CFD Analysis of Single Turn Pulsating Heat Pipe by Comparing Ethylene Alcohol & Water

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Abstract - *With the advancement in technology of electronic equipment, two problems mainly arise when we came to practical aspect. First is of overheating and second is that of reduction in their size in spite of them being already very small in size. Hence a heat releasing device which is having high heat removal rate and also can maintain uniform temperature, is needed to meet the technological advancements. Due to its superior heat transmission qualities, pulsating heat pipe has a bright future as an effective cooling solution. In terms of design and operation, it differs from traditional heat pipes. It's made of a long, continuous capillary tube that has already been twisted into numerous turns and holds more working fluid. Pulsating heat pipes can be used to cool power electronics like diodes, thyristors, power modules, and IGBTS, among many other applications. The study utilizes Ansys software to do a CFD analysis to compare the effectiveness of pulsing heat pipes with Ethylene alcohol and water as working fluids. The outcome of this analysis shows that the water shows the better thermal performance than ethylene alcohol when heat inputs are varied at fixed filling ratio of 60%. Also, the surface tension of water is more than ethylene alcohol & hence shows better thermal performance. The contours of volume fraction also show water having low thermal resistance as compared to ethylene alcohol in PHP after a certain amount of time for a limited no. of iterations and under all the same conditions.*

Key Words: Pulsating Heat Pipe, Heat transfer, Ethylene Alcohol, Water, Thermal Performance ,Thermal Resistance

1.INTRODUCTION

Pulsating heat pipe (PHP) is a passive heat transfer device that was invented in the 1990s and has possible applications in solar cell, fuel cell, space, and electronic cooling. PHP, also known as oscillating heat pipe, is a heat transfer device that transmits heat from the evaporator region of the arrangement to the condenser region. The heat is dissipated to the sink in a condenser, which is accomplished through the phase change phenomena of the working fluid, which is being filled in at a specific volume ratio. This device can transfer a big amount of heat over a long distance with only a minor drop in temperature. The most common types of pulsating heat pipes are open loop and closed loop, which are both vertically oriented. The condenser region of an open loop PHP is open, thus water and water vapour rising from the evaporator due to heat flux imposed through the latter exits the PHP from one end. Water, the working fluid, would have to be available at all times. The closed loop PHP, on the other hand, has a constant flow of working fluid throughout most of the implementation procedure. The pulsating heat pipe (PHP) is a new addition to the heat pipe and thermosiphon families of passive two-phase heat transfer devices as it is different from the traditional micro heat pipes, where we can see that the liquid-and-vapor counter flow in the wick pipe may be hindered due to the pipe becoming small in diameter, Also the PHP, which is normally made of wickless micro or miniature looped pipes, shows an increasingly promising prospects of application in many industrial fields, especially the electronic cooling field, for its outstanding behaviour like excellent heat transfer performance (several ten times that of metal), compact structure, no external mechanical power requirement, etc. The objectives of this work is to investigate how CLPHPS work and how various parameters (geometry, fill ratio, materials, working fluid, and so on) affect their performance. The non-equilibrium characteristics of the evaporation and condensation processes, bubble formation and collapse, and the linked response of the multiphase fluid dynamics among the multiple channels make understanding its functioning all the more problematic. A pulsing heat pipe (PHP) is a passive, very effective technique of transmitting heat between a hot and cold source. Ansys Software is used to simulate a 2D single loop pulsating heat pipe. After conducting an extensive study on the subject, it has become clear that few sources adequately describe how to create a pulsing heat pipe. As a result, the primary objective of this post is to teach anyone how to recreate this simulation. This procedure starts with simplifying assumptions in order to carry out the simulation, and then proceeds to show the procedure step by step, which is also physically explained as it has been introduced.

1.1 Literature Review

Vipul M. Patel et al. conducted an experiment on a testing section of 2 mm, 9 turn copper capillaries to see how different working fluids affect the start-up mechanism and thermal performance of a CLPHP. The 11 working fluids were chosen for this purpose and were divided into three categories: pure fluids (distilled water, ethanol, methanol, and acetone), binary fluids (water-based mixtures of ethanol, methanol, and acetone), and surfactant fluids (water-based mixtures of ethanol, methanol, and acetone) (Sodium Dodecyl Sulphate).After taking into account the vertical bottom heating position, the heat input to the working substance is altered between 10-110W, demonstrating that binary fluids and surfactants have an advantage over DI water when it comes to making an effect. The experimental equipment includes a testing section (evaporator, adiabatic condenser), a monitoring and control panel, a temperature measuring scanner, and a computer to store experiment data. There is also a variance in critical diameter as a function of time for various working fluids.1. To evacuate the capillary tube to the necessary vacuum, a Pirani Gauge and a Vacuum Pump are used. The experiment is repeated three times to ensure that the results are accurate, with the mean of the data being in the range of +-2 percent. For all working fluids, the thermal resistance is found to be inversely proportional to the heat input.

Atul N. Pote and Pramod R. Pachghare's enclosed loop pulsating heat pipe is built of copper tubing with an internal diameter of 3mm and an exterior diameter of 4mm, with two meandering turns. The evaporator and condenser sections were 380mm long. The experiment was carried out in a vertical position with a 50% filling ratio. The heat load ranged from 6 to 72 watts. The ZnO/Water nanofluid concentrations were 0.25 percent, 0.5 percent, 0.75 percent, and 1 percent w/v. The temperatures of the evaporator and condenser sections' outside walls, as well as the entrance and exit of cooling water, were recorded. The overall thermal resistance was calculated for various heat inputs. Thermal resistance of CLPHP utilizing ZnO/water nanofluid as working fluid was shown to be superior to thermal resistance using pure water. The thermal resistance of ZnO/water nanofluid reduces as the mass concentration of ZnO/water nanofluid increases. For a 1% w/v concentration and a 72W heat input, the minimum thermal resistance is 0.829oC/W. This is 77.7% less than the purity of pure water. The thermophysical qualities of working fluids have a significant impact on PHP's thermal performance.

1.2 Governing Equations

For modelling the slug flow in capillaries, the generic technique to modelling two-phase flow using a single fluid formulation based on the VOF method will be used. The equations for mass, momentum, and energy conservation, as well as an additional advection equation to define the gas-liquid interface, known as the Volume of Fluid equation, can be used to describe hydrodynamics (VOF). Following are the formulas for Governing Equations

1.2.1 Conservation of Mass

$$\nabla.\vec{u} = 0$$

1.2.2 Conservation of Momentum

$$\frac{\partial(\rho\vec{u})}{\partial t} + \nabla.(\vec{u}.\rho\vec{u}) = -\nabla p + \nabla.[\mu(\nabla\vec{u} + (\nabla\vec{u})^T)] + \vec{f_o}$$

1.2.3 Conservation of Energy

$$\frac{\partial(\rho c T)}{\partial t} + \nabla.(\rho c \vec{u} T) = \nabla.(k\nabla T)$$

Where ρ is density, u is velocity vector, p is pressure, μ is dynamic viscosity, c is specific heat capacity, T is temperature, and k is thermal conductivity. The surface tension force is represented by the source term f in the above momentum equation. The governing equations are solved in phases, and the volume of fluid (VOF) approach is used to represent the interface

2. CFD SIMULATIONS

The main goal is to investigate the heat transfer performance of a PHP in an evaporator under various load circumstances using Ethylene Alcohol and water as the working fluids. This research has been carried out on ANSYS which is a CFD software. Additionally, the ethylene alcohol and ethylene alcohol vapour flow patterns within the PHP must be watched in order to forecast the path. Temperature changes in the evaporator and condenser can also be considered a performance parameter. Geometry creation, Grid generation, Fluent setup, Solution methods, and Results are the five stages of the CFD analysis procedure. The tube's 3-D fluid flow and heat transfer analysis is completed. ANSYS FLUENT software was used to do the analysis, which was based on the control volume method.

2.1 Methodology

First, a review of the literature on the operation and performance of pulsing heat pipes is conducted. To come up with the stated problem statement, relevant recommendations provided in papers and journals are considered. The experimental analysis was used in this paper, and the groundwork for the CFD analysis was laid. After that, the tools for solving the model are chosen and developed. The simulation is performed until the desired convergence conditions are met once the appropriate schemes have been set. There are numerous tools and techniques for displaying findings. The information from the findings is categorized and compared to our baseline. The outcome of the computer-based CFD is then confirmed analytically.

2.2 Geometry

PHP is a closed type with a single turn of copper tube with a diameter of 4 mm. The copper domain is not taken into account in the geometry modelling; only the fluid domain is taken into account. The PHP design uses 1 copper tubes with a total channel length of 361.68 mm, and copper pipe. The copper domain is not monitored for geometry simulation because it is simply the topic of the liquid domain of interest. The PHP is divided into three sections: evaporator, adiabatic, and condenser, with lengths of 90.84 mm, 180 mm, and 90.84 mm, respectively.

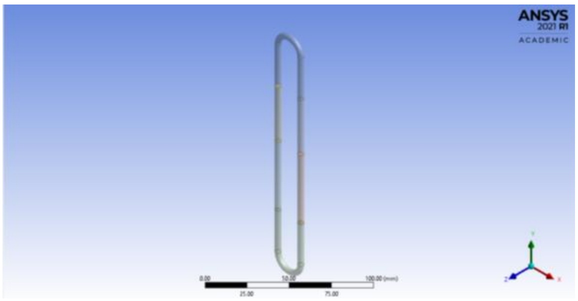

Fig -1: Geometry of Single Loop Closed Pulsating Heat Pipe

2.3 Meshing

ANSYS Meshing offers more control over the automatic settings by allowing us to define the pairs of point controls, edge controls, surface controls, and/or body controls. Each of them has its own set of settings and may be used to alter the mesh in a variety of ways. The automated mesh form method had been selected in this scenario. The mesh, on the other hand, is manually sized. As illustrated in fig. 2, the minimum and maximum mesh sizes were chosen to be 0.0002 mm. Meshing is created using 42959 nodes and 37246 elements when this control setting is used. It is in the meshing phase of Ansys Fluent that the sections of the geometry are given names, making it easier to define the domain and establish boundary constraints in the setup section.

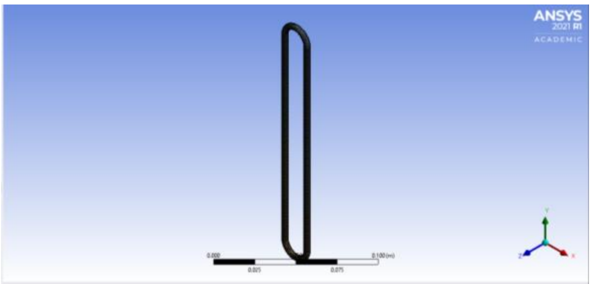

Fig -2: Automated Ansys Meshing form of Geometry of CLOHP

3. BASIC SETTING FOR DOMAINS

For the overall geometry of PHP, three domains were defined as: condenser, adiabatic area, and evaporator. Furthermore, the adiabatic zone is separated into two domains in order to account for the rise in Ethylene alcohol and water levels in the PHP caused by the evaporator at the bottom. The ethylene alcohol from the adiabatic region's base for a water fill ratio of 60% by volume.

3.1 Boundary Conditions

The Heater Section or Evaporator zone was given a variable heat input at 40W, 50W &60W. Heat flux in the adiabatic region is zero. Negative heat flux was reported in the condenser region; this heat flux was determined from an experimental reference article. For the CFD analysis, the VOF model is used along with the enhanced wall treatment and k-epsilon is being used. The walls in all domains are of the no-slip variety. All of the walls are believed to be smooth. A thermal boundary condition with a fixed temperature of 298 K is set in the condenser. Similarly, the boundary condition in adiabatic zones is adiabatic, defining the heat flux rate as 0 Wm-2K-1. The surface tension is kept at 0.0473 N/m at the interface of ethylene alcohol and air while the surface tension is kept at 0.0720 N/m at the interface of water and air.

3.2 Turbulence Model

The k-epsilon model, one of the most well-known turbulence models, was used in this investigation, as it is in most general-purpose CFD systems, and is considered the industry standard model. It has a well-established predictive capability and has proven to be stable and numerically robust. The k-epsilon is a suitable balance between accuracy and robustness for general-purpose simulations. The k-epsilon turbulence model in CFX uses traditional two-equation models. These two equations are simply transport equations (or partial differential equations) for turbulent kinetic energy (k) and dissipation (), respectively, and employ the scaled wall-function technique to improve resilience and accuracy when the mesh of the near wall one of the finest. As a result, it delivers accurate forecasts for fluid flow in the domain.

3.3 Condenser

All components of velocity (u, v, and w) in the condenser zone are set to 0 m/s, and relative pressure is set to 40 Pa. Because there is just low pressure air at low temperature in the initial condition, there will be less turbulent flow in the condenser. Accordingly, the volume fraction value for air is 1, whereas the volume fraction values for ethylene alcohol and ethylene alcohol vapour are both zero. This is because there is no ethylene alcohol or ethylene alcohol vapour in the condenser in the first place, and thermal boundary condition with a fixed temperature of 298 K is established after the evaporator is heated. Similarly , conditions for water and water vapour with air were also kept same with the volume fraction for water and steam at 0 and for air at 1.The temperature of Condensor section is kept at 298K.

3.4 Evaporator

In the evaporator, all of the velocity components are set to 0 m/s, and the relative pressure is set to 40 Pa. In terms of volume fractions, ethylene alcohol, Ethylene alcohol vapour, and air are given values of 0, 0 and 1 respectively. The walls in all domains are of the no-slip variety. All of the walls are believed to be smooth. Similarly, the boundary condition in adiabatic zones is adiabatic, defining the heat flux rate as 0 Wm-2K-1. Similarly, conditions for water and water vapour with air were also kept same with the volume fraction for water and steam at 0 and for air at 1.The temperature of Condenser section is kept at 373 K.

4. RESULTS & DISCUSSIONS

Water and Ethylene alcohol were used as working fluids in this analysis, which was carried out under steady-state conditions with varied heat inputs at 40,50,60W and at 60% filling ratio. The heat input was changed from 40 to 60 watts in 10 watt increments, while the filling ratio was constant at 60% as determined theoretically to be more suitable. The temperatures in the evaporator and condenser portions were set accordingly at varied heat inputs as per the data obtained theoretically from various experiments conducted before, and the heat pipe's performance was assessed in terms of thermal resistance. The equation is used to compute the thermal resistance.

$$R_e = (T_e - T_c) / Q$$

where $\mathbf{T_e}$ = Evaporator temperature (K) , $\mathbf{T_c}$ = Condenser temperature (K) and **Q** = Heat input (W)

In the following section, the impact of heat input at constant filling ratio and impact of surface tension of working fluids on PHP performance is explored.

4.1 Effect of Heat Input

As a pulsing heat pipe (PHP) may be subjected to various heat-load situations, it is critical to investigate the performance behaviour of a PHP when subjected to various heat inputs. For all working fluids with a 60% filling ratio, heat inputs of 40 W to 60 W in steps of 10 W were investigated in this investigation. Figure 3 depicts the fluctuation in PHP thermal resistance as a function of heat input for FR 60% for water and ethylene alcohol. At the given filling ratio of all the working fluids are evaluated, the thermal resistance of the PHP has reduced as the heat input has increased. The lower thermal resistance corresponds to a higher heat transfer coefficient, implying that the PHP's performance improves with the increase in heat input.

Table -1: For Water

Heat flux(W)	Evaporator Temp (K)	Condenser Temp(K)
40 W	363 K	298 K
50 W	373 K	300 K
60 W	384 K	303 K

Table -2: For Ethylene Alcohol

Heat flux(W)	Evaporator Temp(K)	Condenser Temp(K)
40 W	383 K	302 K
50 W	392 K	302 K
60 W	404 K	306 K

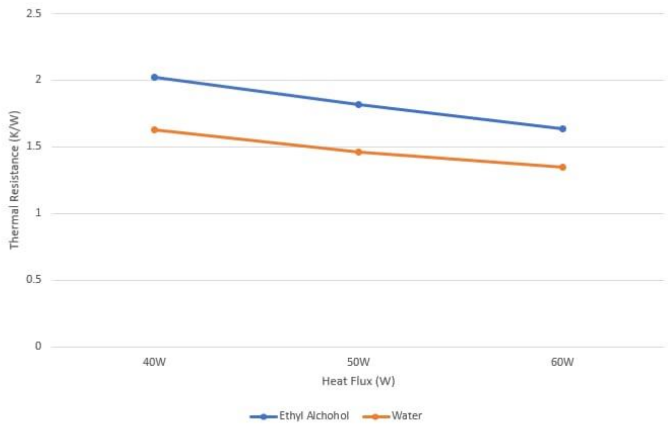

Fig -3: Variation of thermal Resistance with Heat Input

The filling ratio (FR) is the ratio of the amount of liquid (measured in volume) contained in the heat pipe to the total internal volume of the heat pipe . In most cases, it's given as a percentage. For example, FR 0 % means that the PHP is liquid-free and so operates in pure conduction mode. The value FR 100% denotes that the PHP is completely filled with liquid and hence functions as a thermosyphon. When the filling ratio is kept between 20% and 80%, the PHP is said to act as a real pulsing device. The precise range, however, varies according on the working fluid, operating temperatures, and structure.

4.2 Effect of Working Fluid Properties

Since the working fluid's thermophysical properties, such as surface tension, thermal conductivity, latent heat, specific heat, and viscosity, have a stronger impact on the PHP's performance, it's critical to understand the role of each type of working fluid in the PHP's efficient operation. According to literature reviews, water and ethylene alcohol are good operating fluids for a PHP. As we know that the surface tension of water is 0.072 N/m and of ethylene alcohol it is 0.0473 N/m which shows that water has higher surface tension as compared to Ethylene Alchohol. As the dimensionless no. Kutateledze no. (Ku) and Bond no.(Bo) depends on the surface tension by the relations:-

$$Ku = \frac{\dot{q}_c}{\rho_v h_{fg}\left[\sigma g\left(\frac{\rho_l - \rho_v}{\rho_v^2}\right)\right]^{1/4}}$$

when g is gravitational acceleration (m/s^2), h_{fg} is latent heat (kJ/kg), ρ_l is liquid density (kg/m^3), ρ_v is vapor density (kg/m^3), and σ is surface tension (N/m).

$$Bo = \frac{g(\rho_l - \rho_v)D_i^2}{\sigma}$$

As the surface tension of water is more than ethylene alcohol hence the Kutateledze no.(Ku) of water is more than ethylene alcohol as **[Ku α σ]** (Ku no. Is directly proportional to surface tension).

Also it is observed from the experimental studies that, Kutateledze no. has a direct impact on thermal performance on the closed loop oscillating heat pipe. The higher Ku no. signifies the higher thermal performance of the heat pipe & it also operates closer to the critical state.

Bond no. of water being used as base fluid has lower value as compared to ethylene alcohol being used as **[Bo 1/α σ]** (Bo no. Is inversely proportional to surface tension).

It has been evidently founded from the studies that as the Bond no. is increased, then the thermal performance of closed loop oscillating heat pipe gets decreased. It is being observed from the fact that as the surface tension decreases (Bond No. increases) , vapour tends to form into small bubbles. As the small bubbles have less capacity to transfer the heat from evaporator section to the condenser section , hence resulting in less thermal performance.

Hence, this shows that Thermal performance of Water being used as base fluid as compared to ethylene alcohol is better.

4.3 Analysis using Contours of Volume Fraction

The output of the simulation of the single turn pulsating heat pipe is being observed by using the contours of volume fraction of water & ethylene alcohol along with air after performing the iterations on ANSYS Fluent software for a count of nearly about 47000+ iterations for both water and ethylene alcohol.

The contours of volume fraction of water and ethylene alcohol were taken by keeping all the necessary operating conditions & design parameter same like pressure was kept at 40 pascal and no. of mass transfer mechanism as 1 and no. Of Eulerian phases as 3. Time step size was kept at 0.001 and maximum time steps taken at a time were 500 with 20 iterations per time step.

Radius of the tube is kept at 2 mm while the temperature of heater section and condenser section was kept at 373 K and 298 K and the modelling was done in ZX plane with gravity equals to g=9.8m/sec^2 in y direction. The no. Of tube for PHP was kept at 1 and material of tube is used as Copper.

Contours of Volume Fraction of Ethylene Alcohol

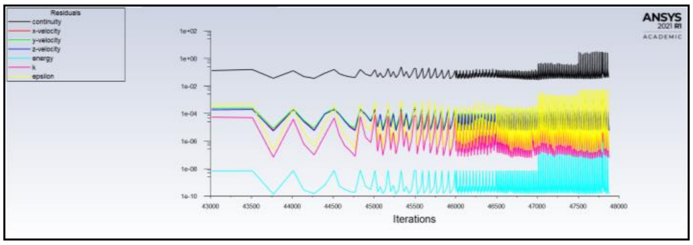

Fig -4: No. Of Iterations Performed on Ethylene Alcohol

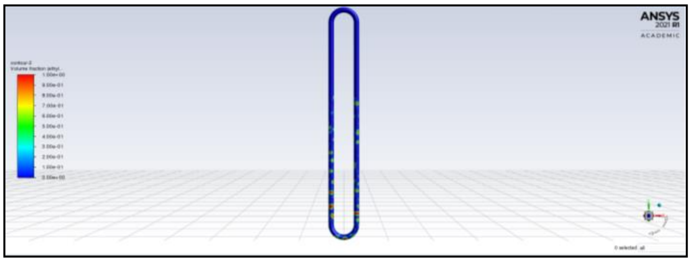

Fig -5: Contour of Volume Fraction of Ethyl Alcohol Vapour

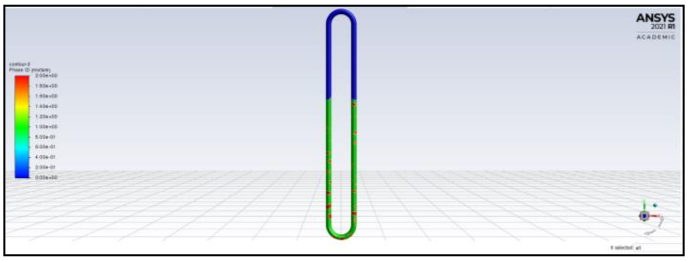

Fig -6: Contour of Volume Fraction of Phase Id Mixture

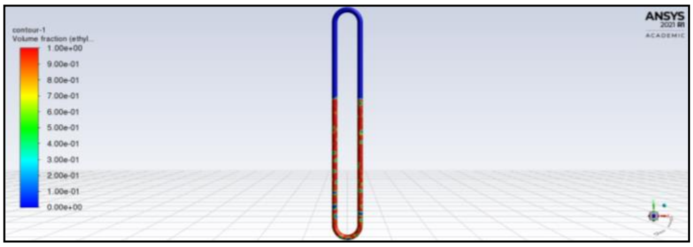

Fig -7: Contour of Volume Fraction of Ethyl Alcohol Liquid

Fig (4) shows the no. of time steps which signifies the no. of times the flow equations solved per time step. As we can see from the contours of ethylene alcohol as shown in fig 5,6,7 that the liquid slug are formed at near the evaporator section and after 47000 iterations the liquid and vapour slug is not reaching the condenser section. This shows the Thermal performance of Ethylene Alcohol not up to the limits due to the less circulating flow of ethylene alcohol inside the PHP after extracting the heat from Heater Section and releasing it to the Condenser section.

Contours of Volume Fraction of Water

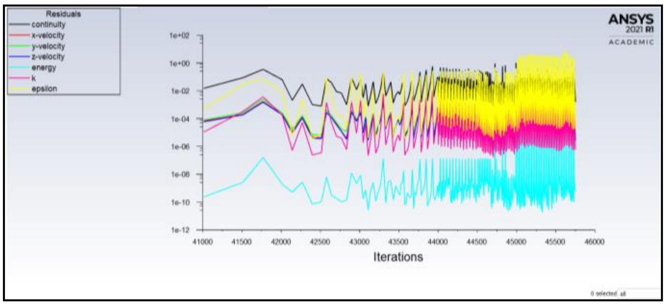

Fig -8: No. Of Iterations Performed on Water

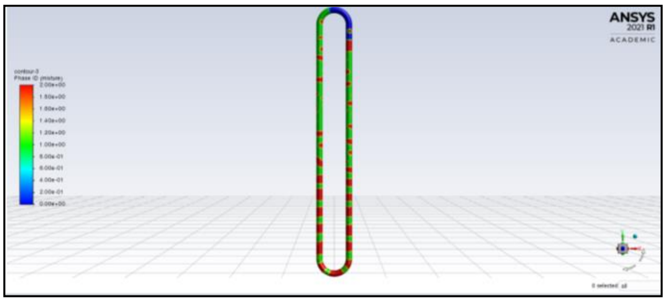

Fig -9: Contour of Volume Fraction of Phase Id Mixture

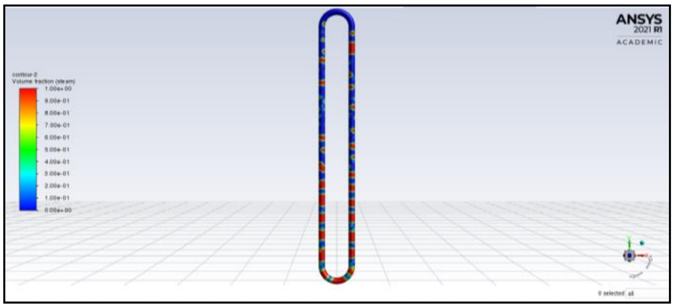

Fig -10: Contour of Volume Fraction of Steam(Water Vapour)

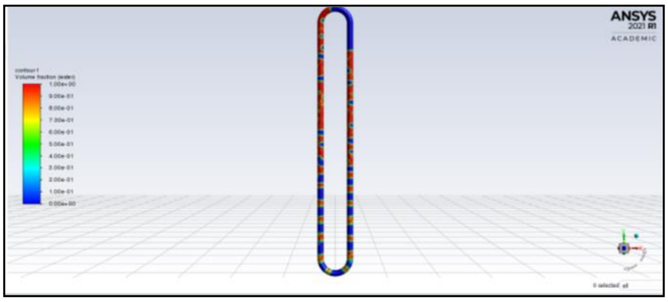

Fig -11: Contour of Volume Fraction of Water

Fig (8) shows the no. of time steps which signifies the no. of times the flow equations solved per time step. As we can see from the contours of volume fraction of water as shown in fig 9,10,11 that the liquid slug are formed at near the evaporator section and after 45000 iterations the liquid and vapour slug are reaching the condenser section. This shows the Thermal performance of water is much better than ethylene alcohol as in water the circulating flow of water inside the PHP after extracting the heat from Heater Section and releasing it to the Condenser sections is much better as compared to ethylene alcohols when operated at same conditions and approximately for same no. Of iterations.

5. CONCLUSIONS

- Based on the CFD analysis of PHP, it can be concluded that two phase flow can be successfully reproduced in Ansys Fluent in this study.
- The fluctuation in evaporator and condenser wall temperatures with flow time is noted in CFD study.
- Due to chaotic fluid flow, the thermal resistance falls and the heat transfer coefficient increases as the heat flux increases.
- The operating fluids utilized were water and ethylene alcohol.
- With a steady fill ratio of 60% and heat inputs, the tests were completed successfully at (40W, 50W, 60W).
- Thermal resistance and heat transfer coefficients were successfully validated for the base fluids and the theoretical as well as numerical approach is showing that Water having high thermal performance as compared to Ethylene Alcohol.
- Working fluids have a wide range of properties and are quite sensitive to changes in parameters as due to the surface tension also the water is having an upper hand over ethylene alcohol.

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