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Nonlinear thermomechanical finite-element modeling, analysis and characterization of multi-turn oscillating heat pipes

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ABSTRACT

Oscillating heat pipes (OHPs) are promising heat dissipation devices for modern electronic systems due to their high heat transfer rate, simple construction and low manufacturing cost. Despite the unique features of OHPs, how to initiate and sustain the slug flow within the capillary tube and how different parameters affect the performance of an OHP are not well understood. This paper presents an advanced, fully nonlinear thermomechanical finite-element model that can simulate the parametrically excited oscillation of the liquid slug, the temperature distribution along the two-phase flow and the heat transfer performance of OHPs. The model can account for the influences of nonlinear spring effect of vapor slugs, interphase mass-transferring effect, fluid filling ratio, operating temperatures of the evaporator and condenser, different heating modes (top- or bottom-heating), gravity, bending pressure loss, properties of the working fluid, and different random distributions of initial velocities and lengths of fluid slugs. An Euler predictor–corrector method with convergence check is used to solve for the oscillation of and the temperature distribution within each fluid plug. The dynamics of OHPs is characterized using a newly developed time–frequency analysis technique. Numerical results show that an OHP is a parametrically excited nonlinear thermomechanical system. Latent heat transfer provides the driving force for the oscillation, and sensible heat transfer induced by forced convection contributes more than 80% of the total heat transfer rate. Generally speaking, working fluids with high thermal conductivity, low latent heat, and low viscosity are favorable for efficient heat transfer. These results provide better understanding of heat transfer mechanisms of OHPs and can be used for design optimization of OHPs.

1. Introduction

With everlasting miniaturization of microelectronic systems and highly developed high-density packaging technology, electronic industry has achieved a prominent development in recent years. Electronics, computers for instance, have decreased from a giant machine to a portable laptop. Although high-density packaging of integrated circuits (ICs) has brought us convenient working environment, powerful computation capability and fast development in space technology, compactly assembled circuits and high-power electronic components also produce large magnitudes of heat fluxes, leaving thermal engineers new challenges of thermal management of these electronic devices. Electronics with a local heat flux from 10 W/cm^2 to 40 W/cm^2 and a total heat power from 10 W to 150 W are already commonly seen in the electronic market [1]. A newly designed high density computer chip for next generation desktops can produce as much as 80 W/cm^2 heat flux with a total heat power of 300 W. Metal oxide semiconductor controlled thyristors can reach a heat flux from 150 W/cm^2 to 200 W/cm^2. Moreover, some laser diode devices can even generate a heat flux of 500 W/cm^2 [2]. If not being effectively dissipated, such large amount of heat will be amassed inside of computer chips, temperature of circuits will increase dramatically, and normal functions of computers will be seriously affected. In addition, the reliability of a silicon chip decreases by 10% for every 2 °C temperature rise and a typical temperature limit for a silicon chip is about 125 °C [3]. According to a survey of the U.S. Air Force, about 55% electronics failures are caused by superheat [3]. If proper thermal management is conducted to control the electronics temperature, electronics can be more durable and reliable.

Traditional heat rejection methods include convective heat transfer devices, heat sinks and etc. The most popular way of dissipating heat out of CPUs is to mount an electric fan on an aluminum heat sink. Heat generated inside a computer chip is conducted to the adjacent heat sink and then dissipated through the large contact area between the metal fins and the flowing air by forced convection. Despite wide applications of these heat dissipation methods in mechanical manufacturing factories, transformer stations and super computers, it is still impossible to dissipate a

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localized heat flux up to 500 W/cm^2 by conventional thermal rejection methods. Applications of heat sinks are limited due to their low thermal conductivity, big sizes and heavy weight associated with metal fins. Additional pumps together with pump power supplies are needed if cooling jets are impinged into a forced-convection system [4]. Hence, effective thermal management is becoming a critical issue to be resolved due to urgent and continuous demand of microelectronic systems.

In order to meet the critical demand in the thermal management field, convention heat pipes (CHPs) were designed in 1960s [5]. CHPs are two-phase capillary-driven passive heat-removal devices in which phase change of the working fluid is the main way of removing heat. A flat hollow metal plate with wick structures inside is an important design of CHPs. Working fluids are partially filled into the space formed among pores. When heat flux is added to one end of a CHP from the bottom of the metal base, the working fluid evaporates and the curvature of the liquid–vapor interface becomes larger and results in the capillary pressure. Driven by the capillary pressure, working fluid is pumped from the condenser section to the evaporator section and meanwhile the vapor is transmitted to the condenser section where the heat is removed [4]. The high transport capability of the capillary flow and the high phase-change heat transfer rate give CHPs salient features for electronic heat dissipation, but the main limitation of CHPs results from termination of a normal capillary flow [6,7]. When heat flux continuously increases in the evaporator side, liquid–vapor interface radius eventually reaches its minimum value and the capillary force simultaneously reaches its peak value. To maintain a normal liquid flow within the wick structure, total pressure head loss should never surpass the maximum capillary pressure.

To avoid the inherent limitations of conventional heat pipes, a new type of heat pipes known as oscillating heat pipes or pulsating heat pipes (OHPs or PHPs) were invented and patented by Akachi et al. in 1990s [5,8]. Similar to CHPs, this new type of heat pipes also employs working fluid flow and phase change to transfer heat, but it works in a different way. Fig. 1(a) shows a typical tubular OHP that is often used in experiments. A tubular OHP consists of a long wickless capillary tube bent into many turns meandering in a plain, an evaporator and a condenser located at two opposite ends, and an adiabatic region located in between. A chosen working fluid (e.g. water, acetone, or ammonia) is filled into the tube with a designated liquid–vapor ratio. The inner tube diameter must be sufficiently small (ranging from 0.1 mm to 5 mm) so that the capillary force is significant enough to counteract the gravity and hence the liquid and vapor can be discretized into separated liquid and vapor slugs (instead of stratifying into liquid and vapor layers as in CHPs) [9]. Without any external mechanical excitation, an OHP employs phase change heat transfer and forced convection to efficiently convey heat from the evaporator to the condenser through a self-excited oscillation. Each oscillating liquid slug leaves a thin film on the tube wall as it moves along the tube. Because the thickness of the thin film is very small and hence has a low thermal resistance, it can be easily evaporated at the evaporator section. When the liquid films are evaporated into the adjacent vapor slugs, the masses and pressures of the vapor slugs increase. On the other hand, when a vapor slug of high temperature and high pressure moves to the condenser section, condensation takes place and a thin liquid film forms on the tube wall resulting in decreases of the vapor slug's pressure and mass. The capillary force formed between the thin film and the adjacent liquid slugs will pump the liquid in the thin film to join the adjacent liquid slugs. The time-varying pressure difference between the high pressure of vapor slugs in the evaporator and the low pressure of vapor slugs in the condenser pushes liquid slugs to oscillate and move toward the condenser.

Although an OHP is simply constructed with only a meandering capillary tube charged with a proper working fluid, it bears many advantages that enable extraordinary heat transfer characteristics. Compared with CHPs, the outstanding features of OHPs include low pressure drop, high driving force for oscillation, high heat transfer coefficient, and low manufacturing cost. Because an OHP uses no wicking structures to return the condensate back to the evaporator, the pressure drop within the working fluid is very small. Moreover, because vapor and liquid slugs are moving in the same direction, the pressure drop due to unwanted friction force between the liquid and vapor flows does not exist. A CHP is merely driven by the capillary force from a wicking structure, but an OHP is driven primarily by the pressure difference between the heated vapor slugs and the cooled vapor slugs. The thermally driven oscillating fluid slugs inside the capillary tube will continuously sweep the tube wall, leave thin films on the tube wall, and significantly promote heat transfer through thin film evaporation

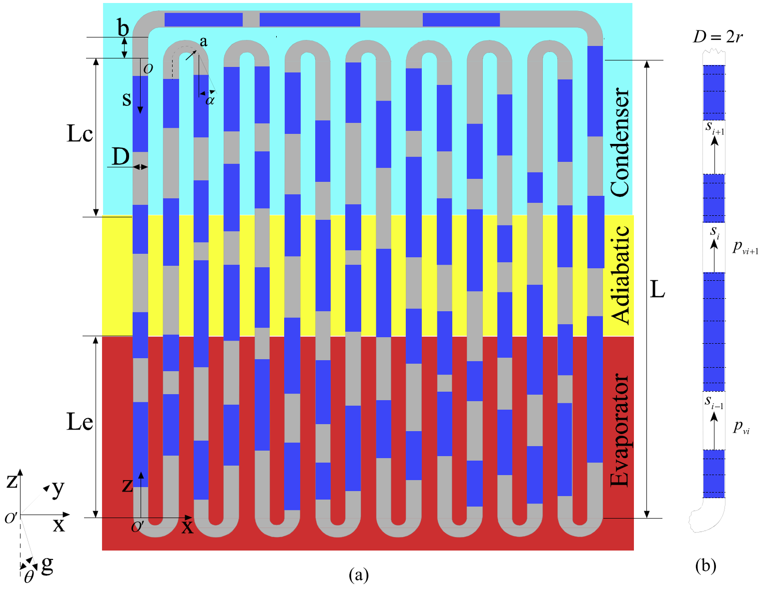

Fig. 1. A multi-turn OHP: (a) coordinate systems, and (b) numbering and finite-element discretization of fluid and vapor slugs.