Applied Thermal Engineering 144 (2018) 137–146

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

# Cross-impingement and combustion of sprays in high-pressure chamber and opposed-piston compression ignition engine

Zhenyu Zhang, Peng Zhang*

*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong, PR China*

ARTICLE INFO

*Keywords:*
Spray impingement
Droplet bouncing
Kinetic energy recovery coefficient
High-pressure chamber
Opposed-piston compression ignition

ABSTRACT

Spray cross-impingement in a high-pressure chamber (10–30 atm) was studied experimentally, the results being compared to the spray opposed-impingement. The comparison was subsequently extended to the spray combustion in a model opposed-piston compression ignition engine. To account for the ambient pressure effects in collision outcomes, a recently proposed pressure-dependent droplet collision model was implemented in the KIVA-3V computer program for simulating the experiments. Compared with the widely used Estrade et al.'s and O'Rourke's models, the pressure-dependent model produces satisfactory predictions to spray characteristics. The uncertainty of the kinetic energy recovery coefficient, which affects the post-collision characteristics of bouncing droplets, was found to cause insignificant difference in model predictions. In the high-pressure chamber, droplet collisions in cross-impingement occur earlier than those in the opposed-impingement and result in more coalescence, consequently producing larger droplet sizes. With increasing the ambient pressure, the increasing tendency of droplet bouncing diminishes the difference of these two spray impingements. In the model OPCI, the presence of strong swirling flow deflects sprays from impingement and therefore the opposed-impingement shows slightly better combustion performance by producing more spatially uniform droplet distribution. However, the spray cross-impingement enhances droplet collision hence promotes atomization in the absence of swirling flow.

## 1. Introduction

In recent years, there are rekindled interests in opposed-piston compression ignition (referred to as OPCI hereinafter) engines [1–12], where cylinder head is absent and fuel injectors are mounted on the cylinder liner. In order to sufficiently utilize the in-cylinder air, two fuel injectors are usually so oriented that their sprays tend to impinge with each other, rendering binary droplet collision a frequent event in cylinder. It is evident that the collision outcomes, such as droplet bouncing, coalescence and separation, can substantially influence the size and velocity distributions of droplets and in turn the subsequent combustion and emission [13].

Earlier experiment [14] on water droplet collision under atmospheric environment shows that the collision outcomes are either coalescence or stretching separation, depending on the collision Weber number, $We = 2\rho_l U^2 R_s/\sigma$, the impact parameter, $B = X/(R_s + R_L)$, and the size ratio $\Delta = R_s/R_L$, where $\rho_l$ is the liquid density, $U$ is the relative velocity of the colliding droplets, $\sigma$ is the surface tension coefficient, $X$ is the projection of the distance between the mass centers of the droplets in the direction normal to the relative velocity, $R_s$ and $R_L$ are the radii of smaller and larger droplets, respectively. This result was subsequently adopted by O'Rourke [15] in developing his droplet collision model, which is implemented in the widely used KIVA [16] computer program for the Eulerian-Lagrangian simulation of spray combustion.

By recognizing that liquid alkanes are more relevant to the hydrocarbon fuel, Jiang et al.'s [17] and Qian and Law's [18] experiments on droplet collision of liquid alkanes, for the first time, identify droplet bouncing as a commonly encountered collision outcome, which is however seldom seen for water droplet collision under atmospheric pressure and hence absent in O'Rourke's [15] collision model. Duo to its incomplete description on the main collision outcomes of hydrocarbon fuel droplet, the over-simplified O'Rourke's droplet collision model was subsequently improved by a number of models, which has been summarized in a few reviews [19–22]. Majority of the models aim to estimate the collision probability [23,24], to reproduce the complex collision outcomes [19,20,22,25–30], and to predict the post-collision characteristics of droplets [31]. However, the influence of ambient pressure on droplet collision has never been concerned.

Although Qian and Law [18] experimentally confirmed that droplet bouncing is promoted by increasing ambient pressure and that the

* Corresponding author.
*E-mail address:* pengzhang.zhang@polyu.edu.hk (P. Zhang).

https://doi.org/10.1016/j.applthermaleng.2018.08.038
Received 3 July 2018; Received in revised form 7 August 2018; Accepted 13 August 2018
Available online 16 August 2018
1359-4311/ 

underlying physics has been theoretically delineated by Zhang and Law [32], no modelling effort was made previously to account for the influence of ambient pressure until very recently Zhang et al. [22] proposed a practically simple pressure-dependent droplet collision model based on the experiment results of Qian and Law [18] and the theoretical analysis of Zhang and Law [32]. Compared with the previous models, for example Estrade et al.'s [33] bouncing-coalescence model, which does not account for the fact that increasing of ambient pressure promotes droplet bouncing, the pressure-dependent model produces better predictions to the available experimental data [34] on impinging spray characteristic, especially under high ambient pressures.

Zhang et al. [35] also applied the pressure-dependent model to study spray impingement and combustion in a model OPCI engine, where two oppositely-oriented multiple-nozzle injectors with $C_2$ symmetry were investigated and optimized. Although the model again shows better performance than others in predicting the spray characteristics under high pressures, its advantage is not easily perceived when the in-cylinder swirling flow is sufficiently strong to deflect the inter-injector sprays (from two different injectors) from being impinged. The impingement of intra-injector spray (from two different nozzles of the same injector) is always presented and enhanced by the swirling flow, but it is not the same effective as the inter-injector spray impingement in promoting droplet collisions.

The present study was motivated by exploring new spray setup to promote inter-injector spray impingement, which has been found to enhance fuel atomization and subsequent fuel/air mixture and combustion [34,36–38]. Recognizing that the in-cylinder swirl suppresses the inter-injector spray impingement from two opposed-oriented injectors, we audaciously proposed a spray setup with perpendicularly oriented injectors, which may result in the spray cross-impingement. The present study aims to experimentally and numerically investigate spray cross-impingement in a high-pressure chamber and in a model OPCI engine, the results were compared with that of opposed-impingement. In the following text, we shall describe the experimental and numerical specifications of the cross-impingement sprays, in Section 2. The results and discussion of spray cross- and opposed-impingement in high-pressure chamber, in Section 3, followed by the spray combustion of cross- and opposed-impingement in a model OPCI, in Section 4.

## 2. Experimental specifications and numerical methods

### 2.1. Spray layout of cross- and opposed-impingement

Fig. 1 shows the schematic of spray cross- and opposed-impingement layouts. It should be noted that, the present cross-impingement spray layout was developed based on Zhao et al.'s [11] spray patterns, while the opposed-impingement layout was developed according to Hofbauer's [2] optimized results. The cross-impingement was developed to promote spray impingement and atomization, while opposed-impingement was designed to generate more uniform droplet distribution in the combustion chamber.

For the cross-impingement shown in Fig. 1(a), each injector consists of three nozzles, No. 1 – No. 3 refers to one injector while No. 4 – No. 6 refers to the other one. No. 2 and No. 5 are on the Z = 0 plane, No. 2 and No. 5, projections of No. 1 and No. 4 (similarly, No. 3 and No. 6) on Z = 0 plane are symmetrical with respect to the plane X = Y. No. 1 and No. 3 (similarly, No. 4 and No. 6) are on the same plane with an angle of 3° respect to X = 0 plane. The angles between No. 1 – No. 3 and the Y-axis on Z = 0 plane are 45°, 5° and 30°, respectively. Similarly, angles between No. 4 – No. 6 and the X-axis on Z = 0 plane are also 45°, 5° and 30°, respectively.

For the opposed-impingement shown in Fig. 1(b), No. 1–No. 3 are the same to that in cross-impingement, the opposed-impingement possesses the $C_2$ symmetry so that that No. 1 and No. 4 sprays (similarly, No. 2 and No. 5, and No. 3 and No. 6) can interchange their positions by rotating for 180° with respect to the Z = 0 axis.

### 2.2. Experimental apparatus

The experiment in the present paper contains two synergetic parts, which serve to validate the simulation for the non-reacting and isothermal sprays in constant-volume chamber and then for the reacting and variable-temperature sprays in an OPCI model engine.

The simplest the first, we investigated the non-reacting impinging sprays in a constant-volume chamber without heating; the temperature in the chamber was constant at 298 K. The objective of the non-reacting impinging spray in the constant volume vessel is to validate the adopted pressure-dependent droplet collision model. Isothermal chamber suppresses droplet evaporation so that liquid droplets in the chamber have longer residence time, which facilitates the comparison of the predictions from different droplet collision models (i.e., O'Rourke's [16] model, Estrade et al.'s [33] model and the pressure-dependent model [22]). It is extremely difficult to experimentally measure the spray evolution in the operating engine, although it definitely merits future study. Subsequently, we extended the investigation to the combustion of cross-impingement impinging sprays in an opposed-piston compression ignition (OPCI) engine, where the moving pistons make the chamber flow statistically unsteady. The combustion temperature, varying with the crank angle, is similar to that in real engines.

Schematics of the experimental apparatus for non-reacting cross- and opposed-impingement sprays in a high-pressure chamber and cross-impinging spray combustion in a model OPCI engine are shown in Fig. 2(a) and (b). A complete description of the experimental apparatus for impinging sprays can be found in our previous publication [22], so only a brief description of the experimental set up will be given here. For non-reacting spray impingement, time-resolved shadowgraph images in the chamber (1) with two opposed glass windows were taken by a Fastcam SA4 camera (10000 fps) (2) combined with a stroboscope (3). The chamber was filled with pure nitrogen with varying pressure at 10 atm, 20 atm, and 30 atm, respectively. A Bosch CP1H3 common rail system (4) was adopted for fuel injection. The injection pressure was 160 MPa and the injection duration was 1.5 ms with total of 90 mg/cycle liquid diesel was injected into the chamber by two injectors, simultaneously.

The model OPCI (5) with 100 mm in bore and 110 mm in stroke for each piston is schematized in Fig. 2(b). Similarly, the detailed description of OPCI working principle can be found in one of our previous publication [35]. For a briefly introduce, the engine prototype has two cylinders and a total displacement of 3.4 L with the rated speed is 2100 rpm. Each cylinder contains two oppositely moving pistons, namely, intake piston and exhaust piston, respectively. Thus, cylinder head is absent and fuel injectors can only be installed on the cylinder liner. The OPCI engine employs a port-to-port uniflow scavenging system for gas exchange, and the port opening and closing are controlled by corresponding pistons. In this study, the exhaust ports open at 100° ATDC (after top dead center) and close at 113° BTDC (before top dead center); the intake ports open at 116° ATDC and close at 110° BTDC. Engine power and torque were measured by an electrical dynamometer. A Kistler-6056A cylinder pressure transducer (6) together with a Kistler 2614B crank angle sensor (7) were used to collect the cylinder pressure data with a crank angle interval of 0.2° CA and for 200 engine cycles. The pressure data was used to estimate heat release rate by using Krieger and Borman's [39] method. Intake pressure and exhaust pressure were measured by a Kistler 4005B pressure sensor (8) and a Kistler 4049A pressure senor (9), respectively. The measured intake and exhaust pressure were adopted to set up the numerical simulation, while the measured cylinder pressure was used to estimate heat release rate and validate the simulation results.