EXPERIMENTAL ANALYSIS OFMULTI TURN CLOSED LOOP PULSATING HEAT PIPE–IMPACTOFFILL RATIO

N. Santhi Sree[1*], N. V. V. S.Sudheer[2], P. Bhramara[3]

[1]Research Scholar, Acharya Nagarjuna University, Guntur, Andhra Pradesh-10

[2]Professor, Department of Mechanical Engineering, RVRJC College of Engineering, Andhra Pradesh, India

[3]Professor, Department of Mechanical Engineering, JNTUH Hyderabad, India-500085

Abstract

The heat transfer devices involving phenomena of two phase heat transfer are proven to be the best solution for handling moderate to high heat fluxes in different applications. In this regard, an emerging and new technique is "Pulsating heat pipe cooling", when it comes to the field of electronics thermal management. CLPHP development meets the current requirements for elimination of moving parts in a cooling system. As the demand for effective and small heat transfer devices is increasing, the present paper describes an experimental analysis of a closed loop pulsating heat pipe. Vertical bottom heat mode is considered as the position of CLPHP for the experimental work. PHP consists of a copper tube of length 262 mm, with capillary dimensions of 2 mm and 3.1 mm having internal and external diameter respectively. The tube is bent in a serpentine manner with 8 number of turns and is connected end to end. Before filling the working fluid in the tube, it is first evacuated partially. Based on the total volume, 50%, 60%, and 75 % filling ratios are considered for analysis. Different pure working fluids, viz., Ethanol, Methanol, Acetone and their mixtures, viz., Ethanol-Methanol, Ethanol-Acetone, and Methanol-Acetone are considered for experimentation. The experiments are conducted for different heat inputs varying from 20 to 100 W. The maximum heat input is dependent on the boiling point of the particular fluid. CLPHP is affected by various parameters like heat input, filling ratio, working fluid etc. Acetone shows least thermal resistance value among pure fluids whereas Ethanol-Acetone shows least thermal resistance and better heat transfer performance among mixtures. For low heat input conditions ethanol shows better performance.

Keywords: Binary mixtures, closed loop pulsating heat pipe, fill ratio, heat input, thermal resistance, working fluids

NOMENCLATURE

PHP   Pulsating Heat pipe

CLPHP Closed loop Pulsating Heat pipe

Rth   Thermal resistance

FR   Fill ratio

Te   Average Evaporator temperature

Tc   Average Condenser temperature

Q   Heat input in Watt

I. Introduction

In electronic product development, thermal management is a major challenge in the present scenario. Two phase heat transfer devices are the best solution for this. Several methods are adopted to control the electronic devices. Pulsating heat pipes are one among them due to their simple design and low cost, high thermal performance, and heat load rapid response with agreeable results. Akachi proposed and patented PHP [I]. PHP's are mostly used in the fields of electronic components heat transfer, heat exchangers, aerospace control systems, laptop computers, servers etc. [XII]. A PHP is a simple structure with capillary tubes in a planar orientation. PHP is a passive heat transfer device involving boiling and condensation, making it a two phase heat transfer phenomena. Working fluid is filled in the tubes after the evacuation process is completed.
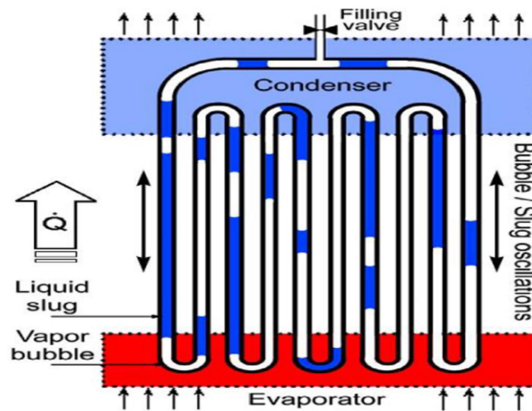
Fig. 1: Schematic representation of PHP [3]

No external force is required for fluid distribution in the tube. Due to the capillary dimensions, fluid distributes itself in the tube with the help of its surface tension. This causes liquid slugs and vapor bubbles in the tube [VI]. PHP can basically be divided into three major parts namely evaporator, adiabatic and condenser sections. In the

evaporator, working fluid gets heated up through the absorption of heat, resulting in the formation of vapor bubbles. A sudden pressure change occurs and this pressure pushes the fluid into the condenser section through the adiabatic section. Water will be circulated from inlet and outlet of condenser jacket continuously which helps condenser to stay cool. The vapor bubbles that are formed get condensed in the condenser and the pressure reduces. The pressure difference acts as the driving force for working fluid's pulsating movement [III]. Temperature also changes from the evaporator section to the condenser section. These temperature and pressure imbalance conditions causes PHP's pulsating movements and helps maintain a self-sustained movement [IV].CLPHP's may be of different types like closed loop and open loop. Due to high thermal performance closed loop is themost effectively used device [XIII]. The operation of PHP is different from any ordinary heat pipe operation due its wickless structure. Due to phase change, PHP transfers sensible heat via vapour-liquid pulsating along with latent heat transfer. The performance of PHP mainly depends upon various factors – diameter of pipe, shape of cross section, filling ratio, orientation, number of turns, and the physical and thermal properties of working fluids. Properties like surface tension, viscosity, density, latent heat influence more effectively in the selection of working fluid. Several experimental studies have been carried out to understand the behavior of PHP.

II. Literature Review

Among all factors, selection of the working fluid is a challenging one as many fluids fall under the operating range. Barua et al. [II] conducted experiments with water and ethanol as working fluids in a CLPHP with a 2.2 mm inner diameter tube, bent into a U shape with 3 turns, at five different filling ratios and concluded that between 0 and 25 W, heating power of ethanol at 80% fill ratio and water at 70% fill ratio represented better performance of heat transfer. Yang, Khandhekhar et al. [XI] concluded that the PHP of diameter 2 mm was found to be better than 1 mm diameter PHP when operating with R123 as working fluid with 30%, 50% and 70% fill ratios. This isbecause 1 mm inner diameter PHP is having higher values of thermal resistance compared to 2 mm diameter tubes. Zhang [X] conducted experiments with FC-72, water and ethanol and indicated that working fluid mainly affects the required minimum amount of heat input for initiation of oscillatory motion in PHP. Rama Narasimha et al. [VIII] conducted experiments on single loop PHP with acetone, methanol, propane and ethanol as working fluids. And found that acetone shows better performance among all the fluids. Pramod R. Pachghare et.al [VII] conducted experiments on PHP for refrigeration system and suggested that pulsating heat pipe can also be used in refrigerators. High power consuming compressor can be replaced by cooling coil PHP. This reduces consumption of power and distribution of flow will be uniform. Vipul M. Patel et al. [IX] conducted a review on Dry-out mechanism of Pulsating Heat Pipe. According to this, to observe Dry out phenomena mechanism, factors like inner diameter, filling ratio, working fluid and number of turns are to be considered in the performance evaluation of CLPHP.

Different experiments have been carried out to understand the effect of working fluids and its mixtures on PHP. Most of the results are limited to single fill ratio. In the present work, characteristics of thermal resistance by varying heat inputs for different working fluids and binary mixtures of fluids and also at different fill ratios have been determined. The fluids Ethanol, Methanol, Acetone and its binary mixtures are considered as working fluids. The thermo physical properties of working fluids have been listed in table 1. Because of its low boiling point, latent heat of vaporization and specific heat, Acetone is most widely used for the starting-up of CLPHP. Under gravitational force ethanol has been considered as one of the preferred fluids. Due to its high purity, methanol is considered. By considering all of the above, these fluids are selected as working fluids. The CLPHP used has 8 turns with capillary dimensions of 2 mm and 3.1 mm inner and outer diameters respectively. Position of CLPHP is bottom heated mode i.e. vertical position is considered for this study.

Table 1: Thermo physical Properties of Working Fluids

Working fluids	boiling point($\mathfrak{e}$)	C_p KJ/kg C at 20°C	h_{fg}(KJ/kg)	$v X10^{-6}$ (Pa-s)	$\sigma X10^3$
Methanol	64.7	2.84	1101	.60	22.6
Ethanol	78.3	2.39	846	1.15	22.8
Acetone	56.2	2.35	523	.32	23.7

III.   Description of Experimental Setup

The setup used for experimentation is shown in a schematic form.CLPHP is made up of a copper tube bent into 8 U-turns in the evaporator and condenser sections. For visualization of pulsating motion in the tube the Adiabatic section is made up of borosilicate glass .To set the dominance of surface tension force over gravitational force the inner diameter of copper tube was selected less than critical diameter of CLPHP. CLPHP consists of three sections namely evaporator, adiabatic and condenser sections with 42mm, 170 mm, and 52 mm lengths respectively.Evaporator section was constructed by using (length of 330mm, breadth 55 mm and height 90mm) material of size 330*55*90 mm. Condenser section was constructed by 320*55*95 mm. A thick layer of insulating material was wrapped around the evaporator block from all sides to avoid heat loss to the atmosphere.
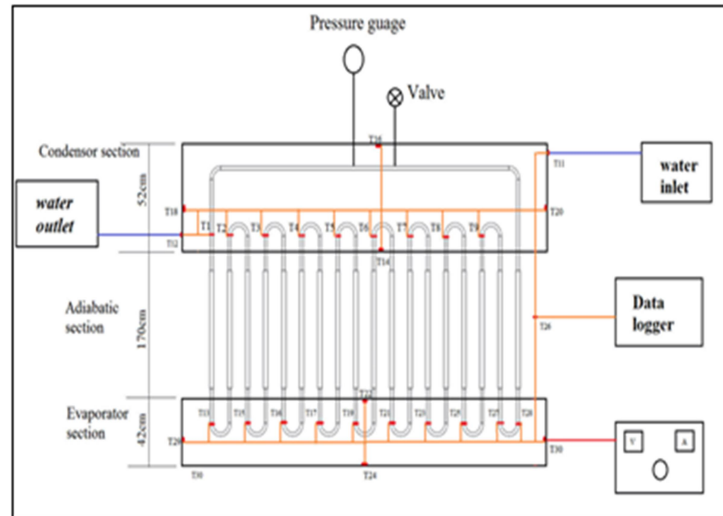
Fig. 2: Schematic diagram of 8 turn CLPHP[13]

The tube was folded in such a way as to obtain 16 parallel channels and 8 U tube bends in the evaporator zone and then closed end to end to make a closed circuit by means of T-joints. A pressure transducer is provided at the condenser section for pressure readings. Two non-return valves were provided to the outer copper tube. One valve was connected to the vacuum pump while the other valve was used for filling and removal of working fluid. To create vacuum inside PHP, reciprocating vacuum pump was connected to the Filling valve. The CLPHP was equipped with 30 thermocouples. Among them, 9 thermocouples were placed on the condenser tubes. 10 thermocouples were placed on the evaporator tubes. 4 thermocouples were placed on the 4 sides of the condenser and evaporator boxes respectively in order to maximize the thermal contact. One thermocouple was placed in such a way as to measure the environment/ambient temperature. Heat input to the evaporator was controlled through control panel. It consists of a digital voltmeter and an ammeter. To record temperature data for every 5 seconds, the temperature scanner with data acquisition system was used for all thermocouples. Condenser was cooled by water jacket from a cold bath. A tiltable frame arrangement was made in cooled order to mount the CLPHP.

IV.   Results and Discussions

For all working fluids, the tubes were filled with 50 %, 60% and 75% fill ratio. Generally, By using variacheat input was varied from 20 to 100 watts .Depending upon the operating temperature limits, heat input variation differs from working fluid to fluid. The heat input was increased stepwise from lower number to a higher number throughout the experimentation. The temperature readings were recorded at evaporator and condenser sections for every 5 sec. The difference in

evaporator and condenser average temperatures was obtained. The thermal resistance was calculated for all the fluids and mixtures by using the following formula

$$Rth = (Te - Tc)/Q \qquad (1)$$

Where, Q = heat input in Watts,

$(Te - Tc)$= Average difference in temperature between evaporator and condenser in ℃

Rth =Thermal resistance ℃/W

IV.i. Ethanol, Methanol, Acetone as Working Fluids

Thermal resistance is defined as the ratio of average evaporator and condenser temperature difference to heat input. With the increase of heat input, decrease in thermal resistance is observed for all the working fluids. As there is no fluid inside the tube for 0% fill ratio, only pure conduction mode of heat transfer takes place. When the filling ratio is 100% i.e. the working fluid is fully filled in the tube, transfer of heat is only due to buoyancy induced liquid circulation in CLPHP. At initial states, for lower power input values there is no considerable pulsation is observed. They are not capable of generating enough liquid slugs and vapor bubbles for heat transfer. This results in a poor performance of the CLPHP. As the heat input is increased stepwise upto a certain value, the flow takes place in a fixed direction. At this point there is no reversal of flow with respect to time. Due to circulation of fluid, the tubes alternately become hot and cold. This happens as there is a change in the evaporator and the condenser temperature difference in the tube. The following curve shows at 50 % fill ratio thermal resistance variation with given heat input for all the working fluids considered.
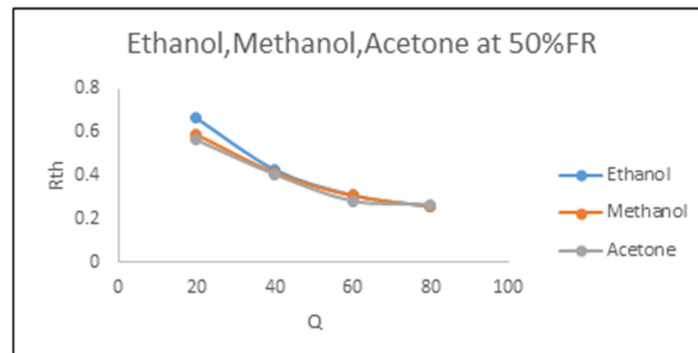
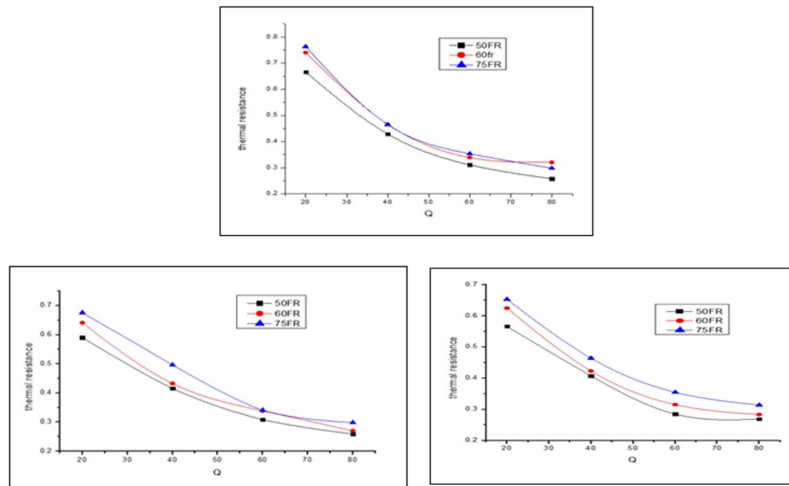**Fig. 3:**Variation of thermal resistance in CLPHP with pure fluids (Ethanol, Methanol, and Acetone)

Acetone shows least thermal resistance and better performance among all pure fluids. With acetone as a working fluid, PHP pulsation starts more easily because of its lesser values of latent heat of vaporization, specific heat and boiling point.

IV.i.1. Effect of Filling Ratio on Pure Working Fluids

As there is not enough working fluid in case of filling ratio less than 10 percent, no considerable amount of heat transfer is observed. Whenever the system attains maximum heat transfer then only optimum filling ratio can be determined. At low heat transfer limit, higher thermal resistance is observed and performance of CLPHP is very poor. For above 80 % filling ratios, sufficient bubbles arenot developed to provide pumping action in the fluid. So at this FR drastic deterioration of performance occurs. Keeping in mind all the data, in the present study experiments are conducted for 50%, 60 % and 75% FR. At these fill ratios CLPHP is in a true pulsating mode. At 75% filling, it gives higher thermal resistance values compared to 50% and 60 % fill ratios. Experiments are conducted for ethanol, methanol and acetone and binary mixtures working fluids. The following cures shows effect of all fill ratios for all working pure fluids.

0-degree

45-degree   90-degree

Fig.4.1: Variation of thermal resistance for Ethanol, Methanol and Acetone CLPHP at different fill ratios

IV.ii. Methanol-Acetone Mixture as Working Fluid

Acetone and Methanol are very close to each other's thermo physical properties. Properties like latent heat of vaporization and specific heat are high for methanol compared to acetone. The gas-liquid coexisting regions are much smaller as

the boiling point between methanol and acetone is very close. Acetone is mixed with methanol to study the performance of PHP with both binary mixture and pure fluids - acetone and methanol**.**There is rapid increase in thermal resistance was observed for pure acetone and methanol fluids. At 50%FR, at high heat inputs, acetone -methanol mixtures show the same trends as that of pure working fluids. The following curves show variation of thermal resistance with heat input for acetone methanol and its binary mixture. The Acetone methanol curve lies between methanol and acetone. At 50% FR, 60W heat input, the thermal resistance of methanol is 0.30828°C/W, pure acetone is 0.284615°C/W and that of mixture 0.293422°C/W. This shows that mixture resistance lies in pure fluids. Due to the increasing quality of working fluids in the pipe, both pure fluids and mixtures maximum heating power also increases.
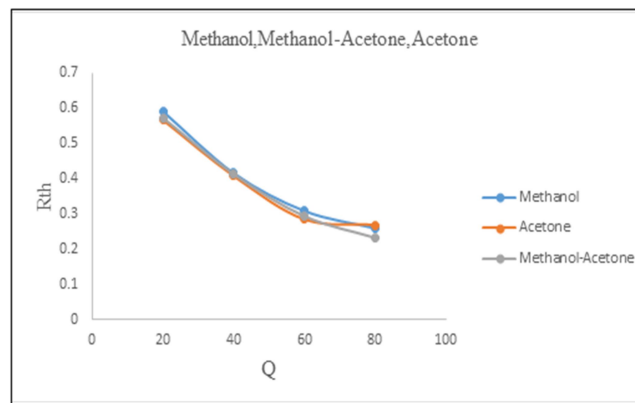
Fig.4.2: Variation of thermal resistance CLPHP for fluids Methanol, Methanol-Acetone, and Acetone

At high fill ratios**,** with increase in heating power Methanol-Acetone mixture resistance gradually approaches to pure fluids resistance values. At heat input in the range of 60-80 W, in all the curves same approach was observed. At 80W, 75% FR, thermal resistance of mixture is 0.263509C/W compared to 60% when the value is 0.259295° C/W. insideCLPHP, the flow rate of tubes and ability of energy carrying dominates the performance of CLPHP. As the values of latent heat of evaporation and specific heat properties are almost similar for both acetone and methanol, the ability of energy carrying is similar for acetone methanol mixture and of pure fluids. The following graph shows the effect of Methanol Acetone at different fill ratios. From the graph it is clear that at 75%FR the resistance is higher than at 60% compared to a 50% FR thermal resistance value.
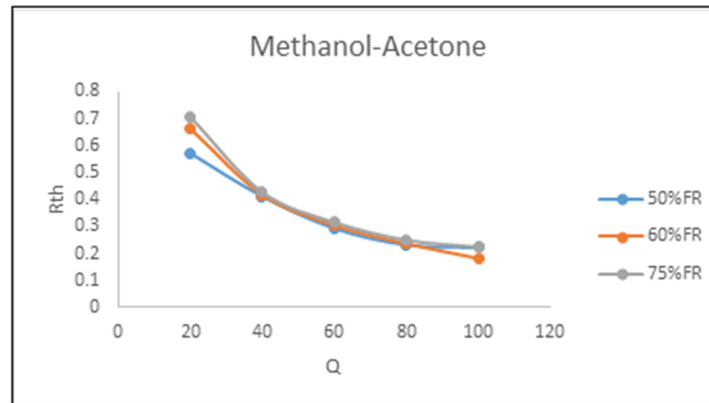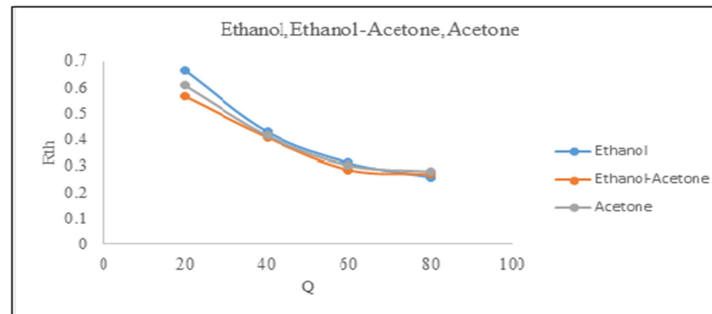
Fig.4.3: Variation of thermal resistance for CLPHP with Methanol-Acetone mixture at different fill ratios

IV.iii. Ethanol-Acetone as Mixture

In Ethanol–Acetone mixture, vapour phase boiling point is greater than the acetone liquid phase. The boiling point difference between ethanol and acetone is 22.1 Kelvin only. Between acetone and ethanol, phase transition slightly differs due to their properties. The bubble growth of acetone ethanol mixture is almost closer. In the present study, the experiments are conducted by mixing acetone with ethanol in equal proportions to investigate CLPHP heat transfer performance in case of acetone-ethanol mixtures and that of pure fluids.
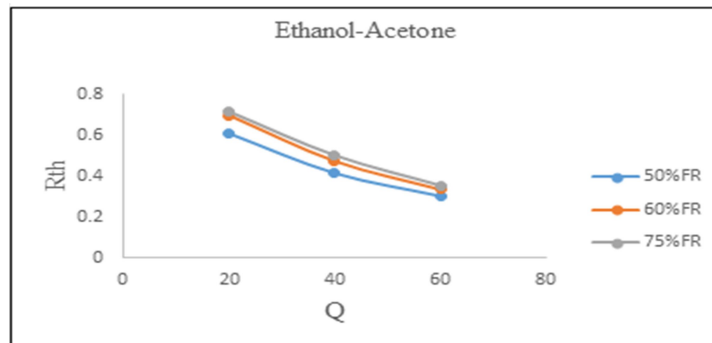
The following figure shows thermal resistance of Ethanol, Acetone and its mixture. For heating power less than 30 W, at lower fill ratios, thermal resistance of CLPHP with pure fluids and mixtures of acetone-ethanol increases as the heat input decreases. For higher heat input values thermal resistance of pure fluids increases more rapidly than mixture. The mixture thermal resistance curve exhibits similar trends as that of pure ethanol and acetone. A slatent heat of vaporization value of ethanol is more than that of acetone, the mixture's capability to carry energy is in between pure ethanol and acetone. Acetone and ethanol are having similar boiling points at lower fill ratios. It is difficult to resist dry out of tube when ethanol is added to acetone at lower fill ratios.

Fig.4.4: Variation of thermal resistance for CLPHP with fluids Ethanol, Ethanol-Acetone, and Acetone

The average evaporator and condenser temperature difference along with its respective heat input represents thermal resistance. These values of CLPHP with ethanol, acetone, and ethanol-acetone mixtures are measured and the curves are drawn. The variation of thermal resistance at 60% fill ratio follows the same trend as that of 50 %. For the increase of heat input from 30 to 50W, thermal resistance significantly drops. As fillratio is increases it can be observed that the anti-dry out condition is also increases for both pure fluids and mixtures. The vaporization of acetone component in the mixture reduces the vaporization of ethanol as ethanol boiling point is higher that of acetone. This causes the slight strength to anti-dry-out ability.

The following curve represents Ethanol-Acetonemixture variation at different fill ratios. At higher heat inputs, vapour plugs provide the necessary force for working fluid circulation in the mixture. The thermal resistance of CLPHP operating with pure ethanol, pure acetone and mixture of ethanol and acetone gradually converges and reaches same level beyond 60 W and almost approaches at 80W.

Fig.4.5: Variation of thermal resistance for CLPHP with Ethanol-Acetone mixture at different fill ratios
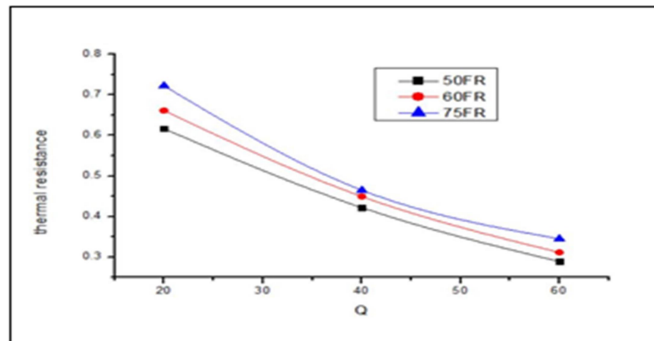
IV.iv.   Ethanol –Methanol as Mixture

The following graphs explain the operation of CLPHP operating with ethanol, methanol, and ethanol-methanol mixture. The heat input increase results in reducing thermal resistance value for all fluids. Due to higher latent heat values, ethanol-methanol mixture did not start up immediately at low heat values.
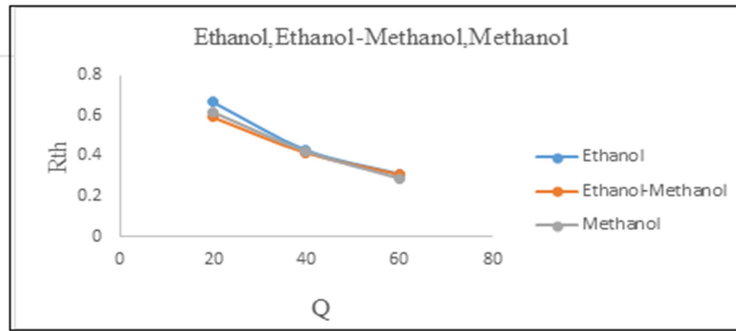
Fig.4.6: Variation of thermal resistance for CLPHP with fluids Ethanol, Ethanol-Methanol, and Methanol

Thermal resistance value is maximum for higher fill ratios and least for lower fill ratio. This is due to proper liquid slug and vapor plug distribution. The quick movement of working fluid is possible due to the disturbances in pressure difference obtained in evaporator and condenser sections. This pressure difference gives highest heat transfer rates. For high fill ratios thermal resistance increases due to the reduction in pulsating action of fluid. For the experimentation, the CLPHP is charged with ethanol-methanol mixture in equal proportions. The heat transfer performance variation with ethanol-methanol lies in between pure ethanol and methanol fluids.

Fig.4.7: Variation of thermal resistance for CLPHP with Ethanol-Methanol mixture at different fill ratios

Among all Ethanol based mixtures, Ethanol-Acetone shows least thermal resistance and better heat transfer performance. Methanol based mixtures and Methanol-Acetone shows better performance.

V.   Conclusions

The performance of PHP with pure fluids and mixtures is mainly dependent on its thermo physical properties, characteristics of phase change phenomena.

1. Among all the mixtures Ethanol-Acetone shows better performance. Its value at heat input of 80W and 50%FR is   0.274729°C/W. and acetone is the best among all pure working fluids considered for experimentation.

2. In all working fluids, acetone is having lower value of thermal resistance. Its value at 80W and 50% fill ratio is 0.218478°C/W.

3. Thermo physical properties play an important role for working fluids. The fluid having lower values of latent heat will give better performance=Among all fluids, acetone shows better performance.

4. Under stable operating conditions, higher heat performance of CLPHP can be obtained at lower filling ratio.

5. At filling ratio of 50% FR, acetone ethanol mixture will have better performance. Pure fluids exhibit better performance compared to mixtures at higher fill ratios. And 60 % is the optimum filling ratio among all conducted experiments.

6. When Ethanol is added to Acetone, a considerable improvement in heat transfer is obtained compared to Methanol added to Acetone. Therefore, Ethanol-Acetone is preferred compared to Ethanol-Methanol. In case of Ethanol- Methanol and Ethanol -Acetone Mixtures Ethanol-Acetone shows better performance.

7. Methanol-Acetone shows better performance in case of Methanol mixtures,

8. At very high fill ratios the CLPHP performance with mixtures is more inferior to that of pure fluids. This results in poor performance at higher fill ratios.

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