THERMAL ANALYSIS OF HEAT PIPE USING SELF REWETTING FLUIDS

by

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This paper discuses the use of self rewetting fluids in the heat pipe. In conventional heat pipes, the working fluid used has a negative surface-tension gradient with temperature. It is an unfavourable one and it decreases the heat transport between the evaporator section and the condenser section. Self rewetting fluids are dilute aqueous alcoholic solutions which have the number of carbon atoms more than four. Unlike other common liquids, self-rewetting fluids have the property that the surface tension increases with temperature up to a certain limit. The experiments are conducted to improve the heat-transport capability and thermal efficiency of capillary assisted heat pipes with the self rewetting fluids like aqueous solutions of n-butanol and n-pentanol and its performance is compared with that of pure water. The n-butanol and n-pentanol are added to the pure water at a concentration of 0.001 moles per liter to prepare the self rewetting fluids. The heat pipes are made up of copper container with a two-layered stainless steel wick consisting of mesh wrapped screen. The experimental results show that the maximum heat transport of the heat pipe is enhanced and the thermal resistances are considerably decreased than the traditional heat pipes filled with water. The fluids used exhibit an anomalous increase in the surface tension with increasing temperature.

Key words: *heat pipe, self rewetting fluid, surface tension, thermal efficiency, thermal resistance*

Introduction

The heat pipe is an extremely effective device, which is capable of transferring large quantities of heat through relatively small cross-sectional areas and with very small temperature differences between the evaporator and condenser side without any power input [1, 2]. The heat pipe is a chamber of different cross-section whose inner surfaces are lined with a porous capillary wick. The heat pipe is filled with a small amount of working fluid and the wick is saturated with the liquid phase of working fluid and the remaining volume of tube contains the vapour phase. The heat pipe is energized at the evaporator section by an external

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source and it vapourizes the working fluid in that section. The resulting difference in pressure drives vapour from the evaporator to the condenser where it condenses and releases the latent of vapourization to a heat sink. The heat pipes are more advantageous in heat recovery systems [3, 4], solar energy [5], electronics cooling [6], air craft cooling, and light water nuclear reactors [7]. Heat pipes are widely used for miniaturized electronic devices and high-tech equipment like notebook PC due to their less weight, maintenance-free, reliability and increased heat dissipation.

The requirements of high efficiency and compact size in such electronic devices strongly affect their thermal management that is critical and directly influences cost, reliability, and performances. A good heat pipe is characterized by a low thermal resistance and a higher dry-out limit in evaporator section. The type of heat pipe, thickness of wall, wick porosity and type of structure, and even the contact condition between the wick and the container wall will affect the performance of the evaporator [8, 9]. The most important factor to be considered for the design of heat pipe is related to the characteristics of the evaporator.

All of the heat pipes, including conventional heat pipes and micro heat pipes have common problem of heat transfer limitation. The heat transfer limitations determine the maximum heat transfer rate for a particular heat pipe under the normal working conditions. The various limitations of the heat pipe are continuum flow limit, frozen startup limit, viscous limit, sonic limit, entrainment limit, capillary limit, condenser limit, and the boiling limit. Among them the capillary limit and boiling limits are important for heat pipe under the normal working conditions. The surface tension is a salient key factor for capillary limit along with boiling limit, sonic limit, entrainment limit, viscous limit, and condenser limit. Surface tension of all pure liquids is normally decreasing with increase in temperature; indeed, the liquid is moved along the interface toward the cooler condenser zone. This effect, known as Marangoni effect, could influence negatively the heat transfer capability.

The effectiveness of a heat pipe is represented by its maximum heat load value, and in order to ensure a large heat load without reaching the boiling limit at the evaporator, the most important factor is the wetting of the heated wall by the working fluid. The developments of Marangoni flow, counteracting the capillary forces, play an important role in evaporator priming because it can cause the reduction of the condensate return's amount. This effect has been observed in axially grooved gas-loaded variable-conductance heat pipe [10], where large surface tension gradients related to temperature gradients in the gas blocked zone induce a surface flow toward condenser, and it is accompanied by a subsurface flow in the groove of equal magnitude but in opposite direction (recirculation).

Surface tension is also a significant factor for all heat transfer limitations, like boiling and capillary limits. The negative surface tension gradient associated with all normal working fluids, that is, the classic Marangoni effect will reduce the critical temperature difference between the condenser and the evaporator, when the operating temperature at the evaporator section is increased. All working fluids used in existing heat transfer devices, including loop heat pipes (LHP), capillary pumped loop heat pipes (CPL) and the conventional heat pipes, have a negative gradient of surface tension against temperature that induce a Marangoni flow around vapour bubbles, pressing the bubbles on the heating surface and resulting in an unfavourable situation for boiling performance, because of avoiding bubbles venting in vapour groove. The influence of surface tension on the capillary limit is the absolute available capillary pumping head:

$$\Delta p_{\mathrm{c}} = \frac{2\sigma \cos\theta}{r_{\mathrm{eff}}} \tag{1}$$

where σ is the surface tension, r_{eff} is the interface radius of curvature, and θ – the effective contact angle between the working fluid and the wall or the wick surface. The effective contact angle decreases when the evaporator temperature increases as the surface tension decreases with an increase in temperature and the operation becomes unstable.

Tien [11], Tien *et al.* [12] studied about the operational characteristics of a two-component working medium in heat pipe filled with different water-ethanol solutions. A theoretical framework has been performed to foresee the performances gained by this type of heat pipe and it is found that the performance depends on several factors like initial composition of two components mixture and heat pipe geometry.

Brommer [13] analyzed the two-component heat pipes using water-methanol binary mixture. It has been shown that, the startup behaviour of heat pipes are enhanced by using these working fluids, when it is initially frozen and the freezing point of the working medium can be lowered by adding together with an appropriate liquid, like methanol in water for low temperature range. Kadoguchi *et al.* [14] examined the two-component heat pipes with binary mixture working fluid which is a more advantageous heat transfer device than a gas-loaded variable-conductance heat pipe for controlling the temperature of electric device. The previous studies on heat pipe did not take in account of possible Marangoni effect due to the preferential evaporation of more volatile component; the benefit of the Marangoni effect in heat pipes was first focused by Kuramae.

Kuramae *et al.* [15], Kuramae [16, 17] proposed the use of alcohol solution in heat pipe but his approach was totally different when compared with that of Brommer. The rewetting problem of the evaporator in wickless heat pipes filled with ethanol-water mixture has been examined so that the evaporation of the more volatile component (ethanol) in the evaporator area could induce a solutal Marangoni flow for the evaporator liquid-supply in wickless heat pipes.

The use of innovative working fluids for heat pipe systems using very dilute long chain alcohol solutions (aqueous solution with a concentration of alcohol in the range of 0.0005 and 0.008 moles per litre) has been suggested by Zhang [18] which is found to yield a non-linear relationship of the surface tension with temperature and a positive gradient with increasing temperature in a suitable range of temperatures and concentrations.

In some recently conducted experiments, the surface tension behavior of self rewetting fluids induces a thermo capillary flow in the liquid-vapour interface from a lower temperature region to a higher temperature region. In addition, the measurements of the surface tension of high carbon alcoholic aqueous solutions have been performed [19-21]. The heat transfer characteristics of the self rewetting fluids have been analyzed by Yoshiyuki [22] in which the Marangoni effect results in a strong liquid inflow at the nucleation sites during the course of boiling. Savino *et al* [23] proposed the use of self-rewetting fluids for terrestrial and space heat pipes such as tubular heat pipes and thin flat heat pipes, under the normal gravity as well as the low-gravity conditions.

In general, the heat transfer capability of the heat transfer devices is limited by the working fluid transport properties. One of the methods for the heat transfer enhancement of the heat transfer devices is the application of additives to the working fluids to change the fluid transport properties and flow features. Therefore, in order to further enhance thermal performance of heat transfer devices, the use of rewetting fluids is proposed [24]. It is sufficient that only a small amount of the long-chain alcohols, in the order of 10^{-3} mole per liter, is required to change the surface tension characteristics of water without affecting the other bulk properties of the water.

In the proposed method, heat pipe of copper container with stainless steel wick material and aqueous solutions as working fluid have been analyzed. 0.001 mole per liter of n-butanol and n-pentanol is added to the pure water separately and this solution is used as working fluid for the heat pipe. Wrapped screen wick structure with two layers of 1600 strands per sq. metre were used in the heat pipe. The experiments were conducted for various flow rates (0.06, 0.08, and 0.100 kg per minute) and for various inclinations of heat pipe to the horizontal (0°, 30°, 45°, 60°, and 90°) with different heat inputs (40, 60 and 80 W). The results are compared with water heat pipe.

Experimental set-up

The experimental set-up is shown in fig. 1. The specifications and limitations of heat pipe are tabulated in tab. 1 and tab. 2, respectively. The limitation values are calculated using the relationship as specified in [3]. The maximum heat transport capability of heat pipe is determined from these limitations and the heat pipe is designed for the lowest value given in that table. The heat pipe was charged with 50 ml of working fluid, which approximately corresponds to the amount required to fill the evaporator. Before charging, the heat pipe is cleaned with acetone and evacuated using vacuum pump to pressure of 25 mm of Hg (vacuum). Heat input was supplied at the evaporator section using an electric heater attached to it with proper electrical insulation and heater has been energized with an AC supply through a variac. The desired heat input was supplied to the evaporator end of the heat pipe by adjusting the variac and it was measured using a power transducer with uncertainty of ±1 W.

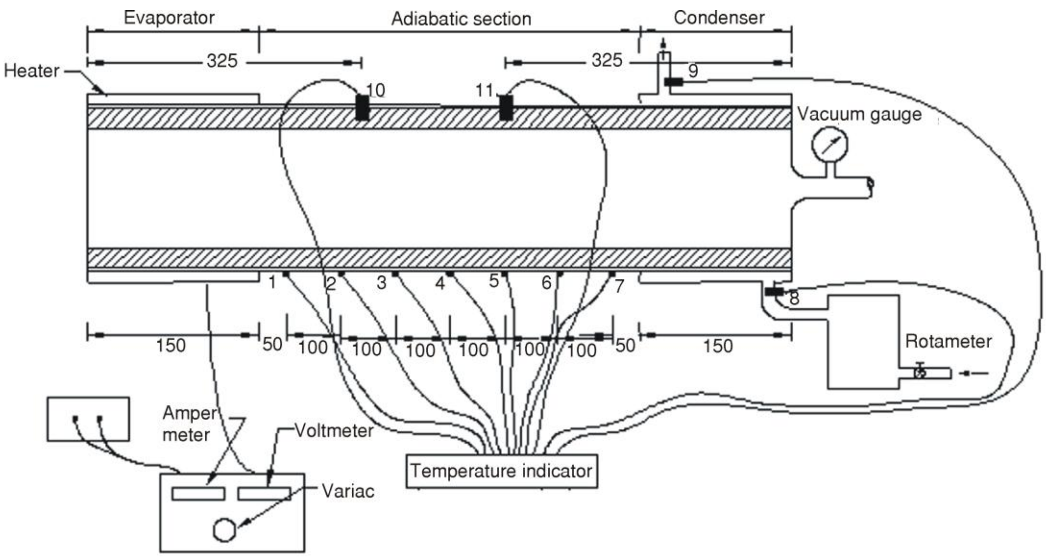

Figure 1. Experimental set-up

Water jacket (iner diameter 46 mm and outer diameter 50 mm) was provided at the condenser end to remove the heat from the pipe. The heat pipe has the ability to transfer the heat through the internal structure. As a result, sudden rise in wall temperature occurs which could damage the heat pipe if the heat was not released at the condenser properly. Therefore, the cooling water was circulated first through the condenser jacket before applying the heat to the evaporator. The power input was gradually raised to the desired power level. The surface temperatures at seven different locations along the heat pipe were measured using copper constantan (T-type) thermocouple with an uncertainty of ±0.1°C at a regular time interval of ten minutes until the heat pipe reaches the steady-state condition. Simultaneously the evaporator wall temperature, wick temperature, water inlet and water outlet temperatures, were also measured using copper constantan (T-type) thermocouples. The water flow rate was measured using a rotameter on the inlet line to the jacket that has an uncertainty of ±1%. Once steady-state was reached, the input power was turned off and cooling water was allowed to flow through the condenser to cool the heat pipe and to make it ready for further experiments. Then the power was increased to the next level and the heat pipe was tested for its performance. Experimental procedure was repeated for different heat inputs and different inclinations of pipe to the horizontal and observations were recorded. The output heat transfer rate from the condenser was computed by applying an energy balance to the condenser flow.

Table 1. Specifications of the heat pipe

Specifications	Dimensions
Outer diameter of the heat pipe	0.022 m
Inside diameter of the heat pipe	0.196 m
Evaporator length	0.15 m
Condenser length	0.15 m
Adiabatic length	0.70 m
Wick mesh size	1600 holes per m^2
Wick porosity	0.769
No. of layers of wick	2
Wick permeability	$2.213 \cdot 10^{-9}$ m^2

Table 2. Limitations of the heat pipe

Limitations	Values
Capillary limit	109 W
Sonic limit	83853 W
Entrainment limit	5553 W
Boiling limit	712 W

Results and discussions

Effects of tilt angle, heat input, water flow rate, and working fluid on thermal efficiency

The heat pipe thermal efficiency can be evaluated by finding the ratio between the heat removed at the condenser section and the heat supplied at the evaporator section ($mc_p\Delta T/Q$), where m is the water mass flow rate, c_p – the water specific heat, ΔT – the temperature difference of the water at the outlet and inlet sections of the condenser, and Q – the thermal power supplied at the evaporator section. Figures 2 to 10 shows the efficiency of gravity assisted heat pipe with angle of inclination for various heat inputs, flow rate of water in condenser section and with different working fluids. From all the figures (except 80 W heat input), it is found that the efficiency of heat pipe with the aqueous solution of n-pentanol increases with an increase in the tilt angle up to 30° in horizontal position of the heat pipe. It is due to the fact that, the temperature of the working medium increases and hence more amount of heat can be removed in the condenser section and also the positive surface tension gradient of aqueous solution of n-pentanol. Conversely, when the angle of inclination increases above 30° in horizontal position, the efficiency of the heat pipe tends to decrease at 45° and thereafter its value gradually increases for all the working fluids used in the experiment. The efficiency of the heat pipe seems to decrease as the formation of the liquid film inside the condenser results in the increased value of the thermal resistance between the cooling water and the vapour of the working fluid in the heat pipe. In case of 80 W heat input, the efficiency increases for increasing values of the inclination angle. The maximum thermal efficiency of heat pipe is attained at 30° for both water as well as self rewetting fluids (except for 80 W heat input). At low flow rate (0.06 kg/min.) the efficiency of the aqueous solution of n-pentanol is higher at 45º than the other inclination angles (for 40 W heat input). However the efficiency of aqueous solution of n-butanol is greater at 45º (for 60 W heat input) than the other inclination angles for the same lower flow rate (0.06 kg/min.). For 80 W heat input, the heat transfer from the evaporator surface to the working medium is higher. This higher heat transport causes the working medium which is in the form of vapour to move vigorously in the condenser section. The cooling water in the condenser absorbs this excessive heat and as a result the efficiency of the heat pipe increases. For 80 W heat input the thermal efficiency is higher at vertical position of the heat pipe because gravity force acting on the heat pipe is higher at vertical position than the other inclinations. The aqueous solution of n-pentanol gives the better thermal efficiency than water and the aqueous solution of n-butanol.

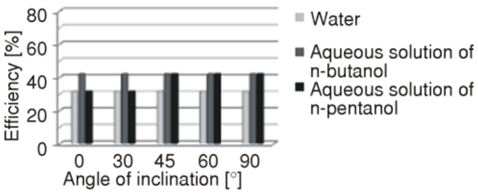

Figure 2. Heat pipe efficiency for 40 W heat input and flow rate of 0.06 kg/min.

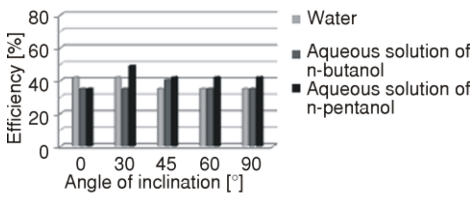

Figure 3. Heat pipe efficiency for 60 W heat input and flow rate of 0.06 kg/min.

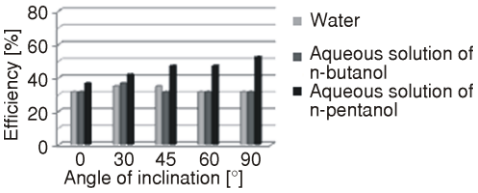

Figure 4. Heat pipe efficiency for 80 W heat input and flow rate of 0.06 kg/min.

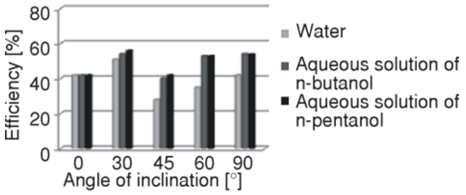

Figure 5. Heat pipe efficiency for 40 W heat input and flow rate of 0.08 kg/min.

At lower flow rate of water (0.06 kg/min.) in the condenser section, the efficiency of the heat pipe is less when compared with the other flow rates (0.08 kg/min. and 0.1 kg/min.).

It is due to the improper heat transfer between the heat pipe and the working medium (water) in the condenser *i. e*. at low flow rate; the water does not flow effectively across the condenser. At higher flow rate the amount of heat transfer between the heat pipe and the condensing fluids are more resulting an increase in efficiency. The temperature distri-

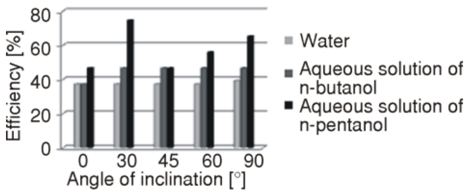

Figure 6. Heat pipe efficiency for 60 W heat input and flow rate of 0.08 kg/min.

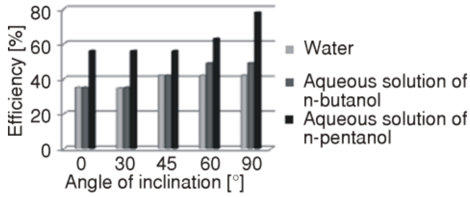

Figure 7. Heat pipe efficiency for 80 W heat input and flow rate of 0.08 kg/min.

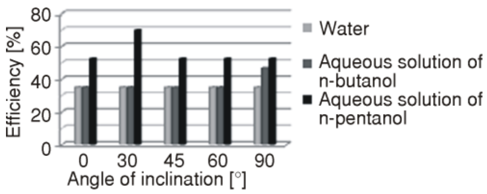

Figure 8. Heat pipe efficiency for 40 W heat input and flow rate of 0.100 g/min.

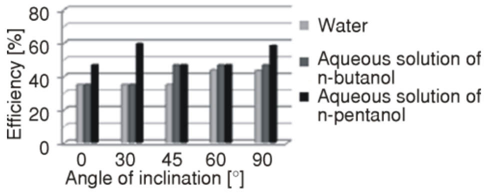

Figure 9. Heat pipe efficiency for 60 W heat input and flow rate of 0.100 kg/min.

bution of the heat pipe is uniform. The surface temperature of the heat pipe is higher when it is in the horizontal position (0° inclination) than the other inclinations. It is due to the gravity forces acting on the heat pipe that drags the working fluid and it settles down in the bottom of the container. The wall temperature of the heat pipe in the adiabatic section is nearly constant and its variation of temperature in this section is less than 1.5 °C.

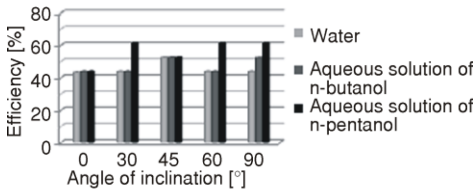

Figure 10. Heat pipe efficiency for 60 W heat input and flow rate of 0.08 kg/min.

Effects of tilt angle, heat input, water flow rate, and working fluid on thermal resistance

The thermal resistance of the heat pipe (R) is defined as:

$$R = \frac{T_{\mathrm{e}} - T_{\mathrm{c}}}{Q} \tag{2}$$

where T_{e} and T_{c} are the average surface temperatures of the heat pipe at the evaporator and the condenser region, respectively. Q is the thermal input given at the evaporator. The thermal resistance of the heat pipe is studied for various conditions and evaluated for all the heat inputs and inclinations. Figures 11-19 shows the variation of thermal resistance of the heat pipe related to various tilting angles at 40, 60 and 80 W heat input for water and self rewetting fluids.

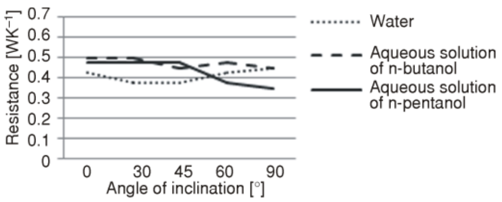

Figure 11. Heat pipe thermal resistance for 40 W and flow rate of 0.06 kg/min.

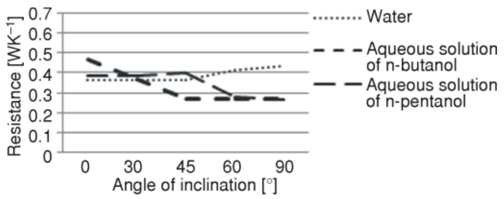

Figure 12. Heat pipe thermal resistance for 60 W and flow rate of 0.06 kg/min.

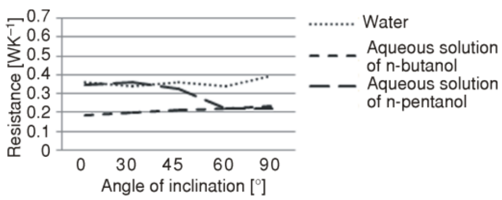

Figure 13. Heat pipe thermal resistance for 80 W and flow rate of 0.06 kg/min.

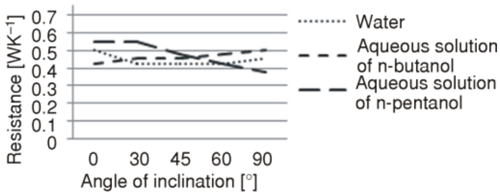

Figure 14. Heat pipe thermal resistance for 40 W and flow rate of 0.08 kg/min.

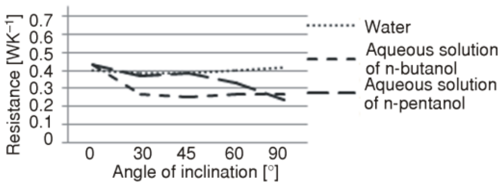

Figure 15. Heat pipe thermal resistance for 60 W and flow rate of 0.08 kg/min.

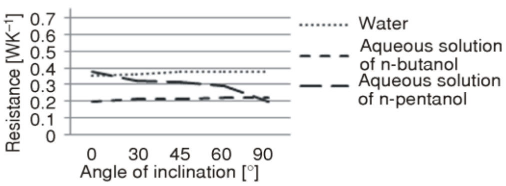

Figure 16. Heat pipe thermal resistance for 80 W and flow rate of 0.06 kg/min.

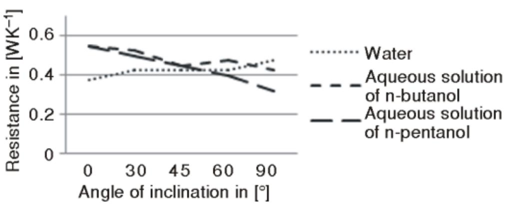

Figure 17. Heat pipe thermal resistance for 40 W and flow rate of 0.100 kg/min.

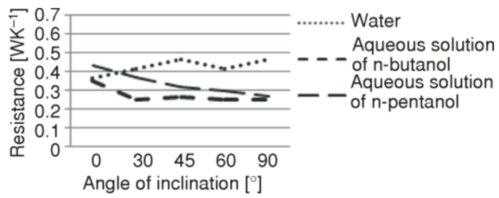

Figure 18. Heat pipe thermal resistance for 60 W and flow rate of 0.100 kg/min.

For most of the cases, the thermal resistance of the water heat pipe increases with an increase in inclination angle. The thermal resistance of the aqueous solution of n-pentanol decreases with increasing values of inclination angle and its value is always less than the water and aqueous solution of n-butanol. It is due to the fact that the surface temperature of the self rewetting fluids heat pipe is less than that of the water heat pipe *i. e.* more amount of heat is carried away by the self rewetting fluids in the evaporator section. For the high-temperature heat source, a large amount of the aqueous

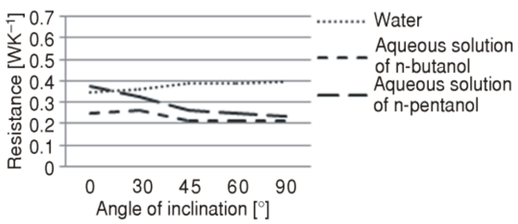

Figure 19. Heat pipe thermal resistance for 80 W and flow rate of 0.100 kg/min.

solution of n-pentanol could be vapourized in the heat pipe and that vapour moves to the condenser section quickly and powerfully. It results in an increase in the condenser section temperature, subsequently lower thermal resistance for higher heat input than the lower heat input.

At lower heat input (40 W), the thermal resistance of water heat pipe is less than the self rewetting fluids up to 45° inclinations. It is due to the difference in boiling point and the dew point in the non-azeotropic mixtures. However such a drawback can be drastically improved in higher thermal input region. The reason may be the difference in the wettability characteristics of water and alcohol aqueous solutions. Moreover, the contact angle of water to metallic surface is larger than alcoholic aqueous solutions, wettability between water and wick structure is considered to be much more sensible to the characteristics of metallic surface. It is, therefore, likely that the thermal performance of water heat pipes is subject to more appreciable influence of the surface characteristics of wick.

Conclusions

The heat pipe technology is widely used for various heat transfer equipments and variety of applications like electronic components. However, the heat transfer capability is limited by the working fluid transport properties. The enhancement of heat transfer device can be improved by changing the transport properties of the fluid used in the heat pipe. The experiment results show the improvement in the surface tension of the working fluid owing to the fact that thermal efficiency increases up to a certain value of temperature. This value of temperature depends on the type, surface tension, temperature gradient, and concentration of long chain alcohol in the water. It provides an additional mechanism for liquid return from the condenser to the evaporator, other than capillary and gravitational forces. The results obtained show that the heat pipes filled with self rewetting fluids have more stable, higher thermal efficiency, and lower thermal resistance than heat pipe filled with water. However the aqueous solution of n-pentanol gives the better results than the aqueous solution of n-butanol as it has the better surface tension characteristics. Moreover, the experimental results show the suitability of self rewetting fluids to improve heat pipe performances.

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