

NON-ISOTHERMAL SPRAY IMPINGEMENT

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ABSTRACT

Spray impingement is a prevalent phenomenon in numerous applications. In turbine combustion chambers and internal combustion engines, spray impingement is a consequence of fuel injection. The impinging spray can result in secondary spray and/or film formation. Characteristics of spray play a major role in combustion performance, hence the importance of understanding the impingement mechanism in this context.

A single droplet impinging on a wall is the key phenomenon underlying the whole spray impingement mechanism. A droplet hitting the wall can bounce, smear, break, splash or any combination of these. The fate of such a droplet is a function of various parameters: initial size and velocity, droplet physical properties such as surface tension and viscosity, and wall surface conditions such as wettability, roughness, and temperature.

In this study, a simple, recently developed, analytical model for an impinging droplet is used to analyse the effect of the different physical parameters and wall conditions on some of the key features of impingement, such as “crowning” and splashing.

INTRODUCTION

Spray impingement is a prevalent phenomenon in numerous applications. In a turbine combustion chamber fuel is often sprayed radially into the crossing air stream. Some of the spray is impinged on an outer wall. The impinging spray is reflected or adheres to the wall, to be further broken up into a spray of different characteristics. The characteristics of a spray play a major role in combustion and performance of turbine. Small and evenly distributed droplets of spray in the combustion chamber are paramount for efficient combustion, which results in low fuel consumption and low level of pollutants[1]. Secondary spray formation through wall reflection and film break up are not entirely understood, and the effect of primary spray conditions on secondary spray characteristics is yet to be investigated.

A single droplet impinging on a wall is the key phenomenon underlying the whole spray impingement mechanism. A droplet hitting the wall can bounce, smear, deform or any combination of these. The fate of such a droplet hitting the wall is a function of various parameters: initial size and velocity, droplet physical properties such as surface tension and viscosity, and wall surface conditions and temperature. A recent review of theoretical and experimental results of droplet impingement can be found in [2]. Some common relations, used mainly in the context of numerical simulations as wall conditions, are given in [3]. The effect of wall temperature has been recognized experimentally [4], however no comprehensive theory of the effect is available.

The parametric effect of wall temperature is very important. A relatively hot wall (relative to oncoming droplets) can alter impingement consequences. Physical properties such as: surface tensions, contact angles and viscosity are temperature dependent, and since the impact

process is transient, temperature at relevant locations (surface of droplet, and contact line) is not necessarily at the equilibrium value. Considering typical order of magnitude values: For a $10^{-4} m$ size droplet, travelling at $10 m/s$, the estimated typical impact time is of the order of $t \approx 10^{-5} s$. Typically, a metal wall (steel) has 100 times larger thermal diffusivity than the droplet ($\alpha_{wall} \approx 10^{-5} m^2/s$, $\alpha_{drop} \approx 10^{-7} m^2/s$), therefore, the temperature at the contact interface (and line) would be close to the wall temperature upon impact. However, since $Fo_{drop} = \alpha_{drop} t / D^2$ has a very small value ($\approx 10^{-4}$), while the impacting droplet size (D) is still around its initial value ($10^{-4} m$), it means that most of the droplet external surface and volume are at a temperature which is closer to the initial spray temperature, rather than to the wall temperature, during the first stages of impact.

Wall temperature has been recognized as an important parameter affecting impingement (see [4], and [5]), however its effect is yet to be analysed. The relationship between temperature and physical properties of liquid can generally be evaluated. In this study, a single droplet impingement model [6] is used, to analyse the effect of wall temperature and other parameters on impinging behaviour, via its effect on the physical properties of the liquid.

AN IMPINGEMENT MODEL

A model for a single droplet hitting a wall has been developed in [6]. It simplifies the hitting droplet geometry as a disc, with small upper surface deformations (Fig. 1). The average disc height as a function of time from wall hitting is

evaluated using an overall energy balance, accounting for the kinetic, surface, and dissipated viscous energy:

$$E_{kinetic} + E_{surface} + E_{viscous} = E \quad (1)$$

Further, a boundary layer type approximation is incorporated, where it was assumed that a potential flow velocity profile prevails in the bulk of the disc, except for in the area very near the wall. Therefore the velocity profile is given by [7]:

$$v_z \approx \frac{z}{h} \dot{h}, \quad v_r \approx -\frac{1}{2} \frac{r}{h} \dot{h}, \quad (2)$$

The relevant energies involved are given as (see [8]):

$$E_{kinetic} = \frac{1}{2} \rho \iiint_{\tilde{V}} v^2 d\tilde{V} \quad (3a)$$

$$E_{surface} = \pi R^2 (\sigma_{lg} + \sigma_{sl} - \sigma_{sg}) \quad (3b)$$

$$E_{viscous} = C \pi R^3 \rho V^2 \frac{1}{\sqrt{Re}} \quad (3c)$$

Using the above velocity profile and energy expressions, and non-dimensionalising, an expression for the average disc height change rate can be developed ([6]):

$$\frac{\dot{\tilde{h}}}{\tilde{h}} = -\frac{\dot{\tilde{h}}}{\tilde{h}} \sqrt{6 \frac{(We + 12)\tilde{h} - 4(1 - \cos \theta + 2CWeRe^{-1/2})}{We(2\tilde{h}^3 + 1)}} \quad (4)$$

The upper surface deformations were modelled by considering the flow in the vicinity of this free surface:

$$\rho \left(\frac{\partial v_r}{\partial t} + v_r \frac{\partial v_r}{\partial r} \right) = -\frac{\partial p}{\partial r} = -\frac{\partial}{\partial r} (\Delta p) = \sigma_{lg} \frac{\partial}{\partial r} \left(\frac{h'}{r\sqrt{1+h'^2}} + \frac{h''}{(1+h'^2)^{3/2}} \right) \quad (5)$$

An approximate solution of eq. (5) was developed in [6], to give the impinging droplet's geometry:

$$\tilde{h} = \frac{1}{144} \frac{\tilde{\beta}}{\tilde{h}^2} We (\tilde{r}^4 - 4\tilde{r}^2) - \left(\frac{1}{2\sqrt{3}} \frac{1}{\sqrt{\tilde{h}}} + \frac{1}{3} \frac{1 - \cos \theta}{\tilde{h}^2} \right) \tilde{r}^2 + \tilde{h} \quad (6)$$

where,

$$\tilde{\beta} = \frac{3}{2} \frac{1}{(2\tilde{h}^3 + 1)^2} \frac{1}{We} \left[(1 - \cos \theta + 2CWeRe^{-1/2}) (8\tilde{h}^3 + 1) - \frac{3}{2} (We + 12)\tilde{h}^4 \right] \quad (7)$$

This solution was used to estimate the critical conditions for splashing, assuming that splashing occurs as a result of an unstable crown rim, which extends beyond a critical height:

$$Oh > \frac{1}{Re} \sqrt{\frac{125\alpha_{cr} + 31 + 95(1 - \cos \theta)}{(1 - 20CRe^{-1/2})}} \quad (8)$$

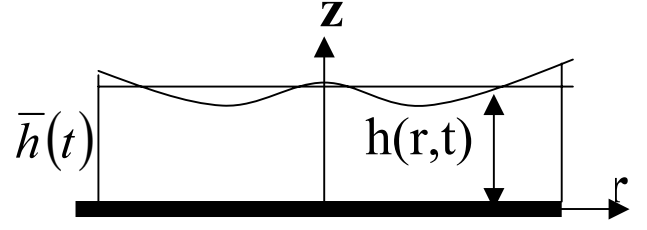


Fig. 1: Model geometry

PARAMETRICAL ANALYSIS OF PHYSICAL CONDITIONS

Figure 2 represents solutions of Eq. (4) for two sets of Weber numbers and contact angles. If a droplet of an inviscid fluid on a non-heated surface is represented by the blue (upper) curve, the pink (lower) curve can represent the behaviour of the same droplet impinging a heated surface. A higher surface temperature can reduce surface tension by an order of magnitude, and consequently reduce contact angle and increase the Weber number. The lower curve represents a possible extreme case. In real cases, where the surface is colder, or impingement is faster to make droplet's effective temperature lower, the curve can be between the upper and lower presented curves.

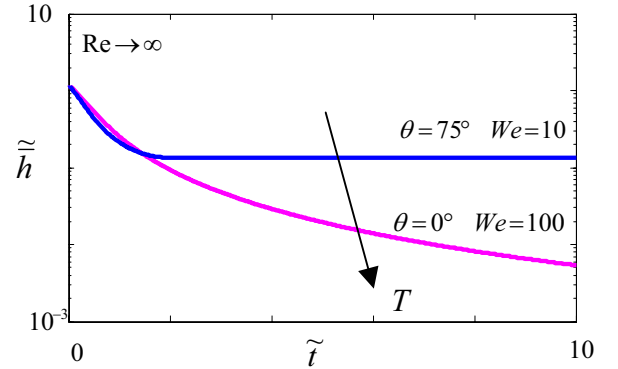


Fig. 2: Impinging droplet average height

Figure 3 presents behaviour of impinging droplet, as predicted by eq. (6), for an isothermal plate. It can be seen that at some time during the impinging process, there is considerable "crowning", that is, an elevated rim. This behaviour is qualitatively consistent with experimental observations [7].

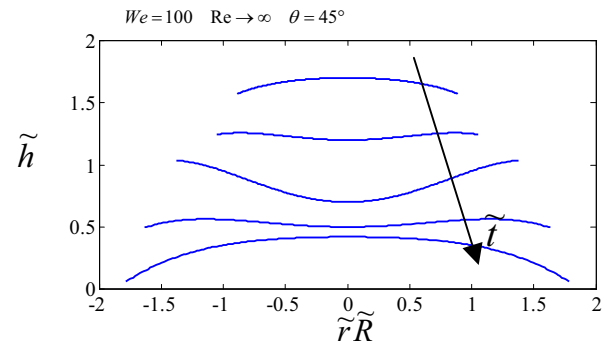


Fig. 3: Impinging droplet profile

Figure 4 presents the rim height during the impinging process, as theoretically predicted using Eq. (6) and compared to measured results from [9]. If the rim is elevated beyond a critical value, splashing may occur. Figure 5 presents predictions of splashing limit made by eq. (8), compared to experimental data from [10]. Critical rim elevation in Eq. (8) is determined by best fit to these experimental values.

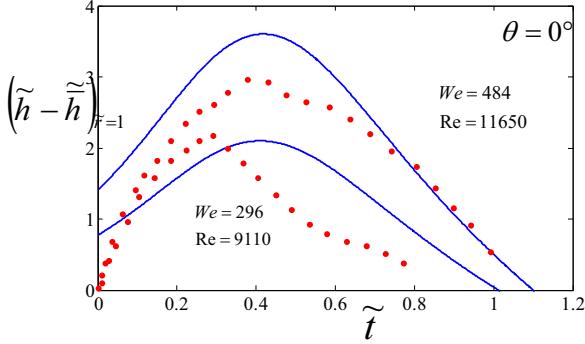


Fig. 4: Rim height during impingement

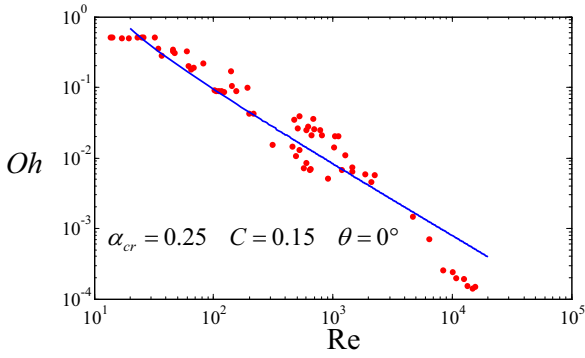


Fig. 5: Splashing limit

Figure 6 demonstrates the effect of different parameters on splashing limits. A hydrophobic surface (contact angle up to 180°) serves to elevate the splash limit, while a hydrophilic surface (contact angle down to 0°) lowers it. Surface roughness can augment the effect of the surface, whether it is to elevate or lower the splash limit, as roughness increases contact area between liquid droplet and solid surface (change modelled through Wenzel's equivalent contact angle: $\cos \theta_{eq} \rightarrow r_w \cos \theta$). Temperature elevation (due to a hot wall, for example) serves to lower the splash limit through several mechanisms: lowering of viscosity, lowering of surface tension, and the possible consequential lowering of the contact angle with a hydrophilic surface. For a water droplet impinging a wall of temperature between $T_s = 20^\circ C \rightarrow 300^\circ C$, viscosity can vary between $\mu = 1000 \mu Pa \cdot s \rightarrow 80 \mu Pa \cdot s$, and surface tension can vary between $\sigma = 70 mN/m \rightarrow 7 mN/m$, respectively.

CONCLUSIONS

Surface conditions like wettability, roughness and temperature are concluded to have an important effect on impingement behaviour and splashing limits. A simple analytical modelling approach that has been used before is shown to be a useful start point for the analysis of these

parametrical effects. Surface wettability appears to increase impinged droplet spread and lower splashing limit. Surface roughness serves to amplify surface's wetting characteristics effect. Surface temperature has a multiple mechanism effect that amounts to lowered splashing limits at elevated surface temperatures. These effects may play an important role in analysing non-isothermal spray applications, like fuel-injected combustion systems.

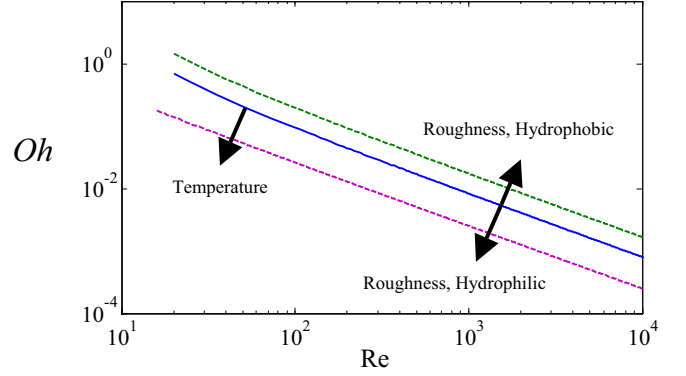


Fig. 6: Parametric effects on splashing limit

NOMENCLATURE

Symbol	Quantity	SI Unit
C	Constant	-
D	Droplet initial diameter	m
E	Energy	J
h	Height	m
\bar{h}	Average height	m
$\dot{\bar{h}}$	Average height change rate	m/s
$\tilde{h} \equiv \frac{h}{\frac{1}{2}D}$	Non-dimensional height	-
$Oh \equiv \frac{\mu}{\sqrt{\rho\sigma D}} = \frac{\sqrt{We}}{Re}$	Ohnesorge number	-
p	Pressure	Pa
r_w	Roughness	-
$\tilde{r} \equiv \frac{r}{R}$	Non-dimensional radial coordinate	-
R	Radius	m
$\tilde{R} \equiv \frac{R}{\frac{1}{2}D}$	Non-dimensional radius	-
$Re \equiv \frac{\rho V D}{\mu}$	Reynolds number	-
$\tilde{t} \equiv \frac{t}{\frac{1}{2}D/V}$	Non-dimensional time	-
T	Temperature	K
v	Velocity	m/s
V	Droplet	m/s

$$We \equiv \frac{\rho V^2 D}{\sigma_{lg}}$$

initial velocity Weber number -

Greek

$$\alpha_{cr} \equiv \left(\tilde{h} - \tilde{h} \right)_{\max, cr}$$

Critical non-dimensional crown rim height -

μ Viscosity Pa-s

θ Contact angle deg

ρ Density Kg/m³

σ Surface tension N/m

Subscripts

lg Liquid-Gas

r Radial

s Surface

sg Solid-Gas

sl Solid-Liquid

z Axial

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