Effect of Filling Ratio on Thermal Performance of Thermosyphon Heat Pipe

[1]Faddas Nikhil Ashok, [2]K. V. Mali, [3]P. G. Anjankar3

Mechanical Department, SCOE, Pune 411041, India1,2,3
Email: [1]nafaddas@gmail.com, [2]kvmali.scoe@sinhgad.edu, [3]pganjankar.scoe@sinhgad.edu

Abstract: This study presents experimental performance of thermosyphon heat pipe.The objective of this study is to investigate combine effect of filling ratio and inclination angle on thermal performance of thermosyphon. Thermosyphon was manufactured by using a copper tube of 1000 mm length with inside and outside diameter of 24 mm and 26 mm respectively. Working fluid used in the thermosyphon is binary mixture of ethanol and methanol. Experiments were carried out on the filling ratio 10% to 70% with inclination angle 50^o to 90^o. ΔT vs heat load graphs were drawn for each filing ratio and at all inclination angle. Maximum ΔT found at 22^{o}C which was higher at 40% and 60% filling ratio with 70^o, 80^o and 90^o inclination angle.

Index Terms: Binary mixture, Filling ratio, Inclination angle

I. INTRODUCTION

Energy plays a vital role in day to day life as well as in heat transfer applications. Due to the human need for energy, a more efficient way of using it is a major challenge in the scientific community. The heat pipe and the thermosyphon specially designed by the engineers for transferring heat from a distance. The thermal performance of thermosyphon is one the most important part of these types of investigation in the field of heat transfer.

Natural convection refers to the process wherein heat, transferred to a fluid, raises its temperature and reduces its density, giving rise to buoyant forces that lift the fluid (due to density difference) and transport the absorbed heat to some other location where it can be removed. Natural convection occurs in a similar manner in two-phase systems. Here, the application of the liquid phase produces a low-density vapour that is free to rise though the liquid and condense at some other location. In either case, continuous circulation of the heat transfer fluid is maintained [1].

The Perkins tube, a two-phase flow device, is attributed to Ludlow Patton Perkins in the mid nineteenth century. Schematic of perkins boiler is shown in fig 1.

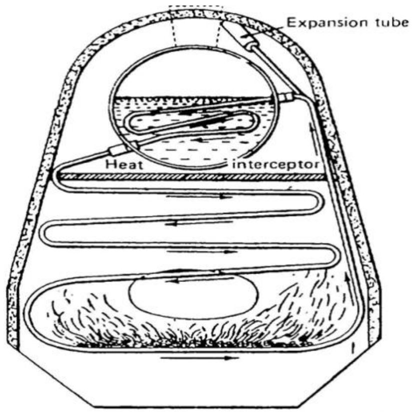

Fig. 1 Perkins boiler [1]

The Perkins tube, which was actually a single-phase, closed-loop thermosyphon, was used to transfer heat from the furnace to the evaporator of a steam boiler. A demonstration of the excellence of this design is the air expansion tube, which provides a space for the air inside the tube when the liquid (water) expands and also functions as a valve for regulating the operating pressure. Early applications of the Perkins tube include steam generation, domestic heating, warming greenhouses, preventing window fogging, removing heat from dairy products, cooling car engines, and in heat exchangers. The development of modern thermosyphon technology and applications did not start until the 1940s. In 1942 and 1944, Gaugler proposed a two-phase closed thermosyphon tube incorporating a wick or porous matrix for capillary liquid return [1]. In 1963, Grover studied this phase heat transfer device and named it “heat pipe”. Tremendous effort has since been invested in thermosyphon and heat pipe research, resulting in broad applications. The heat pipe differs from the thermosyphon by virtue of its ability to transport heat against gravity by an evaporation-condensation cycle [2].

Thermosyphon heat pipes utilized in heat transfer related applications for many years. Heat pipes can operate over a wide range of temperature with a high heat removal capability. Thermosyphon heat pipes have being found to be useful in a number of technologies such as electronic cooling, spacecraft thermal control, transportation systems, automotive industry, permafrost stabilization, bio related applications, solar system and manufacturing. Heat pipe constitute an efficient, compact tool to dissipate substantial amount of heat [2].

Thermosyphon is a property of physics and refers to a method of passive heat exchange based on natural convection which circulates a substance (liquid, or gas such as air) without the necessity of a mechanical pump. Thermosyphon is used for circulation of liquids and volatile gases in heating and cooling applications, such as heat pumps, water heaters, boilers, furnaces and solar chimney. This circulation can either be open-loop, as when the substance in a holding tank is passed in one direction via a heated transfer tube mounted at the bottom of the tank to a distribution point and it can be a vertical closed-loop circuit with return to the original container. Its purpose is to simplify the transfer of liquid or gas while avoiding the cost and complexity of a conventional pump [3].The thermosyphon is similar in some respects to the heat pipe. The thermosyphon is shown in Fig. 2. A small quantity of water is placed in a tube from which the air is then evacuated and the tube sealed. The lower end of the tube is heated causing the liquid to vaporise and the vapour to move to the cold end of the tube where it is condensed. The condensate is returned to the hot end by gravity. Since the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from end to end. Thus, the structure will also have a high effective thermal conductance. The thermosyphon has been used for many years and various working fluids have been employed [2].

The basic heat pipe differs from the thermosyphon in that a wick, constructed for example from a few layers of fine gauze, is fixed to the inside surface and capillary forces return the condensate to the evaporator. In the heat pipe the evaporator position is not restricted and it may be used in any orientation. If, of course, the heat pipe evaporator happens to be in the lowest position, gravitational forces will assist the capillary forces.The term 'heat pipe' is also used to describe high thermal conductance devices in which the condensate return is achieved by other means, for example centripetal force, osmosis or electro hydrodynamics.

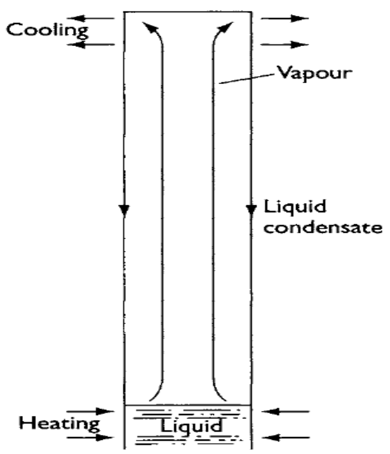

Fig. 2Thermosyphon [2]

Thermosyphon are enclosed, wickless passive two phase heat transfer devices. They make use of the highly efficient heat transport process of evaporation and condensation to maximize the thermal conductance between a heat source and a heat sink. They are often referred to as thermal superconductors because they can transfer large amounts of heat over relatively large distances with small temperature differences between the heat source and heat sink. The amount of heat that can be transported by these devices is normally several orders of magnitude greater than pure conduction through a solid metal. They are proven to be very effective, low cost and reliable heat transfer devices for applications in many thermal management and heat recovery systems. They are used in many applications including but not limited to passive ground/road anti-freezing, baking ovens, heat exchangers in waste heat recovery applications, water heaters and solar energy systems and are showing some promise in high-performance electronics thermal management for situations which are orientation specific [3].

II. CHARACTERISTIC OF THERMOSYPHON AND WORKING FLUID

As an effective heat conductor, thermosyphon can be used in situations when a heat source and a heat sink need to be placed apart, to aid heat conduction of a solid, or to aid heat spreading of a plane. However, not every thermosyphon heat pipe is suitable for all applications. For that reason and to develop an experimental model the following need to be considered while designing heat pipes.

A. Heat transfer limitations of the thermosyphon

There are various parameters that put limitations and constraints on the steady and transient operations of thermosyphon. In other words, the rate of heat transport though a thermosyphon is subjected to a number of operating limits. The physical phenomena for each limitation are briefly presented below.

Sonic limit

The rate at which vapours travels from evaporator to condenser known as sonic limit. The evaporator and condenser sections of a thermosyphon represent a vapour flow channel with mass addition and extraction due to the evaporation and condensation, respectively. The vapour velocity increases along the evaporator and reaches a maximum at the end of the evaporator section. The limitation of such a flow system is similar to that of a converging-diverging nozzle with a constant mass flow rate, where the evaporator exit corresponds to the throat of the nozzle. Therefore, one expects that the vapour velocity at that point cannot exceed the local speed of sound. This choked flow condition is called the sonic limitation. The sonic limit usually occurs either during heat pipe start up or during steady state operation when the heat transfer coefficient at the condenser is high. The sonic limit is usually associated with liquid-metal heat pipes due to high vapour velocities and low densities. When the sonic limit is exceeded, it does not represent a serious failure. The sonic limitation corresponds to a given evaporator end cap temperature. Increasing the evaporator end cap temperature will increase this limit to a new higher sonic limit. The rate of heat transfer will not increase by decreasing the condenser temperature under the choked condition. Therefore, when the sonic limit is reached, further increases in the heat transfer rate can be realized only when the evaporator temperature increases. Operation of heat pipes with a heat rate close to or at the sonic limit results in a significant axial temperature drop along the heat pipe [4].

Boiling limit

The rate at which the working fluid vaporizes from the added heat. If the radial heat flux in the evaporator section becomes too high, the liquid in the evaporator section boils and the wall temperature becomes excessively high. The vapour bubbles that form near the pipe wall prevent the liquid from wetting the pipe wall, which causes hot spots, resulting in the rapid increase in evaporator wall temperature, which is defined as the boiling limit. However, under a low or moderate radial heat flux, low intensity stable boiling is possible without causing dry out. It should be noted that the boiling limitation is a radial heat flux limitation as compared to an axial heat flux limitation for the other heat pipe limits. However, since they are related though the evaporator surface area, the maximum radial heat flux limitation also specifies the maximum axial heat transport. The boiling limit is often associated with heat pipes of non-metallic working fluids. For liquid-metal heat pipes, the boiling limit is rarely seen [4].

Entrainment limit

This limit occurs due to the friction between working fluid and vapour which travel in opposite directions. A shear force exists at the liquid-vapour interface since the vapour and liquid move in opposite directions. At high relative velocities, droplets of liquid entrained into the vapour flowing toward the condenser section. If the entrainment becomes too great, the evaporator will dry out. The heat transfer rate at which this occurs is called the entrainment limit. Entrainment can be detected by the sounds made by droplets striking the condenser end of the heat pipe. The entrainment limit is often associated with low or moderate temperature heat pipes with small diameters, or high temperature heat pipes when the heat input at the evaporator is high [4].

Vapour pressure limit

At low operating temperatures, viscous forces may be dominant for the vapour moving flow down the heat pipe. For a long liquid-metal heat pipe, the vapour pressure at the condenser end may reduce to zero. The heat transport of the heat pipe may be limited under this condition. The vapour pressure limit (viscous limit) is encountered when a heat pipe operates at temperatures below its normal operating range, such as during start up from the frozen state. In this case, the vapour pressure is very small, with the condenser end cap pressure nearly zero [4].

Flooding limit

The flooding limit is the most common concern for long thermosyphon with large liquid fill ratios, large axial heat fluxes, and small radial heat fluxes. This limit occurs due to the instability of the liquid film generated by a high value of interfacial shear, which is a result of the large vapour velocities induced by high axial heat fluxes. The vapour shear hold-up prevents the condensate from returning to the evaporator and leads to a flooding condition in the condenser section. This causes a partial dry out of the evaporator, which results in wall temperature excursions or in limiting the operation of the system [5].

B. Working fluid

Binary mixture

From the literature review, it is found that various researches has been done on various working fluid solutions like water, distilled water, butanol, ethanol, etc. [4, 17 and 20], refrigerant like R-12, R-22, R-134a, FC-72, FC-77, FC-84, etc. [6, 9, 16 and 20] and nanoparticles such as Al_2O_3, Ag_2O_3 and Fe_2O_3, etc. In many investigation of thermosyphon it is seen that water as a working fluid has a better performance than other solutions. But because of its high boiling point it cannot be used for cold temperature regions. By using other solutions as a working fluid does not get better thermal performance than water. So it is need of time to use binary mixture of various solutions to get better thermodynamic property for using working fluid in thermosyphon heat pipe.

Ethanol-Methanol mixture

As far as selection of working fluid for thermosyphon is concerned, first go through various thermodynamic properties of ethanol and methanol.

Table 1.Properties of ethanol and methanol [6]

Property	Methanol (CH_3OH)	Ethanol (C_2H_5OH)
Molecular Weight	32	46
Boiling point (^oC)	65	78
Melting point (^oC)	-98	-144
Useful temperature range (^oC)	10 to 130	0 to 130
Thermal Conductivity at 300K (W/m-K)	0.202	0.171
Latent heat of vaporization (kJ/kg)	1100	846

In this experiment we used ethanol and methanol ratio 60:40 (by volume) because at this ratio these two solutions are completely soluble with each other.

Table 2. Properties of ethanol-methanol mixture

Property	ethanol-methanol mixture
Boiling point (^{o}C)	72.8
Melting point (^{o}C)	-125.6
Useful temperature range (^{o}C)	0 to 100
Thermal conductivity at 300 K (W/m-K)	0.1834
Latent heat of vaporization (kJ/kg)	947.6

These thermodynamic properties are useful for the thermosyphon as a working fluid in 0 ^{o}C to 100 ^{o}C temperature applications. Hence ethanol-methanol mixture was selected for the experimental assessment of the thermosyphon as a working fluid.

Thermosyphon reliability

Thermosyphon have no moving parts. However, care must be given when designing and manufacturing the thermosyphon heat pipe. Two manufacturing factors can reduce the reliability of the thermosyphon: the seal of the pipe and the cleanness of pipe internal chamber. Any leakage in the thermosyphon pipe will eventually fail the pipe. If the internal chamber is not thoroughly clean, when the thermosyphon subjected to heat, the residual may generate non-condensable gas and degrade the pipe performance. Improper bending and flattening of the pipe may also cause the leakage on the pipe seal. There are some external factors that may also shorten the life of a thermosyphon such as shock, vibration, force impact, thermal shock and corrosive environment.

III. EXPERIMENTATION

A. Factors for experimental analysis

Filling ratio

It is one of the important parameter. Filling ratio considered for this experimentation 10% to 70%.Filling ratio has two opposite effects on the rate of evaporation. First, at higher fill ratio it is possible to have more heat transfer from the evaporator wall to the working fluid, as more evaporator's wall surface is in contact with the working fluid. This can increase the evaporation rate and consequent thermosyphon performance. From experimentation it is proved that 10% to 60% filling ratio, increases thermosyphon performance.

However higher height of working fluid has a negative effect of large bubbles or film formation in the lower parts of the evaporator. This has direct effect on heat transfer rate to the evaporator and can decrease the thermosyphon performance. From experimentation, onwards 70% filling ratio decreases thermal performance of thermosyphon.

Inclination angle

It is also important factor which affect thermal performance of thermosyphon to great extent. The lower end of the thermosyphon tube was heated causing the liquid to vaporise and the vapour to move to the cold end of the tube where it is condensed. The condensate is returned to the hot end by gravity. This is why thermosyphon is kept vertical i.e, 90^{o} with horizontal. Experimentation also includes study at various inclination angles to evaluate thermal performance. At various inclination angles and at various heat loads thermal performance is varying [1, 3, 11, 16]. So after experimentation we got best configuration factor of inclination angle and heat load which is responsible for higher thermal performance.

Heat Load

Heat load is given to the evaporator section of the thermosyphon. After applying heat, working fluid get vaporize in the evaporator. But heat load is dependent on working fluid. It defines boiling limit of the working fluid. If the boiling point of the working fluid is higher near about 100 ^{o}C, then heat load can be applied from 100 ^{o}C to the point where maximum fluid will evaporate [1 and 16]. In this experimental model, we have used binary mixture of ethanol-methanol as a working fluid. Thermodynamic properties of ethanol and methanol are shown in Table 2. Ethanol and methanol has lower boiling points than water and under vacuum mixture gain low boiling point. So for experimentation we have selected heat load range of 25 W to 200 W.

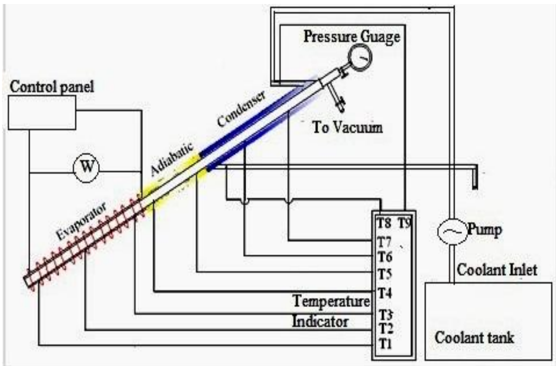

Fig. 3 Schematic diagram of thermosyphon experimental setup

Above figure shows schematic view of thermosyphon experimental setup showing all the components necessary for the setup.

Table 3 Experimental setup description

Component	Specification
Working fluid	Ethanol-Methanol mixture
Tube material	Copper
Internal diameter (mm)	24
External diameter (mm)	26
Total length (mm)	1000
Evaporator length (mm)	300
Condenser length (mm)	450
Adiabatic length (mm)	250
Aspect ratio (L/D ratio of evaporator section)	11.53

B. Experimentation Parameters.

Experimentation was carried on the thermosyphon heat pipe. Working fluid is important parameter in the experimentation. Ethanol-Methanol binary mixture was used as a working fluid. Other parameters and its description as follows.

Table 4 Experimentation parameters

Parameter	Description
Filling ratio	10%, 20%, 30%, 40%, 50%, 60% and 70%
Inclination angle with horizontal axis	90^o(Vertical), 80^o, 70^o, $60^o$and 50^o
Heat load (W)	25, 50, 75 100, 125, 150, 175 and 200
Coolant flow rate (Kg/hr)	3.6
Aspect ratio	11.53

Fig. 4 Thermosyphon experimental setup

The performance of the thermosyphon was evaluated by knowing factors affecting the thermal performance of the thermosyphon. For that purpose calculate heat input, heat output and heat transfer efficiency at all filling ratio, inclination angle and heat load. Then ΔTvs heat load graphs were drawn. Graphs were analysed and discussed and find out best possible factors affecting thermal performance of thermosyphon heat pipe.

IV. RESULTS AND DISCUSSION

A. Effect of filling ratio

This is one of the effective parameter from which one can better understand thermal performance of thermosyphon. Filling ratio was varied in the range of 10%, 20%, 30%, 40%, 50%, 60% and 70%. Thermosyphon heat transfer performance increases from 20% filling ratio to 60% filling ratio. However its performance deceases from 70% filling ratio.

This is because in the bottom section of the evaporator, the generated thick layers of vapour are stuck to the wall. Because of a low thermal conductivity of vapour, these thick vapour layers can cause a significant thermal resistance and consequently decrease the overall heat transfer. However, in upper region of evaporator the vapour layers become smaller. In addition, close to the evaporator liquid surface the bubbles moves toward the middle regions of the liquid pool for escaping from liquid surface. Fig. 5.20 to Fig 5.26 shows graphs of ΔT vs heat load at each filling ratio and at all inclination angle.

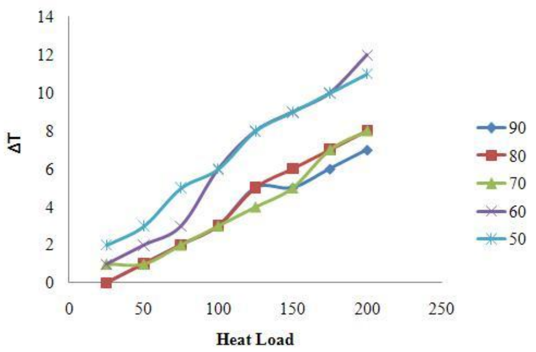

Fig. 5ΔT vs Heat load at 10% filling ratio and at all inclination angles

At 60^o inclination angle shows maximum ΔT which is 12^oC. This shows that for 10% filling ratio, 60^o inclination shows maximum thermal performance. This graphs shows linear curves of ΔT due to large axial heat fluxes.

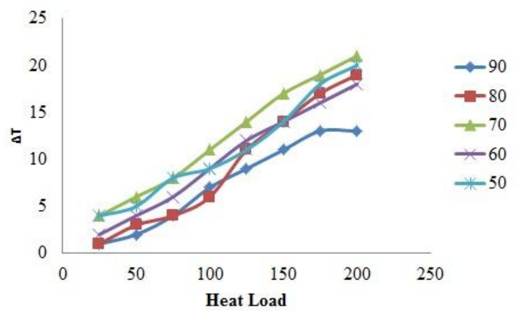

Fig. 6ΔT vsHeat load at 20% filling ratio and at all inclination angles

Above fig shows that at 70^o inclination gets maximum ΔT which is 21^oC. Now evaporator wall surface contact with working fluid is increasing which increases evaporation rate. Due to this reason ΔT gets increases. This shows that for 20% filling ratio maximum thermal performance gets at 70^o inclination angle.

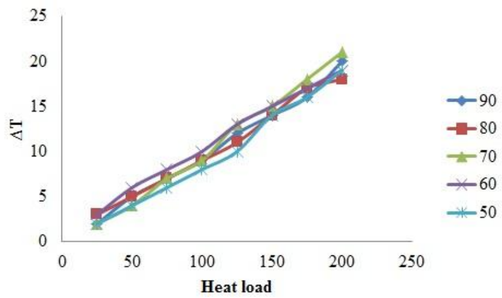

Fig. 7ΔT vsHeat load at 30% filling ratio and at all inclination angles

In this graph maximum ΔT gets at 70^o inclination which is 21^{o}C. . It is concluded that for 30% filling ratio, 70^o inclination angle shows maximum thermal performance.

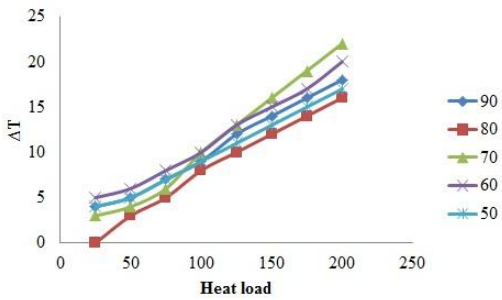

Fig. 8ΔT vsHeat load at 40% filling ratio and at all inclination angles

Maximum ΔT is 22^{o}C gets at 70^o inclination angle. Again evaporator wall surface contactness with working fluid is increasing which leads to higher evaporation rate as compared to below 30% filling ratio.

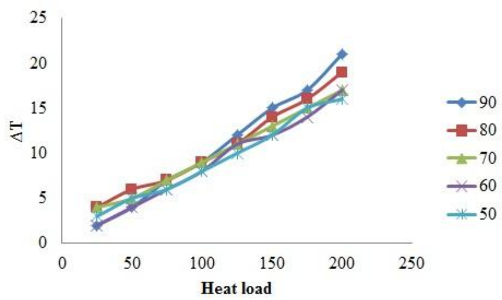

Fig. 9ΔT vsHeat load at 50% filling ratio and at all inclination angles

At 90^o inclination angle, maximum ΔT shows 21^{o}C. As filling ratio increases, evaporation rate also increases which shows thermal performance is also increasing.

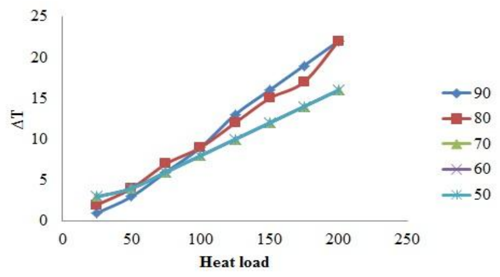

Fig. 10ΔT vsHeat load at 60% filling ratio and at all inclination angles

From fig it is seen that at 90^o and 80^o inclination angle gets maximum ΔT which is 22^{o}C. Because of maximum surface contactness with working fluid, evaporation rate is higher as compared to other filling ratios.

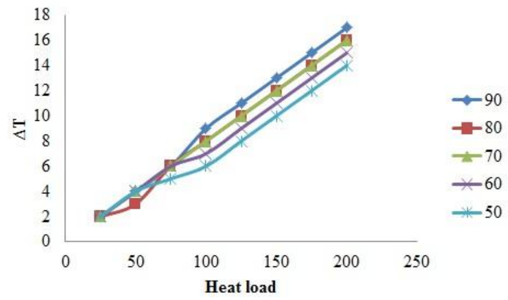

Fig. 11ΔT vsHeat load at 70% filling ratio and at all inclination angles

In this fig, maximum ΔT is 17^{o}C gets at 90^o inclination angle which shows that evaporation rate is decreasing. This shows formation of large bubbles or liquid film in the evaporator region causing less heat transfer. From this filling ratio flooding limit and entrainment limit starts to appear due to this reason thermal performance gets decreases.

From above discussion it is cleared that, from 10% to 60% filling ratio, heat transfer rate gets increases and from 70% filling ratio heat transfer start to decreases.

B. Inclination angle

At each inclination angle, thermosyphon shows various performances. Inclination angle was varied in the range of 90^o, 80^o, 70^o , 60^o and 50^o . From the experimentation we got best inclination angle at 90^{o}with 60% filling ratio, at 80^{o}inclination angle with 60% filling ratio and at 70^{o}inclination angle with 40% filling ratio.

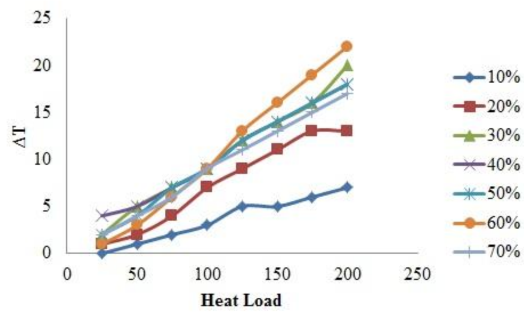

Fig. 12 ΔT vs heat load at 90^o inclination angle and at all filling ratios

Above fig shows maximum ΔT as 22^{o}C at 60% filling ratio. Because of maximum surface contactness with working fluid, evaporation rate is higher which shows maximum thermal performance as compared to other.

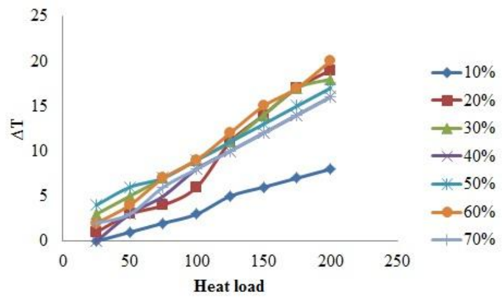

Fig. 13 ΔT vs heat load at 80^o inclination angle and at all filling ratios

Above fig shows maximum ΔT as 20^{o}C at 60% filling ratio. This shows that 60% filling ratio is better according to thermal performance point of view.

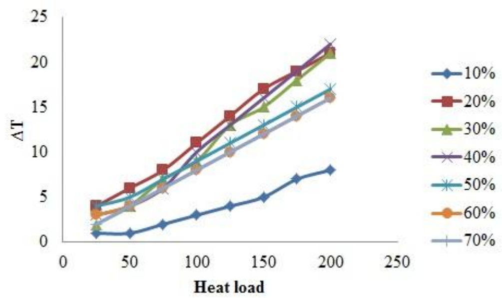

Fig. 14 ΔT vs heat load at 70^o inclination angle and at all filling ratios

At 40% filling ratio maximum ΔT gets 22^{o}C. This linear curves show axial temperature drop along the length of the heat pipe.

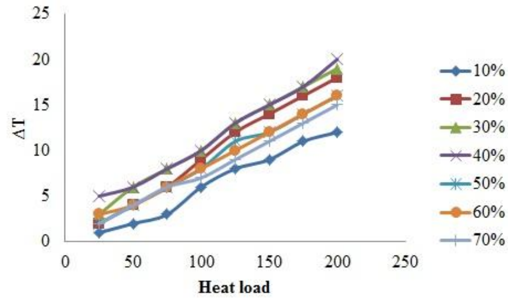

Fig. 15 ΔT vs heat load at 60^o inclination angle and at all filling ratios

Above fig shows maximum ΔT as 20^{o}C at 40% filling ratio which shows maximum thermal performance.

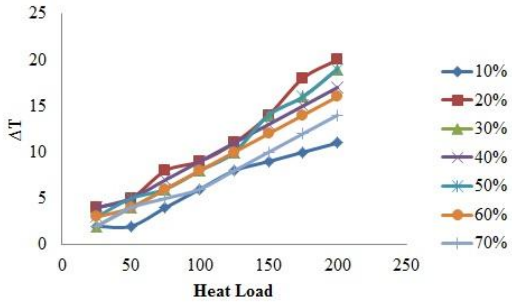

Fig. 16 ΔT vs heat load at 50^o inclination angle and at all filling ratios

Above fig shows maximum ΔT as 20^{o}C at 40% filling ratio which shows maximum thermal performance. This irregular linear curves show that fluctuations in axial heat flux.

From above discussion it can be concluded that increasing the filling ratio has two opposite effects on the rate of evaporation. First, at higher filling ratio it is possible to have more heat transfer from the evaporator wall to the working fluid, as more evaporator's wall surface is in contact with the working fluid. This can increase the evaporation rate and consequent thermosyphon performance. However higher height of working fluid has a negative effect of large bubbles or film formation in the lower parts of the evaporator. This has direct effect on heat transfer rate to the evaporator and can decrease the thermosyphon performance.

CONCLUSION

The experimental investigation was carried out on thermosyphon heat pipe charged with ethanol-methanol mixture. The combine effect of filling ratio and inclination angle on the performance of thermosyphon was experimentally investigated.. Filling ratio was varied from 10% to 70% along with inclination angle 90^{o}to 50^o.

Maximum value of ΔT found at 22^{o}C which is higher at 40% filling ratio with 70^o inclination angle and 60% filling ratio with 80^{o}and 90^o inclination angle. Thermal performance increases from 10% to 60% filling ratio and decreases onwards 70% filling ratio. This is so because as more surface of evaporator gets in contact with working fluid which increases heat transfer and consequently increases thermal performance. Flooding and entrainment limit responsible for reduction in heat transfer from 70% filling ratio.

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