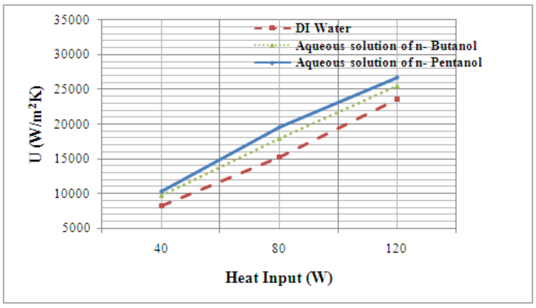

Fig. 12: Overall heat transfer coefficient for various heat input at 30° orientation.

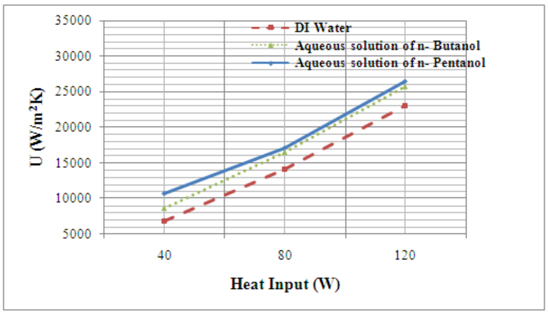

Fig. 13: Overall heat transfer coefficient for various heat input at 45° orientation.

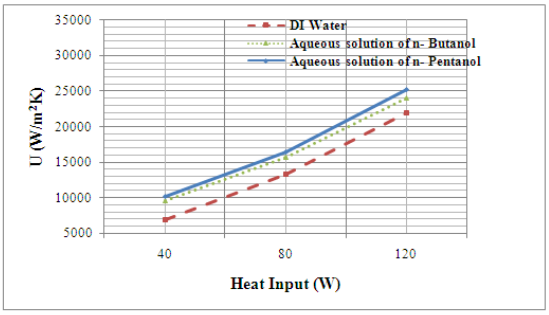

Fig. 14: Overall heat transfer coefficient for various heat input at 60° orientation.

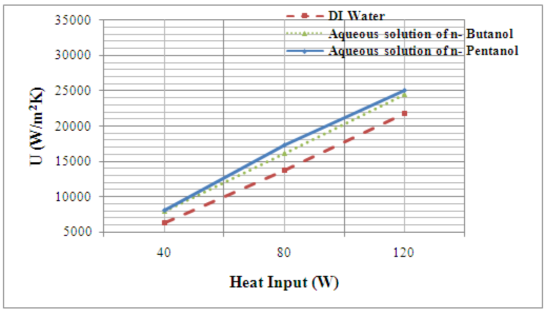

Fig. 15: Overall heat transfer coefficient for various heat input at 75° orientation.

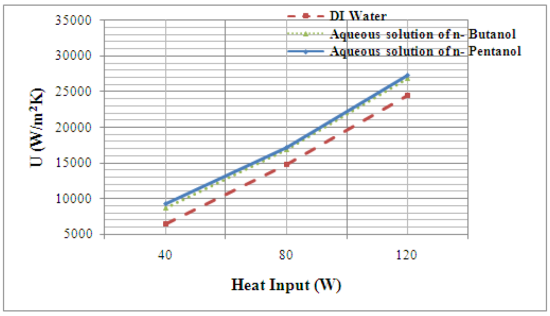

Fig. 16: Overall heat transfer coefficient for various heat input at 90° orientation.

For de-ionized water, the overall heat transfer coefficient ranges from 6300 to 24500 W/m^{2}K, for aqueous solution of n-Butanol, the range is from 7900 to 26900 W/m^{2}K and for aqueous solution of n-Pentanol, the range is from 8100 to 27250 W/m^{2}K. The overall heat transfer coefficient is increasing due to the increased heat transport capacity of the aqueous solution of long chain alcohols in the wickless heat pipe. The maximum overall heat transfer coefficient is obtained at 120 W heat input and at vertical direction (90°). The overall heat transfer coefficient increases when the temperature difference between the evaporator and condenser section increases. It is higher at vertical orientation. The overall heat transfer coefficient of aqueous solution of n-Pentanol is higher than all other working fluids.

Variation of Evaporator Temperature with Time and Orientation:

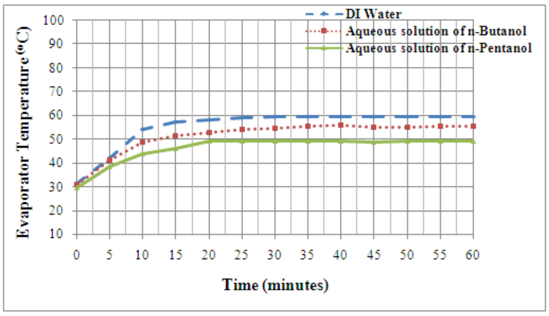

Fig. 17: Variation of evaporator temperature at 40 W heat input.

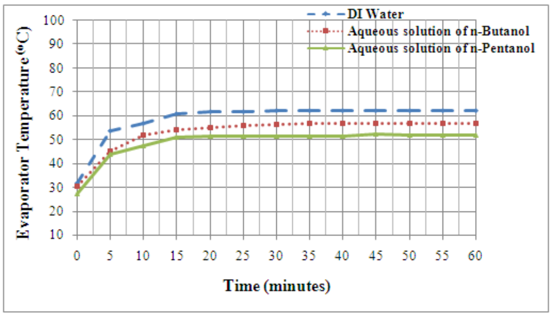

Fig. 18: Variation of evaporator temperature at 80 W heat input.

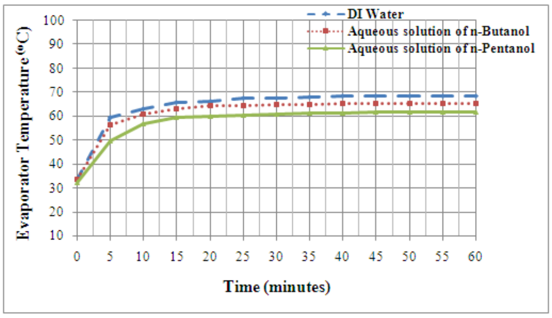

Fig. 19: Variation of evaporator temperature at 120 W heat input.

The variations of evaporator temperature with respect to time taken for reading for the working fluids and heat inputs for 90° orientation are represented in the figs. 17 - 19. The wickless heat pipe takes about 45 to 60 minutes to reach the steady state. The evaporator surface temperatures at six locations are taken and the average of all these values is considered for calculation. The steady state evaporator temperature is attained quickly in the case of aqueous solution of long chain alcohols compared to that of DI water. This shows the heat transport capacities of the aqueous solution of long chain alcohols are higher than the DI water.

Conclusion:

The thermal performance of wickless heat pipe is analyzed experimentally for different orientations and heat inputs for the three different working fluids namely de-ionized water, aqueous solution of n-Butanol and aqueous solution of n-Pentanol. The following conclusions are obtained from the study.

- The thermal efficiency of wickless heat pipe is obtained for aqueous solution of n-Pentanol for 90° orientation
- The thermal efficiency of wickless heat pipe increases with increase in heat flux as the temperature gradient between the evaporator and condenser section increases
- The thermal resistance is high for low heat input for all the working fluids
- Overall heat transfer coefficient of wickless heat pipe increases with increase of heat input for the working fluids and the maximum is obtained for aqueous solution of n-Pentanol
- The steady state evaporator temperature is attained quickly in the case of aqueous solution of long chain alcohols compared to that of DI water.
- Wickless heat pipe with aqueous solution of n-Pentanol shows better performance than the deionized water and aqueous solution of n-Butanol.

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