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Heat transfer of single drop impact on a film flow cooling a hot surface

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ABSTRACT

A water drop impacts a thin heated wafer which is being cooled by a film flow generated from water jet impingement. The drop impact breaks the steady-state cooling and causes the local temperature around the drop landing location to change. This transient heat transfer process is experimentally investigated using an IR camera to record the surface temperature (T_s) of the wafer's underneath. The measured temperature shows two stages of the process: a response stage when the temperature quickly decreases as a result of the drop impact, followed by a recovery stage during which the temperature returns to the steady state. It is found the recovery time decreases with increasing the film flow rate. Although during the entire process T_s is lower than the steady state, the heat transfer coefficient (h_t) is revealed to change by three steps. The first step is the increase of h_t across the impact area, which indicates enhanced convection. In the second step, h_t decreases toward and eventually below the steady state. In the third step the heat transfer coefficient increases toward and returns to the steady state. An enhancement factor based on the change of heat transfer coefficient rather than the temperature change is introduced to evaluate the enhancement of convection. The distribution of local maximum enhancement (η_{max}) along the center line of the impact area and the peak value of η_{max} are used to investigate the enhancement effects of film flow rate, drop diameter, and drop impact velocity. It is found η_{max} does not follow a monotonic trend with increasing the impact velocity. The peak enhancement is found to be proportional to the square root of the ratio of the drop flow rate to the film flow rate.

1. Introduction

Spray cooling has been considered as an important cooling method for high heat flux applications. In spray cooling, a large number of drops impinge on a hot surface which is covered by a flowing liquid film. Extensive research [1–7] has been conducted to study the heat transfer performance of spray cooling in relation to parameters such as drop size, drop velocity, drop flux, volumetric flux, nozzle-surface distance, spray angle, and enhanced surface. Chen et al. [1] showed the drop velocity is the most dominant parameter in affecting CHF (critical heat flux). Xie et al. [2] demonstrated that the surface temperature distribution depends solely on the drop flux distribution in the non-boiling regime. Mudawar and Estes [3] found that the optimal nozzle-surface distance for maximum CHF is determined when the spray footprint is exactly enclosed within the cooling surface. Wang et al. [5] found that inclined sprays with optimal orifice-surface distances provide better cooling performance. Bostanci et al. [6] examined the effects of enhanced surfaces on CHF with ammonia as the working fluid, and showed that the enhanced surfaces could increase CHF by 18% over the smooth surface.

Most of the parameters have been revealed to have significant relationships to the spray cooling performance. The physics behind the relationships are the effects of the parameters on the drop and film flow conditions. The drop and film flow conditions are the flow parameters that directly determine the spray cooling performance for two reasons. First, in spray cooling heat transfers from the surface to the fluid on the surface. Second, the flow dynamics of the fluid on the surface is determined by the film flow and also the drops impacting the film.

The fluid dynamics involved in the drop impacting a flowing film is complicated. Fig. 1 shows a water drop impacting a radially flowing water film generated by a vertical jet impinging on a transparent surface. High speed images are taken from the side and under the surface. Fig. 1a shows the interaction of the drop and film produces a crown-like rising liquid sheet. For cooling applications, the rising liquid sheet can be considered as local loss of coolant, which does not contribute to local convection heat transfer on the surface. From Fig. 1b, the drop impact generates a spreading area, where local flow spreads downstream and upstream. The spreading area deforms and moves over time. Fig. 1 clearly shows

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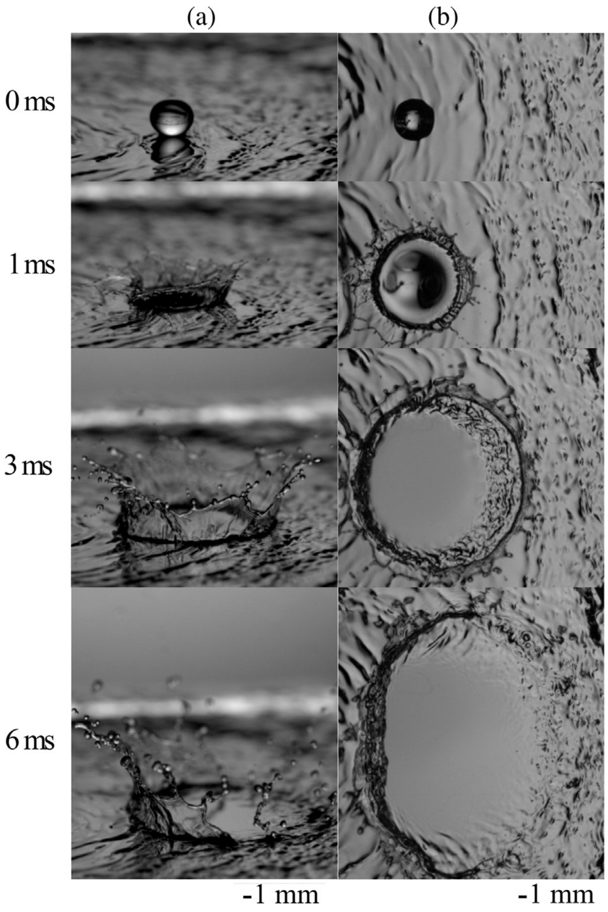

Fig. 1. A water drop impacting a water film radially flowing on a transparent substrate: (a) high speed images taken from the side and (b) high speed images taken under the substrate.

a transient development of the flow as a result of the drop impact. The flow development must cause transient change of the local convection heat transfer, which will eventually affect cooling performance. Unfortunately, there is very limited study on this topic.

Most previous studies of drop impact on liquid films focus on the fluid mechanics aspects. There has been a few studies on the fluid dynamics of drop impacting stationary liquid films [8–10], and flowing liquid films [11–13] under isothermal conditions. Most of previous studies on the heat transfer of drop impact are only for dry surfaces [14–19]. Pasandideh-Fard et al. [14] experimentally and numerically found that increasing drop impact velocity enhances heat flux around the impact area. Bernardin et al. [16] showed that the surface roughness has small effects on the CHF temperature but significantly affects the Leidenfrost point temperature. Tran et al. [18] showed that the maximum spreading of a drop impacting a heated surface follows a universal scaling with the Weber number. Adera et al. [19] reported the formation of non-wetting droplets on a super-hydrophilic micro-structured surface by heating the surface above the saturation temperature of the droplet fluid.

Recently, a few studies have been reported on the heat transfer of continuous droplets impinging on hot surfaces [20–22]. Qiu et al. [20] found that the surface temperature above the boiling temperature enhances the spreading rate of flowing film significantly and affects the splashing angle. Soriano et al. [21] presented experimental observation of multiple droplet train impingement. The impact spacing between multiple droplet streams affects spreading and splashing, and the optimal cooling performance is achieved when the film velocity is not disturbed by adjacent droplet streams. The simulation results [22] also demonstrated the impact velocity played a dominant role in promoting local heat transfer.

Despite plenty of previous work on drop impact, very limited work has been done to investigate the heat transfer of drop impact on flowing films. There is lack of information and understanding regarding the effects of the drop and film flows on the heat transfer of spray cooling. Therefore, the focus of the present work is on the heat transfer involved in the impact of a single drop on a flowing film.

2. Experimental methodology

Tests were conducted using the experimental setup shown schematically in Fig. 2. It is composed five components: (1) a substrate with uniform surface heat flux; (2) a circular water jet which impinges on the substrate to generate radially flowing film; (3) a drop generator to generate water drops impacting the film flow; (4) a HS (high speed) camera for recording flow dynamics; (5) an infrared camera for recording temperature distribution and change.

The substrate is a silicon wafer with a diameter of 76 mm and a thickness $b = 380\ \mu\text{m}$. The properties of the silicon are: thermal conductivity $k = 149$ W/m K, density $\rho = 2329\ \text{kg/m}^3$, specific heat $c_p = 705$ J/kg K. As shown in Fig. 2, the upper surface of the wafer is exposed to the spray, while the underneath is coated with a gold layer, which serves as an electrical heater. Between the wafer and the gold layer are a dielectric layer and an adhesive layer. The gold layer is painted black which has high radiative emissivity calibrated to be 0.95. All the layers have a total thickness less than 2 μm, which has negligible resistance to heat conduction. The electrical resistance of the gold layer is $\sim 1\ \Omega$. The heater power is determined based on the electrical current read from the DC power supply (Model 62050P, Chroma System Solutions) and the voltage measured across the gold-coated area.

Heat loss includes the free air convection and radiation from the coated underneath and conduction through the wafer edge and electrical connections. For the free convection, a heat transfer coefficient of $10\ \text{W/m}^2$ K and an ambient air temperature of 20 °C are used. A large surrounding with temperature 20 °C is used for calculating the radiation. Due to the high heat transfer coefficient of the film flow, the heat loss accounts for less than 0.3% of the total heater power. The coated area and the electrical connection are

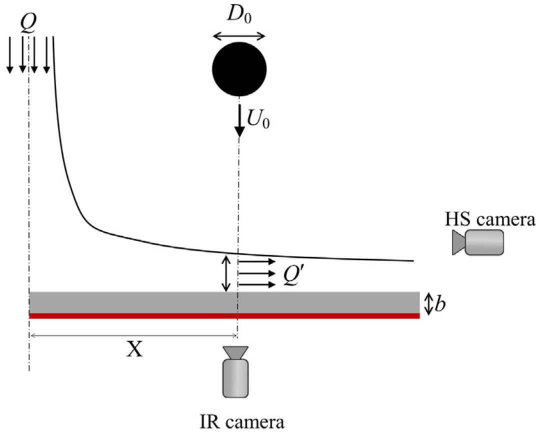

Fig. 2. Schematic of test setup for studying a liquid drop impacting a radially flowing film generated by jet impingement on a silicon wafer. The lower surface of the wafer is coated with a thin gold film as electrical heater. Only half of the wafer is shown.