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Thermomechanical finite-element analysis and dynamics characterization of three-plug oscillating heat pipes

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ABSTRACT

Presented here are a nonlinear thermomechanical finite-element model of U-shaped three-plug oscillating heat pipes (OHPs) and numerical methods that can accurately predict the model's oscillation frequency and calculate the time-varying spatial distribution of temperature and the global heat transfer efficiency. The model accounts for the influences of nonlinear spring effect of vapor bubbles, mass transferring effect, fluid filling ratio, operating temperature, gravity, pressure loss due to pipe bend, and temperature difference between the evaporator and condenser. Dynamics of OHPs is characterized using a newly developed time–frequency analysis algorithm, and an Euler predictor–corrector method with convergence check is used to solve for the temperature distribution within the fluid plug. Results show that an OHP is a parametrically excited nonlinear thermomechanical system. An explicit formula for accurate prediction of the model's oscillation frequency is derived, and it reveals that the oscillation frequency is mainly determined by the fluid plug mass, initial vapor pressure, and the vapor-plug-length/pipe-cross-sectional-area ratio. Parameters that determine the oscillation amplitude include the temperature difference between the evaporator and condenser, heat transfer coefficients, fluid filling ratio, and initial temperature. Moreover, the existence of gravity directing from the evaporator to the condenser increases the oscillation frequency. These results provide better understanding of heat transfer mechanisms of OHPs and can be used to optimize designs of OHPs.

1. Introduction

Modern micro manufacturing and dense packaging technologies for faster communication speeds and greater overall computing power makes today's electronic devices require high-intensity heat dissipation in compact spaces to a power level over 300 W and a localized heat flux over 100 W/cm^2 [1]. Moreover, metal oxide semiconductor controlled thyristors generate heat fluxes from 100 W/cm^2 to 200 W/cm^2, and some laser diode applications have reached a heat flux level of 500 W/cm^2. Such high power levels far exceed the possible heat transport capacity of commonly used heat rejection methods like forced convection, heat sinks, and traditional capillary-driven passive heat pipes [2,3]. Moreover, today's electronics also require cooling devices to have high reliability for long-term services, structural simplicity for fine processing in production, and low cost. Due to continuous demands for faster and smaller microelectronic systems, effective thermal management becomes a critical issue that needs to be resolved [2,3].

An Oscillating Heat Pipe (OHP) is a promising heat transfer device that can be utilized to transfer a large amount of heat from heating to cooling sections [2,3]. The research and development of OHPs has sped up since the 1990s due to increasing demands for faster and smaller microelectronic systems [4]. An OHP consists of a long capillary wickless tube bent into many turns and an evaporator and a condenser located at two opposite sides, as shown in Fig. 1. The thin liquid film left on the tube wall by each moving liquid plug within the evaporator section is evaporated into and increases the mass and pressure of the following vapor plug. On the other hand, each vapor plug leaves a thin liquid film on the tube wall and its mass and pressure decrease within the condenser section. After the oscillation in an OHP is initiated, the pressure increase of vapor plugs in the evaporator section and the pressure decrease of vapor plugs in the condenser section result in a net force pushing liquid plugs to move toward the condenser and liquid plugs in the next channel to move toward the evaporator. Hence, OHPs utilize phase-change heat transfer (latent heat) in addition to forced convection (sensible heat) through self-excited oscillation of liquid and vapor plugs between the evaporator and condenser without any external mechanical power. However, challenging modeling, design and control issues exist.

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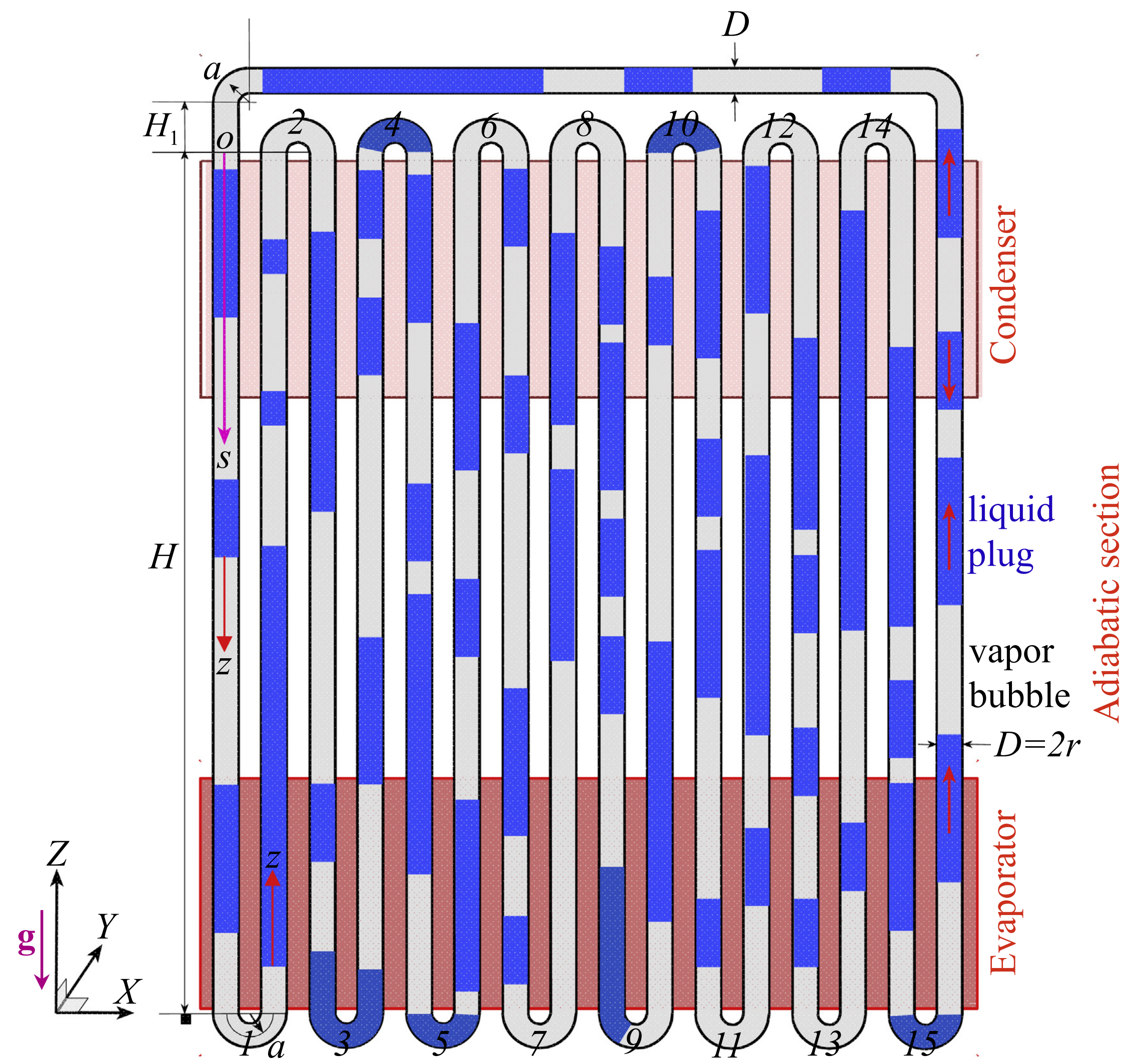

Fig. 1. Components, coordinate systems, and setup of an oscillating heat pipe.

OHPs can achieve a heat-removal rate much higher than that of conventional heat pipes because OHPs have five favorable features that do not exist in conventional heat pipes [2,3]. (1) An OHP is an "active" cooling device that converts heat from the heat generating area into the kinetic energy of fluid plugs to initiate and sustain the oscillating motion. (2) Because liquid and vapor plugs form separately in the small diameter tube, the neighboring liquid and vapor plugs flow along the same direction and do not interfere with each other and hence pressure drop is small. (3) The thermally-driven oscillating fluid plugs leave thin liquid films on the capillary tube to significantly enhance the phase-change heat transfer. (4) The oscillating motion in the capillary tube significantly enhances the forced convection in addition to the phase-change heat transfer. (5) As the input power increases, the oscillation frequency and hence the heat transport capability of an OHP increases dramatically. Because of these favorable features, the working mechanism and design of OHPs have been extensively investigated in the past ten years [5–28]. Unfortunately, there is still no way to control or even predict the actual oscillation modes and frequencies of OHPs due to the lack of accurate thermo-mechanical models for numerical simulations and design optimization [22–28].

Zhang and Faghri [29] showed that sensible heat transfer contributes more than latent heat transfer in an open loop OHP, but latent heat transfer introduces oscillation to enhance sensible heat transfer. The oscillation generated by a variable-frequency shaker could result in a thermal diffusivity up to 17,900 times higher than that without oscillation in a capillary tube [30,31]. Unfortunately, the use of a mechanical shaker to create oscillation is bulky, expensive, and infeasible. Hence, OHPs highly depend on thermally excited oscillations to have a high heat transport capability, but how the oscillation can be initiated and maintained is the main issue in designing efficient and reliable OHPs. Our previous research results show that the heat transport capability of OHPs is affected by the fluid filling ratio, power density, working fluid, surface condition of materials, gravity, dimensions and surface roughness of pipes, number of turns, three-dimensional design, heat conduction through the adiabatic section, nanoparticles, and frequency of self-excited oscillation [12–28]. Moreover, because an OHP is a dynamical system consisting of multiple degrees of freedom (DOFs), multiple oscillation modes are expected to exist in an OHP's general oscillation. The multi-mode response can be due to the time-varying temperature difference between the evaporator and condenser, spatially-distributed quasi-periodic thin film evaporations, spatially-distributed nonlinear spring effects of vapor bubbles, and others. Because quantitative influences of these factors are unknown, the actual working mechanisms of thermally excited oscillation and heat transfer of OHPs are still not fully understood [22–28].