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Effect of tube heat conduction on the pulsating heat pipe start-up

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Abstract

In this work, we present our first simulation results on the start-up, functioning and stopping (dry-out) of the multi-branch pulsating heat pipe (PHP) accounting for the fluid-tube thermal interaction and bubble generation (boiling). A theoretical model that generalizes an earlier proposed approach is described. It is shown that the account of tube heat conduction changes substantially the PHP behavior. In particular, in the presence of tube heat conduction, the PHP cannot provide stable oscillations without bubble generation. While the bubble generation may not be directly involved in the development of first oscillations, its role is crucial in preventing the oscillations halt. The mechanism of the oscillation sustainment by bubble generation is discussed. The PHP simulation shows basic phenomena of bubble interaction and regimes observed experimentally in transparent PHPs. The PHP ceases functioning when the evaporator power is larger than a threshold. The liquid films are evaporated so the evaporator dries out completely and the oscillations stop; the evaporator temperature rises steeply.

Keywords: pulsating heat pipe, oscillation, liquid films, phase change, simulation

1. Introduction

Pulsating (or oscillating) heat pipe (PHP) is a simple capillary tube bent into branches meandering between hot and cold spots and partially filled with a two-phase, usually single component working fluid. During PHP functioning, a moving pattern of multiple vapor bubbles separated by liquid plugs forms spontaneously inside the tube. Because of their simplicity and high performance, PHP's are often considered as highly promising [1]. Their industrial application is however limited because the functioning of PHPs is not completely understood; the absence of calculation tools that would allow their dimensioning is a substantial obstacle to their development.

During the last decade, researchers have extensively studied PHP [2, 3]. It has been observed by many researchers that the main flow pattern inside the PHP is the slug flow, i.e. the flow of the "Taylor bubbles" where the gas is surrounded by liquid films. A major part of mass exchange occurs on their interface with the vapor like in the conventional heat pipes. Since the mass exchange provides both a moving force for the oscillations and the heat exchange, the films are extremely important for the PHP functioning.

Because of complex bubble and plug interactions and non-stationary dynamics, correlation-based system level approaches fail to predict the heat transfer in multi branch PHP and its direct numerical simulation seems to be the only possibility. One dimensional (1D) simulation models is the best choice because they are the simplest and at the same time are capable to describe the relevant physical phenomena. The pioneering approach [4] introduced basic principles for the 1D modeling. The PHP meander was represented by a straight tube with periodic boundary conditions; the evaporator, adiabatic and condenser sections followed each other sequentially. A coherent thermodynamic description of vapor has been introduced. The vapor was described as a compressible ideal gas which allowed its spring-like action. The heat conduction in the liquid plugs has been introduced. The imposed fixed temperatures T_c, T_e at the internal tube walls were assumed. Periodic oscillations were encountered. However, their amplitude was weak (smaller than the evaporator size), which contradicts the experimentally observed behavior.

One knows that the strongest heat and mass exchange occurs from thin liquid films. The films with uniform thickness δ_f, but varying length were introduced into the modeling [5] of the simplest, single branch PHP so that a partial evaporator dry-out could be described. The introduction of the heat conduction inside the tube walls [6] enabled the fluid-solid thermal interaction. The latter is quite important because it accounts for such effects as e.g. transfer of the heat from hot liquid plugs to the walls, heat accumulation in the solid and its later reinjection into the fluid. Besides, much realistic imposed heat power thermal boundary conditions become possible to simulate. The approach [6] has been reused with some improvements by another group [7] without correcting the crucial default in the model [6]: unlike [4], the vapor heat exchange was described with an inconsistent equation (cf. [8]), without which it was apparently impossible to obtain large amplitude oscillations. The vapor phase modeling problem has been analyzed and a new, "film evaporation/condensation model" (FEC) has been developed [9] for the single branch PHP. The FEC model is deprived

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