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New design of a liquid bridge heat switch to ensure repetitive operation during changes in thermal conditions

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HIGHLIGHTS

- A liquid bridge heat switch is investigated to ensure proper ON/OFF operation.
- A conical surface is employed to ensure the repetitive and stable switching motion.
- The movement mechanism of liquid bridge is verified for heating plate.
- The effect of the conical surface was evaluated with an LED device.

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ABSTRACT

A liquid bridge heat switch is investigated to ensure proper ON/OFF operation in the presence of a temperature gradient. A temperature gradient along a plate can lead to changes in liquid properties such as the surface tension and contact angle. Eventually, these changes deteriorate the stability of the switching operation. The stationary position of the liquid bridge moves toward the colder zone over repetitive operations, and residuals of the liquid bridge remain after retraction. In addition, the liquid bridge cannot be generated properly with a predetermined clearance that is sufficient to form the liquid bridge between two plates with a uniform temperature. In order to enable a repetitive switching operation, a conical surface is employed at the hot plate of a heat switch just above the liquid channel. The conical surface reduces the clearance between the top plate and the liquid channel. Also, it provides the highest wettability at the desired zone and maintains the stationary position of the liquid bridge. The effect of the conical surface is evaluated with an LED device in terms of cooling time and thermal resistance. The conical surface extends the thermal resistance range more than three times. As a result, a design methodology for the liquid heat switch system is suggested to guarantee a stable switching operation against changes in thermal conditions. Moreover, the cyclic switching operation reduces the cooling time by almost 20 s compared with the non-cyclic operation.

1. Introduction

Over the past decades, efficient cooling systems have been a hot topic in the field of thermal management [1]. Novel designs of cooling systems are needed to meet the various cooling requirements according to the target performance of the systems. In order to enhance the thermal performance of these systems, researchers have investigated several cooling methods including the phase change material (PCM) heat sink, piezoelectric fan, synthetic air-jet pump, vapor chamber, and heat switch [2–6]. Among those, the heat switch has been specialized for thermal systems under cyclic or intermittent heat load [7]. Devices such as the PCM heat sink can also be adapted to periodic temperature conditions [8]. However, the heat switch provides a greater range of thermal control than a PCM heat sink. A heat switch can maintain a uniform temperature against changing external thermal conditions [9], and it can be adopted to a pulsed heat addition/rejection system [10]. In this respect, several heat switches have been reported as solutions for temperature-variant conditions [11].

In previous research it was confirmed that a heat switching system based on liquid bridge volume control allows not only thermal resistance control but also the precise regulation of the junction temperature of LEDs [12]. The liquid–solid contact-based heat switch has superior thermal contact resistance and design flexibility

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compared with the solid–solid contact-based switch. However, applications of this type of heat switch are quite limited because temperature-variant field parameters such as surface tension and the contact angle of the liquid may cause undesirable behavior in the liquid bridge under certain conditions. Therefore, it is necessary to clarify the effects of temperature change on the liquid bridge behavior in order to extend the working range of the switching system.

In this paper, the effect of the temperature gradient on liquid bridge behavior is investigated and a design methodology for a liquid bridge switch is proposed. Based on this new design, a liquid bridge heat switch having a conical surface on the hot plate was fabricated to achieve stable switching operation in the presence of a temperature change. The proposed heat switching system for an LED device was evaluated with respect to the precise control of the thermal performance, such as the thermal resistance and the LED junction temperature. The results show that the proposed heat switch functions well and enhances the switch performance under a heating condition.

2. Heat effect on the liquid bridge behavior

In general, heat switching systems operate under changing thermal conditions. Temperature changes may deteriorate the working performance of the liquid bridge heat switch because certain liquid properties, for example the surface tension and the contact angle, are a function of temperature. A change in the liquid properties during the heat switching operation leads to changes in the generation and rupture conditions of a liquid bridge. Therefore, the design methodology of the liquid bridge heat switch must ensure precise operations under temperature field changes.

The liquid bridge behavior with a heated surface was investigated to verify the effect of the wettability gradient caused by the temperature distribution on the rupture process. The temperature field of the target system was too complex to allow the proper generation of a liquid bridge, because the heat flow was affected by the movement of the stationary position of the liquid bridge and vice versa. Hence, temperature change effects were observed in terms of the motion of the liquid bridge and were compared with a non-heating surface. The experimental setup was the same as that described in previous research [12] and is shown in Fig. 1. A high-powered LED was employed as the spot heat source and a copper heat sink of the LED was used as the top plate to provide a temperature difference along the plate. The bottom plate was an aluminum heat sink with a 1 mm diameter flow channel. The clearance between the two plates was regulated by spacers.

2.1. Rupture failure of a liquid bridge with a heated surface

At first the cyclic motions of the liquid bridge were conducted with a non-heating plate. The clearance and volume of the liquid bridge were set at 1 mm and 13.3 μl to ensure its rupture of the liquid bridge. Thus, the generation and destruction of the liquid bridge occurred within 10 repetitions with the results shown in Fig. 2: ① depicts the initial state of a single cycle, ② depicts the initial generation of the liquid bridge, ③ depicts the generation of the liquid bridge, ④ depicts the fully developed liquid bridge, ⑤ depicts the retraction of the liquid, and ⑥ depicts the destruction of the liquid bridge.

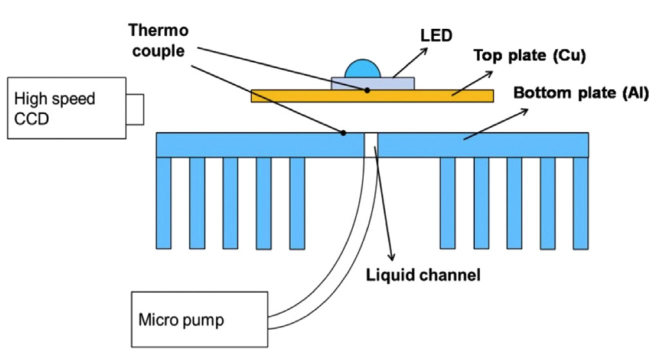

Fig. 1. Experiment setup to observe the liquid bridge behavior.

Next, the liquid bridge was observed under the same conditions but with the top plate heated by the LED. The LED had a consumed power of 1.8 W which led to a temperature of about 69 °C at the LED junction. The temperature distribution of the surface was measured by the infrared camera as shown in Fig. 3 and it was compared with the supplied voltage. In contrast with the uniform temperature case, the residual liquid bridge was observed after several cycles as shown in Fig. 4. In these captured images, the liquid bridge with the heated plate shows changes in the contact angle and the position of the liquid bridge. Between these two events, it was thought that the dominant factor creating the residual liquid bridge was the change in the stationary position of the liquid bridge during the operation.

As shown in Fig. 4(b), the stationary position of the liquid bridge moved about 1 mm to the left after the repetitions ended. The other processes of the liquid bridge were the same as for the case of a flat plate with uniform temperature. After the third cycle, the moving interface of the liquid bridge passed through the flow channel before the bridge ruptured because of a discrepancy between the center of the liquid bridge and that of the flow channel.

This result indicates that the temperature difference on the plate creates a wettability gradient along the surface of the plate, since the surface tension and contact angle are temperature-variant properties [13,14]. This result is similar to that of the movement of a liquid droplet on a plate with a temperature gradient [15–17]. From the previous study, a droplet on a surface with a temperature difference tends to move toward the cold area due to the wettability gradient [15], so that the temperature field causes non-uniformity of the adhesion force along the surface corresponding to the geometry difference. Although the geometry of the plates is ideally consistent everywhere, the temperature distribution along the hot surface generates a difference in the adhesion force. The occurrence of a residual liquid bridge can be explained by observing the liquid bridge behavior. When the liquid is retrieved, the interface with the lowest adhesion force moves to the liquid channel. After rupture, a small droplet remains at the top plate and is positioned at the center of the next generation of the liquid bridge. Again, the interface located near the heat source has the lowest adhesion force and moves to the liquid channel. In contrast, the interface far from the hottest zone maintains a stationary position and the droplet after rupture remains at that position. In this way, the center of the generated liquid bridge moves away from the hottest zone, and the residual liquid bridge is found as shown in Fig. 4(b).

In order to accomplish the cyclic operation of a liquid bridge with a heated plate, the supplied volume of the liquid bridge was cautiously set at 10 μl. After the tenth cycle, the liquid bridge was completely ruptured as shown in Fig. 4(c). It was thought that the difference in temperature along the solid–liquid contact area was not sufficient to cause the liquid bridge to move. This means that cyclic motion control of the liquid bridge can be achieved under restricted conditions.

2.2. Failure of a liquid bridge generation with a heated surface

It was found that a large clearance and a large flow channel were preferred to prevent the occurrence of the residual liquid bridge