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Transient two-phase boundary layer modeling for hollow cone sprays

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ABSTRACT

This paper presents a spray model suited for dense sprays. It captures the transient evolution of the two-phase jet characteristics resulting from hollow cone injection. The model is designed for fast model response as needed in engine system simulation. It is based on the description of the gas phase boundary layer surrounding the dense spray. Mass and momentum equations are solved for both the dispersed liquid and the continuous gas phase. Spatial gradients are resolved along one dimension, namely the main injection direction. The conservation equations are expressed in conical coordinates. The model's response is studied qualitatively and global characteristics such as the penetration behavior are compared to both experimental and CFD data.

1. Introduction

The major part of today's transportation relies on combustion of liquid fuels. Fuel metering is accomplished by injectors which inject fuel into an oxidant, mainly air. Models of the injection process therefore need to reproduce *two-phase* characteristics.

Continuous injection of liquid fuel, such as in jet propulsion engines, may be described as quasi-stationary: Transients are only introduced due to changes in the engine operating condition. In reciprocating engines, on the other hand, fuel is injected discontinuously. Even in steady state engine operation, injection is a *transient* process.

In the simulation of a reciprocating engine system, a large range of physical time scales is involved: While individual injection events are completed within fractions of milliseconds, a transient engine operation (such as an acceleration process) generally takes several seconds until completion. Because small time scale effects (e.g. variable cylinder pressure during injection or between different injections during one working cycle) determine large time scale behavior (e.g. the heat release during combustion), all time scales need to be resolved in order to *predictively* describe the engine's thermodynamic process.

In industrial development, full 3D computational fluid dynamic (CFD) analysis of fuel injection processes concentrates on small volumes (e.g. the engine cylinder) and short time periods (say one working cycle) due to limited computational resources. With the focus on the dynamic engine working process, engine system simulation is conducted by simplified models. The (one-dimensional) gas dynamics in the engine's pipe system are resolved, while the engine heat release is accounted for by experimental data. Models for the injection process ("spray models") are rarely applied.

Available spray models focus on round jets typical for Diesel injectors. In the "packet model" (Hiroyasu et al., 1983), the two-phase flow is treated as a two-phase mixture. Using this assumption, correlations for e.g. the spray tip velocity, which are explicit in time, are derived. Several authors adopted this mixture model assumption, e.g. Kouremenos et al. (1997).

Wan (1997) avoided the mixture model assumption and derived a spray description based on assumed top-hat cross-stream profiles of the mean quantities of both phases. The cross-stream diffusion rate is accounted for by means of an assumed jet opening angle. In a second step, velocity differences between both phases are again neglected (mixture model assumption) and the spray front propagation is explicitly described depending on the assumed jet opening angle. The model was validated for Diesel engine applications (Krueger, 2001).

The assumption of steady state conditions within the main part of the two-phase flow enables a cross-stream integration of the

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momentum equation. A square root dependence of the spray tip velocity on time is found. For round Diesel jets, the accuracy of this correlation was confirmed for a wide variety of experimental data (Roisman et al., 2007). The transient part of the injection – i.e. the start of injection and the flow at the tip of the spray – was modeled applying individual droplet kinematics (Sazhin et al., 2003).

In comparison to round Diesel jets, hollow cone sprays are much less applied in industry. As a consequence, less research work has been done on this configuration to date.

The major difference of the hollow cone spray compared to the Diesel jet is its lower level of stability: The fuel mass distribution of the round Diesel jet exhibits a double (rotational) symmetry in space with respect to the presumed spray center line. By contrast, the liquid sheet of the hollow cone spray is exposed to non-symmetric boundary conditions: Inside the hollow cone, the volume available for carrier phase entrainment is much smaller than the outside of the hollow cone sheet. Depending on injection and gas phase boundary conditions, a recirculation zone is formed. This was observed experimentally both for pressure-swirl injectors (Chryssakis et al., 2003) as well as for piezo-electrically driven, outward-opening injectors (Prosperi, 2008). Based on the assumption of spatial self-similarity and steady state conditions, Cossali (2001) focused on the modeling of the gas entrainment into the spray.

The models mentioned previously are not applicable to injection conditions relevant for engine operation in regard to three important aspects (where the last two result from the first one):

1. Almost throughout the injection process, the two-phase flow is in *transient* conditions: The injector opening and closing events impose transient boundary conditions. When multiple injections are applied, fuel is injected into an altered carrier phase environment (accelerated flow field, increased fuel vapor saturation, etc.). In such transient flow conditions, the steady state assumption is not applicable.
2. Also due to the short injection times, a kinetic equilibrium along the streamwise direction is not reached in general. As a consequence, (transient) streamwise profiles of the conserved variables are formed. This effect necessitates at least a *one-dimensional* description. In particular, a relation for the spray front propagation, which explicitly depends on time-variant injection characteristics (such as injection pressure), lacks accuracy, because it neglects the time required for the injection "signal" to travel from the injection outlet to the current spray front position.
3. Due to the high injection pressures (and consequentially high injection velocities) of the liquid fuel, high slip velocities between the two phases occur locally. In order to capture the changes in the *two-phase* flow field in a transient and one-dimensional description, also the heterogeneous character of the flow has to be maintained, i.e. the two-phase mixture model assumption is not applicable.

In this paper, we propose a transient, one-dimensional, and two-phase description designed for hollow cone sprays. In Section 2, both theoretical and numerical analysis of the injection induced hollow cone spray is presented. It is the basis for the Section 3, which presents a transient, one-dimensional, two-phase hollow cone sheet model. It is based on the identification of a "dense spray zone" (DSZ) onto which the dispersed phase mass is projected in a modeling step. The inter-phase exchange of mass and energy is accounted for by means of modeled boundary conditions to this "dense spray zone". The model is based on a boundary layer description, hence the name "*transient two-phase boundary layer (ttBL) model*". The transient response of the ttBL model to a set of injection boundary conditions is presented.

2. Methodology

In this section, cone specific conservation equations are analyzed based on a suitable coordinate transformation (Section 2.1). Based on the momentum conservation, a boundary layer analysis is performed (Section 2.2). The characteristic length scale associated with the injection induced boundary layer is used later to model the deceleration of the injected liquid droplets. The conclusions are supported by selected results from a CFD analysis (Section 2.3). The findings from the CFD investigation are then utilized to qualitatively discuss the injection induced cross-stream length scales and their temporal evolution (Section 2.4).

2.1. Conservation equations in conical coordinates

The dominant direction of the injection induced flow is the direction at which liquid fuel is injected into initially quiescent carrier phase. For this reason, the conservation equations are transformed to conical coordinates: The starting point is the cylindrical 2D coordinate system (r,z) (Fig. 1). Note that the circumferential dependency is neglected because a zero gradient is assumed in the circumferential direction. The streamwise coordinate ξ and the cross-stream coordinate η, which is pointing towards the outside of the hollow cone, are described by the geometric relations

$$\xi = r\ \sin\theta - z\ \cos\theta \qquad \hat{u} = u\ \sin\theta - w\ \cos\theta, \tag{1}$$

$$\eta = r\ \cos\theta + z\ \sin\theta \qquad \hat{w} = u\ \cos\theta + w\ \sin\theta. \tag{2}$$

The general transport equation of a conserved quantity Φ in terms of the conical coordinates (ξ,η) is

$$\frac{\partial \Phi}{\partial t} + \frac{\partial(\Phi \hat{u})}{\partial \xi} + \frac{\partial(\Phi \hat{v})}{\partial \eta} + \Phi \frac{\hat{u}\ \sin\theta + \hat{v}\ \cos\theta}{\xi\ \sin\theta + \eta\ \cos\theta} = \Phi^{(visc)} + \Phi^{(src)}. \tag{3}$$

Correspondingly, the continuity equations and the streamwise and cross-stream momentum equations are written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho \hat{u})}{\partial \xi} + \frac{\partial(\rho \hat{v})}{\partial \eta} + \underbrace{\rho \frac{\hat{u}\ \sin\theta + \hat{v}\ \cos\theta}{\xi\ \sin\theta + \eta\ \cos\theta}}_{RADconti} = \Gamma^{(evap)}, \tag{4}$$

$$\begin{aligned} &\frac{\partial(\rho \hat{u})}{\partial t} + \frac{\partial(\rho \hat{u}^2)}{\partial \xi} + \frac{\partial(\rho \hat{u}\hat{v})}{\partial \eta} + \underbrace{\rho \frac{\hat{u}^2\ \sin\theta + \hat{u}\hat{v}\ \cos\theta}{\xi\ \sin\theta + \eta\ \cos\theta}}_{RADmomX} = -\frac{\partial p}{\partial \xi} + \underbrace{I_\xi}_{dragX} \\ &+ \mu_{eff}\left[\underbrace{\frac{\partial^2 \hat{u}}{\partial \xi^2}}_{\frac{viscX1}{\mu}} + \underbrace{\frac{\sin\theta\ \frac{\partial \hat{u}}{\partial \xi} + \cos\theta\ \frac{\partial \hat{u}}{\partial \eta}}{\xi\ \sin\theta + \eta\ \cos\theta}}_{\frac{viscX2}{\mu}} + \underbrace{\frac{\partial^2 \hat{u}}{\partial \eta^2}}_{\frac{viscX3}{\mu}} - \underbrace{\sin\theta\ \frac{\hat{u}\ \sin\theta + \hat{v}\ \cos\theta}{(\xi\ \sin\theta + \eta\ \cos\theta)^2}}_{\frac{viscX4}{\mu}}\right], \end{aligned} \tag{5}$$

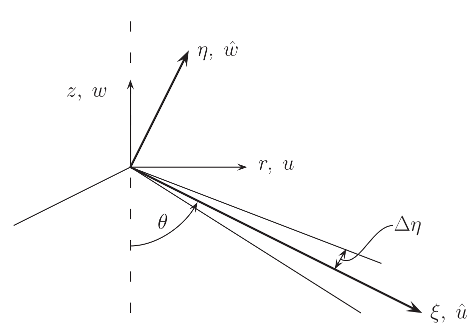

Fig. 1. Cone coordinates.