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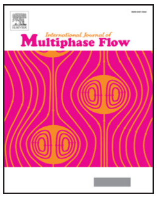

Development of an improved liquid film model for spray/wall interaction under engine-relevant conditions

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ABSTRACT

The dynamics and heat and mass transfer characteristics of the liquid film formed by spray/wall interaction have significant influences on the fuel/air mixing process in engines, which subsequently considerably affects engine combustion and emissions. In this paper, an improved liquid film model using the Lagrangian method was proposed with special emphasis on the engine-relevant conditions. By modifying the source term of the impingement momentum, the film dynamics sub-model was improved with consideration of the effect of droplet/film interaction on the film dynamics, as well as the dissipative energy loss during the expansion of the lamella formed by the deformation of the deposited droplet. Taking account of the effect of gas compressibility on the gas/film heat transfer and introducing the Chilton–Colburn analogy for calculation of the film evaporation coefficient, the film heat and mass transfer sub-models were further enhanced. By comparing with the available experimental data from constant-volume bombs and a diesel engine, it is found that the improved liquid film model is capable of satisfactorily reproducing the film dynamics, film/wall heat flux, and film evaporation rate under a wide operating range. Due to take the engine-relevant conditions into account, the predictions with the improved film model are in better agreement with the measurements in engines than that of the previous models.

Introduction

Spray/wall interaction is an important aspect of internal combustion engines, especially for gasoline direct-injection (GDI) engines and diesel premixed charge compression ignition (PCCI) engines with early in-cylinder injection (Zhao et al., 1999; Drake et al., 2003; Yao et al., 2009). In GDI engines, liquid film deposited on the piston is the main source of soot emissions (Stevens and Steeper, 2001). In diesel PCCI engines, spray impingement is unavoidable due to the relatively low in-cylinder ambient temperature and pressure during the injection process by employing early injection strategy (Lechner et al., 2005). As the spray/wall interaction occurs, the splashed droplets produced by spray impingement, which can be easily vaporized, promote the fuel/air mixing. However, the wall film is simultaneously formed, and its dynamics and heat and mass transfer characteristics have significant impact on engine-out emissions and fuel economy. Fang et al. (2007) indicated that the rich fuel/air mixture near the piston wall arising from the slow evaporation of the liquid film resulted in incomplete combustion and high emissions. In addition, excessive thermal stress caused by the high rate of heat transfer to the piston surface through the liquid film can damage the piston (Weingartz et al., 2009).

The spray/wall interaction can be divided into the splash process and the wall film formation process. The splash process of spray wall impingement has been well understood by experiment. Meingast et al. (2000) investigated the splashed droplet characteristics (i.e., the droplet size and velocity distributions) by utilizing phase Doppler interferometry (PDI) under diesel engine-relevant conditions. Andreassi et al. (2007) conducted both experimental and numerical study on the penetration of the impinging spray under the conditions of high injection pressure. Recently, by summarizing the state of the art about the droplet and spray impingement, Moreira et al. (2010) conducted a comprehensive review, and it was concluded that deeper knowledge about the droplet/wall interaction will promote understanding the complicated spray/wall interaction behavior.

Regarding the wall film formation process, Akop et al. (2013, 2014) systemically investigated the effect of the related parameters on the liquid film mass for diesel spray in a constant-volume bomb, whereas the film dynamics is not considered in their study. The radius of the liquid film formed by the normal impingement of diesel spray was measured by Saito et al. (1993) using high-speed photography. It was indicated that the radius of the liquid film increased with increasing injection pressure. Mathews et al. (2003) studied the film

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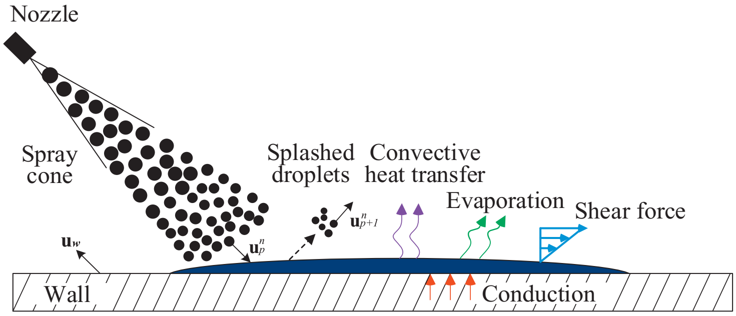

Fig. 1. Basic mechanisms governing the film dynamics and heat and mass transfer.

dynamics characteristics and film thickness distributions under different injection angles via optical equipment. It was observed that the film shape became more elliptical as the injection angle (from the normal direction) increased. Recently, Schulz et al. (2015) developed a new approach based on the laser-induced fluorescence (LIF) to measure the distribution of the film thickness under high-temperature and high-pressure conditions.

Concerning the heat transfer characteristics during the spray/wall interaction, Wolf and Cheng (1989) measured the wall heat flux at the impingement point for non-combusting and combusting sprays in a rapid-compression machine. Senda et al. (1995) investigated the wall heat flux at different locations using relatively low injection pressures. Focusing on the conditions with high injection pressure, Meingast et al. (2004) systematically studied the effect of various parameters on the distribution of the wall heat flux with spray impingement. It was found that the wall heat flux decreased with the increased radial distance from the impingement point. Recently, the infrared thermography method was adopted by Schulz et al. (2014) to simultaneously obtain the information on the film dynamics and heat transfer characteristics during the spray/wall interaction.

Due to the complex configuration and transient characteristics, it is extremely difficult to study the spray/wall interaction process in practical engines by experiment. As an alternative approach, computational modeling is promising to deeply understand the splash and wall film formation processes. Several splash models have been developed in the last 30 years (Naber and Reitz, 1988; Senda et al., 1994; Bai and Gosman, 1995; Stanton and Rutland, 1996; Han et al., 2000; Lee and Ryou, 2000; O'Rourke and Amsden, 2000), and a summary of the related models can be found in Jia et al. (2008). Recently, Zhang et al. (2014) proposed an improved splash model emphasizing on the conditions of high injection pressure. It was indicated that satisfactory agreements between the predictions from the Zhang et al. (2014) model and the measurements can be achieved under a wide range of operating conditions. Zhang et al. (2015) further updated the splashed mass ratio sub-model in the splash model based on the recent experimental data of the spray impingement, and the characteristics of the liquid film mass under PCCI engine conditions were also explored.

For the wall film modeling, the models based on the Eulerian method by solving the film mass, momentum, and energy equations have been proposed (Bai and Gosman, 1996; Foucart et al., 1998; Stanton and Rutland, 1998). However, as the Eulerian method is used, the diffusion of the film edge over several adjacent wall cells unfortunately occurs, which could be moderated by employing finer mesh with the penalty of higher computational cost (Trujillo and Lee, 2003). Moreover, because most of the present spray models are based on the discrete droplet method (DDM), additional interaction model between the wall film and the impinging droplets must be introduced in order to realize the Eulerian description of the wall film and Lagrangian description of the spray (Ning, 2007).

O'Rourke and Amsden (1996) developed a particle-based wall film model, in which the wall film is represented by discrete particles. The utilization of the particle-based method not only can be compatible with the popular particle spray model but also can be applied using relatively coarse grid with acceptable accuracy. In the wall film model, O'Rourke and Amsden (1996) took account of the effects of gas flow, wall, and the impinging spray on the film dynamics. However, the influence of the droplet/film interaction on the film movement, as well as the dissipative energy loss for the deposited droplet, were not considered by O'Rourke and Amsden (1996). Because the temperature distribution within the liquid film is important for the film heating and evaporation, Song et al. (2015) and Yan et al. (2015) developed analytical temperature profiles for modeling the film heating process, whereas significantly high computational cost is still needed as they are applied for multi-dimensional simulations. For simplicity, O'Rourke and Amsden (1996) adopted a piecewise linear temperature profile for description of the temperature distribution within the wall film. However, the effect of gas compressibility on the gas/film heat transfer is neglected in the O'Rourke and Amsden (1996) model, which could have considerable influence on the film evaporation under engine-relevant conditions with high ambient pressure.

In the present study, based on the O'Rourke and Amsden (1996, 2000) model, an improved wall film model is proposed with the enhanced film dynamics and heat and mass transfer sub-models. In the updated film dynamics model, a uniformly distributed source term of the impingement momentum along the impinging direction for each impinging droplet is adopted with consideration of the effect of droplet/film interaction on the film dynamics. Moreover, the dissipative energy loss during the expansion of the lamella formed by the deformation of the deposited droplet is also taken into account. For modeling the film heat transfer and evaporation, an improved submodel is introduced to consider the effect of gas compressibility on the gas/film heat transfer, and an updated film evaporation coefficient is analogically obtained. The rest of this paper is organized as follows. First, the O'Rourke and Amsden model and the improved wall film model are presented in section "Model formulation". Then validations of the improved models against available experimental data are conducted in section "Results and discussion". Finally, major conclusions are drawn in section "Conclusions".

Model formulation

Film dynamics model

During the spray/wall impingement, liquid film initially accumulates around the impingement point and then spreads away. The dynamics of the liquid film is dominantly determined by the viscous forces exerted by the wall, the tangential stresses above the film surface due to the gas flow near the film, and the mass and momentum additions by the impinging spray (see Fig. 1).