Frontiers in Heat and Mass Transfer (FHMT), 19, 14 (2022)
DOI: 10.5098/hmt.19.14

Global Digital Central
ISSN: 2151-8629

Frontiers in Heat and Mass Transfer

Available at www.ThermalFluidsCentral.org

NUMERICAL ANALYSIS TO PREDICT THE BEHAVIOR OF LIQUID VAPOR SLUG FLOW IN VERTICALLY PLACED U-SHAPED CLOSED CAPILLARY TUBE

Roshan Devidas Bhagat[a,*], Samir J. Deshmukh[b],

[a] *Ph.D. Scholar, Prof. Ram Meghe Institute of Technology and Research, Badnera-Amravati, Maharashtra, 444701, India*
[b] *Associate Professor, Prof. Ram Meghe Institute of Technology and Research, Badnera-Amravati, Maharashtra, 444701, India*

ABSTRACT

Numerical analysis of liquid vapor slug flow in a vertically placed U-shaped closed capillary tube is carried out with family of hydrocarbon fluid like Acetone, Ethanol, Methanol and Pentane. A 3D computational domain has been developed for vertically placed U-shaped capillary tube sealed at both end with three small turns in evaporator section, two small and one large turn in condenser section. The diameter of vertically placed U-shaped capillary tube is taken as 2mm. The volume of fluid (VOF) approach, suitable model of K-epsilon is used to predict the behavior of liquid vapor slug flow along the wall of capillary tube. Fill ratio (FR) of 61% is used with the working fluid that occupies 61% of the total volume of tube. At the start of iteration process the evaporator and condenser temperature are set to 343 K and 298 K. The liquid, vapor slug flow inside the capillary tube and flow patterns are observed for Acetone, Ethanol, Methanol and Pentane. The contours of liquid volume fraction and wall temperature are observed along the length of tube. Alternate liquid and vapor slug formation and the complex phenomenon of evaporation and condensation process are visualized in the analysis. The aim of the numerical analysis is to find the suitable working fluid, models, simulation settings that accurately predict the phase change phenomenon and to investigate the effect of liquid vapor slug flow, changing simulation parameters on the performance of U-shaped capillary tube.

Keywords: capillary tube, filling ratio, liquid vapor slug, numerical analysis, working fluid

1. INTRODUCTION

With the extensive use of electronic gadgets, the thermal management of system performs an important function to ensure the longer lifespan and overall high performance of these electronics devices. Noh and Kim (2020) performed the numerical simulation on pulsating heat pipes to optimize the thermal performance. Jubori and Jawad (2020) carried out the computational evaluation of thermal behavior of a wickless heat pipe under various conditions. Lin *et al.* (2013) performed the simulation of a miniature oscillating heat pipe in bottom heating mode using CFD with unsteady modelling to understand the fluid flow behavior. Kang *et al.* (2021) performed the numerical study of a novel single-loop pulsating heat pipe with separating walls within the flow channel to understand the behavior of fluid. Venkatasuresh and Bhramara (2017) carried out the CFD analysis of copper closed loop pulsating heat pipe, the analysis was also carried out with multi turn pulsating heat pipe to determine the effect of working fluid on performance of pulsating heat pipe. Kafeel and Turan (2014) performed the simulation on the response of a thermosyphon under pulsed heat input conditions.

Most of the research studies published earlier was focused on a particular aspect of PHP i.e., the parameter that were tested earlier was limited to either working fluid or with the orientation of PHP. Number of working fluids that were tested with the CFD simulation was limited due to lack of computational power as the time involved in CFD simulation is very high. The past research studies have not given in depth simulation data regarding the behavior of different working fluid with different combinations like orientation, changes in aspect ratio or change in cross section of evaporator and condenser section.

This research work has made sincere attempt to highlight these areas in detail with the help of CFD simulation software Ansys. This research work will be beneficial to select the working fluid while designing a thermal management system that can be used for cooling electronic equipment where the vertical and horizontal space occupied by heat exchanger device is of prime importance.

2. GEOMETRY AND MESH DEVELOPMENT

2.1 3D Geometry of Vertically Placed U-shaped Capillary Tube

A 3D computational domain is generated with the help of Ansys design modeler. Mesh is generated with meshing tool in Ansys workbench. The table 1 gives the percentage of total volume of tube occupied by the respective zones of vacuum, hydrocarbon liquid and hydrocarbon vapor. Out of the entire volume, 15% of the volume occupied by evaporator section and 22 % of the volume occupied by the condenser section.

Table 1 Volume of fluid domain

Domain	Volume	% Of Total Volume
Vacuum	2203.9 mm^3	38.67 %
Liquid	3495.1 mm^3	61.32 %
Heater	856.2 mm^3	15 %
Condenser	1261.5 mm^3	22 %
All Domain	5699 mm^3	100 %

The evaporator section is purposefully kept smaller than the condenser section. Larger condenser segment ensure fluid has sufficient time in the

* *Corresponding author. Email: roshan.bhagat25@gmail.com*

Frontiers in Heat and Mass Transfer (FHMT), 19, 14 (2022)
DOI: 10.5098/hmt.19.14
Global Digital Central
ISSN: 2151-8629

segment for absorption and rejection of heat associated with it. The heat rejected then firmly absorbed by the secondary fluid available in the condenser.

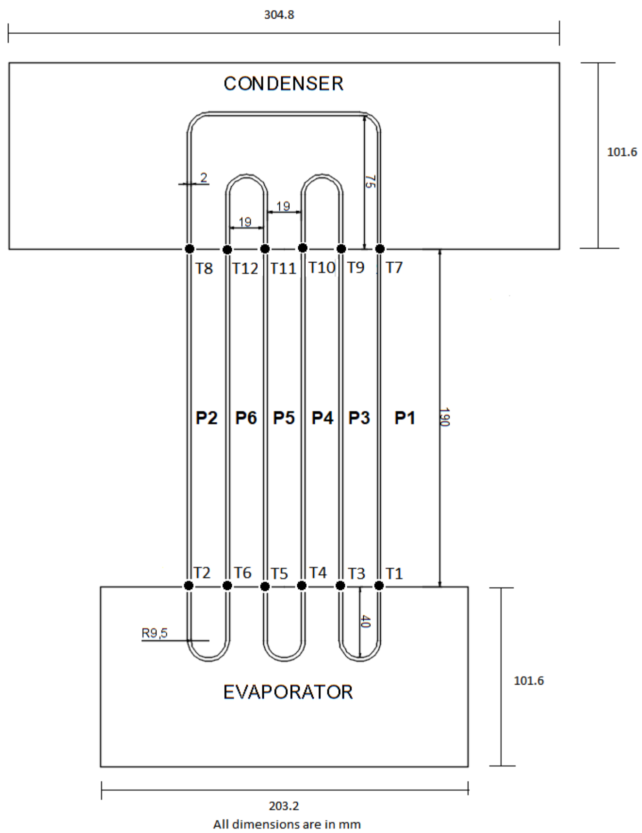

Fig. 1 Specification of vertically placed U-shaped closed capillary tube

2.2 Mesh Generation for Vertically Placed Capillary Tube

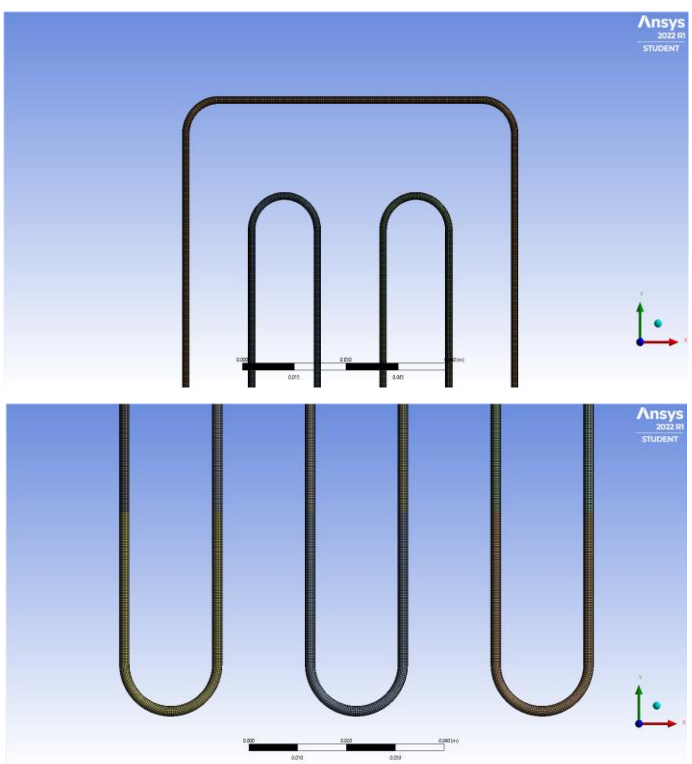

Fig. 2 Mesh generation at evaporator and condenser Section

Table 4 Mesh information for vertically placed U-shaped capillary tube

Domain	Nodes	Element
Vacuum	176587	154923
Liquid	281970	248997
All Domain	458557	403920

2.3 Mesh Independence Study

To established the accuracy of solution the vertically placed U-shaped closed capillary tube was analyzed using k-epsilon model. The grid convergence study was performed by developing three different meshes with coarse, medium and fine. The CFD simulation time highly depends on number of mesh nodes generated. The mesh generated has near wall resolution $Y+ < 10$. It was ensured to have skewness value near to 0 and orthogonal quality near to 1 while generating the different size of mesh. Mesh generated satisfying the above criteria is used for performing the CFD simulation. As the student version of Ansys is used, the limitation of nodes and element for the student version are taken into consideration.

3. BOUNDARY CONDITIONS

The boundary condition is precise at evaporator and condenser section. wall temperature is applied on evaporator. The material of pipe is designated as copper. During the evaluation, hydrocarbon operating fluids (HCOF) are used i.e., acetone, ethanol, methanol and pentane. greater attention is given on developing 3D numerical model with the assist of Ansys design modeler and processor tools that consists of the complicated bodily phenomenon of the heat transfer in evaporation and condensation. The liquid and vapor slug behavior are found with distinctive working fluid to obtained appropriate working fluid for given operating temperature range. The usage of CFD model lessen the vital experimental work to test the performance of system, that can then be optimized. The performance of final optimized model can be validated with the experimental effects, which drastically reduces the expenses towards fabrication.

3.1 Physical Factors and Guesses

A straight-shaped capillary tube closed at both ends has an inner diameter of 2mm and an outer diameter of 3mm. The filling rate is considered to be 61%. The two categories are specified hydrocarbon liquid, hydrocarbon vapor. The volume of fluid model (VOF) is used as it traces the phase interphase. The components of Eulerian are liquid and vapor phase, there is a vacuum inside the pipe, which is described, it is defined as one of the phases with negligible pressure. The reason for describing the vacuum zone is that while preparing the geometry it has to be sliced based on filling ratio, heater and condenser section are specified in mesh with name selection. The boundary conditions are then applied at the evaporator and condenser section. The k-epsilon model is selected, with improved wall treatment, thermal effect and curvature correction.

3.2 Volume of Fluid Method

The volume of fluid method has two limits ranging from 0 to 1, tracking the visible contour between two phases of hydrocarbon working fluid. The contours have a value 1 or 0 where the control volume is completely filled with one of the segments.

3.3 Defining the Phase of Working Fluid

The table 2 shows the primary phase defined as vapor and secondary phase is defined as liquid. Evaporation and condensation mechanism is specified with surface tension and saturation temperature of fluid used.

Table 2 Defining the phase

Description	Phase
Primary Phase	Vapor
Secondary Phase	Liquid

DOI: 10.5098/hmt.19.14
ISSN: 2151-8629

3.4 Equations Under Consideration

The governing equations are used to mathematically describe the physics of fluid that flows in the vertically placed U-shaped capillary tube is having liquid and vapor slug transformation. The continuity equation, momentum equation, are also known as Navier stroke equations, these equations are needed to describe the state of fluid flow and are solved for all types of CFD modelling, the conservation of mass equation needs to be considered.

$$\frac{\partial(\alpha_v \rho_v)}{\partial t} + \nabla.(\alpha_v \rho_v v_v) = \dot{m}_{lv} - \dot{m}_{vl} \quad (1)$$

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

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

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

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

3.5 Cell Zone Condition on Computational Domain

The “working situations” are set having the “working pressure” as 43000 Pa for acetone, 10000 Pa for ethanol, 25000 Pa for methanol and 101000 Pa for pentane. Boundary conditions are implemented in the evaporator phase and temperature specific as 343 K. The condenser temperature is at temperature 298 K. As capillary movement has to takes place because of smaller diameter of tube contact angle of operating fluid want to be specified at all wall geometry. The distinct contact of 20^0 is selected.

3.6 Initializing Simulation and Patch

After configuring the two important boundary situations i.e., evaporator and condenser the closing step before beginning the simulation is initializing it and characterizing initial positions for the liquid and vapor for the start of the simulation. After the initialization the zones patching is achieved wherein the geometry is patch with respective hydrocarbon liquid as operating fluid. Vapor section is considered 0 at initial stage.

3.7 Simulation Setting

The difficulty while setting the simulation of multiphase flows is that the time step needs to be sufficiently small to capture the motion of the fluid particle and on the identical time it wishes to be large and sufficient to reduce the computational time. A stability to be maintained whilst performing the simulation i.e., decreasing the computational time without compromising the accuracy of the answer.

The table 3 shows the exceptional mixtures of time step earlier than the very last simulation run the version is examined at specific time step and divergence is located with decrease time step as much as 0.001. For the given geometry to keep away from the divergence inside the velocity discipline the time step of 0.0005 is chosen for numerical evaluation, the computational time is higher with this time step.

Table 3 Issue with different time step

Time Step	Issue
0.1	Diverge very fast
0.01	Diverges
0.001	Diverges after some time
0.0005	Takes long time but never diverge

3.8 Post Processing

In post processing to visualize the result on 3D computational domain, the transparency of 0.9 is set, this helps to visualize the fluid flow. The contours of liquid volume fraction and wall temperature are obtained from volume rendering. The time step, date and flow time are specified.

4. FLOW SIMULATION

4.1 Capillary Tube with Acetone as Working Fluid

Thermal analysis of vertically placed U-shaped capillary tube is carried out with fluid flow fluent, the contours of liquid fraction acetone, wall temperature and its behavior are studied at numerous time step.

4.1.1 Contours of Liquid Volume Fraction for Acetone

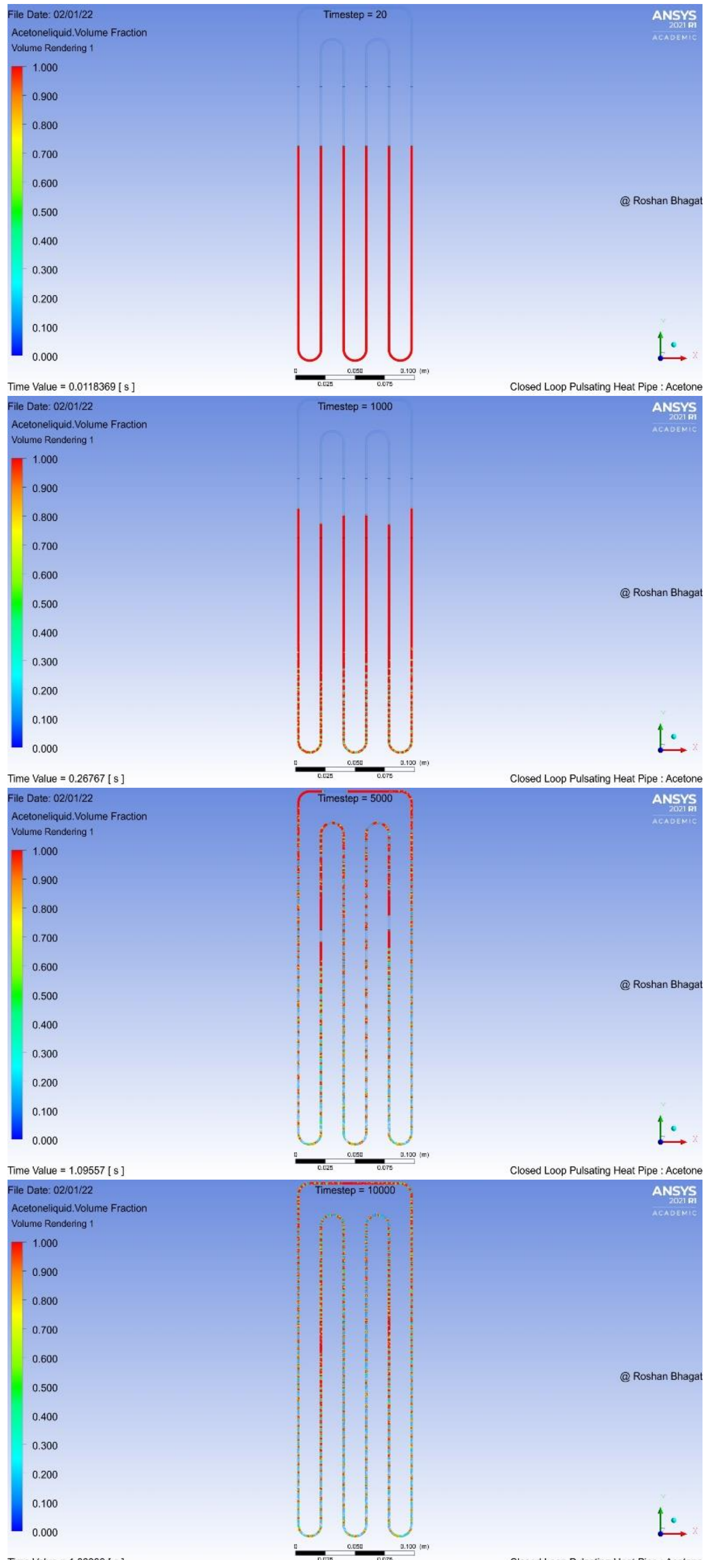

Fig. 3 Contours of liquid volume fraction from time step of 20 to 10000

Frontiers in Heat and Mass Transfer (FHMT), 19, 14 (2022)
DOI: 10.5098/hmt.19.14

Global Digital Central
ISSN: 2151-8629

4.1.2 Contours of Wall Temperature for Acetone

Thermal evaluation of vertically placed U-shaped capillary tube with acetone as working is carried out. Figure 4 indicates the contours of wall temperature. At preliminary time step of 20 maximum temperature are visualized at evaporator section only.

With the enhancement in the time step, maximum value of temperature is discovered along the length of tube. The graphs show the temperature along six pipes wherein consistent temperature is observed at time step of 1000. The contours of wall temperature show the enhancement of temperature along the length of pipe. The flow is visualized from time step of 20 to a time step of 10000.

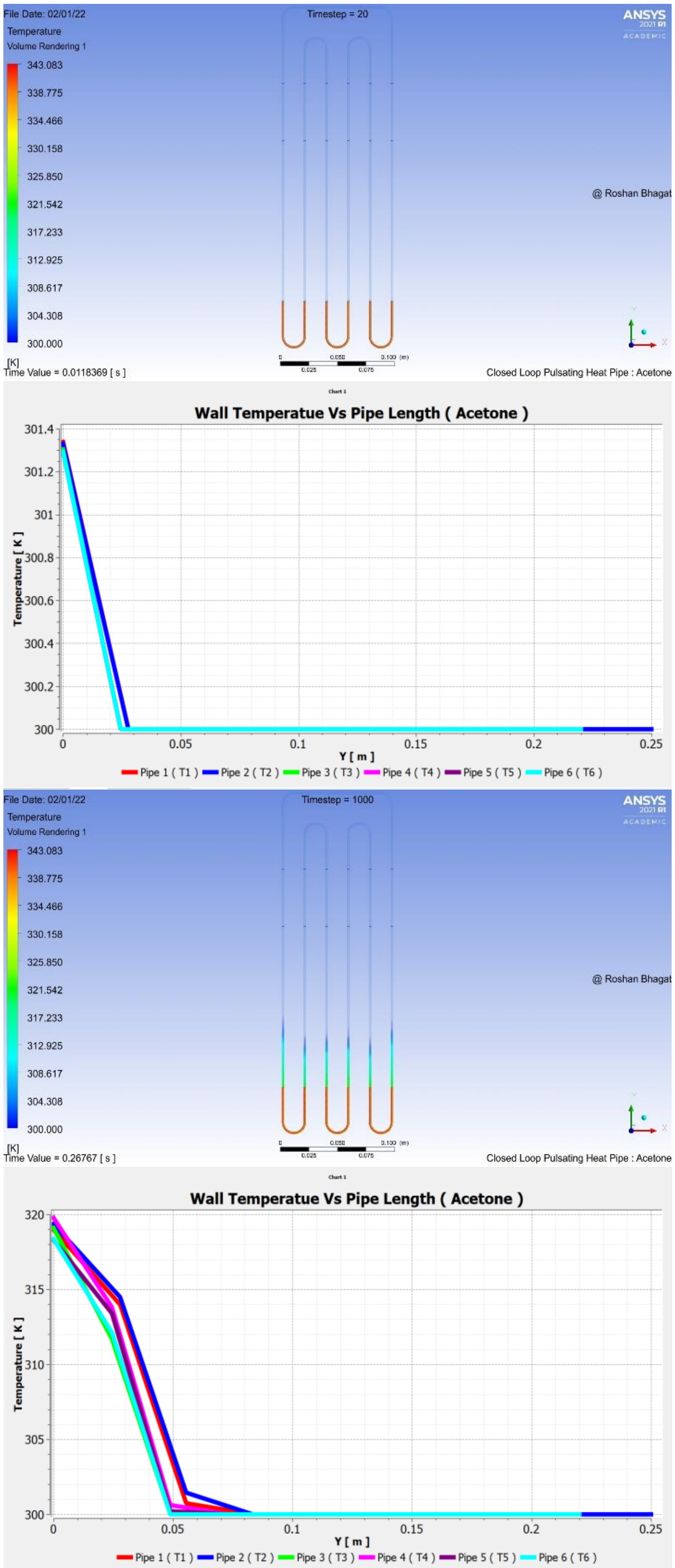

Fig. 4 Contours of wall temperature for acetone at time step 20 to 1000.

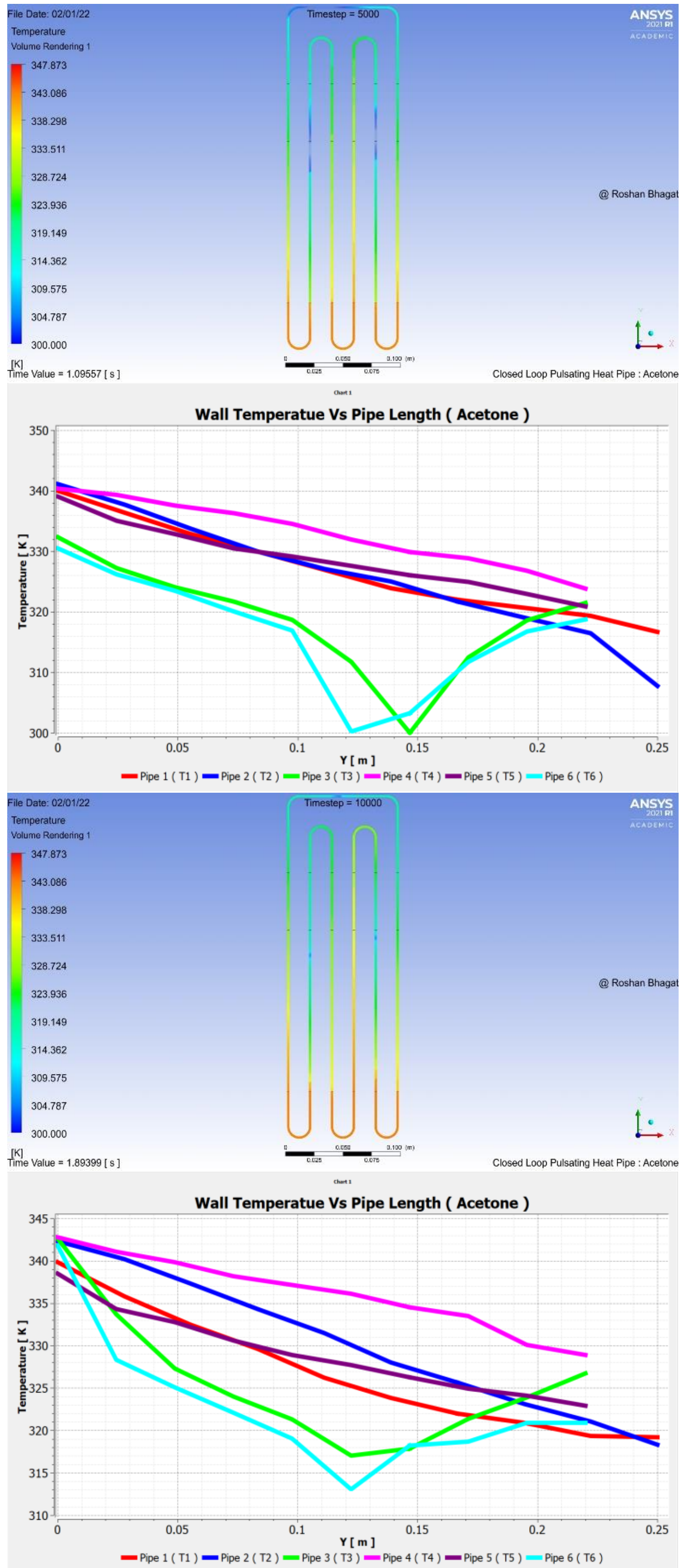

Fig. 5 Contours of wall temperature acetone at time step 5000 to 10000.

4.2 Capillary Tube with Ethanol as Working Fluid

4.2.1 Contours of Liquid Volume Fraction for Ethanol

The contours of liquid volume fraction show the development of liquid and vapor slug along the length of vertically placed capillary tube from time step of 20. The liquid and vapor slug moves towards the condenser section and rejects the heat in the form of sensible and latent heat.

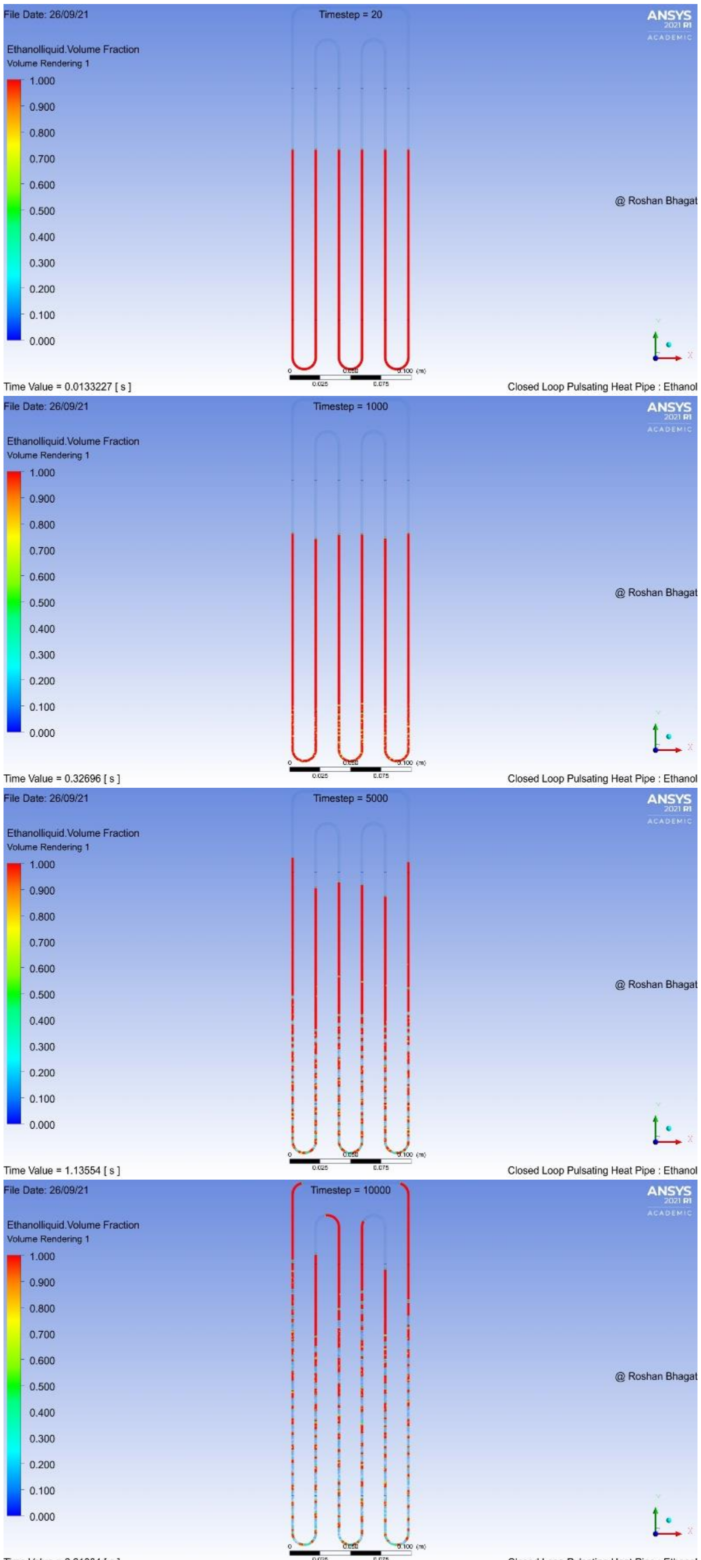

Fig. 6 Contours of liquid volume fraction for ethanol at time step of 20 to 10000

4.2.2 Contours of Wall Temperature for Ethanol

The contours of wall temperature are studied at an extraordinary time step from 20 to 10000 and the variation of wall temperature along the length of the tube is observed. At initial time step of 20 higher temperature is observed only at evaporator section.

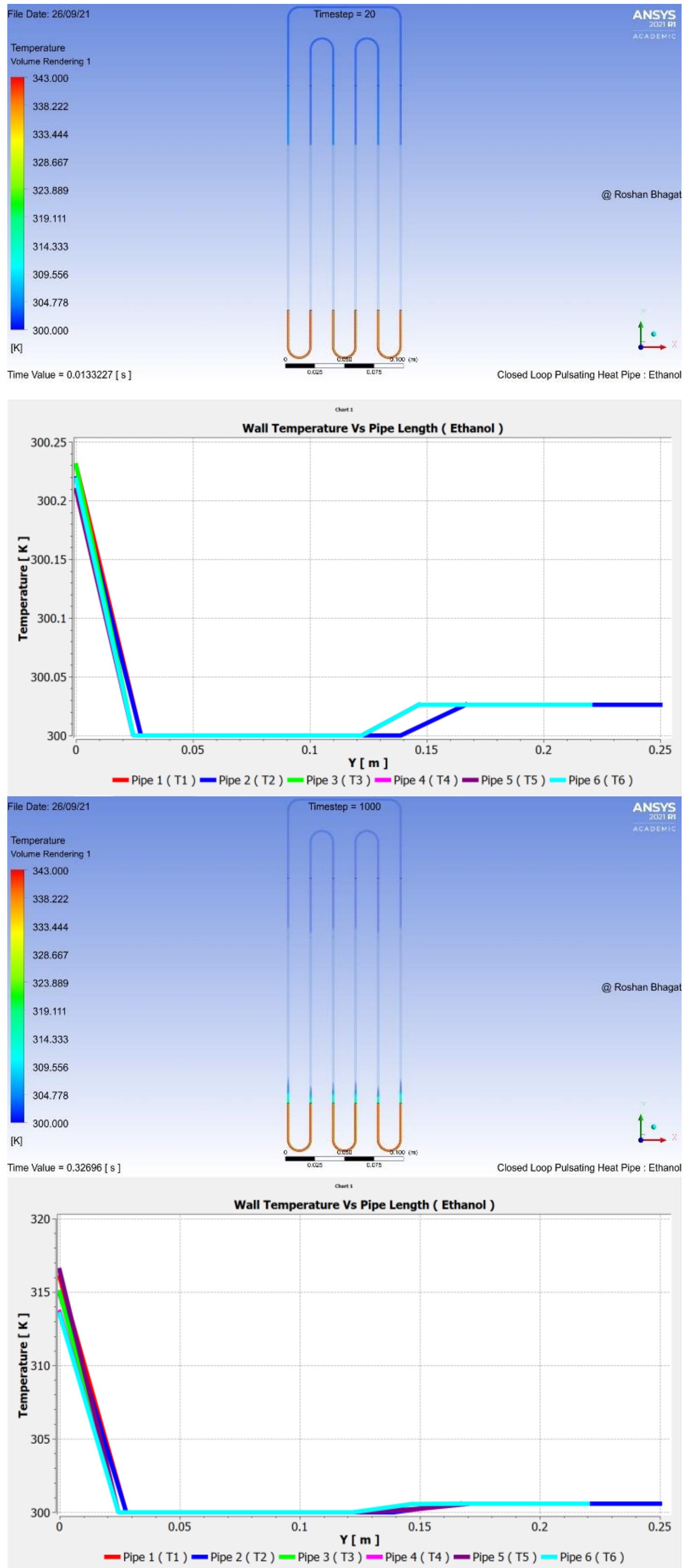

Fig. 7 Contours of wall temperature for ethanol at time step of 20 to 1000

With the growth in time step, temperature rise is determined alongside the 0.1 m length of tube capillary tube. The pipe 1 and pipe 6 shows the comparatively higher temperature rise along the length at time step of 5000. With further increase in time step temperature rise observed for pipe 4 and pipe 5. The pipe 2 has temperature 337K at evaporator section at the time step of 10000.

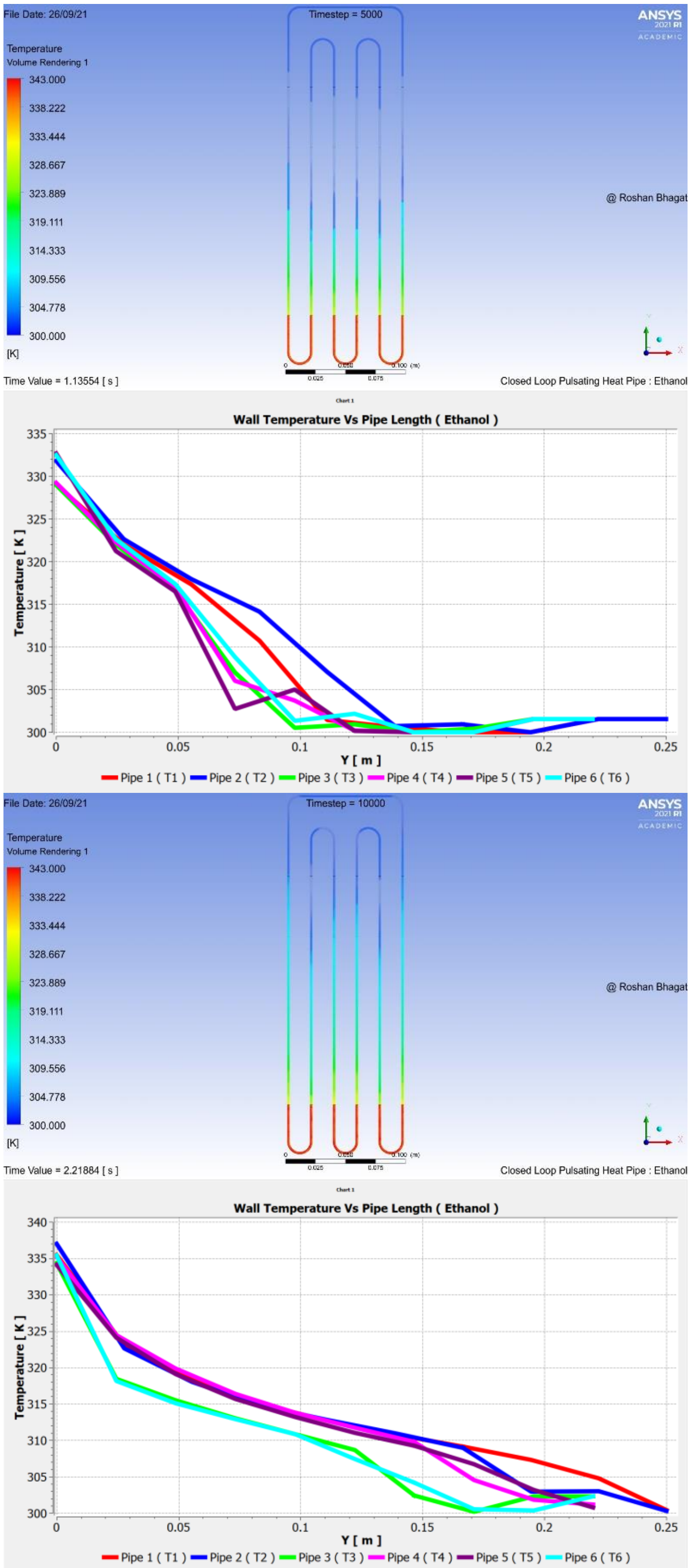

Fig. 8 Contours of wall temperature for ethanol at time step of 5000 to 10000

4.3 Capillary Tube with Methanol as Working Fluid

4.3.1 Contours of Liquid Volume Fraction for Methanol

The movement of liquid vapor slug flow is widespread after the time step of 1000, so as the predict the flow and to check the possibility of dry out circumstance higher time steps are necessary whilst the fluid is flowing within the tube.

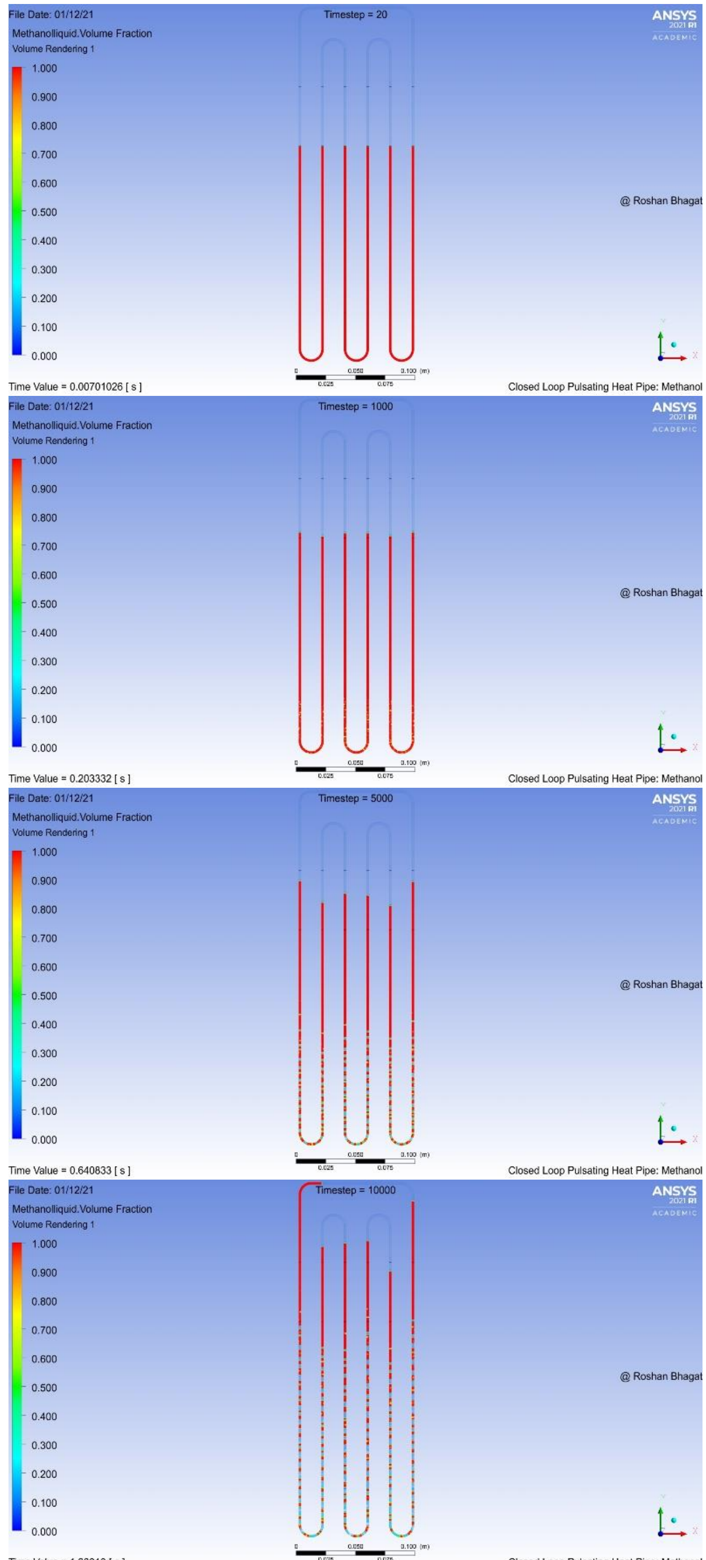

Fig. 9 Contours of liquid volume fraction for methanol at time step of 20 to 10000

4.3.2 Contours of Wall Temperature for Methanol

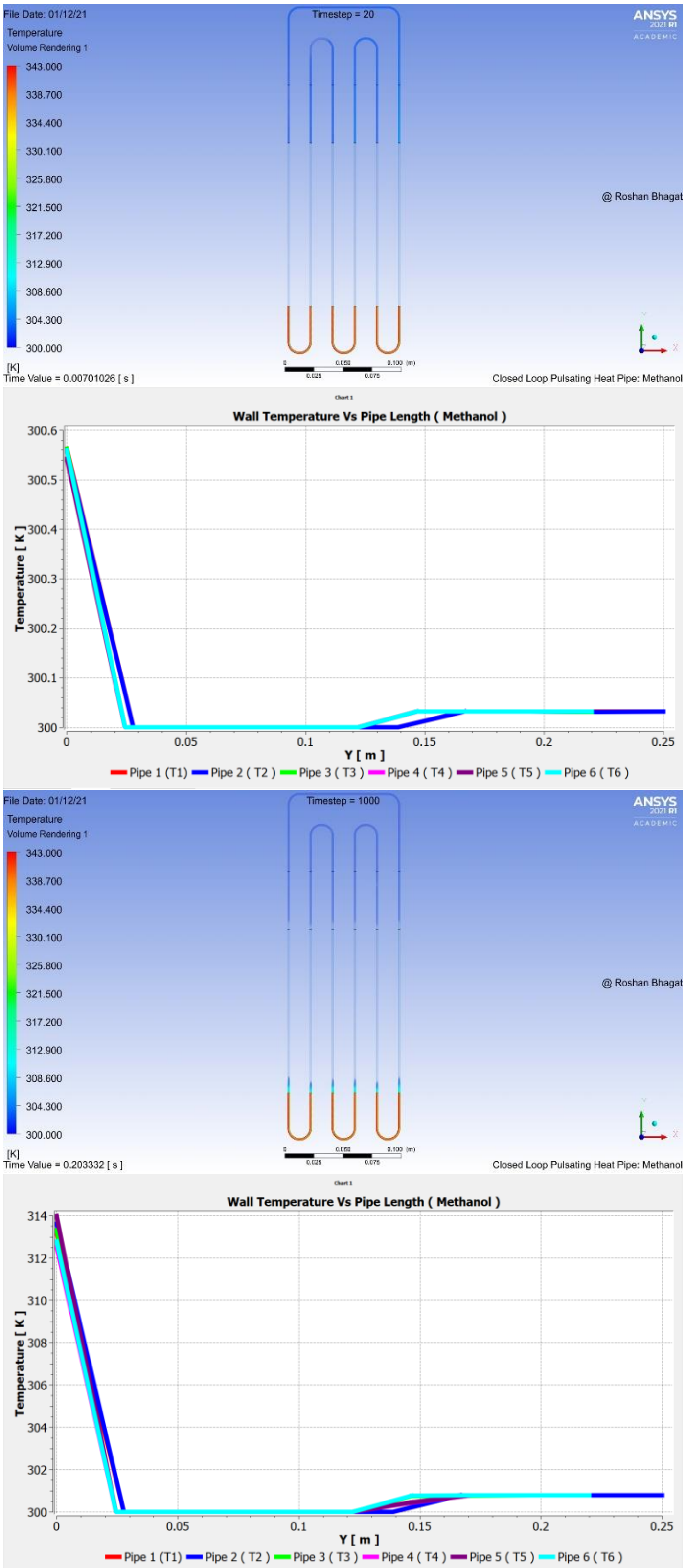

Fig. 10 Contours of wall temperature for methanol at time step of 20 to time step of 1000

The contours of wall temperature indicates that at a time step of 20 higher temperatures are discovered only in the evaporator segment of U-shaped capillary tube. The negligible variation is observed after 0.03m length of tube.

The figure below shows the rise in temperature along the length of tube.

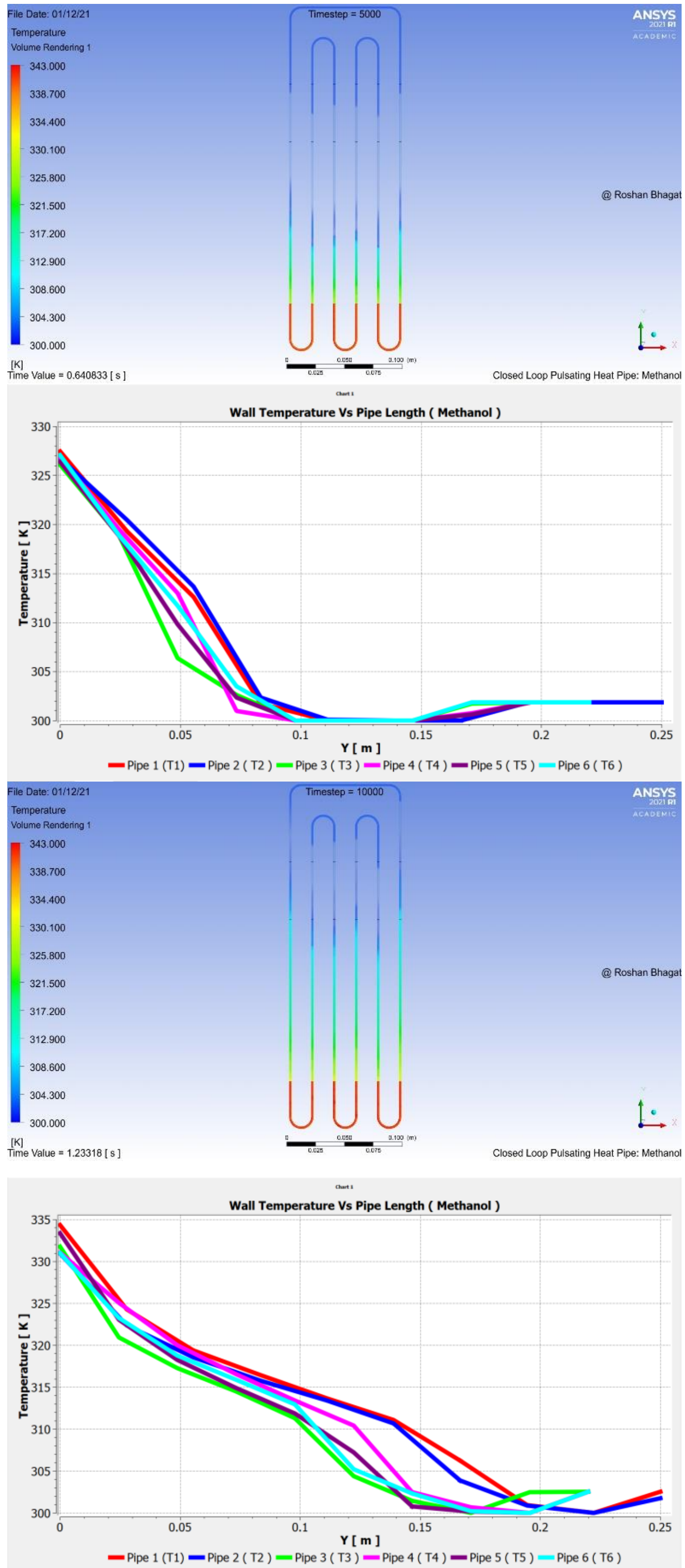

Fig. 11 Contours of wall temperature for methanol at time step of 5000 to 10000

From a given time step of 5000 to 10000 its can be visualized that the liquid and vapor slug convey heat while it moves from evaporator to condenser section. Higher temperature along the length is observed in pipe 1 and pipe 6 as compared to others.

4.4 Capillary Tube with Pentane as Working Fluid

4.4.1 Contours of liquid Volume Fraction for Pentane

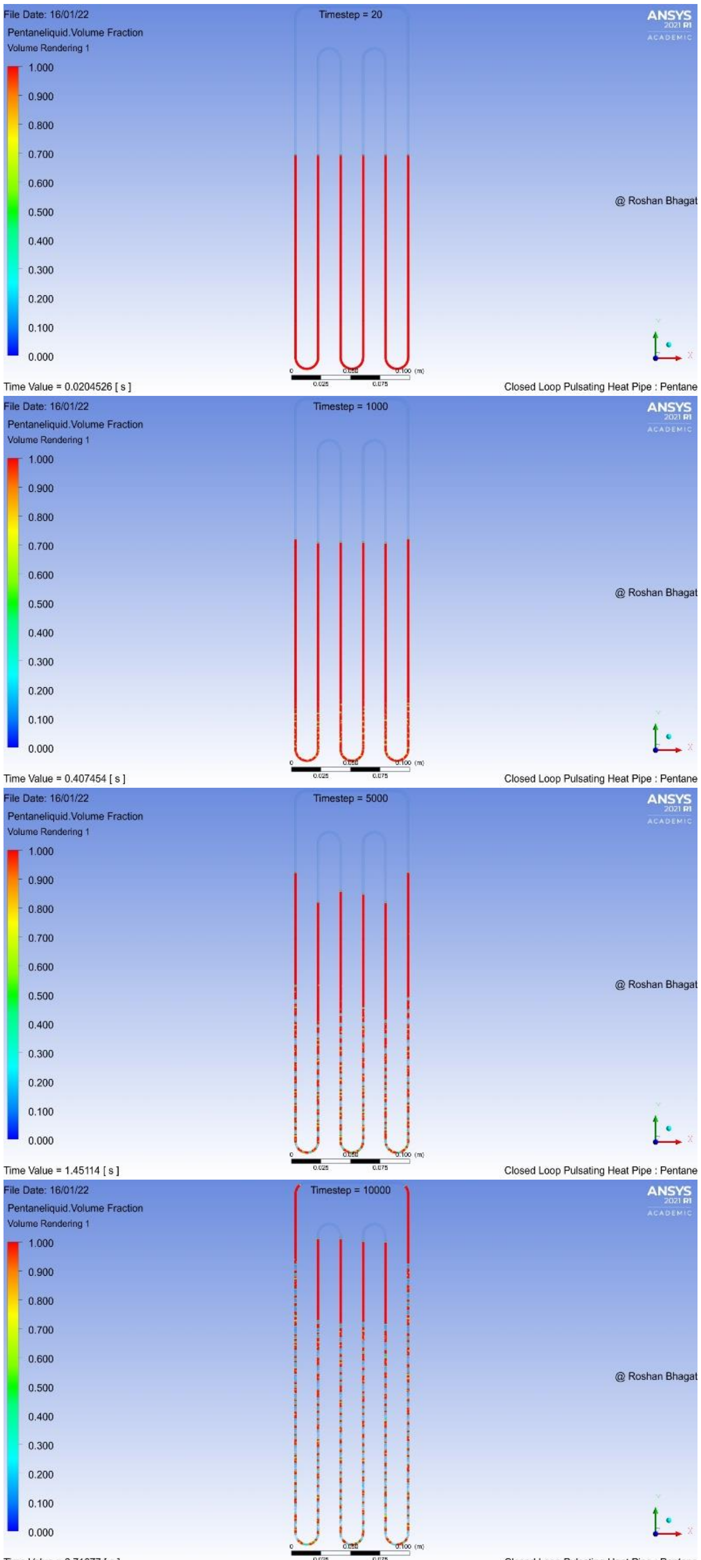

Fig. 12 Contours of liquid volume fraction for pentane at time step of 20 to 10000

The liquid and vapor slug flow development are significant at time step of 5000 and 10000. The two phase fluid flow occurs from evaporator to the condenser section due to temperature difference between two section.

4.4.2 Contours of Wall Temperature for Pentane

The contours of wall temperature are obtained as shown in figure below.

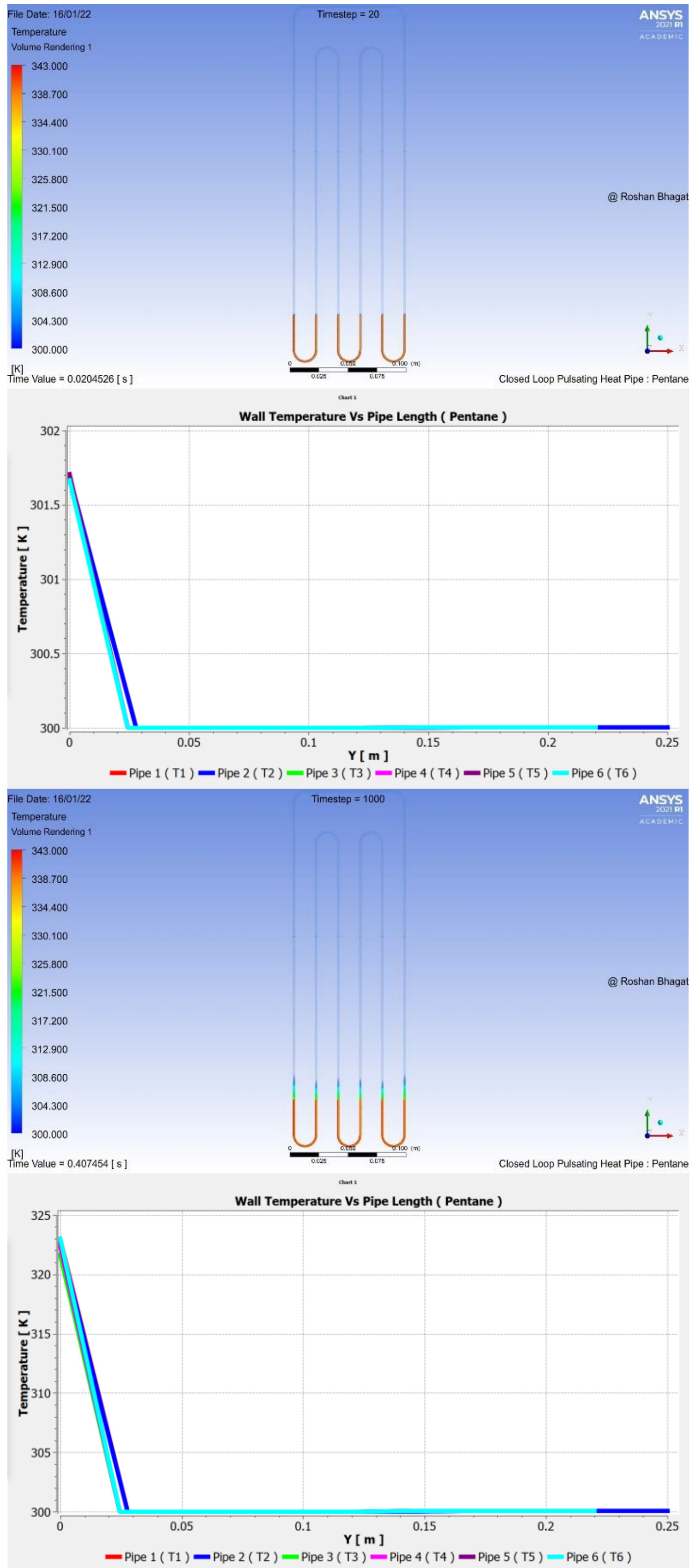

Fig. 13 Contours of wall temperature pentane at time step of 20 to 1000

At the initial time step of 20 to 1000 negligible variation is temperature observed along the length of tube this is primarily due to insufficient liquid and vapor slug formation at the beginning of the heating process.

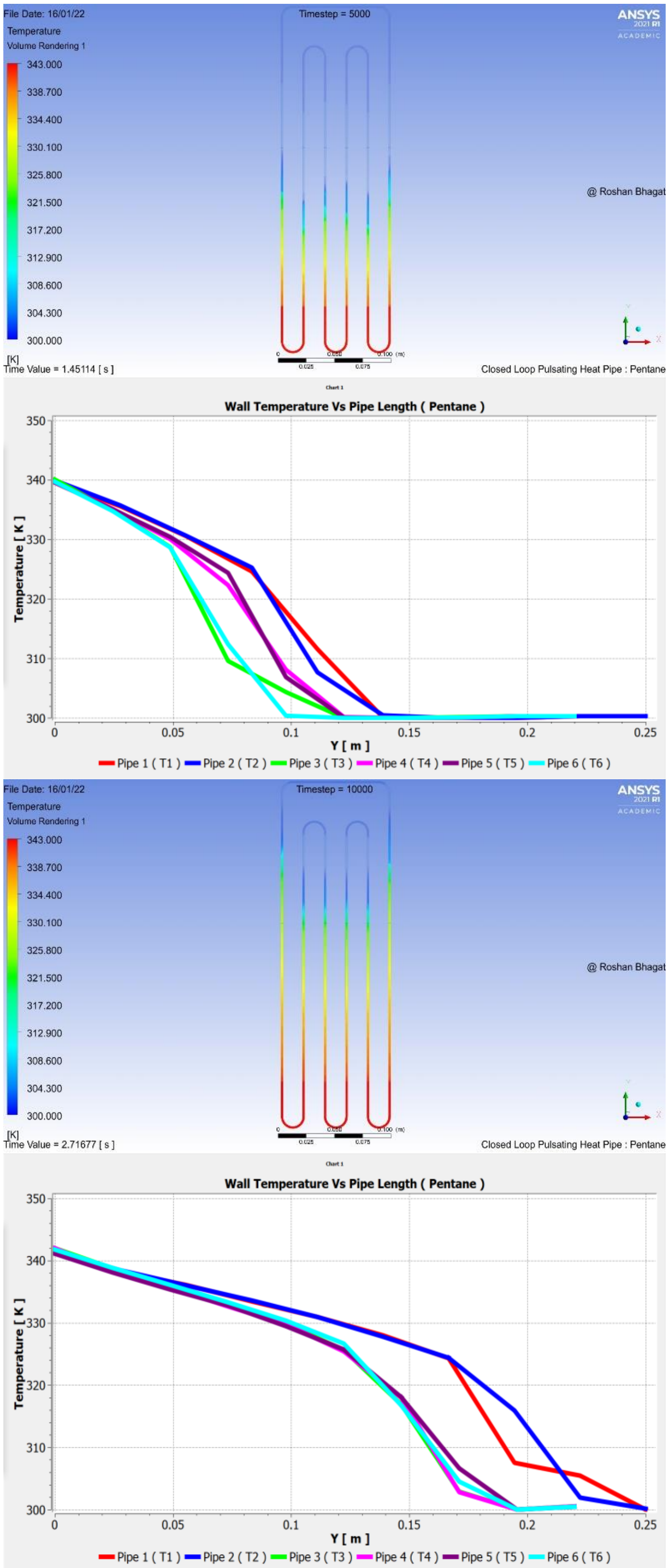

Fig. 14 Contours of wall temperature pentane at time step of 20 to 10000

At the time step of 5000 and 10000, pipe 1 and pipe 2 shows the considerable higher temperature than the other pipes. At evaporator the temperature of 341K is observed. The variation in temperature is due to flow of liquid and vapor slug from evaporator to the condenser section carrying heat in the form of sensible and latent heat.

5. CONCLUSIONS

The numerical analysis of vertically placed U-shaped capillary is carried out with acetone, ethanol, methanol and pentane as working fluid. The numerical analysis of fluid flow with Ansys Fluent assisted in estimating the flow of fluid, and the behavior is evaluated at various flow times. The contours of the liquid volume fraction, the wall temperature and the temperature variation with respect to tube length are all evident. The flow development is different for distinctive working fluid. For fluid having lower boiling point like acetone and pentane, the flow is getting advanced at lower time step whereas for ethanol and methanol the flow has advanced at higher flow time.

The post-processing tool in Ansys Fluent allows for a satisfactory understanding of the evaporation and condensation phenomena. This is very helpful in selection of suitable working fluid for vertically placed U-shaped capillary tube. If the inner diameter of the vertically placed U-shaped capillary tube is greater than the critical diameter of 2 mm, liquid and vapor slug formation does not occur. In order to have the pulsating motion that permits the passage of heat in the form of sensible and latent heat, the aspect ratio is also important.

The simulation result shows U-shaped capillary tube with acetone and pentane as working are more suitable for lower operating temperature range. Whereas, ethanol and methanol are suitable for higher temperature ranges. There is possibility of dry out conditions with acetone and pentane if higher heat input is given as both working fluid has lower boiling point.

NOMENCLATURE

HCWF	Hydro Carbon Operating Fluid
CFD	Computational Fluid Dynamics
PHP	Pulsating Heat Pipe
VOF	Volume of Fluid
FR	Fill Ratio
$\dot{m}$	Mass transfer rate
l	liquid
v	Vapor
t	Time
P	Pressure
T	Temperature
F_{VOL}	Volume Force
μ	Viscosity
P	Pressure

REFERENCES

Akachi, H., 1990, “Structure of a Heat Pipe,” U.S. Patent 4921041.

Arab, M., Soltanieh, M., Shafii, M.B., 2012, “Experimental Investigation of Extra-Long Pulsating Heat Pipe Application in Solar Water Heaters,” Experimental Thermal Fluid Science, **42**, 6–15. https://doi.org/10.1016/j.expthermflusci.2012.03.006

Ayad, M., Jubori, A.L., 2020 “Computational Evaluation of Thermal Behavior of a Wickless Heat Pipe Under Various Conditions,” Case Studies in Thermal Engineering, 22. https://doi.org/10.1016/j.csite.2020.100767

Bhagat, R.D., Watt, K.M., 2015, “Experimentation to Predict the Thermal Performance of Closed Loop Pulsating Heat Pipe with Acetone and Methanol as Working Fluid,” International Journal for Research in Engineering and Technology, **4**(4), 23-27. http://dx.doi.org/10.15623/ijret.2015.0404005

Bhagat, R.D., Watt, K.M., 2015, “An Experimental Investigation of Heat Transfer Capability and Thermal Performance of Closed Loop Pulsating Heat Pipe with A Hydrocarbon as Working Fluid,” Frontiers in Heat Pipes, **6**(7). http://dx.doi.org10.5098/fhp.6.7

Bhagat, R.D., 2016, "An Experimental Investigation of Thermal Performance of Conventional Heat Pipe with Water, Acetone and Methanol as Working Fluid," Frontiers in Heat Pipes, **7**(4). http://dx.doi.org/10.5098/fhp.7.4

Bhagat, R.D, Deshmukh, S.J., 2021, "Numerical Analysis of Passive Two Phase Fluid Flow in a Closed Loop Pulsating Heat Pipe," Frontiers in Heat and Mass Transfer, **16**(23). http://dx.doi.org/10.5098/hmt.16.23

Bhagat, R.D., Deshmukh, S.J., 2022, "Experimental Investigation and Numerical Analysis of Horizontally Placed Flat Pulsating Heat Pipe for Electronic Cooling," 8th World Congress on Mechanical, Chemical, and Material Engineering, HTFF-191, **1**-11. http://dx.doi.org/10.11159/htff22.191

Bhagat, R.D., Deshmukh, S.J., 2022, "Numerical Analysis of Horizontally Placed Closed Loop Pulsating Heat Pipe for Electronic Cooling," Proceedings of the 9th International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'22), 207, 1-9. http://dx.doi.org/10.11159/ffhmt22.207

Burban, G., Ayel, V., Alexandre, A., Lagonotte, P., Bertin, Y., Romestant, C., 2013, "Experimental Investigation of a Pulsating Heat Pipe for Hybrid Vehicle Applications," Applied Thermal Engineering, **50**, 94–103. https://doi.org/10.1016/j.applthermaleng.2012.05.037

Charoensawan, P., Khandekar, S., Groll, M., Terdtoon, P., 2003 "Closed Loop Pulsating Heat Pipes- Part A: Parametric Experimental Investigations," Applied Thermal Engineering, **23**(16), 2009-2020. http://dx.doi.org/10.1016/s1359-4311(03)00159-5

Clement, J., Wang, X., 2013, "Experimental Investigation of Pulsating Heat Pipe Performance with Regard to Fuel Cell Cooling Application," Applied Thermal Engineering, **50**, 268–274. https://doi.org/10.1016/j.applthermaleng.2012.06.017

Dang, C., Jia, L., Lu, Q., 2017, "Investigation on Thermal Design of a Rack with The Pulsating Heat Pipe for Cooling CPUs," Applied Thermal Engineering, **110**, 390–398. https://doi.org/10.1016/j.applthermaleng.2016.08.187

Deng, H.R., Liu, Y.M., Ma, R.F., Han, D.Y., Gan, Z.H., Pfotenhauer, J.M., 2015, "Experimental Investigation on A Pulsating Heat Pipe with Hydrogen," IOP Conference Series Material Science and Engineering, Proceedings of the Cryogenic Engineering Conference (CEC), **101**, 1–8. https://doi.org/10.1088/1757-899X/101/1/012065

Faghri, A., 2014, "Heat Pipes: Review, Opportunities and Challenges**,"** Frontiers in Heat Pipes (FHP), **5**(1). http://dx.doi.org/10.5098/fhp.5.1

Fairley, J.D., Thompson, S.M., Anderson, D., 2015, "Time–Frequency Analysis of Flat-Plate Oscillating Heat Pipes," International Journal of Thermal Science, **91**, 113–124. https://doi.org/10.1016/j.ijthermalsci.2015.01.001

Hiratsuka, W., Fukue, T., Shirakawa, H., Nakayama, K., Koito, Y., 2020, "CFD-Based Study on Heat Transfer Enhancement Behind A Projection in A Miniaturized Flow Channel by Pulsating Flow" Frontiers in Heat and Mass Transfer (FHMT), **15**(16). http://dx.doi.org/10.5098/hmt.15.16

Ibrahim, M.M., Kasem, M.M., 2021, "Numerical Thermal Study of Heat Transfer Enhancement in Laminar-Turbulent Transition Flow Through Absorber Pipe of Parabolic Solar Trough Collector System," Frontiers in Heat and Mass Transfer (FHMT), **17**(20). http://dx.doi.org/10.5098/hmt.17.20

Kafeel, K., Turan, A., 2014, "Simulation of The Response of a Thermosyphon Under Pulsed Heat Input Conditions," International Journal of Thermal Sciences, 80. https://doi.org/10.1016/j.ijthermalsci.2014.01.020

Kargarsharifabad, H., Mamouri, J.S., Shafii, M.B., Taeibi Rahni, M.T, 2013, "Experimental Investigation of The Effect of Using Closed-Loop Pulsating Heat Pipe on The Performance of a Flat Plate Solar Collector," Journal of Renewable Sustainable Energy, **5**. https://doi.org/10.1063/1.4780996

Kang, Z., Shou, D., Fan, J., 2021 "Numerical Study of a Novel Single-Loop Pulsating Heat Pipe with Separating Walls Within the Flow Channel," Applied Thermal Engineering, 196. https://doi.org/10.1016/j.applthermaleng.2021.117246

Khandekar, S., Groll, M., 2003, "On the Definition of Pulsating Heat Pipe," Proceedings of 5th Minsk International Seminar (Heat Pipes, Heat Pumps and Refrigerators), Minsk, Belarus.

Kearney, D.J., Suleman, O., Griffin, J., Mavrakis, G., 2016, "Thermal Performance of A PCB Embedded Pulsating Heat Pipe for Power Electronics Applications," Applied Thermal Engineering, **98**, 798–809. https://doi.org/10.1016/j.applthermaleng.2015.11.123

Khandekar, S., Gautam, A.P., Sharma, P.K., 2009, "Multiple Quasi-Steady States in A Closed Loop Pulsating Heat Pipe," International Journal of Thermal Science, 48 (3), 535–546. https://doi.org/10.1016/j.ijthermalsci.2008.04.004

Khodami, R., Abbas Nejad, A., Ali Khabbaz, M.R., 2016, "Experimental Investigation of Energy and Exergy Efficiency of a Pulsating Heat Pipe for Chimney Heat Recovery," Sustainable Energy Technology Assessment, **16**, 11–17. https://doi.org/10.1016/j.seta.2016.04.002

Lin, Z., Wang, S., Shirakashi, R., Zhang, L.W., 2013, "Simulation of A Miniature Oscillating Heat Pipe in Bottom Heating Mode Using CFD With Unsteady Modelling," International Journal of Heat and Mass Transfer, 57. https://doi.org/10.1016/j.ijheatmasstransfer.2012.09.007

Lim, J, Kim, SJ., 2018, "Fabrication and Experimental Evaluation of a Polymer-Based Flexible Pulsating Heat Pipe," Energy Conversion and Management, 156:358–64. https://doi.org/10.1016/j.enconman.2017.11.022

Lips, S., Bensalem, A., Bertin, Y., 2010, "Experimental Evidences of Distinct Heat Transfer Regimes in Pulsating Heat Pipes (PHP)," Applied Thermal Engineering, 30(8), 900–907. https://doi.org/10.1016/j.applthermaleng.2009.12.020

Liu, X., Chen, Y., 2014, "Fluid Flow and Heat Transfer in Flat-Plate Oscillating Heat Pipe," Energy and Building, 75:29–42. https://doi.org/10.1016/j.enbuild.2014.01.041

Lv, L., Li, J., Zhou, G., 2017, "A Robust Pulsating Heat Pipe Cooler for Integrated High Power LED Chips," Heat Mass Transfer, **53**, 3305–3313. https://doi.org/10.1007/s00231-017-2050-3

Mameli, M., Marengo, M., Khandekar, S., 2014, "Local Heat Transfer Measurement and Thermo-Fluid Characterization of a Pulsating Heat Pipe," International Journal of Thermal Science, 75, 140–152. https://doi.org/10.1016/j.ijthermalsci.2013.07.025

Maydanik, Y.F., Dmitrin, V.I., Pastukhov, V.G., 2009, "Compact Cooler for Electronics on the Basis of a Pulsating Heat Pipe," Applied Thermal Engineering, **29**, 3511–3517. https://doi.org/10.1016/j.applthermaleng.2009.06.005

Mochizuki, M., Nguyen, T., Mashiko, K.i, Saito, Yu., Wuttijumnong, V., 2011, "A Review of Heat Pipe Application Including New Opportunities," Frontiers in Heat Pipes, 2, 013001.
https://doi.org/10.5098/fhp.v2.1.3001

Narasimha, K. R., Sridhara S.N., Rajagopal, M.S., Seetharamu, K.N., 2012, "Influence of Heat Input, Working Fluid and Evacuation Level on the Performance of Pulsating Heat Pipe," Journal of Applied Fluid Mechanics, **5**(2), 33-42.

Natsume, K., Mito, T., Yanagi, N., Tamura, H., Tamada, T., Shikimachi, K., Hirano, N., Nagaya, S., 2011, "Heat Transfer Performance of Cryogenic Oscillating Heat Pipes for Effective Cooling of Superconducting Magnets," Cryogenics, **51**, 309–314.
https://doi.org/10.1016/j.cryogenics.2010.07.001

Nikolaenko, Y.E., Pekurb, D.V., Kravets, V.Yu., Sorokin, V.M., Kozak, D.V., Melnyk, R.S., Lipnitskyi, L.V., Solomakha, A.S., 2021, "Thermal Performance of Low-Cost Cooling Systems for Transmit/Receive Modules of Phased Array Antennas with And Without Gravity Heat Pipes," Frontiers in Heat and Mass Transfer (FHMT), **18**(23).
http://dx.doi.org/10.5098/hmt.18.23

Noh, H.Y., H., Jin Kim. S.J, 2020, "Numerical Simulation of Pulsating Heat Pipes: Parametric Investigation and Thermal Optimization," Energy Conversion and Management, 203.
https://doi.org/10.1016/j.enconman.2019.112237

Nookarju, B.C., Kurma Rao, P.S.V., Nagasarda, S., 2015, "Experimental and Numerical Analysis of Thermal Performance of Heat Pipes," Procedia Engineering, 127.
https://doi.org/10.1016/j.proeng.2015.11.415

Nuntaphan, S., Vithayasai, N., Vorayos, N., Vorayos, N., Kiatsiriroat, T., 2009, "Use of Oscillating Heat Pipe Technique as Extended Surface in Wire-On-Tube Heat Exchanger for Heat Transfer Enhancement," International Communication in Heat Mass Transfer, **37**(3), 287–292.
https://doi.org/10.1016/j.icheatmasstransfer.2009.11.006

Patel, V.M., Mehta, H.B., 2019, "Channel Wise Displacement-Velocity-Frequency Analysis in Acetone Charged Multi-Turn Closed Loop Pulsating Heat Pipe," Energy Conversion and Management, 195:367–83.
https://doi.org/10.1016/j.enconman.2019.05.014

Patel, V.M., Mehta, H.B., 2017, "Influence of Working Fluids on Startup Mechanism and Thermal Performance of a Closed Loop Pulsating Heat Pipe," Applied Thermal Engineering, **110**, 1568–1577.
https://doi.org/10.1016/j.applthermaleng.2016.09.017

Qu, J., Zhao, J.T., Rao, Z.H., 2017, "Experimental Investigation on the Thermal Performance of Three-Dimensional Oscillating Heat Pipe," International Journal of Heat Mass Transfer, **109**, 589–600**.**
https://doi.org/10.1016/j.ijheatmasstransfer.2017.02.040

Schily, F., Polifke, W., 2021, "Low-Order Model of The Dynamics and Start-Up of a Pulsating Heat Pipe," Frontiers in Heat and Mass Transfer (FHMT), **17**(16).
http://dx.doi.org/10.5098/hmt.17.16

Singh, R., Mochizuki, M., Mashiko, K., Nguyen, T., 2019, "Data Center Energy Conservation by Heat Pipe Based Pre -Cooler System," Frontiers in Heat and Mass Transfer, **13**(24).
https://doi.org/10.5098/hmt.13.24

Tong, B.Y., Wong, T.N., Ooi, K.T., 2001, "Closed Loop Pulsating Heat Pipe," Applied Thermal Engineering, **21**(18), 1845-1862.
https://doi.org/10.1016/S1359-4311(01)00063-1

Velardo, J., Singh, R., Ahamed, M.S., Mochizuki, M., Date, A., Akbarzadeh, A., 2021, "The Thermal Management Modules Using Flattened Heat Pipes and Piezoelectric Fans for Electronic Devices," Frontiers in Heat and Mass Transfer, **17**(1).
https://doi.org/10.5098/hmt.17.1

Venkatasuresh, J., Bhramara, P., 2017, "CFD Analysis of Multi Turn Pulsating Heat Pipe," 5th International Conference of Materials Processing and Characterization (ICMPC 2016), Materials Today: Proceedings, **4**(2).
https://doi.org/10.1016/j.matpr.2017.02.146

Venkatasuresh, J., Bhramara, P., 2018, "CFD Analysis of Copper Closed Loop Pulsating Heat Pipe," Materials Today: Proceedings, **5**(2).
https://doi.org/10.1016/j.matpr.2017.12.138

Wang, H., Qu, J., Peng, Y., Sun, Q., 2019, "Heat Transfer Performance of a Novel Tubular Oscillating Heat Pipe with Sintered Copper Particles Inside Flat-Plate Evaporator and High-Power LED Heat Sink Application," Energy Conversion and Management, 189:215 22.
https://doi.org/10.1016/j.enconman.2019.03.093

Wang, D., Cui, X., 2010, "Experimental Research on Pulsating Heat Pipe with Different Mixtures Working Fluids," The 21*st* International Symposium on Transport Phenomena 2-5 November, Kaohsiung City, Taiwan.

Xu, J.L., Li, Y.X., Wong, T.N., 2005, "High Speed Flow Visualization of a Closed Loop Pulsating Heat Pipe," International Journal Heat Mass Transfer, **48**(16), 3338–3351.
https://doi.org/10.1016/j.ijheatmasstransfer.2005.02.034

Xu, R.J., Zhang, X.H., Wang, R.X., Xu, S.H., Wang, H.S., 2017, "Experimental Investigation of a Solar Collector Integrated with A Pulsating Heat Pipe and A Compound Parabolic Concentrator," Energy Conversion and Management, 148:68–77.
https://doi.org/10.1016/j.enconman.2017.04.045

Zhang, Y., Faghri, A., 2002, "Heat Transfer in a Pulsating Heat Pipe with Open End," International Journal of Heat and Mass Transfer, **45**(18), 2501-2508.
https://doi.org/10.1016/S0017-9310(01)00348-9

Zhou, W., Li, Y., Chen Z., Deng, L., Gan, Y., 2019, "A Novel Ultra-Thin Flattened Heat Pipe with Biporous Spiral Woven Mesh Wick for Cooling Electronic Devices," Energy Conversion and Management, 180:769–83.
https://doi.org/10.1016/j.enconman.2018.11.031