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Physical mechanisms involved in grooved flat heat pipes: Experimental and numerical analyses

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ABSTRACT

An experimental database, obtained with flat plate heat pipes (FPHP) with longitudinal grooves is presented. The capillary pressure measured by confocal microscopy and the temperature field in the wall are presented in various experimental conditions (vapour space thickness, filing ratio, heat transfer rate, tilt angle, fluid). Coupled hydrodynamic and thermal models are developed. Experimental results are compared to results of numerical models. Physical mechanisms involved in grooved heat pipes are discussed, including the boiling limit and the effect of the interfacial shear stress. Finally, recommendations for future experimental and theoretical research to increase the knowledge on FPHP are discussed.

1. Introduction

Capillary heat pipes and two-phase thermosyphons are well-known heat transfer devices, having numerous industrial applications (electronic cooling, aeronautics, space…). Nevertheless, their integration in electronic or microelectronic systems implies their miniaturisation and an increase of the heat fluxes to be transferred. To face these new challenges, original two-phase cooling devices were developed, such as micro heat pipes or flat plate heat pipes (FPHP) [1]. A FPHP is a hermetic cavity of small thickness partially filled with a two-phase working fluid. Heat sources and heat sinks are located anywhere on the walls of the cavity, with the other parts being insulated. Vapour is generated at the heat source (evaporator) and it condenses at the heat sink (condenser). The liquid returns from the evaporator to the condenser through a capillary structure that can be made of micro-grooves, meshes or sintered powder wicks.

Since the nineties, several works were published on this type of systems and a lot of numerical or analytical models were proposed in order to predict their thermal performance and/or their capillary limit. The aim of the models is to calculate liquid and vapour pressures and velocities and the temperature field in the wall from heat sources to heat sinks. For grooved capillary structure, hydrodynamic models are based on the balance equations and the Young–Laplace law, which connects the liquid and vapour pressures to meniscus curvature radii in the grooves [2–9]. For other capillary structures (mainly meshes, sintered powder wicks or crossed grooves), such an approach is not possible. The flow in the capillary structure is modelled by the Darcy's law in 2D [10] or 3D [11,12].

In thermal models, longitudinal heat conduction in the wall and transversal heat transfer from the vapour to the wall have to be taken into account. Thermal and hydrodynamic models are highly coupled since the mass balance depends on the heat conduction in the wall. Furthermore, the transversal heat flux depends on the shape of the liquid in the capillary structure. As an example, for grooved capillary structures, the transversal heat transfer depends on the meniscus curvature radius in the grooves that is calculated by hydrodynamic models [13–15].

Although theoretical works on FPHP are based on physical descriptions including both thermal and hydrodynamic parameters, most of the experimental works provide only external temperature measurements to characterize the systems [1]. Furthermore, the studied FPHP are always opaque, which prevents observations inside the system in working conditions. This is for example the case in one of the most comprehensive study on flat plate heat pipes [16].

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