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Experimental Investigation and Numerical Analysis of Horizontally Placed Flat Pulsating Heat Pipe for Electronic Cooling

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Abstract - The experimental investigation and numerical analysis of horizontally placed flat pulsating heat pipe is carried out. The flat pulsating heat pipe with a width of 11 mm and thickness of 2mm is used for experimental investigation. Out of the total volume of the tube 72 % of the volume is filled with water as working fluid. The processor of a computer act as heat source. The flat pulsating heat pipe takes heat from the processor of and rejects heat at another end. The externally powered fan is used to increase the rate of heat transfer. During the operation the 8 watts of power is consumed by the processor. The maximum temperature recorded during the operation of processor of computer is 323 K. The temperatures are measured with the help of digital laser thermometer. The numerical model is developed with Ansys design modeler. The volume of fluid approach is used to predict the physics of fluid flow during complex phenomenon of evaporation and condensation.

Keywords: Pulsating Heat Pipe, Working Fluid, Heat Transfer

1. Introduction

The heat pipes are commonly used in case of electronics equipment [1]. As there is a limitation of space in vertical direction, the flat pulsating heat pipe (PHP) look promising in transferring large quantity of heat with greater heat drop [2]. The numerical simulation is helpful in reducing the experimentation required [3]. The simulation results give the understanding of fluid flow pattern inside the pulsating heat pipe [4]. The phenomenon of dry out condition is also predicted with the help of numerical analysis [5]. The analysis of fluid flow is useful to select the suitable working fluid as per the operating temperature range [6].

2 Governing Equations

The flow inside the PHP has liquid and vapor slug and the phase change takes place, the conservation of mas equation 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.

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

3 Setup Description

The setup consists of flat copper heat pipe for electronic cooling, the width of copper tube is 1.1cm and thickness is 0.2cm. the evaporator is kept at lower elevation than the condenser. The digital laser thermometer is used for measuring the temperature.

Fig. 1 Setup for horizontally placed flat pulsating heat pipe.

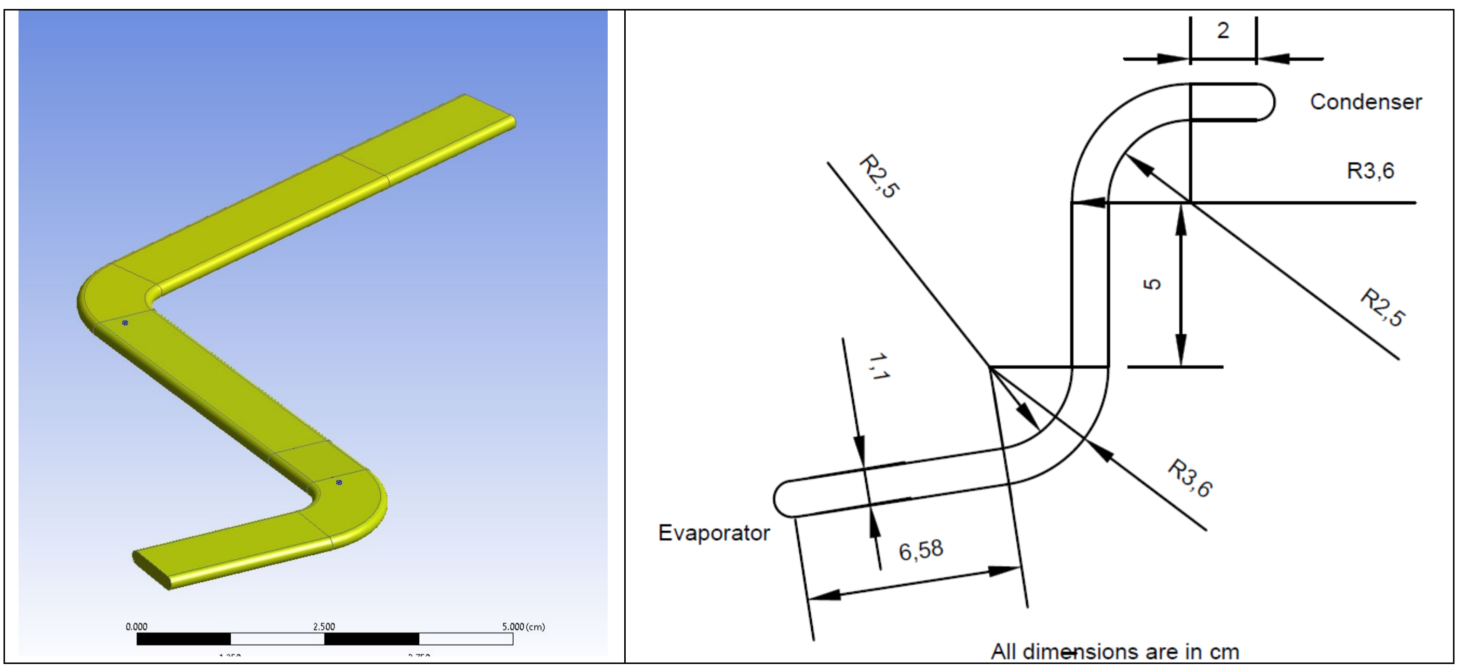


Fig. 2 3D geometry of horizontally placed flat pulsating heat pipe

The figure 2 shows the geometry of horizontally placed flat PHP, it uses water as working fluid. out of the total volume of the tube, 72 % of the volume occupied by liquid water. The water is used due to its compatibility with copper tube.

4 Experimentation

A fan is used for quick transfer of heat to the surrounding. The bottom of the condenser is attached with fins where the the air is circulated with the help of fan. The processor act as heat source, the copper heat pipe is used to carry this heat to the surrounding. The digital laser thermometer is used for measurement of temperature.

Table 1 Temperature across the horizontally placed flat pulsating heat pipe during a typical time of day

Sr. No.	Time	Evaporator Temperature	Condenser Temperature	Status of Fan
1	3.14 PM	33.6	33.6	Off
2	3.15 PM	35.0	33.6	Off
3	3.16 PM	35.9	35.2	Off
4	3.17 PM	38.0	36.0	Off
5	3.18 PM	39.9	37.0	Off
6	3.19 PM	43.5	36.4	Off
7	3.20 PM	48.3	36.5	Off
8	3.21 PM	48.1	37.3	Off
9	3.22 PM	49.0	38.0	Off
10	3.23 PM	51.0	39.1	On
11	3.24 PM	49.0	35.5	On
12	3.25 PM	44.0	34.4	On
13	3.26 PM	43.0	34.0	On
14	3.27 PM	36.0	34.1	Off

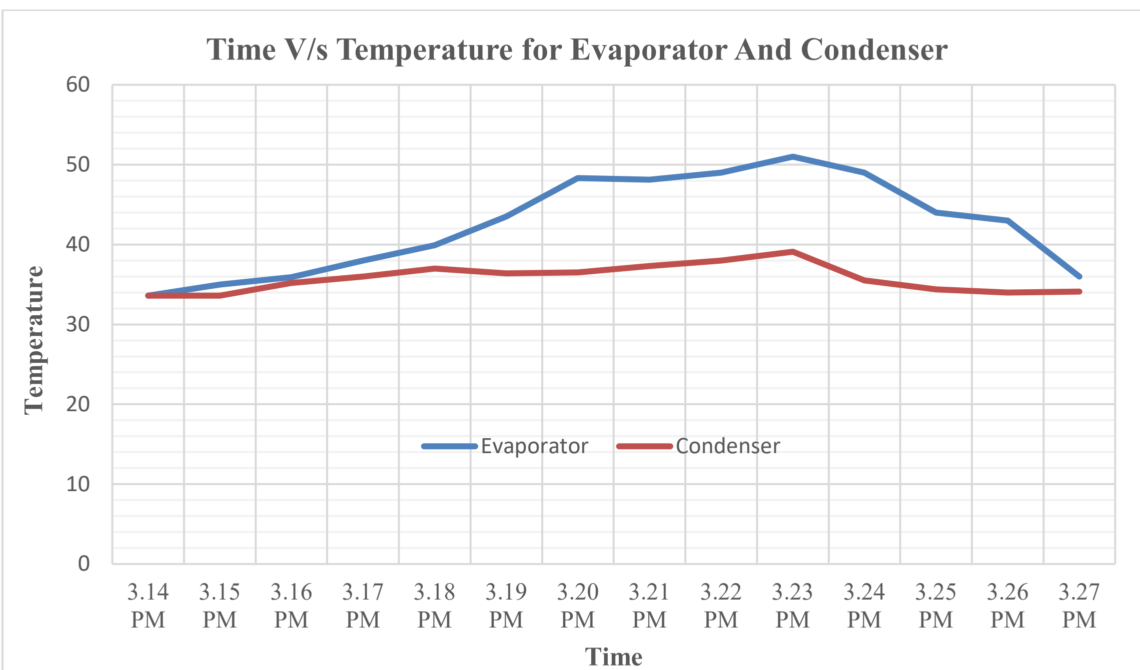


Fig. 3 Experimental results of time v/s temperature at evaporator and condenser for horizontally placed flat PHP

The figure 3 shows, after the heat rejection by the working fluid present inside the flat pulsating heat pipe in the form of sensible and latent heat the temperature of evaporator is reduced and it approaches to the normal temperature. Initially at start of heating process temperature difference is less, then it increases for around nine minutes and then the difference of temperature again reduces.

Table 2 Temperature across the horizontally placed flat pulsating heat pipe during a typical time of day for 780 seconds

Sr. No.	Time	Evaporator Temperature	Condenser Temperature	Status of Fan
1	4.28 PM	32.9	32.9	Off
2	4.29 PM	33.8	33.5	Off
3	4.29 PM	34.9	34.1	Off
4	4.29 PM	35.5	35.3	Off
5	4.30 PM	36.1	35.1	Off
6	4.31 PM	36.9	36.2	Off
7	4.31 PM	37.5	36.9	Off
8	4.31 PM	38.7	36.9	Off
9	4.32 PM	39.1	36.9	Off
10	4.32 PM	39.7	37.8	Off
11	4.32 PM	41.7	38.1	Off
12	4.33 PM	43.6	38.4	Off
13	4.33 PM	44.6	39.4	Off
14	4.33 PM	46.0	38.6	Off
15	4.34 PM	46.0	37.9	Off
16	4.34 PM	46.6	37.3	Off
17	4.35 PM	47.6	38.2	Off
18	4.35 PM	47.2	39.0	Off
19	4.35 PM	47.5	38.4	Off
20	4.35 PM	47.4	38.7	Off
21	4.36 PM	48.3	38.4	Off
22	4.36 PM	49.6	38.4	Off
23	4.36 PM	49.7	38.0	Off
24	4.36 PM	50.9	38.2	Off
25	4.37 PM	51.7	38.4	Off
26	4.38 PM	51.0	39.6	On
27	4.38 PM	51.2	39.3	On
28	4.38 PM	51.3	36.3	On
29	4.39 PM	50.3	36.0	On
30	4.39 PM	49.2	36.0	On
31	4.39 PM	47.6	36.5	On
32	4.39 PM	46.2	35.5	On
33	4.40 PM	45.0	35.0	On
34	4.40 PM	44.0	35.0	On
35	4.40 PM	44.0	35.0	On
36	4.40 PM	43.2	35.9	On
37	4.41 PM	42.6	35.8	On
38	4.41 PM	42.8	35.5	On
39	4.41 PM	42.2	35.5	Off

Table 2 shows experimental results for variation of tempeature at evaporator and condenser of horizontally placed flat pulsating heat pipe. The fan used for cooling starts when temperature reaches to 50^0c and automatically shuts off after 3 minutes.

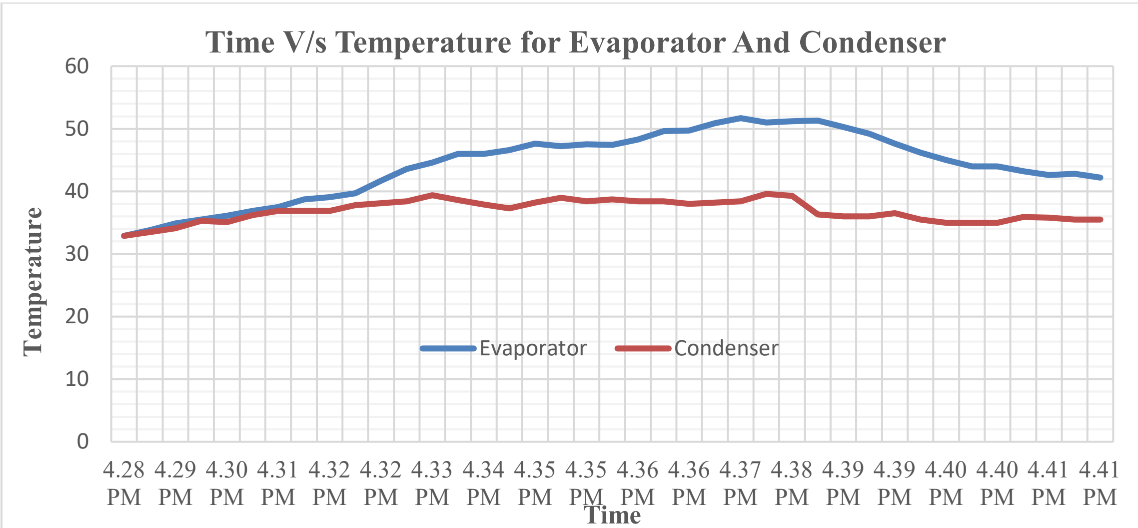


Fig. 4 Experimental results of time v/s temperature at evaporator and condenser for horizontally placed flat pulsating heat pipe

Table 3 Temperature across the horizontally placed flat pulsating heat pipe during night condition

Sr. No.	Time	Evaporator Temperature	Condenser Temperature	Status of Fan
1	10.05 PM	31.6	31.6	Off
2	10.05 PM	32.0	32.9	Off
3	10.06 PM	33.3	33.2	Off
4	10.06 PM	34.4	34.4	Off
5	10.07 PM	35.4	34.2	Off
6	10.07 PM	36.6	36.0	Off
7	10.08 PM	38.1	35.9	Off
8	10.08 PM	37.9	36.2	Off
9	10.08 PM	38.2	36.2	Off
10	10.09 PM	39.0	37.1	Off
11	10.09 PM	39.8	36.6	Off
12	10.09 PM	40.2	37.2	Off
13	10.10 PM	42.0	37.5	Off
14	10.11 PM	42.1	39.3	Off
15	10.11 PM	44.4	40.1	Off
16	10.12 PM	44.5	39.0	Off
17	10.12 PM	45.0	39.8	Off
18	10.12 PM	45.7	40.6	Off
19	10.13 PM	46.5	40.5	Off
20	10.13 PM	48.0	40.6	Off
21	10.13 PM	49.2	40.0	On
22	10.13 PM	48.8	38.0	On
23	10.14 PM	48.4	38.0	On
24	10.14 PM	48.0	36.8	On

25	10.14 PM	47.2	35.1	On
26	10.14 PM	45.7	34.6	On
27	10.15 PM	43.9	34.3	On

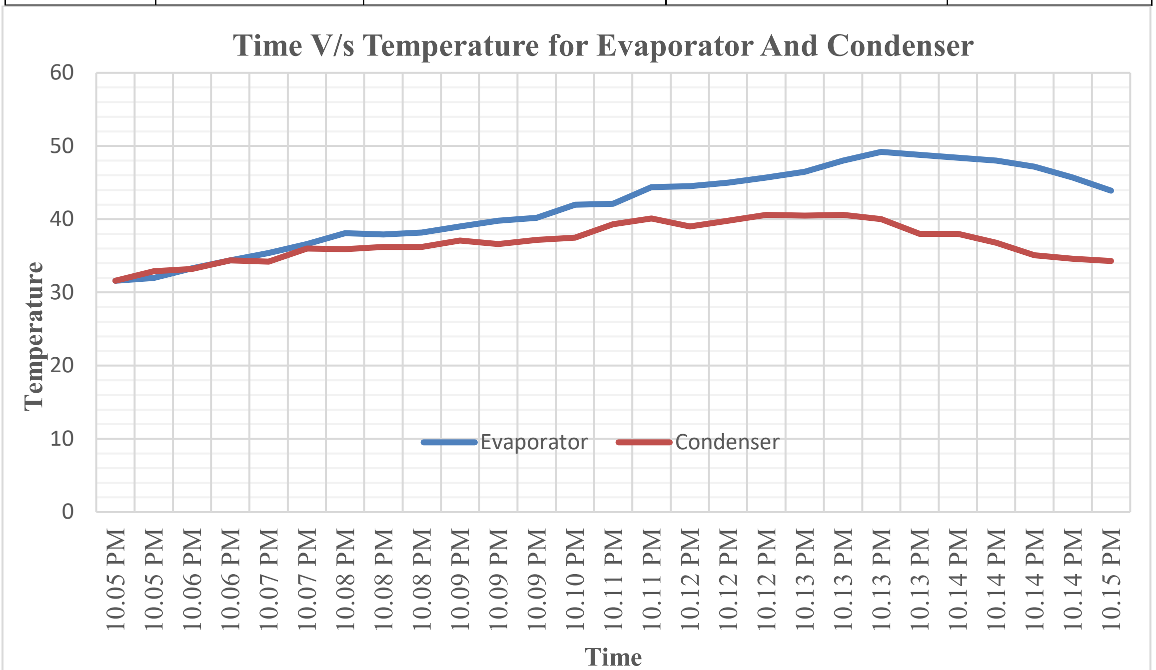


Fig. 5 Experimental results of time v/s temperature at evaporator and condenser for horizontally placed flat pulsating heat pipe

5 CFD Simulation for Horizontally Placed Flat Pulsating Heat Pipe

The CFD simulation involves the contours of liquid volume fraction and contours of wall temperature for water from a time step of 20 to time step of 50000. Higher time steps are selected to capture the movement of fluid particles from evaporator to the condenser section of horizontally placed flat heat pipe. The working fluid is specified as water and specified with cell zone condition of 4000 Pa, and the evaporator temperature is specified at 323 K.

5.1 Geometry Creation

The geometry is prepared with ANSYS design modeler, the material of the tube is taken as copper. The material selection is done though material library in ANSYS.

5.2 Mesh Generation for Horizontally Placed Flat Pulsating Heat Pipe

The mesh is generated with the help of meshing tool available in the ANSYS. The mesh has been modified to avoid the divergence in the velocity field thus the problem of courant number is overcome. Out of the total volume of the heat pipe 71 % of the volume is occupied by liquid, whereas 28 % of the volume is occupied by air. Name selection is done with evaporator and condenser so as to apply the thermal boundary conditions in setup and visualize the result in post processor.

Table 4: Information about mesh, volume occupied by domain for flat pulsating heat pipe

Sr. No.	Domain	Nodes	Element	Volume (m^3)	% of Total Volume
1	Air	135125	122382	0.97811×10^{-6}	28%
2	Liquid	338032	306729	2.451×10^{-6}	72 %
3	All Domains	473157	429111	3.42911×10^{-6}	100 %

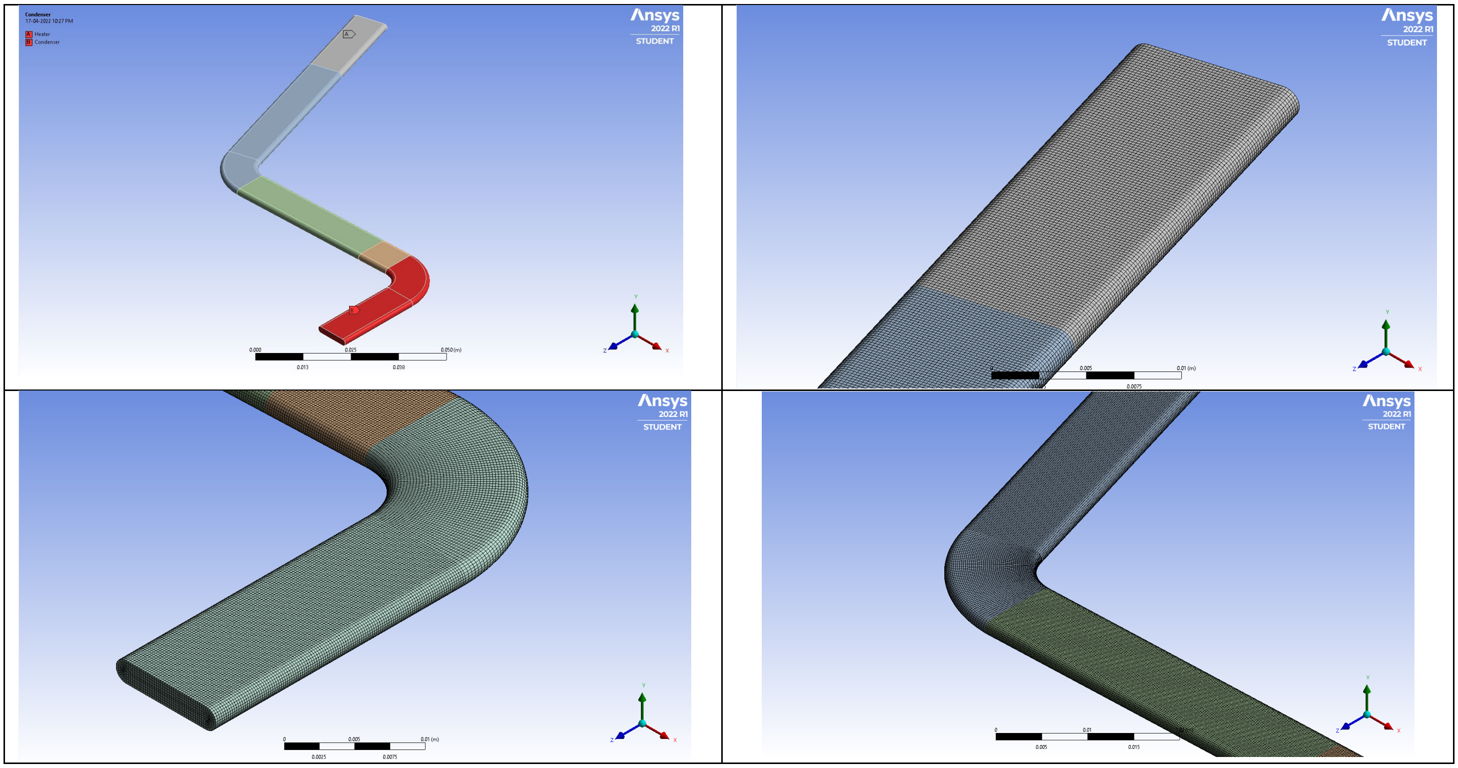


Fig. 6 Mesh at evaporator, condenser and adiabatic section for horizontally placed flat pulsating heat pipe.

Figure 6 shows the mesh generated at evaporator, condenser and adiabatic section the element size selected is 0.000215. The linear element order is selected for preparation of mesh and limitation of student version taken into consideration.

5.3 Simulation Setup for Horizontally Placed Flat Pulsating Heat Pipe

5.3.1 Solver Selection

The pressure-based solver and the transient model is selected as the temperature variations are taking place over the period of time. The gravity is specified as 9.81 m/s^2 in the negative direction of Y axis.

5.3.2 Model Selection

The alternate liquid and vapor slug flow will takes place from evaporator to the condenser section, VOF model is most suitable to track the interface of fluid particle, which is very important to predict the flow of fluid to enhance the thermal performance of system. The energy equation needs to be turn on as there is involvement of temperature. Viscous k epsilon model with enhance wall treatment and thermal effect and curvature correction are considered.

5.3.3 Material Selection

The material selection is done from the fluent database, the data base has default material library, the fluid along with the solid materials with their properties are available. From the database water liquid and water vapor is selected as working fluid.

5.3.4 Defining the Phase

The number of Eulerian phases is defined during the model selection which involves the primary and secondary phase. The primary phase is selected as vapor and secondary phase is selected as liquid. The surface tension coefficient for working fluid is specified as 0.0736 N/m. The heat and mass transfer process i.e., the process of evaporator and condensation is specified.

5.3.5 Cell Zone Condition

In cell zone condition the operating pressure of working fluid is specified and vacuum is introduced, for water the pressure of 4000 Pa is specified, this pressure is the saturation pressure of water working fluid at temperature of $30^0 C$.

5.3.6 Boundary Conditions

Name selection done in meshing is useful for applying the boundary conditions in setup, the thermal boundary conditions are applied at evaporator and condenser section, the thermal boundary conditions include the application of heat flux or temperature. The thickness of wall can also be specified. The angle of contact between the wall and the working fluid of 20^0 is specified for given working fluid.

5.3.7 Initialization and simulation patch

After applying the boundary condition, the step before starting the simulation is initialization and patch. In initialization the portion liquid phase is patch with working fluid. The value is specified as 1, to have understanding that only liquid phase is present before the heating process starts.

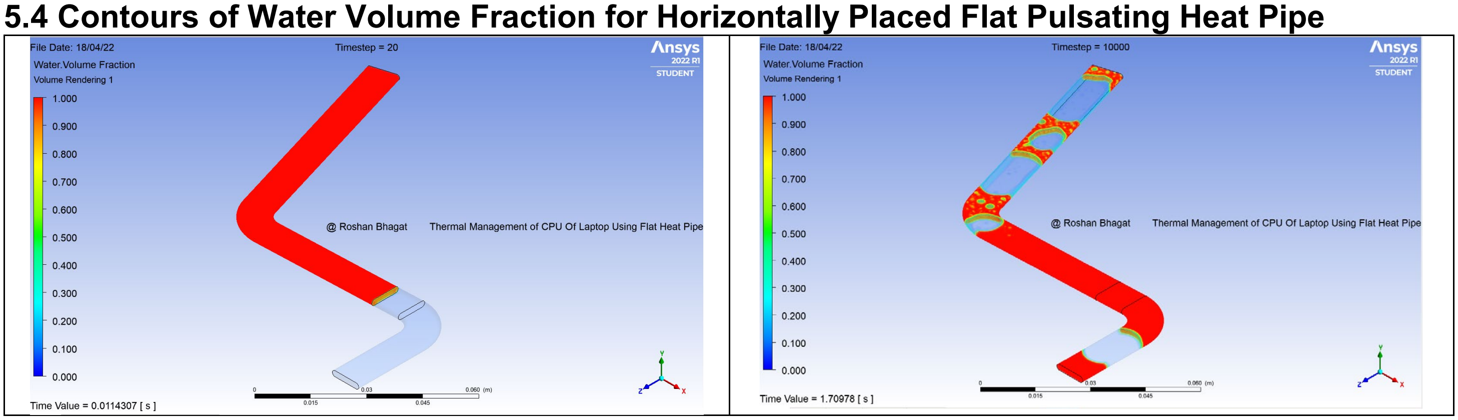
5.3.8 Solution Animation

The solution animation is useful to track behaviour of fluid particle during the process of iteration, animation is set for the contours of liquid volume fraction and contours of wall temperature and contours of mass transfer rate. The parameters can be set on floats to have better visualization of legends on contours.

5.3.9 Calculation

The time step selection is carefully done to avoid the divergence in the velocity field at the same time it is also ensure that the time required for simulation will be less. There are issues with different time steps, a time step of 0.0005 is selected as there are less chances of divergence in the velocity field and the problem of courant number are eliminate. The time step needs to be small enough to capture the movement of fluid particles with consideration of computational time required for performing the lengthy process of iterations.

5.4 Contours of Water Volume Fraction for Horizontally Placed Flat Pulsating Heat Pipe



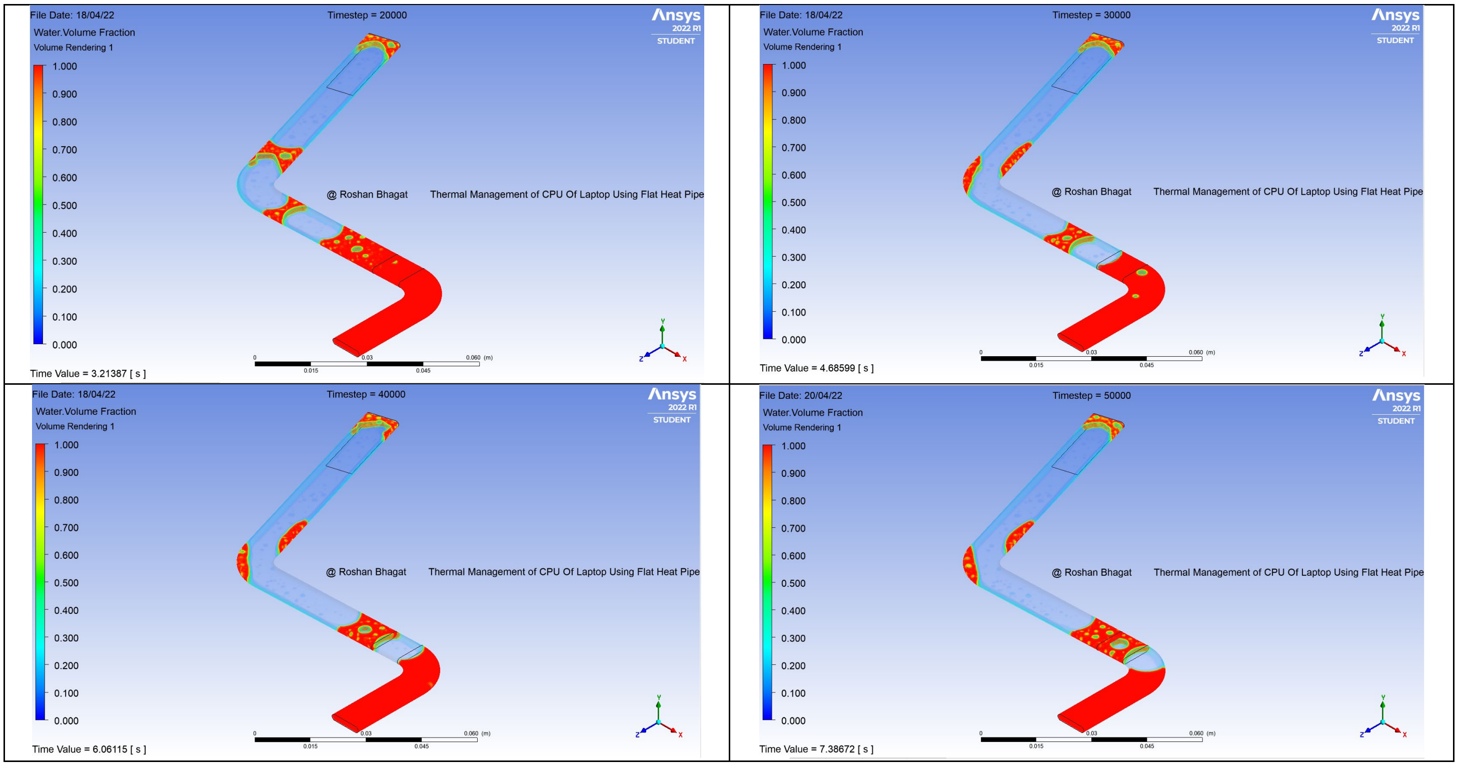
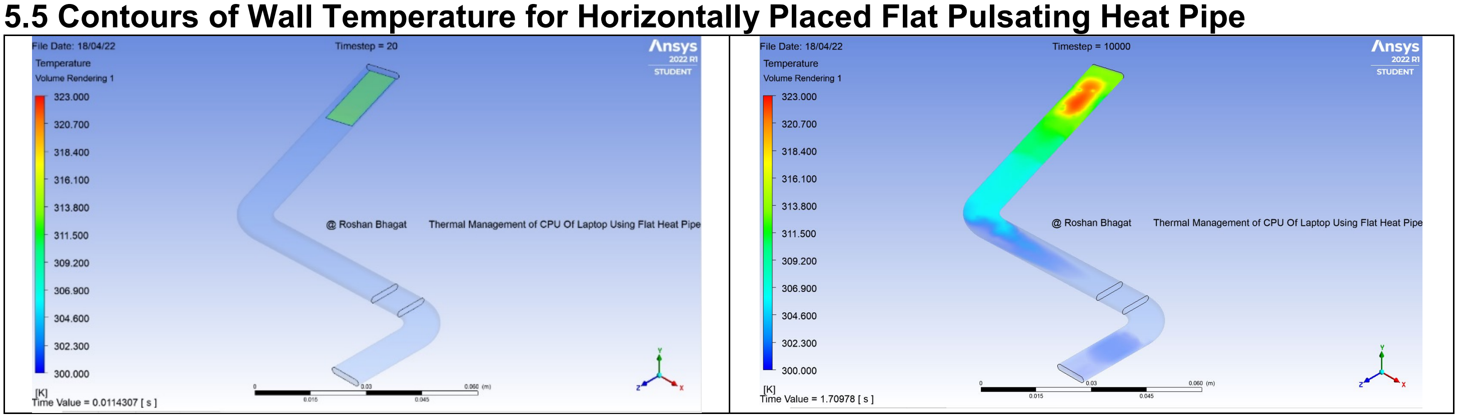


Fig. 7 Contours of water volume fraction for horizontally placed flat pulsating heat pipe at a time step of 20

Figure 7 shows the contours of water volume fraction at a time step of 20, during the initial times step of 20 liquid volume fraction is observed along the tube, the vapor bubble formation is yet to start at this time step, at this time step alternate liquid and vapor slug formation is observed along the length of flat pulsating heat pipe. Figure shows the liquid slug with sensible heat is transfer to the condenser section the larger bubbles are observed as compared with the earlier time steps. Figure shows major portions of liquid is accumulated in the condenser section where liquid after condensation returns back to the evaporator section. The liquid after condensation returns back to the evaporator section some particles of water are observed along the length of flat heat pipe. Figure shows the less percentage of liquid occupied by the given volume of tube. That is an indication of possibility of dry out condition.

5.5 Contours of Wall Temperature for Horizontally Placed Flat Pulsating Heat Pipe



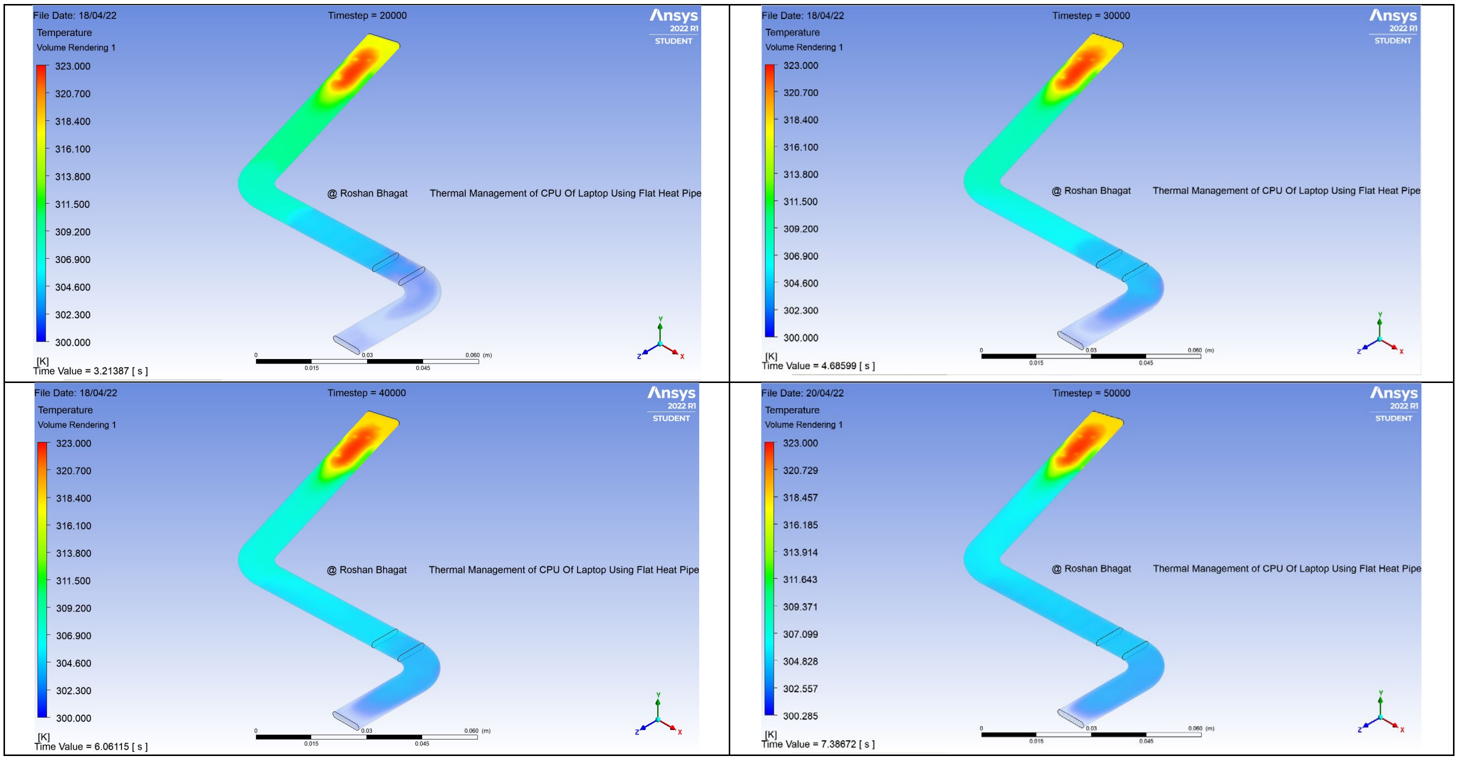


Fig. 8 Contours of wall temperature for horizontally placed flat pulsating heat pipe at a time step of 20

The figure 8 shows the contours of wall temperature at the initial time step of 20 lower temperatures are observed in the evaporator section. The figure shows the bottom face where the thermal boundary conditions are applied. The heated zones are observed in the evaporator section. The temperature starts increasing from evaporator to the condenser section along the length of flat heat pipe. The legend shows the temperature variation from 300 K to 323 K which is corresponding to the thermal boundary conditions applied at evaporator and condenser section. Figure shows the increase in temperature at a time step of 30000, at this time step the flow of liquid from evaporator to condenser section takes place, this liquid carries the sensible heat towards the condenser section. Figure shows the wall temperature at a time step of 40000, the flow is said to be developed and higher temperature contours are visible from simulation.

6 Experimental V/s CFD Results

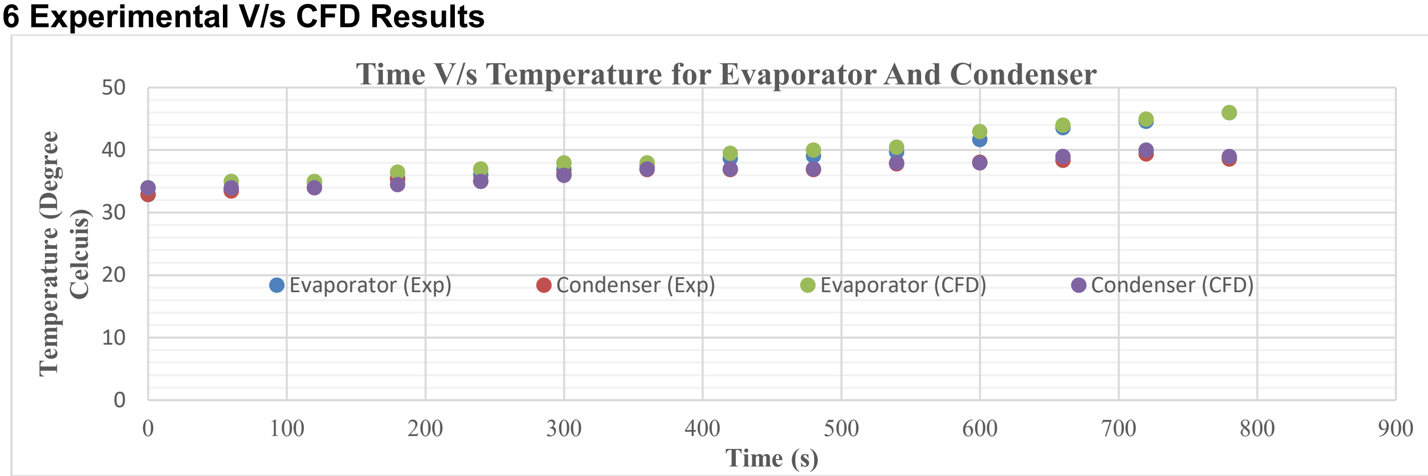


Fig. 9 Experimental v/s CFD result

The figure 9 shows the comparison of experimental and numerical results. These results comply each other at many points thereby ensuring the accuracy of solution obtained from numerical simulation.

7 Conclusion

The experimental results show, when the evaporator temperature reaches to 51^0C, the cooling starts with the help of fan. The fan helps to increase the rate of heat transfer. The operation of fan continues till the temperature at evaporator drop to a temperature around 34^0C. The fan runs for around 3 minutes to cool the processor. The numerical simulation shows that the working fluid after rejecting heat in the condenser section returns back to the evaporator section. The reverse flow is due to density difference and the higher elevation of condenser with reference to the evaporator section. The simulation results shows that there is possibility of dry out of working fluid.

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