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Performance of Closed Loop Pulsating Heat Pipe: A Numerical Analysis

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Abstract: The advancement in technology incorporated a huge number of components to a single chip where the performance improved but the heat rejection rate increased owing for a highly efficient cooling method. Conventional method of heat pipe cooling failed to achieve the best, paved way for a next generation of pulsating heat pipe. The current work reflects simulation study to understand the performance of a complex pulsating heat pipe with 16 number of turns using CFD. Water was used as the working fluid. Here a discussion of various factors affecting the performance is held and a detailed study is conducted by through a CFD simulation using VOF Model.

Index terms: **Pulsating heat pipe, CFD, Water**

I. INTRODUCTION

Electronic components perform on the current passed through it and this makes them critical spots of excess heat generation when the flow of current is through a resistance followed by generation of heat. The development in electronics field though with its advantages flourished enviously but flipped the coin in the matter of heat generation. Excess heat generation insisted for a controlled and proper design of cooling systems otherwise threatens the safety and reliability of overall systems.

Ample designs of conventional heat pipes are although present, industries frequently point out the limitations of those. This led to the research of newer and newer concepts to meet the ever increasing demands of various industries. Pulsating Heat Pipes, have a plethora of applications as it is simple in design and of less cost with a much higher heat transfer performance which provides them a promising future. A temperature differential exists between the two ends, resulting in unbalanced pressure conditions by which the bubbles grow and migrate towards the high pressure side pushing the liquid to low temperature end (condenser) as in Fig.1. Thus a non-equilibrium condition arises increasing the pressure difference which enhance the driving potentials and accelerates the oscillatory motion in order to equalize the pressure within the system.

II. MATHEMATICAL DEVELOPMENT OF PULSATING HEAT PIPE

The recent researches in closed loop pulsating heat pipe indicate that there are two independent aspects while analyzing them viz. thermal and the involvement of hydrodynamics. According to the studies of Groll et.al [1] the slug and plug movement are caused mainly due to surface tension, inertia, viscous and buoyancy forces in the pipe. As here the surface tension dominates than all others the critical diameter of pipe is calculated using a dimensionless number known as Eotvos Number [2] calculated using the equations (1) and (2) given below.

$$.E_o = {B_0}^2{}_{critical} = \frac{D^2 \cdot g \cdot (\rho_{liq} - \rho_{vap})}{\sigma} \approx 4 \qquad (1)$$

$$D_{critical} = 2\sqrt{\frac{\sigma}{g \cdot (\rho_{liq} - \rho_{vap})}} \qquad (2)$$

III. EFFECT OF DIFFERENT PARAMETERS

Pramod Pachghare et.al [3] conclude from their research that the number of turns define the flow pattern inside the tube. Whenever the number of turns increase from a critical value there occurs a stop-over which causes the U-sections of the pipe to be filled with vapour bubbles and the rest with liquid which may lead to dry out phenomena. Thus, an optimum number of turns exits for a heat input given.

Studies conducted at different stages were not able to understand the working of PHP. Many investigations found contradictory results to that of the experimental one. A common conclusion found was that the performance of PHP strongly depends on the working fluid selected.

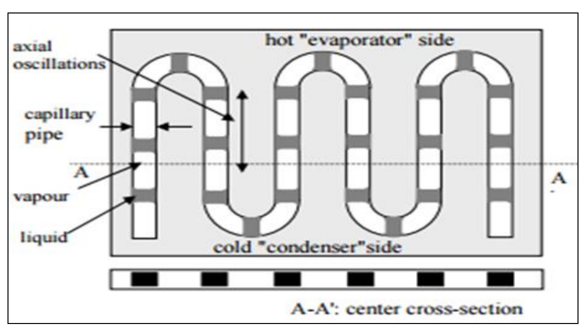

Figure 1: Working of Pulsating Heat Pipe.

Investigations so far suggest that working fluid selection plays a vital role in improved thermal transport of PHPs. Heat transferred from condenser to evaporator is mainly due to forced convection, that is by sensible heat.

IV. DEVELOPMENT OF CFD MODEL

Analysis of Pulsating Heat pipe is done using CFD. A geometry as per the requirements was made using design modular in ANSYS as in Fig 2. The length and width of the model is 150 mm and 96 mm respectively with 16 turns [4]. Initially the working fluid chosen is water and water-vapour.

Of the two models present in Fluent for multiple fluid study the VOF Model paves the interest as it is the core tool for interface tracking of immiscible fluids [5]. In VOF Model the movement of both liquid and vapour is traced by solving the transport and energy equations according to the boundary conditions applied.

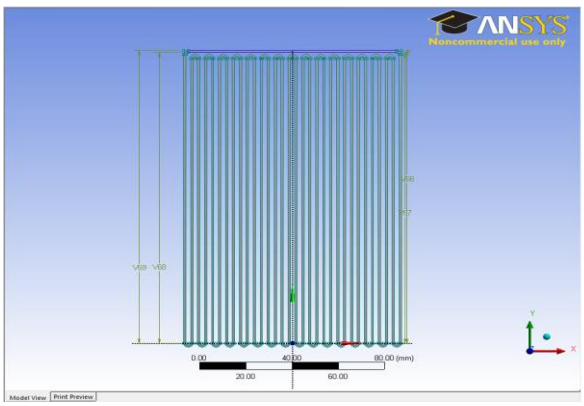

Figure 2: PHP Model in Ansys Workbench

Simulation in CFD are carried out in almost five different stages:

- Creation of basic Geometry
- Generation of mesh complying with the geometry exactly
- Defining the simulation situations and boundary conditions
- Simulation time setup and convergence criteria
- Analysis of results through plots and contours

. Meshing was done on geometry in FLUENT – Meshing with triangular surface meshing techniques. Meshing element details are given in the Table 1.

Table 1: Meshing Details

Details	Pulsating Heat Pipe
Size of Mesh	0.01
Total Cells in geometry	121462
Total Nodes in geometry	145708
Orthogonal Quality (Minimum)	0.87
Aspect Ratio (Maximum)	2.86

Water was chosen for initial study reported here under the assumption that the properties remain constant with temperature except that for surface tension. The temperature of the fluid was assigned as 473K at the evaporating end and the ambient to be 298 K.

V. USER DEFINED CODES IN CFD

The existing codes is unable to capture the heat and mass transfer occurring during the phase change. Evaporation and Condensation models generally used in CFD are based on models developed by Lee and by Tanasawa [6].

The UDF defined include the calculations of local wall heat flux at various locations in the PHP and compute the coefficient of local heat transfer using equation (3). For finding the average heat transfer coefficient weighted area average of local wall flux is found and given in equation (4). Thus the average heat transfer and average Nusselts number are obtained from equations (5) and (6).

$$h(x) = \frac{q_w(x)}{T_w - T_{sat}} = \frac{-k_f \frac{\partial T}{\partial y}\Big]_{y=0}}{T_w - T_{sat}} \qquad (3)$$

$$\overline{q_w} = \frac{\int_0^L q(x)\, dA_s}{\int_0^L dA_s} \qquad (4)$$

$$\bar{h} = \frac{\overline{q_w}}{T_w - T_{sat}} \qquad (5)$$

$$\overline{N_u} = \frac{\bar{h}}{k_f}\left[\frac{\mu^2{}_f}{\delta^2{}_f\, g}\right]^{1/3} \qquad (6)$$

After assigning the initial values for simulation the calculation was started for a very small value of time step to meet the convergence faster with accurate result. The other residuals such as energy was assigned a convergence criteria of 10^{-6} , and for both continuity and momentum it was 10^{-4}.Time step for the current simulation is taken as 10^{-5}sec.

VI. RESULTS AND DISCUSSIONS

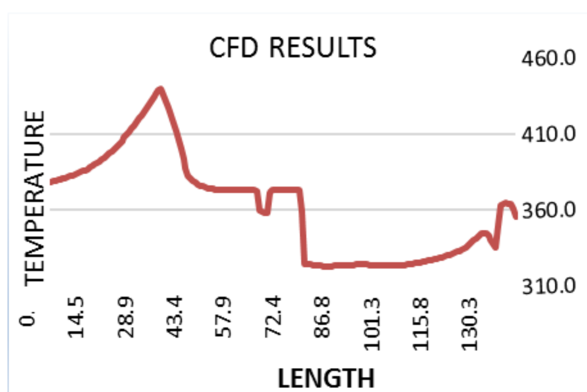

Figure 4: Wall Temperature of water at 50% fill ratio

The above graph depicts the behavior pattern of a pulsating heat pipe evidently. At the evaporator section of temperature 473K assigned the vapour gets superheated to that temperature and then gradually cools down to the assigned condenser temperature of 302K.

Figure 5 depicts the contours of the phase flow. The liquid plugs and vapour slugs (red indicates vapour and blue liquid) oscillate to and fro to transfer the heat effectively. As the phase change occurs during the oscillatory motion the vapour slugs reduce their size and that of liquid plugs do increase. A menisci outline is formed at the edge of the liquid plug due to the surface tension forces.

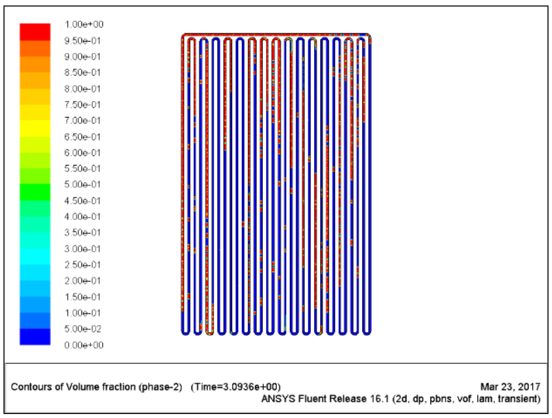

Figure 5: Contour of Volume Fraction

The temperature contours (Figure 6) below show a higher temperature fluctuation at the adiabatic section because the train of vapour and liquid passing from evaporator to condenser undergoes complex mass and heat transfer. A non-equilibrium condition exists at the adiabatic section as the high temperature saturated vapour liquid mixture id brought to low temperature conditions at the condenser section.

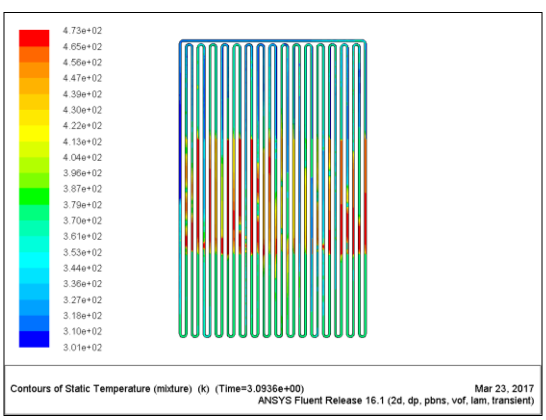

Figure 6: Contour of Static Temperature

The balancing of internal enthalpy from the latent heat occur by the evaporation mass transfer from liquid to vapour. While a look into the pressure of the mixture a high pressure difference is seen that drives the oscillating motion. The figure below shows a high pressure at some areas and even a negative pressure at some areas which induces the to and fro motion.

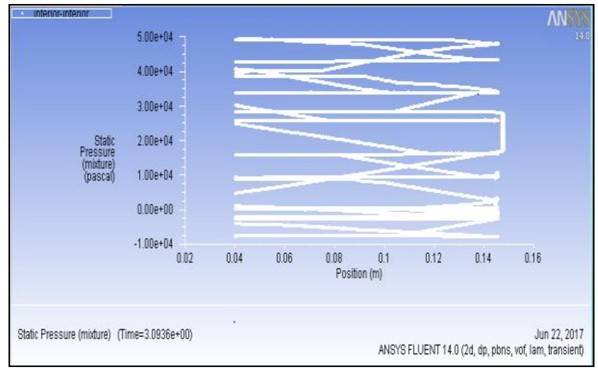

Figure 7: Static Pressure Plot of PHP

VII. VARIATION IN THERMAL RESISTANCE

The impact of thermal resistance on pulsating heat pipe can be determined using the equation (7)

$$R_{th} = \frac{T_e - T_{ref}}{Q} \qquad (7)$$

As shown in the graph below the thermal resistance decreases as there is an increment in the heat input. At lower heat input the difference in temperature is high and as the input increases the temperature difference get reduced resulting in fall of thermal resistance. The simulation done for working fluid as water was compared to the experimental results of Yuwen Zhang .et.al [7] and found to be following the same pattern.

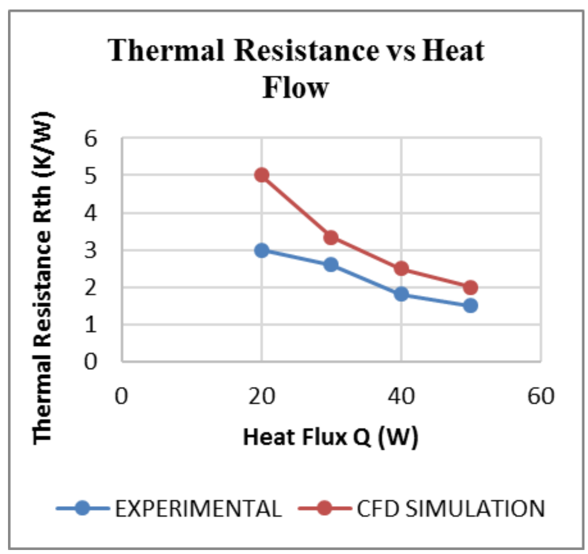

Figure 8: Thermal Resistance Vs Heat Flux Plot of water for 50% filling ratio

The performance of Pulsating Heat pipe can be find out using the effective thermal conductivity coefficient calculated using equation (8).

$$h = \frac{Q}{\Delta T * S} \qquad (8)$$

S is the sum of inner cross-sectional area of all pines found by equation (9).

$$S = (2 * N * \pi * {D_{in}}^2)/4 \qquad (9)$$

$$= (2*16*3.14*1^2)/4$$

$$= 25.12\ mm^2$$

The value of Q is directly obtained from Fluent and putting this value in the above equation to find the effective heat transfer coefficient, h

$$h = 4/ (40*25.12)$$

$$= 3980.89\ W/m^2K$$

From all the observations above the performance of PHP is studied and evaluated. Observations suggest that limitation exist for a single fluid in latent heat, viscosity, surface tension and sensible heat as a working fluid in PHP. Eventually the use of refrigerants as working fluid can reduce the surface tension and viscosity caused by the use of a single fluid.

VIII. CONCLUSION

Conclusions from the CFD simulation study evidently reflects the results obtained from experiments and numerical analysis done by various researchers. So it is the need of the hour to have a efficient working fluid capable of better heat transfer. Recent studies states that change from water to refrigerants or acetone like fluids can reduce the number of turns and will contribute to a higher heat transfer rate due to its decreased thermal resistance.

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