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Single droplet impingement of urea water solution on a heated substrate

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ABSTRACT

In the present work, impingement behaviour of an aqueous urea solution is investigated experimentally. The effects of droplet diameter, impact velocity and substrate temperature are evaluated by monitoring single droplet impingement with a high-speed camera. Results allow the formulation of four different interaction regimes and a regime map depending on hydrodynamic and thermal parameters is proposed. The regimes *deposition, splash, boiling-induced breakup, rebound with breakup* and the transition boundaries are discussed in detail. Results show that the solute significantly affects the outcome of droplet impingement promoting droplet disintegration by enhanced nucleation and bubble formation. Comparison with literature data reveal the strong dependency of droplet impact behavior on the Weber number as a combination of initial droplet diameter and impact velocity.

1. Introduction

The interaction of single droplets with hot solid surfaces is a fundamental process for a wide range of technical applications reaching from small scale processes, e. g. inkjet printing, to industrial processes like spray cooling or falling film reactors. In automotive industry, spray/wall interaction is important for both fuel injection in internal combustion engines and exhaust gas aftertreatment systems. Particularly in ammonia selective catalytic reduction (SCR) systems, spray/wall interaction is of growing interest (Birkhold et al., 2006; 2007; Brack et al., 2014; Postrioti et al., 2015; Brack et al., 2016; Sadashiva Prabhu et al., 2017). Here, an aqueous urea solution serving as ammonia precursor is injected into the tailpipe. Highly transient conditions in the tailpipe can lead to incomplete evaporation and decomposition of the injected solution. Resulting spray impingement on the tailpipe wall causes the formation of liquid films and solid deposits, which impair system efficiency.

Extensive research has been done on single droplet impingement on dry, solid substrates by numerous authors (Bernardin et al., 1996; 1997; Bernardin and Mudawar, 1999; Karl and Frohn, 2000; Šikalo et al., 2002; 2005a; 2005b; Roisman et al., 2008; Cossali et al., 2008; Castanet et al., 2009; Marengo et al., 2011; Berberović et al., 2011; Sinha-Ray et al., 2014; Roisman et al., 2015; Schremb et al., 2017). Continuing developments in high-speed imaging techniques and image analysis tools enable detailed experimental investigations (Celata et al., 2006; Hutchings et al., 2007; Thoroddsen et al., 2008; Thoraval et al., 2013). Despite these efforts, literature lacks in consistency in describing the effects of various influencing factors. Spreading dynamics, disintegration and secondary droplet characteristics are significant hydrodynamics of the droplet impact. Boiling characteristics, thermal breakup and levitation of droplets due to the Leidenfrost effect (Gottfried et al., 1966) further determine the impact behavior of droplets.

Generally, droplet impact is classified by characteristic thermal and hydrodynamic interaction regimes. For non-heated, dry substrates, the interaction mechanisms are usually identified as *deposition* (liquid spreads and recedes but remains on wall), *splash* (kinetic disintegration) and *rebound* (droplet reflection by hydrophobicity) (Bai and Gosman, 1995; Rioboo et al., 2001; Castanet et al., 2009). Concerning disintegration, Rioboo et al. (2001) further differentiate between prompt splash (instantaneous disintegration) and corona splash (lamella breakup at maximum spreading length). The respective regime is determined by the impaction energy which is represented by the Weber number containing the droplet diameter d_0 and its impact velocity u_0, the liquid density ρ_l and surface tension σ_{lv}.

$$We = \frac{\rho_l \cdot d_0 \cdot u_0^2}{\sigma_{lv}} \tag{1}$$

Many authors use the splashing parameter $K = f(We, Re)$, which is a function of the Weber and Reynolds number for additional consideration of the liquid viscosity η_l (Stow and Hadfield, 1981; Mundo et al., 1995). Depending on the boundary conditions, different correlations for K are stated in literature (Moreira et al., 2010). In this work, a K value according to Mundo et al. (1995) is used:

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Nomenclature

Latin letters

d	diameter	m
g	gravity acceleration	ms^{-2}
K	splashing parameter	–
R_a	average roughness	m
Re	Reynolds number	–
T^*	dimensionless temperature	–
u	velocity	ms^{-1}
We	Weber number	–

Greek letters

η	dynamic viscosity	Pas
ρ	density	Kgm^{-3}
σ	surface tension	Nm^{-1}
θ	contact angle	○

Subscripts

0	initial
cr	critical
c	capillary
dec	decomposition
L	Leidenfrost
l	liquid
s	saturation
v	vapor
w	wall

$$Re = \frac{\rho_l \cdot d_0 \cdot u_0}{\eta_l} \tag{2}$$

$$K = We^{\frac{1}{2}} \cdot Re^{\frac{1}{4}} \tag{3}$$

For heated substrates, regime maps are extended by droplet *breakup* (thermal disintegration) and *rebound* (reflection by Leidenfrost effect). Depending on the boundary conditions, various transition regimes, e.g. ***rebound with breakup, boiling induced breakup***, can be found in literature (Bai and Gosman, 1995; Vignes-Adler, 2002; Castanet et al., 2009; Staat et al., 2015; Liang et al., 2016). Here, the wall temperature T_w and the liquid saturation temperature T_s are crucial for regime identification and expressed in the dimensionless parameter T^*.

$$T^* = \frac{T_w}{T_s} \tag{4}$$

Based on K and T^*, comprehensive regime maps are established capturing the effects of all relevant parameters on the outcome of droplet impingement. The position of regime boundaries (K_{cr}, T^*_{cr}) depends on the physical properties of the liquid (vapor pressure, viscosity, surface tension), the droplet momentum (droplet size, velocity, impact angle) and the solid surface characteristics (temperature, wettability, roughness) in a complex way. Many authors have studied the interaction regimes for pure liquids, e.g. water and fuels (Moita and Moreira, 2007; Castanet et al., 2009; Tran et al., 2012; Staat et al., 2015; Breitenbach et al., 2015; Bertola, 2015; Khavari et al., 2015). Here, global dependencies and trends will be discussed in the following.

Moita and Moreira (2007) use high-speed visualization and image processing to study the wetting and disintegration mechanisms of water and fuel droplets on heated targets. High droplet momentum (u_0, d_0) promotes spreading of the lamella up to lamella breakup (splash). For cold surfaces, the outcome of droplet impact is mainly influenced by surface wettability (θ) and topography (R_a). High wettability supports lamella spreading and disintegration, whereas surface roughness decreases the critical velocity for disintegration. The same effect is observed by changes of the liquid properties to higher surface tension and viscosity (Karl and Frohn, 2000).

For heated substrates, the increase of wall temperature and heat transfer to the liquid induces instabilities and bubble nucleation in the spreading droplet and promotes early lamella breakup. This effect is intensified at high Weber numbers leading to a decreased lamella thickness. Surface roughness at high wall temperature further increases bubble nucleation site density and promotes breakup of the spreading droplet (Bernardin et al., 1996). The boundary between wetting and non-wetting regimes T^*_{cr} is directly dependend on the liquid properties (T_s) and the critical wall temperature, which is referred to as Leidenfrost temperature T_L (Liang and Mudawar, 2017). For single droplet impingement, the Leidenfrost temperature represents the minimal wall temperature at which the droplet rebounds by formation of a stable vapor layer between droplet and wall (Gottfried et al., 1966). Existing literature is contradictory concerning the dependencies of different parameters on the Leidenfrost temperature. An increased impact velocity is partly claimed to decrease the Leidenfrost temperature due to the squeeze film effect (Wang et al., 2005; Celata et al., 2006), whereas other works show a contradictory dependency (Karl and Frohn, 2000; Richter et al., 2005). Further, there is no distinct conclusion about the influence of droplet size and impact angle. Several authors state, that the effect of droplet size on the Leidenfrost temperature is negligible (Gottfried et al., 1966; Kunihide and Michiyoshi, 1979), others show that increased droplet diameters lead to higher Leidenfrost temperatures (Nishio and Hirata, 1978). Small impact angles with respect to the surface have been observed to decrease the Leidenfrost temperature (Yao and Cai, 1988). Other investigations show that the effect of impact angle is negligible (Kang and Lee, 2000). Bernardin and Mudawar (1999) study the effects of surface properties on the Leidenfrost temperature by sessile drop evaporation experiments. Results show that the Leidenfrost temperature is relatively insensitive to wetting conditions of the surface and that increased roughness could lift the wetting boundary up to higher temperatures.

Concerning real applications, there is a strong need for research on single droplet impingement of two-component liquids. Technical applications reach from general heat transfer (Frost and Kippenhan, 1967; Yang and Maa, 1983) to fire suppression (Manzello and Yang, 2002). Manzello and Yang (2002) study the evaporation and collision dynamics of aqueous sodium acetate trihydrate solution compared to water for various We numbers and wall temperatures. The authors state that higher salt concentrations lead to an increased heat transfer resistance and reduced evaporation rates. Solid residues of the additive-containing droplets are assumed to cause differences in the collision dynamics particularly for low We numbers. Cui et al. (2001) investigated the impact of single sodium bicarbonate solution droplets. Depart from lowering the vapor pressure of the liquid, the authors state that the solute promotes bubble formation and breakup. Due to decomposition of sodium bicarbonate at high temperatures, additional gas bubbles are formed which enhance boiling and droplet disintegration. Liang et al. (2016) studied the impact of single NaCl solution droplets in comparison to water, butanol and ethanol by high-speed imaging and shadowgraphy. They found that for certain conditions, the impact of the NaCl droplets lead to a formation of a central jet, explained by gas entrainment and intense nucleation. Qiao and Chandra (1997) studied the evaporation of water droplets containing a surfactant and report enhanced vapor bubble nucleation and foaming compared to pure water. Here, bubble formation gets visible in the photographs. The effect of droplet disintegration by foaming was further observed by Breitenbach et al. (2015) and explained by the increasing solute