

DOCTORAL DISSERTATION ABSTRACT

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Title of the doctoral dissertation:

„Numerical and Experimental Study of a Small Cryogenic Pulsating Heat Pipe”

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The dissertation integrates experimental investigations with numerical modeling of pulsating heat pipes (PHP), which are passive heat exchangers without moving parts. The primary objective is to develop a numerical PHP model for cryogenic conditions. The experimental part provides a consistent high-quality reference data set for model validation and extends the description of heat and mass transfer mechanisms at low temperatures. Heat rejection was provided using a two-stage cryocooler with two dedicated thermal interfaces matched to the cold ends of both stages and with radiation shielding that limited parasitic heat fluxes to the cryostat. The campaign covered two inner diameters of the capillary channel, three working fluids, namely neon, nitrogen, and argon, and selected filling ratios. Measurements were carried out over 27.3 to 105 K and the operating window depended on the working fluid. The pressure in the tube and the temperatures in the evaporator and condenser were recorded, enabling the determination of thermohydraulic characteristics complemented by a full uncertainty analysis.

The modeling was carried out in OpenFOAM using the Volume of Fluid method with the MULES algorithm in a fully compressible formulation with thermophysical properties dependent on temperature and local saturation parameters. In cryogenics, the properties of liquids and vapors depend strongly and non-linearly on temperature and pressure and differ markedly from those of fluids under ambient conditions. Therefore, a compressible approach was adopted with precise property correlations and strict control of mass and energy balances. The phase change was described by the Tanasawa relation and the Hardt and Wondra approach, treated as a mass flux across the phase interface resulting from interfacial kinetics and controlled by superheat or subcooling relative to saturation. The solver includes in-house modifications that are tailored to cryogenic conditions and to the specific operation of PHP.

Validation was carried out in stages, from reference tests and benchmarks to comparisons with experimental data. The parametric analyzes covered the effects of the working fluid, the filling ratio and the inner diameter on a prescribed heat flux. The calculations were performed in parallel using an MPI environment, enabling a systematic parameter survey and sensitivity analyzes within the desired turnaround time. The results showed how the choice of fluid, filling ratio, and channel diameter governs PHP operating regimes, thermal resistance, and the evolution of pressure and temperature. Parameter regions that minimize thermal resistance and thresholds for loss of pulsation stability were identified. Comparison of the model with experiments indicated agreement within acceptable error bounds. Recommendations were developed to select the working fluid, diameter, and filling ratio for cryogenic systems, and directions were defined for further model development.

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