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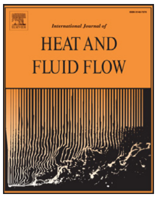

Numerical and experimental investigations of crown propagation dynamics induced by droplet train impingement

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ABSTRACT

In this study, hydrodynamics of HFE-7100 droplet train impinging on a pre-wetted solid surface was investigated experimentally and numerically. Experimentally, single stream of mono-dispersed droplets were produced using a piezoelectric droplet generator with the ability to adjust parameters such as droplet impingement frequency, droplet diameter and droplet velocity. Crown propagation events were imaged using a high-speed camera system given the high-frequency of droplet impingement. Relationships between droplet-induced crown propagation and crater formation were investigated experimentally. The high-frequency droplet impingement process was simulated numerically using CFD tool. Crown propagation dynamics were evaluated and analyzed experimentally and numerically, with reasonable agreement between the two methods. A revised theoretical crown propagation model based on numerical results is proposed in this paper, which takes into account the impinged liquid velocity distribution and film thickness at the moment of initial spot formation. The revised theoretical crown propagation model gives predictions with improved accuracy, which are in better agreement with the numerical results.

1. Introduction

Droplet impingement is a common phenomenon encountered in nature and a number of technical applications. Examples include rain drop impact on solid surfaces (sandy surfaces, flat surfaces, porous surfaces) and liquid surfaces (deep liquid pool, thin liquid film), ink jet printing, surface coating, spray cooling of hot surfaces (semiconductor chips, turbine blades, machining work piece), and fuel injection in engines, to name a few. The associated phenomena of droplet impingement are diverse and strongly dependent on droplet impingement conditions. For instance, droplet may impact hot dry surfaces, thin liquid films or deep liquid pools, which exhibit different physical mechanisms.

The crown propagation dynamics induced by droplet impingement is a fascinating fluid dynamics behavior. Studies of droplet-induced crown propagation have been conducted by various researchers over the last two decades. Yarin and Weiss (1995) proposed a theoretical model to predict the radial extension of the droplet-induced crown. Rieber and Frohn (1999) revised the crown propagation model proposed by Yarin and Weiss (1995) by taking into account different assumptions. Shetabivash et al. (2014) numerically validated the revised model proposed by Rieber and Frohn (1999). Shetabivash et al. (2014) also found that the model proposed by Yarin and Weiss (1995) greatly over-predicts time-dependent crown propagation diameter.

Even though the studies of droplet impingement have received considerable attention in the last two decades, very few studies have considered a theoretical crown propagation formulation for droplet train impingement. The crown propagation model proposed by Yarin and Weiss (1995) should be revised so that accurate time-dependent crown propagation diameter predictions can be obtained. Furthermore, recent studies about droplet train impingement (Zhang et al. 2014; Soriano et al. 2014; Soriano, 2011; Alvarado and Lin, 2011; Trujillo et al., 2011; Trujillo and Lewis, 2012) have provided different definitions for droplet-induced crater and crown. Therefore, there is a need to differentiate between droplet-induced crater and crown, and to investigate the physical relationship between them. With the goal of gaining a better understanding of the hydrodynamics of droplet train impingement, well-controlled experiments, and numerical simulations have been performed with the following specific objectives:

- To clarify and simplify the definitions of droplet-induced crater and crown.
- To investigate the physical relationships between droplet-induced crater and crown.
- To revise the Yarin and Weiss (1995) Model for the purpose of obtaining accurate crown propagation predictions.

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Nomenclature

A_d	projected area of droplet
d_c	instantaneous crown diameter
$d_{c,\,rim}$	crown rim diameter
$d_{c,\,base}$	crown base diameter
d_{cra}	crater diameter
d_d	droplet diameter
d_{orf}	orifice diameter
f	droplet impingement frequency
h_0	unperturbed liquid film thickness
h_{spot}	instantaneous liquid film thickness within the initial impingement spot
$\bar{h}_{spot}$	average liquid film thickness within the initial spot
L	length of crown propagation domain
Q	volumetric flow rate
r	radial position
R	radius of the initial spot
S_{in}	inter-droplet spacing
t	dimensional time
$\vec{u}$	velocity vector
$\bar{u}(r)$	average radial flow velocity in the direction normal to the liquid film
V_d	droplet impingement velocity
x	volume fraction of liquid phase
Δ	element size
ρ	density
σ	surface tension
ν	kinematic viscosity
μ	dynamic viscosity

Non-dimensional numbers

We	droplet Weber number, $\frac{\rho d_d V_d^2}{\sigma}$
d_c^*	non-dimensional crown diameter, $\frac{d_c}{d_d}$
h_0^*	non-dimensional unperturbed liquid film thickness, $\frac{h_0}{d_d}$
$t*$	non-dimensional time, $2\pi ft$

Subscripts

base	base
rim	rim
c	crown
cra	crater
d	droplet
g	gas
l	liquid
max	maximum
orf	orifice

From this study, the numerical and experimental results reveal that the radial velocity distribution within the liquid film is dependent on radial position. The revised droplet train impingement model based on the Yarin and Weiss (1995) approach accurately accounts for the unperturbed liquid film thickness, which is used to predict time-dependent crown propagation diameter.

2. Literature review

Generally, droplet impingement studies can be classified as: single droplet impingement and droplet train impingement. Single droplet impact on dry surfaces exhibits complicated features due to the effect of droplet properties, surface roughness, and wettability (Rioboo et al., 2001, 2002; Mundo et al., 1995). For instance, in the experimental studies conducted by Rioboo et al. (2001), six distinct outcomes of single droplet impact on dry surfaces were identified, namely: deposition, prompt splash, corona splash, receding break-up, partial rebound and complete rebound. Qualitative analysis have also been conducted to investigate the effects of experimental variables, such as droplet velocity, droplet diameter, surface roughness and contact angle on the hydrodynamics of droplet impingement. It has been found that not all outcomes are achievable for a given droplet-surface combination (Rioboo et al., 2001).

Rioboo et al. (2002) studied the evolution of single droplet impingement on dry surfaces. Four evolution phases have been identified, namely: kinematic phase, spreading phase, relaxation phase, and wetting/equilibrium phase. It has been found that the diameter of the spreading droplet is proportional to $t^{1/2}$ only in the kinematic phase. Similar physical behavior has been observed when droplets impinge on thin liquid films (Cossali et al., 1997, 2004).

Other researchers have also studied the relationships between crown propagation diameter and time for single droplet impact on thin liquid films (Cossali et al., 1997, 2004). Cossali et al. (2004) articulated a relationship between crown diameter (d_c) and time (t), which takes the form of $d_c = K{\bullet}t^n$, where K is a constant and n is very close to 0.5.

Yarin and Weiss (1995) studied the hydrodynamics of droplet train impingement and proposed a theoretical model (hereinafter referred to as the YWM) to predict crown base diameter as a function of time, as follows:

$$d_{c,base} = 2 \cdot (2Ft)^{1/2} \tag{1}$$

The value of F in Eq. (1) depends on the conditions of initial spot formation, which is defined as the moment when the crown base propagation velocity equals the droplet impingement velocity (Yarin and Weiss, 1995; Rieber and Frohn, 1999; Yarin, 2006). Eq. (2) is used to determine the value of F, as follows:

$$F = \int_0^L \bar{u}(r)dr \tag{2}$$

where L is the length of the crown propagation domain, $\bar{u}(r)$is the average radial velocity in the direction normal to the liquid film.

Yarin and Weiss (1995) in their model formulation assumed that $\bar{u}(r)$is equal to V_d at the initial spot, while $\bar{u}(r)$is equal to 0 elsewhere:

$$\bar{u}(r) = \begin{cases} V_d, & 0 \le r \le R \\ 0, & r > R \end{cases} \tag{3}$$

In Eq. (3), V_d refers to droplet impingement velocity. The radius of the initial spot, R, is estimated from the mass balance equation, as follows:

$$\rho\pi R^2 \bar{h}_{spot} = \frac{1}{6}\rho\pi d_d^3 \tag{4}$$

In Eq. (4), d_d refers to droplet diameter and $\bar{h}_{spot}$refers to the average liquid film thickness within the initial spot. Yarin and Weiss (1995) assumed that $\bar{h}_{spot}$ is equal to the thickness of the unperturbed liquid film (h_0) produced by impinged droplets:

$$\bar{h}_{spot} = h_0 \tag{5}$$

By using the above assumptions shown in Eqs. (3), (4) and (5), a simplified YWM takes the mathematical form of:

$$d_{c,base} = \left[2d_d \cdot \left(\frac{2}{3}\right)^{1/4} \frac{V_d^{1/2}}{d_d^{1/4} h_0^{1/4}}\right] t^{1/2} \tag{6}$$

The non-dimensional form of this simplified YWM is as follows:

$$d^*_{c,base} = \left[\frac{2V_d^{1/2}}{6^{1/4} h_0^{1/4} \pi^{1/2} d_d^{1/4} f^{1/2}}\right] (t^*)^{1/2} \tag{7}$$

where

$d^*_{c,base} = \frac{d_{c,base}}{d_d}$
$t^* = 2\pi ft$