Experimental Study on the Thermal Performance of the Pulsating Heat Pipe with Pure Fluids and Azeotropic Mixture of Ethanol and Toluene

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Abstract: *A closed loop pulsating heat pipe self-excited thermally driven two phase passive heat transfer device. It is a one of the class of wickless heat pipes. With the development of the technology and the demand for the miniaturization the requirement for the dissipation of the higher heat flux developed demands for the effective cooling devices with higher heat transfer rate. Pulsating heat pipe has been proven to be one of the promising alternative due to its various advantages as a cooling devise.*

In the present paper the preliminary experimental results on the thermal performance of the PHP made of copper capillary tube of internal diameter of 2 mm and external diameter of 3 mm meandered in 5 turns are presented. For all the experiments the filling ratio was maintained to be 50% and controlled heat input varying between 10 W to 120 W is supplied in the vertical bottom heating configuration. Equal lengths of the evaporator, condenser and the adiabatic section is maintained to be 100 mm. the pitch between adjacent turns is maintained to be 50 mm. the working fluid selected for the investigation are water, ethanol and the azeotropic mixture of ethanol and toluene. The thermal performance of the PHP with these working fluids is investigated and compared in this paper.

In the investigation it is found that the thermal resistance of the azeotrope PHP is less with intermediate power inputs from 30 W to 70 W. for other power inputs there is no considerable difference is found in the thermal resistance of pure ethanol and azeotrope PHP. It is also observed that for all heat inputs the azeotrope PHP has lower resistance than the water PHP at same filling ratio and other operating conditions. However, the thermal resistance of the PHP decreases more rapidly with increase in the heating power from 30 W to 70 W, and slowly afterwards.

Nomenclature		*Subscripts*	
Cp	*Specific heat (kJ/kg0C)*	*a*	*adiabatic section*
D	*Diameter (m)*	*b*	*boiling*
Eö	*Eötvös number = (Bo)2*	*c*	*condenser section*
P	*Electrical input power (W)*	*e*	*evaporator section*
Q	*Heat Input (W)*	*avg*	*Average*
Rth	*Thermal Resistance*	*liq*	*liquid*
hfg	*Latent heat of vaporization*	*vap*	*vapor*
T	*Average temperature*	*sat*	*Saturation*
Greek symbols			
ρ	*Density (kg/m3)*		
μ	*Dynamic viscosity (Ns/m2)*		
υ	*Kinematic viscosity (Pa.s)*		
σ	*Surface tension (N/m)*		

I. INTRODUCTION

The dissipation of the heat generated within the machines and the electronic components while in operation is the prime area of interest of the researchers for a long time as the excess of heat accumulated within the system can potentially damage the system and can prevent the normal working of the system. The development of the system and the resulting miniaturization is resulting in the increased heat flux generated within the system and thus demanding for more efficient, versatile and flexible heat transfer device. However Pulsating heat pipe (PHP) introduced and patented by H. Akachi back in 1990[1] seems to meet these seemingly conflicting demands to a great extends. exist. Due to its excellent features, such as high thermal performance, rapid response to high heat load, simple design and low cost, PHP has been considered as one of the promising technologies for various cooling applications such as electronic cooling, heat exchanger applications, spacecraft thermal control systems, solar heat exchanging applications, cell cryoprevention etc. The PHP is a self excited thermally driven two phase passive heat transfer device which works on the principle of capillarity and the thermally driven oscillating motion. Since the introduction the PHP is considered to have excellent applications prospects in the areas of solar energy utilization, waste heat recovery, aerospace thermal management and electronic cooling due to its following distinct advantages[2-4]: (1) simple structure and low cost: PHP is made of a long capillary tube meandered into many turns. The fact that no wick structures are required in the PHP is a great favour in manufacturing. The small diameter of the PHP is also helpful for cost saving; (2) excellent heat transfer capability: according to the results of Shang et al.[5] and other researchers, the equivalent thermal conductivity of PHP can reach dozens of times of that of copper;(3) easy to achieve miniaturization: the size of the PHP can be very small compared to other heat transfer devices for same capacity due to the small inner diameter of the PHP, which is one of the most striking characteristics of the PHP; and (4) higher level of flexibility: PHP channel can be arranged to any arbitrary configuration required according to the situation of application. In a broad sense, PHP is a proven simple, reliable, noiseless and an economically feasible choice for the dissipation of heat generated within various systems.

Over the years many experimental and mathematical models are developed in order to predict the thermal performance of the pulsating heat pipe. Qu and Ma[6] presented a mathematical model to study the start-up of a PHP during the initial phase of operation. From the work they concluded that the surface condition of inner wall of the capillary tube, evaporation in the hot section, extend of the superheat, bubble growth, and the amount of vapor bubble trapped in cavities affected the start-up of a PHP. Shafii et al.[7, 8] presented a model to investigate the heat transfer mechanism of the PHP they concluded that the majority of the heat transfer taking place in the PHP (i.e. around 95% of total) is in the form of sensible heat and not due to the latent heat of vaporization of the working fluid. Latent heat serves only for thermal excitation and driving the oscillating flow in the PHP. They also demonstrated that the gravity force has an insignificant effect on the thermal performance of the PHP. Even though wide-ranging studies have been carried out to investigate the performance, some of the key aspects of the PHP remain poorly understood as there exists contradiction between the results obtained analytically when compared to the experimental results of the investigations carried by different researchers. Based on the number of researches carried out on the PHP it can be said that thermal performance and the heat transport capabilities of the PHPs mainly depends on the working fluids, evaporation/condensation lengths, inner diameters, number of turns, etc[5]. A number of researches are been carried out with different working fluids ranging from pure working fluids, binary mixtures even Nano-fluids and Nano-emulsion fluids.

There are numerous methods to improve the performance of a pulsating heat pipe, among all available methods the most direct and effective one is to select an excellent functional fluid as the working fluid for a given PHP. The physical properties of the working fluid such as the surface tension, wettability, latent heat, specific heat, viscosity etc. have a reflective effect on the thermal performance of the PHP. ethanol. Qu et al.[9] compared the heat transfer performances of the PHP when the working fluids were methanol, water and acetone, respectively. The results indicated that for the tested PHP with 0.38 charge ratio, acetone was the best choice among them when the heat flux was low. Saha et al.[10] presented a study of an open PHP, the PHP was charged with water, methanol and acetone. It was found that the PHP with water showed the best performance for the vertical mode of operation (i.e. when the inclination angle was 90°), whereas the PHP with methanol showed best performance for the horizontal mode of operation (i.e. when the inclination angle was 0°). Pachghare P. et al.[12-13] investigated PHP for various pure and binary mixtures as working fluids and found that acetone shows best thermal performance among the pure working fluids and the use of binary mixtures does not affect the thermal performance considerably and there was a very slight variation in the thermal performance. Qu et al.[13] proposed that when the nanofluid was used as the working fluid, the PHP could start-up quickly and operate stably at lower heat flux. At the same time, the thermal resistance of the PHP with TiO_2/H_2O nanofluid was lower than that of PHP with water. Qu et al.[13] experimentally investigated the heat transfer performance of the PHP charged with $FC72/H_2O$ Nano-emulsion fluid. The results showed that the temperature difference between the Evaporation section and condensation section of the PHP decreased significantly with the using of Nano-emulsion fluid, which revealed that the heat transfer performance of PHP was enhanced.

Experimental Setup Description

The schematic of the experimental setup used for the investigation is shown in the figure 2. The loop pulsating heat pipe for the current investigation is made of copper capillary tube of ID = 2 mm and OD = 3 mm, meandered into 5 turns to form a closed loop. The evaporator, adiabatic and condenser section length are taken as 100 mm respectively, the pitch distance between the adjacent turns is maintained to be 50 mm. Heating in the evaporator section is achieved with the oil bath which in turns is heated by two (500 W) coil heaters. The cooling in the condenser section is done by cooling water tank with a fixed mass flow rate of 25 ml/min. The adiabatic section is well insulated from the environment to prevent loss of heat and error in the measurements. For all the investigations vertical bottom heating mode with a fixed filling ratio of 50% is used. The controlled heat input to the oil bath heaters is varied from 10 W to 120 W using the dimmer stat assembly provided on the control penal. For temperature measurements at various sections 12 type k thermocouples are mounted on different locations as shown in the schematic diagram. All the thermocouples are mounted on the wall of the PHP.

The inner diameter of the tube is the vital geometric parameter as it essentially manifests the fundamental definition of the closed loop pulsating heat pipes (CLPHPs). The normal operation of PHP is based on the formation of the vapor slugs and liquid plugs. The formation of the two depends on the relative strength of the gravity and the surface tension, which is indicated by a dimensionless number known as Bond number.

$$B_o = \sqrt{E_o} = \sqrt{\frac{g(\rho_l - \rho_g)D^2}{\sigma}} \quad \text{... (1)}$$

Various researchers proposed the tentative criteria that for the normal operation of the PHP the Bond number should be less than or equal to 2 (Bo≤2). Thus the formula for the calculation of the maximum inner diameter can be written as,

$$D_{crit} = 2\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}} \quad \text{... (2)}$$

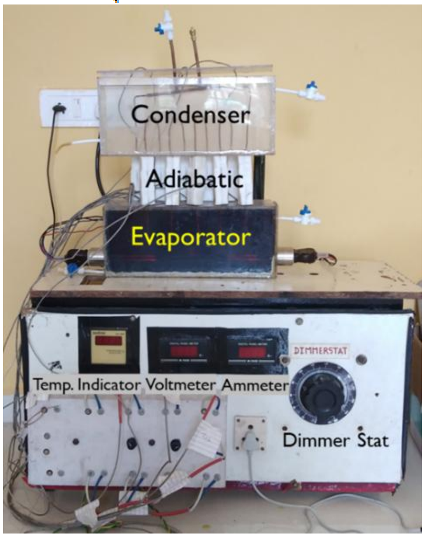

Figure 1. Photograph of Experimental Setup

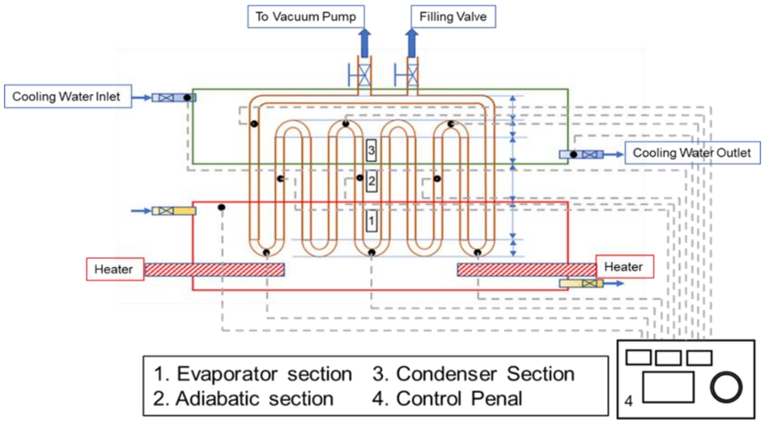

Figure 2. Schematic of the experimental setup

For the current research the working fluids used are pure water, pure ethanol and the azeotropic mixture of ethanol and toluene. The critical diameter calculated for these fluids is depicted in table 1.

Table 1: Critical Diameter of Copper Tube for Different Working Fluids

	Working Fluid	Ethanol	Water	Toluene
Temperature	0°C	3.627	5.45	3.962
	100°C	2.83	5.01	3.669

The thermophysical properties of the various working fluids used in the investigation at their respective boiling point are depicted in table 2.

Table 2: Thermo-physical properties of the working fluids at the boiling temperature

Working fluid	T_b (˚C)	P_v (10^5 Pa)	h_{fg} (KJ/Kg)	ρ (Kg/m³)		μ (10^{-7} Ns/m²)		k (W/m-K)		σ (10^{-3} N/m)	C_p (KJ/Kg-K)	
				liq	vap	liq	vap	liq	vap		liq	vap
Water	100	1.013	2251.20	958.7	0.596	2790.0	121.00	0.680	0.02480	58.91	4.22	2.034
Ethanol	78.3	1.033	0962.45	758.1	1.372	4452.6	102.39	0.169	0.01973	17.46	0.73	1.604
Toluene	110.6	1.032	0451.71	866.9	3.162	2699.0	110.25	0.539	0.02773	28.52	0.560	1.325

II. RESULTS AND DISCUSSION

The data required for the thermal performance analysis of the PHP (for pure working fluids and the azeotropic mixture of the ethanol and toluene) was obtained according to the following procedure: Heat input was stepwise increased, for each heat input value the readings are taken once the quasi-thermal equilibrium was established. Then, the spatial temperatures and heat input were recorded, so the thermal resistances could be determined. The thermal resistance (R_{th}) is defined by

$$R_{th} = \frac{T_{e,avg} - T_{c,avg}}{Q_{in}} \quad \dots(3)$$

Where, $T_{e,avg}$ and $T_{c,avg}$ are the average evaporator and condenser surface temperatures, defined as,

$$T_{i,avg} = \frac{T_{i,1} + T_{i,1} + T_{i,3}}{Q_{in}} \qquad where, i = e \ or \ c \quad \dots(4)$$

Q_{in} is the heat input to the PHP at the evaporator section, considering the thermal losses the heat input can be determined as,

$$Q_{in} = P - Q_{loss} \quad \dots(5)$$

Where, P is the input electrical power. Q_{loss} is the heat loss, which was taken to be 15 to 20% depending on the heat load.

The effect of using the azeotropic mixture on the average evaporator temperature is shown in figure 3 It can be seen and interpreted from the variation of the average evaporator temperature with the varying heat flux as shown in figure 3 that there was no major variation was found in the average evaporator temperature for all the heat inputs provided i.e. starting from 10 W to 120 W for both pure ethanol and the ethanol based azeotropic mixture. Also the PHP with the mixture as a working fluid follows the same increasing trend for the evaporator temperature as followed by the PHP with pure working fluids.

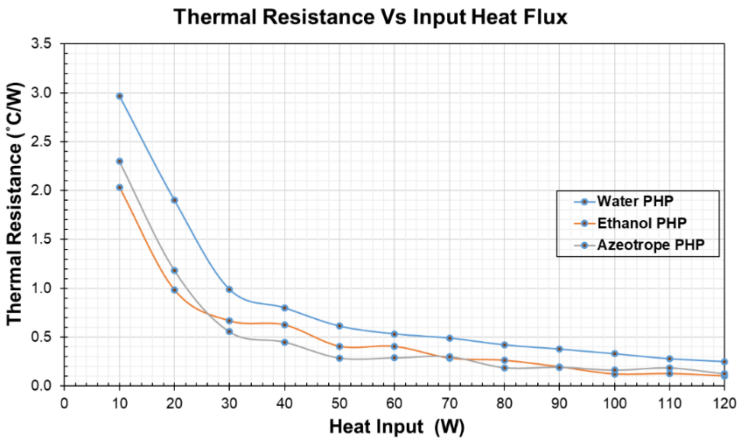

Figure 3: Thermal Resistance Vs Input Heat Flux for Azeotrope PHP

The average evaporator temperature for the PHP with pure ethanol and mixture as a working fluid is found lower than that of water PHP for all input heat flux provided. The higher value of saturation temperature for water can be one of the reason for this effect. Also, the reason for the small difference in the temperature values for the PHP with pure ethanol and the azeotropic mixture of ethanol and toluene can be a small difference between the boiling temperature value of the two.

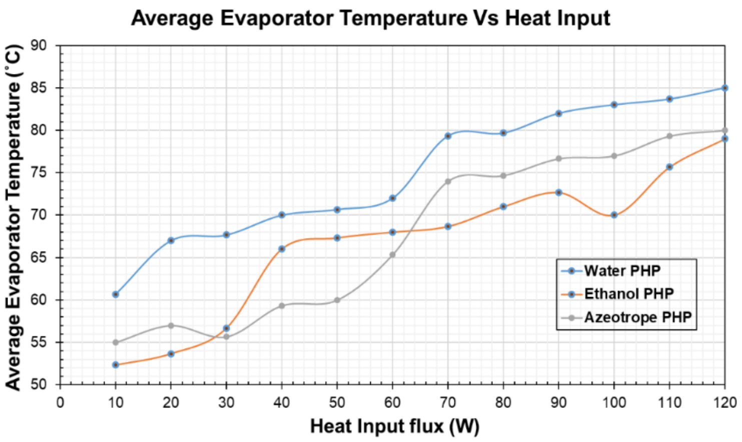

Figure 4: Avg. Evaporator Temp. Vs Heat Input of Azeotrope PHP

The figure 4 shows the variation of the evaporator-condenser temperature difference for the PHP's with varying heat input flux. As can be seen from the variation trends the evaporator-condenser temperature difference nearly equal for the ethanol PHP and azeotrope PHP but for the pure water PHP the temperature difference is significantly high. And as we know that the higher the evaporator-condenser temperature difference implies the higher thermal resistance thus for the water PHP the thermal resistance is high as can be seen from figure 5. Looking at the variation of the thermal resistance of the pulsating heat pipe with varying input heat flux we can conclude that there is no significant difference in the thermal resistance for the ethanol and azeotrope PHP between the heat input range of 10W to 30W. The thermal resistance for water PHP is higher than the remaining two for all heat input provided. There is a slight difference found in the thermal resistance of the pure ethanol and azeotrope PHP between the heat input range of 30W to 50W after which the trend for both does not show any significant difference. From the trend shown in figure 5 we can say that the thermal resistance of pure ethanol PHP and azeotrope PHP is nearly equal at all heat input and no significant difference has been recorded for the PHP running with azeotropic mixture and the PHP running with the pure ethanol. And both these PHP's are equally effective as compared with the pure water PHP.

The boiling point and the latent heat for the water is more as compared to the pure ethanol and the azeotropic mixture of ethanol and toluene. Thus for lower heat inputs the water in the evaporator section of the PHP can hardly boil. Furthermore during the start-up period the thermal oscillations are hard to achieve for the w3ater PHP due to higher surface tension and higher dynamic viscosity of water. Therefore, the evaporator section temperature is higher and the condenser section temperature is lower and the evaporator-condenser section temperature is higher, and accordingly the thermal resistance is higher for the water PHP. At higher heat inputs the temperature of the evaporator section is high enough to boil the higher temperature working fluid and sufficient to generate and maintain the oscillating flow and the smooth unidirectional flow of the working fluid in the PHP tube. Thus, the thermal resistance reduces flat and the difference between the same for all the working fluid decreases at the increased heat input flux.

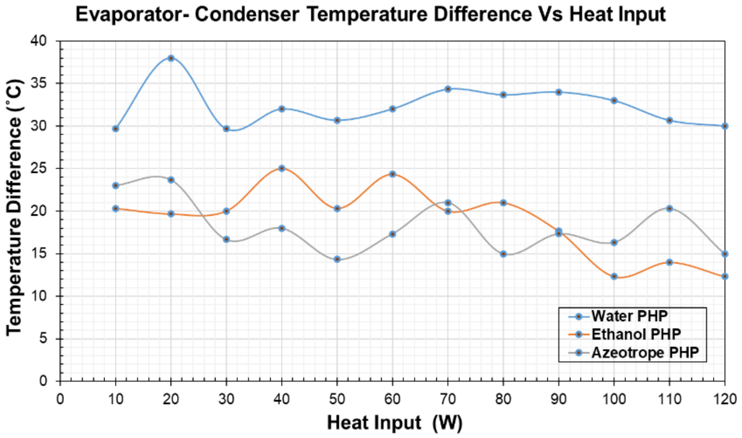

Figure 5: Evaporator- Condenser Temperature Diff. for Azeotrope PHP

III. SUMMARY AND CONCLUSION

In the current work the closed loop pulsating heat pipe is experimentally investigated with different working fluids such as pure water, ethanol and the azeotropic mixture of ethanol (68% V/V) and toluene (32% V/V). in the experimentation the heat input is varied from 10 W to 120 W with the step of 10 W. The test is performed on a PHP made of a copper capillary tube of 2 mm inner diameter and 3 mm outer diameter. The electric heating power supplied by coil heaters is transfer through oil, working fluid by conduction and convection to the condenser section where it is dissipated to the cooling water flowing with a constant flow rate. The temperature data for at the different location is obtained at 12 different power inputs and a constant filling ratio of 0.5.

For the investigation conducted on the thermal performance of the CLPHP with pure and azeotropic mixtures the following conclusion can be drawn:

- For the PHP with pure working fluids and the Azeotrope PHP both the thermal resistance for the PHP decreases with the increase in the heat input.
- The time required for the steady state varied from 90 minutes to 270 minutes and it is observed that the time decreased with the increase in heat flux for all the PHP.
- For intermediate heat inputs i.e. from 30 W to 60 W the thermal resistance of the Azeotrope PHP is less as compared to all the other PHP's investigated.
- There is no measurable difference found in the thermal resistance of Azeotrope PHP and pure ethanol PHP at higher power inputs.
- Form the plots drawn for the validation we can conclude that the thermal resistance of the PHP is decreased to a small extent by increasing the heat reception and dissipation area by slightly varying the geometry.
- The efficiency of heat transfer for the ethanol and Azeotrope PHP are found nearly same at lower power inputs up to 70 W beyond 70 W up to 100 W the Azeotrope PHP has higher efficiency of heat transfer beyond 100 W there is again no measurable difference found between that of the two.

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