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Resident time of a compound drop impinging on a hot surface

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Abstract

The resident time of a water-in-diesel compound drop impinging on a hot surface at a temperature higher than the Leidenfrost temperature was investigated experimentally. Past experimental evidence suggested that the resident time of a pure liquid drop was independent of the impact velocity. And this independency could also be seen for compound drops. For both pure drops and compound drops, the resident time became longer with increasing outer diameter of the drop. For water-in-diesel compound drops of a given outer diameter, the resident time decreased as the volume of the core water drop increased. By using a modified Weber number which took into account of the two interfaces of the compound drop, a correlation of the non-dimensional resident time was obtained and was in good agreement with the experimental data.

Keywords: Resident time; Compound drop; Leidenfrost temperature; Weber number

1. Introduction

Collision of liquid drops with a hot surface occurs frequently in engineering fields such as spray cooling, spray coating and steelmaking. The works of Wachters and Westerling [1], Ueda et al. [2], Xiong and Yuen [3], Bernardin et al. [4] and Pasandideh-Fard et al. [5] dealt with impinging heat transfer on a heated surface.

In contrast to studying heat transfer to the heat surface, some experimental investigations focused on the dynamic behaviors, namely breakup, rebound, and spread, of the liquid drops impacting on a surface heated above the Leidenfrost temperature of the liquid [6–10]. According to their observations, the outcome of a liquid drop impacting on a sufficiently hot surface depends mainly on the impact Weber number, i.e. the ratio of kinetic to surface energy of the drop. When a liquid drop impacts on a surface heated above the Leidenfrost temperature, which is commonly accepted as the lowest boundary of the non-wetting impact [3,11,12], a vapor cushion immediately forms between the drop and the surface so that direct contact is obstructed. Due to the impact energy, the impinging drop deforms into a disk. After the maximum spread is reached, the peripheral surface tension force pushes back to induce the rise of the center portion of the disk to form a liquid rod and rebounds from the hot surface with remarkable elasticity.

From touching the hot surface to leaving it, the impinging drop "contacts" the hot surface for a very short time. This time interval of "contact" is called by researchers "the resident time" of the drop on the surface. The resident time is of interest to researchers because of its importance to the heat transfer process. Some publications like Wachters and Westerling [1], Ueda et al. [2], Akao et al. [13], Makino and Michiyoshi [14], Hatta et al. [15,16] discussed the resident time of a drop on a hot surface. They, except Akao et al. [13], used the first-order period of a freely oscillating drop, i.e. $\pi/4\sqrt{\rho d_o^3/\sigma}$, to predict the resident time and a good correspondence of this expression to the experimental results could be seen in their studies. However,

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Nomenclature

C	proportional constant in Eq. (10)
d_o	outer diameter of compound drop
d_w	outer diameter of core drop
d^*	core-to-outer diameter ratio
E_k	kinetic energy, $E_k = \frac{1}{2}\frac{\pi}{6}\left[\rho_f(d_o^3 - d_w^3) + \rho_w d_w^3\right]v_{1n}^2$
E_s	surface energy, $E_s = \sigma_{f/a}\pi d_o^2 + \sigma_{w/f}\pi d_w^2$
f	frequency of drop generation
m	number of video frames
$\dot{Q}_w$	volume flow rate of water
$\dot{Q}_f$	volume flow rate of diesel
s	spacing between two drops in a drop stream
T_s	surface temperature
t_r	resident time
t_r^*	non-dimensional resident time, $t_r^* = \frac{t_r}{\left(\frac{d_o}{v_{1n}}\right)}$
v_1	drop velocity before impact
v_{1n}	impact velocity normal to the inclined surface
We_n	normal Weber number, $We_n = \frac{\rho v_{1n}^2 d_o}{\sigma}$
We_n^*	modified normal Weber number, $We_n^* = \frac{\left[\rho_f\left(d_o^3 - d_w^3\right) + \rho_w d_w^3\right]v_{1n}^2}{\sigma_{f/a}d_o^2 + \sigma_{w/f}d_w^2}$
x_1	contact point of drop impinging on hot surface
x_2	departure point of drop impinging on hot surface

Greek symbols

δt	time interval between two video frames
θ_1	inclined angle
ρ	density
ρ_f	density of diesel oil
ρ_w	density of water
σ	surface tension
$\sigma_{f/a}$	surface tension of diesel–air interface
$\sigma_{w/a}$	surface tension of water–air interface
$\sigma_{w/f}$	surface tension of diesel–water interface

Akao et al. [13] found that this expression did not correlate well with the experimental data. In addition, Chandra and Avedisian [12] compared the measured resident time to the predicted value, and found that the measured resident time was larger than the predicted value by about 3 ms for an *n*-heptane drop of 1.5 mm diameter impinging on a polished stainless steel surface. Bernardin et al. [11] gave a detailed list showing several of the correlations and models for the drop spreading characteristics. Table 1 shows the values and ranges of the parameters of some past works.

Most previous experiments concerning the phenomena of a liquid drop impinging on a hot surface were conducted for one-component liquid drops, e.g., water drops, ethanol drops, *n*-heptane drops, *n*-decane drops, and so on (see Table 1). No work has been done on the resident time of a compound drop on a hot surface. In spray combustion of blended fuel, the presence of fuel drops composed of more than one immiscible liquid fuels is expected and the impact of this type of drops with furnace walls could be frequent.

Table 1
Values and ranges of parameters used in some past works

Authors	Parameters	Notes
Ueda et al. [2]	$0.9 < d_o < 3.0$ mm $0.6 < v_1 < 3.0$ m/s $T_s = 300$ °C $10 < We_n < 200$	Fluid: water, Freon 113 and Freon 11 Surface: copper and stainless steel
Chandra and Avedisian [12]	$d_o = 1.5$ mm $v_1 = 0.93$ m/s T_s: 24–250 °C $We_n = 43$	Fluid: *n*-heptane Surface: stainless steel
Hatta et al. [15]	$0.3 < d_o < 0.6$ mm $1.7 < v_1 < 5.7$ m/s $T_s = 500$ °C $10 < We_n < 200$	Fluid: water Surface: Inconel alloy 625
Hatta et al. [16]	$0.3 < d_o < 0.6$ mm $1.48 < v_1 < 3.42$ m/s $T_s = 500$ °C $10 < We_n < 65$	Fluid: water Surface: Inconel alloy 625, stainless steel and silicon

In the present study, the resident time of a compound drop impinging on a hot surface was inspected and was compared to that of a one-component drop. Then, the effects of the core drop on the resident time were incorporated into a modified Weber number and a correlation between the dimensionless resident time and the modified Weber number was obtained.

2. Experimental setup and measurement

The experimental setup, which consisted of a compound drop generation system, a visualization system, and a surface heater system, is shown in Fig. 1.

The compound drop utilized in this study was composed of a core water drop encased in a diesel shell. The compound drop generation system contained a piezoelectric compound-drop generator with a concentric nozzle, two liquid reservoirs, a pulse generator, and a voltage amplifier. The concentric nozzle was assembled by inserting a dental needle of 0.17 mm inside diameter into a glass tube of 0.40 mm inside diameter. The core liquid, water, was issued through the dental needle from the water reservoir and the shell liquid, diesel, through the glass tube from the diesel reservoir. For easier identification, the core liquid was dyed red.

The pulse generator generated alternating pulses, which were amplified by the voltage amplifier, to control the fre-