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Numerical and experimental study of a single-loop cryogenic pulsating heat pipe

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A Pulsating Heat Pipe (PHP) is an energy-efficient heat transfer device that operates using the processes of evaporation and condensation to effectively transport heat across long distances. Notably, room-temperature PHPs find crucial applications in cooling electronic components, such as CPU chips. In cryogenic environments, superconducting magnets that are cooled using cryocoolers require efficient conduction cooling to maintain the magnets in their superconducting state. Traditional heat conduction via copper straps becomes less effective when the distance between the cryocooler and the magnet is substantial. To address such challenges, the straightforward design of a PHP with its exceptional heat transport capabilities is a highly suitable alternative. The experimental studies on cryogenic PHP mainly focus on the heat transfer potential of the PHP. Understanding the complex two-phase flow behaviour and the transient nature of the temperature and pressure field inside the PHP is crucial. In the present study, a novel two-dimensional CFD model for a cryogenic pulsating heat pipe has been developed in ANSYS Fluent. The PHP is configured in a vertical heating mode, featuring the evaporator positioned at the bottom and the condenser at the top. The orientation of the PHP has been set in vertical heating mode, with the evaporator at the bottom and the condenser at the top. The PHP is a two-channel single loop with an inner diameter of 1.8 mm and an outer diameter of 3.16 mm. Nitrogen serves as the working fluid, and the tube structure material is chosen to be stainless steel. The total length of the PHP is 120 mm, with each of the three sections equal to 40 mm. The evaporator section is subjected to a constant heat flux boundary condition, while the condenser section is set at a constant temperature of 77 K. The Volume of Fluid (VOF) model has been chosen as the multi-phase Eulerian model, and the Lee model has taken care of the phase interaction between the liquid and vapour. A User Defined Functions (UDF) code is written to solve the mass transfer between the two phases and the corresponding heat transfer due to evaporation and condensation. The thermal physical properties of liquid and vapour nitrogen have been set as polynomial functions with temperature except for vapour density, which obeys the ideal gas law. Moreover, the saturation temperature and the latent heat follow a polynomial variation with pressure. The system is initialized with a FR of 50 % and has been tested at different thermal loads. The CFD model helps to understand the transient behaviour of temperature and pressure inside the PHP and the evolution of flow patterns with time. The evaporator temperature and pressure of the system initially rise as the evaporator is supplied with heat load and then reaches a quasi-steady state. However, the condenser temperature does not change significantly during the operation. The fluid under operation eventually distributes itself as liquid slugs and vapour plugs under gravity and surface tension combined. The thermal efficiency of the single-loop PHP has been assessed at varying heat loads by determining the effective thermal conductivity parameter. An increase in the thermal conductivity of the PHP has been observed as the heat loads rise.
Furthermore, an experimental setup of a single-loop PHP has been constructed with stainless steel (SS) as the tube material with geometric configurations, as stated above. The condenser section of the PHP is contained inside a condenser shell filled with liquid nitrogen. The entire PHP is kept inside a vacuum dewar to avoid undesirable heat leakage. Temperature sensors are attached to the evaporator side to measure the evaporator temperature. Two additional sensors are fed inside the adiabatic section to measure the transient behaviour of the fluid temperature inside the adiabatic section.

Submitters Country

India

Authors: SINGH, Abhinav (Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur); Dr GHOSH, Indranil (Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur)

Presenter: SINGH, Abhinav (Cryogenic Engineering Centre, Indian Institute of Technology Kharagpur)

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