Numerical and experimental study of a single loop nitrogen pulsating heat pipe

Abhinav Singh, Indranil Ghosh
Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur, 721302, India.
Email: abhnv11295@kgpian.iitkgp.ac.in

ICEC/ICMC
29th International Cryogenic Engineering Conference
International Cryogenic Materials Conference 2024
July 22-26, 2024, Geneva, Switzerland
Poster ID - 295

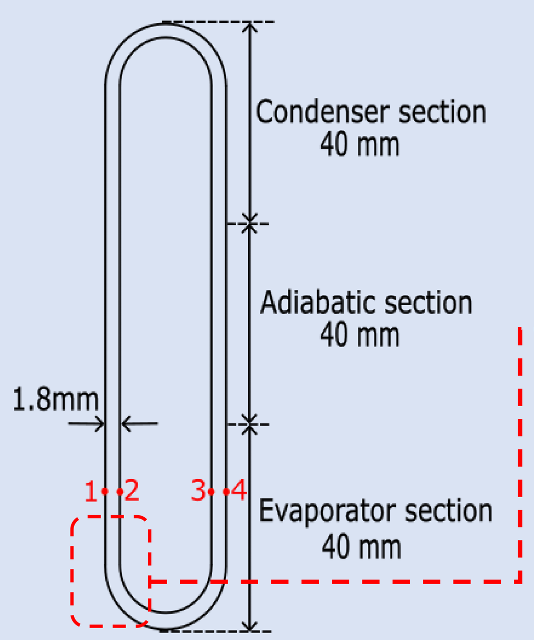
Abstract

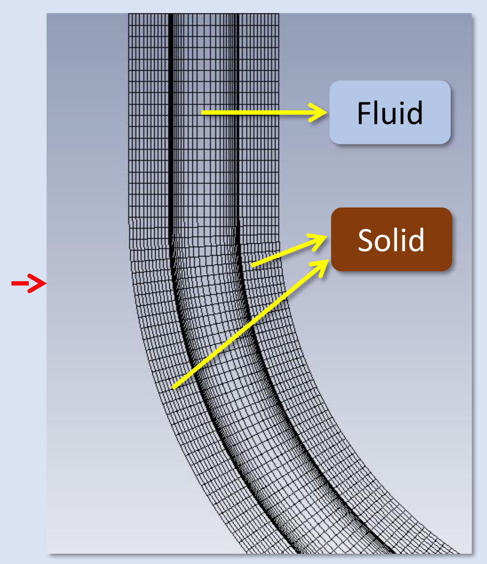
In the present study, a novel two-dimensional CFD model for a nitrogen pulsating heat pipe (PHP) has been developed in ANSYS Fluent. The total length of the PHP is 120 mm, with each of the three sections equal to 40 mm. The volume of fluid (VOF) model has been chosen as the multi-phase Eulerian model, and the Lee model as the phase interaction model. A user-defined function (UDF) code is written to solve the mass transfer between the two phases and the corresponding heat transfer due to evaporation and condensation. The CFD model helps to understand the transient behaviour of temperature and the evolution of flow patterns with time. Furthermore, an experimental setup of a single-loop PHP has been constructed with stainless steel as the tube material. The condenser section of the PHP is contained inside a condenser shell filled with liquid nitrogen. The entire PHP is kept inside a double walled vessel to avoid undesirable heat leakage.

Introduction

- In the 1990s, Akachi invented a new type of heat pipe known as the pulsating or oscillating heat pipe (PHP or OHP).
- The operating temperature of a PHP is between the triple and critical points of the working fluid.
- Cryogenic PHPs offer various applications such as cooling of superconducting magnets used in MRI systems, cooling of infrared sensors (IR sensors).
- In this study we aim to develop a 2D CFD model for a cryogenic PHP using nitrogen as a fluid to understand its complex two phase behavior.
- Furthermore, an experimental setup has been developed to investigate the thermal performance at different operating conditions.

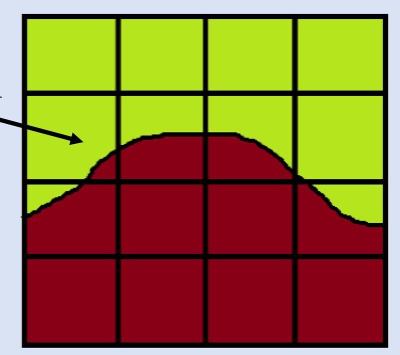
Numerical modelling





- Structured mesh
- Denser at the fluid-solid interface to capture the wall effects

VOF model



$$\alpha_v + \alpha_l = 1$$

GOVERNING EQUATIONS

Continuity Equation

$$\frac{1}{\rho_v}\left[\frac{\partial(\alpha_v\rho_v)}{\partial t} + \nabla.(\alpha_v\rho_v\vec{v_v})\right] = \sum_{l=1}^{n}(\dot{m}_{lv} - \dot{m}_{vl})$$

If $T_l > T_{sat}$ (Evaporation):

$$\dot{m}_{vl} = \beta_e * \alpha_l\rho_l * \left(\frac{T_l - T_{sat}}{T_{sat}}\right)$$

If $T_v < T_{sat}$ (condensation):

$$\dot{m}_{lv} = \beta_c * \alpha_v\rho_v * \left(\frac{T_v - T_{sat}}{T_{sat}}\right)$$

Momentum Equation

$$\frac{\partial(\rho\vec{v})}{\partial t} + \nabla.(\rho\vec{v}\,\vec{v}) = -\nabla p + \nabla.\left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^T\right)\right] + \rho g + \vec{F}$$

Force due to surface tension.

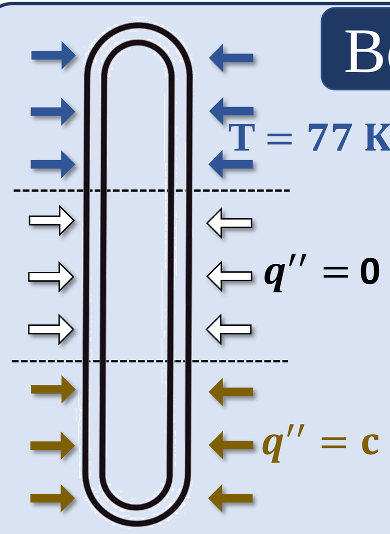
Energy Equation

$$\frac{\partial(\rho E)}{\partial t} + \nabla.(\vec{v}(\rho E + p)) = \nabla.[k\nabla T] + S_h$$

$$\frac{\partial(\rho_w E_w)}{\partial t} = \nabla.[k_w\nabla T] + S_{h,w}$$

(Energy source term)
$S_h = \dot{m}_{lv} * h_{LH} = -\dot{m}_{vl} * h_{LH}$.

Boundary conditions and initialization



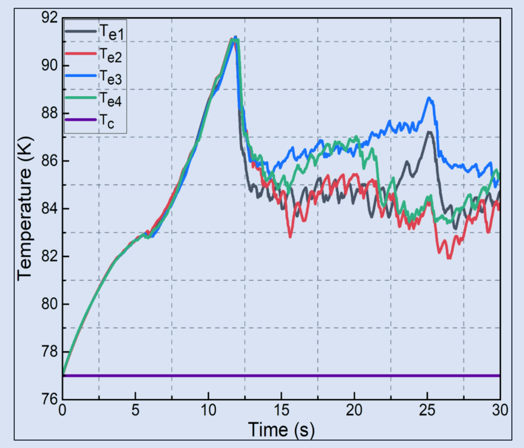
BOUNDARY CONDITIONS

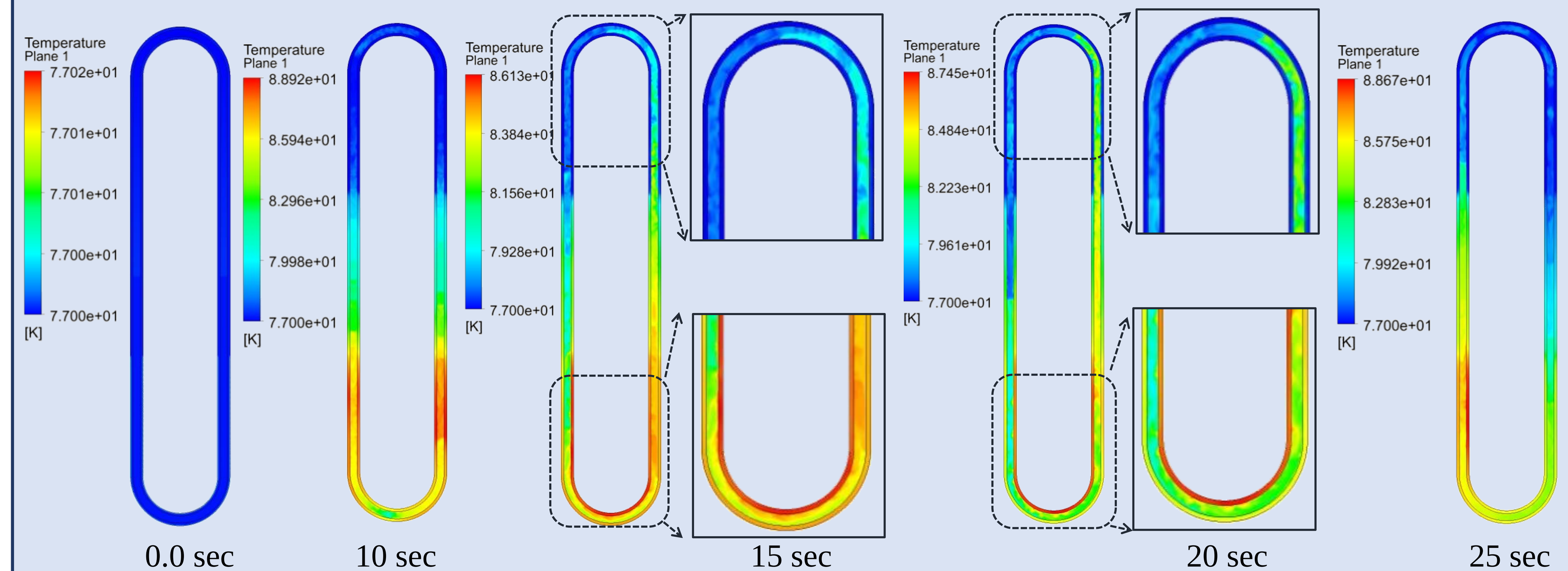
PROPERTIES:
- Working fluid- **Nitrogen**
- Vapor density – Ideal gas
- Other properties- polynomial functions with temperature

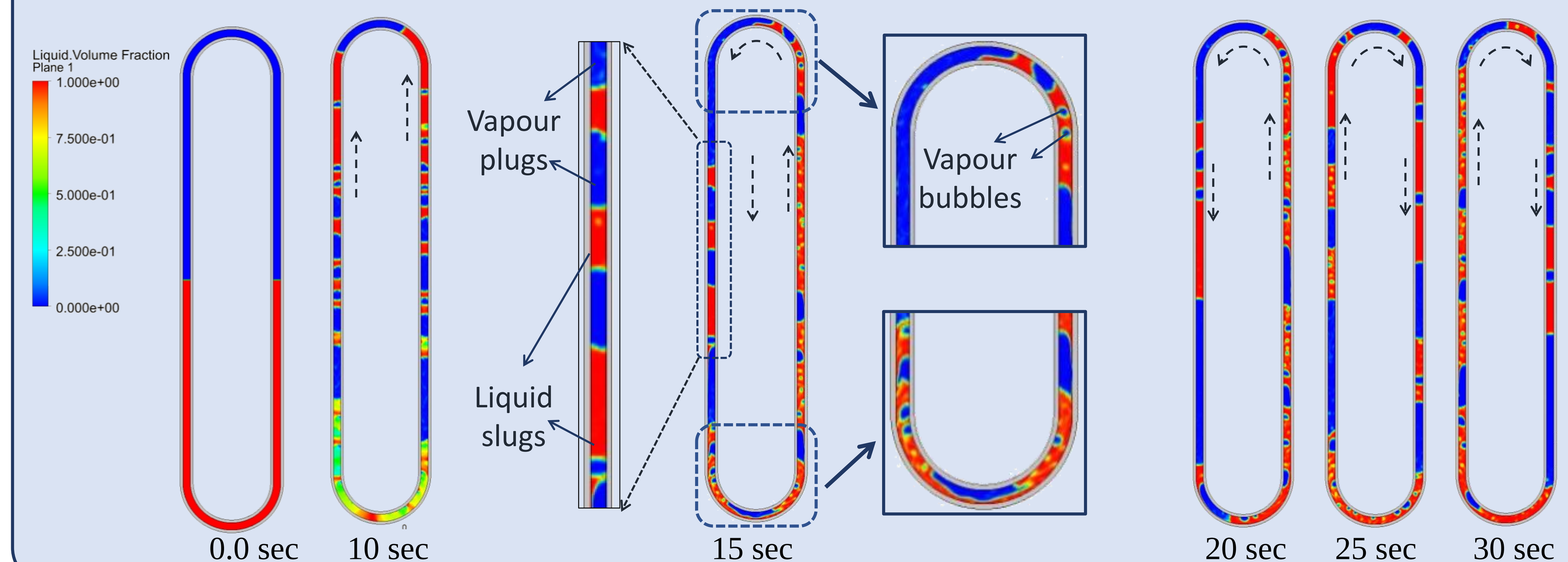
INITIALIZATION:
- Fill Ratio – 50%
- Initial temperature – 77K
- Initial pressure – 101.325 kPa

Results

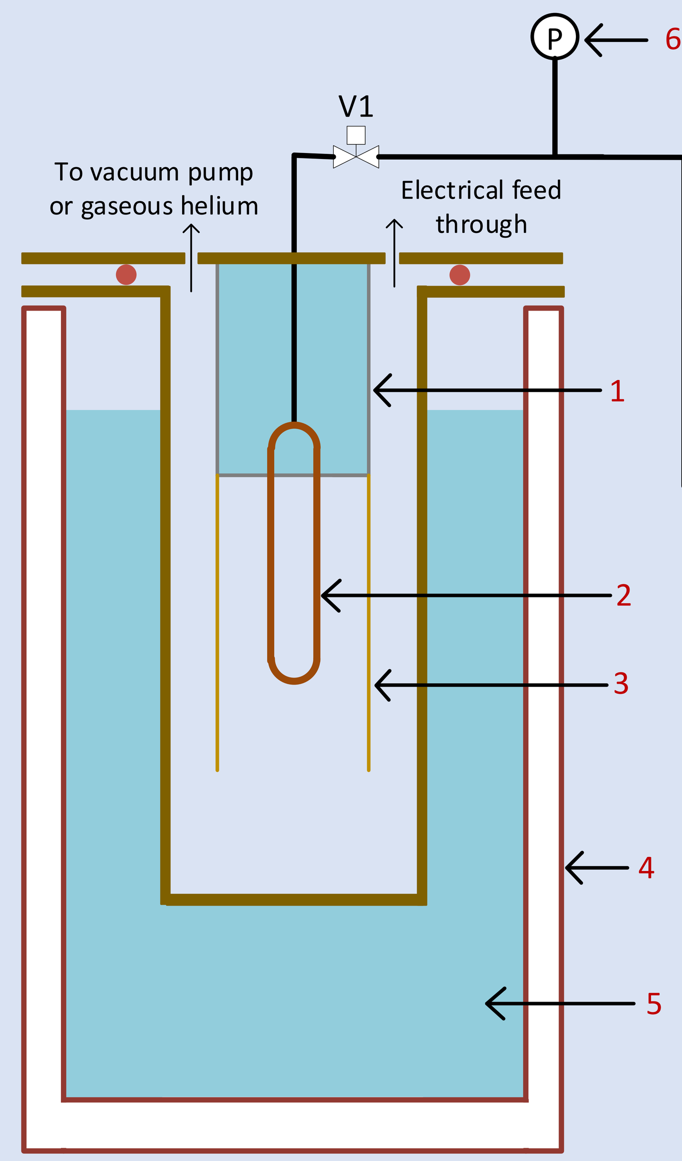
- The temperature fluctuations give rise to the oscillating/pulsating motion of fluid inside the PHP.
- The fluid flow is slug flow and the direction of fluid flow changes with time.



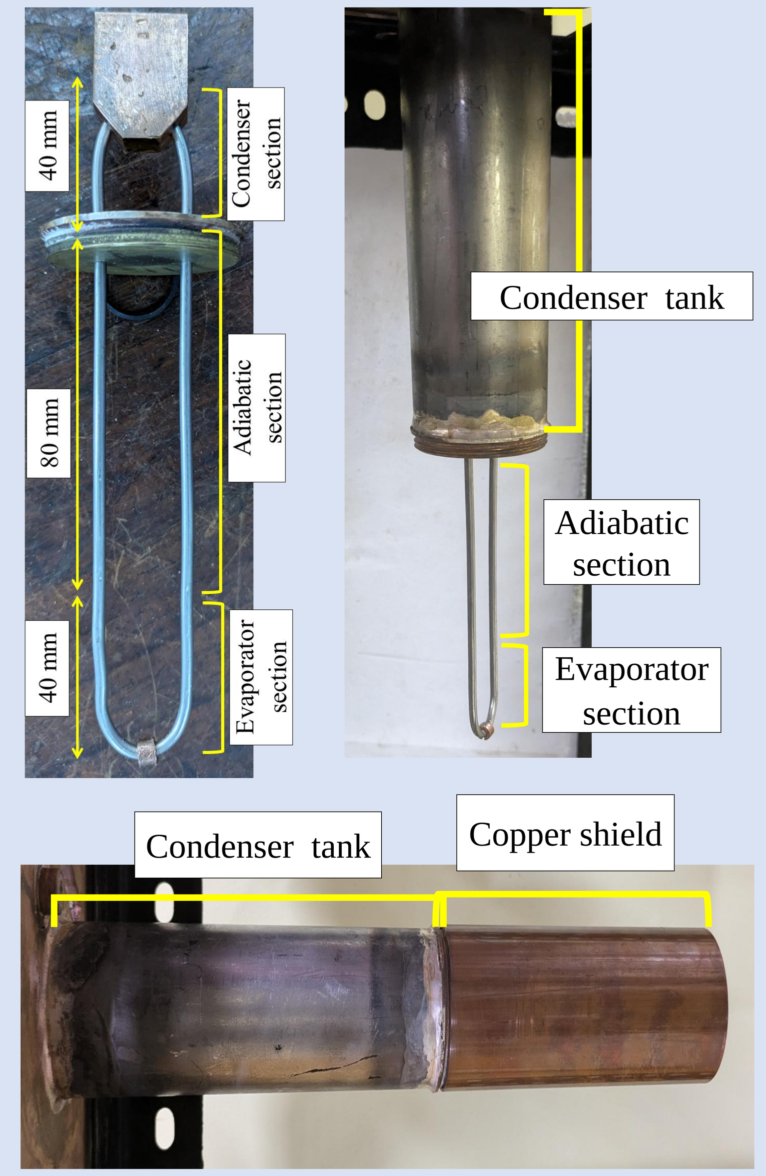




Experimental setup



1 – Condenser tank
2 – Pulsating heat pipe
3 – Copper shield
4 – Insulated double walled LN2 tank
5 – LN2 bath
6 – Pressure gauge
7 – Buffer tank
8 – Vacuum pump
9 – Nitrogen gas cylinder



Conclusions

- A 2D CFD model has been established for a single loop nitrogen pulsating heat pipe using ANSYS Fluent. The temperature contours and the volume fraction contours provided a better insight into the temperature fluctuations and flow structure inside the PHP.
- An experimental setup has been developed with the condenser section kept inside a condenser tank and cooled using liquid nitrogen. The evaporator and the adiabatic section assembly are placed inside a copper shield, and the entire PHP assembly is kept inside a vacuum insulated LN2 bath to avoid any heat leak.

Acknowledgement

We acknowledge the National Supercomputing Mission (NSM) for providing computing resources of 'PARAM Shakti' at IIT Kharagpur, which is implemented by C-DAC and supported by the Ministry of Electronics and Information Technology (MeitY) and Department of Science and Technology (DST), Government of India.