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Numerical Analysis of Horizontally Placed Closed Loop Pulsating Heat Pipe for Electronic Cooling

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Abstract **–** Numerical analysis of horizontally placed open and closed loop pulsating heat pipe (CLPHP) is carried with water as working fluid. The filling ratio (FR) of working fluid is taken as 77 %. The processor of laptop act as heat source. The 3D Computational domain is prepared with the help of Ansys design modeler. The Volume of Fluid (VOF) Approach is used to simulate the liquid vapor slug flow in horizontally placed open and closed loop pulsating heat pipe. Adaptive simulation settings with the time step of 0.0005 is selected to capture the movement of liquid and vapor slug flow. The contour of liquid volume fraction, wall temperature and visualized in the analysis. The objective of numerical simulation is to predict the behaviour and to understand the flow pattern of liquid vapor slug flow during the complex process of evaporation and condensation. The maximum temperature recorded for heat source is 323 K.

Keywords**:** Pulsating heat pipe, working fluid, numerical analysis, slug flow.

1. Introduction

The heat pipe is known for transferring large quantities of heat with minimum temperature drop [1]. With the thin size of electronics equipment's like a laptop, need arises to implement the most effective cooling technique to enhance the performance of system without any compromise [2]. With the complexity of electronic devices having limitation of vertical space in laptop cabinet, horizontally placed closed loop pulsating heat pipe (CLPHP) looks promising to cool the processor and graphics card of a laptop [3]. The processor and graphics card generate tremendous heat during the high-end operations which involve one or more processors running simultaneously, where the Central Processing Unit (CPU) and Graphics Processing Unit (GPU) utilization approaches to 100 %. The generated heat if not removed may result in abnormal behaviour of the components subsequently can reduce the life of battery and electronics equipment's. To cope up with the disadvantages of conventional heat pipe (CHP), where the latent heat is only involved in the transfer of heat [4]. The pulsating heat pipe (PHP) provides the advantage of combined sensible and latent heat transfer thereby improving the thermal performance [5].

The 3D computational domain is prepared in Ansys design modeler and grid is generated. The domain is divided into many small elements called cells volume. The development of three-dimensional Computational Fluid Dynamics (CFD) model shortens the design cycle through carefully controlled parametric studies, thereby reducing the required amount of testing. In 3D computational domain the boundary conditions are specified at the face of domain. The boundary conditions involved are the temperature at the heat source, heat sink, operating pressure of working fluid and surface tension of working fluid. K epsilon model is used in the analysis as it tracks the interface between two or more phase and is suitable for flow with sharp interface such as liquid and vapor slug. The governing equations are used to mathematically describe the physics of fluid flow. The equations are needed to describe the state of any fluid flow and are solved for all types of CFD Modelling.

2. Boundary Conditions on 3D Computational Domain

The 3D Computational Domain consist of horizontally placed open and CLPHP with the ID of 2mm and OD of 3mm. The small diameter is preferred to have capillary action. The processor of laptop act as heat source. The maximum temperature of 323 K is observed on heat source. The surface area of the condenser kept higher than the area of the evaporator.

2.1. Physical Characteristics and Assumption

The heat pipe used in experimental setup has an ID of 2mm. The filling ratio (FR) is taken as 77%. Volume of fluid (VOF) approach is most suitable as it tracks the interaction of phases. Pressure based solver is selected, K-Epsilon model is preferred as it offers the enhance wall treatment and thermal effect and curvature corrections. The three Eulerian phases involved are liquid, vapor and air even though there is a vacuum inside the pipe, air is still defined as one of the phases. In cell zone condition the "Operating Pressure" is set as 4000 Pa for water, these are values of saturation pressure at a given temperature of water.

2.2 Governing Equations

The flow inside the PHP has liquid and vapor slug transformation. As the phase change takes place at the saturation temperature, the conservation of mas equation needs to be taken into consideration.

$$\frac{\partial(\alpha_v \rho_v)}{\partial t} + \nabla.\,(\alpha_v \rho_v \mathrm{v}_v) = \dot{m}_{lv} - \dot{m}_{vl} \tag{1}$$

The momentum equation is solved throughout the domain Eq. (2) which is reliant on volume fractions of all the phases.

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla.\,(\rho \vec{v} \vec{v}) = -\nabla P + \nabla.\,[\mu\,(\nabla \vec{v} + \nabla \vec{v} T)] + \rho \vec{g} + \vec{Fvol} \tag{2}$$

The energy equation shared among the phases is shown in Eq. (3). Here, Sh is energy source caused by phase change.

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\,(\vec{v}(\rho E + P)) = \nabla.\,(K.\,\nabla T + (\overline{\overline{\tau}}.\,\vec{v})) + Sh \tag{3}$$

2.3 Cell Zone Condition

The computational domain uses water as working fluid having an operating pressure of 4000 Pa. The thermal boundary conditions are applied on the computational domain i.e., on heater and condenser.

2.4 Defining the phase

The Eulerian phases specified are water liquid and water vapor. The working fluid properties are selected as per the Ansys fluent data base. While defining the phase enhance wall treatment and thermal effect and correction options are considered for analysis. The evaporation and condensation mechanism from water to vapor is also specified with surface tension of water as 0.0732 N/m. The angle of contact of liquid with the tube is specified as 20^0.

2.5. Initializing Simulation and Patch

The point to be remembered with simulation of multiphase flows is that the time step needs to be sufficiently small to capture the movement of the fluid particles, and at the same time need arises to consider computational time required for simulation, a balanced has to be maintained between the computational time and accuracy of solution by proper size of mesh.

2.6 Simulation Setting.

To capture the movement of fluid particle and to predict the physics of multiphase flow, taking into consideration the limitation of time and limited capacity of computer, adaptive time step with times step size of 0.0005 is considered.

Table 2: Simulation Setting

Sr. No.	**Time Step Type**	**Time Step**	**Issue**
1	Adaptive	0.1	Diverge very fast
2	Adaptive	0.01	Diverges
3	Adaptive	0.001	Diverges after some time
4	Adaptive	0.005	Takes long time but never diverge

3. Mesh Generation on Computational Domain

The mesh is generated on the computational domain with the help of default meshing tool available in Ansys workbench. The mesh has been modified to avoid the problem of courant number in further analysis. The heater and condenser sections are specified with name selection tool in meshing so as to apply the boundary condition in setup.

3.1 Mesh Generation for Horizontally Placed Open Loop Pulsating Heat Pipe

Table 2: Information about number of nodes, element, volume occupied by domain for Open Loop Pulsating Heat Pipe

Sr. No.	Domain	Nodes	Element	Volume (m^3)	% of Total Volume
1	Air	8840	7482	0.13071×10^{-6}	23 %
2	Liquid	31290	26760	0.43389×10^{-6}	77 %
3	All Domains	40130	34242	0.56461×10^{-6}	100 %

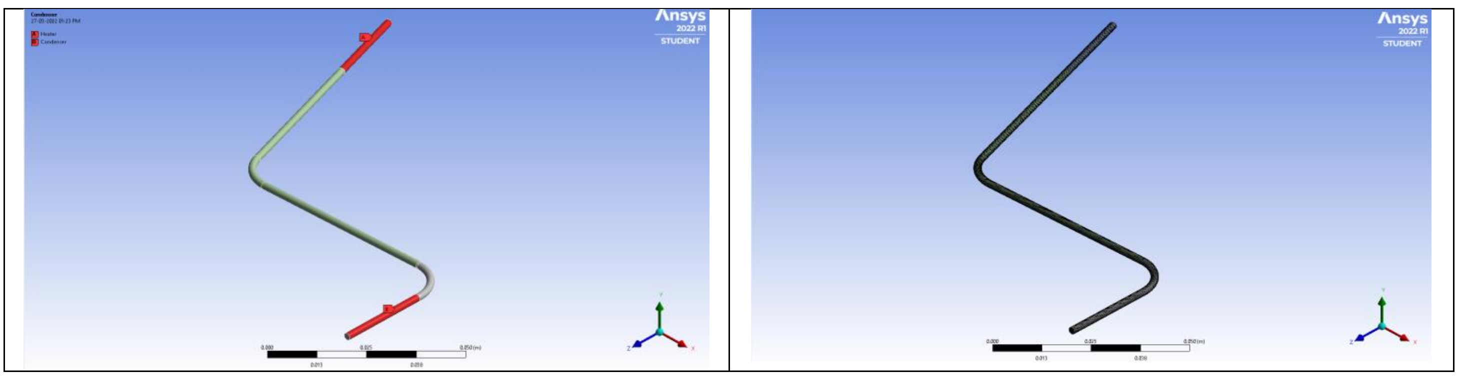


Fig. 1: Location of Heater, Condenser and Mesh for Horizontally Placed Open Loop Pulsating Heat Pipe

The computational domain has two major part, air which occupies 23 % of total volume of tube and liquid which occupies the 77 % of the total volume of the tube.

3.2 Mesh Generation for Horizontally Placed Closed Loop Pulsating Heat Pipe

Table 3: Information about Number of Nodes, Elements, Volume Occupied by domain for Closes Loop Pulsating Heat Pipe.

Sr. No.	Domain	Nodes	Element	Volume (m^3)	% of Total Volume
1	Air	13617	10906	0.26901×10^{-6}	23%
2	Liquid	80835	72200	0.94019×10^{-6}	77 %
3	All Domains	94452	83106	1.2109×10^{-6}	100 %

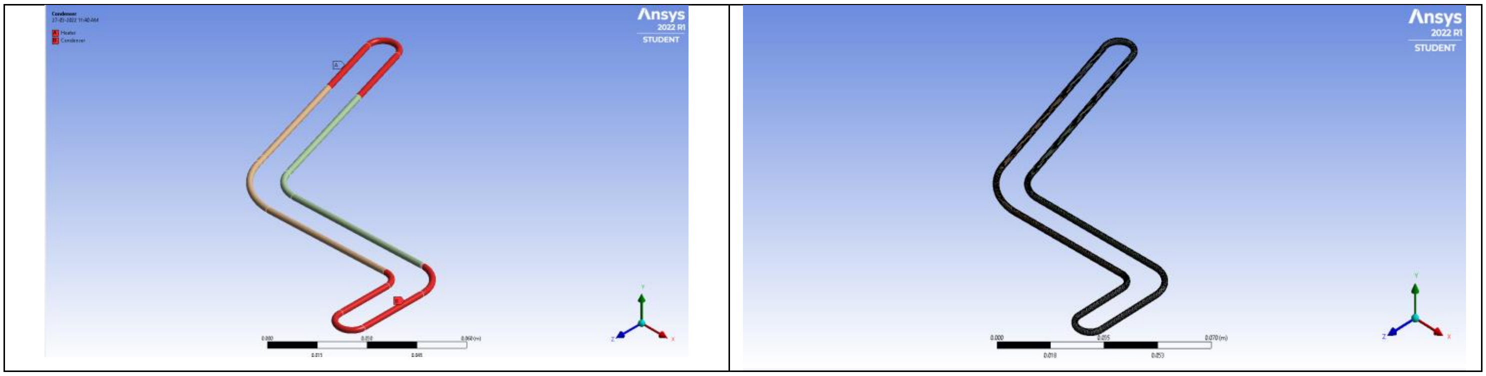
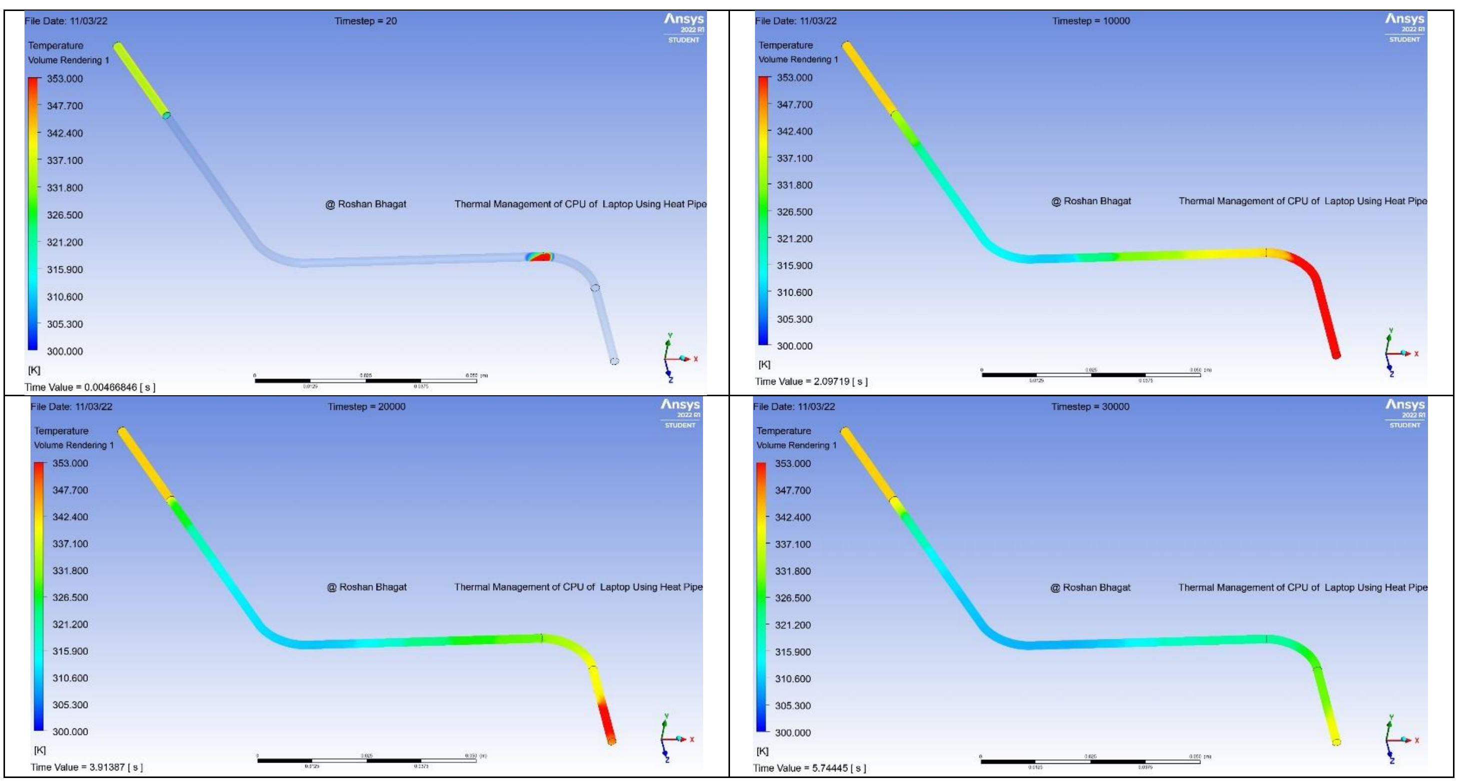


Fig. 2: Location of Heater, Condenser and Mesh for Horizontally Placed Open Loop Pulsating Heat Pipe

4. CFD Simulation

The simulation is performed with water as working fluid. The complex physical phenomenon of evaporation and condensation is observed from time step of 20 to 50000. The use of CFD model reduces the experimental work necessary to predict the performance of system.

4.1 Contours of wall temperature for Horizontally Placed Open Loop Pulsating Heat Pipe



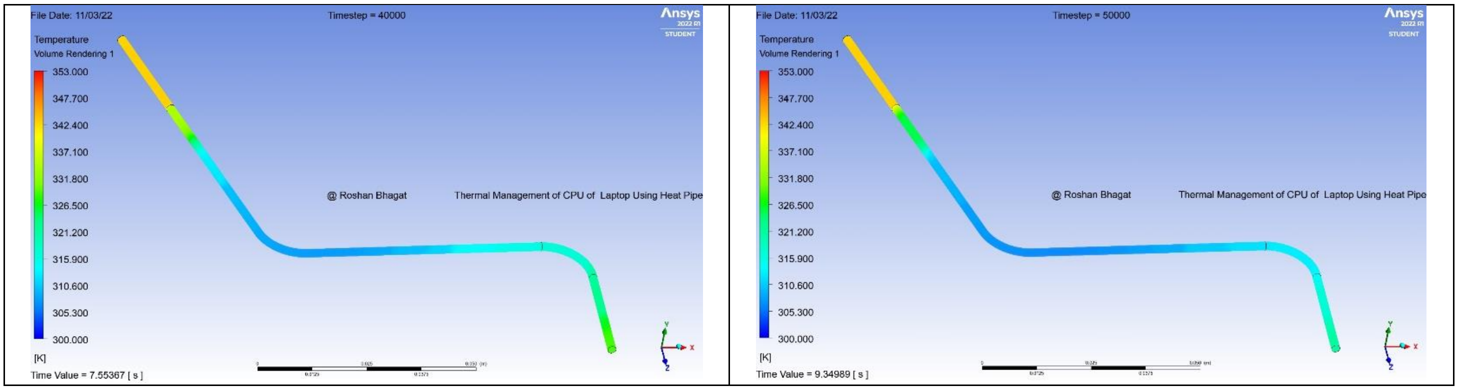
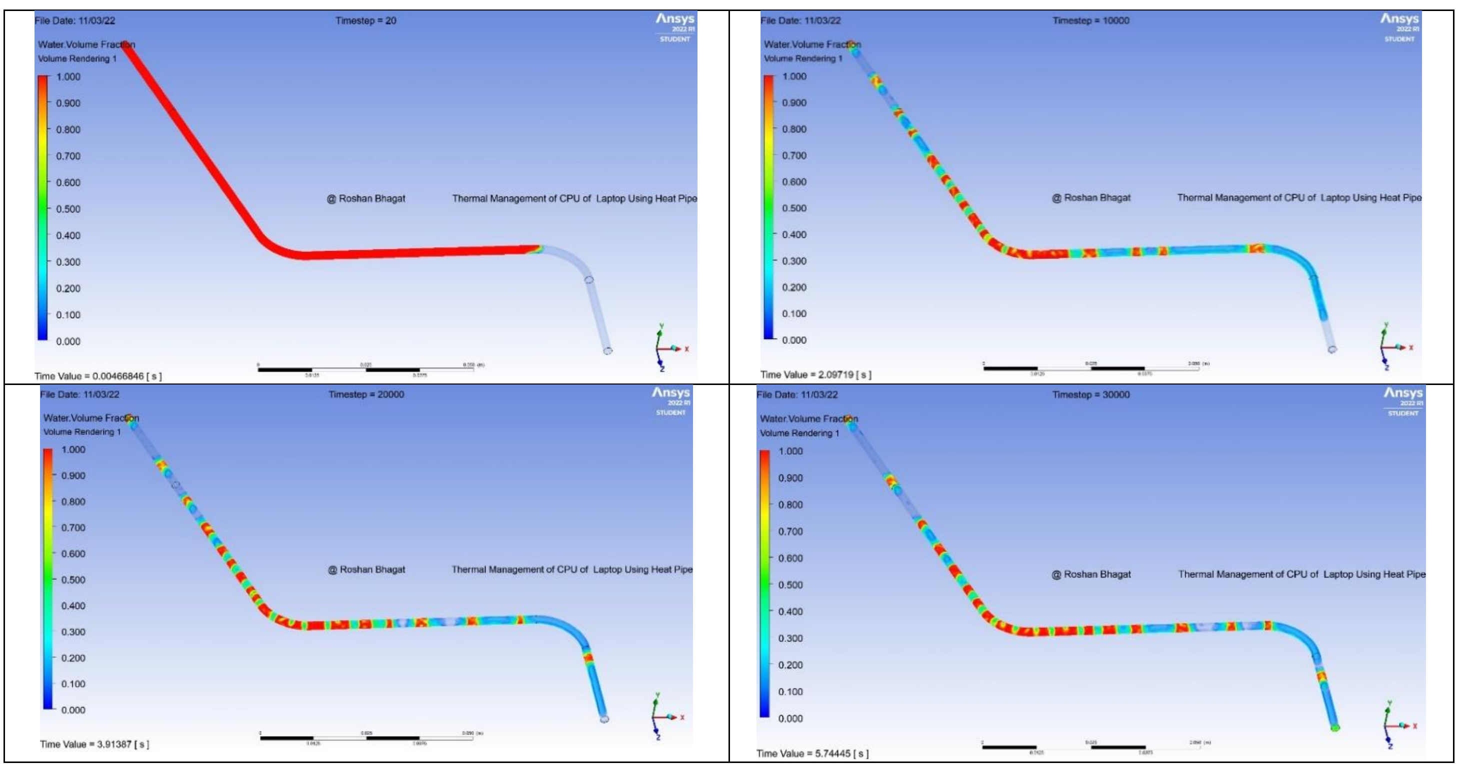


Fig. 3: Contours of wall temperature for open Loop Pulsating Heat Pipe.

The contours of wall temperature show the temperature variation along the length of OLPHP. The variations are observed from the time step of 20 to 50000. At initial time step of 20, higher temperature is observed at the evaporator section only which is indicated by red colour. The colour contours show the process of evaporation and condensation. Lower temperature is observed if the fluid rejects heat in the condenser section.

4.2 Contours of liquid volume fraction for Horizontally Placed Open Loop Pulsating Heat Pipe



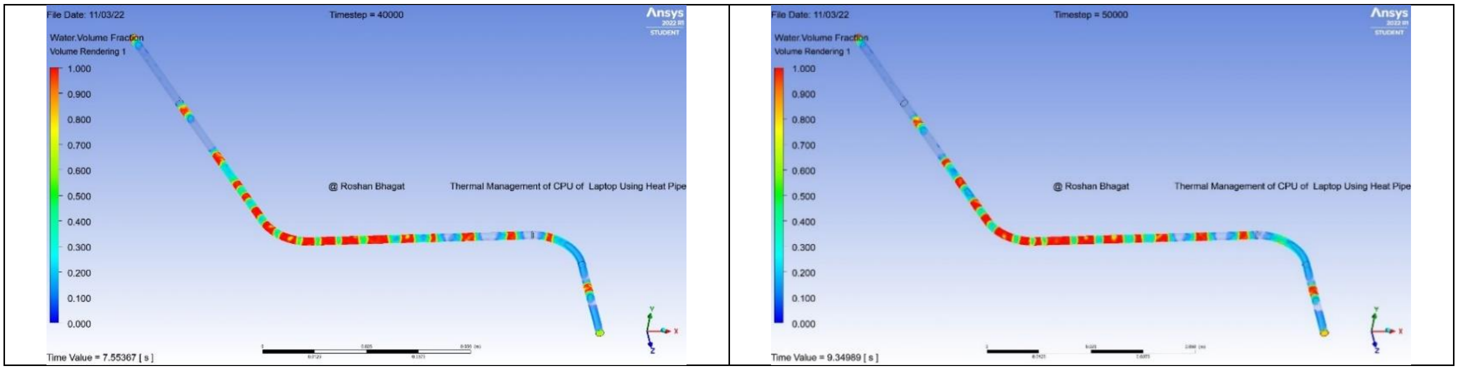
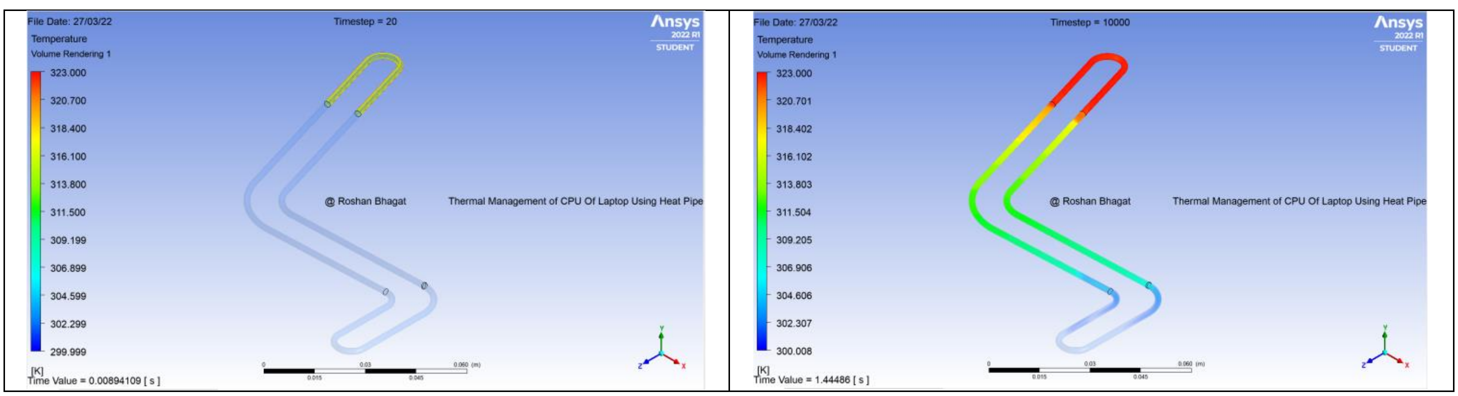


Fig. 4: Contours of liquid volume fraction for open Loop Pulsating Heat Pipe.

The contours of liquid volume fraction are observed from the time step of 20 to 50000. The volume fraction of fluid is shown on the gradient line values starting from 0 to 1. At initial time step of 20 only liquid volume fraction is available along the tube. As heating continues at the evaporator section liquid starts converting into vapor. As the time step increases the alternate liquid vapor slug formation can be seen in the simulation. The heat is absorbed in the evaporator section and is rejected at the condenser section. The flow of fluid is due to difference in density between the evaporator and condenser section. The liquid vapor slug rejects heat and again come back to the evaporator section due to gravity. The direction of fluid flow depends on the difference of temperature and density of working fluid. The flow pattern of working fluid can be different for different simulation run. As the tube is slightly inclined after the evaporator section the liquid return back due to gravity towards the evaporator section after rejecting heat in the condenser section.

4.3 Contours of Wall Temperature for Horizontally Placed Closed Loop Pulsating Heat Pipe



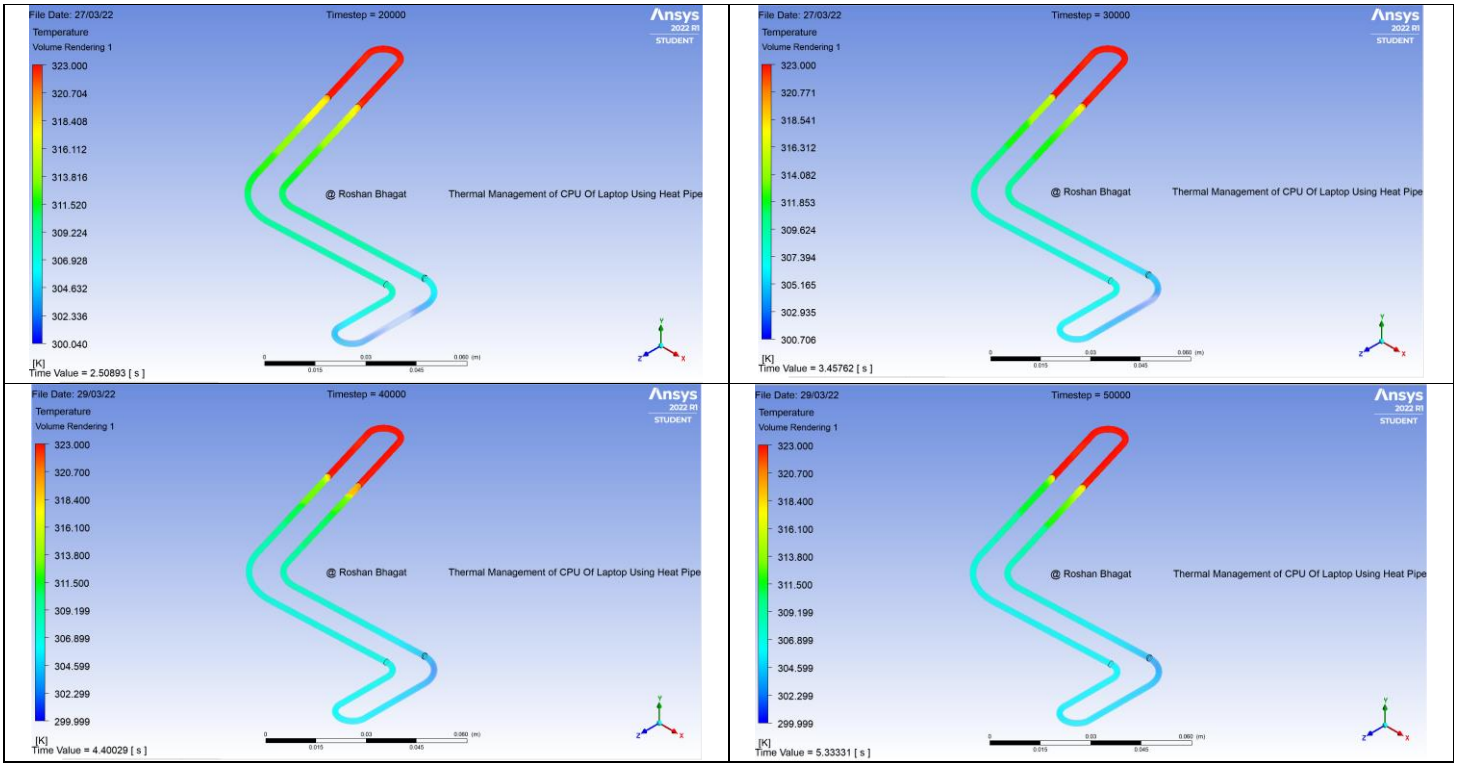
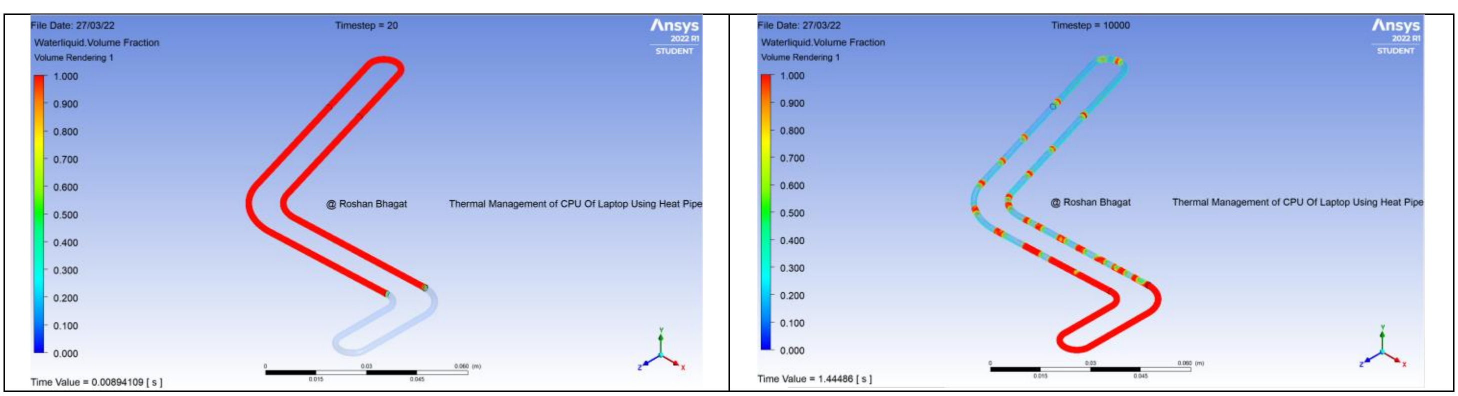


Fig. 5: Contours of wall temperature for Horizontally Placed Closed Loop Pulsating Heat Pipe

The contours of wall temperature are visualized in fig. 5. The variations in temperature along the length of tube is significant from the time step of 20 to time step of 50000. At initial time step of 20, the higher temperature is observed at the evaporator section only. Once the fluid carry heat in the form of sensible and latent heat of liquid and vapor slug, higher temperatures are observed along the length of tube. The temperature variations are observed from 300 K to 323 K. As the fluid rejects heat in the condenser section, drop in the temperature is observed along the tube. The red zone indicates the higher value of temperature whereas and the blue zone indicates the lower value of temperature.

4.4 Contours of Liquid Volume fraction for Horizontally Placed Closed Loop Pulsating Heat Pipe



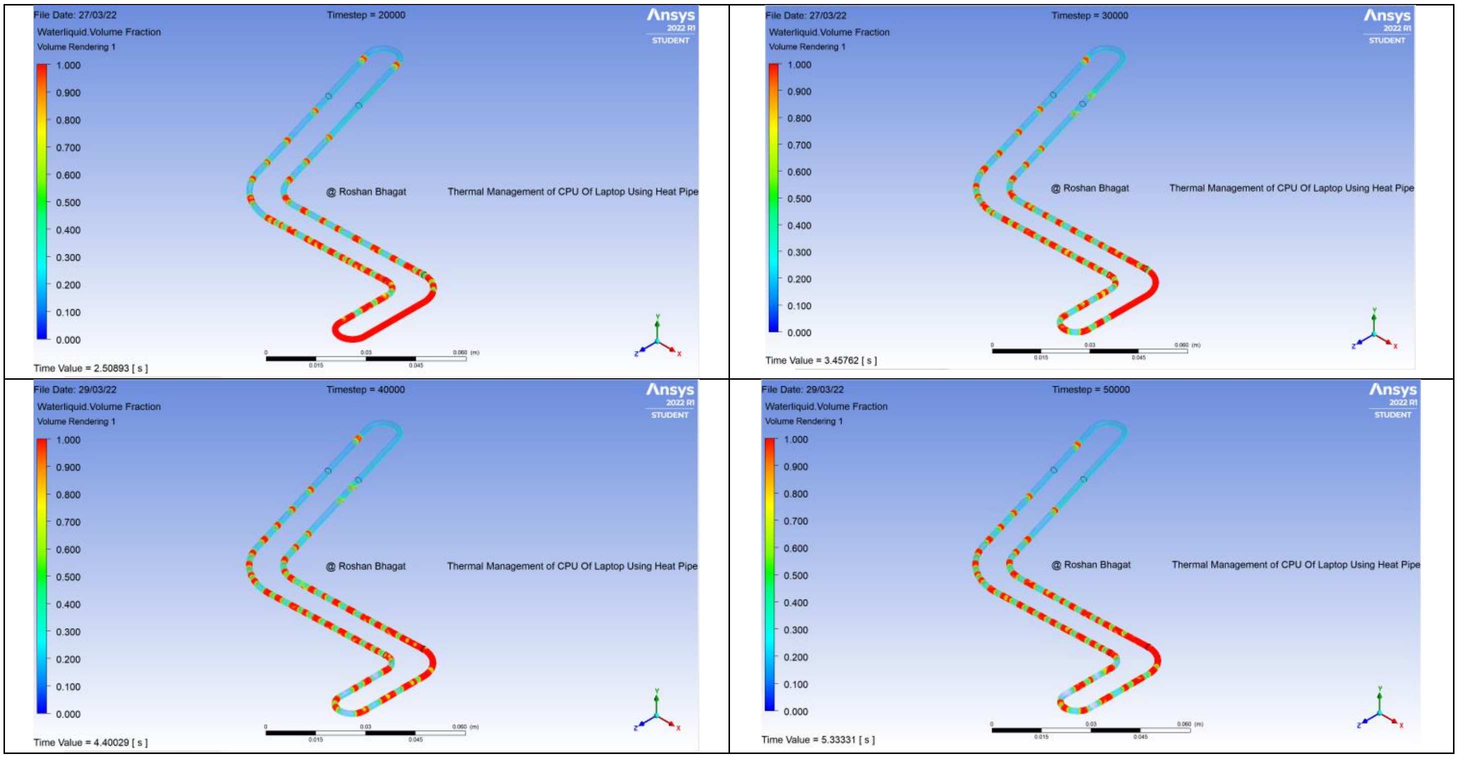


Fig. 6: Contour's liquid volume fraction for Horizontally Placed Closed Loop Pulsating Heat Pipe

The contours of liquid volume fraction are as shown in fig. 6 from time step value of 20 to 50000. At initial time step of 20 only liquid volume fraction is available. As heat is absorbed by the working fluid liquid vapor slug formation starts with higher time step. The liquid vapor slug transport carries sensible and latent heat towards the condenser section where the heat rejection takes place. The phenomenon of evaporator and condensation can be observed at higher time step.

5. Conclusion

The simulation results show that in CLPHP fluid after rejecting the heat comes back easily towards the condenser section as two tubes are available for flow, the direction of flow depends on difference in temperature and density of working fluid. In OLPHP heated fluid pushes the cold fluid, hence flow pattern are not observed. Latent heat transfer is more dominant than the sensible heat. The flow visualization using CFD tools helped in predicting the flow pattern of fluid, the behaviour is studied at various flow time and time step. The contours of liquid volume fraction, contours of wall temperature are visualized. The phenomenon of evaporation and condensation understood with CFD results. These CFD results helped in selection of suitable geometry for given CLPHP. If length of tube between evaporator and condenser section is more, complete dry out can takes place before working fluid reach to condenser section.

It is observed that for CLPHP with inner diameter of 2mm the liquid and vapor slug formation depends on boiling point and latent heat of working fluid. From the visualization CLPHP is more suitable as compared to OLPHP pipe as there are possibility of dry out condition in open loop pulsating heat pipe as the flow of fluid is restricted.

Nomenclature

CLPHP	:	Closed Loop Pulsating Heat Pipe
FR	:	Filling Ratio
VOF	:	Volume of Fluid
CFD	:	Computational Fluid Dynamics
ID/OD	:	Inner/Outer Diameter
CPU	:	Central Processing Unit
GPU	:	Graphics Processing Unit
K	:	Thermal Conductivity

α	:	Void Fraction
E	:	Energy
P	:	Pressure
$\dot{m}$	:	Mass transfer rate
F_{VOL}	:	Volume Force
l, v	:	Liquid, Vapor
μ	:	Viscosity
ρ	:	Density

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