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Transient microscale flow boiling heat transfer characteristics of HFE-7000

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ABSTRACT

A detailed experimental study was conducted to identify the important parametric trends governing the temperature response of a microdevice to transient heat loads for flow boiling of HFE-7000. The microdevice consisted of a micrograp etched on a silicon wafer and placed centrally over a thin-film heater deposited on a Pyrex wafer. A step change in heat flux and a rectangular pulse were applied to the heater. The effects of mass flux, heat flux (pulse amplitude), and pulse width on the heater temperature response and boiling dynamics were investigated in detail. Conditions at which onset of boiling occurred were identified and the repeatability of the boiling process was studied. Onset of boiling and the subsequent bubble dynamics was recorded with a high-speed video camera. Boiling initiated at very high wall superheat due to the smoothness of the heater surface and low surface tension of HFE-7000. At high heat fluxes, onset of boiling resulted in the formation of a vapor film on the surface and rapid heater temperature rise was observed. Time taken to initiate boiling decreased rapidly with increasing heat flux and then reached a constant value. The wall superheat at which boiling started increased with increasing heat flux and subsequently reached a constant limit.

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1. Introduction

Thermal management is a critical issue facing the electronics packaging industry. Miniaturization of electronic devices and systems has resulted in significantly higher transistor packaging densities. This has resulted in markedly increased power generation and heat production both at the chip and device levels as well as in large-scale systems like data centers, super computers, and military ships and aircrafts. Failure to effectively dissipate the heat flux generated in the electronic devices would result in increased device temperatures. The challenge facing thermal engineers is further exacerbated by the transient nature of the power profile frequently encountered in electronic systems. High device temperatures as well as transient temperature cycling are responsible for increased device failure rates, poor performance and low reliability. Effective heat dissipation methods and cooling technologies need to be developed to efficiently cool high power electronics operating at either steady-state or transient conditions. Refrigerant based two-phase (boiling and condensation) cooling systems have showed significant promise in dissipating high heat fluxes while maintaining low surface temperatures.

The heat transfer rate is significantly higher in flow boiling compared to single-phase flow due to a combination of the effects of latent heat of vaporization and enhanced mixing of the flow due to the movement of the bubbles [1]. In the literature, microscale flow boiling has been studied in detail under steady-state heating conditions [2,3] but there is lack of experimental studies investigating flow boiling heat transfer at microscale for transient heating conditions. In the majority of the steady-state studies [4–15], the boiling process was studied by increasing the heat flux in infinitesimal amounts and allowing the system to reach steady state before measuring the temperature, pressure, and identifying the corresponding bubble dynamics and boiling regimes. In transient experiments, the heat flux was increased from zero to maximum over a very short time period, and the flow regime made a rapid transition from single-phase flow to different boiling regimes [16]. Transient inputs could be classified into three categories: step response, frequency response, and impulse response [17]. In the present study, the boiling dynamics of HFE-7000 was studied for a step change in heat flux (step response) and pulsed heat inputs (frequency response).

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Nomenclature

A	area of heater, m^2
G	mass flux, kg/m^2-s
R	resistance, Ω
T	temperature, K
t	time, s
q''	heat flux, W/m^2

Greek Letters

Δ	wall Superheat, K
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ	pulse width, s

Subscripts

heater	heater
sat	saturation

Several conventional scale transient pool boiling experiments were conducted using thick metallic blocks [16,18–20] or thin wires [16,21–25] as the test section. The heat flux was applied in the form of a step change. The test fluids were water [25], liquid nitrogen [21,23,26], liquid helium [24], refrigerants like FC72 [19] and R113 [20] or organic fluids like pentane [16,18] and ethyl alcohol [27]. The effects of different parameters such as heat flux, preheating, saturation pressures, test section dimensions, and thermal properties of the fluid and the solid on the temperature response of the system were studied in detail. The transient input was in the form of a step change in heat flux. The effects of thermal inertia on the temperature response were studied in detail. Onset of boiling was initiated either by activation of preexisting gas or vapor nuclei trapped in the cavities on the heater surface [16,18] or by explosive vaporization similar to homogeneous nucleation [27]. A detailed review of the superheat limits for different fluids is given in Avedisian [28]. Sakurai et al. [24], on the other hand, observed heterogeneous nucleation on a thin platinum wire immersed in liquid nitrogen and helium under an exponential heat input. Explosive vaporization near the homogeneous nucleation point required a very high heating rate [27]. For steady-state experiments, nucleation was almost always due to the activation of nucleation sites on the heated surface [1]. A premature transition to film boiling at heat fluxes lower than the critical heat flux at steady-state was observed in few studies [20,22,23] while a steady nucleate boiling regime with no or delayed transition to film boiling was observed in other studies [21]. Due to the significant thermal inertia in the experiments, the heat flux boundary condition was not accurately measured in the experiments. The studies at the conventional scale were for pool boiling configurations.

The force generated on the fluid by the nucleation, growth, and collapse of the bubbles is used as an actuation mechanism in various applications such as thermal ink jet printers, DNA detection, biosensors, micropumps, fuel injection system [29]. These applications motivated several microscale pool boiling studies [29–38]. Only a few flow boiling studies were conducted at the microscale [39–41]. None of the flow boiling studies [39–41] used low surface tension fluids like refrigerants or organic fluid. The heat flux was applied to a micron sized titanium or platinum heater in the form of a single μs wide pulse. The main objective of the studies was to determine the bubble nucleation mechanisms and growth dynamics for different operating conditions and heater dimensions. The heating rate was very high and generally explosive vaporization at very high superheat was observed. Under these conditions, the boiling process was highly repeatable and afforded a great deal of control on bubble shape and size. Due to the potential application of the bubbles as an actuation mechanism, a high degree of repeatability was desirable. However, explosive vaporization at high wall superheats is not particularly efficient in dissipating high heat fluxes.

Although a significant number of steady-state studies [2–15] have shown that flow boiling is an efficient cooling mechanism, the effectiveness of the boiling process in dissipating high heat fluxes under transient operating conditions has not been studied in detail. In the present work, transient flow boiling heat transfer characteristics of HFE-7000 were experimentally studied in a microchannel heat sink for a step change in heat flux and pulsed heat inputs. The effects of mass flux, heat flux (pulse amplitude), pulse width on bubble dynamics, boiling characteristics, and temperature response of the system were determined. The bubble dynamics and boiling characteristics were correlated to the temperature response of the microdevice in order to identify the best operating conditions to dissipate the heat generated in the device. Onset of boiling was identified using high-speed video imaging. The wall superheat and time taken to initiate boiling were of particular interest. The variability in the conditions at which boiling was initiated and bubble dynamics post onset of boiling was experimentally identified. For reliable and efficient operation, onset of boiling should be controllable and repeatable and result in significant temperature drop. The heating rate was considerably lower and the pulse width was longer than the previous microscale studies [29–41]. HFE-7000 is a dielectric fluid with very low surface tension and is highly wetting in nature. Previous flow boiling studies [39–41] have used water as the test fluid, which is a high surface tension non-wetting fluid. The present set of experiments were carried out on a millimeter sized heater that is in between the heater sizes used in the microscale studies [29–41] and the macroscale experiments [16,18–20].

2. Experimental apparatus and data acqusition

Flow boiling experiments with HFE-7000 were conducted in a microdevice that was placed in a closed flow loop (Fig. 1). HFE-7000 was degassed prior to the experiments to remove any non-condensable gases. A deep vacuum was created in the pressure vessel containing the test fluid and the dissolved gases were allowed to escape over a period of two days. The flow loop consisted of a condenser, preheater, and an auxiliary heat exchanger that were used to condition the fluid to the correct temperature at the test section inlet.

The flow loop was fitted with an array of thermocouples and pressure transducers to monitor the temperature and pressure at various points in the loop. The microdevice consisted of a silicon wafer bonded to Pyrex wafer. The microdevice was square shaped with a side length of 0.02 m. The thickness of the silicon wafer was 0.45 mm and that of the Pyrex wafer was 1.0 mm. A 10 mm long, 1.2 mm wide, and 0.2 mm high microgap was etched on the silicon wafer. The microgap was placed centrally over a 1 mm $\times$ 1 mm thin film titanium heater that was deposited on the bottom surface of a Pyrex wafer (Fig. 2). The heater was in direct contact with the

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