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Research Paper

# Numerical simulation of injection rate of each nozzle hole of multi-hole diesel injector

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## HIGHLIGHTS

- A three-dimensional gas-liquid two-phase model of cavitation flow was developed.
- Taking the effect of injection conditions on bubble number density into account.
- The model can be used to simulate the injection rate of each nozzle hole accurately.

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## ABSTRACT

The relative differences in injection rates within nozzle holes of multi-hole diesel injectors significantly influences the combustion and emission characteristics of diesel engines. To study systematically the injection rate of each nozzle hole of a multi-hole diesel injector, a three-dimensional gas-liquid two-phase model of cavitation flow was developed, taking the influence of injection conditions on bubble number density into consideration. To verify validity of the model, the injection rate of each nozzle hole of the injector was experimentally measured on a fuel injection system based on the transient measurement of spray momentum flux. The compared results of the measured and simulated injection rates of each nozzle hole shows that the developed model has relatively high precision and can be used to simulate the injection rate of each nozzle hole accurately.



## 1. Introduction

In order to ensure effective combustion and lower emission for diesel engines, a study on optimization of the combustion spray process based on injection rates and spray characteristics is crucial [1,2]. In fact, spray development and fuel air interactions are all directly affected by injection rates, which further influences the combustion process [3]. Therefore, further understanding of injection rates is of utmost importance to design improvement and performance optimization of diesel engines.

With regards to several techniques used to measure injection rates, such as Charge measuring [14] and Laser Doppler Velocimeter [15] methods, the Bosch tube [4–9] and Zeuch measuring [10–13] methods are the most common. All the methods mentioned give accurate testing results of injection rates for multi-hole diesel injectors. Research work and literatures in relations to the possible differences in the injection rate of each nozzle of the multi-hole diesel injector are limited. For the multi-hole diesel injector, discrepancies [16] in the injection rates within each nozzle hole occurs due to workmanship errors and differences in hydraulic conditions, which affects the uniform distributions of fuel (in time and space) in the combustion chamber, thereby leading to thermal load inconsistency with deterioration of the combustion and emission process [16–19]. A deformational testing method [16,17] was proposed by Marčič for testing the injection rates in each hole of the multi-hole diesel injector, Payri et al. also develop a hole to hole mass flow measuring bench [20], but few reports covering relevant measuring units and methods which have been experimentally validated, possess adequate response characteristics and potential to be applied widely.

With the rapid development of computer technology and computational fluid dynamic (CFD), the multi-dimensional numerical simulation has already become an effective means of relevant

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theoretical research in relation to internal combustion engines. To study the injection rate of each nozzle hole of a multi-hole diesel injector systematically, a three-dimensional gas-liquid two-phase model of cavitation flow was developed, the injection rate of each nozzle hole of the injector was experimentally measured (on an experimental rig based on the transient measurements of spray momentum flux) and used to validate the developed model.

In Section 2 of this manuscript, the mathematical model for fuel flow characteristics within the injector nozzle holes of the diesel engine is presented. A three-dimensional gas-liquid two-phase model of cavitation flow is developed in the next section, which predicts the output. The prediction accuracy of the model is validated using the measurements of the transient spray momentum flux of each nozzle hole obtained from experimental data. The investigated outcomes are then summarized in the conclusion section.

## 2. Mathematical model

The two-fluid model approach was used for computations of flow characteristics of the diesel fuel within the nozzle holes of the diesel engine. From the gas-liquid two-phase approach [21], the continuity and momentum equations are as follows:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \nabla \cdot \alpha_k \rho_k v_k = \sum_{l=1, l\neq k}^{2} \Gamma_{kl} \tag{1}$$

$$\frac{\partial \alpha_k \rho_k v_k}{\partial t} + \nabla \cdot \alpha_k \rho_k v_k v_k = -\alpha_k \nabla p + \nabla \cdot \alpha_k (\tau_k + T_k^t) + \alpha_k \rho_k g + \sum_{l=1, l\neq k}^{2} M_{kl} + v_k \sum_{l=1, l\neq k}^{2} \Gamma_{kl} \tag{2}$$

where the value for the parameter $k$ is either 1, for gas phase only, or 2 for only liquid phase. The summation of the volume fractions at phase k($\alpha_k$) is $\sum_{k=1}^{2} \alpha_k = 1$. $\rho_k$ and $v_k$ respectively represent the density and velocity at phase $k$. $\Gamma_{kl}$ is the interfacial mass transfer between the phases $k$ and $l$, $T_k^t$ is the Reynolds stress at phase $k$ and $M_{kl}$ represents the interfacial momentum transfer between phases $k$ and $l$.

From the two-fluid model approach, the gas phase pressure ($p_1$) and the liquid phase pressure ($p_2$) are equal and can be represented by P, that is:

$$p = p_1 = p_2 \tag{3}$$

For phase $k$, the shear stress ($\tau_k$) is:

$$\tau_k = \mu_k \left[ (\nabla v_k + \nabla v_k^T) - \frac{2}{3} \nabla \cdot v_k \right] \tag{4}$$

$\mu_k$ being the viscosity at phase $k$.

The Reynolds stress at phase $k$ ($T_k^t$) is:

$$T_k^t = -\rho_k \overline{v_k' v_k'} = \mu_k^t \left[ (\nabla v_k + \nabla v_k^T) - \frac{2}{3} \nabla \cdot v_k I \right] - \frac{2}{3} \rho_k k_k I \tag{5}$$

where $\mu_k^t$ is the viscosity of turbulence.

For the interfacial mass transfer between gas phase and liquid phase, the string cavitation model was used for computations, that is:

$$\Gamma_{12} = \rho_1 N''' 4\pi R^2 \dot{R} = -\Gamma_{21} \tag{6}$$

where $N'''$ is the bubble number density, $R$ is the mean bubble radius in cavitation region and $\dot{R}$ is the rate of change of bubble radius.

For the bubble number density $N'''$ (taking the influence of injection condition into consideration [24]), Eq. (7) was used.

$$N''' = 1.0 \times 10^{12} \left( \frac{p_i - p_o}{1.0 \times 10^6} \right)^3 \tag{7}$$

where $p_i$ and $p_o$ are the injection and ambient (back) pressures respectively.

The linearized Rayleigh-Plesset equation was used for the determination of the rate of change of bubble radius $\dot{R}$, as stated in Eq. (8).

$$\dot{R} = sign(\Delta p) \sqrt{\frac{2|\Delta p|}{3\rho_2}} \tag{8}$$

$\Delta p$ is the effective pressure difference with regards to bubble number growth and collapse due to pressure fluctuations. It is expressed as:

$$\Delta p = p_{sat} - \left( p - C_E \frac{2}{3} \rho_2 k_2 \right) \tag{9}$$

where $C_E$ is the Egler coefficient.

The expression for the interfacial momentum of the gas-fluid two-phase flow take the form:

$$M_{12} = F_{12}^D + F_{12}^{TD} = -M_{21} \tag{10}$$

$$F_{12}^D = -F_{21}^D = C_D \frac{1}{8} \rho_2 A_i''' |v_r| v_r \tag{11}$$

$$F_{12}^{TD} = -F_{21}^{TD} = C_{TD} \rho_2 k_2 \nabla \alpha_1 \tag{12}$$

$$A_i''' = \pi D_b^2 N''' = (36\pi)^{\frac{1}{3}} N'''^{\frac{1}{3}} \alpha_1^{\frac{2}{3}} \tag{13}$$

where $F_{12}^D$ is the drag force between gas and fluid phases, the turbulent dispersion force is $F_{12}^{TD}$, $C_D$ is the drag coefficient, the turbulent dispersion coefficient is $C_{TD}$ and bubble diameter is $D_b$.

The standard $k$-$\varepsilon$ model is used to calculate the turbulence of the core region. The transport equations for the turbulence kinetic energy $k$ and the turbulence kinetic energy diffusivity $\varepsilon$ are respectively expressed as:

$$\frac{\partial \alpha_k \rho_k k_k}{\partial t} + \nabla \cdot \alpha_k \rho_k v_k k_k = \nabla \cdot \alpha_k \left( \mu_k + \frac{\mu_k^t}{\sigma_k} \right) \nabla k_k + \alpha_k P_k + \alpha_k P_{B,k} - \alpha_k \rho_k \varepsilon_k + \sum_{l=1, l\neq k}^{2} K_{kl} + k_k \sum_{l=1, l\neq k}^{2} \Gamma_{kl} \tag{14}$$

$$\frac{\partial \alpha_k \rho_k \varepsilon_k}{\partial t} + \nabla \cdot \alpha_k \rho_k v_k \varepsilon_k = \nabla \cdot \alpha_k \left( \mu_k + \frac{\mu_k^t}{\sigma_\varepsilon} \right) \nabla \varepsilon_k + \sum_{l=1, l\neq k}^{2} D_{kl} + \varepsilon_k \sum_{l=1, l\neq k}^{2} \Gamma_{kl} + \alpha_k C_1 P_k \frac{\varepsilon_k}{k_k} - \alpha_k C_2 \rho_k \frac{\varepsilon_k^2}{k_k} + \alpha_k C_3 \max(P_{B,k}, 0) \frac{\varepsilon_k}{k_k} - \alpha_k C_4 \rho_k \varepsilon_k \nabla \cdot v_k \tag{15}$$

where $k_k$ is the turbulence kinetic energy at phase $k$, $\varepsilon_k$ is the diffusivity of the turbulence kinetic energy at phase $k$, $P_{B,k}$ is the generation component of the turbulence kinetic energy caused by buoyancy, the Prandtl number for the turbulence kinetic energy is $\sigma_{,k}$, $K_{kl}$ is the component of transmission between $k$ phase and $l$ phase, $\sigma_\varepsilon$ is the Prandtl number for the $\varepsilon$ equation, $C_1$, $C_2$, $C_3$, $C_4$ are constants and $D_{kl}$ is the interface exchange component of the $\varepsilon$.equation