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# Dryout analysis of overloaded microscale capillary-driven two-phase heat transfer devices☆

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ABSTRACT

Dryout occurrence at high heat input is one of the detrimental factors that limit the thermal efficiency of a phase-change heat transfer device. In this work, we demonstrate that by employing visualization method, the dryout occurrence of an elongated liquid droplet in a transparent evacuated microscale two-phase flow device can be scrutinized. The circulation of liquid from the condenser to the evaporator is driven by the capillary action which is the primary limitation that governs the maximum heat transport capability of the device. When the evaporation rate exceeds the circulation rate of condensate, dryout will take place in the evaporator end. The propagation of dryout lengths can be accurately determined directly from visualization and a more accurate evaluation of the dryout length compared to the conventional method by measuring the axial temperatures has been developed. By quantifying the performance indicators of the cooling device over a wide range of operating conditions, including the underloaded and overloaded operations, the observation of dryout occurrence in this study correlates highly with the anticipated heat transfer characteristics of a phase-change heat transfer device. This study provides essential insights, particularly on the overloaded conditions, to the design of a microscale two-phase heat transfer device.

## 1. Introduction

Intense heat-flux generation in view of device miniaturization demands highly efficient cooling techniques in electronics industries. Two-phase direct cooling strategies, such as capillary-driven two-phase systems are considered as the most attractive method for electronics cooling, offering significant advantages over traditional single-phase systems [1]. For a given range of temperature, the phase-change heat transfer in two-phase systems yields considerably greater heat transfer coefficients compared to sensible heat transfer in single-phase systems, resulting in significantly higher heat transport capability. As phase-change processes are typically isothermal, uniformity in temperature can be essentially obtained in two-phase systems. Generally, the capillary driven flow in two-phase systems provides self-sustained circulation of working fluid without external power requirements. Miniaturization of two-phase systems is possible due to lower mass flow rate, higher heat transport capability, and elimination of external power source. Therefore, capillary-driven two-phase heat transfer device as a passive system is a promising device in microscale cooling.

A typical microscale two-phase heat transfer device, such as microheat pipe [2–15], constrained vapor bubble heat transfer system [16,17], capillary micro-groove [18–21], and microthermosyphon [22], consists of an evaporator and a condenser. At the evaporator section, the input heat is taken up as the latent heat of vaporization by the working fluid. The resultant vapor flows to the condenser section where it condenses and releases the latent heat to the surroundings. The capillary pressure induced by the internal sharp-angled corners or wick structures drives the liquid phase from the condenser back to the evaporator. A capillary-driven two-phase device operates on the perpetual cycle of phase-change heat transfer and circulation of working fluid. In this work, we investigate the dryout phenomenon of an elongated water droplet in a microscale capillary-driven two-phase heat transfer device. Fig. 1 depicts the schematic of conceptual view of working mechanism of a microscale two-phase flow device. The circulation of liquid phase sustained by the capillary action is the main determinant affecting the thermal performance of such device. Under optimal operating conditions, the maximum possible heat transport rate is achieved when the onsets of dryout at the evaporator end and flooding at the condenser end occur simultaneously [4,7–12]. The sharp-angled corners are depleted of liquid if the capillary pressure is insufficient to overcome the total pressure loss. In such circumstance, dryout will take place at the evaporator section and the device is operated under overloaded condition. It has been shown that the capillary limit would

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**Nomenclature**

| | |
|---|---|
| $L_c$ | condenser length, m |
| $L_d$ | dry-out length, m |
| $L_e$ | evaporator length, m |
| $\dot{Q}_{in}$ | applied heat load, W |
| $k_{eff}$ | effective thermal conductance, W/m °C |
| $T_a$ | ambient temperature, °C |
| $T_c$ | condenser temperature, °C |
| $T_e$ | evaporator temperature, °C |
| $T_h$ | heater temperature with cooling device, °C |
| $T_{h,0}$ | heater temperature without cooling device, °C |
| $\Delta T$ | temperature drop, °C |
| $\eta$ | heat transfer enhancement ratio |
| $\phi$ | fluid charge ratio, % |

reach before any other operating limitations due to the capillary pressure constraint [4–6]. Thus, under steady-state operation, the capillary limit or dryout limit is the primary limitation that governs the maximum heat transport capability of a two-phase device [4–6,11].

The capillary limitation is dependent on several factors such as heat input [2,7–12], type of working fluid [10,12,20,23–26], charge ratio of working fluid [27–31], geometry of flow passage [32,33] and inclination angle of channel with reference to the horizon [8,18,19]. Aiming to predict the onset of dryout and evaluate the corresponding dryout length, numerous studies have been conducted. It is a common practice to detect the prevalence of dryout by physically measuring the axial wall temperature distributions [19,27,28,34,35]. Dryout is considered to take place where the temperature at the evaporator end increases sharply and the corresponding heat input is taken to be the heat transport capacity of the device [28]. At this particular point, a subsequent small increase in heat input gives rise to a dramatic temperature increase [34]. Due to the drastic increase in the temperature difference between evaporator and condenser, the occurrence of dryout significantly deteriorates the thermal performance of a two-phase device. Using thermal resistance as a performance indicator, the dry-out point of a microheat pipe was estimated by identifying a sudden jump in thermal resistance, which was a function of temperature difference between the evaporator section and condenser section [36]. The dryout limit was measured and predicted by using thermal imaging system to detect the temperature gradients for evaluating the effective thermal conductivity of microheat pipe arrays [27]. Manifestly, the identification of dryout occurrence was based on the detection through either drastic increases in temperature and thermal resistance or dramatic decrease in effective thermal conductance. This leads to a conservative estimation where the precise location and input power level at which dryout took place were not accurately determined. The lack in accuracy can be a problem in designing a microscale two-phase device used for cooling a localized heated surface area with low heat transport rate. Inaccurate estimation of dryout point leads to inherent unpredictability and uncertainty in determining the onset of overload and therefore affecting the optimal design of cooling device.

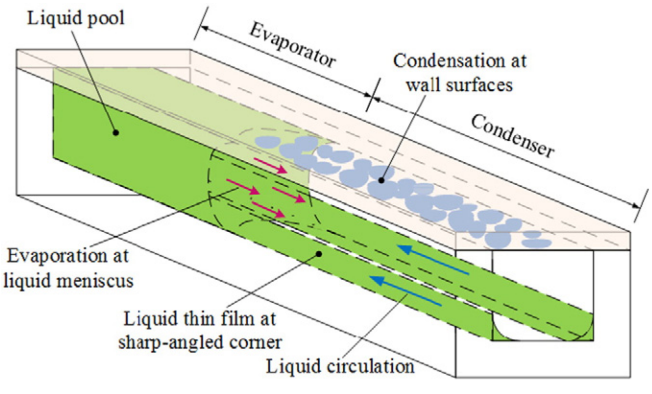

**Fig. 1.** Schematic of conceptual view of working mechanism of a microscale two-phase device.

Owing to the miniature scale of a two-phase device, it is rather difficult to physically measure the axial temperature distribution and determine the dryout point accurately. To this end, we introduce an alternative approach for investigating the dryout phenomena by employing visualization method. In a couple of previous reports, flow patterns of Pyrex-glass-plate covered silicon-based micro-pulsating heat pipes were investigated using a CCD camera at the start-up stage [37,38] and at different inclination angles [39]. The capillary and boiling limits of micro-grooves fabricated using chemical etching and precision milling were compared with the aid of flow visualization [21]. On the other hand, visualization technique has been a common and useful method employed to analyze the flow boiling mechanism in microchannels [40–42]. There also exist a number of studies devoted to visualize the gas–liquid flow patterns in microchannels [43–45]. In this study, an evacuated microscale two-phase device, which is a passive device, with transparent upper wall was fabricated for dryout phenomena observation. A high-resolution imaging device was employed to capture the propagation of dryout lengths which are then accurately determined by using a data digitizer. This proposed technique can be classified as an explicit method where the dryout point is determined directly from visualization and hence it provides a more accurate evaluation of the dryout length compared to the implicit method by measuring the axial temperatures. In line with the heat transfer analysis, the observation of dryout occurrence in this study correlates highly with the anticipated heat transfer characteristics of a two-phase cooling device. In the following sections, we describe the fabrication of a microscale two-phase device, illustrate the experimental setup, visualize and examine the dryout phenomena using a high-resolution imaging device, and analyze the effect of dryout length on the thermal performance under overloaded condition.

## 2. Experimental investigation

### 2.1. Fabrication of specimen and experimental setup

Fig. 2(a) depicts the flow chart for working fluid preparation, charging and evacuation processes of a transparent microscale two-phase heat transfer device. The microscale specimen was made of copper alloy 11,000 ($k = 388$ W/m·K) with a square microchannel of 800 μm × 800 μm and a length of 50 mm using computer numerical control (CNC) machining with a tolerance of ±0.01 mm. The thickness of solid wall was $t_s = 2.6$ mm. One of the two ends of the microchannel was sealed while another one was connected to an access valve for evacuation of air and charging of working fluid, as illustrated in Fig. 2. To visually observe the propagation of dryout length, a layer of transparent polymide film (DuPont™ Kapton® HN) was applied to cover the top surface of the microchannel.

Water was chosen as working fluid in view of its superior properties such as high surface tension, high liquid density, high latent heat of vaporization, low viscosity and non-toxicity. The working fluid charge ratio normally ranges from 16 to 25% of the total volume of channel [27]. In this study, three specimens were charged with 3.2 μL, 6.4 μL and 9.6 μL of distilled, deionized water, corresponding to 10%, 20% and 30% of charge ratios, respectively. Green-color dye (chlorophyllin) was added to water for illustrative purpose and the working fluid was degassed in a vacuumed chamber for 30 min. A small amount (0.2% in volume) of chlorophyllin, is added to deionized water and the variation of thermophysical properties is very marginal. To confirm this, we measure three major thermophysical properties of distilled, deionized water with and without color dye and the values are tabulated in Table 1. Thermal conductivity was measured using a thermal properties