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CFD ANALYSIS OF ALUMINIUM BASED CLOSED PULSATING HEAT PIPE

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Abstract

The Pulsating Heat Pipe is a device which transfers more amount of heat between two mediums when compared to the general heat transfer devices such as metal fins. The key principle of the pulsating heat pipe is that; two phase phenomenon which happens inside the pulsating heat pipe with respect to the oscillatory motion of the bubbles of the fluid medium introduced into it. Due to the capillary action inside the pulsating heat pipe, the flow is modified to multi – phase flow. In regard to all the conditions, the pulsating heat pipes are classified into two types such as the (a) Open Loop PHP (b) Closed Loop PHP. A Closed PHP made of copper has shown a steady thermal performance with water – acetone when compared to other fluid mediums. This performance also depends on the number of loops in the CPHP. For the present study, we are considering a Closed Pulsating Heat Pipe made of Aluminum (Al) and with the working fluid medium as water by 50% of the volume. In total 4 different models of CPHP's are evaluated with different loops ranging from Single – loop – CPHP to Four – loop – CPHP. The evaporation range is set in between the 30,000 to 40,000 heat flux with an inner diameter of 2.00mm and outer diameter as 3.00mm. The performance in terms of the heat exchange in terms of the temperature difference. Upon evaluating the simulations for all the models and all the contours, the closed pulsating heat pipe with 2 – loops have found to be working with a greater difference in temperature changes in the specified regions. The results are plotted graphically for respective intents.

Keywords: Pulsating Heat Pipe, Tuber Inner Diameter, Tue Outer Diameter, Resistance, Density.

Introduction

The Pulsating Heat Pipe is a device which transfers more amount of heat between two mediums when compared to the general heat transfer devices such as metal fins. The key principle of the pulsating heat pipe is that; two phase phenomenon which happens inside the pulsating heat pipe with respect to the oscillatory motion of the bubbles of the fluid medium introduced into it. Due to the capillary action inside the pulsating heat pipe, the flow is modified to multi – phase flow. Regarding all the conditions, the pulsating heat pipes are classified into two types such as the (a) Open Loop PHP (b) Closed Loop PHP. A Closed PHP made of copper has shown a steady thermal performance with water – acetone when compared to other fluid mediums. This performance also depends on the number of loops in the CPHP. Invented in 1990s, pulsating heat pipe (PHP) is a passive heat transfer device that has potential applications in solar cell, fuel cell, space and electronic cooling. PHP, also known as oscillating heat pipe, transfers the heat from its evaporator region to the condenser region. In condenser the heat is dissipated to the sink, which it does by the phase change phenomenon of the working fluid being filled in with certain volume ratio. This device has an ability to transfer a large amount of heat over its length with a small temperature drop. There are mainly two types of pulsating heat pipe, both in vertical these are open loop and closed loop. In open loop PHP the condenser region is open so the water and the water vapor that rises from the evaporator due to heat flux imposed in the later leaves. Here the continuous supply of water, the working fluid, is needed. However, in the closed loop PHP there is a continuous circulating of working fluid within the PHP over the whole time. Pulsating heat pipe (PHP) is a new addition to the family of passive two-phase heat transfer devices, e.g., Heat pipes and Thermosyphons.

The PHP has been classified into mainly two categories 1) Open loop Pulsating Heat pipe and 2) closed loop pulsating heat pipe). [1] (Sameer K et al, 2003), has performed the modeling of the PHP experimental, they had described the heat transfer systems with a very strong thermohydrodynamic coupling governing the thermal performance. [2] (Mohammad B. Shafii et al, 2001) the analytical study on the both the thermal modelling of the looped and the unlooped model of the PHP and the under stand the effect of the gravity on the performance and understand how the diameters, charge ratio and heating wall temperature effect the Heat pipe. [3] (P. sakulchangsatjatai et al, 2010) in this paper the mathematical modeling of Closed- end PHP has been studied and understand their performance at the highest evaporator temperature (150°C for this study) and inclination angles of 70–80 degrees from horizontal axis. [4] (sakulchangsatjatai et al, 2021) the application of nanofluids, magnetic field and surfactant, applied for enhancing the performance of the PHPs have been discussed. At the end, applications of PHP and future scope have been discussed. [5] (Robert Thomas Dobson et al, 2003) calculating Lyapunov exponents it is shown that the theoretical model is able to reflect the characteristic chaotic behaviour of these devices. It was concluded that the model represents the experimental situation well and that it is important to consider the evaporation of liquid deposited on the surface by the trailing edge of the liquid plug. It is recommended that convective heat transfer is further investigated and the water pumping ability of the device is exploited. [6] (Sejung Kim et al, 2013) There results showed that the frequency of the liquid slug oscillation decreases with increasing amplitude and frequency of the periodic fluctuation of the wall temperature. However, the change of different standard deviations did not have any effect on the performance of the PHP.

[7] (H.B. Ma et al, 2006) There results show that the oscillating motion depends on the temperature difference between the condensing section and evaporating section, the working fluid, the operating temperature, the dimensions, and the filled liquid ratio. The results of this investigation will assist in the development of miniature pulsating heat pipes capable of operating at increased power levels. [8] (V M Patel et al, 2018) Nine major influencing input variables are considered for the first time to develop the prediction models. Feed-forward back-propagation neural network is developed and verified. Backward regression analysis is used in RCA-based regression model. Linear and power-law regression correlations are developed for input heat flux in terms of dimensionless Kutateladze (Ku) number, which is a function of Jakob number (Ja), Morton number (Mo), Bond number (Bo), Prandtl number (Pr) and geometry of a PHP. The prediction accuracy of present regression models (R2 = 0.95) is observed to be better as compared with literature-based correlations. [9] (D. yan et al, 2014) the Results show that the heat input needed to start the oscillating motion in an OHP depends on the filling ratio. When the filling ratio increases, the heat input required to start up the oscillating motion increases; furthermore, there exists an upper limit. This upper limit of the filling ratio is dependent on the properties of the working fluid. [10] (G. Gursel et al) Simulations show that including asymmetry into the system results in a good agreement with experimental results. Finally, four different modes of motion are observed: Oscillatory motion, translation, combined oscillatory-translation motion and no motion. Motion composition of a PHP as a function of heat input is studied. It is seen that translational and combined motion become dominant with increasing heat input. Also, the thermal performance of the PHP increases when the percentage of the translational and combined motion increases. [11] (Zirong Lin et al, 2012) The simulation results of MOHPs with different heat transfer lengths (L) and inner diameters (Di) at different heating powers, were compared with the experimental results at the same condition. This showed that the inner diameter had a greater impact on the thermal performance of MOHPs than the heat transfer length. Increasing the inner diameter was beneficial to improve the thermal performance of MOHPs. [12] (Rudresha S et al, 2014) CFD results analysis to comparison for Experimental results show that at a heating power of 10w, 14w, 18w, 22w the Thermal resistance, Thermal heat transfer Co-efficient, Thermal Thermal conductivity and Efficiency for CLPHP SiO2/DI Water and Al2O3/DI Water heat pipe are 69.37%, 75.99% and 11.98% DI water respectively, which are better than that of pipes using DI water as the working na-nofluids

[13] (Pramod R. Pachghare et al, 2014) CFD analysis by VOF model in Star CCM+ simulation is carried out to validate the experimental results. The result shows that the thermal resistance decreases smoothly up to 40W heat input, thereafter reasonably steady. In comparison with all working fluids, water-acetone binary working fluid has shown the best thermal performance over other working fluids used in CLPHPs. [14] (Jiansheng Wang et al, 2015) The numerical results are compared with available experimental results at the same condition. It's found that the start-up time and the thermal resistance of CLPHP reduces with the increase of input power. At the same filling ratio and input power condition, reducing the length of condenser within a suitable range would accelerate the start-up process and decrease the thermal resistance while the dry-out occurred easily at low filling ratio. Two types of start-up, sudden temperature increasing starts at lower input power and the smooth temperature increasing starts at higher input power are observed. The bubbles creation and growth motions are observed inside the CLPHP with vapor plugs oscillation and circulation motions. [15] (Poomin Krisangsri et al, 2021) The closed-loop oscillating heat pipe (CLOHP) tested was made of a copper capillary tube with various inner diameters and working fluids. Two evaporator sections in the outer end of CLOHP were heated by a Ni-Cr alloy resistance wire heater. The heat was removed from the condenser section in the middle of CLOHP by forced convection heat transfer of ambient air blowing the section. The results showed that, for the inner diameters of 1.5 and 2.0 mm, the thermal resistance decreased when the inner diameter and the latent heat of evaporation increased. [16] (FABLIHA ISLAM et al, 2017) The results depict that the CLPHP acts in pulsating mode only up to a definite diameter which is 2.5mm as per the performed experiment. The 3.5 mm pipe acts not as a PHP but as a mere heat pipe only. The thermal performance however increases with increasing diameter and hence the diameter of 2.5mm exhibits good performance.

[17] (Keerthi k et al, 2017) the working fluid of the heat pipe and the filling ration will effect the performance of the heat pipe [18] (Zilong D et al, 2017) the experimental study on the thermal performance on the anti-gravity for the PHP [19] (Sarangi RK et al, 2012) they experimental start up and the maximum heat load of the Closed loop PHP. There are several studies performed to the simulation of the PHP is [20, 23, 24, 25, 26] [21] (Pramod R. Pachghare et al, 2014) The CFD analysis by VOF model in Star CCM+ simulation is carried out to validate the experimental results. The result shows that the thermal resistance decreases smoothly up to 40W heat input, thereafter reasonably steady. In comparison with all working fluids, water-acetone binary working fluid has shown the best thermal performance over other working fluids used in CLPHPs. [22] (Himel B et al, 2013) f research work presented in this paper is to better understand the heat transfer characteristics of these mechanisms through experimental investigations. Experiments are conducted on a CLPHP made of capillary tube of 2.2mm inner diameter. The heat transfer characteristics and the performance of the CLPHP are investigated for filling ratios of 100 %, 82.5%, 63%, 41.3% and 28%. The results indicate that the performance of this device changes with the changing of working fluid, filling ratios and heat input. [27] (Takawale et al, 2008) Experiments are performed in the vertical bottom heating mode with ethanol as the working fluid. The pressure inside the PHPs and temperatures at the evaporator and condenser region are measured along with a recording of the internal flow regimes using a high-speed camera. Slug-plug flow is observed to be the dominant flow regime in both the PHPs. However, the amplitude of oscillations is found to be higher in CTPHP as compared to FPPHP. The reduction in thermal resistance of FPPHP and CTPHP due to the presence of working fluid is about 83% and 35% of the corresponding thermal resistances without any working fluid respectively. CTPHP shows better thermal performance than FPPHP due to the presence of lateral conduction arising in the latter which has a detrimental effect on the slug-plug oscillations.

Research Methodology

This general approach to the modelling of two-phase flow using a single fluid formulation based on the VOF method will be formulated for the modelling of the slug flow in capillaries. The conservation of the mass, momentum and energy has been taken into consideration for the simulation.

$$\nabla\vec{u}=0\rightarrow(1)$$

$$\frac{\partial(\rho\vec{u})}{\partial t}+\nabla(\vec{u}\,\rho\vec{u})=-\nabla p+\nabla[u(\nabla\vec{u}+(\nabla\vec{u})^{T})]+\vec{f}_{\sigma}\rightarrow(2)$$

$$\frac{\partial(\rho cT)}{\partial t}+\nabla(\rho\,\vec{c}\,uT)=\nabla(K\nabla T)\rightarrow(3)$$

The heat exchangers are generally used to transfer heat between two mediums or two sources. This exchange of heat can be between a process steam and a utility steam or any other two mediums which result in the integration of the energy and reduction in the external heat losses. They can be either of two streams or multi streams. The term heat exchanger actually refers to all the equipment placed between the two mediums for the heat transfer to take place.

For the present study, we are considering a Closed Pulsating Heat Pipe made of Aluminum (Al) and with the working fluid medium as water by 50% of the volume. In total 4 different models of CPHP's are evaluated with different loops ranging from Single – loop – CPHP to Four – loop – CPHP. The evaporation range is set in between the 30,000 to 40,000 heat flux with an inner diameter of 2.00mm and outer diameter as 3.00mm. The performance in terms of the heat exchange in terms of the temperature difference. The results are plotted graphically for respective intents.

A Closed Pulsating Heat Pipe made of Aluminum (Al) and with the working fluid medium as water by 50% of the volume. In total 4 different models of CPHP's are evaluated with different loops ranging from Single – loop – CPHP to Four – loop – CPHP. The evaporation range is set in between the 30,000 to 40,000 heat flux with an inner diameter of 2.00mm and outer diameter as 3.00mm.

Model	**No of Loops**	**Heat of the Evaporation**
1	1	45000
2	2	50000
3	3	55000
4	4	60000

Table 1: the design data of the Pulsating Heat Pipe

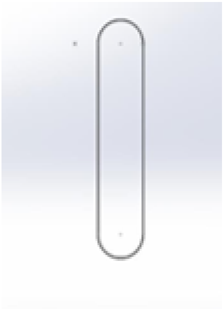

Fig. 1: Design of Model – 1

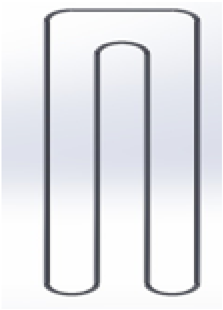

Fig. 2: Design of Model – 2

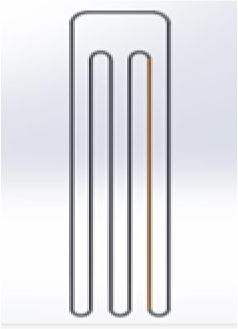

Fig. 3: Design of Model – 3

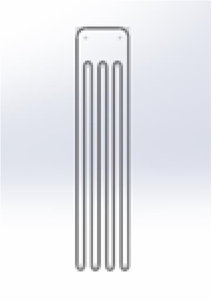

Fig. 4: Design of Model – 4

The Figure 1 to Figure 4 represent the Cad models of the PPH the model-1 represent the single loop Closed PHP and the model 2 represent the Double loop Closed PHP and similarly the model 3 and 4 are 3 loop and 4 loop closed PHP, the Simulation is performed by varying the Heat flux in evaporation zone from 45000 to 60000, with an difference of 5000 the VOF simulation has been performed in the Ansys software, in the Fluent work bench

2.1. Boundary Conditions

- Inlet: Velocity inlet was taken for the nozzle inlet and the value of velocity inlet was taken as 2m/sec. Initial gauge pressure was taken as 101325 Pascal. Temperature was taken as 500K.
- Outlet: The diffuser was set as outflow and the flow rate as 1.
- Wall: In wall, the motion of wall is selected as stationary wall.
- Controls Set Up: The solutions controls are set as listed below. The under-relaxation factor was set as given-

☐ Pressure-0.3
☐ Density-1
☐ Body forces-1
☐ Momentum-0.7
☐ Energy – First Order Upwind (For turbulent flow Power Law was taken into consideration)

- Initialization

☐ Solution initialization is done. Initial values of velocity are taken as 2m/sec along all zones of direction. Temperature is taken as 500K.

☐ Residual Miniaturization is done and convergence criteria are set up. The convergence Criteria of various parameters are listed below.

☐ Continuity- 0.001
☐ X-Velocity- 0.001
☐ Y-Velocity- 0.001
☐ Z-Velocity- 0.001
☐ Energy- 1e-06

Result

The Simulation is performed on the Closed Pulsating Heat Pipe is modified in terms of the loops. There are four different models considered ranging from 1 – loop to 4 – loop. The dimensions are kept constant as they depict the better values at those variations [1]. The heat input is varied in between a range of 45000 – 60000 watts. Upon considering the evaluations, greater change is observed for model – 2 i.e., Closed Pulsating Heat Pipe with 2 – loops. The simulation results are obtained as shown in the table:

	Heat Flux	**Condenser (TC)**	**Evaporation (TE)**	**ΔT=TE-TC**
	45000	299.996	344.361	44.365

M1	50000	299.96	349.00884	49.04884
	55000	299.996	354.5427	54.5467
	60000	299.996	359.9934	59.9974
M2	45000	299.996	348.6	48.604
	50000	299.996	353.789	53.793
	55000	299.996	359.1527	59.1567
	60000	299.996	364.58	64.584
M3	45000	299.996	345.45	45.454
	50000	299.996	351.14	51.144
	55000	299.996	356.08	56.084
	60000	299.996	361.41	61.414
M4	45000	299.996	349.972	49.976
	50000	299.996	355.5375	55.5415
	55000	299.996	361.07	61.074
	60000	299.996	366.5	66.504

Table 2: Contour values in terms of condensation, evaporation, and adiabatic regions

The Counter of the Simulated design are Shown in From the Figure 6 to the Figure 9 bellow for the model 1. The simulation values are plotted accordingly for better understanding the as show in the Figure 5. The contours of the Simulated model 2, has been represented for the figure from 9 to 11 respectively. The contours of the Simulated model 3, has been represented for the figure from 12 to 14 respectively. The contours of the Simulated model 4, has been represented for the figure from 15 to 17 respectively.

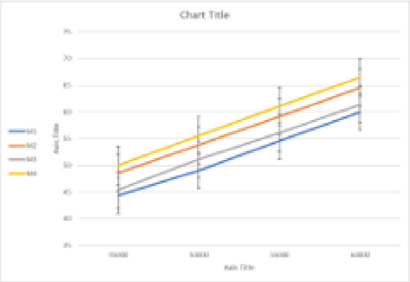

Figure 5: Plot of Difference in temperature upon varying the heat flux

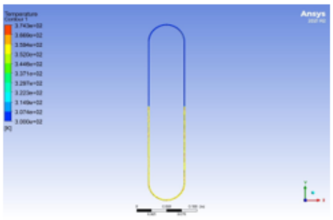

Figure 6: Static Temperature contour representation of Model – 1

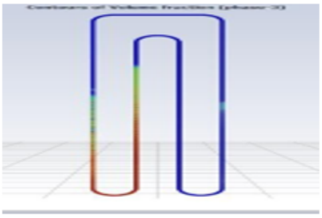

Figure 10: Volume Fraction of Water Vapor in liquid form contour representation for Model:2

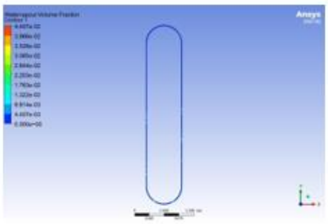

Figure 7: Volume Fraction of Water Vapor in liquid form contour representation for Model:1

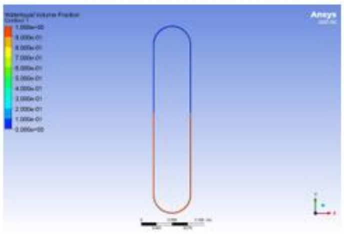

Figure 8: Volume Fraction of Water in liquid form contour representation for Model – 1

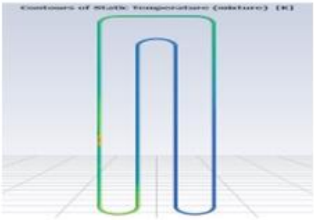

Figure 9: Static Temperature contour representation of Model – 2

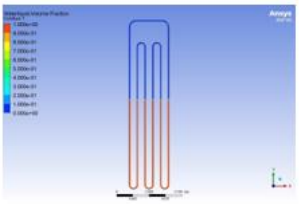

Figure 14: Volume Fraction of Water in liquid form contour representation for Model – 3

Figure 15: Static Temperature contour representation of Model – 4

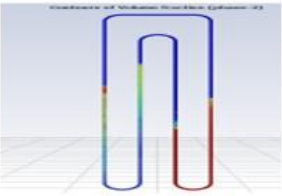

Figure 11: Volume Fraction of Water in liquid form contour representation for Model: 2

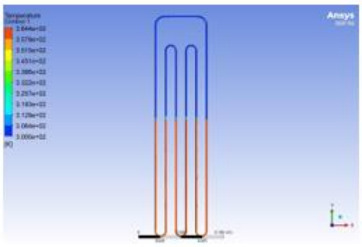

Figure 12: Static Temperature contour representation of Model – 3

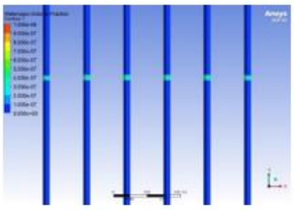

Figure 13: Volume Fraction of Water Vapour in liquid form contour representation for Model – 3

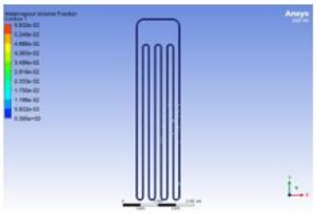

Figure. 16: Volume Fraction of Water Vapour in liquid form contour representation for Model – 4

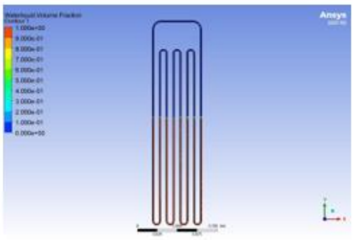

Figure. 17: Volume Fraction of Water in liquid form contour representation for Model - 4

Conclusions

A Closed Pulsating heat pipe made of Aluminum is considered for the experiment with the working fluid medium by 50% of the volume. Total four different models with respect to change in the number of loops are considered for the simulations. The evaporation ranges are kept constant in between 30,000 – 40,000 heat flux. So as the dimensions of the pipe with an inner diameter of 2.00mm and an outer diameter of 3.00mm. Upon evaluating the simulations and the results obtained in terms of the pressure, static temperature and volume fractions for water vapor and water liquid;

the closed pulsating heat pipe with two loops i.e., model – 2 is considered to be the better one as the concerned contour values exhibited better values especially in the heat transfer. Thereby concluding the closed pulsating heat pipe with two loops made of aluminum as an optimum design module with a heat transfer of 7.84%.

Nomenclature
A PHP – Pulsating heat pipe
Q – Heat Energy/Heat Input
Di – Tube inner Diameter
Do – Tube Outer Diameter
R – Resistance
ρ – Density
σ – Surface tension
A – Adiabatic section
C – Condenser section
Liq – liquid
Th – Thermal
CLPHP – Closed loop pulsating heat pipe
TC – the temperature at condensers
TE – the temperature at evaporation
K – kelvin

References

[1] Sameer K., Piyanun C, Manfred G, Pradit T. Closed loop pulsating heat pipes part B: visualization and semiempirical modelling. Applied Thermal Engineering, 2003; 23(16): 2021-2033.

[2] Mohammad BS, Amir F, Yuwen Z. Thermal Modeling of Unlooped and Pulsating Heat Pipes. ASME Journal of Heat Transfer, 2001; 123(6): 1159-1172.

[3] Sankulchangsatjatai P, Chareonsawan P, Waowaew T, Terdtoon P, Murakami M. Mathematical modelling of closed-end pulsating heat pipes operating with a bottom heat mode. Heat Transfer Engineering, 2008; 29(3): 239-254.

[4] Sankulchangsatjatai P, Terdtoon P, Wongratanaphisan T, Kamonpet P, Murakami M. Operation modelling of closed-end and closed-loop oscillating heat pipes at normal operating condition. Applied Thermal Engineering, 2004; 24(7): 995-1008.

[5] Dobson RT. Theoretical and experimental modelling of an open oscillatory heat pipe including gravity. International Journal of Thermal Sciences, 2004; 43(2): 113-119.

[6] Sejung K, Yuwen Z, Jongwook C. Effects of fluctuations of heating and cooling section temperatures on performance of a pulsating heat pipe. Applied Thermal Engineering, 2013; 58(1-2): 42-51.

[7] Ma HB, Hanlon MA, Chen CL. An investigation of oscillating motions in a miniature pulsating heat pipes. Microfluidics and Nanofluidics, 2006; 2(2): 171-179.

[8] Patel VM, Mehta HB. Thermal performance prediction models for a pulsating heat pipe using artificial neural network (ann) and regression/correlation analysis (rca). Sadhana, 2018, 43: 184.

[9] Yin D, Rajab H, Ma HB. Theoretical analysis of maximum filling ratio in an oscillating heat pipe. International Journal of Heat and Mass Transfer, 2014: 353-357.

[10] Gursel G, Frijns AJH, Homburg FGA, Van Steenhoven AA. A mass-spring-damper model of a pulsating heat pipe with a non-uniform and asymmetric filling. Applied Thermal Engineering, 2015; 91(5): 80-90.

[11] Zirong L, Shuangfeng W, Ryo S, Zhang LW. Simulation of a miniature oscillating heat pipe in bottom heating mode using CFD with unsteady modeling. International Journal of Heat and Mass transfer, 2013; 57(2): 642-656.

[12] Rudresha S, Vijee K. CFD Analysis and Experimental Investigations on Thermal Performance of Closed loop Pulsating Heat pipe using different Nanofluids. International Journal of Advanced Research, 2014; 2(8): 753-760.

[13] Pramod P, Ashish M. Thermo-hydrodynamics of closed loop pulsating heat pipe: an experimental study. Journal of Mechanical Science and Technology,2014 ;28 (8) ; 3387-3394.

[14] Jiansheng W, He M, Qiang Z. Effects of the evaporator and condenser length on the performance of pulsating heat pipes. Applied Thermal Engineering, 2015; 91(5): 1018-1025.

[15] Kammuang-Lue N, Sakulchangsatjatai P, Terdtoon P. Effect of working fluids and internal diameters on thermal performance of vertical and horizontal closed-loop pulsating heat pipes with multiple heat sources. Thermal Science, 2016; 20(1): 77-87.

[16] Islam F, Akhter F, Haider SB, Ali M. Effect Of Inner Diameter On The Thermal Performance Of Closed Loop Pulsating Heat Pipe. International Journal of Mechanical and Production Engineering, 2017; 5(7): 69-72.

[17] Keerthi K, Srinath M, Ranjit KG. Effect of working fluid, heat input and filling ratio’s on performance of closed loop pulsating heat pipe. International Journal of Advances in Scientific Research and Engineering, 2017; 3(1): 209-215.

[18] Zilong D, Yi Z, Xiangdong L, Bingping Z, Yongping C. Experimental study on thermal performance on anti-gravity pulsating heat pipe and its application on heat recovery utilization. Applied Thermal Engineering, 2017;125 : 1368-1378.

[19] Sarangi RK, Rane MV. Experimental investigations for start up and maximum heat load of closed loop pulsating heat pipe. In: 3rd Nirma University International Conference on Engineering, pp. 683 – 687, 2012.

[20] Hua H, Xiaoyu C, Yue Z, Shende S. A comparative study of the behaviour of working fluids and their properties on the performance of pulsating heat pipes (PHP). International Journal of Thermal Sciences, 2014; 82: 138-147

[21] Pramod R. Pachghare, and Ashish M. Mahalle Thermo-hydrodynamics of closed loop pulsating heat pipe: an experimental study / Journal of Mechanical Science and Technology 28 (8) (2014) 3387~3394

[22] Himel B, Mohammad A, Md Nuruzzaman, Quamrul I, Chowdhury M. Effect of filling ratio on heat transfer characteristics and performance of a closed loop pulsating heat pipe. In: 5th BSME International Conference on Thermal Engineering, pp. 88-95; 2013.

[23] Sameer K, Xiaoyu C, Manfred G. Thermal performance modeling of pulsating heat pipes by artificial neural network. In: 12th International Heat Pipe Conference, Moscow, Russia, pp. 215-219; 2002.

[24] Subhash N, Pramod P. Experimental and CFD Analysis of closed loop Pulsating Heat Pipe with DI-water. In: International Conference on Energy Efficient Technologies for Sustainability, pp.185-190; 2013.

[25] Xiangdong L, Yingli H. Numerical Simulation of Vapor-Liquid Two-Phase Flow In A Closed Oscillating Heat Pipe. In: International Mechanical Engineering Congress & Exposition, Florida, USA pp.609-617; 2009.

[26] Kwon G. H. and Kim S.J., Analysis of Pulsating Heat Pipe with a Dual-Diameter Tube,10th International Conference on Heat Transfer.Fluid Mechanics and Thermodynamics, 14-26 July, 2014.

[27] Takawale, Abraham S, Pattamatta A, Sielaff A, Stephan P. A comparative study of flow regimes and thermal performance between flat plate pulsating heat pipe (fpphp) and capillary tube pulsating heat pipe(ctphp). In: 10th International Conference on Boiling and Condensation Heat Transfer, Nagasaki, Japan; 2008