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Investigation of single-droplet/wall collision heat transfer characteristics using infrared thermometry

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ABSTRACT

This study experimentally investigated the heat transfer characteristics during the collision of a single droplet with a plate heated to temperatures ranging from 176 to 375 °C. The heated plate was made of infrared (IR)-transparent sapphire with a very thin IR-opaque platinum film on top, which allowed the top-surface temperature to be measured from below using an IR camera. The dynamics of the droplets and the corresponding top-surface temperature distribution of the heated plate during collision were acquired using synchronized high-speed video and IR cameras. The three-dimensional transient conduction equation for the heated plate was solved numerically using the measured surface temperatures as boundary conditions, and the time- and space-resolved surface heat flux was obtained. Various physical characteristics associated with the heat transfer during the collision of a single droplet with a heated plate were analyzed, including the local heat flux distribution, effective heat transfer area, instantaneous heat transfer rate, total heat transfer, and vapor film thickness. In addition, the crucial surface temperature at which the total heat transfer from a single-droplet collision is significantly degraded, known as the dynamic Leidenfrost point, was detected.

1. Introduction

The heat transfer from a droplet collision with a heated wall is important in numerous applications, including spray cooling of electronic components, fire-suppression systems, fuel splay in internal combustion engines, and heat treatment of metal alloys. Droplet/wall collision heat transfer characteristics are also important for predicting the peak cladding temperature during cooling of overheated fuels while reflooding following a loss-of-coolant accident in light-water nuclear power plants [1]. Numerous studies have been conducted to develop mechanistic models for droplet/wall collision heat transfer, but a lack of understanding of the complex fluid-flow and heat transfer characteristics during droplet/wall collisions still exists. Thus, accurate predictions of the cooling rate and peak cladding temperature while reflooding are still limited.

A droplet impinging on a hot surface undergoes all of the classic boiling regimes in a matter of seconds. The wall temperature and the droplet Weber number just prior to impact have been identified as the parameters that affect the droplet/wall collision heat transfer behavior. The present study focuses on the droplet dynamic and thermal characteristics as functions of the surface temperature as the droplet passes through the Leidenfrost temperature, which is the crucial surface temperature that results in dramatic degradation of the droplet collision heat transfer.

Many studies have investigated the effects of surface temperature on droplet/wall collision heat transfer. However, most of the previous work on droplet/wall collision heat transfer has been done using high-speed photographic techniques along with *average* surface-temperature measurements from thermocouples, e.g., Pedersen [2], Castanet et al. [3], and Bernardin et al. [4]. Such studies were interested in studying the heat transfer regimes, but could not provide time and space-resolved measurement data relevant in developing mechanistic heat transfer models for droplet/wall collisions, such as the surface temperature distribution, local heat flux, effective heat transfer area, instantaneous heat transfer rate, and vapor film thickness. In contrast, the recent studies such as Lelong et al. [4], Dunand et al. [5], and Chatzikyriakou et al. [7] used a high-speed infrared (IR) thermometry technique to investigate the detailed characteristics of droplet/wall heat transfer. Especially, Chatzikyriakou et al. [7] performed droplet/wall heat transfer experiments on an IR-transparent heated substrate and the measurement results obtained by the IR thermometry technique

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Nomenclature

A_{eff}	effective heat transfer area, mm^2
C_p	specific heat capacitance, J/kg-k
D	diameter, mm
E	total heat transfer, J
H	height, m
h_{LV}	latent heat, J/kg
k	thermal conductivity, W/m-k
L	length, m
m	mass, kg
$\dot{q}_s$	surface heat transfer rate, W
q''	heat flux, W/m^2
R	radius, m
T	temperature, °C
t	time, s
W	width, m
We	Weber number, dimensionless

Greek symbols

α	thermal diffusivity, m^2/s
ε	effectiveness, dimensionless
ρ	density, kg/m^3
σ	surface tension, kg/s
τ	Rayleight time (=$\pi(\rho R^3/2\sigma)^{1/2}$), dimensionless

Subscripts

D	droplet
eff	effective
err	error
exp	experiment
I	initial
i	inner
l	liquid
Max	maximum
Min	minimum
n	normal
nc	natural convection
nor	normalized
o	outer
SAT	saturation
s	surface
1D	one droplet

were quite impressive and useful for determining the surface temperature distribution and local heat flux during droplet collision with a heated wall.

The objectives of the present work were to study the detailed dynamics and heat transfer characteristics associated with the first collision of a single droplet with a heated wall as functions of the surface temperature and to investigate the effect of the surface temperature on the total heat transfer during the collision. In addition, the effect of the collision velocity at the same surface temperature was investigated. An IR camera synchronized with a high-speed video (HSV) camera was used to simultaneously capture views of the droplet behavior and the surface temperature distribution upon impact. The local heat flux on the collision surface was obtained by numerically solving the transient heat-conduction equation for the heated wall using the measured surface temperature data. The various microscopic characteristics during the droplet/wall collision, including the local heat flux distribution, effective heat transfer area, instantaneous heat transfer rate, total heat transfer, and vapor film thickness, were investigated. The dynamic Leidenfrost point was also determined and compared with available data in the literature.

2. Experiments

2.1. Experimental apparatus and procedure

Fig. 1 shows a schematic diagram of the experimental setup for measuring the heat transfer from a single-droplet/wall collision, which mainly consisted of a single-droplet generation system, a test plate on a temperature-controlled block, and a visualization and data acquisition system.

The droplet-generation system produced single droplets using a syringe pump (KSD-100, KD Scientific Inc.) and a syringe with a 31-gauge needle with D_o = 260 μm and D_i = 130 μm (Hamilton Inc.). The syringe was stood up vertically with the needle tip above the test sample. A predetermined amount of liquid to generate a constant-diameter single droplet was injected using the syringe pump, and the droplet was allowed to fall onto the test sample by gravity. The height of the needle tip was adjusted to change the droplet collision velocity onto the test sample. The speed of the droplet colliding with the sample was measured by analyzing high-speed images taken from the side.

A test plate made of sapphire (25.4 × 25.4 × 0.5 mm^3) was placed on a temperature-controlled stainless steel block with four 500 W embedded cartridge heaters. As illustrated in Fig. 1, the heating block had a 10-mm-diameter vertical through-hole underneath the center of the test sample, which permitted temperature measurements of the test sample from below using an IR camera. The sapphire was highly transparent (>80%) in the wavelength range in which the IR camera used in the present study detected radiation. On the upper-side surface of the IR-transparent sapphire plate, a very thin IR-opaque platinum (Pt) film (100 nm in thickness) was deposited. As a result, the temperature distribution on the surface of the sapphire plate on which the droplets collided could be measured from below using the IR camera.[1]

The IR camera used in the present study was an SC6000 model from FLIR Systems Inc. As configured for this study, the IR camera had a spatial resolution of 52 μm and a capture rate of 1 kHz. The camera had an indium antimonide (InSb) detector that operated in the 3–5 μm wavelength range (mid-IR) and had a maximum resolution of 640 × 512 pixels. Simultaneously, the dynamics of the droplet/wall collision were visualized from the side using a Phantom v7.3 high-speed camera from Vision Research Inc. The camera had a maximum resolution of 800 × 600 pixels and was monochrome. As configured for this study, the HSV camera had a spatial resolution of 25 μm and a capture rate of 1 kHz.

Two sets of experiments were conducted to investigate the effects of the surface temperature and the collision velocity on the single-droplet/wall collision heat transfer. One set of experiments were conducted by varying the temperature of the test sample over the range from 176 to 370 °C while the diameter and velocity of the impacting droplet were fixed as 2.4 mm and 0.44 m/s, respectively. The Weber number of the droplet ($We = \rho v^2 D/\sigma$) was ~6.3. Another set of experiments were

[1] The IR camera located below the sapphire sample in fact acquired the temperature distribution of the underside surface of the Pt film. However, a simple conduction heat transfer calculation shows that the temperature difference across the Pt film is negligible (<0.02 °C, even for a tremendously high heat flux of 10 MW/m^2). Therefore, the temperature of the surface on which the droplet collides can be assumed to have been measured accurately using the IR camera.