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Behavior of a water drop impinging on heated porous surfaces

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ABSTRACT

In this work, thermal and hydrodynamic behavior of a water drop impinging on heated porous surfaces was investigated experimentally. Four porous substrates having different permeability and surface roughness were prepared by sintering small glass beads with different sizes and the surface temperature was varied from 60 °C to 300 °C. The impinging velocity was varied from 0.8 m/s to 2.3 m/s while the drop diameter was fixed at 2.6 mm. Two primary impingement regimes were identified: contact and non-contact regimes, each in the low and the high temperature ranges, respectively. The contact regime, in which the drop evaporated or boiled while maintaining contact with the surface, was further divided into three sub-regimes: internal evaporation, internal boiling, and surface nucleate boiling. In the non-contact (surface film boiling) regime, the drop was levitated but at the lower wall temperature with the larger-bead substrates due to active nucleation on the rougher surfaces. Larger impinging velocity resulted in higher transition temperature from the contact to the non-contact regimes, which is due to the increase of the impact pressure at the liquid–solid interface. Time variation of the surface temperature consisted of three stages: right after the drop impact, the surface temperature sharply decreased and then increased with time to reach a temporal thermal-equilibrium between the permeated liquid and the porous solid (stage I). Then the surface temperature gradually decreased until the evaporation was completed (stage II), and finally increased up to the initial wall temperature (stage III). The total evaporation time decreased with the higher impact velocity because of the larger spreading and wet-diameter ratios. Also, there was an optimum glass-bead size (of the substrate) to minimize the evaporation time. In summary, the spreading and wet-diameter ratios, and the time for complete permeation turned out to be the major indicators of the cooling performance, which were strongly influenced by both the impact condition and the structural characteristics of the porous substrates.

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1. Introduction

To enhance the surface cooling performance, a spray cooling technique in combination with construction of porous surfaces [1–4] was recently proposed. By adopting porous substrates, the cooling performance can be enhanced because the sprayed water drops permeated into the structures and spread out to the larger target area. At the same time, larger amount of liquid could be retained in the heated substrates without flowing over the surface. However, estimation of the cooling performance of the sprays on the porous substrate is still a challenging issue, because understanding of the heat transfer mechanism between the drops and the substrates is yet in the primitive stage. Therefore, as an initial step, the behavior of the single-drop impact on porous surfaces should be studied in detail. The knowledge inferred from the single-drop impact may provide the necessary basic information such as the mass of liquid deposited onto the surface, the time of contact, and the vapor release rates [5].

Generally, the heat transfer mechanism of a single drop impinging onto a heated surface depends on the heat transfer mode (e.g. single phase evaporation, nucleate boiling, and film boiling), which is determined by the hydrodynamic behavior [6]. In other words, prior to modeling the heat transfer behavior, the hydrodynamic post-impingement regime should be classified and the transition criteria between the regimes should be identified.

According to the previous studies, drop size, impact velocity and surface tension, represented by the impinging Weber number, and the wall temperature are considered as the most influential factors on the post-impingement behavior of a single drop. For porous substrates, various characteristics such as suppression of the Leidenfrost phenomenon and decrease in evaporation time of the drop [7–9], elimination of the receding process [10], and transition of criteria (critical Weber or Sommerfeld numbers) for the spread–splash threshold [11–13] were reported in accordance with the

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Nomenclature

D_{film}	spreading diameter of liquid film (m)	v_{imp}	impact velocity (m/s)
D_{wet}	wet-area diameter (m)	We	impinging Weber number (–)
d_{imp}	drop diameter before impact (m)	z	distance between nozzle and substrate (m)
$\bar{d}_p$	Sauter mean diameter of glass beads (m)	β_{film}	spreading ratio of liquid film (–)
K	permeability (m^2)	β_{wet}	wet-diameter ratio (–)
T_w	surface temperature (°C)	$\bar{\lambda}$	mean surface roughness (m)
t	time (s)	φ	porosity (–)

permeation of the drop into the porous structures. In those studies, simply the impinging behavior was compared between the porous and the non-porous substrates, or only one porous material was used. However, to determine the transition criteria of the post-impingement regimes appropriately and to analyze the impinging behavior for the porous substrates, the factors determining the liquid permeation should be examined in addition to the wall temperature and the impinging Weber number.

Therefore, in the present study, dependence of the post-impingement behavior on porous substrates having different levels of permeability was investigated experimentally as well as on the wall temperature and the impinging velocity.

2. Experimental method and conditions

Fig. 1 shows a schematic of the experimental setup employed in the present study to observe the post-impingement behavior of a water drop on the porous substrates. Uniform-sized drops were formed by dripping through a needle using a syringe pump. A needle with an inner diameter of 410 μm (gauge 22) was used to generate a water drop of 2.60 ± 0.03 mm in diameter.

The impact velocity of the drop was controlled by changing the vertical distance between the tip of the needle and the surface of the substrate (z) so that it ranged from 0.8 m/s to 2.3 m/s (±0.1 m/s). The impact velocity was estimated by measuring the distance between two successive drop images just prior to impact and the time interval between them. The corresponding Weber number ranged from 25 to 200 (±10) which was estimated based on the measured drop diameter, velocity, and water properties at the ambient temperature.

The post-impingement behavior of the drop was visualized with the aid of a high-speed camera (Phantom V7, Vision Research, Inc.) at 5000 frames/s. A halogen lamp was used as the light source and positioned at the opposite side of the camera for back lighting. A light-diffusive glass plate was placed between the substrate and the lamp. Thereby, the change of the shape of the drop and the behavior of the vapor bubbles generated inside the drop could be observed clearly. A high-speed IR-camera (SC5500-M, FLIR Systems, Inc.) was used to measure the temperature distribution over the surface of the substrate with the filming rate of 200 frames/s. In order to examine the time variation of wetted (permeated) region, the surface of the substrate was also visualized using another digital CCD camera (D3200, Nikon) at 60 frames/s.

The porous substrate was heated from below using a hot plate. In order to ensure reliability of the temperature data measured by the IR-camera, two K-type thermocouples were additionally installed on the top surface of the substrate as shown in Fig. 1. Each thermocouple was located at the radially opposite point with the distance from the center of the drop impact region being 15 mm. The temperatures measured by the IR-camera deviate from the thermocouple measurement by +4.4 °C ~ −1.4 °C, as shown in Fig. 2. The wall temperature was varied from 60 °C to 300 °C (±2 °C) by controlling the electric power of the hot plate. Each

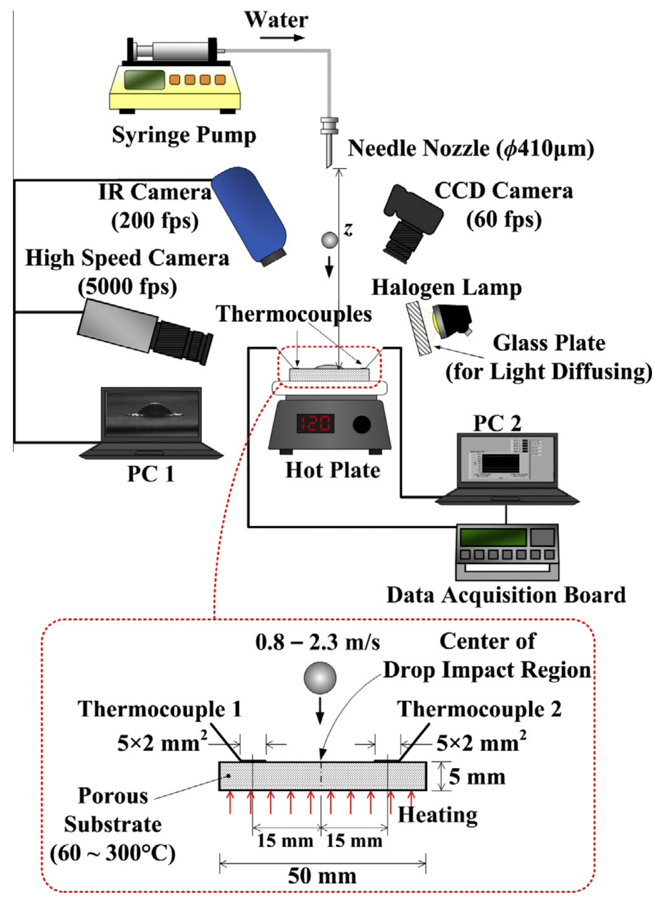

Fig. 1. Experimental setup.

impinging test was performed once the wall temperature reached the designated temperature and remained unchanged at least for five minutes. Thus, except for the region of the drop impact, the temperature of the other region remained constant with time; this approximately simulates the case of drop impact against an infinite medium at constant temperature. All the tests were made under the ambient temperature condition at 31 ± 3 °C.

Fig. 3 shows one of the porous substrates used in this study. Four different sizes of glass beads, ranging from 63.9 μm to 269 μm in Sauter mean diameter, were sintered in manufacturing the substrates. The permeability of each substrate was obtained through measurement of the one-dimensional pressure drop. The surface roughness amplitude was measured with a surface roughness tester (SJ-400, Mitutoyo). The detailed information about the manufacturing process of the substrate is introduced in the previous work by Kim [13]. The properties of each substrate are summarized in Table 1.

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