EXPERIMENTAL INVESTIGATION OF HIGHER CARBON ALCOHOLS WITH LOW LATENT HEAT OF VAPORIZATION AS SELF REWETTING FLUIDS IN CLOSED LOOP PULSATING HEAT PIPES

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Abstract: Heat recovery plays an important role in all energy systems. The dissipation of heat is drastically increasing due to the advancement of electronic components. To cool the electronic components many heat recovery devices are introduced and out of which heat pipes play an important role. Pulsating Heat Pipe (PHP) is a new type of heat transfer device which was introduced by Akachi in mid-1990. It is used mainly in the cooling of electronic components because of its potential for removing high heat flux. An experimental study was made to investigate the heat transfer performance of PHP using self-rewetting fluids of high carbon alcohols. The latent heat of vaporization plays an important role in the heat transfer performance of PHP. It was observed that the high carbon alcohols showed a decrease in the latent heat of vaporization. The high carbon alcohols such as 1-Butanol, 1-Pentanol, 1-Hexanol, 1-Heptanol, and 1-Octanol were mixed with the deionized water to form a self-rewetting fluid. These self-rewetting fluids showed a unique behavior due to the inverse Marangoni effect. It was observed that the lower thermal resistance and higher heat transfer coefficient was obtained, especially in the dilute aqueous solution of 1-Octanol.

Keywords: PHP; CLPHP; Self rewetting fluids; higher carbon alcohols; thermal performance.

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1. Introduction

Heat pipes are a passive heat transfer device that is used to transport heat from the hotter section to the colder section without any moving parts. PHP is introduced first by Akachi [1]. Further, Akachi [2] proposed the Closed-Loop Pulsating Heat Pipe (CLPHP), which is a special type of PHP consisting of closed meandering tubes in which the heat is transferred from the hotter section to the colder section by the creation and destruction of the vapor bubbles. In general, PHP is a wickless structure, consisting of long capillary tubes, which is easier to be constructed compared to conventional heat pipes and it is mainly used for high heat flux thermal management systems. As per Akachi [3] the main geometrical parameter determines whether the device will function as PHP is the internal tube diameter. The maximum inner diameter of the tube that can hold a vapor plug, which is given by:

$$D_{\max} = 2\sqrt{\frac{\sigma}{g(\rho_{liquid} - \rho_{vapor})}} \tag{1}$$

Where σ – surface tension, g – acceleration due to gravity, ρ – density (Akachi et al.) [3].

1. According to Groll and Khandekar [9], if $D<D_{max}$, then the surface tension force dominates and the stable plugs are formed inside the tube, else if $D>D_{max}$, then the liquid and vapor phases will be stratified due to the gravity and hence no pulsations will occur in the PHP. The majority of overall heat transfer, i.e., greater than 90% of the heat transfer in a PHP takes place by the sensible heat and the effect of latent heat is mainly used to the oscillatory motion. Zhang and Faghri [20] found that the optimum filling ratio is between 20-80%. Wang and Cui [18] found that the thermal resistance of the PHP decreases with the increase of the heat input. Khandekar et al. [10] investigated the 2.0 mm

diameter water-filled PHP, and found that it does not work in horizontal mode. Verma et al [17] conducted experiments CLPHP with water, methanol and nano particles for various filling ratios and varying the inclination of CLPHP, in which the Al_2O_3 nanoparticle suspended in DI water showed better heat transfer coefficient. Rahman et al. [13] conducted an experiment on CLPHP with distilled water and methanol. The results of the study clearly showed that the thermal resistance and the heat transfer coefficient were better for methanol compared with the distilled water. Srikrishna et al [15] investigated on single CLPHP with 50% filling ratio of methanol as the working fluid, in which, the maximum heat load was given upto 70W and observed that the thermal resistance decreases with the increase of heat input. Zhao et al. [21] observed the optimum filling rates for both water-based heat pipe and nanofluid-based heat pipe was about 21% at a given heating power of 25 W. Parametric studies were carried out to compare the effects of the heat pipe distributions (linear and disperse), and inclination angles (0°, 45°, and 90°) on the comprehensive cooling performance, in which the results strongly indicate that the heat transport capacity and the start-up performance are enhanced by gravity. Arulselvan et al. [4] studied the three different modes of cooling, viz., air cooling, water cooling, and cooling with extended surfaces in the condenser section of a heat pipe system, in which the results indicate a better performance with a simple cooling with water. Moreover, the effective thermal conductivity of the heat pipe is also determined and reported. Rahman et al. [12] conducted another experiment with vertically orientated CLPHP has an increase in heat transfer coefficient and decrease in thermal resistance for methanol when compared to ethanol. Borkar and Pachgare [5] investigated on PHP with different heat inputs, working fluids, filling ratio and the number of turns. The results suggest that the fluid with lower boiling point (acetone) was suitable for lower heating power. Further, thermal performance of PHP was based on the selection of the working fluids, the optimum filling ratio in a PHP should to be 50%, and the minimum number of turns should be 2 to occur perturbations in a PHP. Kravet et al. [11] showed that decrease of the vapor space dimensions in heat pipes leads to deterioration of their heat-transfer properties such as an increase of thermal resistance, a reduction of transferred heat fluxes, and an increase of the temperature difference between the evaporator and the condenser. Fumoto et al. [7] analyzed the performance of open loop PHP with self-rewetting fluids, water and ethanol. The self-rewetting fluids showed better heat transfer characteristics compared to other two liquids and also a thin layer of liquid found attached to the wall of the channels. Smoot et al. [14] conducted experiments on OHPs, in which the results show that the heat pipe does form liquid plugs and vapor bubbles as seen in typical OHPs, but oscillates in a slightly different manner compared to a typical OHP with the motion confined to the evaporator region. George and Binulal [8] found out that the performance of PHP with an aqueous solution of 1-Butanol was better when it was operated under different orientations compared to pure water. Yamagami et al. [19] worked on the use of pure water and self-rewetting fluids such as an aqueous solution of 1-Butanol with different concentrations in a flat plate PHP and observed that the self-rewetting fluids showed better heat transfer performance due to its unique surface tension behaviour than pure water. Fumoto et al. [6] studied about PHP with self-rewetting fluids such as 1-Butanol and 1-Pentanol and its aqueous solution and concluded that the 1-Pentanol aqueous solution performed better compared to the 1-Butanol aqueous solution in terms of thermal resistance and the heat transfer coefficient. Su et al. [16] studied the heat transfer performance of a PHP with self-rewetting nano-fluids like graphene oxide of different concentrations, and found out that the nano-fluids of graphene oxide performed well than the 1-Butanol aqueous solutions of different concentrations. Niti Kammuang-Lue et al [22] conducted an experiment to study the effect of working fluids and internal diameter of the tube of the horizontal and vertical closed loop pulsating heat pipes. The experiments were conducted with different working fluids such as R123, ethanol and water and the internal diameters of 1.0mm, 1.5mm, 2.0mm and also the input heat fluxes of the heat source were made to vary with six different patterns. It is concluded that when the latent heat of evaporation increases in the case of vertical CLPHP, and when the dynamic viscosity of the liquid increases in the case of horizontal CLPHP, the thermal performance gets decreases. Chansin Sriwiset et al [23] done an experimental work to investigate the optimum number of turns in the horizontal and vertical CLPHP. The evaporator of the CLPHP is made of 50mm and 150mm and the number of turns used are 5, 7, 10, 16 and 30. It is concluded that the optimum number of turns for the evaporator section of 50mm is 10 for the vertical CLPHP and the evaporator length of 150 mm has an optimum number of turns of 5 and 10 for the horizontal CLPHP. Harshal B. Jagtap et al [24] investigated CLPHP with water and 0.1wt % Al_2O_3-water nanofluid as a working fluid by using sound waves. The CLPHP is tested with different orientations such as 90°, 60°, and 30°.In comparison with the working fluids 0.1wt % Al_2O_3-water nanofluid showed better oscillation characteristics at all orientations of CLPHP except 90° where the use of sound waves leads to dry-out condition. Phrut Sakulchangsatjatai et al [25] studied an experimental work on Rotating closed loop pulsating heat pipes with R123, ethanol and water as a working fluids. The Rotating closed loop pulsating heat pipes were rotated with different centrifugal accelerations. It is concluded that when the internal diameter increases, the driving force increases and the thermal resistance decreases. Piyanun Charoensawan et al [26] did an experimental work on visual study on the flow boiling phenomenon happens inside the closed loop pulsating heat pipes with distilled water and ethanol as a working fluid. The two phase flow patterns were recorded by digital still and video cameras. It is concluded that the oscillating flow was discovered in the evaporator region at 50% and 80% of filling ratios of water and at these filling ratios the thermal resistance of water is lower than that of ethanol. In this study, the two turn PHP was experimentally tested with low latent heat high carbon alcohols such as 1-Butanol, 1-Pentanol,1-Hexanol,1-Heptanol, and 1-Octanol were mixed with the suitable proportions of deionized water and formed as self-rewetting fluids. These self-rewetting fluids were filled with varying filling ratios (FR)and with different heat inputs in a PHP and its heat transfer performance like thermal resistance and heat transfer coefficients were found out. The results obtained in this study shall provide a new insight for improving heat transfer performance by using low latent heat of high carbon alcohols.

The above review of the literature shows the investigation of many working fluids such as water, acetone, methanol, ethanol, propanol and some higher carbon alcohols such as 1-butanol, 1-pentanol and so on. The experimental work above shows that the performance of pulsating heat pipes related to thermal resistance and heat transfer coefficient. The working fluid is used with different filling ratio's and an optimum filling ratio is found out from the experimental investigation which shows the decrease in thermal resistance and higher heat transfer coefficient. It is said above that by using self-rewetting fluids the working fluid is drawn to the heater section (evaporator region) from the cooling section (condenser region) again by means of the inverse marangoni effects. Therefore the low latent heat of higher carbon alcohols such as (1-Butanol, 1-Pentanol, 1-Hexanol, 1-Heptanol, and 1-Octanol) are used as a self-rewetting fluids and experimentally investigated in a 2 turn closed loop copper pulsating heat pipes. The higher carbon alcohols are investigated with different filling ratio's and the performance of pulsating heat pipe is found better with the use of 1-Octanol as a working fluid.

2. Experimental Setup and Working Principle

The experimental setup is shown in the Fig.1. A copper tube with an inner diameter of 2mm and an outer diameter of 3mm, with 2 turns is made for the CLPHP which is clearly shown in top right corner of Fig. 1. The PHP is vacuumed by the vacuum pump around 0.084 MPa. The PHP has an evaporator section of 50mm, an adiabatic section of 50mm and a condensing section of 50mm. The evaporator section is heated by a nichrome coil (26 gauges). The coil is wound around the evaporator section and is insulated by a glass fiber to prevent heat loss. The adiabatic section is also insulated by the glass fiber. The condenser section is cooled by water. The condenser section is made by an acrylic tank and the water is circulated by a pump. The power source is given by an external Direct Current (DC) power supply, which has a capacity of 150 W. The check valves are arranged to prevent vacuum loss. The pressure gauge is fitted in the setup to indicate the vacuum pressure. The data are read by an Arduino Mega 2560 board and it is connected to the Personal Computer (PC).

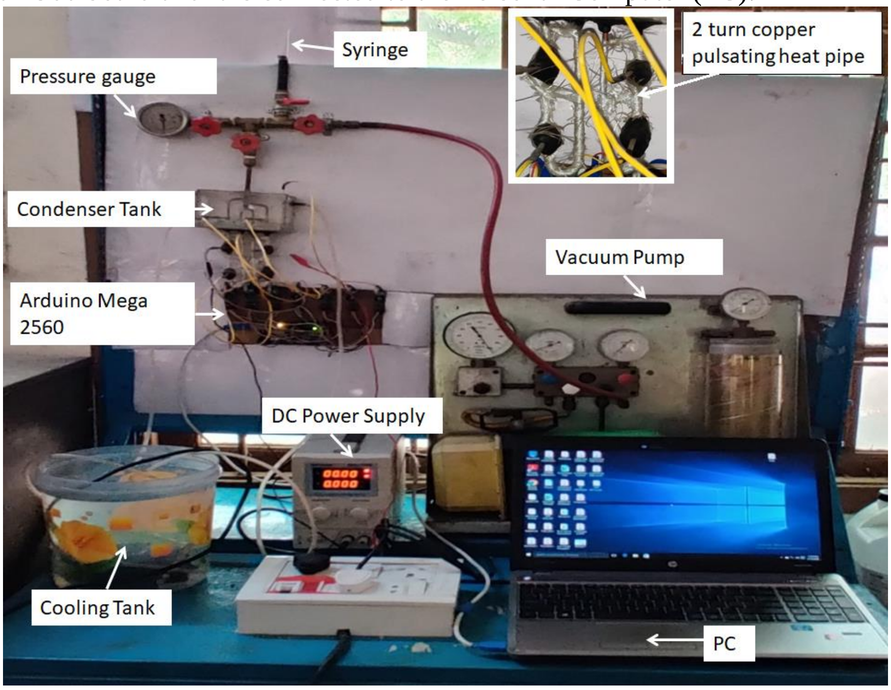

Fig.1. Experimental Setup

The self-rewetting fluid is filled inside the CLPHP and it naturally distributes into liquid slugs and vapor plugs through the capillary diameter. The evaporator section gets heated by the nichrome coil and the fluid evaporates and enters into the adiabatic section and then to the condenser section. The heat gets rejected in the condenser section through cooling water arrangement and the evaporated self rewetting fluid turns in to liquid state and again enters into the evaporator section. This cycle causes pulsating effect and CLPHP pulsates till the dry out occurs.

3. Uncertainty analysis

In the calculation of uncertainty in the given electrical heat input, the uncertainty associated with voltage and current is taken as the least count of the device used to measure them in this present study. From the calibration of thermocouples, it is assured that the measured temperature in this present study is accurate to within ± 0.25°C.

The uncertainty in the given electrical heat input is calculated as below. For a case of the power level of 5 W the uncertainty in the calculation of given electric heat input is given by:

$$\sigma_P = \pm\sqrt{\left(\frac{\partial P}{\partial V}\sigma_V\right)^2 + \left(\frac{\partial P}{\partial I}\sigma_I\right)^2} \quad (1)$$

(2)

$$\sigma_P = \pm\sqrt{(0.5 \times 0.1)^2 + (10 \times 0.01)^2}$$

$$\sigma_P = \pm 0.1118$$

$$\frac{\sigma_P}{P} = \pm 0.0223$$

or $\pm$ 2.22%

Quantity measured	Uncertainty	Unit
Temperature	± 0.25	°C
Voltage	± 0.1	V
Current	± 0.01	A
Power	± 2.22	%

Table 1. Uncertainty of the experimental calculations

4. Results and Discussion

4.1 Surface Tension Behavior for Self-Rewetting Fluids (SRWF)

In general, the surface tension decreases with the increase in temperature for pure working fluids. But in the case of self-rewetting fluids (i.e., dilute aqueous-alcoholic solutions), the surface tension increases with the increase in temperature. When heating the dilute aqueous-alcoholic solutions of higher carbon (i.e., number of carbon atoms ≥4) the surface tension decreases initially and thereafter the surface tension increases with the increase in temperature which is shown in the Fig. 2.

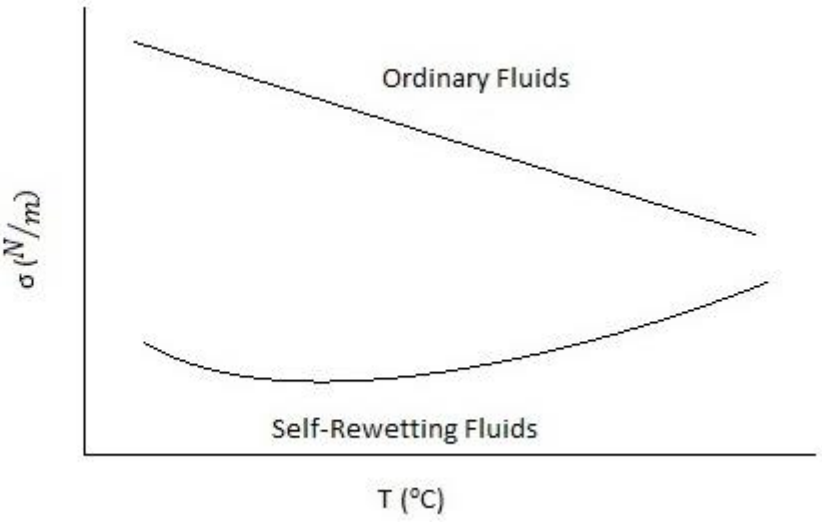

Fig.2. Surface tension behavior of ordinary and self-rewetting fluids [27]

In PHP the liquid gets vaporized in the evaporator section and the vapor is condensed into liquid in the condenser section. Conventional heat pipes like wicked heat pipes capillary force dominate so that the vapor condensed into liquid in the condenser section flows to the evaporator section through the porous wick by the capillary action over the effect of gravity. However, in PHP, because of the absence of wick structure the surface tension dominates over the effect of gravity. So surface tension plays an important role in PHP. Pure liquids like water, the surface tension decrease with the increase of temperature, i.e., the fluid flows from the hot end to the cold end (i.e., from the evaporator section to the condenser section). When using SRWF in PHP with the increase in temperature the surface tension initially decreases and increases by further heating. Therefore, the fluid transportation takes from the colder section to the hotter section (i.e., from the condenser section to evaporator section) and the dry out is eliminated in the evaporator section and hence the heat pipe works for a long time. This principle is called Inverse Marangoni Flow and it is shown in the Fig. 3.

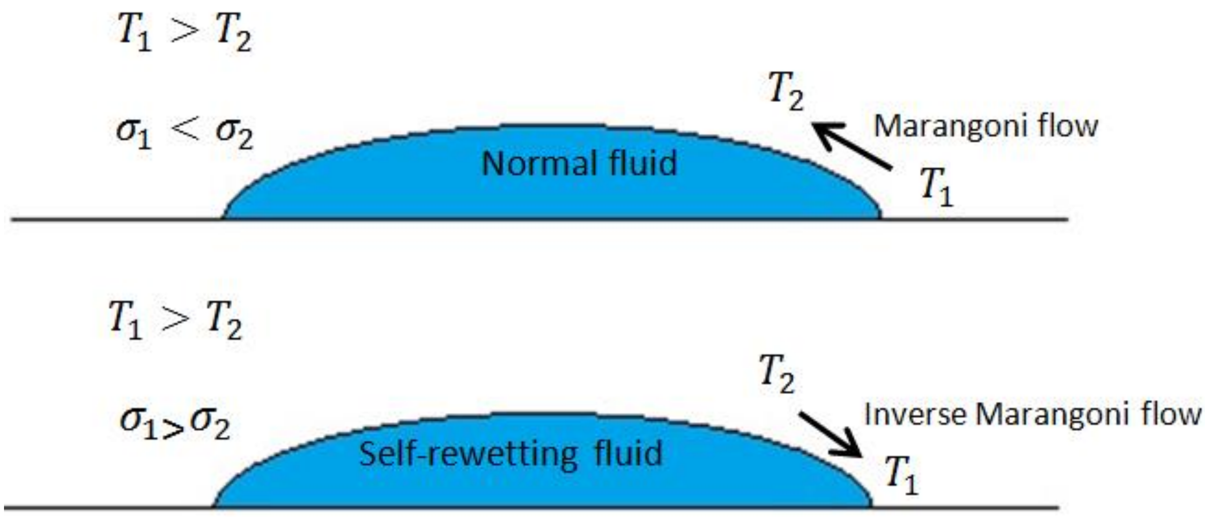

Fig.3. Pictorial representation of Marangoni and Inverse Marangoni Effects [28]

3.2 Effect of Latent Heat of Vaporization for a PHP:

The heat transfer in a PHP takes place by the combination of sensible heat and latent heat. In a capillary tube, the working fluid distributes in the form of liquid slugs and vapor plugs. The sensible heat is responsible for the heat transfer of liquid slugs and the latent heat is responsible for the heat transfer of vapor plugs. The latent heat of vaporization is the most important parameter in a PHP, and low latent heat is desirable for a PHP, because it results in a higher vapor generation and results in improvement of oscillations of liquid slugs, thus the PHP performance is increased. Alcohols show a decrease in latent heat with an increase in carbon numbers. Alcohols having a carbon number greater than or equal to 4 i.e., starting from 1-Butanol, 1-Pentanol, 1-Hexanol, etc., shows the decline of latent heat. In this work, alcohol like 1-Butanol, 1-Pentanol, 1-Hexanol, 1-Heptanol, and 1-Octanol are mixed with the deionized water in suitable proportions to form a self-rewetting fluids. This sequence of reduction in latent heat of vaporization of fluids is experimentally investigated in a CLPHP, and their performances like thermal resistance and heat transfer coefficient are found out. The properties of latent heat of vaporization of higher carbon alcohols are shown in the Table. 2.

Test Sample	1-Butanol	1-Pentanol	1-Hexanol	1-Heptanol	1-Octanol
Latent heat of vaporization (kJ/kg)	707.9	647.1	603	574.95	486

Table 2. Properties of Latent heat of vaporization for various higher carbon alcohols

3.3 Self-Rewetting Fluids Compositions with Deionized Water

The higher carbon alcohols are mixed with a suitable volume of deionized water with the help of an ultrasonic agitator. The various combination of binary mixture of dilute aqueous alcohol solutions are given below:

1. Deionized water – 1 Butanol 5% Vol
2. Deionized water – 1 Pentanol 2% Vol
3. Deionized water – 1 Hexanol 0.6% Vol
4. Deionized water – 1 Heptanol 0.1% Vol
5. Deionized water – 1 Octanol 0.05% Vol

3.4 Effect of Thermal Resistance

The thermal performance, heat transfer characteristics and the efficiency are calculated by measuring wall temperatures of different locations in a CLPHP. The thermocouples are placed in the evaporator section, adiabatic section, and the condenser section. For calculating the thermal resistance (R_{th}) in a CLPHP the wall temperatures of evaporator and condenser section is measured and it is found out by the formula

$$R_{th} = \frac{(\bar{T}_e - \bar{T}_c)}{Q} \quad (2)$$

$$\bar{T}_e = \frac{T_{e1} + T_{e2} + T_{e3} + T_{e4} + T_{e5}}{5} \quad (3)$$

$$\bar{T}_c = \frac{T_{c1} + T_{c2} + T_{c3} + T_{c4} + T_{c5}}{5} \quad (4)$$

where, $\bar{T}_e$ and $\bar{T}_c$ = Average evaporator and condenser temperature respectively.

After calculating the thermal resistances of self-rewetting fluids it is plotted against the heat input. The following graphs representing the thermal resistance vs heat input for different self-rewetting fluids with different filling ratios are presented. The filling ratio is varied from 40% to 70%. The heat input is varied from 5W, 10W, 15W and 20W. Fig. 4 shows the thermal resistance vs heat input for deionized water with a 5% volume of 1 Butanol. In this graph, the thermal resistance is lower for 50% of the filling ratio. The self-rewetting fluid of 1-Butanol gives a better result for the 50% of the filling ratio. Fig. 5 shows the thermal resistance vs heat input for the self-rewetting fluid of 1-Pentanol. In this mixture the self-rewetting fluid of 1-Pentanol the thermal resistance is again lower for the 50% of the filling ratio. In the case of self-wetting fluid of 1-Hexanol which is shown in Fig. 6, the thermal resistance is lower for 50% of the filling ratio, again. As the thermal resistance is inversely proportional to the heat input, which is evident from observation, that the thermal resistance decreases as the heat input increases. When using the self-rewetting fluid of 1-Heptanol, the thermal resistance is lower for the 60% of the filling ratio which is shown in Fig.7. The other filling ratios of 40% and 50% show somewhat non-linear variations in thermal resistance of self-rewetting fluids of 1-Hexanol and 1-Heptanol. Fig. 8 shows the variation of thermal resistance with heat input for self-rewetting fluid of 1-Octanol and it is noticed that the lowest thermal resistance is found in the case of 70% of the filling ratio. Hence, the lowest thermal resistance in all the mixture of deionized water with high carbon alcohols is found in the case of 1-Octanol.

The convective heat transfer coefficient (h) of a CLPHP is given by:

$$h = \frac{Q}{A(\bar{T}_e - \bar{T}_c)} \tag{5}$$

where, Q = Heat input in Watts, A = Wetted Surface Area of the evaporator in m^2, $\bar{T}_e$ and $\bar{T}_c$ = Average evaporator and condenser temperature respectively.

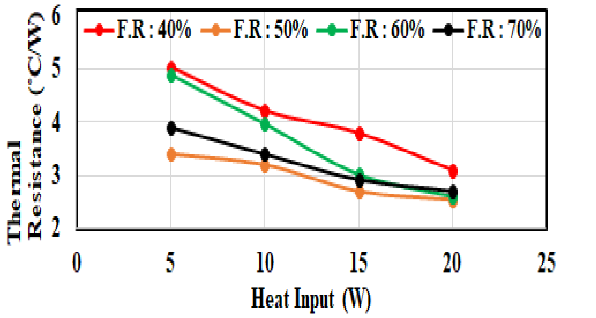

Fig.4. Thermal resistance versus Heat input for the mixture of deionized water with 5% volume of 1-butanol

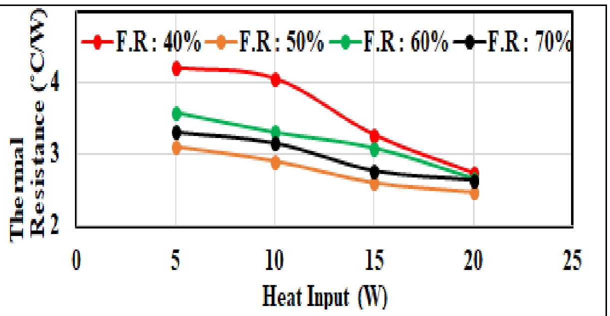

Fig.5. Thermal resistance versus Heat input for the mixture of deionized water with 2% volume of 1-pentanol

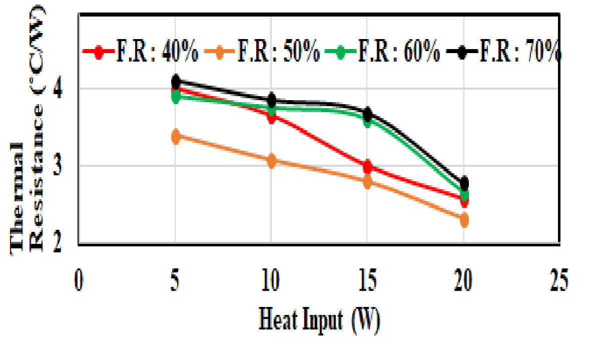

Fig.6. Thermal resistance versus Heat input for the mixture of deionized water with 0.6 % volume of 1-hexanol

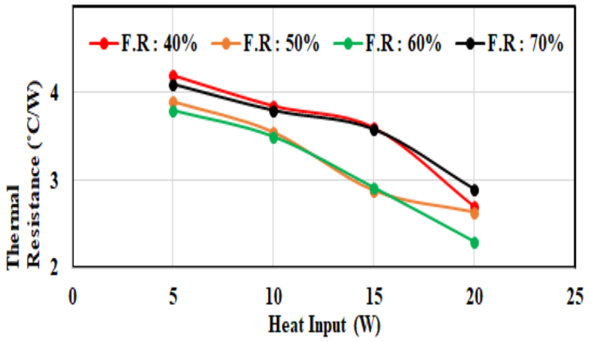

Fig.7. Thermal resistance versus Heat input for the mixture of deionized water with 0.1% volume of 1-heptanol

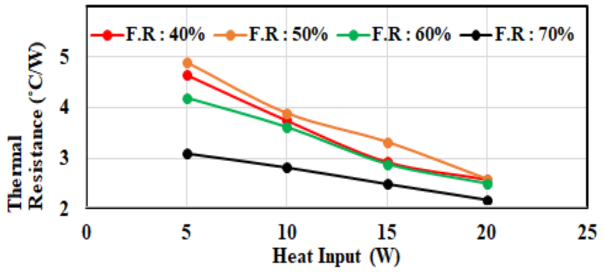

Fig.8. Thermal resistance versus Heat input for the mixture of deionized water with 0.05% volume of 1-octanol

3.5 Effect of Molecular Weight

The molecular weight of self-rewetting fluid plays an important role in the thermal performance of the closed loop pulsating heat pipes. In general fluids having low molecular weight flow easily than fluids having high molecular weight. The molecular weights of the self-rewetting fluids are calculated and it is shown in Table 3. It is observed that the molecular weight of self-rewetting fluids keeps on decreasing and it is found low for deionized water mixed with 1 Octanol. Self-rewetting fluids of 1 Octanol has low molecular weight and it can flow easily than other self-rewetting fluids. Therefore it is found that the thermal performance of the closed loop pulsating heat pipe improved with the self-rewetting fluids of 1 Octanol.

S.No	SRWF	Molecular Weight (gram/mole)
1	Deionized water +1 Butanol 5% Vol	20.820566
2	Deionized water +1 Pentanol 2% Vol	19.4179744
3	Deionized water +1 Hexanol 0.6% Vol	18.52016032
4	Deionized water +1 Heptanol 0.1% Vol	18.11414472
5	Deionized water+1 Octanol 0.05% Vol	18.07138736

Table 3: Molecular Weight of the SRWF

4. Conclusions

From this experimental study's observations, the following conclusions were drawn: The self-rewetting fluids with higher carbon alcohols work better in the CLPHP.

- The thermal performance measures like the thermal resistance and heat transfer coefficient were improved by using self-rewetting fluids along with a decrease in startup time during trials.
- The filling ratio was well within the recommended 40% to 70% range.
- Dry out of CLPHP was completely eliminated before reaching steady state, as a result the working hours of CLPHP has been prolonged.
- The thermal resistance got decreased and the heat transfer coefficient got increased starting from self-rewetting fluids of 1-Butanol to 1-Octanol.
- The minimum value of thermal resistance and maximum value of the heat transfer coefficient was found in the self-rewetting fluid of 1-Octanol.
- Hence, it is concluded that by using low latent heat of higher carbon alcohols the CLPHP performance gets increased.

Nomenclature

Al_2O_3	-	Aluminum oxide
CLPHP	-	Closed Loop Pulsating Heat Pipe
DI	-	Deionized
D_{max}	-	Maximum diameter (mm)
D_{min}	-	Minimum diameter (mm)
FR	-	Filling ratio
h	-	Heat transfer coefficient ($W/m^2 °C$)
OHP	-	Oscillating Heat Pipe
PC	-	Personal Computer
PHP	-	Pulsating Heat Pipe
SRWF	-	Self -Rewetting Fluid
σ	-	Surface tension (N/m)
R_{th}	-	Thermal resistance (°C/W)
Vol	-	Volume
W	-	Watts

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- Paper submitted: 09 May 2020
- Paper revised 26 November 2020
- Paper accepted: 29 November 2020