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Phenomenological models for prediction of spray penetration and mixture properties for different injection profiles

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HIGHLIGHTS

- Phenomenological model for prediction of spray penetration.
- Model capable of predicting multiple pulse and ramped up ROI profiles.
- Transient calculation of spray velocity profile for various ROI.
- Transient prediction of mean equivalence ratio for various ROI.

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ABSTRACT

Accurate and quick prediction of spray characteristics such as penetration length, mean axial velocity profile and equivalence ratio distribution inside combustion chamber are important for the understanding and control of air–fuel mixing process in a compression ignition (CI) engine. In this study phenomenological model has been developed for prediction of spray penetration, air–fuel ratio and spatial distribution of velocity profile in terms of available analytical solution for steady sate, constant velocity sprays with variable radial profile for a characteristics injection velocity. Phenomenological model is able to accurately predict the transient spray tip penetration for single pulse, multiple pulse and linearly ramped up fuel injection profiles. Predicted values of mean axial spray velocity profile and mean axial equivalence ratio distribution by this model were following the trends of reference numerical model for various rate of injection (ROI) profiles.

1. Introduction

Increasing stringent emissions regulations and demand for higher efficiency pose challenges for development of compression ignition (CI) engines. Pollutant formation and combustion efficiency are highly dependent on mixing process of fuel and air. To achieve these objectives computer-aided optimizations to improve the mixture formation and combustion processes, which usually rely on predictions of various physical processes of mixture formation and combustion in the engine are extensively used [1,2]. With advancement in fuel injection technology, higher injection pressure and multiple injections with controlled shape of injection pulse have become important control parameters for improving the air–fuel mixing process [3–5]. Quick and robust calculation of temporal and spatial behavior of fuel sprays is critical for the prediction of engine performance and improvement of its design [6]. Researchers have investigated the spray characteristics of the high pressure injectors by experimental and theoretical approaches [7–14]. Developments in computational fluid dynamics (CFD) models, which are a helpful tool in analyzing engine performance have increased understanding of spray penetration and mixing processes [2,12,13,15–20]. Desantes et al. presented a model to predict the spray penetration using temporal variation of the spray momentum flux as an input [21]. Abdelghaffar et al. reported that spray penetration length for all tested nozzles, increased with increasing injection pressure and decreased with increasing in-cylinder pressure [22]. Johnson et al. experimentally measured penetration between 2000 and 3000 bar injection pressures with ultra-low sulfur diesel fuel [23]. Experimental investigation of Hillamo et al. gave a tool to divide the development of spray into acceleration region and deceleration region [24]. Results showed that injection pressure had low effect on overall spray penetration. At distances from the nozzle higher than 40 times orifice diameter, the ambient density seemed to dominate the penetration [24].

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Measurement of spray penetration by Naber and Siebers at different ambient conditions showed that at high ambient densities, predictions of non vaporizing sprays was applicable even for vaporizing sprays [1]. They also developed satisfactory analytical model for predicting spray properties [1].

Despite the great effort spent on fuel spray modeling and enhancement in computing power, complex phenomena that take place at short time and length scales in diesel fuel sprays make spray modeling a difficult task [2,25]. Different [2,26–29] spray models have been recently developed, which do not rely on CFD calculations but rather on analytical or empirical correlations for reducing the computational effort. These models result in faster prediction. Siewert developed a phenomenological model for prediction of spray trajectory. The model considered one-dimensional spray and ignored the boundaries imposed by the combustion chamber or cylinder wall and was unmoved by air motion, turbulence, or mixing. This model was useful tool for quickly predicting the spray characteristics of direct-injection engines that use liquid fuels [25].

In continuation with the ongoing effort of developing quick and robust models for predicting the spray penetration, this study attempts to develop phenomenological models for predicting the spray penetration, mean axial distribution of spray velocity profile, mean axial distribution of equivalence ratio profile (average spray velocity and average equivalence ratio over a cross section of spray) for various rate of injection (ROI) profiles. Purpose of attempting to develop the phenomenological model is to make the faster predictions of spray penetration, equivalence ratio distribution and spray velocity profile distribution (practically instantaneous) for various ROI profiles in order to apply the phenomenological model within engine fast models such as real time models that can be used for model based control or for hardware in loop (HIL) applications. For developing fast phenomenological models for various ROI profiles, well accepted steady jet solution proposed by Naber and Siebers [1] model at constant characteristic injection velocity (when fuel is continuously injected at constant speed) has been used as basis for calculating various spray properties and compared with Musculus and Kattke [30] model for unsteady jets.

2. Development of the model

In this one-dimensional model attempt has been made for expression of spray penetration, air–fuel ratio and spatial distribution of velocity profile in terms of steady sate, constant velocity analytical solution of Naber and Siebers [1] with variable radial profile for a characteristics injection velocity. Results for transient cases are compared with Musculus and Kattke model [30]. Musculus and Kattke model [30] of spray development treats spray penetration with arbitrary injection rates by incorporating multiple control volumes, solving for mass and momentum exchange along a single (axial) direction of the spray. The model requires inputs for spray spreading angle and ROI. Widely accepted Musculus and Kattke model in the numerical studies of engine combustion network (ECN) [31] has proven useful for analysis of the entrainment rate into the spray and penetration after the end of injection. Its predictions were accurate for both penetration and fuel mixture fraction even with constant input spreading angle [7,8]. With the use of variable spreading angle and educated ROI profiles the match between model predictions and experimental measurements further improved [8]. It provides a prediction of the local mixture fraction at any position within the jet, dependent upon model inputs such as the full spreading angle θ, fuel density ρ_f, air density ρ_a, and the assumed radial fuel concentration profile shape [7,30]. For variable ROI profiles, this model has the capability to accommodate general injection rates by incorporating multiple control volumes. Requirement of numerical analysis for the mass and momentum exchange between multiple grids of control volumes for general ROI profiles in Musculus and Kattke model [30] takes some time for calculations. For making the predictions of spray penetration, equivalence ratio distribution and spray velocity profile distribution practically instantaneous for various ROI profiles, results of these quantities are expressed in terms of steady state spray characteristic solutions. Simple linear correlations have been developed for predicting spray penetration, spray velocity and equivalence ratio distribution profiles for the following cases.

2.1. Single square pulse injection

Typical square shaped ROI profile for common rail direct injection (CRDI) engines can be characterized by duration of first injection pulse (t_1), first dwell duration (td_1) and duration of second injection pulse (t_2) as shown in Fig. 1. Single square pulse will be represented only by t_1.

If time after start of injection (t) is before the t_1 then penetration, spray velocity and air fuel ratio distribution profiles can be directly calculated from the analytical solution of Naber and Siebers [1] model because up to this time the situation is exactly similar to the steady injection pulse. After the end of injection pulse, onset of entrainment wave as described by Musculus and Kattke starts [30]. Entrainment rate of air in the fuel jet after the end of injection (EOI) pulse varies with time and axial distance in the direction of spray propagation. After the EOI the maximum air entrainment rate becomes higher in comparison to entrainment rate in steady fuel injection pulse (when fuel is continuously injected) at some axial locations [30]. From continuity consideration in the space occupied by fuel jet, when incoming volume of fuel coming in the jet reduces (due to end of fuel injection pulse) the volume is occupied by driving comparatively larger quantity of air from the surrounding of spray jet. This is the reason for variation in equivalence ratio in axial direction of spray with respect to steady jet. This transient variation in spray characteristics is referred to entrainment wave. Reduction in spray penetration in comparison to steady state injection pulse, after the end of injection is expressed in terms of advancement of entrainment wave by Eq. (3). After EOI the advancement of spray tip is expected to slow down with respect to steady injection because forward momentum supply to spray jet stops after EOI. Position of the head of the entrainment wave was determined by Eq. (2). In the description of Musculus and Kattke [30], it was mentioned that travel speed of entrainment wave was two times of the travel speed of spray head. But here ratio of 1.5 between entrainment wave travel speed and spray head progress was giving better match. $S(t)$ and $P(t)$ are spray penetration at time t for steady injection profile and general ROI profiles respectively.

For $t < t_1$,

$$P(t) = S(t) \tag{1}$$

For $t > t_1$, position of entrainment wave $Ew(t)$ at t was found by:

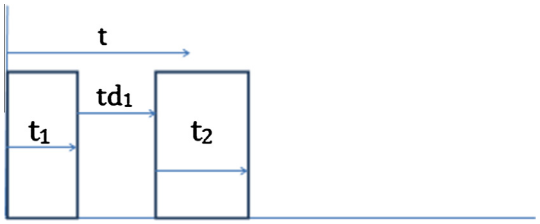

Fig. 1. Nomenclature for representation of square pulse ROI shape.