MODELING AND SIMULATION OF LIQUID FILMS FORMED BY SPRAY-WALL INTERACTION

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ABSTRACT

A mathematical model of formation and transport of liquid films, incorporating a droplet-wall impaction model and exchange mechanisms with the gas-phase, has been developed and incorporated into the STAR-CD computational fluid dynamics code. It has been applied to a test case representation of the multi-point fuel injection in four stroke SI engines. The results indicate that the major features of droplet impaction and film development are reproduced by the model. The qualitative agreement with data in the region of spray impaction is good.

1.0 INTRODUCTION

The formation of liquid films through impaction of a liquid spray on solid surfaces is of practical importance with respect to mixture preparation and combustion characteristics in both SI and diesel engines. It is the former application which is of interest here, but the methodology we describe is applicable to both cases.

The spatial homogeneity and temporal variation of the induction charge composition in SI engines, especially with multi-point fuel injection systems, is critically dependent on the design optimization of the "charge delivery" system, i.e., the intake system configuration, injection system operation parameters and the associated liquid spray characteristics. An influential component of the charge preparation process - especially with respect to combustion characteristics under severe engine operating conditions - is the deposition, transport and vaporization characteristics of the liquid-film(s) formed through impaction of the fuel spray(s) on the solid surfaces of the induction system.

There is evidence that the fuel-film characteristics of the induction process substantially influences the in-cylinder charge (in)homogeneity [1,2], thereby engendering instability of the spark-flame initiation process, cyclic variation of the combustion, and overall impairment of the performance, fuel economy and emissions. However, the large number of intake system design configuration and fuel delivery system operation parameters has rendered performance optimization complicated and time consuming. A fundamental understanding of the liquid film deposition, transport and vaporization characteristics and their dependence on the influential induction/fuel delivery system parameters can assist identification of optimum design optimization strategies and improve the development cost-effectiveness.

The mathematical modeling of the liquid film processes within the framework of multi-dimensional computational fluid dynamics (CFD), in conjunction with the stochastic spray model, offers an expedient tool for investigation of the liquid-gas phase interactions in the SI engine induction system. This paper reports the development of a mathematical model of thin liquid films formed by liquid spray impaction on solid surface, its implementation into the STAR-CD general purpose CFD code, and its application to a test case model of an SI engine intake system. A qualitative comparison of the computations with the experimental data on transient liquid-film development is provided.

The remainder of this paper is organized as follows. The first Section provides a description of the mathematical model of the liquid film and the assumptions invoked in its derivation, and outlines the solution method for the two-phase gas-liquid film flow within the framework of the general non-orthogonal coordinate system employed in STAR-CD code. In the second Section, details of the application test case with regard to geometry, gaseous flow and spray simulation data are provided. Section 3 presents results of the numerical simulation of the transient liquid film and comparison with data. Finally in Section 4, the main findings and conclusions are summarized.

2.0 THE LIQUID FILM CALCULATION METHOD

2.1 The Mathematical Model

The development of a mathematical model of the liquid-film transport is based on the conservation equations for a multiphase flow in the general (non-orthogonal) coordinate system:

$$\frac{\Delta}{\Delta t}\left(J\rho\theta_i\Phi_i\right)+\frac{\Delta}{\Delta x^{(j)}}\left[\rho u^{(j)}\theta_i\Phi_i-\Gamma_{\Phi i}\theta_i g^{(jm)}\frac{\partial\Phi_i}{\partial x^{(m)}}\right]=S_{\Phi i}$$

in which J is the Jacobian of the local coordinate system, $g^{(jm)}$ are components of the transformation tensor, θ_i is the volume fraction of phase "i" and Φ_i is a scalar dependent variable associated with the phase "i".

In obtaining the momentum conservation equation, several choices for decomposition of the velocity vector exist [3]. The present methodology adopts the contravariant physical component decomposition arrangement [3].

The integral equations governing mean (i.e., height-averaged) liquid-film hydrodynamic, composition (component mass fraction, in the case of a multicomponent liquid) and thermal energy conservation are derived, through integration of the general transport equations with respect to normal distance from the surface and invocation of the "stratified two-phase" (i.e., the liquid and gaseous phases) flow condition. The integral equations are exact, but complex for numerical solution in a general coordinate system. Accordingly, in this initial implementation, simplifications are invoked in the light of the fact that in engine circumstances the films are usually "thin".

The integral liquid film conservation equations are simplified within the framework of the boundary layer theory, invoking the principal assumption that the inertial component of momentum transport is negligible. However, the gas-liquid film interfacial exchange terms, the gravitational body-force, and the droplet-liquid film interaction sources are fully accounted for in the governing film transport equations. In particular, the contribution of the incident droplet inertia to tangential - with respect to the surface - liquid film inertia and conversion of its normal incident energy to an effective pressure gradient [4] are taken into account.

The derivation of the integral liquid film mass, momentum and energy conservation equations requires assumptions regarding the profiles of the dependent variables in the direction normal to surface. In the present implementation several options for the velocity profile are catered for, namely the linear profile (Couette flows), the parabolic profile (laminar flow) and the equilibrium turbulent boundary layer profile, in which case the turbulent viscosity of the liquid film is evaluated from an auxiliary mixing length turbulence model [5].

The present liquid-film model also incorporates the Bai & Gosman [6] droplet-wall interaction model.

2.2 The Solution Method

The liquid-film integral transport equations are discretized on a general non-orthogonal surface mesh, adopting explicit temporal and upwind spatial discretization schemes. The solution method is coupled to the stochastic spray simulation method, through the droplet-wall interaction model, and the implicit gas phase solution method through the interfacial shear force.

3. TEST CASE DETAILS

The test case configuration and geometry pertain to the experimental investigations of spray and liquid film development in a specially-constructed intake of a spark ignition engine by Johnen & Haug [7]. This consists of a horizontal square-section channel that incorporates quartz windows for optical access, the fuel injector and the liquid-film measurement instrumentation. The test section is connected to the intake side of a four-stroke SI engine.

The studies of the injection and liquid-film formation pertain to the condition of "fuel storage mode," where the injection starts immediately after the inlet value closure and, hence, the fuel residence is at its longest. The engine and injection system operating conditions are presented in Table 1.

Owing to the absence of experimental details on the injection equipment and the spray characteristics (injection rate schedule, spray angles, droplet size-velocity distribution, etc.) the following assumptions were made in simulation of the 4-hole injector spray:

1. A "square-wave" injection rate schedule was imposed

2. A uniform droplet size of 85 micron, injection velocity of 31m/sec and temperature of 294 were assumed. The injection velocity was derived from the experimental data on the delay time between start of injection and spray impaction on the wall, presented in [7]. This drop size-velocity combination produced droplet incident Weber numbers in the "adherence" mode, according to the criteria reported by Bai & Gosman [6].

3. The 4-hole spray angles were deduced from the photographic data in [7]. A uniform distribution of the injection fuel mass flow between the four injector nozzles was assumed.

4. The gas-phase pressure and temperature boundary conditions for the computational domain were estimated as 0.3 bar and 294 K, since no measurements of these quantities were provided. For this reason, the pressure-wave induced gas-phase flow in the intake system could not be simulated and the gas flow mainly occurred during intake valve opening, assumed to be 0 -180 ADTC intake.

5. The momentum exchange between spray and air was accounted for in the simulations, but the heat and mass exchange were neglected. Inclusion of these effects is in progress.

TABLE 1: EXPERIMENTAL AND COMPUTATIONAL DATA FOR FLOW AND SPRAY SIMULATION

GAS PHASE	
Engine Speed	2000 rpm
Displacement	625 cm^3
Bore/Stroke	85 mm/110 mm
Inlet Pressure	0.3 bar
Inlet Temperature	294 K
LIQUID PHASE	
Fuel	Iso-Octane
Injector	4-Hole
Start of Ignition	120 CAD ABCD (Intake)
Injection Duration	96 CAD
Fuel Mass	11.5 mg/cycle
Fuel Mass/Injector	11.5/4
Injection Schedule	Square-Wave
GEOMETRY	
Dimension	100 mm × 41 mm × 41 mm
Mesh	50 × 21 × 21

The computational mesh and main spray features of the 4-hole gasoline injector are shown in Figures (1) and (2), respectively.

The transient formation and buildup of the liquid film were simulated through several engine cycles. Periodic (i.e., engine-cycle repeatable) solutions were obtained after simulation of sixteen engine cycles.

4.0 RESULTS & DISCUSSION

The results presented in this section pertain to the periodic (i.e., engine cycle repeatable) simulation of a single four-stroke engine cycle.

4.1 Multidimensional Field Results

The multidimensional results of the temporal evolution of the gas-phase velocity field during the engine cycle are presented in Figures 3. The corresponding results for the liquid film, depicting evolution of the film height and film velocity, are presented in Figures 4 and 5, respectively.

The gas velocity results in Figure 3 show the spray-induced velocity fields at CA = 130, 170 and 215 degrees after bottom-dead-center of intake, corresponding to 10, 50 and 95 degrees after start of fuel injection (hereafter, ABCD intake). The velocity field plots for CA = 310 through CA = 525 degrees ABCD intake, shows the decay of the spray-induced gas-phase velocity field, in the absence of pressure waves in the induction system. The vector plots at CA = 600 ABCD intake shows the velocity field generated by the induction process (Inlet Value Opening period is CA = 540 - 720 degrees ABCD intake). This velocity field decays rapidly after the intake valve closure, as depicted by the results at CA 735 degrees ABCD intake. (The residue velocity field at CA = 735 degrees ABCD intake is due to the compressibility effects within the simulation domain.) The gas-phase velocity field decays and becomes almost stagnant prior to the spray injection for the succeeding engine cycle.

The results in Figure 4 show the evolution of the liquid film thickness throughout the engine cycle. The contour plot at CA = 130 degrees ABCD intake show the structure of the periodic residual film, prior to the impaction of the liquid spray on the surface. The liquid film is notably non-uniform, with height variation in the range of 10 - 260μm. During the fuel injection phase, shown at CA = 170 and 215 degrees ABCD intake, the predictions show a continuous buildup of the liquid film in the regions of spray impaction, without major apparent change of the film height non-uniformity pattern.

The plots in Figure 5, depicting the corresponding evolution of the liquid film velocity field, show major influence of the spray on the liquid film structure, owing both to momentum exchange through impaction on the surface and via the interphase shear of induced gas-phase velocity field. The field at CA = 170 degrees ABCD intake shows maximum velocities of order 10 - 20 m/sec at the location of spray-wall impaction; outside the regions of direct spray-wall interaction, the film velocity is of order 0.1 m/sec.

The radial/elliptical spread of the liquid film in the region of direct droplet impaction on the surface, depicted in Figure 4 and indicated by the velocity field in Figure 5, is noteworthy. This is due to the pressure gradient field engendered by the conversion of the normal-to surface droplet energy.

The film evolution during CA = 310 through 525 degrees ABCD intake, depicted by the film thickness plots in Figure 4 and film velocity vector plots in Figure 5, show gradual spread, owing to the remnants of the spray-induced gas-phase velocity field (see Figure 3) and the hydrostatic pressure field. The transformation of the velocity field between CA = 310 degrees ABCD intake and CA = 410 degrees ABCD intake clearly shows the increasing predominance of the hydrostatic field in leveling out the film.

The predictions in Figures 4 and 5 corresponding to CA = 600 degrees ABCD intake show the transport and depletion of the film due to the drag of the gas flow during the induction process. The peak film velocity is of order 4 m/sec the gas mean velocity is of order 25 m/sec. The peak film velocity occurs in regions of maximum film height, so the overall effect, in addition to film drainage, is to reduce the thickness non-uniformity. However, the time-scale of the induction process (1.5×10^{-2} second) is insufficient to eradicate this.

The results at CA = 735 degrees ABCD intake show the liquid film after completion of induction. The film thickness distribution in Figure 4 shows persistence of the major film features associated with the fuel injection/stage. The velocity field in Figure 5, however, indicates a reversion to the pattern associated with the hydrostatic field.

4.2 Temporal Results at Measurement Locations

The temporal variation of the computed liquid film heights at four measurement locations are presented in Figure 6; the corresponding measurements are shown in Figure 7. The measurement locations 4, 3, 2, 1 correspond to X = 28, 38, 48 and 53 mm downstream of the injector location (on the opposite wall), respectively.

The many uncertainties about the gas-phase thermodynamic and flow conditions during the four-stroke engine cycle and numerous assumptions which had to be made regarding the fuel injection and spray characteristics, which are all influential with respect to the liquid film calculations, render quantitative comparison of the computations and measurement meaningless. Therefore, a qualitative comparison is presented here.

The computational results at measurement locations 4 and 3, within the region of two (rear and front) sprays impaction on the wall, show rapid increase of the liquid film thickness corresponding to the fuel injection phase. The liquid film height reduces rapidly, after termination of fuel injection, owing to gravity. This process continues until CA = 540 ABCD intake, i.e., the beginning of the engine induction process. The film height thereafter reduces at an accelerated rate, during the gas-phase induction period CA = 540 - 720 ABCD intake, due to the induced shear imposed by the gas flow.

The predictions at locations 2 and 1 downstream of the spray impaction depict an almost constant film thickness, with small variations associated with the fuel injection and engine induction processes.

The computed temporal variations of film thickness at locations 3 and 4 are in good qualitative agreement with experimental data. In particular, the magnitude of film height variation associated with the fuel injection is well predicted. This indicates is that the liquid-film velocity field induced through droplet interaction is accurately simulated. The predicted "residual" film thickness at locations 3 and 4 and cycle-mean film heights at locations 1 and 2 are in acceptable agreement with data, taking into account the numerous uncertainties and absence of vaporization in the calculations. The most noticeable discrepancy between the computation and measurements at locations 1 and 2 is the apparent passage of large amplitude waves in the experiment. These are likely assoicated with formation of waves at the upstream impaction locations, or induced by gas oscillations due to pressure waves. The identification of the origin(s) of these waves requires more extensive experimental data, preferably the simultaneous film and gas velocities.

5.0 CONCLUSIONS

A mathematical model of thin liquid films, incorporating spray-wall interaction and models for mass, momentum and energy exchanges with the spray and gaseous phase, has been developed and incorporated into the STAR-CD computational fluid dynamics code.

Application of the computational method to a test case representation of multipoint fuel injection in a four stroke SI engine demonstrates that the method can reproduce the major features of spray-wall impaction, liquid film formation and development. Further application and quantitative assessment of the methods in a broader spectrum of test case geometric configurations and injector operation parameters, is necessary for evaluation of the mathematical method.

6.0 REFERENCES

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