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Spreading and receding characteristics of a non-Newtonian droplet impinging on a heated surface

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ABSTRACT

The present study aims to investigate the influence of the Weber number and surface temperature on the spreading and receding characteristics of Newtonian (DI-water) and non-Newtonian (xanthan gum solution) droplets impinging on heated surfaces. The surface temperature was in the range from 25 °C to 85 °C, which is below the Leidenfrost temperature (~300 °C). Using high-speed camera images, this study measured the dynamic contact angle as well as spreading and receding diameters. It also used a modified model to predict the maximum spreading diameter by using the effective viscosity. From the results, the modified model using the effective viscosity was in good agreement with the experimental data in predicting the maximum spreading diameter. In addition, the maximum spreading diameter for a DI-water droplet was larger than that of a non-Newtonian droplet because of the difference in liquid viscosity. In particular, for the Newtonian and non-Newtonian droplets, the dynamic contact angle was almost similar in the spreading regime, but in the receding regime, it substantially changes with temperature owing to the variation of viscosity with temperature. Moreover, the spreading diameter rapidly decreased with the increase in surface temperature in the receding regime in which the change in viscous dissipation energy would be important for the receding motion. Finally, the retraction rates of the Newtonian droplet remained constant with temperature, whereas those of the non-Newtonian droplet increased with temperature, thereby supporting the assertion that the viscosity effect is dominant in the receding characteristics after impact.

1. Introduction

Recently, droplet impacts on solid surfaces have been an important research topic for various applications related to multiphase flows, thermal management, spray coating, corrosion of solid surfaces, and ink-jet printing. A fundamental understanding of dynamic droplet behavior and heat transfer characteristics on a solid surface is thus crucial for determining controllable factors such as surface wettability, impact conditions, and fluid properties [1–5]. In fact, many studies have investigated the droplet impact behavior and heat transfer characteristics for a Newtonian droplet impinging on a solid surface. Roisman et al. [4] studied the spreading and receding characteristics by measuring the spreading diameter and dynamic contact angle (DCA), and they compared the experimental data with the numerical results. In addition, they developed a new model to estimate the DCA. Alizadeh et al. [6] examined the thermal effects on the spreading and receding dynamics of a Newtonian droplet on chemically and mechanically textured hydrophilic and hydrophobic surfaces. Pasandideh-Fard et al. [7] investigated the effects of some important parameters, including the droplet diameter, impact velocity, and thermo-physical properties of a liquid on the heat transfer characteristics during droplet impact. In addition, they developed a cooling effectiveness model to evaluate the thermal characteristics during impact and showed that the impact velocity could enhance the heat transfer. Their model has been widely used to investigate the heat transfer characteristics of droplets impinging on heated surfaces [8–10]. Negeed et al. [11,12] conducted the experiments on dynamic behavior of micrometric single water droplets impinging on heated surfaces with and without superhydrophilic coating by using a high-speed camera. They suggested the empirical correlations for the hydrodynamic characteristics of a droplet and examined the influence of the surface roughness and oxidation layer on the dynamic behavior of a droplet on the surfaces [13]. In addition, the effect of surface condition on evaporation of sprayed liquid droplet was investigated and some empirical relationships for the maximum spread of droplet and the solid–liquid contact time were provided [14].

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Nomenclature

a	consistency index
D^*	dimensionless spreading diameter
D_{MAX}	maximum spreading diameter
D^*_{MAX}	dimensionless maximum spreading diameter
d_o	the equivalent droplet diameter [26]
d_x	the measured horizontal droplet diameter
d_y	the measured vertical droplet diameter
n	power law index
t	time
v_0	impact velocity
v_{ret}	receding (retraction) velocity

Greek symbols

$\dot{\gamma}$	shear rate
$\acute{\varepsilon}$	retraction rate
$\acute{\varepsilon}_{32}$	retraction rate at Weber number of 32
$\acute{\varepsilon}_{126}$	retraction rate at Weber number of 126
μ	shear viscosity with time
μ_o	zero shear viscosity
μ_∞	infinite-shear viscosity
ρ	density
γ_{LV}	surface tension between liquid and vapor phases
θ_a	advancing contact angle at maximum spread
θ_e	equilibrium contact angle between a droplet and a solid surface
θ_d	dynamic contact angle

Dimensionless numbers

Re	Reynolds number ($=\rho v_o d_o/\mu_o$)
Re$_{\mathrm{eff}}$	Effective Reynolds number ($=\rho v_o d_o/\mu_{\mathrm{eff}}$)
We	Weber number ($=\rho v_o^2 d_o/\gamma_{\mathrm{LV}}$)

Recently, interest in non-Newtonian fluids for industrial applications has rapidly increased, and many results have been reported on the heat transfer and dynamic behavior of non-Newtonian droplets [15–23]. The pioneering work of Bergeron et al. [15] incorporated small amounts of a flexible polymer that inhibited the droplets' receding motion and suppressed the rebound without changing the shear viscosity. Later, Moon et al. [20] measured the spreading diameter and DCA for Newtonian and non-Newtonian droplets impinging on unheated solid surfaces. They reported that the evolution of the DCA in the spreading regime was similar for non-Newtonian and Newtonian droplets, whereas in the receding regime, the DCAs of non-Newtonian droplets increased owing to the increase in shear viscosity at lower shear rate.

An and Lee [16,17] examined the impact dynamics of a non-Newtonian droplet on various solid surfaces with different hydrophobicities and suggested a new model for estimating the maximum spreading diameter. German and Bertola [21] discussed the dynamic behaviors of a non-Newtonian droplet that were associated with yield stress and shear-thinning characteristics. They showed that the maximum spreading diameter was affected by the surface wettability and yield stress. Meanwhile, Bertola [24] studied a bouncing droplet of polymer additives to examine the Leidenfrost phenomena of non-Newtonian droplets on a heated surface. Bertola [22] also investigated the impact of a water droplet containing a polymer additive on a hot surface above 100 °C. Bartolo et al. [19] measured the retraction rate of a Newtonian liquid droplet impinging on hydrophobic surfaces for cases with a very high Weber number. Their results demonstrated that the retraction rate of Newtonian droplets rarely depended on the Weber number based on the impact velocity. Even with the many studies [7,9,10,25] that have been reported, there is still a lack of experimental studies on non-Newtonian droplets impinging on a heated surface. Thus, the present study aims to investigate the influence of important factors such as surface temperature, liquid property, and impact velocity on the dynamic behavior of Newtonian and non-Newtonian droplets.

2. Experimental setup

As shown in Fig. 1, a free-fall droplet was detached from a flat-tipped metal needle (30 gage, Hamilton), which was connected to a syringe pump (LSP01-1A, LongerPump). The detached droplet had an equivalent droplet diameter of 2.30 mm ± 0.05 mm, which was estimated from $d_o = (d_x{}^2 \times d_y)^{1/3}$ [26]. Using the droplet diameter and liquid property, the density of de-ionized (DI) water and xanthan gum liquid can be estimated from the weight measured by a microbalance (AC121S, Sartorius). The impact velocity was controlled by changing the height between the tip of the needle and top of the solid surface. The Weber numbers, which were defined as $\rho v_o^2 d_o/\gamma_{\mathrm{LV}}$, were determined to be 32, 64, and 126, for impact heights of 50, 100, and 200 mm, respectively. The present study focused only on the deposition regime under a relatively low Weber number [2,16].

The present study used DI-water and a xanthan solution to prepare the Newtonian and non-Newtonian droplets, respectively. Xanthan gum was mixed with DI-water in different concentrations of 0.1, 0.2, and 0.5 wt.% (hereafter denoted as X0.1, X0.2, and X0.5, respectively). When preparing the xanthan gum solutions, a magnetic stirrer was used to mix DI-water with xanthan gum particles for 24 h, and a vacuum pump was utilized to remove bubbles from the liquid. For the imposed shear rate, the liquid shear viscosity

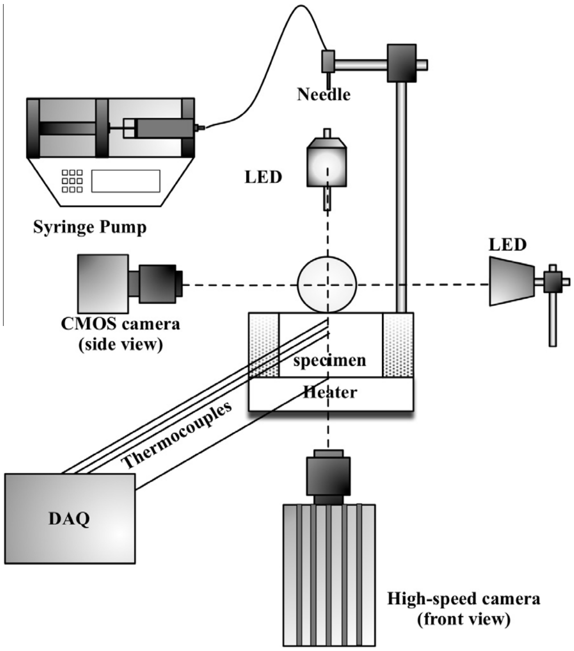

Fig. 1. A schematic diagram of the experimental setup.