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.

Spray dynamics, including injection, break-up, atomization and vaporization could have drastic impacts on the formation of combustible mixture and mixture preparation prior to ignition plays a very important role in ignition and combustion inside the GDI engines. In the previous study [1-2], 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. Numerical simulations were carried out to estimate the maximum spray droplet sizes intended for GDI homogeneous regime. The predicted maximum droplet sizes were found to decrease with square root of engine RPM with a minimum of 12 μm at 9,000 RPM.

In piston engines, the complexities of droplet combustion are caused by the occurrence of successive multiple transient events including preheating, gasification, ignition, flame propagation, formation of diffusion flame and ultimate burn-out. The liquid spray consists of a statistical collection of droplets and clusters which undergo group combustion behaviors [3,4] due to the collective interactions among droplet clusters. The combustion structures attributed to group combustion theory in diesel engines exhibit the complexities in modern spray and droplet science technology and its group combustion modal transition has been regarded to play the major role on emissions and performance in practical spray systems [5].

The present study is to update the physical models in KIVA3V [6] and simulate the spray combustion characteristics inside the motorcycle gasoline direct injection engines. The time histories of the spray injection, fuel vaporization, and flame kernel formation and development are obtained to elucidate the in-cylinder spray combustion phenomena. Spray injection timing plays a fatal role in mixture preparation, and the subsequent turbulent combustion processes within the limited time per cycle in GDI engines. Group Combustion theory is adopted to describe the group vaporization and
combustion among the interacting droplets and surrounding gas. The global Chiu number is proposed and calculated to elucidate global group combustion modal change inside the motorcycle GDI engine.

2 Numerical Simulations

To describe the physical modeling of spray combustion inside the internal combustion engines, two phase flow theory including chemical reactions and spray vaporization are used to establish the Eulerian and Lagrangian equations for the gas and liquid phases respectively. The updated KIVA3V-R2 capabilities in the present study include shell ignition model, KH-RT breakup model, flame surface density model, artificial neural network for autoignition, combination with chemkin, and also modifications for multi-cycle runs allowing different valve profiles and fuel mixtures. The original grid generation code in KIVA3V is used to generate the computational mesh close to the real 500CC motorcycle engine geometry. The grid system used in this study is shown in Fig. 1.

In this study, the geometrical group combustion number, \( G_c \), is defined on the basis wherein how the liquid spray structures relax along spray evolution with the droplet size and change of number density by neglecting the convection effect [5]. The original group combustion number defined above is expressed as \( G=Ge*Cv \), where \( Cv \) is used to account the convection effect. On the basis of droplet number density, the above equation can be reduced to the following form, named as the global Chiu number in this study, as follows:

\[
G = 2\pi ndR_c^2
\]

where \( n \) is the droplet number density, \( d \) is the droplet sauter mean diameter and \( R_c \) is the characteristic droplet cloud spherical radius. The characteristic length, \( R_c \), of the in-cylinder volume should be defined and obtained by considering the equal-sized droplet cloud sphere.

3 Results and Discussions

The modified GDI motorcycle 4-valve piston engine is derived from the original 500cc PFI engine, and the spray-guided GDI type is selected for the fuel mixture preparation. The Bosch GDI injector with one 547 \( \mu \)m hole is adopted to deliver the high pressure fuel flow into the combustion chamber at 100 bar with the hollow cone spray. At 2500 rpm, the injected fuel mass is 23 mg according to the liquid fuel delivery rate obtained by the experimental measurement group at Advanced Engine Research Center, Kao Yuan University. The initial fuel injection velocity is 110 m/s with the discharge coefficient at 0.6 and spray hollow cone angle is 60 degrees with 10 degrees thickness. Once the liquid fuel is injected at 120 CAD with the 34.2 CAD duration, the KH-RT breakup model is applied to account the droplet breakup behaviors with the proper constants obtained from the constant volume fuel injection validations.

The development of spray injection and fuel vaporization is shown in Fig. 2 to demonstrate the multi-interactions among spray, droplet and in-cylinder flow. Once the liquid fuel directly injected into the cylinder, the liquid droplets are heated up and start to vaporize to form the fuel vapor. The fuel vapor cone is observed and kept until 150 CAD. After 150 CAD, the entrained air destroys the fuel vapor cone and the fuel vapor is mixing with the air intensively to form the air-fuel mixture. The wall impingements are observed after 150 CAD, and there are amount of liquid fuel forming the liquid film on the cylinder and piston walls with accumulated mass at 0.04 mg and 0.02 mg respectively.
The in-cylinder liquid fuel is fully vaporized after 270 CAD and the flame kernel is initialized at 300 CAD. The initial high temperature flame kernel is shown around the ignition region at 305 CAD, but decreased to lower temperature for 30 degrees due to the fuel vaporization heat sinks. At 345 CAD, the air-fuel mixture is ignited at near ignition region and form the high temperature iso-surface very quickly, and spread radially against the crank angles.

The post-processing program is also developed to calculate the burn duration, thermal efficiency and combustion efficiency to facilitate the analysis and design of the modern motorcycle GDI engine and aid to design the optimal engine control strategy. At 2500 rpm case as shown in Fig.3, the burn duration is 46.1 CAD, the thermal efficiency is 34.9 %, and the combustion efficiency is 89.5 %. The design tool is well established to conduct the parametric study, such fuel start of injection (SOI) to investigate the combustion characteristics and performance of the GDI engine. The better performance is found between 85 to 100 CAD SOI.

Global Chiu number defined in this study is regarded as the measure of droplet group tightness under the aerothermalchemical environment. The effect of fuel injection timing on the global Chiu number is shown in Fig. 4 to demonstrate the transient Group combustion characteristics. Two major scenarios, characterized by the characteristic point: pre-ignition (θ_{ig}) (the largest G-value) includes the pre-vaporization, and post-vaporization regions, which exhibit the overall spray vaporization complexities inside the GDI engines. The ignition transience featured by sudden G-valued transition after pre-ignition point (θ_{ig}) is regarded as the unique group combustion phenomena in the GDI engine. Before the start of ignition (300CA), the group combustion mode changed from external mode to internal...
mode and finally single droplet mode. The fuel injection timing at 110 CA results in the best thermodynamic efficiency and its the critical value \( G^* = 1.0 \) for transition between external and internal group combustion modes is located at about 200 CAD.

4 Conclusions

The updated spray combustion simulation code is developed and applied to analyze the in-cylinder spray evolution, and flame propagation to investigate the combustion characteristics and engine performance, and aid the design of motorcycle GDI engine. The analysis at different SOI is performed and the better engine performance is found with the proper SOI range. The dynamic transience of the \( G \)-valued degeneration and variation in the spray evolution against the crank angle is examined and correlated to the engine performance and combustion efficiency. The further simulations with different operating parameters will be performed to aid the investigation of transient group combustion behaviors inside the motorcycle GDI engine.

References