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Analysis of Closed Loop Pulsating Heat Pipe Using Python Programming

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Abstract
A computer program has been developed using PYTHON for the analysis of multi turn CLPHP made up of copper with capillary dimensions such as 2mm and 3.1 mm inner and outer diameters. The central difference finite difference equations are used to determine the temperatures at various sections by using numerical methods. The heat transfer equations for each cell solved iteratively, and the temperature values are updated at each time step until the solution converged. The performance of the heat pipe was analysed by varying the heat inputs and working fluid conditions. PYTHON code is developed for different fluids by using libraries such as NumPy, SciPy, and Matplotlib to obtain temperature matrix. Thermal resistance as a performance parameter is calculated with the help of temperatures. The obtained temperatures by running Python code are compared with the existing experimental results.

1. Introduction
Thermal management is a critical aspect of system design, ensuring electronic components and systems are operating within their optimal temperature range for reliable and efficient operation. Effective thermal management involves multiple strategies including proper heat sink design, thermal interface materials and active cooling methods such as fans or liquid cooling. In some cases, thermoelectric cooling or heat pipes can also be used[1]. Simulation and analysis tools are used to optimize the thermal performance during the design phase. Monitoring and controlling temperatures in real-time with sensors and feedback systems can help prevent overheating and temperature-related failures. Proper thermal management is critical to extending the life reliability and performance of electronic systems, especially in high power applications. Convection is a method of heat transmission that takes place in gases or liquids. A thermal gradient is produced when two locations in a fluid differ in temperature, which causes the phenomenon. The colder, denser fluid sinks while the warmer, less dense fluid rises as a result of the gradient. Heat is transferred from the hotter to the cooler area as a result of the fluid's movement since it carries heat energy along with it. Weather patterns, ocean currents, and food preparation are just a few of the natural and man-made processes that benefit from convection. Additionally, it may have a big effect on the ecology and climate change [2]. When the working liquid passes through the adiabatic section and wick material in the evaporator and condenser parts of a heat pipe, a change in phase takes place that causes the device to function passively. The evaporator, wick, and condenser the three main parts of the heat pipe assembly make up its three portions. They consist of a sealed container that is

partially filled with a working fluid, which is often a substance with a low boiling point like water or ammonia. The working fluid vaporises and condenses to create a vapour when heat is applied to one end of a heat pipe[3]. This vapour then travels to the cooler end of the pipe and releases the latent heat of vaporisation.

2. Literature Review

CLPHP is a closed-loop heat transfer device that uses capillary action and vapor-liquid phase change to transfer heat from the heat source to the heat sink. It consists of an evaporator, adiabatic section, and condenser, which work on evaporation and condensation phenomenon. The operation limitations of CLPHPs with varying filling ratios (30%, 50%, and 70%) using copper tubes with specific inner and outer diameters (1mm and 2mm, respectively) and R134 as the working fluid [4]. explored the filling ratio effects on the performance and operational limits of the CLPHP, such as heat transfer performance, thermal resistance, and stability under different operating conditions. The CFD analysis [13] on CLPHP of 2mm and 3mm diameter with 2 turns and working fluids as water, vertical and horizontal and 20, 40, 60W as heat inputs [5]. Thermal resistance of vertical one is compared with experimental value. By developing and implementing numerical algorithms based on finite difference methods the governing equations of convection and diffusion in cylindrical coordinates for a 2D convection-diffusion problem are solved by knowing the [6] insights into the distribution of temperature, concentration, or other quantities of interest in such systems, and could contribute to the field of computational fluid dynamics and heat transfer. Using CFD simulation model the thermal and fluidic behavior of the CLPHP, including the heat transfer characteristics, fluid flow patterns, and pressure drop are studied. [7]. Additionally, the volume fraction analysis gives the idea to quantify the distribution and behavior of the working fluid phase (liquid and vapor) within the CLPHP which could contribute to the understanding and development of pulsating heat pipes for different applications. In the present study the experimental study [12] is compared with the computational simulation. Firstly, the experiment conducted by N.SanthiSree et.al has thoroughly understood. The experiment is carried out on closed loop pulsating heat pipe by varying different operating conditions and at different working conditions. The temperatures were recorded at different locations to determine the heat transfer characteristics of CLPHP. The basic heat transfer correlations are considered for determining performance parameters. In the present analysis the basic governing equations of heat transfer are considered. Finite difference method is applied and computational program using Python is developed to determine the temperatures. The main objectives of present work are developing python code for the existing CLPHP and obtain the temperature distribution for the considered fluids at different heat inputs. Also compare the experimental values with respect to the python generated values. The following flow chart explains the procedure adopted for the present work.

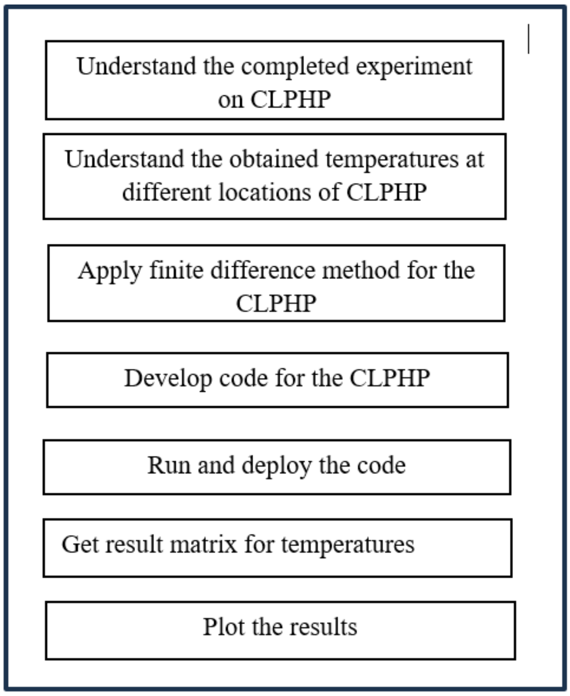

Figure 1 Flow Chart

3. Mathematical Modeling of Clphp

Numerical techniques have been used to solve temperature distribution in heat-conduction issues with or without phase change. Finite-difference techniques were successful in past, but interest in complex shapes and heat flow/stress problems has shifted to finite-element techniques. The number of numerical approaches and variations of each has rapidly expanded, but it is still unknown how they compare in terms of accuracy, stability, and cost[13]. The Crank-Nicolson approach solves a large number of equations in each time step. Gaussian elimination remains a possibility, but at the cost of substantial calculating and cumulative round-off error.

$$\Delta t = 1 \rho = 10000$$
$$C_p = 4.187 \text{ KJ/KgK}$$
$$k = 385 \text{ W/mK } \Delta z = 0.1$$

The basic equation for temperature distribution using central difference sche 303K be written as

$$T_{i,j+1} = T_{i,j} + \left[\frac{k\Delta t}{\rho C_p \, \Delta z^2}\right]\left[T_{i+1,j} - 2T_{i,j} + T_{i-1,j}\right] \text{----(i)}$$

$$T_{1,2} = T_{1,1} + \left[\frac{385*1}{1000*4.187*0.1}\right]\left[T_{2,1} - 2T_{1,1} + T_{0,1}\right]$$
$$T_3 = T_1 + [9.195][T_2 - 2T_1 + 303]$$
$$17.39T_1 - 9.195T_2 + T_3 = 2786.085$$
$$T_{1,3} = T_{1,2} + [9.195]\left[T_{2,2} - 2T_{1,2} + T_{0,2}\right]$$
$$373 = T_3 + [9.195][T_4 - 2T_3 + 303]$$
$$17.39T_3 - 9.195T_4 = 2413.085\_\_\_\_\_\_\text{(ii)}$$
$$T_{2,2} = T_{2,1} + [9.195]\left[T_{3,1} - 2T_{2,1} + T_{1,2}\right]$$
$$T_4 = T_2 + [9.195][303 - 2T_2 + T_3]$$
$$T_4 + 17.39T_2 - 9.195T_3 = 2786.085\_\_\_\_\_\_\_\_\text{(iii)}$$
$$T_{2,3} = T_{2,2} + [9.195]\left[T_{3,2} - 2T_{2,2} + T_{1,2}\right]$$
$$373 = T_4 + [9.195][303 - 2T_4 + T_2]$$
$$17.39T_4 - 9.195T_2 = 2413.05\_\_\_\_\_\_\_\_\_\_\_\text{(iv)}$$

Applying Gauss Elimination Method

$$\begin{bmatrix} 17.39 & -9.195 & 1 & 0 \\ 0 & 0 & 17.39 & -9.195 \\ 0 & 17.39 & -9.195 & 1 \\ 0 & -9.195 & 0 & 17.39 \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 2786.085 \\ 2413.05 \\ 2786.085 \\ 2413.05 \end{bmatrix}$$

Step – 1; **Multiply row 1 by 100/1739: R_1= (100/1739) R_1**

$$\begin{bmatrix} 1 & -0.5287 & 0.0575 & 0 \\ 0 & 0 & 17.39 & -9.195 \\ 0 & 17.39 & -9.195 & 1 \\ 0 & -9.192 & 0 & 17.39 \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 160.211 \\ 2413.05 \\ 2786.085 \\ 2786.085 \end{bmatrix}$$

Step – 2; Swap row 2 with row 3

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 160.211 \\ 2786.085 \\ 2413.05 \\ 2413.05 \end{bmatrix}$$

Step – 3; **Multiply row 2 by 100/1739: R_2 = (100/1739) R_2**

$$\begin{bmatrix} 1 & -0.5287 & 0.0575 & 0 \\ 0 & 1 & -0.5287 & 0.0575 \\ 0 & 0 & 17.39 & -9.195 \\ 0 & -9.195 & 0 & 17.39 \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 160.211 \\ 160.211 \\ 2413.05 \\ 2413.05 \end{bmatrix}$$

373K 4; **Multiply row 3 by 100/1739: R_3 = (100/1739) R_3**

$$\begin{bmatrix} 1 & -0.5287 & 0.0575 & 0 \\ 0 & 1 & -0.5287 & 0.0575 \\ 0 & 0 & 1 & -0.5287 \\ 0 & -9.195 & 0 & 17.39 \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 160.211 \\ 160.211 \\ 138.760 \\ 2413.05 \end{bmatrix}$$

Step – 5; **Multiply row 4 by 100/1739: R_3 = (100/1739) R_4**

$$\begin{bmatrix} 1 & -0.5287 & 0.0575 & 0 \\ 0 & 1 & -0.5287 & 0.0575 \\ 0 & 0 & 1 & -0.5287 \\ 0 & -0.5287 & 0 & 1 \end{bmatrix}\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} = \begin{bmatrix} 160.211 \\ 160.211 \\ 138.760 \\ 138.760 \end{bmatrix}$$

$$T_1 = 301.597K, T_2 = 299.57K, T_3 = 295.885K, T_4 = 297.161K$$

By using finite difference method, the temperatures obtained are 301.59,299.57,295.88 and 297.16K respectively.

4. Python Programming

The differential equation is solved using the finite difference method can be solved by Programming in Python [10]. and each point in the pipe will have an array reflecting the temperature and other data. As the mathematical calculations requires lot of time and manual work python is the best tool for solving heat transfer problems where the temperatures can be found out at each and every point. The code is developed on 4 faces (top, bottom, and two sides) and the temperature distribution is obtained. The basic governing equations such as continuity, Navier-stokes and energy equations are considered. The temperature at bottom row is fixed for the analysis. The dimensionless parameters Biot Number (Bi), Fourier Number (Fo) and Nusselt Number (Nu) are considering for developing the code [11]. The code is developed for water, ethanol and methanol CLPHP's.

5. Results and Discussions

As the experimental conclusions are taken on the basis of experiments carried out on water, methanol and ethanol base fluids the same fluid properties are applied for python simulation also. Number of iterations at each time step shows the variation of temperatures. The following fig shows the temperature distribution in CLPHP when it is working with the considered fluids.

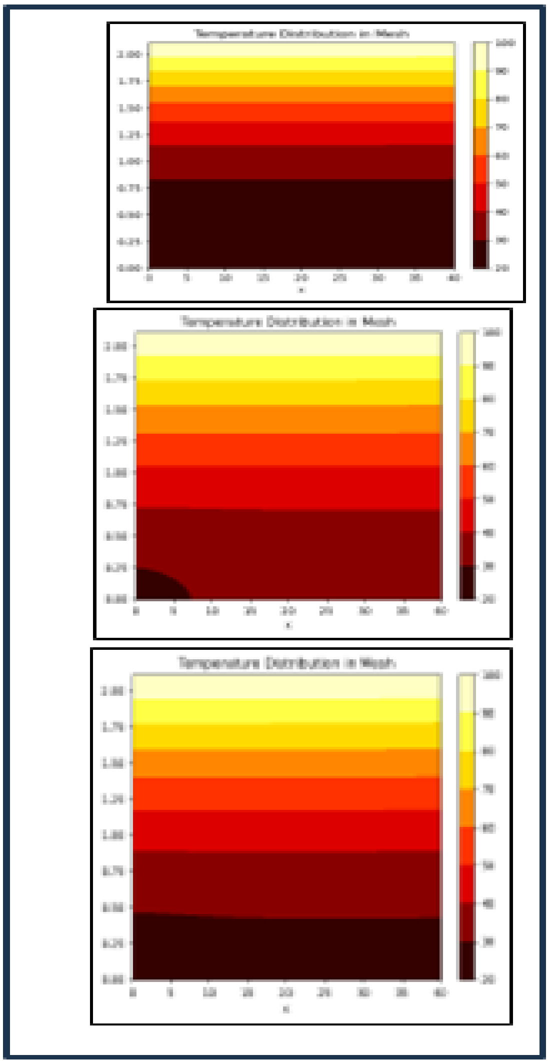

Figure 2 **Temperature Distribution in (A) Water (B) Ethanol (C) Methanol**

6. Comparison of Computational (Python) Vs Experimental

The python code is considered for water, ethanol and methanol base fluids at different heat inputs for comparing with experimental work [12,15]. Heat input of 20W,40 W and 60 W is considered. For water heat input at 20W, 40W and 60W is 28.025℃, 38.35℃, and 40.38℃ temperatures are obtained, whereas for ethanol 25.89℃, 24.08℃ and 29.56℃ temperature are obtained and for methanol 34.65℃, 36.65℃ and 38.56℃ temperatures are obtained for the considered heat inputs. respectively. These temperatures are compared with experimental values [12]. The comparative results are shown below graphically.

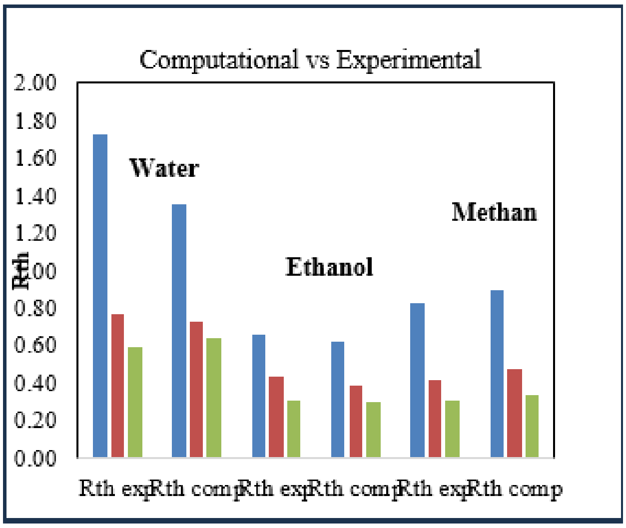

Figure 3 **Comparative Analysis from Experimental to Python at Different Heat Inputs**

Conclusions

The following conclusions are drawn from the computational simulation of Closed loop Pulsating Heat Pipe.

- Experimental study has been carried out.
- Python code has been developed using libraries like numpy, matlobplot, etc.
- By running the Python code, the temperatures obtained
- For water heat input at 20W, 40W and 60W is 28.025, 38.35, and 40.38 temperature respectively.
- For ethanol heat input at 20W, 40W and 60W is 25.89, 24.08 and 29.56 temperature respectively.

- For methanol heat input at 20W, 40W and 60W is 34.65, 36.65 and 38.56 temperature respectively.

The comparison of error percentage for computational to experimental values

- For Water heat input at 20W the error percentage is 21.51%.
- For Ethanol heat input at 20W the error percentage is 5.69%.
- For Methanol heat input at 20W the error percentage is 8.33%.

Future Scope

The same code can be developed for water-based mixtures and nano fluids CLPHP working with binary mixtures and nano fluids. So that it will reduce the operational cost and increases the effective performance. To increasing iteratives values it will be generating more accuracy values.

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