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Droplet–wall interaction upon impingement of heavy hydrocarbon droplets on a heated wall

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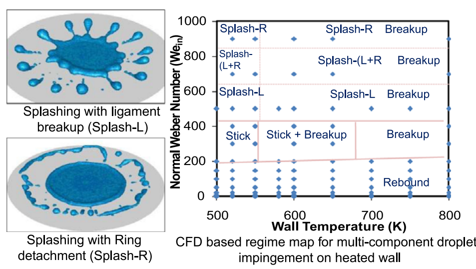
HIGHLIGHTS

- Regime maps for multi-component and single-component droplets are found to differ.
- 'Splash-L' (ligament formation) and 'Splash-R' (ring detachment) are reported.
- Improved correlations for regime transition and stretch diameter are presented.

GRAPHICAL ABSTRACT



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ABSTRACT

Regime maps that predict the heavy hydrocarbon droplet impingement behavior on a heated wall (Weber number of the impinging droplet v/s wall temperature) are constructed based on CFD simulations using the Volume of Fluid model with the geo-reconstruct scheme. Based on the simulation results, maps are constructed for single-component droplets with a diameter of 50 and of 100 μm. The applied CFD model is validated by comparing these with regime maps available in literature, constructed based on experimental data for model liquids and liquid mixtures. The impingement regimes of Splash, Stick, Rebound and Breakup are well-predicted. Two distinct types of Splash (Splash with ligament formation and Splash with ring detachment) are reported for the first time. Using the validated CFD model, regime maps are constructed for multi-component heavy hydrocarbon droplets with a diameter of 50 and of 100 μm. Significant differences between the single-component and the multi-component droplet impact behavior are observed. Improved and new correlations for regime transitions, droplet stretching on the wall, droplet rebounding velocity and number of splashed droplets are derived based on energy balances. They are found to correlate well with CFD predictions.

1. Introduction

Droplet impingement on walls has been widely studied in various research areas like internal combustion (IC) engines (Ogawa et al., 1997), spray drying, spray cooling (Horacek et al., 2005), spray coating (Werner et al., 2007), to name a few. The desired behavior of the droplet upon wall impingement greatly varies depending on the application. In spray coating/painting and spray cooling applications the entire mass of the droplet is expected to remain deposited on the wall preferably without splashing or rebounding. Whereas, in spray dryers and IC engines the droplet is expected to rebound from the wall with minimal stick to ensure complete evaporation. Droplet behavior other than expected would result in lower operational efficiency of these equipments e.g. in direct injection type IC engines, deposition of fuel droplets on the engine wall results in incomplete evaporation

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of the liquid fuel and reduced fuel efficiency. Deposition of the droplet on spray dryer walls reduces the heat transfer rate in dryers. Rebound of droplets in spray coating and spray cooling applications results in loss of coating materials and environmental issues.

More recently, due to the use of heavier hydrocarbon feeds, droplet impingement on the internal tube walls of superheaters in the convection of steam crackers, resulting in thermal coke formation was investigated (Mahulkar et al., 2012, 2014). Understanding the physics of the droplet–wall interaction is essential to manipulate the droplet–wall interaction. The principle physical forces acting on an impinging droplet are inertia, surface tension, viscous

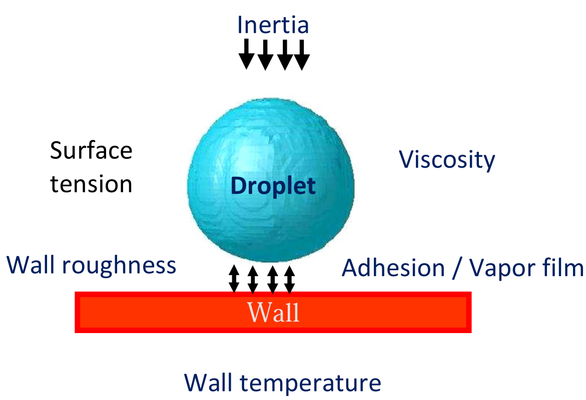

Fig. 1. Dominant forces in droplet impingement.

forces and adhesion (Fig. 1). These forces are mainly governed by droplet properties like diameter density, surface tension, viscosity, velocity, and wall properties like wall roughness and wall temperature (Fig. 1). The balance between the physical forces determines the droplet behavior upon wall impingement. This behavior has been extensively characterized by constructing so-called regime maps; plots presenting the droplet behavior as a function of the impinging Weber number (We_{in}) and the wall temperature (T_{wall}). Fig. 2 shows two such regime maps as presented by Grover and Assanis (2001) and Bai and Gosman (1995).

The Weber number in the regime map is calculated based on the droplet impinging velocity component *normal* to the wall surface, as the latter determines the impact behavior of a droplet. All the Weber numbers and Reynolds numbers used in this paper are based on the droplet velocity normal to the wall. Depending on the values of We_{in} and T_{wall}, the droplet may either stick, rebound, splash, spread or breakup upon wall impingement. The regime map of Grover and Assanis (2001) distinguishes between stick and rebound based on the boiling point temperature (T_{BP}) of the droplet, while Bai and Gosman (1995) observed more distinct regimes as a function of wall temperature. Bai and Gosman (1995) observed boiling induced breakup between the pure adhesion temperature (T_{PA}) and the Nukiyama temperature (T_{NU}), while rebound was observed above the Leidenfrost temperature (T_{LF}). The Nukiyama temperature (T_{NU}) is the temperature at which the film boiling is intermittently observed while the Leidenfrost temperature (T_{LF}) is the temperature at which a stable vapor film is definitely formed in between the droplet and the surface. At T_{NU},

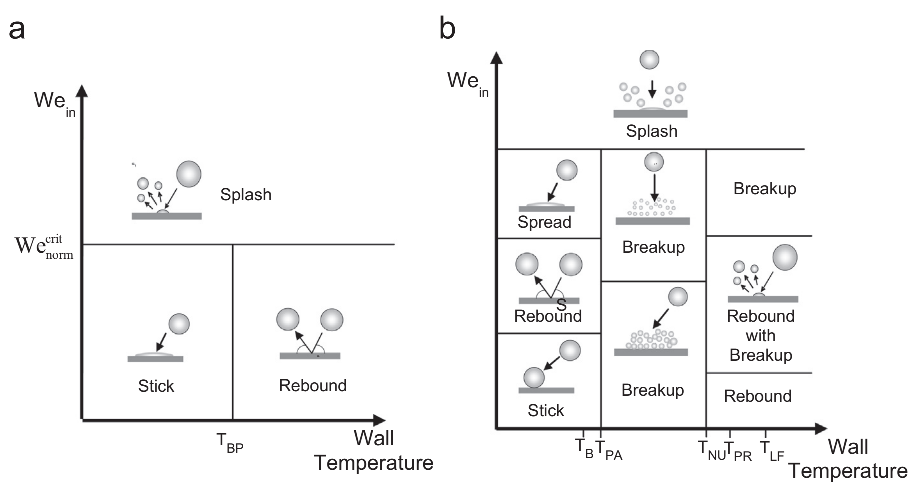

Fig. 2. Regime maps for droplet–wall interaction from (a) Grover and Assanis (2001) and (b) Lee and Ryu (2006) based on a modified regime map of Bai and Gosman (1995).

Table 1
Summary of some major droplet impingement studies.

S. no.	Reference	Droplet diameter (mm)	System	Key finding
1	Bai et al. (2002)	0.001–0.3	Water	Regime map; stick splash transition criterion; post-splash behavior
2	Mundo et al. (1995)	0.06–0.15	Water-ethanol-sucrose	Analysis of droplet splash on moving substrate; no. of splashed droplets
3	Vander Wal et al. (2006)	2	Alkanes	Stick-splash criterion
4	Shen et al. (2010)	1–1.3	water	Spread and rebound analysis
5	Chandra and Avedisian (1991)	1.5	n-heptane	Droplet deformation, spread and splash analysis
6	Wachters and Westerling (1966)	2	Water	Rebound analysis; correlation to predict outlet rebound Weber number
7	Demoulin et al. (2013)	2	Water	Rebound; Oscillations in the rebounding droplets
8	Negeed et al. (2013)	0.3–0.7	Water	Max. spread and contact time between droplet and surface
9	Fujimoto et al. (2010)	0.5–2.5	Water	Photographic analysis of spread and splash
10	Slanciauskas and Kalpokaite (2006)	0.75	Heavy fuel oil	Effect of surface roughness and oxidation of fuel on hot surface
11	Sikalo et al. (2005)	1–3	Water-glycerol-iso-propanol	Analysis of spread and splash on inclined surface.