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Simulation of liquid drop impact on dry and wet surfaces using SPH method

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Abstract

Spray–wall interactions occur in many combustion devices and have significant effects on mixture distribution and combustion quality. This paper describes an advanced numerical method, based on smoothed particle hydrodynamics (SPH), for predicting the detailed outcomes of drop–wall interactions. SPH is a Lagrangian mesh-free method suitable for capturing the surface evolution of a deforming liquid. In simulating the drop impact on a dry surface, the present model was able to predict the spread of the drop on the wall, and the evolution of the predicted wall film diameter agreed with the experimental data. In simulating the drop impact on a wet surface with an existing liquid film, the model captured the formation of the crown, the generation of secondary droplets, and the eventual receding of the crown. Results show that as the impact velocity increased, both the maximum crown height and the time to reach the maximum crown height increased. These predictions agreed with the measurements for various operating conditions. This agreement indicates that the present numerical method has the potential to accurately predict the details of spray–wall interactions in combustion system environments.

Keywords: Drop–wall interaction; Wall film; Smoothed particle hydrodynamics

1. Introduction

The impact of liquid drops on solid surfaces occurs in a wide range of engineering applications, such as fuel spray in engines, spray cooling, ink-jet printing, and solidification during material processing [1]. The outcome of a drop impacting on a surface depends on the properties and conditions of the liquid drop and of the surface. In the case of a dry surface, the influencing properties include the shape, roughness, and wettability of the surface. The impinging drop may spread, splash, or form a crown, depending on the size of the drop, the impact velocity of the drop and the surface properties of the wall. In the case of a wet surface, the influencing properties include the thickness and physical properties of the liquid film, in addition to the conditions of the impinging drop. In many cases, the liquid film is formed by the prior drops impacting on the surface, and the drop impact usually results in a crown that exhibits many

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intriguing phenomena [2]. As a result, both the dry wall and wet wall scenarios will need to be considered in predicting the outcomes of spray–wall interactions.

In an internal combustion engine, the fuel drops may impinge on the piston surface or the cylinder wall, potentially leading to inadequate combustion or deterioration of lubrication oil. Much research on drop–wall interactions, under engine conditions, has been conducted, including experimental and numerical studies [3–6]. In general, experimental research requires more resources and time, while numerical studies can be effective in identifying the major outcomes of drop–wall interactions. Accurate computational models can also be used as a tool for the design and optimization of combustion systems. The present study is focused on the development and validation of an advanced numerical method, rather than the semi-empirical phenomenological models, in simulating drop–wall interactions.

The mainstream approaches for simulating drop–wall interactions include boundary element method [7,8], volume of fluid [9,10], Lattice Boltzmann method [11], level set method (LSM) [12], and finite element method [13]. These methods have their successes in predicting the interactions of liquid drops and solid walls. All of these methods are grid based, i.e., relying on the use of very fine computational grids. In addition to the above traditional grid-based methods, in recent years, a Lagrangian mesh-free numerical scheme named smoothed particle hydrodynamics (SPH) [14,15] has emerged for simulating liquid deformation, especially in the field of solidification during material processing. In SPH, the drop, surrounding gas, and the solid wall are discretized into free-moving and/or fixed particles. As a result, it becomes straightforward to track drop deformation and the interface of the liquid and gas. Several studies using SPH were conducted to simulate the solidification process when a liquid drop contacts a cold wall [16,17]. However, the SPH method has not been formulated and tested to predict the outcomes of drop-wall interactions in a detailed manner.

In the present study, a numerical method based on SPH was developed and applied to simulate drop–wall interactions. The ultimate goal is to provide fundamental physical insight and derive a physics-based drop-wall interaction model for use in engine spray simulations. The advantages of SPH method include its abilities to track highly-deformed free surface, model the surface properties by using SPH particles with different properties, and predict the outcome of drop–wall interactions without the need to use any prescribed criteria. Unlike some mesh-based methods, the SPH method conserves mass. SPH does not present issues caused by mesh because it is a mesh-free particle method.

2. SPH method

The SPH method is a mesh-free method that uses particles to replace the fluid field and solves governing equations on the basis of the Lagrangian particles. The SPH particles carry physical properties of the fluid, such as density, mass, pressure, and velocity. The SPH particles move at the fluid velocity. The method uses the so-called kernel approximations in place of functions and their derivatives. A basic SPH equation is

$$A(\boldsymbol{r}_a) = \sum_b A(\boldsymbol{r}_b) W(\boldsymbol{r}_a - \boldsymbol{r}_b,\ h) \frac{m_b}{\rho_b}. \tag{1}$$

where A can be any function of the fluid field, $\boldsymbol{r}_a$ is the position of particle a, $W(\boldsymbol{r}_a - \boldsymbol{r}_b,\ h)$ is called the kernel function or smoothing function, m and ρ are the mass and density, respectively. b is the particle in the neighborhood of particle a. The summation is taken over all the neighboring particles of a, including particle a itself. The size of the neighborhood depends on the smoothing length h of the kernel function W. There are many different kernel functions that can be used. In the present study, the cubic spline kernel in three-dimensional space is applied,

$$W(s, h) = \frac{1}{4\pi h^3} \begin{cases} (2-s)^3 - 4(1-s)^3, & 0 \le s < 1 \\ (2-s)^3, & 1 \le s < 2 \\ 0, & s \ge 2 \end{cases} \tag{2}$$

where $s = r/h$, and r is the distance between two particles. More details of the SPH method can be found in the literature [18–20].

The SPH method was used in the present work to simulate the process of drop impact on a dry or wet surfaces. The dynamics of the fluid is governed by the Navier–Stokes (N-S) equations,

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \boldsymbol{u} \tag{3}$$

$$\frac{d\boldsymbol{u}}{dt} = \boldsymbol{g} - \frac{1}{\rho}\nabla p + \frac{\mu}{\rho}\nabla^2 \boldsymbol{u} \tag{4}$$

where ρ is the fluid density, $\boldsymbol{u}$ is the fluid velocity, p is the fluid pressure, μ is the dynamic viscosity of the fluid, and $\boldsymbol{g}$ denotes the body force acting on the fluid, such as gravitational force. With the SPH kernel summations, the N-S equations can be written in the following form,

$$\frac{d\rho_a}{dt} = \sum_b m_b \boldsymbol{u}_{ab} \cdot \nabla_a W_{ab} \tag{5}$$

$$\frac{d\boldsymbol{u}_a}{dt} = \boldsymbol{g}_a - \sum_b m_b \left(\frac{P_a}{\rho_a^2} + \frac{P_b}{\rho_b^2} \right) \nabla_a W_{ab} + \sum_b \frac{2 m_b \mu \boldsymbol{r}_{ab} \cdot \nabla_a W_{ab}}{\rho_a \rho_b \left(r_{ab}^2 + \eta \right)} \boldsymbol{u}_{ab} \tag{6}$$