International Journal of Thermal Sciences 115 (2017) 210–224

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Performances analysis of novel heated tip injector with multi-physical fields coupling simulation

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ARTICLE INFO

Article history:
Received 5 May 2016
Received in revised form
25 January 2017
Accepted 4 February 2017

Keywords:
Heated tip multi-hole injector
Multi-physical fields coupling
Electromagnetic field
Fluid flow
Spray

ABSTRACT

A novel heated tip multi-hole spark ignition direct injection (SIDI) injector is designed and manufactured. Compared with the conventional SIDI injector, the novel heated tip SIDI injector can heat the fuel and increase the fuel temperature in a short time. The relationship and formation among the electromagnetic, thermal, fluid flow and spray fields are analyzed based on coupling theories. The data information interface platform based on the commercial software is used to calculate the key parameters of the novel SIDI injector. The coupling models based on FEM (Finite element method) are established to analyze the comprehensive performances systematically. The systematic experiments are utilized to validate and verify the coupling mechanism and the accuracy of the simulation model. In order to investigate the relationship between the temperature and performances of the injector, the multi-physical fields coupling analysis of the novel heated tip SIDI injector are carried out by simulation and experiments. According to the systematical analysis, it is found that the heat generate from the heater and magnetic circuit is the most significant factor that influence on the electromagnetic field, fluid flow and spray. The experiment and simulation result shows that the maximum temperature on the heater of the SIDI injector is about 160 °C, which is sufficient to heat the fuel in the injector chamber to boiling, and the flow pattern moved to a developed cavitation at a higher temperature. The main spray plumes completely disappear as the temperature achieves 120 °C, which indicates that the spray has totally collapsed, and the spray particle size can be significantly reduced by increasing the fuel temperature.

1. Introduction

Spark ignition direct injection (SIDI) engine have become dominant in the recent automotive market, as SIDI engines have significantly improved fuel economy, faster transient response and lower cold start emissions, comparing with the traditional port fuel injection (PFI) gasoline engines [1,2]. In order to reduce the emissions and fuel consumption during cold-start, some fuel-heating system with conventional heat approaches were performed, such as water bath [3], microwave generator [4], and external heated tip [5]. However, all the heat approaches mentioned above are difficult to build the systems in a small volume, and most of them have lower heat efficiency and response speed. Because of the disadvantages mentioned above, a novel heated tip multi-hole SIDI injector with inner heater and controllable temperature is designed to solve the problems.

For SIDI engines, the fuel is directly injected into the cylinder. After fast atomization and evaporation, the gaseous fuel mixes with fresh air to form combustible mixture. This process goes on for a very short time, and fast fuel droplet breakup and quick evaporation are necessary. In order to promote the atomization and vaporization process of liquid fuel, high injection pressure is a well-accepted way for engine manufacture enterprises. Currently the fuel injection pressure for SIDI engines is higher than 25 MPa, the Sauter Mean Diameter (SMD) of the droplet sizing is in range of 5–20 μm [6]. Although high injection pressure can improve the atomization and vaporization of liquid fuel, it will also bring some problems. Firstly, the fuel injection with longer penetration due to high injection pressure could easily hit the piston surface and/or engine cylinder walls, resulting in high level of unburned hydrocarbon (UHC) and soot emissions [7,8]. Secondly, all the fuel apply system must be tough and tensile enough to endure this high pressure, and advance materials and technology are also needed to satisfy the requirements. Besides, the droplet reduction effect of

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http://dx.doi.org/10.1016/j.ijthermalsci.2017.02.002
1290-0729/

high injection pressure is diminished when the injection pressure increase to a high level. Therefore, the way to reduce the droplet size by high injection pressure will cost much but with lower income [9]. In order to overcome these shortcomings, the new ways of utilizing high temperature to improve the characteristics and formation of fuel spray have been founded by some experts, for example, Jason Charles Short [10], Qing N. Chan [11] and M. Levy [12], etc. Especially, when the fuel temperature exceeds the local boiling point, the fuel is superheated and the sprays will experience flash boiling process. Comparing with the non-flash boiling liquid spray, the flash boiling spray shows severe spray structure transformation, remarkable different fuel air mixing and significantly reduced droplet size [13–15]. All those observation indicates that different mechanisms govern the atomization and vaporization process of flash boiling spray and non-flash boiling spray.

With the progress of the computer science and mathematical technique, large scale simulation analysis has been widely used to investigate the comprehensive performances and process principle of the mechanical-electrical products, especially for multi-physical fields coupling problems. Peiman Naseradinmousavi [16] established a coupled nonlinear mathematical model for electromagnetics, fluid dynamics and mechanical dynamics of the butterfly valves driven by solenoid actuators. E. Lisowski [17] calculated the forces associated with the flow process (pressure force and viscous force) using 3D CFD modeling, and the accuracy of the CFD simulation results was satisfactory. S.V. Angadi [18] used a comprehensive multi-physical theoretical model based on the finite element method to analyze the performance of a solenoid valve. The multi-physical model included the coupled effects of electromagnetic, thermodynamics and solid mechanics was established. The temperature distribution, mechanical and thermal deformations, and stresses are analyzed by FEM simulation.

The aim of this paper is to analyze the process principle and coupling mechanisms of a novel heated tip multi-hole injector. The multi-physical fields coupling simulation based on finite element is used to calculate the electromagnetics, fluid dynamics, mechanical dynamics, thermodynamics and spray characteristics of a novel heated tip multi-hole injector. The multi-physical fields coupling simulation methods and experimental approaches include infrared thermal imaging technique, transient laser displacement test technique, and high-speed photography technology, etc. are used to analyze its comprehensive performances.

2. SIDI injector configuration and working principle

For SIDI engines, the fuel is injected directly from the multi-hole injectors, usually at an injection pressure of 5–20 MPa. The cross-sectional view of heated tip SIDI injector is presented in Fig. 1. The main components include nozzle (with 5–8 cylindrical or conical holes of diameter ranging from 150 μm to 250 μm), heater, coil, nozzle needle with solenoid armature, spring, etc. The injectors are electronically controlled by a solenoid actuator, and it can withstand a high pressure of 25 MPa. A magnetic field is generated when the current passes through the coil, and then the actuator lifts the needle to open the valve at the precise time, and a metered amount of fuel is injected into the cylinder. The spray plumes directions and injector opening timings are adjusted according to the design and application of engine. When the coil is de-energized, the valve needle is pressed back down to the valve seat by the spring force, and the fuel injection process is stopped. For the novel heated tip injector, there is a heater at the tip of the SIDI injector, and it is used to heat the liquid fuel in the nozzle. The heater is driven by PWM voltage, and the fuel temperature can be controlled at different condition.

3. Multi-physical field models

3.1. Multi-physical field coupling formations

According to the multi-physical field coupling mechanism, there are six different coupling formations, including direct/indirect, single direction/dual direction, strong/weak, boundary/region, algebra/differential and quasi-static/kinetics coupling [19]. All these coupling formations have effect on the SIDI injector. Therefore, it is difficult to descript the problem clearly with the conventional methods. In order to establish the multi-physical coupling model, a simplified block diagram is used to descript the relationship among the different coupling formations, as shown in Fig. 2.

3.2. Simulation mechanism

In order to carry out the multi-physical field coupling simulation, a data information interactive platform is established based on the commercial software ANSYS Workbench™. The solving mechanism is descripted in Fig. 3. Firstly, the 3D model is built in the SOLIDWORKSTM, and saved as the format which can be accepted by the simulation software. Secondly, the driven circuit is designed in the Simplorer™, and then the electronic and magnetic are coupled in Ansoft Maxwell™, the simulation results data is input to the data information interactive platform. The simulation results data include current on the coil, magnetic field parameters, magnetic force, dynamic response and power losses, etc. Thirdly, the software ANSYS Thermal™ is used to transfer the simulation data which is generated by the Ansoft Maxwell™ to calculate the temperature rising. The temperature data is input to the data information interactive platform. Fourthly, the temperature data is set as boundary condition in the FLUENT™ for inner flow simulation. After inner flow simulation, the inner flow simulation data is used to simulate the spray characteristics.

4. Simulation and experiments

4.1. Electro-magnetic simulation

The 2D and 3D transient finite element code Ansoft Maxwell™ is used to simulate the electro-magnetic characteristics of the magnetic circuit of the SIDI injector. The non-linearity BH curve of the soft magnetic material and the electromagnetic loss are considered in this investigation. It can be seen from Figs. 4–6 that when the temperature is increased the magnetic flux density is reduced, the magnetic induction intensity is weaken, and the total loss is increased. All mentioned above are unfavorable to the comprehensive performance and life time of the SIDI injector. So the detailed analysis must be done to reveal the mechanism of the multi-physical fields coupling of SIDI injector.

4.2. Thermal simulation

In order to validate the multi-physical field coupling simulation results, the infrared thermal imager (Type: Fluke Ti27) is used to measure the temperature distribution at different time. Fig. 7 indicate the temperature distribution of the SIDI injector before and after optimization with the working time of T = 120s. The multi-physical field coupling simulation results are in good agreement well with the experimental results, and the highest temperatures are almost the same.

To reveal the mechanism of temperature rising, 3D electronic and magnetic transient simulation model of the SIDI injector are imported to Ansoft Maxwell™ for magnetic field and power losses