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Estimate of Maximum Allowable Droplet Size for Motorcycle Gasoline Direct Injection Engines

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Abstract

Due to their high operating speeds, motorcycle engines with gasoline direct injection would require injectors with finer spray droplet sizes than those currently used in cars. An estimate of the maximum allowable droplet sizes under various engine speeds is useful for proper selection of injectors. Numerical simulations were conducted with a modified KIVA-3V code and a single droplet evaporation model for estimating the maximum spray droplet sizes intended for GDI homogeneous regime. The predicted maximum droplet sizes from KIVA-3V were found to decrease with square root of engine RPM with a minimum of 12 μm at 9,000 RPM. The predictions from the single droplet model exhibit a similar trend and they were higher by about 70% at high RPMs.

1 Introduction

Gasoline direct injection engines (GDI) offer many potential advantages, such as fuel economy, high torque output, and low emission. These positive features have drawn many attractions in both automobile and motorcycle sectors. Mixture preparation prior to ignition plays a very important role in the subsequent turbulent combustion processes within the limited time per cycle in GDI engines. At high and intermediate loads, GDI is intended to operate with stoichiometric/lean homogeneous combustion. At low loads, depending on the fuel injection techniques (spray-guided or wall-guided types), stratified charge is used as the mixture is overall too lean for flame propagation if the mixture is homogeneous. Spray dynamics, including injection, break-up, atomization and vaporization, can have drastic impacts on the formation of combustible mixture. For normal operation, motorcycle engines are operated at RPMs almost twice of those for automobile engines; thus, the time available for droplet vaporization in motorcycle engines is roughly reduced by half. As such, selection of a proper fuel injector is very important to ensure proper droplet size and spatial distribution for the direct injection motorcycle engines.

In order to meet the requirements for producing cleaner and fuel efficient power plants, the state-of-the-art design philosophy and tools are needed. Multidimensional models were developed for predictions of combustion phenomena in the internal combustion engines since the seventies. Now, comprehensive computer models are routinely used to study combustion processes in direct-injection diesel engines, stratified-charge rotary engines, and in homogeneous-charge reciprocating engines, etc.

The objective of the present study is to use numerical analysis for estimating the maximum spray droplet sizes for mixture preparation inside a representative GDI motorcycle engine.

2 Mathematical Formulations

In the beginning of 1940, researches on droplet gasification were merging. Droplet is considered the building block for providing fuel vapour in combustion systems. Droplet researches over the past decades have revealed a wide range of dynamic and energetic complexities. Several self-organized synergetic processes occur under various physical conditions and factors, such as hydrodynamic environmental factors, operational conditions, and thermo-chemical properties of the liquid and gaseous phases. Once the liquid fuel is injected into the engine through the injector, the liquid spray begins to undergo various physical processes and interact dynamically with the turbulent fluid inside the cylinder. Due to the high density of liquid fuel, the momentum of liquid spray has a profound impact on local flow field creating higher turbulence. Injected liquid fuel breaks up into droplets forming a spray. Droplets can collide and coalescence producing droplets of different sizes. Due to the tight confinement of engine, impingement of droplet spray on cylinder walls/piston may occur. Liquid films can form on the wall/piston surfaces and they may evaporate.

In piston engines, the complexities of droplet combustion are further caused by the occurrence of successive multiple transient events including preheating, gasification, ignition, flame propagation, formation of diffusion flame and possible occurrence of the transformation of the flame from a wake or a boundary layer flame configuration to an envelope flame mode and ultimate burn-out [1-2].

Information on transient droplet dynamics is useful to the engine design. A zero-dimensional droplet model has been used for many decades to estimate the engine performance and time and space for droplet vaporization. These droplet correlations could be obtained by experimental methods and numerical simulations. These correlations have been implemented in three-dimensional (3-D) simulation codes, e.g., KIVA-3V [4] subject to the piston engine operational conditions. In the present study, two methods are adopted to calculate the droplet vaporization lifetimes inside the motorcycle engine under motoring conditions: one is one-dimensional transient droplet simulation, and the other uses 3-D KIVA-3V code to estimate the droplet vaporization inside the piston engine. Both methods are described briefly in the following paragraphs.

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(1) 1-D single droplet modelling

The single droplet gasification behaviour is investigated by discretizing the interior of droplet with a one-dimensional numerical model. Air is assumed to surround the droplet, and for the present study, no convective flow around the droplet is included. Such a configuration is used to estimate the maximum allowable droplet size in a lean spray combustion engine. The liquid droplet is assumed to be spherically symmetric and there is one interface separating the interior of liquid droplet from the surrounding air. On the interface, conservation of heat and mass must be met during the droplet evaporation process. The governing equations for the droplet interior flow is modelled as described in literature [5], and they include conversation of mass, species mass, and energy.

(2) KIVA-3V code description

KIVA code [4] solves a set of 3-D conservation equations including the mass, momentum, energy and chemical species coupled with physical sub-models for describing the transient turbulent aerothermochemical processes including the gas phase combustion model, chemical kinetics, heat transfer, spray model, droplet gasification rate etc. Modelling of fuel sprays plays a key role in the design of GDI engines, but the spray models are largely semi-empirical. The developments of KIVA code for modelling multidimensional two-phase flows offer a systematic approach for further improvements in modelling sprays. Since the source code of KIVA-3V (Release 2) is available to public, the code is adopted as the numerical framework in this study

The major assumptions in KIVA-3V code include: (1) the fluid is Newtonian flow, (2) the liquid droplet remains spherical during its lifetime, (3) the internal circulation in the droplet is neglected and the temperature inside the droplet is uniform, (4) the ideal gas law is considered for the gas phase. A spray consists of many complex thermochemical processes involving many droplets in a turbulent gaseous environment. These are multi-scale, time and spatial dependent processes. The description of the spray systems requires the detailed characterization of the exchange of the mass, momentum and energy between the gaseous phase and the droplets. The KIVA code adopts the Discrete Droplet Model (DDM) model for engine spray analysis. Droplet parcels are injected through the injectors with specified initial conditions of droplet position, size, velocity and number of droplets in the parcels according to the size distribution or prescribed injection velocity profile, initial spray angle, liquid fuel temperature and injected fuel rate at the injector nozzle exit. The KIVA-3V code has been modified to include an advanced droplet break up model with combined Kelvin-Helmholtz (KH) surface waves and Rayleigh-Taylor (RT) disturbances [1]. This model is used in the current simulation.

3 Numerical Analysis and Procedures

3.1 1-D single droplet simulation

The numerical code is developed on the basis of the algorithm from literature [5] to solve the governing equations for the interior droplet flow and the interfacial equations simultaneously. As illustrated in Figure 1, the grid system is similar to the staggered grid concept and adopted to locate the variables in the grid cell center and face during the computational processes. Time stepping is performed for a fixed period of time during which air temperature and pressure vary according to the instantaneous engine condition during the intake and compression strokes. The thermo-chemical and liquid fuel properties of gasoline are taken from KIVA-3V fuel library. Due to the simplicity of the 1-D model, each run only takes less than a minute on a Pentium CPU; thus enabling us to perform a fast estimate.

3.2 KIVA 3V R2

In order to provide efficient solutions to the time-dependent multi-dimensional fluid dynamics with coupling two-phase source terms and complex moving geometries, KIVA-3V code [3-4] implemented the Arbitrary Lagrangian Eulerian (ALE) computing method, which is both Lagrangian and Eulerian in nature and they are applicable to flows at all speeds. The ALE method uses the finite volume method to discretize the equations for the gas phase. The KIVA-3V code is run to simulate a representative GDI single-cylinder motorcycle engine using a grid sketched in Fig. 2. The calculation starts from the beginning of intake process and finishes at the end of compression stroke at top dead center (TDC).

4 Results and Discussions

The maximum allowable droplet size is determined by two numerical codes according to the droplet vaporization status and remaining liquid droplets and described in the following paragraphs respectively.

4.1 Single droplet results

The evaporation of a single droplet is simulated with surrounding pure air during the intake and compression strokes. A well-mixed reactor with the Woschni heat transfer model and engine wall temperature at 430 K is used to determine the temperature and pressure histories during these two strokes. During the intake stroke, the air flow through the intake valve is modelled by an equivalent orifice formulation with a discharging coefficient of 0.6 using the same valve lift profile used in the KIVA-3V code. Figure 3 presents the predicted temperature and pressure profiles versus CAD for a 4-stroke pent-roof engine with a compression ratio of 9.7 and displacement volume of 560 cc. The predicted temperatures inside the cylinder can drop slightly below the initial temperature (310.15 K) during the intake stroke (CAD from -360^o to -180^o) when the engine speed exceeds 3,000 RPM due to low volumetric efficiency and less time for heat transfer. Both peak temperature and pressure increase with engine speed. The maximum allowable droplet size at the beginning of intake stroke is determined such that the droplet is completely vaporized at the end of compression stroke.

Figure 4 presents the square of maximum allowable droplet diameters normalized by their initial values versus CAD for different engine speeds showing almost identical development. For single droplet evaporation in air at constant temperature and pressure, the well-known D-square law would be represented by straight lines. Due to the varying temperature and pressure history during engine intake and compression strokes, the time evolution of D-square follows a slightly different path. During the intake strokes, the air temperature inside the cylinder drops causing the evaporation process to slow down. After the intake process and during the early part of compression stroke, the droplet evaporates at a rate following closely the D-square law. At the end of compression stroke, air temperature increases sharply leading to a fast evaporation process near TDC.

The corresponding average droplet temperatures are plotted in Figure 5 showing a similar trend following the air temperatures plotted in Figure 3. As engine speed increases, less time is available for heat transfer from engine wall to the air inside the cylinder. The air temperature drops below ambient temperature (300 K) during the intake stroke. This drop becomes larger at higher RPM as revealed in the figure. The results from the single droplet simulation provide a crude estimate of the maximum allowable droplet size at a given engine RPM as droplet interactions and possible impingement on engine walls are not included. The predicted maximum droplet sizes are summarized in Figure 6 and they decrease with engine speed in a manner different from the trend of 1/RPM based on the estimate of residence time only. At 1,000 RPM, the predicted maximum allowable droplet size is about 61 μm. At the highest engine speed at 9,000 RPM, the allowable droplet size is 21 μm. The predicted results can be fit very well by a curve as

$$D_{\max,allowable,Single-droplet} \approx 1970/\sqrt{RPM} \quad \mu m. \tag{1}$$

The above relation is believed to result from the increases of peak temperature and pressure with RPM during the compression stroke as heat transfer is less at higher RPM.

4.2 3D simulation results

Three-D simulations of spray dynamics were carried out for a pent-roof 4-stroke engine with a grid system of 45,000 cells. The coarse grid is used so that each simulation takes about 2 hours to perform on an Intel CPU computer. Increasing the grids to about 70,000 cells did not significantly change the outcome. Three thousand droplets were used and the injection takes place at 70 CAD after the beginning of intake stroke with injection angles toward the cylinder center. A typical result is presented in Figure 7 showing the initial development of droplet spray. Different injection speeds were tried to produce different initial droplet sizes. By trial and error, the maximum droplet size is determined when 95% of liquid fuel is vaporized at the end of the compression stroke. In Figure 6, these maximum droplet sizes expressed in terms of Sauter Mean Diameter (SMD) are compared with the predicted maximum sizes obtained from the simple 1-D droplet evaporation model. The results from KIVA-3V can be fit reasonably well by

$$D_{\max,allowable,KIVA-3V} \approx 1291/\sqrt{RPM} \quad \mu m. \tag{2}$$

Similar to the WMR predictions, the predicted peak temperature and pressure also increase with engine speed. As more physical processes (e.g. droplet break-up, collision and coalescences, droplet impingement on cylinder walls and piston top) are included in the simulation, the KIVA-3V predicts lower maximum droplet sizes compared to those from the simplified 1-D model. However, at low RPMs, the two predictions are found to approach each other as there is sufficient residence time to vaporize most of the droplets. As engine speed increases, the differences between the two model predictions increase but maintaining a reasonable ratio. This suggests that the 1-D single droplet model can be used as a rough estimate. For example, at 9,000 RPM, the 3-D model gives maximum allowable size of 12 μm about 57% of that predicted by the 1-D model.

4.3 Fuel Injector Nozzle Size

Based on the predicted results in Figure 6, the fuel injector will need to produce an initial spray with droplet size about 10 μm at 9,000 RPM. This requirement is smaller than the 15 μm often quoted for the automobile applications [6]. For a given injector, the droplet size scales roughly inversely with the square root of injection pressure. For GDI motorcycle engines, the injection pressure needs to be about twice of that used in GDI automotive engines if the same injectors are used.

5 Conclusions

An estimate of the maximum allowable droplet sizes under various engine speeds has been conducted for a perspective gasoline direct injection (GDI) motorcycle engine. Numerical simulations were conducted with a modified KIVA-3V and a single droplet evaporation model for estimating the maximum spray droplet sizes intended for the GDI homogeneous regime. As residence time decreases with engine speed, both models predict a decrease in the maximum allowable droplet size with engine RPM. Both results can be reasonably scaled by $D_{max,allowable} \sim 1/\sqrt{RPM}$. The predicted maximum droplet size from KIVA-3V was 12 μm at 9,000 RPM (the highest anticipated engine speed). The prediction from the single droplet model gives 21 μm. The differences are attributed to the lacking of details in droplet spray in the single droplet model. However, the overall correlation between the two predictions is good over all the engine speeds suggesting that the 1-D single droplet model can be used as a rough estimate for selecting GDI injector.

6 Acknowledgements

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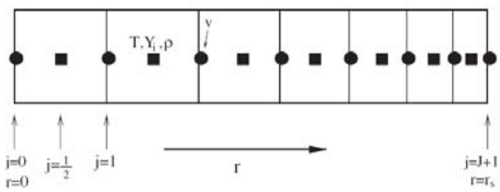

Fig. 1 Schematic of one-dimensional grids for the interior of single droplet simulation adopted from [5].

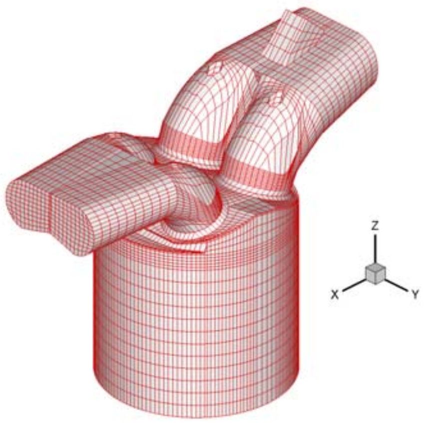

Fig. 2 Grid system used in KIVA3-V R2 simulation.

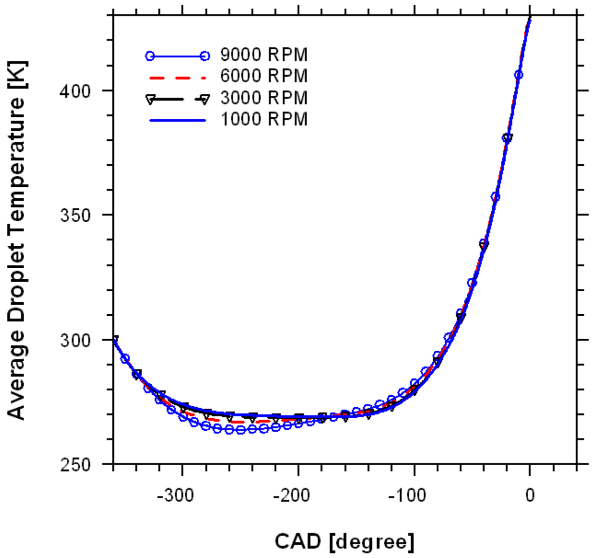

Fig. 5 Average droplet temperature value versus crank angle degree (CAD) for different engine speeds.

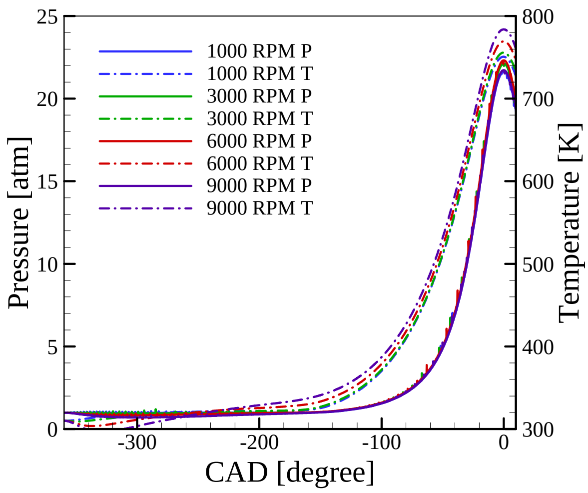

Fig. 3 Pressure and temperature time histories inside the GDI engine motoring for different engine RPMs.

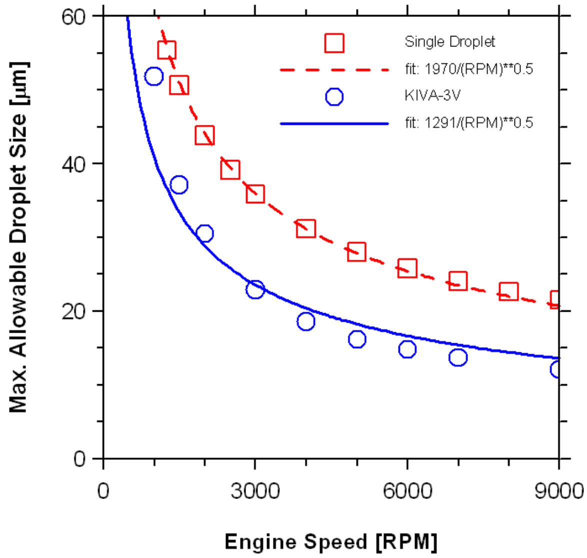

Fig. 6 The maximum allowable droplet sizes for different motorcycle operational conditions. Both predictions can be scaled well by $D_{max.\ allowable} \sim 1/\sqrt{RPM}$.

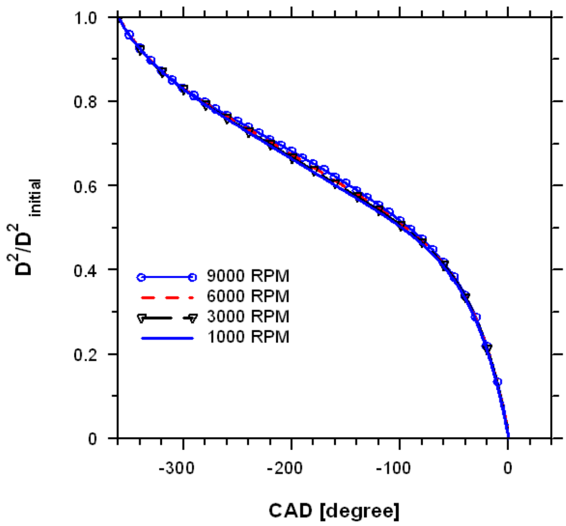

Fig. 4 Square of droplet diameters normalized by their initial values versus crank angle degree (CAD) for different engine speeds.

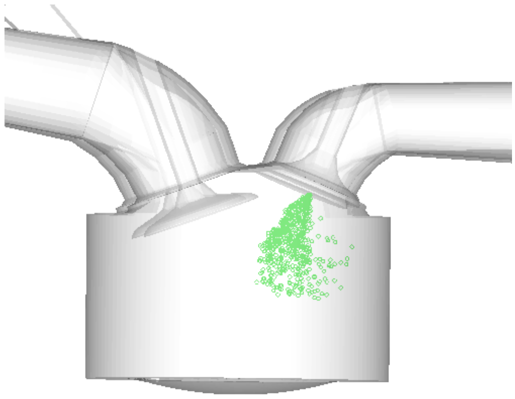

Fig. 7 A typical GDI spray pattern predicted by KIVA-3V for a proposed GDI motorcycle engine.