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Effect of pure and binary fluids on closed loop pulsating heat pipe thermal performance

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Abstract

This paper presents preliminary experimental results on thermal performance of closed loop pulsating heat pipe (PHP) using copper tube having internal and external diameter with 2.0 mm and 3.6 mm respectively. For all experimentation, filling ratio (FR) was 50 %, ten turns and different heat inputs of 10 to 100W was supplied to PHP. The position of the PHP was vertical bottom heat mode. The equal length of evaporator, adiabatic and condenser section was maintained 50 mm. Working fluids are selected as Methanol, ethanol, acetone, water and different binary mixtures. In order to study, characteristics of the thermal resistance and average evaporator temperatures at different heat input for various working fluids. Experimental study on PHP indicated working fluid is an important factor for the performance of PHPs. The result shows that, the thermal resistance decreases more rapidly with the increase of the heating power from 20 to 60 W, whereas slowly decreases above 60 W. Pure acetone gives best thermal performance in comparisons with the other working fluid. No measurable difference has been recorded between the PHP running with pure and binary mixture working fluids.

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Keywords: Pulsating heat pipe, binary mixtures, heat flux, pure natural convection.

Nomenclature

C_p	Specific heat (kJ/kg ⁰ C)
D	Diameter (m)
$Eö$	Eötvös number = $(Bo)^2$
P	Electrical input power (W)
\dot{Q}	Heat input (W)
R_{th}	Thermal resistance (⁰ C/W)
\bar{T}	Average temperature (⁰ C)
h_{fg}	Latent heat of vaporization (kJ/kg)

Subscripts

a	adiabatic section
b	boiling
c	condenser section
e	evaporator section
liq	liquid
sat	saturation
vap	vapor

Greek symbols

ρ	Density (kg/m ³)
μ	Dynamic viscosity (Ns/m ²)
ν	Kinematic viscosity (Pa.s)
σ	Surface tension (N/m)

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1. Introduction

Pulsating or Looped type Heat Pipes proposed and patented by Akachi [1] in 1990s. This is the new member of wickless heat pipes. Their operation is based on the principle of oscillation for the working fluid and a phase change phenomena in a capillary tube. The diameter of the tube must be small enough such that liquid and vapor plugs 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 electronic cooling, heat exchanger, cell cryopreservation, the spacecraft thermal control system, etc.

Various mathematical models have been developed in recent years to predict the oscillating motion and heat transfer performance of the PHPs. Qu and Ma [2] presented a mathematical model to describe the startup of a PHP. They found that the inner wall surface condition, evaporation in the hot section, superheat, bubble growth, and the amount of vapor bubble trapped in cavities affected the startup of a PHP. Shafii et al. [3, 4] concluded that the majority of the heat transfer (95%) is due to sensible heat, not due to the latent heat of vaporization. Latent heat serves only to drive the oscillating flow. They also demonstrated that the gravity force has an insignificant effect on the PHP performance.

Although extensive studies have been carried out, certain key aspects of the PHP remain poorly understood, and some analytical results obtained by different investigators are even contradictory to the experimental data. A number of researchers have conducted experimental investigations on PHPs, and the results indicated that the heat transfer capability of PHPs mainly depends on the working fluids, evaporation/condensation lengths, inner diameters, number of turns, etc [5]. Charoensawan et al. [6] indicate that in vertical orientation for the 2.0 mm devices, water filled devices showed higher performance as compared to R-123 and ethanol; in contrast R-123 and ethanol showed comparable performance in case of 1.0 mm devices with water showing very poor results. Khandekar et al. [7] demonstrate the effect of input heat flux of the working fluid on the thermal performance of the device. Although the Eötvös number of water and ethanol was much below the prescribed maximum limit of $Eö = 4$, gravity forces were definitely seen to affect the performance. There is a smooth decrease of the thermal resistance with increasing heat power input.

Kammuang-lue et al. [8] studied that, the higher latent heat of the working fluid, the higher critical heat flux. Yang et al. [9] pointed out that increasing heat load clearly improves the thermal performance. Meena et al. [10] concluded that as working fluids change from R-123 to Ethanol and water the critical heat flux decreased. The latent heat of vaporization affects the critical heat flux. The working fluid with the lower latent heat of vaporization exhibits a higher critical heat flux. Dadong and Cui [11] indicate that the thermal resistance decreases with the increase of the heating power at the same filling ratio. The thermal resistance decreases more slowly for the power inputs larger than 60W. For the pure working fluids PHP, the sequence of the thermal resistances is acetone, methanol, ethanol and water from small to large. Mameli et al. [12] conducted experiments on the thermal performance of a PHP working with an azeotropic mixture of water (4.5% wt.) and ethanol (95.5% wt.), in comparison to pure ethanol. No measurable difference has been recorded between the PHP running with the azeotropic mixture and the PHP running with pure ethanol, in terms of overall thermal resistance.

At different situations, different pure working fluids have their advantages [13]. But till now, mixtures used as working fluids in PHP have not been thoroughly investigated. The non-azeotropic mixtures, which have the characteristics of phase transition with temperature floating, can make heat source and working fluids match well in temperature [14]. Binary fluid is quite a new developing topic in recent years. Therefore, we can call as the pure fluid and binary fluid as a working fluid. Experimental investigation has been done to find the thermal performance of CLPHP by using different pure and binary mixture of working fluid. Analyze the thermal resistance by measuring the temperatures of the PHP.

2. Experimental setup and methodology

The details of the experimental setup are shown in Fig. 2. The setup consists of a closed loop PHP, temperature recorder, power supply unit, and water tank cooling system for condenser. Both the evaporation and adiabatic sections were well thermally insulated by the proper insulation materials. The PHP, consisting of 10 turns, is made of copper capillary tube having inner diameter is 2.0 mm; the outer diameter is 3.6 mm. The pitch distance between tubes was maintained 15 mm. The PHP consists of evaporation, adiabatic and condensation sections with the height of 50 mm for each section. The heating power is provided by a carefully designed power supply unit. Heating was done by oil bath and cooling by water tank. The power meter measures the AC voltage, the current and the corresponding power simultaneously. The Filling Ratio was maintained at 50%. The heating configuration was bottom heat orientation ($+90^\circ$). For temperature measurements, ungrounded sheathed eight thermocouples (OMEGA[®] Type-‘K’, $D = 0.5$ mm, accuracy $\pm 0.2^\circ\text{C}$) were used. All the thermocouples are mounted on the wall of the PHP. Three were symmetrically located in the evaporator section, three were attached to the condenser section, and another two were located in the adiabatic section, as depicted in Fig. 2.

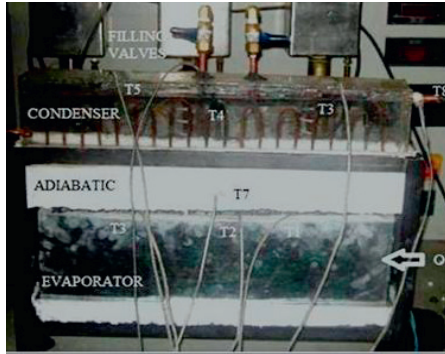


Fig.1. Experimental setup photograph

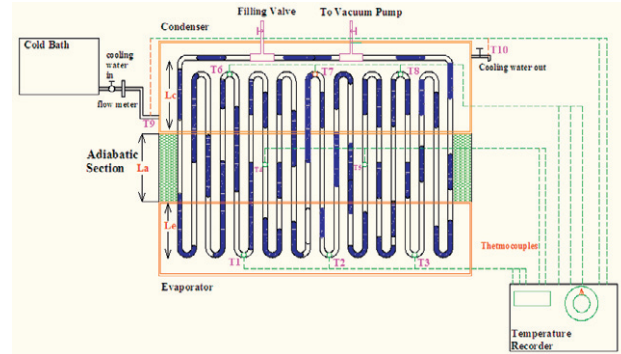


Fig. 2. Experimental setup Details.

About the tube design, the most important condition of PHP is the creation of the liquid slug. According to the literature review, Akachi [15] proposes that the appearance and movement of bubbles are affected by surface tension and buoyancy in the channel. Relation of surface tension and buoyancy could be explained by the dimensionless formula:

$$Eö = \frac{gD^2 (\rho_{liq} - \rho_{vap})}{\sigma} \tag{1}$$

When $Eö \approx 4$, the bubble will get seized on both side of the wall but not moving statically, and the liquid forms liquid slug flow, to calculate the pipe diameter D of PHP. The dimension formula is

$$D \leq 2 \times \sqrt{\frac{\sigma}{(\rho_{liq} - \rho_{vap})g}} \tag{2}$$

PHP loop is divided into evaporator, adiabatic and condensation composing of three sections. The intact structure of PHP loop and the experimental apparatus structure are in Fig. 2.

Table1: Thermophysical properties of working fluids at boiling temperature [17].

Working Fluid	T_b ($^{\circ}C$)	P_v (10^5 Pa)	h_{fg} (kJ/kg)	ρ (kg/m^3)		μ (10^{-7} Ns/m 2)		k (W/m-K)		σ (10^{-3} N/m)	C_p (kJ/kg-K)	
				liq	vap	liq	vap	liq	vap		liq	vap
Methanol	64.7	1.358	1119.59	750.8	0.566	3291.4	109.64	0.201	0.00182	18.87	2.52	1.601
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
Acetone	56.2	1.046	0520.56	748.5	2.123	2340.6	089.25	0.169	0.01398	19.09	2.28	1.385
Water	100	1.013	2251.20	958.7	0.597	2790.0	121.00	0.680	0.02480	58.91	4.22	2.034

3. Results and discussion

The PHP performance data (for pure and binary mixture of working fluid) were obtained according to the following procedure: Heat input was stepwise increased until a quasi thermal equilibrium was established. Then, the spatial temperatures and heat input were recorded, so the thermal resistances could be determined. The thermal resistance is defined by

$$R_{th} = (\bar{T}_e - \bar{T}_c) / \dot{Q} \tag{3}$$

Where, \bar{T}_e and \bar{T}_c are the average evaporator and condenser surface temperatures, defined as,

$$\bar{T}_i = (\bar{T}_{i,1} + \bar{T}_{i,2} + \bar{T}_{i,3}) / 3 \quad \text{where, } i = e \text{ or } c \tag{4}$$

\dot{Q} is heat input power to the PHP. Considering thermal losses, \dot{Q} can be determined by:

$$\dot{Q} = P - \dot{Q}_{loss} \tag{5}$$

Where, P is the input electrical power (measured with accuracy of $\pm 1.5\%$). \dot{Q}_{loss} is the heat loss, which was verified to be about 4% to 9%, depending on the heat load. In order to keep a good operation of working fluid in PHP, vertical bottom heat mode condition, 50% filling ratio was chosen for comparison with different working fluid as in the following test.

3.1. Effect of Pure and binary mixture Working Fluids PHP on the thermal resistance

From Fig. 3 and 4, it is clear that, for pure and binary working fluids of PHP, thermal resistance is smoothly decreases with the increasing heat input power [11]. With increasing heat input to the device, the evaporator temperature rises resulting in a greater density gradient in the tubes. Simultaneously the liquid viscosity also drops diminishing the wall friction. Initially at low heat input upto 20W, PHP is not sufficient to sustain a stable behavior. During the starting period fluid motion is chaotic, the circulation is not initiated. The respective adjacent tubes of the PHP become and remain alternatively hot and cold thereafter. The circulation direction which the liquid takes is arbitrary; remaining fixed for a given experiment but may change with different experimental runs. The PHP is best suitable for all working fluid at the range of 30 to 80 W. Thereafter behavior and the dry-out conditions of the thermal resistance are according to the boiling temperature of the respective working fluid. Whereas in Fig. 4, shows the trend of thermal resistance of all binary mixture are almost same as pure working fluids [12]. The PHP get dry-out for the water-methanol, water-acetone and water-ethanol is around at 85W, 80W and 90W heat input respectively, which is approximate the algebraic mean values of the boiling point of binary mixture. Almost the temperature trends have been recorded for the CLPHP working with pure and binary mixture working fluid. There were no quantifiable differences.

It is also clear that, behavior of the working fluid is strongly depending on the thermo-physical properties. Although there are many properties of working fluid, the latent heat of vaporization is the main property that strongly affects the motion of liquid slug and vapor bubble in the tube and the heat transfer of the PHP. Therefore this property of working fluid will be concentrated. As shown in Table 1, the boiling points and the latent heat of water are larger more than ethanol, methanol and acetone. Thus, water PHP can boil hardly in low power inputs. Furthermore, the thermal oscillation of water is hard for the large surface tension and dynamic viscosity at the start-up period. Therefore, the evaporation section temperature of water PHP is high and the condensation section temperature of water PHP is low, and accordingly, the thermal resistances are large. The behavior of the thermal resistance is according to the algebraic mean values of the latent heat of vaporization.

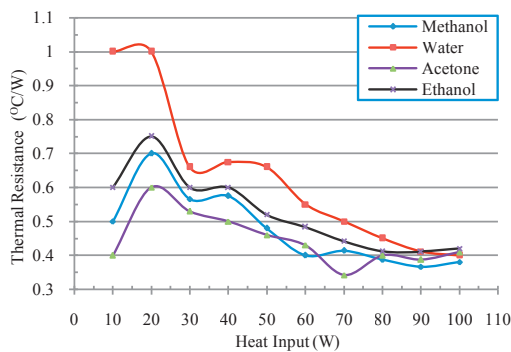


Fig. 3. Thermal resistance of pure working fluid PHP.

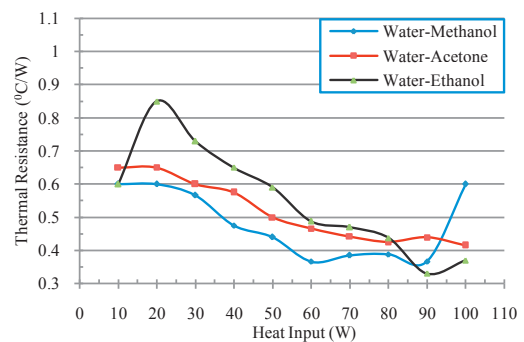


Fig. 4. Thermal resistance of binary working fluid PHP.

3.2. Effect of pure and Binary mixture Working Fluids PHP on an average evaporator temperature

The behavior of the average evaporator temperature along with the heat power input in the PHP for all pure working fluids is shown in Fig. 5. In high power inputs, the temperature of the evaporation section is high enough to keep the working fluids of high boiling points can boil vehemently and smoothly flow in one direction. Therefore, all the thermal resistances reduce flat and the differences between the working fluids are smaller with the increasing of heating power inputs. The evaporation section temperature of methanol is low for the high $(dp/dT)_{sat}$ and the specific heat. Thus, the evaporation section temperature of methanol is low in high power inputs.

Also in Fig. 6, represents the behavior of the average evaporator temperature along with the heat power input of the binary mixture working fluid in the PHP. The trends of all the binary mixture are almost same. During starting upto 20W, all the binary mixtures are having same evaporator temperature because no circulation of the fluid. In 20 to 80 W heat input, the average evaporator temperature of water-ethanol binary mixture is more at the same heat input followed by water-acetone and water-methanol according to the boiling point of the fluid. Thereafter 80 to 100W, mixed trend is found because of the dry-out condition at the various heat input. Water-ethanol and water-acetone is certainly mixed trend of evaporator temperature. Thus, the evaporation section temperature of water-methanol is low in high power inputs.

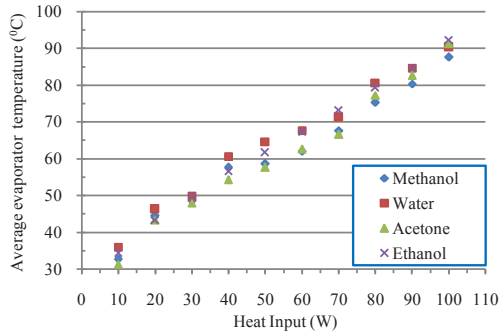


Fig. 5. Average evaporator temperature of pure working fluid PHP

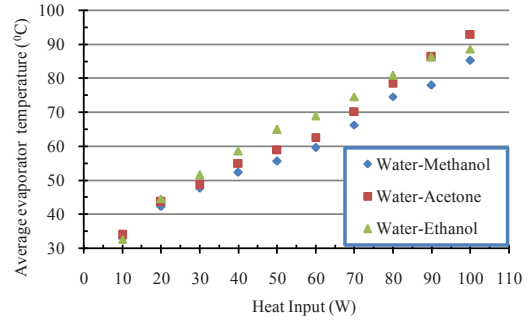


Fig. 6. Average evaporator temperature of binary working fluid PHP

3.3. Effect of Pure and binary mixture with same constituents working Fluids PHP on thermal resistance

In Fig. 7, water-methanol PHP gives the better thermal performance than pure working fluids of same constituent. It is also clear that during starting at 10 to 30W, the thermal resistance of the pure working fluid are varying drastically, but in 30 to 80W heat input, all fluids behaves same, in 80 to 100W heating zone, water-methanol binary mixture PHP is get dry-out. Whereas in Fig. 8, water- acetone binary mixture working fluid pure acetone gives the better thermal performance than pure water and binary mixture working fluids of same constituent. Initially, pure working fluids are varying due to no circulation of liquid. In the high heating zone 80 to 100W, all pure and binary working fluids are stable. Also in Fig. 9, water-ethanol binary mixture working fluid pure ethanol gives the better thermal performance than pure water and binary mixture working fluids of same constituent in low and moderate heat zone from 10 to 80W. But in high heat zone the situation is reverse.

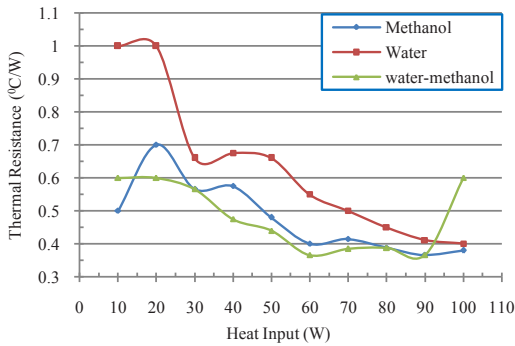


Fig. 7: Thermal resistance of water-methanol PHP

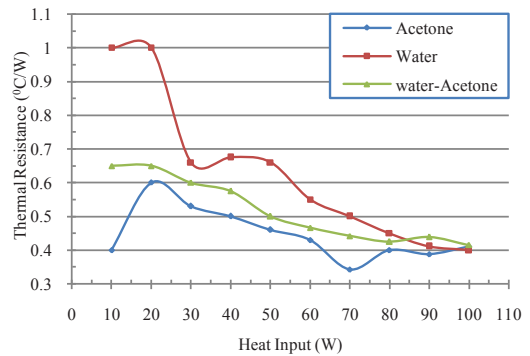


Fig. 8: Thermal resistance of water-acetone PHP

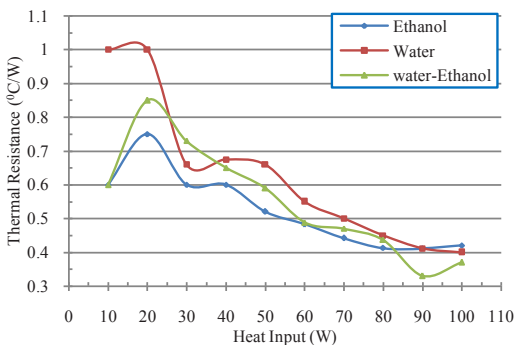


Fig. 9: Thermal resistance of water-Ethanol PHP.

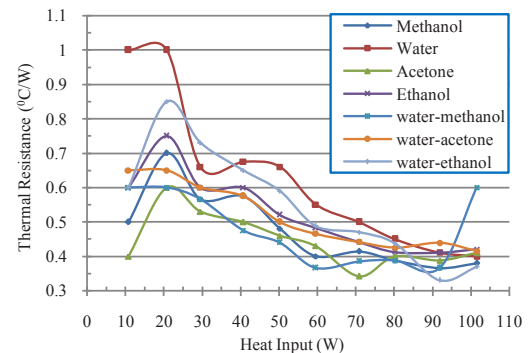


Fig. 10: Thermal resistance of all working fluid PHP

From Fig. 10, it is clear that trends of thermal resistance for all working fluids are approximately same in nature, as the difference in thermophysical values is minimal. Among all the working fluids, pure water is having more thermal resistance whereas pure acetone is having lesser thermal resistance. So in this PHP, pure acetone gives best thermal performance in comparisons with the other pure and binary mixtures working fluid.

4. Summary and conclusions

A closed loop pulsating heat pipes has been experimentally investigated to study the effects of pure and binary mixture working fluid on the thermal performance. The various working fluids have been demonstrated. Different fluids are beneficial under different operating conditions. An optimum tradeoff of various thermophysical properties has to be achieved depending on the imposed thermo-mechanical boundary conditions. The following main conclusions can be drawn from the study:

1. For pure and binary working fluids of PHP, thermal resistance is decreases with the increasing heat inputs. The dry-out for the water-methanol, water-acetone and water-ethanol PHPs are at 85W, 80W and 90W heat input respectively, which is approximate the algebraic mean values of the boiling point of binary mixture.
2. The evaporator temperature of methanol is low in high power inputs. A PHP of water-methanol binary mixture gives good thermal performance over other working fluids.
3. For the pure working fluids PHP, the sequence of the thermal resistances is acetone, methanol, ethanol and water from small to large. Whereas in binary mixture working fluid PHPs, the sequence of the thermal resistances is water-methanol, water-acetone and water-ethanol from small to large. In this PHP, pure acetone gives best thermal performance in comparisons with the other pure and binary mixtures working fluid. No measurable difference has been recorded between the PHP running with pure and binary mixture working fluids, in terms of overall thermal resistance.

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