A Review of Performance of Heat Pipes at Different Inclinations

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***Abstract*— Heat Pipe are the superconductors of heat because of their fantastic heat handling and transporting ability with minimum heat loss. A lot of research and experimentation has been carried out on heat pipes in the 21st century due to modernization and miniaturization of equipments. This review aims to collect and compile research works by various authors in the field of heat pipe, where they have studied the performance of heat pipe under different tilt angles or inclinations. Gravitational and capillary forces play a very important role in deciding the overall performance of a heat pipe. At every different inclination, the resultant of these two forces varies, so the efficiency of a heat pipe also varies. This is the reason why there is a need to thoroughly study the performance of heat pipes at different inclinations.**

Keywords*— Heat Pipe; Heat Transfer; Nanofluid; Inclination; Wick.

I. INTRODUCTION

In the traditional heat transfer units of the 1880s like Perkin's boiler, the simplest mechanism of transfer of heat was employed where liquid through the pipes was heated by hot gases passing over them. It was not till 1944 when Gaugler's wick concept of heat transfer – which is the basis of heat pipe, came into play. In the early 1960s, Grover after having followed the works of Gaugler introduced term 'Heat Pipe' for the very first time. It is the highest and most economical heat conductance mechanical unit of heat transfer today.

A typical heat pipe mainly consists of 3 sections in a cylindrical container – evaporator section, adiabatic section and condenser section, with a wick material lined on the inner circumference of the container. The wick serves as a path for liquid flow while the inner cavity is where the vapours travel. Initially, the liquid that sits in the evaporator section absorbs heat from an external source causing it to evaporate and travel to the condenser – where it emits heat through free or forced convection, hence condensing the vapours into liquid form. The wick structure returns this liquid condensate back into the evaporator by the virtue of capillary forces, which is sometimes assisted by gravity as well. This unique structure and the working capability of heat pipes make it one of the fastest and most economical units of heat transfer in different applications. The purpose of this review paper is to compile the results of various researchers who have worked on the performance of heat pipe at different inclination angles in the recent years [1-3].

II. STUDY OF HEAT PIPES AT DIFFERENT INCILINATIONS

The inclination angle of the heat pipe plays a very significant role in its overall thermal performance. Another very important factor that governs the performance of the heat pipe is its wick structure and material. When a heat pipe is used under gravity conditions, then wicks with low capillary limit work best. Loh et al. [4] in 2005 studied the combined effects of different tilt angles along with different wick structures in heat pipe. It was concluded from the experiments that gravitational forces and tilt angles have a very less effect on the performance of sintered powdered metal heat pipes because of capillary action associated with it. When the evaporator position lies on the top of condenser, then the author suggested not to use to mesh or groove heat pipes. And lastly, groove heat pipes gave better performance and results compared to mesh and sintered powder metal heat pipe in the inclination range of 0˚ to 90˚.

In 2007, Kumar et al. [5] reported a theoretical and experimental study of a heat pipe with wire screen. The evaporator region of the heat pipe was put to forced convection heating process and the condenser region was subjected to free air convective cooling. By using thermal resistance approach, an analytical model was developed for that heat pipe. With the use of that model, author was able to determine the thermal resistance on the outer surface of the heat pipe as well as inside the heat pipe. Then experimental study was performed to understand the effects of various inclination angles on the performance of the heat pipe. The results obtained from theoretical model and experiments were compared and fair agreement was found between them. It was observed from Kumar's experiments that the annular finned heat pipe performed better at tilted conditions compared to vertical position. When the inclination of heat pipe was increased from 15˚ to 25˚ at same heat input, an increase was observed in the heat transport rate of the heat pipe. The best performance of heat pipe is seen at 25˚ tilt angle corresponding to 70˚C heating fluid temperature over the evaporator section.

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Noie et al. [6] in 2007 investigated the thermal performance of a thermosyphon under normal operating conditions at various inclination angles. A number of experiments were performed at tilt angles varying from 5˚ – 90˚ and evaporator filling ratios varying from 15% – 30%. A thermosyphon made out of copper material having outside diameter, inside diameter and lengths of 16mm, 14.5mm and 1000mm respectively was used in the study. The working fluid inside the container was distilled water. According to the results observed by author, the best thermal performance was seen in the tilt angle range of 15˚-60˚. A genuine agreement was found between author's results and previous literature results. Lastly, the maximum condensation heat transfer coefficient corresponding to filling ratios 22% and 30% was seen at 30˚ and for filling ratio 15%, it was seen at 45˚.

Meena et al. [7] in 2008 used check valve operated closed loop oscillating heat pipes (CLHOP-CV) made up of copper tubes with R123 as working fluid to study the effect of different tilt angles and internal diameters. The fliing ratio inside the evaporator section was fixed at 50% and lengths of all 3 sections of heat pipe were same. Tilt angles were varied from 0˚ to 90˚. The adiabatic section of heat pipe was insulated, also a cold water bath was employed in this study to continuously extract heat out of condenser end. In the results, it was observed that critical temperature of heat pipe increased as the internal diameter was changed from 1.77mm to 2.03mm or when the tilt angle was increased from 0˚ to 90˚.

Huddakorn et al. [8] in 2008 studied the effects of oscillating heat pipe orientation on its overall performance. The heat pipe under investigation was made up of Pyrex glass tube having inner diameter and evaporator length of 1mm and 50mm respectively. The number of meandering turns were ten. All 3 sections of the heat pipe were of same length. The working fluid with filling ratio 50% was R123. It was observed from the results that at horizontal position of the heat pipe, insufficient condensed liquid film resulted in dry-out of evaporator. When the tilt angle was increased from horizontal position all the way up to vertical position, performance limit arose due to evaporator section flooding. The author then performed a second set of experiment known as quantitative study where oscillating heat pipes were made up of copper tubes instead of Pyrex glass, with inner diameters of 0.66mm, 1.06mm and 2.03mm respectively. The meandering turns were kept same but 3 different lengths of evaporator section were employed, i.e. 50mm, 100mm and 150mm. R123, ethanol and water were taken as working fluids with same filling ratio as in first set of experiment. It was found in the results that for all different inclination angles, critical heat flux was inversely proportional to evaporator length, and directly proportional to internal diameter of heat pipe.

Grooten et al. [9] in 2009 used very large length-to-diameter ratio thermsyphons with R-134a as working fluids to perform his experiments to analyse the effects of saturation temperature, inclination angle, filling ratio on the limiting operational heat flux. It was observed that the thermosyphon functions effectively under inclination angles of 83˚. The filling raitio of heat pipe wasn't critical over the values of 25%. It was also observed that when the saturation temperature was increased, or when the inclination angle was decreased – the operation limiting heat flux reduced. Inclination angles more than 83˚ were not recommended by the author for the heat pipe to work properly.

As discussed earlier, Senthilkumar et al. [10] also established that tilt angle and wick structure plays an extremely important role in the overall performance of the heat pipe. The transfer of heat from evaporator section to condenser section is reduced when the working fluid used has negative surface tension gradient. The author studied the behaviour of heat pipe operated on aqueous solutions of n-Pentanol at various orientations. Research objective was to do a comparison test between heat pipe working with water and n-Pentanol as working fluids at different inclination angles. The results drawn out from this study showed superior performance of the heat pipe when working on n-Pentanol fluid for the reason that the aqueous solutions have a positive surface tension gradient with temperature. In order to overcome the limitations of the water, which is widely used as the working fluid in heat pipe systems, it can be replaced by a dilute aqueous solution of n-Pentanol. Besides, the dilute aqueous solution of n-Pentanol 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 that makes it suitable for large heat load applications.

Pachghare et al. [11] in 2013 used Akachi's patented closed loop pulsating heat pipe with 10 turns of copper tubes to experimentally study the effects of its inclination angle on thermal performance. The inner diameter of heat pipe was 2mm while its outer diameter was 3.6mm. The lengths of 3 sections of heat pipe was same, i.e. 50mm while its filling ratio was 50%. Water, methanol and R-134a were employed as working fluids inside heat pipe. It was later found that R-134a's performance was the best compared to other 2. The heat input over evaporator section was increased from 5W to 50W with increments of 5W at different inclination angles. According to the results obtained by the author, as the heat input was increased, the thermal resistance of heat pipe was reduced. The performance was found to be more sensitive under the heat loads of 25W compared to heat loads above 25W. Due to the gravitational forces, it was seen that vertical bottom heat pipe position gave best thermal performance at all inclinations.

Xue et al. [12] in 2014 performed experiments to study the performance of a pulsating closed loop heat pipe with 50% filling ratio ammonia working fluid. The heat pipe was made out of quartz glass with 6 turns. The inner and outer diameters were 2mm and 6mm respectively. The circulation of flow could be seen by visual investigation only, but the author had to perform 4 case tests to determine the effects of heat pipe orientations on its performance. The results showed that, at any random inclination angle, the ammonia circulation was very smooth and easy. Thermal resistance as

low as 0.02 K/W was achieved which reflects on the efficient and fast performance of heat pipe. Also thermal resistance was found to be inversely proportional to inclination angle. The ammonia CLPHP at horizontal 0˚ position when subjected to low input load was very easy to start-up, but the flow of working fluid is such case was slow.
Chen et al. [13] in 2015 studied the thermal performance of cooling enhancement of miniature flat plate heat pipe under different angles. The possibility of cooling enhancement of flat plate heat pipes (FPHPs) by tilting was examined experimentally in this study. All of the FPHPs were made of Al and were partially filled with acetone. They had the same size of 120 mm (length) by 36 mm (width) by 2.5 mm (thickness) and the same liquid filling ratio of 25.1%. The effects of six tilting angles of -30º, -15º, -10º, 0º, 45º, and 90º were explored. The results showed that the thermal resistance decreased and the effective thermal conductivity increased when the tilting angle was increased. By increasing the tilting angle from 0º to 45º and further to 90º, the maximum effective thermal conductivity increased by a factor of 1.205 from 4561 W/mK to 5497 W/mK and of 1.212 to 5530 W/mK, respectively. The corresponding maximum heat transport capability increased by a factor of 2.89 from 39.8 W to 115 W and of 3.27 to 130 W. Hence, by proper tilting into positive angles, cooling enhancement of the FPHPs can be greatly achieved.

In 2015, Yang et al. [14] did a fabrication and performance evaluation of flexible heat pipes for potential thermal control of foldable electronics. Author used a fluoro-rubber tube that acts as a connecting link between the evaporator and condenser sections. Also a strong base treated hydrophilic copper mesh was used as a wick structure. Deionized water in 3 different filling ratios of 10%, 20% and 30% was used as a working fluid so that its effect on the thermal performance on the system could be studied. It was noticed that the fabricated heat pipes could be bended quite easily to the maximum limit of 180º horizontally and they produced low thermal resistances despite undergoing bending over and over again. Obviously, the thermal resistance kept increasing with larger bending angles because bending interrupts normal vapour flow and it also gives rise to increased liquid–vapour interfacial thermal resistance in the evaporator region.

Nazarimenaesh et al. [15] in 2015 studied the effects of inclination angle, evaporator heat load and condenser side cooling fluid temperature on the performance of a U-shaped sintered heat pipe with each section length of 135mm. The diameter of heat pipe throughout its cross-section was taken as 6mm. Ethanol and deionized water were taken as base fluids in which equal amount of silver nanofluid with concentration of 10, 50 and 1000ppm were added. The range of evaporator side heat input was from 10W to 40W and temperature of cooling fluid was taken in the range of 20˚ to 40˚C. It was observed that with the increase in concentration of nanofluids, the thermal resistance of heat pipe was decreased significantly. Also at every tilt angle, overall heat transfer coefficient of the heat pipe was found to be increased. At the inclination angle of 30˚, author achieved lowest thermal resistance for silver nanofluid with 50 ppm. Capillary and gravitational affect the performance of a heat pipe at inclined conditions. At +90˚ these 2 forces act in the same direction while at -90˚ they act in opposite direction. The author reported that least thermal resistance was found at the angle of +90˚.

Cong et al. [16] in 2016 studied the effects of inclination angle on sintered heat pipe radiator. The results indicated that the inclination angle of heat pipe affects the performance of both evaporator as well as condenser sections. The heat pipe performance was more sensitive in case of negative inclinations compared to positive angle inclinations. The change in thermal resistance of heat pipe was insignificant at low heat loads. When the heat input over heat pipe was 138.46 W at 60˚ tilt angle, the heat pipe thermal resistance was found to be reduced by 82.86% in comparison to horizontal 0˚ position. The author recommended to use the heat pipe radiator in a positive inclination angle such that condenser is above evaporator section. Tilt angles from 30˚ to 90˚ showed best results.

Hong et al. [17] performed a multiple orientations research on heat transfer performances of Ultra-Thin Loop Heat Pipes with different evaporator structures where he developed two Ultra-Thin Loop Heat Pipe prototypes with parallelogram and trapezoidal evaporator configurations for battery thermal management system in year 2016. As per the results, both the ULHP prototypes displayed good performances despite low assistance from force of gravity, proving that they could easily work in different orientations. The parallelogram configuration curbed the flow instability quite well and hence it showed better behaviour in nullifying the effect of gravity. But there was a certain angle in each case below which these sort of heat pipes failed to start.

In 2016, Goshayeshi et al. [18] experimentally studied the effect of tilt angle on heat transfer enhancement of a ferrofluid in a closed loop oscillating heat pipe subjected to magnetic flied. Iron-oxide/kerosene nanofluid was used as working fluid in this study. The range of inclination angles of heat pipe was varied from 0˚ to 90˚ and the heat load on evaporator section was varied from 10W to 90W. The heat transfer coefficient was determined with and without the effect of magnetic field. In the results it was seen that heat transfer coefficient increased at higher inclination angles. The critical tilt angle (also the best angle in terms of efficiency and performance) was found to be 75˚. The performance of heat pipe significantly reduced beyond the angle 75˚ because of higher rate of condensed liquid return. Also, when the heat pipe ferrofluid was subjected to magnetic field, the vapour temperature difference between evaporator and condenser section reduced.

III. CONCLUSIONS

This review paper contains the summary of research work done in the period of 2005 to 2016. To conclude - different critical angles were found by different authors, because the performance of a heat pipe does not just depend on its inclination, but also on its container material, wick structure, working fluid, filling ratio and other properties. Also different types of heat pipes produce different results. Vertical position of heat pipe is not recommended as it sometimes results in flooding of evaporator section due to increased speed of condenser return. A tilt angle of 75 was found to be the best by several authors, even though as discussed before, it does not necessarily mean that every heat pipe will follow the same criteria. But heat pipes of generally all types, perform better at inclined conditions compared to horizontal or vertical operation. On the top of that, addition of n-Pentanol or nanoparticles in the working fluid can also significantly improve the performance of heat pipes.

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