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A Review on Thermal Performance of Closed Loop Pulsating Heat Pipe with different Working Fluid

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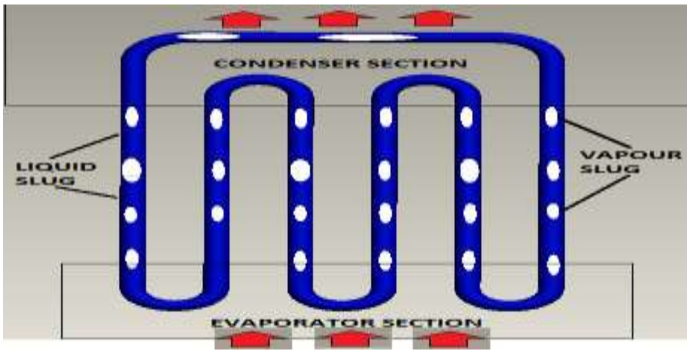
Abstract- *The closed-loop pulsating heat pipe is a type of small heat exchanger with a very high thermal conductivity. The purpose of invention is to meet the requirement for smaller heat transfer devices. It helps to transfer sufficient amount heat for heat dissipation applications in modern electronic devices. The closed loop pulsating heat pipe is made of a long capillary tube, bent into an undulating tube and connected at the ends to form a closed-loop with no internal wick structure. In this paper a review is established on the work done by various researchers on closed loop pulsating heat pipes for improving its thermal performance by using various working fluids and the effect of various operating parameter affecting the functioning of closed loop pulsating heat pipe. Thermal performance of the heat pipe depends on thermo physical properties (latent heat, specific heat capacity, viscosity, surface tension, density, etc) of the working fluid inside the heat pipe.*

Keywords- *closed loop, heat pipe, thermal performance, working fluid, fill ratio.*

I. INTRODUCTION

Akachi [1] very firstly introduced the pulsating (or) oscillating heat pipe (PHP), which was found to be a promising solution for future heat flux management and applications and is especially useful for its comparatively long distance transport ability. The closed loop Pulsating Heat Pipe (CLPHP) is a passive two-phase heat transfer device suitable for low power applications such as the cooling of electronics. It consists of a capillary tube (between 1 and 3 mm), usually made of copper, bent with many turns, which is firstly evacuated and then partially filled with a working fluid. Due to the capillary dimensions, the working fluid distributes itself naturally inside the tube as an alternation of liquid slugs and vapor bubble. When ‘evaporator section’ of closed-loop pulsating heat pipe is subjected to heat or high temperature, the working fluid, which is in liquid slug form, will evaporate, expand, and move through the no heat transferring zone, or ‘adiabatic section’, toward a cooler Section, ‘condenser section’ namely. Then, the vapour plugs will condense, collapse, and relinquish the heat into the environment. Consequently, the vapour plug evaporating in the evaporator section will consequently flow to supersede the vapour plug collapsing in the condenser section. Due to this mechanism, the working fluid can circulate and perpetually transfer heat in a cycle.The consequential feature of the heat pipes is its faculty to convey a substantial magnitude of heat over its length with a diminutive temperature drop. Figure 1 shows the structure of closed loop pulsating heat pipe.



“Figure. 1 Schematic diagram of closed loop pulsating heat pipe with evaporator and condenser section.”

Selection of working fluid depending upon any single thermodynamic property can’t be done successfully. It can be observed from literature reviews on past studies that most of the studies on effect of working fluids on thermal performance of Closed loop pulsating heat pipe frequently defined the latent heat as a quantitative property to identify a type of working fluid because heat transfer mechanism inside the Closed loop pulsating heat pipe can be maintained due to evaporation and condensation of the working fluid, which directly relate to the latent heat. However, it was found that when latent heat of working fluid incremented, thermal performance of the vertical closed loop pulsating heat pipe has possibility to transmute in both ways, i.e., increment and decrement. A First consideration in the cull of a congruous working fluid is the operating vapor temperature range. Within the approximate temperature band, (50 to 1500 C) several possible working fluids may subsist. For the application considered a variety of characteristics must be examined in order to determine the most acceptable of these fluids.

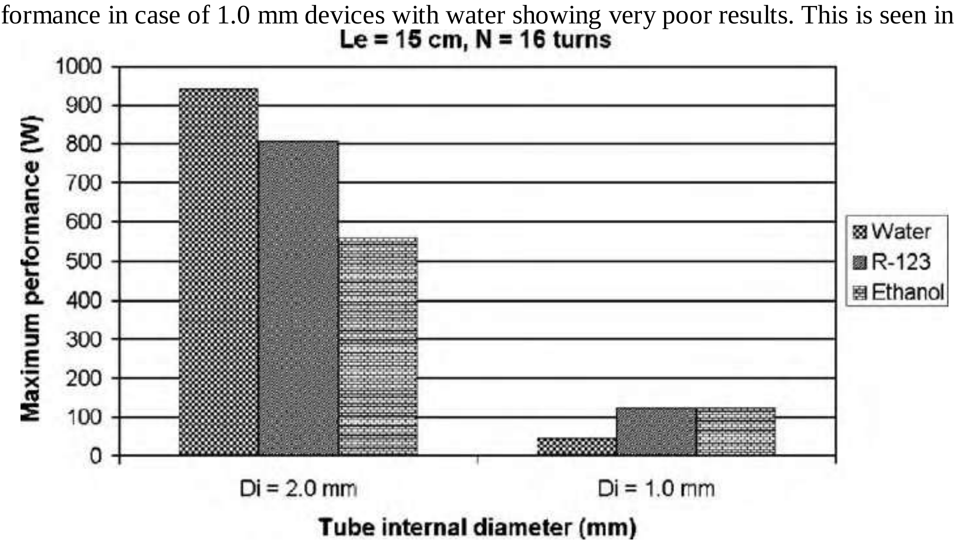
II. Past studies [2-3]

It suggests that the working fluid employed for oscillating/pulsating heat pipes should have the following properties:

A. **High value of (dP/dT)sat**: It ensures that if there is a small change in temperature difference, there will be a large change in saturated pressure inside the bubbles which can affect the bubble pumping action i.e. it can change heat transfer performance of OHP.
B. **Dynamic viscosity** should be small so that it will generate lower shear stress.
C. **Latent heat** of working fluid must be low so that there will quick bubble generation and collapse. It also reveals that sensible heat is the predominant heat transfer mode.
D. **High specific heat** can compliment low latent heat of working fluid.
E. **Low surface tension** may create additional pressure drop. Selection of working fluid directly related to working fluid properties. The properties of working fluid affects heat transfer rate of OHP. Along with these properties of working fluid, compatibility of working fluid with the heat pipe tube material is also very important.

The thermodynamic attributes of water makes it better than any other fluids for the pulsating heat pipes for most commercial electronics cooling applications. Its high latent heat spreads more heat with less fluid flow. It results in low pressure drops and high power throughout. Waters high thermal conductivity minimizes the temperature difference associated with conduction through the two phase flow in the PHP. Also water is a safe substance. Albeit water's high surface tension allows it to generate a large capillary force and allow the heat pipe to operate in any orientation, this may have adverse effect on the operation of PHP. The high surface tension may cause additional friction and hinder the two phase flow oscillation in the PHP. Methanol with lower surface tension (about 1/3rd of water) is a good substitute particularly if the heat pipe is used for sub 0C application [4]

S. Khandekar et.al. [8] [2002] were conducted experiments on a PHP made of copper capillary tube of 2-mm inner diameter. Three different working fluids viz. water, ethanol and R-123 were employed. The PHP was tested in vertical (bottom heat mode) and horizontal orientation. The results strongly demonstrate the effect of input heat flux and volumetric filling ratio of the working fluid on the thermal performance of the device. Wide range of experimental studies of pulsating heat pipes is thereby providing vital information on the parameter dependency of their thermal performance by P.Charoensawan*et.al.* [9] [2003]. The influence characterization has been done for the variation of internal diameter, number of turns, working fluid and inclination angle of the device. CLPHPs are made of copper tubes of internal diameters 2.0 and 1.0 mm, heated by constant temperature water bath and cooled by constant temperature water–ethylene glycol mixture. The number of turns in the evaporator is varied from 5 to 23. The working fluids employed are water, ethanol and R- 123. The results indicate water filled devices showed higher performance as compared to R-123 and ethanol in vertical orientation for the 2.0 mm devices. In contrast R-123 and ethanol showed comparable performance in case of 1.0 mm devices with water showing very poor results. This is seen in Fig.2



"Figure. 2 Graph related with Max performance Vs Tube internal dia."

The other parameters which should be evaluated are as follows.

A. Inner tube diameter

The inner diameter of PHP must be decided carefully so that gravitational force of the working fluid can be overcome by surface tension forces. The critical diameter of PHP occurs when the value of bond number is equals 2. Bond number is the ratio of gravitational force to the surface tension force. It can be given as:

$$Bo = \frac{g(\rho_l - \rho_v)D}{\sigma}$$

Where σ, g, $\rho_{liq,}$ and ρ_{vap} represent the surface tension, gravitational constant, density of liquid and Density of vapor [5]. The operational limitation of CLOHP, which includes the effects of inner diameter, filling ratio, operational orientation and heat input flux on thermal performance of OHP was studied by Yang et al [6]. They found that, 2mm ID tubes giving best performance in the vertical orientation while CLOHP with 1 mm ID tubes have same performance in all the orientations.

B. Filling ratio of Working fluid

The fill ratio is defined as the fraction by volume of the heat pipe, which is initially filled with the liquid. There are two distinct operational fill ratio limits, 0% and 100%. At 0%, the OHP is in a pure conduction mode and has a very high undesirable thermal resistance. For this case there is not enough working fluid for the formation of distinct slugs and there is a tendency for evaporator dry out to occur. At 100%, there are very few bubbles present which causes the OHP to operate as a single phase thermosyphon. While under this condition, oscillations do not occur, but substantial heat can still be transferred due to the liquid circulation in the pipe by thermally induced buoyancy. The thermosyphon action is maximum for an OHP in a vertical orientation and stops in the horizontal orientation [10].

In addition, to the operational fill ratio limits, there are three distinct operational fill ratio regions, near 100%, near 0% and the OHP true working range. For the case of near 100% filled the working fluid inside the OHP cannot form enough bubbles to generate the required perturbations, hindering the performance of the OHP. Even buoyancy induced liquid circulation is hindered from the added surface tension from the bubbles. For the near 0% case, there is not enough liquid present in the OHP to form enough distinct slugs. Under this condition, there is also a tendency for the evaporator to dry out. The optimal performance for an OHP is somewhere between these two extremes, which is known as the OHP true working range. For this, the filled ratio is usually somewhere between 20% and 70%, which causes a two-phase flow to develop and allows the OHP to act as a true oscillating device.

The exact working range will differ for various working fluids, operating parameters and constructions. A lower fill ratio will produce more bubbles and increases the intensity of oscillations, but there is also less liquid mass for sensible heat transfer. Conversely, a higher fill ratio will generate fewer bubbles, reducing the perturbations and reducing the overall performance of the OHP [10].

C. High Specific Heat

It is given the fact that sensible heat is playing the major role in heat transfer in the pulsating mode of pulsating heat pipe operation; albeit there are no specific studies which suggest the effect of specific heat of the liquid on the thermal performance. It is to be noted that if a flow regime change from slug to annular takes place the respective roles of latent and sensible heat transport mechanism may considerably change [7].

D. **Low surface tension**: which, in conjunction with dynamic contact angle hysteresis may create additional pressure drop [6].

E. Compatibility

Selection of working fluid directly related to working fluid properties. The working fluid properties affects heat transfer rate of OHP. Beyond these properties of working fluid, compatibility of working fluid with the heat pipe tube material is also very important. If working fluid is not compatible with the tube material then it can cause various adverse effects on the performance of OHP.

Compatibly of some working fluids with different tube materials are given as in table I :

"Table I – compatibility of working fluid with different tube materials [3]"

Tube Material	**Working fluid**		
	Water	**Acetone**	**Ammonia**
Copper	RU	RU	RU
Aluminum	GNT	RL	RU
Stainless steel	GNT	MC	RU
Nickel	MC	MC	RU

Where, RU- recommended by past successful usage; RL-recommended by literature; MC- May compatible GNT-generation of gas all temperatures.

III. Working fluid temperature range

Selection of working fluid in OHP depends on the temperature range for which it is to be designed. Useful temperature range of various working fluids which can be useful for the selection of required working fluid, Some commonly used working fluid having range above 0^0C can be given as in table II

"Table II –Temperature range of different working fluids [2]"

Sr. No.	Working fluid	Melting point $in^0 C$	Boiling point $in^0 C$	Operating Range $in^0 C$
1	Helium	-271	-261	-271 to -269
2	Nitrogen	-210	-196	-203 to -160
3	Ammonia	-78	-33	-60 to 100
4	Acetone	-95	57	0 to 120
5	Methanol	-98	64	10 to 130
6	Ethanol	-112	78	0 to 130
7	Heptanes	-90	98	0 to 150
8	Water	0	100	30 to 200

For the proper working fluid selection, the Clausius-Clayperon relation could be applied.

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{i_{lv}}{T_{sat} v_{lv}}$$

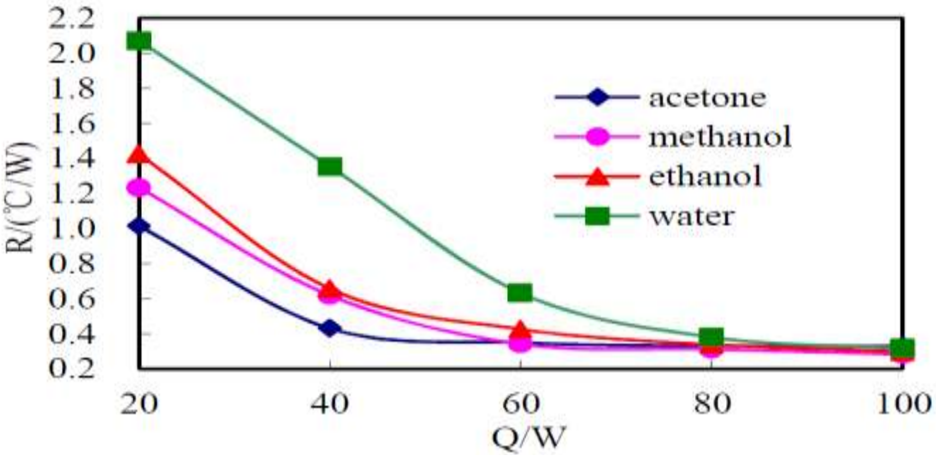
Where, high values for the magnitude of the derivative (*d*P/*d*T)*sat* (slope) must be achieved. This shows that a small change in the saturation temperature will result in a large influence in the saturation pressure, which will directly affect the pumping forces of the PHP during its operation. Other important parameters should also be evaluated, such as: Latent heat of vaporization (i_{iv}): high values of latent heat of vaporization desirable and important regarding the Clausius-Clayperon relation, which can reflect little temperature drop driving force. On the other side, this parameter should present a reduced value in order to result in faster bubble generation and collapse.

"Table III. Thermo physical properties of different working fluid at 1 atm"

Working fluid	T_s $in^0 C$	C_{pl} kJ/kgK	k W/mK	h_{fg} kJ/kg	$\mu_l \times 10^5$ $Pa-s$	$\sigma \times 10^3$ N/m
Methanol	64.7	2.84	0.212	1101	0.60	22.6
Ethanol	78.3	2.39	0.172	846	1.15	22.8
Acetone	56.2	2.35	0.170	523	0.32	23.7
Water	100	4.18	0.599	2257	1.01	72.8

IV) Effect of Pure Working Fluids PHP on the Thermal Resistance

For 50 % filling ratio (FR) ten turns and different heat inputs of 10 to 100W supplied to PHP, the PHP was in position of vertical bottom heat mode. Working fluids are selected as ethanol, methanol, acetone, water and different binary mixtures. Experimental study on PHP denoted working fluid is an important factor for the performance of PHPs. The result shows that, the thermal resistance decreases more rapidly with the incrementation of the heating power from 20 to 60 W, whereas slowly decreases above 60 W. For the pure working fluids PHP, the sequence of the thermal resistances is acetone, methanol, ethanol and water from minute to large. In this PHP, pure acetone gives best thermal performance in comparisons with the other pure working fluid.

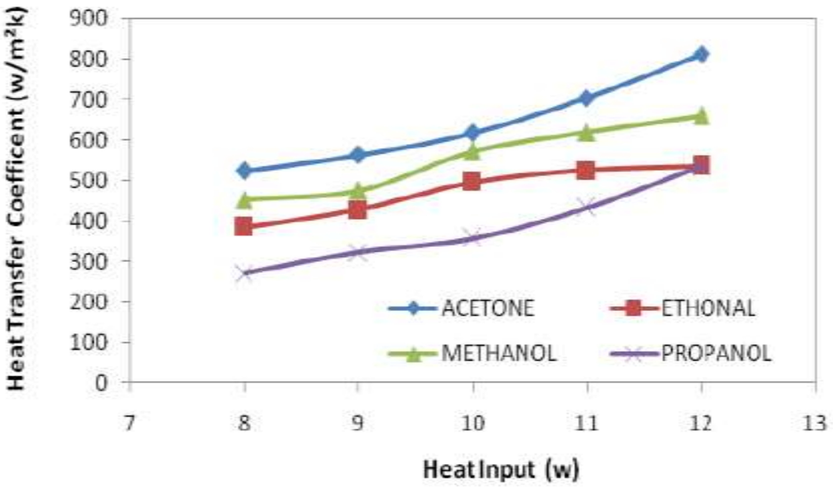


“Figure 3. Thermal resistance of pure working fluids of closed loop pulsating heat pipe at different heat Input”

V) Effect of Working Fluid on Heat Transfer Coefficient

The below figure no. 4 explains the graph of heat transfer coefficient with heat input for acetone, methanol, ethanol as working fluid at 60 % fill ratio.

It can be observed that as the heat input increases, the heat transfer coefficient for all the working fluids increases. Also it is seen that acetone is having higher heat transfer coefficient compared to all other working fluids. As the temperature difference between evaporator and condenser is decreases for acetone the heat transfer coefficient will increases.



“Figure 4. Effect of working fluid on heat transfer coefficient”

VI. Unsolved Issues Related To Working Fluids

1. At different situations, various pure working fluids have their advantages. But till now, mixtures utilized as working fluids in PHP have not been exhaustively investigated. The non-azeotropic coalescences, which have the characteristics of phase transition with temperature floating, can make heat source and working fluids match well in temperature [11].
2. The optimum quantity of working fluid needed depends on different parameters and is still an area of research [9].

VII. CONCLUSION

PHPs are highly attractive heat transfer elements, which due to their excellent thermal performance, simple design and cost effectiveness may find wide applications. Since the invention of $\mathrm{PHP_S}$ in the early nineties, so far they have found market niches in electronics equipment cooling. The work compiled here significantly increases the construal of the phenomena and effect of working fluids that govern the thermal performance of pulsating heat pipes. Many unsolved issues related to working fluids still exist, but continued exploration should be able to overcome these challenges.

Also different working fluids have their own advantages and disadvantages in their respective field of application depending on their operating temp limits. Once the boundary conditions are known it becomes easier to select the best working fluid.

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