Effect of Working Fluid on Thermal Performance of Closed Loop Pulsating Heat Pipe: A Review

Pramod R. Pachghare
Government College of Engineering, Amravati.
Maharashtra,
India444 604

Ashish M. Mahalle
Laxminarayan Institute of Technology, Nagpur.Maharashtra,
India-440 001

Shekhar Khedkar
Government College of Engineering, Amravati.
Maharashtra,
India-444 604

ABSTRACT

Thermal management of electronics semiconductor technology is elixir to transform dream and imagination of the designers into reality. Motivation and need for research in development of novel cooling strategies for modern electronics is of paramount importance. Pulsating Heat Pipes, a novel research topic in heat pipe science, are new two-phase heat transfer devices that rely on the oscillatory flow of liquid slug and vapor plug in a long miniature tube bent into many turns. The unique feature of PHPs, compared with conventional heat pipes, is that there is no wick structure to return the condensate to the heating section; thus, there is no countercurrent flow between the liquid and vapor.

This paper highlights the thermo-hydrodynamic characteristics of these devices. State of art indicates that's at least three thermo-mechanical boundary conditions have to be met for the device to function properly as pulsating heat pipe. This includes the internal tube diameter, the applied heat flux and amount of the working fluid in the system. Additionally the numbers of turns of the device and thermo-physical properties of the working fluid also play a vital role in determining the thermal behavior. Apart from this, paper is a literature review on pulsating heat pipe technology and work performed by researcher; it investigates experimental work performed on operating mechanisms of PHP, by using various working fluids. Finally, unresolved issues on the mechanism of PHP operation with different type of working fluids, and application are discussed.

Keywords

Pulsating heat pipe; oscillating heat pipe

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. Unlike traditional heat pipes, PHPs do not need a wicking structure to transport the liquid and can work at higher heat fluxes. 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 cry preservation, the spacecraft thermal control system, etc.

A Pulsating heat pipe consists of meandering tube of capillary dimensions with many U-turns, as see in figure 1[2]. In contrast to a conventional heat pipe, there is no additional capillary structure inside the tube. There are three ways to arrange the tube- Open Loop System, Closed Loop System, and Closed Loop System with additional flow control check valves.

As the name suggest, in close loop structure, the tube is joined end to end. The tube is evacuated and then filled partially with working fluid, which distributes itself naturally in the form of liquid vapor plugs and slugs inside the capillary tube. One end of this tube receives heat, transferring it to the other end by pulsating action of the liquid vapors/ bubble slug system. There may exist an optional adiabatic zone in between evaporator and condenser.

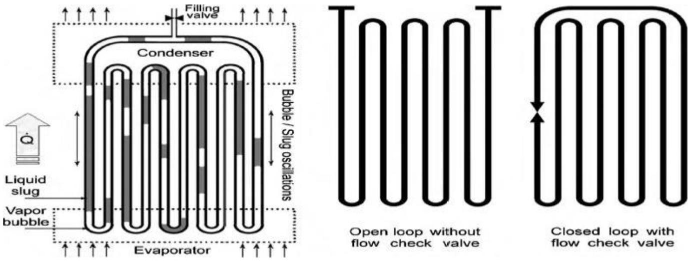

Figure1. Schematic of a pulsating heat pipe and its design variations [2]

The PHP is first evacuated and then partially filled with the working fluid. Effects from surface tension cause the formation of liquid slugs interspersed with vapor bubbles. When one end of the bundle of turns of the undulating capillary tube is subjected to high temperature, the working fluid inside evaporates and increases the vapor pressure, which causes the bubbles in the evaporator zone to grow. This pushes the liquid column toward the low temperature end (condenser). The condensation at the low temperature end will further increase the pressure difference between the two ends. Because of the interconnection of the tubes, motion of liquid slugs and vapor bubbles at one section of the tube toward the condenser also leads to the motion of slugs and bubbles in the next section toward the high temperature end (evaporator). This works as the restoring force. The inter-play between the driving force and the restoring force leads to oscillation of the vapor bubble and liquid slugs in the axial direction. The frequency and the amplitude of the oscillation are expected to be dependent on the shear flow and mass fraction of the liquid in the tube.

2. PRINCIPLES OF OPERATION

2.1 Thermodynamic Principles

Heat addition and rejection and the growth and extinction of vapor bubbles drive the flow in a PHP. Even though the exact features of the thermodynamic cycle are still unknown, Groll and Khandekar [3] described it in general.

2.2 Fluid Dynamic Principles

Fluid flow in a capillary tube consists of liquid slugs and vapor plugs moving in unison. The slugs and plugs initially distribute themselves in the partially filled tube. The liquid slugs are able to completely bridge the tube because surface tension forces overcome gravitational forces. There is a meniscus region on either end of each slug caused by surface tension at the solid/liquid/vapor interface. The slugs are separated by plugs of the working fluid in the vapor phase. The vapor plug is surrounded by a thin liquid film trailing from the slug.

2.3 Heat Transfer Principles

As the liquid slugs oscillate, they enter the evaporator section of the PHP. Sensible heat is transferred to the slug as its temperature increases, and when the slug moves back to the condenser end of the PHP, it gives up its heat. Latent heat transfer generates the pressure differential that drives the oscillating flow. The phase change heat transfer takes place in the thin liquid film between the tube wall and a vapor plug and in the meniscus region between the plug and slug, which requires complex analysis.

3. INFLUENCE PARAMETERS AFFECTING PHP PERFORMANCE

Looking into the available literature, it can be seen that six major thermo-mechanical parameters have emerged as the primary design parameters affecting the PHP system dynamics. These include [4]:

- Internal diameter of the PHP tube,
- Input heat flux to the device,
- Volumetric filling ratio of the working fluid,
- Total number of turns,
- Device orientation with respect to gravity, and
- Working fluid thermo-physical properties.

Other conditions which influence the operation are:

- Use of flow direction control check valves,
- Tube cross sectional shape,
- Tube material and fluid combination, and
- Rigidity of the tube material, etc.

Apart from these variables, the performance is also strongly linked with the flow patterns existing inside the device (which in turn depends on the complex combination of other design parameters). Various flow patterns other than capillary slug flow, e.g. bubbly flow, developing or semi-annular flow and fully developed annular flow (in case of CLPHPs) have also been reported which have a significant effect on the thermal performance of the device. The state of the art strongly suggests that a comprehensive theory of the complex thermo hydrodynamic phenomena governing the operation of PHPs is not yet available. Authoritative quantitative data base explicitly connecting the thermal performance with individual influence parameters is limited but growing continuously. With the available information, very preliminary conclusions regarding the complete design procedure of PHPs may be made.

3.1 Tube Diameter

The internal tube diameter is one of the parameters which essentially define a PHP. The physical behavior adheres to the 'pulsating' mode only under a certain range of diameters. The critical Bond number (or Eötvös) criterion gives the tentative design rule for the diameter. The theoretical maximum inner diameter of capillary tube can be calculated as-

$$D_{cri} = 2\sqrt{\left\{\frac{\sigma}{g(\rho_l - \rho_v)}\right\}} \qquad (3.1)$$

Or

$$E\ddot{0} = [B_0]^2 = 4 \qquad (3.2)$$

Where:

Bo	Bond number = $d \cdot (g(\rho_l - \rho_v)/\sigma)0.5$
D	Tube internal diameter (m)
Eö	Eötvös number = $(Bo)^2$
G	Acceleration due to gravity (m/s^2)
S	Surface tension (N/m)
R	Liquid density (kg/m^3)

If $D < D_{cri}$, surface tension forces dominate and stable liquid plugs are formed. However, if $D > D_{cri}$, the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease. The OHP may operate as an interconnected array of two-phase thermosyphons.

3.2 Applied Heat Flux

The applied heat flux affects the following:-

- Internal bubble dynamics, sizes and agglomeration/
- breaking patterns,
- Level of perturbations and flow instabilities, and
- Flow pattern transition from capillary slug flow to
- semi-annular and annular.

PHPs are inherently suitable for high heat flux operation. Since the input heat provides the pumping power, below a certain level, no oscillations commence. In case of CLPHPs, a Unidirectional circulating flow has been observed at high heat fluxes. In addition, the flow also gets transformed from oscillating slug flow to annular flow. Once a flow direction is established, alternating tubes sections become hot and cold (hot fluid flows from evaporator in one tube and cold fluid from the condenser flows in the adjacent tube). Further increase of heat flux will lead to some dry out mechanism(s) induced by thermo-hydrodynamic limitations. These have not been clearly identified and studied so far.

3.3 Working Fluids

A First consideration in the selection of a suitable working fluid is the operating vapor temperature range. Within the approximate temperature band, (50 to 150^{o}C) several possible working fluids may exist. A variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application considered. The prime requirement are: compatibility with heat pipe material, thermal stability, wettability, reasonable vapor pressure, high latent heat and thermal conductivity, low liquid and vapor viscosities, and acceptable freezing point.

For most commercial electronics cooling applications, the thermodynamic attributes of water makes it better than any other fluids for the pulsating heat pipes. Its high latent heat spreads more heat with less fluid flow. This result in low pressure drops and high power throughout. Its high thermal conductivity minimizes the temperature difference associated with conduction through the two phase flow in the PHP. Water is also a safe substance.

Although water high surface tension allow a it to generate a large capillary force and allow the heat pipe to operate in any orientation. It may have adverse effect on the operation of PHP. in other words, the high surface tension may cause additional frictional 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 ^{0}C application [5].

3.4 Total Number of Turns

The number of turns increases the level of perturbations inside the device. If the number of turns is less than a critical value, then there is a possibility of a stop-over phenomenon to occur. In such a condition, all the evaporator U-sections has a vapor bubble and the rest of the PHP has liquid. This condition essentially leads to a dry out and small perturbations cannot amplify to make the system operate self-sustained.

4. DESIRABLE PROPERTIES OF WORKING FLUID

The experience gained so far by earlier studies suggests that the working fluid employed for pulsating heat pipes should have the following properties:

High value of $(dP/dT)_{sat}$: ensuring that a small change in evaporator temperature generates a large change in corresponding Psat inside the generated bubble which aids in the bubble pumping action of the device. The same is true in reverse manner in the condenser

- Low dynamic viscosity: This generates lower shear stress.
- Low latent heat: should be desirable, aiding quick bubble generation and collapse, given the fact that sensible heat is the predominant heat transfer mode.
- High specific heat: is desirable complimenting the low latent heat requirement; although there are no specific studies which explicitly 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, as explained earlier. This aspect requires further investigation.
- Low surface tension: This, in conjunction with dynamic contact angle hysteresis may create additional pressure drop.

The above noted property trends are based on the available knowledge so far and are subject to change as more studies reveal the thermo-mechanical physics. In addition, quite often instead of individual thermo physical properties, groups of properties affect complex real systems like PHPs. In the wake of flow pattern dependency of the thermal performance of PHPs, different operating regimes of the device are likely to be affected by different groups of thermo physical properties [3].

5. EFFECT OF WORKING FLUIDS

Although Loop Heat Pipes (LHPs) were first developed and tested with water or acetone as working fluids for power electronic cooling, most of the detailed results on PHP performance were presented when ammonia was used as the working fluid for the spacecraft thermal control. With the new interest of using PHPs for computer cooling, fluids like water, acetone, methanol or ethanol have been used. The first experimental results showed a significant effect of the working fluid on the LHP performance [6].

The thermo physical properties of the working fluid coupled with the geometry of the device have profound implications on thermal performance of the device. This affects the following:

- The relative share of latent and sensible heat in the overall heat throughput;
- The possibility of having different flow patterns in the device, e.g. slug–annular flow regime inter-transition;
- The average flow velocity and overall pressure drop (including effect of gravity);
- Bubble nucleation, collapse, shapes, agglomeration and breakage; bubble pumping action, etc. [12]

Kaya and Ku [7] have compared the LHP performance by using three different working fluids: ammonia, water and acetone. The model results are shown in Figure 2. It can be seen that the PHP operating limits are different for each working fluid. The water and acetone PHPs are limited by the absolute vapour pressure at low power levels: the absolute vapour pressure represents the maximum pressure that is available to overcome the total system pressure drops, even when the theoretical capillary pressure head is higher than the total pressure drops. A low pressure corresponding to a fluid temperature near the freezing point severely limits the PHP operation.

While ammonia exhibits many desirable heat transfer characteristics, its freezing point is too high to prevent freezing in the condenser line during a safe mode on a satellite platform. According to Rodriguez and Pauken [8], propylene is a good fluid since it has a lower freezing point and relatively good heat transfer properties. A prototype LHP has been tested with both ammonia and propylene as working fluids. At low sink temperature, the PHP performance was similar for heat loads lower than 100 W (Figure 3). For higher heat loads, the thermal conductance of the ammonia PHP was approximately four times greater than that of the propylene PHP one.

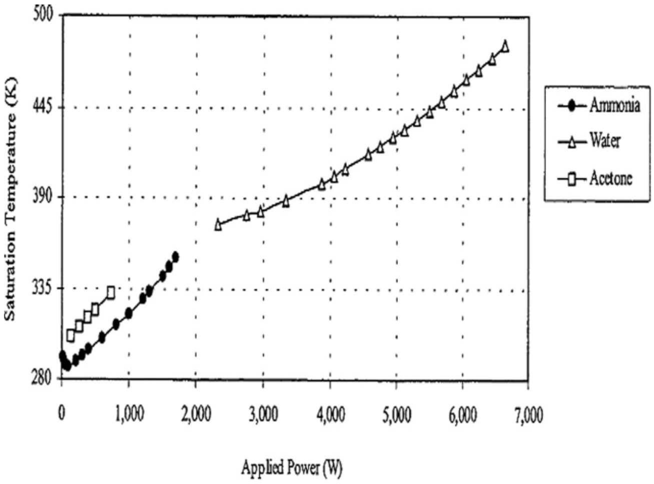

Fig. 2. Effect of the working fluid on the LHP operating temperature (Kaya and Ku [7]).

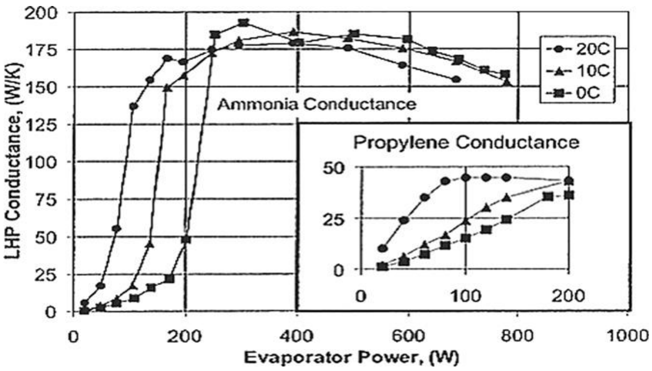

Fig. 3. Comparison of the thermal conductances of ammonia and propylene LHPs

According to Baumann and Rawal [10], the liquid thermal conductivity has two significant effects on the LHP performance. Firstly, a low liquid conductivity reduces the heat transfer coefficient in the evaporator, thus limiting the heat transport capability. Secondly, a low liquid thermal conductivity reduces the LHP operating temperature by reducing the wick effective conductivity.

S.Khandekar *et.al.* [11] 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.* [12] . 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 of1.0 mm devices with water showing very poor results.

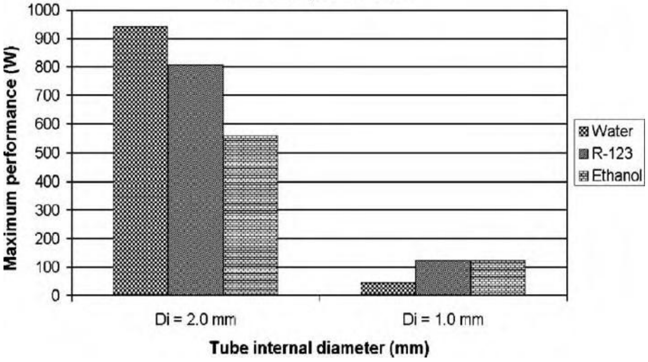

Fig. 5. Effect of working fluid on the thermal performance [12].

Study on behavior and efficiency of closed loop pulsating heat pipe (CLPHP) under low temperature (less than room temperature).

F.DeSouza *et.al* [13] studied an experimental investigation of a co_2 pulsating heat pipe This paper attempts to present preliminary experimental results of pulsating heat pipes operating with an evaporator average temperature ranging from -20°C to 5°C and having carbon dioxide (CO_2) as the working fluid. The present results enables one to conclude that CO_2 can be used as a working fluid to efficiently transfer heat at low temperature.

The effect of evaporator section lengths and working fluids on operational limit of closed loop oscillating heat pipes with check valves (CLOHP/CV) with R123 Ethanol and Water were used as the working fluids have aims by P. Meena *et.al*. [14] [2009]. A set of CLOHP/CV was made of copper tubes in combination of following dimension: 1.77 mm inside diameter: 10 turn: 5, 10 and 15 cm equal lengths for evaporator, adiabatic and condenser sections. The working fluid was filled in the tube at the filling ratio of 50%. The evaporator section was given heat by heater while the condenser section was cooled by volume water in a cold bath. The results obtained, as follows. When working fluids change from R123 to Ethanol and water the critical heat flux decreased.

N.Kammuang-lue *et.al.* [15] have studied the effect of working fluids on heat transfer characteristics of the closed loop pulsating heat pipe at critical state. These results can be compared with the results from the study of the effect of working fluids on heat transfer characteristics of closed end pulsating heat pipe at the same state. The closed loop pulsating heat pipe was made by a long copper capillary tube with the inner diameter of 2.03mm and bent into 10 turns. The evaporator section length was 100mm. The adiabatic and condenser section length were equaled to the evaporator length. R123, ethanol and water was used as the working fluid. The low-voltage high current power transformer was used as the heat source and the cooling medium was the solution of water and ethylene-glycol with 1:1 mixing volume ratio. The adiabatic temperature was controlled at 50^0C. It is found from the study that, the higher latent heat of the working fluid, the higher critical heat flux. When the working fluid changes from R123 to ethanol and water respectively, the average critical heat flux increases from 7.84 kW/m^2 to 14.24 kW/m^2 and 44.97 kW/m^2 respectively

Qu and Ma [16] 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. Also concluded that water should not be selected as working fluid based on the startup performance of PHP, the startup performance can be improved by using a rougher surface, controlling vapor bubble type, and selecting a right working fluid, the globe vapor bubble needs smaller superheat than the one with the Taylor vapor bubble.

6. UNSOLVED ISSUES RELATED TO WORKING FLUIDS

Literature reveals [22] that many working fluids with distinctly varying properties have been tried. Since the domain of experimental activity is quit widespread, all the fluids have not been tested in the entire experimental parameter matrix and amount of data is still growing. At this stage it is certainly difficult to prescribe or proscribe a certain fluid unless all the boundary conditions are exactly known and individual effects have been explicitly quantified. Different working fluids seem to be beneficial at different operating conditions. An optimum trade off of various thermo-physical properties has to be achieved depending on the imposed thermo-mechanical boundary conditions. This certainly requires further research.

At different situations, different pure working fluids have their advantages. 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 [22].

The optimum quantity of working fluid needed depends on various parameters and is still an area of research [12].

7. CONCLUSION

PHPs are highly attractive heat transfer elements, which due to their simple design, cost effectiveness and excellent thermal performance may find wide applications. Since their invention in the early nineties, so far they have found market niches in electronics equipment cooling. The work compiled here significantly increases the understanding 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.

8. REFERENCES

[1] Akachi H, Structure of a heat pipe. US Patent No. 4921041, 1990.

[2] Piyanun Charoensawan, Sameer Khandekar, Manfred Groll, Pradit Terdtoon. (2003): “Closed loop pulsating heat pipes Part A: parametric experimental investigations”. Applied Thermal Engineering, Vol. 23, pp. 2009–2020.

[3] Groll, M., and Khandekar, S., Pulsating Heat Pipes: Progress and Prospects, Proc. International Conference on Energy and the Environment, Shanghai, China, 2003, vol. 1, pp. 723–730.

[4] P. Charoensawan, S. Rittidech (2004) “Closed And Open Looped Pulsating Heat Pipes”. 13th international heat pipe conference, shanghai, china.

[5] G. Karimi t, J.R. Culham “Review and Assessment of Pulsating Heat Pipe mechanism For High Heat Flux Electronic Cooling” Inter society conference on thermal phenomenon 2004.

[6] Stéphane Launay, Valérie Sartre, Jocelyn Bonjour (2007): “Parametric analysis of loop heat pipe operation: a literature review” International Journal of Thermal Sciences 46 (2007) 621–636

[7] T. Kaya, J. Ku, A parametric study of performance characteristics of loop heat pipes, in: International Conference On Environmental Systems, Denver, July 1999 (SAE paper 1999-01-2006), 7

[8] J.I. Rodriguez, M. Pauken, Performance characterization and model verification of a looph heat pipe, in: International Conference On Environmental Systems, Toulouse, July 2000 (SAE paper 2000-01-2317), 7

[9] J.H. Boo, W.B. Chung, Thermal performance of a small-scale loop heat pipe with PP wick, in: 13th IHPC, Shanghai, China, 21–25 September 2004, pp. 259–264.

[10] J. Baumann, S. Rawal, Viability of loop heat pipes for space solar power applications, in: AIAA Thermophysics Conference, 35th, Anaheim, CA, 11–14 June 2001 (AIAA 2001-3078), 10

[11] S. Khandekar, Nicolas Dollinger, and Manfred Groll “Understanding operational regimes of closed loop pulsating heat pipes: an experimental study”. Applied Thermal Engineering 23 (2003) 707–719.

[12] P. Charoensawan, S. Khandekar, Manfred Groll, and Pradit Terdtoon “Closed loop pulsating heat pipes Part A: parametric experimental investigations”. Applied Thermal Engineering 23 (2003) 2009–2020.

[13] Franco Andrey Silvério De Souza “An Experimental Investigation of A Co2 Pulsating Heat Pipe” 14th International Heat Pipe Conference (14th IHPC), Brazil, April 22-27, 2007.

[14] P. Meena, S. Rittidech and P. Tammasaeng “Effect of Evaporator Section Lengths and Working Fluids on Operational Limit of Closed Loop Oscillating Heat Pipes with Check Valves (CLOHP/CV)” American Journal of Applied Sciences 6 (1): 133-136, 2009.

[15] N.Kammuang-lue, P.Charoensawan, S.Ritthidech, K.Booddachan and P.Terdtoon, “Effects of Working Fluids on Heat Transfer Characteristics of a Closed-Loop Pulsating Heat Pipe at Critical State” International Heat Pipe Conference (2008).

[16] W. Qu, H.B. Ma. (2007): “Theoretical analysis of startup of a pulsating heat pipe”. International Journal of Heat and Mass Transfer, Vol. 50, pp. 2309–2316.

[17] J.L. Xu, Y.X. Li, T.N. Wong(2009) “High speed flow visualization of a closed loop pulsating heat pipe” International Journal of Heat and Mass Transfer 48 (2005) 3338–3351.

[18] L. Lin, R. Ponnappan, J. Leland, Experimental investigation of oscillating heat pipes, Thermophys. Heat Transfer 15 (2001) 395–400.

[19] Shung-Wen Kang, Wei-Chiang Wei, Sheng-Hong Tsai, Chia-Ching Huang. (2009): “Experimental investigation of nanofluids on sintered heat pipe thermal performance”. Applied Thermal Engineering, Vol. 29, pp. 973–979.

[20] Jian Qu, Hui-ying Wu, Ping Cheng. (2010): “Thermal performance of an oscillating heat pipe with Al2O3– water nanofluids”. International Communications in Heat and Mass Transfer, Vol.37, pp. 111–115.

[21] H.B. Ma, C. Wilson, Q. Yu, U.S. Choi, M. Tirumala, An experimental investigation of heat transport capability in a nanofluid oscillating heat pipe, J. Heat Transfer 28 (2006) 1213–1216.

[22] S. Khandekar and M. Groll “Pulsating Heat Pipes: Attractive Entrants in the Family of Closed Passive Two-Phase System”. Journal of Energy, Heat And Mass Transfer, Vol. 26, pp.99-115, march-december2004.

[23] Zhang XM, Xu JL, Zhou ZQ. (2004): “Experimental study of a pulsating heat pipe using FC-72, ethanol and water as working fluids”. Experimental Heat Transfer, Vol. 17, pp. 47–67.

[24] H. Yang , S. Khandekar , M. Groll, Performance characteristics of pulsating heat pipes as integral thermal Spreaders, International Journal of Thermal Sciences 48 (2008) 815–824.

[25] Shafii, M. B., Faghri, A., and Zhang, Y., Thermal Modeling of Unlooped and Looped Pulsating Heat Pipes, ASME Journal of Heat Transfer, vol. 123, pp. 1159–1171, 2001.