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Performance Analysis of Heat Pipe Using Copper Nanofluid with Aqueous Solution of n-Butanol

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***Abstract*—**This study presents the improvement of thermal performance of heat pipe using copper nanofluid with aqueous solution of n-Butanol. The nanofluids kept in the suspension of conventional fluids have the potential of superior heat transfer capability than the conventional fluids due to their improved thermal conductivity. In this work, the copper nanofluid which has a 40 nm size with a concentration of 100 mg/lit is kept in the suspension of the de-ionized (DI) water and an aqueous solution of n-Butanol and these fluids are used as a working medium in the heat pipe. The study discusses about the effect of heat pipe inclination, type of working fluid and heat input on the thermal efficiency and thermal resistance. The experimental results are evaluated in terms of its performance metrics and are compared with that of DI water.

***Keywords*—**copper nanofluid with aqueous solution of n-Butanol, heat pipe, thermal efficiency, thermal resistance

I. INTRODUCTION

THE heat pipe is an effective heat transfer device that can transport heat at high rates with a very small temperature gradient by utilizing the phase change of working fluid. Heat pipe make uses of the highly efficient thermal transport process of evaporation and condensation to maximize the thermal conductance between a heat source and a heat sink. The amount of heat transported by these devices is normally several orders of magnitude greater than pure conduction through a solid metal [1,2]. The heat pipes are more advantageous in heat recovery systems [3, 6], solar energy [4], light water nuclear reactors [5], electronics cooling [7, 8] and air craft cooling [8].

The heat transfer characteristics of the heat pipe have been studied by a number of researchers. Lin et al. [9] experimentally analyzed the two-phase flow and heat transfer of R141b in a small tube. Song et al. [10] discussed about the heat transfer performance of axial rotating heat pipes at steady state conditions. Xuan et al. [11] performed experiment on a flat heat pipe under different heat fluxes, inclinations and the amount of the working fluid. Liu et al. [12] considered the effects of the length of the evaporator, vapour temperature on the critical values of the upper and lower boundaries.

All the types of heat pipes have a common problem of heat transfer limitation. These limitations determine the maximum heat transfer rate for a particular heat pipe under the normal working conditions. In heat pipe design, the capillary limit and the boiling limits are important under the normal working conditions. The surface tension is an important key factor for capillary limit. The surface tension of all the pure liquids is normally decreasing with increase in temperature, as the liquid moves along the interface towards the cooler condenser zone. The working fluids currently available for heat pipes have negative surface-tension gradients with temperature, that are unfavourable for the spreading or re-wetting on a heated surface, and therefore, the operating temperature and the heat load of heat pipe systems are limited. The heat pipe systems also suffer from operational instability problems because of the characteristics of the negative surface tension gradient with temperature [13]. For medium temperature applications, water is used as a working fluid, due to its availability, cost, safety, easiness to handle and high surface tension. At elevated temperatures the surface tension of the water also decreases rapidly with increase in temperature.

The heat transfer capability of the all heat transfer devices including heat pipe is limited by the working fluid transport properties. To overcome these limitations, the thermo physical properties of the working fluid have to be improved. The heat transfer rate of heat transfer devices can be improved by adding additives to the working fluids to change the fluid transport properties and flow features. One of the methods is to use the aqueous solutions of alcohols, with chain lengths longer than four carbon atoms.

Vochten and Petre [14] experimentally revealed that the surface tension of aqueous solutions of alcohols, with chain lengths longer than four carbon atoms, have a positive gradient with temperature when the temperature exceeds a certain value. The stable working fluid circulation in a heat pipe is achieved through the capillary pressure head developed by the wick structure. The maximum capillary head developed in the heat pipe must be more than the various pressure losses along the vapour-liquid path which includes liquid pressure drop, vapour pressure drop, gravity pressure drop and pressure drop in wick structure. 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 [15]. Besides, the heat pipe using the dilute solutions of long chain alcohols yields both the high surface tension and the positive surface tension gradient with temperature, when the working fluid operating temperature is at 90^{o}C or above. Because of the very large positive surface-tension gradient

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with temperature, the working fluid tends to move towards the evaporator in the heat pipe, reducing the liquid pressure drop, increasing the capillary limit and the boiling limit, and consequently, increasing the heat load.

Another method is to use the nanofluid in the heat transfer equipments to enhance the thermal performance of heat transfer devices. An innovative way to enhance liquid thermal conductivity is the dispersion of highly conductive solid nanoparticles within the base fluid. This new generation of conductive fluids with nanoparticles is referred to as nanofluids. Nanofluids are nanotechnology-based heat transfer fluids that are derived by stably suspending nanometer-sized particles (1 to 100 nm) in conventional heat transfer fluids, usually liquids. Some experimental investigations have revealed that nano-fluids have remarkably higher thermal conductivity and greater heat transfer characteristics than conventional pure fluids [16-19]. The convective heat transfer feature and flow performance of copper–water nano-fluids in a tube were experimentally investigated by Xuan and Li [20]. Liu et al. [21] have shown that the heat pipe operating pressure has a significant effect on the thermal performance. In another study, Riehl [22] has observed that a higher heat transfer coefficient can be seen when using nanoparticles in water under low heat input conditions. Tsaia [23] investigated the influence of particle size on the heat pipe thermal performance.

From the analysis, it has been found that the nano fluids have the higher heat transfer capacity than the conventional working fluids and also it reduces the overall thermal resistance between the evaporator and the condenser. It is in this direction, a working fluid which is the combination of copper nano particle and the aqueous solution of long chain alcohols has been explored in order to enhance the thermal performance of the heat pipe.

In the present analysis, heat pipe of copper container and the stainless steel wrapped screen is used as a wick material. The copper nanofluid with a size of 40 nm and the aqueous solution of copper nanofluid prepared by adding the 2 ml/lit of n- Butanol is used as working fluid. The concentration of copper nanofluid in the DI water is 100 mg/lit. The nanofluids are prepared using the ultrasonic homogenizer for copper nanofluid and copper particle in the aqueous solution of n-Butanol. The experiments are conducted for various inclinations of heat pipe to the horizontal with different heat inputs. The objective of this work is to study about the thermal efficiency improvement of heat pipe using copper nanofluid and the aqueous solution of n-Butanol in copper nanofluid.

II. EXPERIMENTAL PART

A. Experimental setup

The schematic diagram of the heat pipe under consideration is shown in Fig.1 (a) and the thermocouple locations are shown in Fig. 1 (b). The experiment part consists of a 20 mm outer diameter copper-water heat pipe with a length of 600 mm and a wall thickness of 1.2 mm. The wick consists of two wraps of a stainless steel wire mesh with a wire diameter of 0.183 mm and 2365 strands per meter. The heat pipe is charged with 40 ml of working fluid, which approximately corresponds to the amount required to fill the evaporator. The wall temperature distribution of the heat pipe in adiabatic zone is measured using six evenly spaced copper constantan (T-type) thermocouples with an uncertainty of ±0.1°C, at an equal distance from the evaporator. In addition the thermocouples are also located in evaporator surface (three locations), condenser surface (three locations), inlet and outlet of the condenser jacket. The electrical power input is applied at the evaporator section using cylindrical electric heater attached to it with proper electrical insulation and the heater is energized with 230V AC supply using a variac and measured using a power transducer with an uncertainty of ±1 W.

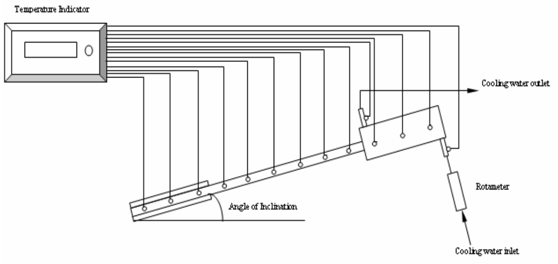

Fig. 1(a) Experimental setup

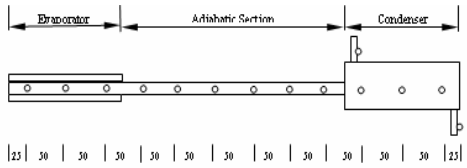

Fig. 1(b) Thermocouple locations of heat pipe

Water jacket has been used 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, a sudden rise in wall temperature occurs which could damage the heat pipe if the heat is not released at the condenser properly. Therefore, the cooling water is circulated first through the condenser jacket, before the heat is supplied to the evaporator. The condenser section of the heat pipe is cooled using water flow through a 150 mm long jacket with an inner diameter of 30 mm and outer diameter of 36 mm. The water flow rate is measured using a rotameter on the inlet line to the jacket that has an uncertainty of ±1% and the flow rate is kept constant at 0.08 kg/min. The inlet and outlet temperatures of the cooling water are measured using two copper constantan thermocouples. The adiabatic section of the heat pipe is completely insulated with the glass wool. The amount of heat loss from the evaporator and condenser surface is negligible.

B. Experimental Procedure

The experiments are conducted using three identical heat pipes which are manufactured as per mentioned dimensions. One of the heat pipes is filled with de-ionized water, second one with copper nanofluid and third one with the aqueous solution of n-Butanol with copper nanofluid. The power input to the heat pipe is gradually raised to the desired power level.

The surface temperatures at six different locations along the adiabatic section of heat pipe are measured at regular time intervals until the heat pipe reaches the steady state condition. Simultaneously the evaporator wall temperatures, condenser wall temperatures, water inlet and outlet temperatures in the condenser zone are measured. Once the steady state is reached, the input power is turned off and cooling water is allowed to flow through the condenser to cool the heat pipe and to make it ready for further experimental purpose. Then the power is increased to the next level and the heat pipe is tested for its performance. Experimental procedure is repeated for different heat inputs (30, 40, 50, 60 and 70 W) and different inclinations of pipe (0^o, 15^o, 30^o, 45^o, 60^o, 75^o and 90^o) to the horizontal and observations are recorded. The output heat transfer rate from the condenser is computed by applying an energy balance to the condenser flow. The vacuum pressure in the inner side of the heat pipe is monitored by vacuum gauge, which is attached in the condenser end of the heat pipe.

III. RESULTS AND DISCUSSIONS

A. Effect of heat pipe inclination in thermal efficiency

Fig. 2 - 6 show the variations of heat pipe thermal efficiency for DI water, copper nanofluid and copper nanofluid with aqueous solution of n-Butanol with various tilt angles for 30 W, 40 W, 50 W, 60 W and 70 W heat inputs respectively. From all the figures, it has been observed that the efficiency of heat pipe increases with increasing values of the tilt angle. This is due to the fact that the gravitational force has a significant effect on the flow of working fluid between the evaporator section and the condenser section along with the capillary action of wick. However, when the heat pipe inclination angle exceeds 30° for de-ionic water and 45° for copper nanofluid and copper nanofluid with aqueous solution of n-Butanol, the heat pipe thermal efficiency tends to decrease. The efficiency of the heat pipe seems to decrease since the formation of the liquid film is at higher rate inside the condenser which results in the increased value of the thermal resistance between the vapour of the working fluid and the cooling medium in the condenser. Therefore the thermal efficiency decreases when the angle exceeds 30° for DI water and 45° for copper nanofluid and copper nano particle in the aqueous solution of n-Butanol.

The heat pipe thermal efficiency can be calculated from the ratio between the cooling capacity rate of water at the condenser section to the power supplied at the evaporator section. Generally, the nanoparticles suspension in the fluid has significant effect on the enhancement of heat transfer due to its higher heat capacity and higher thermal conductivity of working fluid. Therefore, the heat pipe thermal efficiency heat pipe increases with nanofluids as compared to that of the base working fluid.

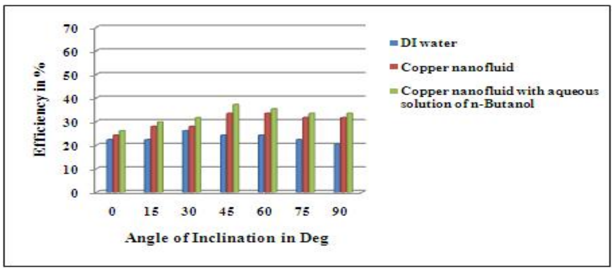

Fig. 2 Variations of heat pipe efficiency for various inclinations at 30 W heat input

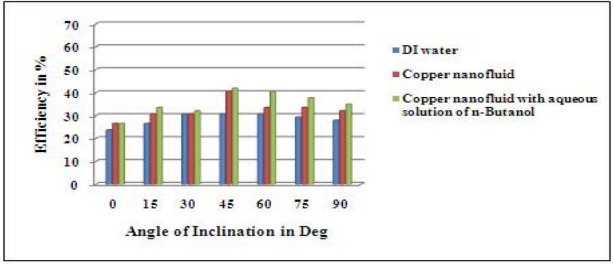

Fig. 3 Variations of heat pipe efficiency for various inclinations at 40 W heat input

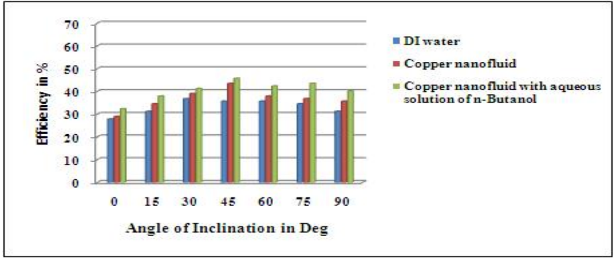

Fig. 4 Variations of heat pipe efficiency for various inclinations at 50 W heat input

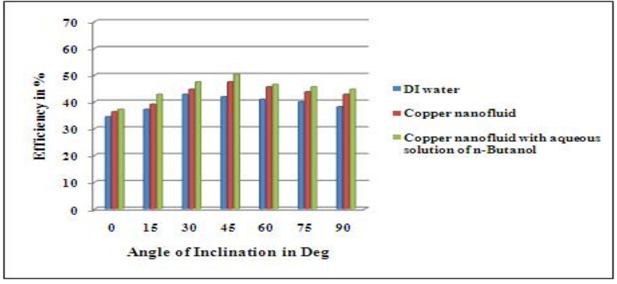

Fig. 5 Variations of heat pipe efficiency for various inclinations at 60 W heat input

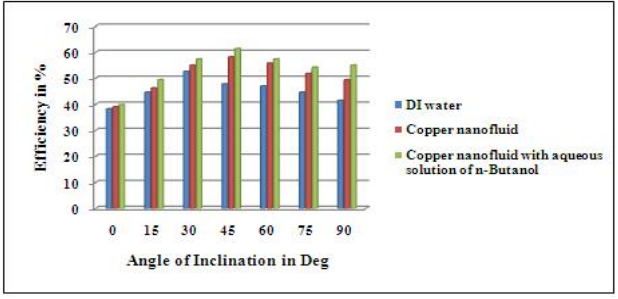

Fig. 6 Variations of heat pipe efficiency for various inclinations at 70 W heat input

In this analysis, the thermal efficiency of heat pipe increases about 10% with copper nanofluid as a working fluid when compared with the DI water. Besides, the heat pipe which uses copper nanofluid with aqueous solution of n-Butanol increases the thermal efficiency to nearly about 15% as compared that of DI water due to the positive surface tension gradient possessed by n-Butanol.

B. Effect of thermal resistance

Fig.7-13 show the comparative results of thermal resistance of heat pipe with DI water, copper nanofluid and copper nanofluid with aqueous solution of n-Butanol. The thermal resistance (R) of the heat pipe is defined as

$$R = \frac{(T_e - T_c)}{Q}$$

where T_e and T_c are average values of temperatures at the evaporator and condenser sections respectively and Q is the heat supplied to the heat pipe. From all the figures, it is clear that the thermal resistance of heat pipe decreases for all the three working fluids with increasing values of angle of inclination and the heat input. However, the thermal resistances of heat pipes using both the base fluid and nanofluids are comparatively high at low heat loads for the reason that a relatively solid liquid film resides in the evaporator section. On the other hand, these thermal resistances condense quickly to its minimum value when the heat load is increased. At higher inclinations of heat pipe (above 60° with horizontal) and higher heat input (more than 50 W) the difference between the thermal resistance of DI water & copper nanofluid is nearly 15%. The thermal resistance of the copper nanofluid with aqueous solution of n-Butanol is less than the DI water and copper nanofluid for all the variables and the value is nearly 25% less than of the DI water.

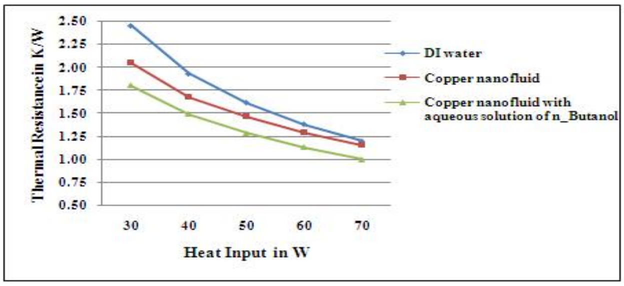

Fig. 7 Thermal resistance of heat pipe for 0° inclination

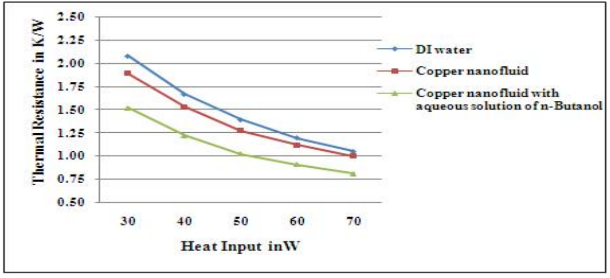

Fig. 8 Thermal resistance of heat pipe for 15° inclination

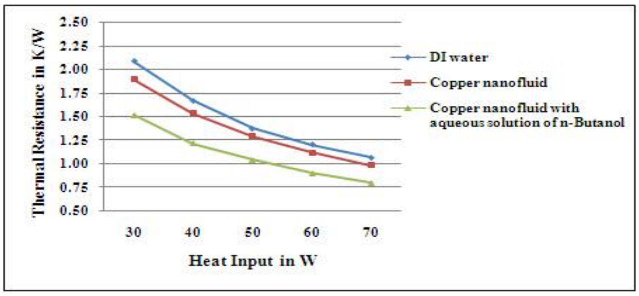

Fig.9 Thermal resistance of heat pipe for 30° inclination

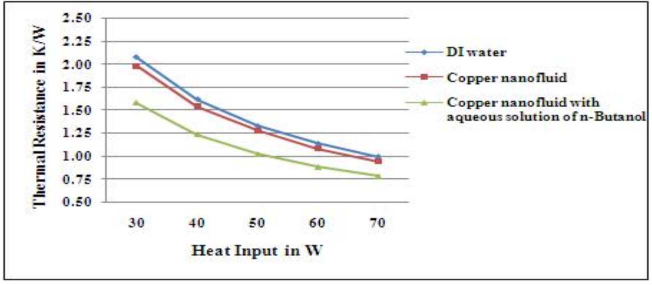

Fig.10 Thermal resistance of heat pipe for 45° inclination

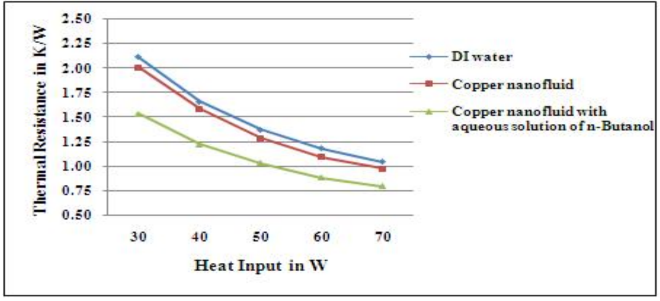

Fig.11 Thermal resistance of heat pipe for 60° inclination

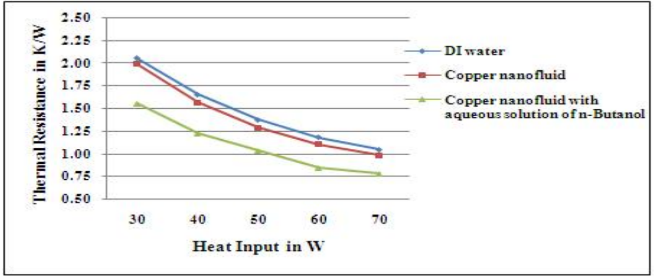

Fig.12 Thermal resistance of heat pipe for 75° inclination

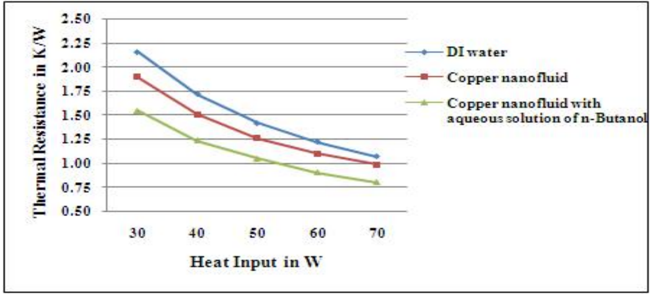

Fig.13 Thermal resistance of heat pipe for 90° inclination

Recently, Do and Jang [24] mathematically presented that the key effect of the heat transfer enhancement of a heat pipe using nanofluids is not due to the thermo physical properties of nanofluids but it is owing to the thin porous coating layer formed by nanoparticles in the evaporation region. Besides, Yang et al. [25] and Kim et al. [26] indicated that the coating layer formed by nanoparticles improves the surface wettability by reducing the contact angle and increasing the surface roughness, which in turn increases the critical heat flux. This not only improves the maximum heat transport rate but also, significantly reduce the thermal resistance of the heat pipe using nanofluids. This may be due to the formation of the thin porous coating layer by nanoparticles suspended in nanofluids. The coating layer on the mesh wick surface provides an additional evaporating surface where high heat transfer rates occur. This drastically reduces the thermal resistance of the mesh wicked heat pipe and also it increases the capillary pumping ability to pull the liquid to the mesh wick surface.

c. Variation of temperature difference between evaporator and condenser

The temperature difference between the evaporator and the condenser for various heat loads is shown in Fig. 14 - 20. From the figures, it is observed that the temperature difference between the evaporator and the condenser increases for increasing values of heat input. It is clear that the temperature difference between the condenser and the evaporator is lesser for copper nanofluid with aqueous solution of n-Butanol than the other working fluids. As the n-Butanol has the positive surface tension gradient with temperature, more amount of condensate is moved to the evaporator from the condenser at higher rate. Moreover, the surface temperature of the evaporator section when the copper nanofluid with aqueous solution of n-Butanol is used as the working fluid is 25% less than DI water and 12 % less than the copper nanofluid. The reason behind that is the aqueous solution of n-Butanol increases the rate of heat transfer.

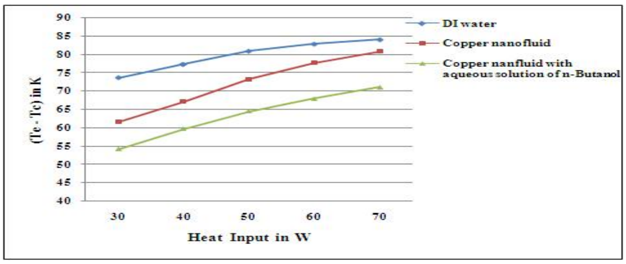

Fig 14 Variation of (T_e - T_c) for 0° inclination

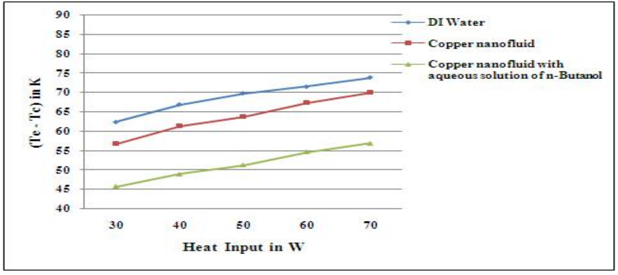

Fig 15 Variation of (T_e - T_c) for 15° inclination

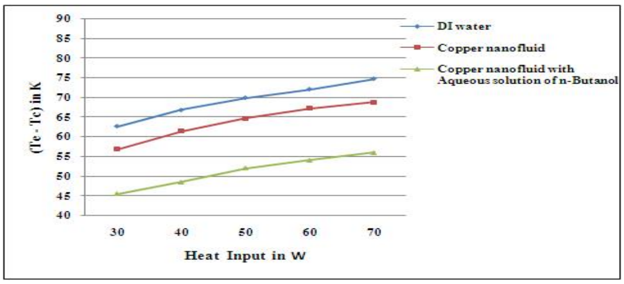

Fig 16 Variation of (T_e - T_c) for 30° inclination

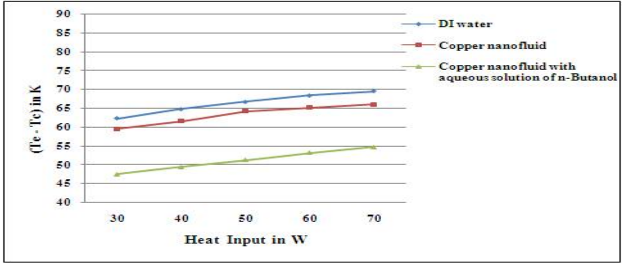

Fig. 17Variation of (T_e - T_c) for 45° inclination

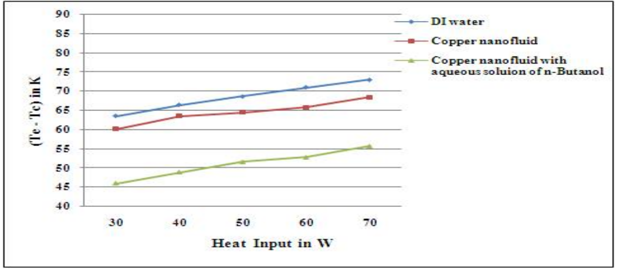

Fig. 18 Variation of (T_e - T_c) for 60° inclination

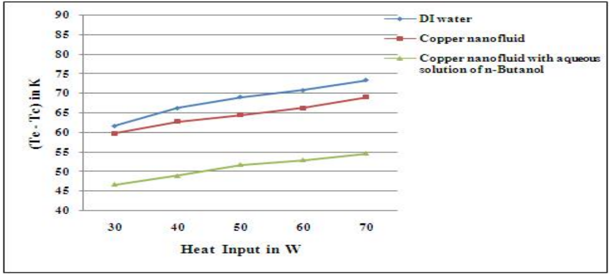

Fig. 19Variation of (T_e - T_c) for 75° inclination

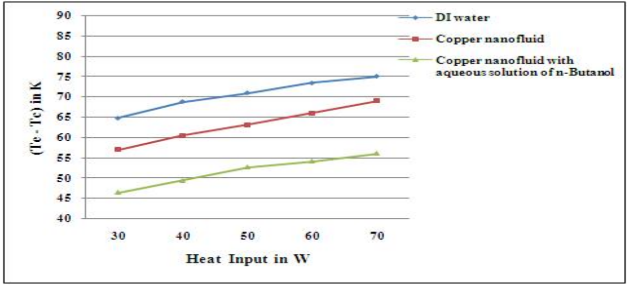

Fig. 20 Variation of (T_e - T_c) for 90° inclination

IV. CONCLUSION

In this study, the thermal performances of the cylindrical heat pipe with wire mesh are experimentally investigated using the DI water, copper nanofluid and copper nanofluid with aqueous solution of n-Butanol as working fluids. To evaluate the thermal performance of the heat pipe using the copper nanofluid and copper nanofluid with aqueous solution of n-Butanol, the thermal efficiency and the thermal resistances between the evaporator and the condenser regions are measured and compared with the heat pipe using DI water. Based on the experimental results, it is found that the thermal efficiency of copper nanofluid with aqueous solution of n-Butanol is higher than the base fluid DI water and copper nanofluid and the thermal resistance also reduces to three fourth of base fluid. The results show that the thermal performances of the heat pipe may be enhanced by adding a very small amount of long chain alcohol which gives the better performance than the conventional working fluid and nanofluid. This may be due to the reason that, the dilute aqueous solution of n-Butanol which is having a positive surface tension gradient with temperature gives rise to an increased value of the capillary limit and the boiling limit of the heat pipe along with the nanofluid.

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