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Research article

Prediction of wall impingement in a direct injection spark ignition engine by analyzing spray images for high-pressure injection up to 50 MPa

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ABSTRACT

This study was performed to analyze the wall impingement and fuel film formation in a DISI engine with injection strategies using image-based analysis and CFD. The direct injection engine uses a high-pressure injection strategy to improve the homogeneity of the air-fuel mixture, so the spray behavior was analyzed by spray visualization for various injection pressures, and the wall impingement was predicted for various engine operating conditions based on the acquired images. The mass distribution of the injected fuel was calculated using the injection profiles and the spray image, and the amount of fuel that impinges on the piston and wall (i.e., the geometric boundaries of the cylinder) was calculated using data from the spray behavior for various engine operation conditions such as load and engine speed. The image-based analysis was limited to understanding the influence of the injection strategy on the droplet behavior after wall impingement of the fuel spray. Therefore, CFD using KIVA 3 V code was additionally conducted to analyze the effects of the injection strategies on wall film formation and droplet rebounding reflecting in-cylinder conditions. In the early- and late-injection conditions, the initial piston position is high, and most of the injected fuel impinges on the piston. As the injection pressure increases, the injection timing at which wall impingement occurs is advanced because of the rapid spray development. The results of the 3D analysis for the temperature and the intake flow in the engine cylinder showed that both the wall impingement and the fuel film were reduced as the injection pressure increased because the fuel evaporation increased due to improved atomization.

1. Introduction

Gasoline engines are widely used as power sources for automobiles today because of their quiet operation and high-power output. Injection systems for gasoline engines have evolved into today's DISI (direct injection spark ignition) engines, in which fuel is supplied into the cylinder directly from the carburetor system through the port injection system. A three-way catalyst has been developed that helps to reduce the exhaust emissions of premixed combustion as a response to environmental pollution problems caused by exhaust emissions of vehicles. To maximize the exhaust emission reduction efficiency of the three-way catalyst, theoretical air-fuel ratio combustion techniques were generalized, and the existing carburetor was replaced by a fuel injector for precise fuel mass control. In the PFI (port fuel injection) injection system, the fuel spray is injected into the intake port and it is targeted at the high temperature intake valve to increase the homogeneity of the mixture in a short period of time. The direct injection system has been introduced to improve the efficiency of the gasoline engines because of global warming caused by greenhouse gas emissions from automobiles and fuel efficiency issues. When the fuel is directly injected into the cylinder, the latent heat of evaporation is absorbed from the intake air in the cylinder, so that the thermal efficiency can be increased by applying a higher compression ratio. However, the uniformity of the mixture can deteriorate in the direct injection system as compared with the port injection system in which the vaporized fuel is supplied to the cylinder by being mixed with the intake air [1,2]. In the direct injection engine, fuel evaporation and mixture formation should sufficiently occur until the end of the compression stroke, wherein spark ignition occurs. The fuel injection strategy is important in the DISI engine because the atomization performance determines the exhaust emission characteristics of the engine. To maximize the quality of the air-fuel mixture in a short period of time, the fuel injection pressure of direct injection engine is higher than that of the port injection system, and the injection pressure of the gasoline direct injection engine has been continuously increased to satisfy emission regulations. PN (particulate number) is a huge emission problem because of

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Nomenclature

E	splash Mach number
E_{crit}	critical splash Mach number
m	incident mass
m_s	splashed mass

Abbreviations

BTDC	Before Top Dead Center
CFD	computational fluid dynamics
DISI	direct-injection spark-ignition
KH	Kelvin-Helmholtz
RT	Rayleigh-Taylor
SMD	Sauter mean diameter

inhomogeneous mixtures in gasoline direct injection engines [3,4]. Various attempts have been made to reduce the fine particles such as ultra-high-pressure injection strategies and attaching gasoline particulate filters. When the fuel injection pressure is increased, the momentum exchange between the fuel and the intake air occurs quickly because of the rapid spray development. A longer time for mixing can occur until ignition after the end of injection because of the shorter injection duration. However, in direct injection engines, the fuel wall film, which adversely affects the exhaust performance, can form on the top of the piston or at the cylinder liner because of the rapid spray development when using a high-pressure injection strategy. Therefore, the injection strategy in direct injection engines is very important, and it should be able to maximize mixing performance and prevent formation of the fuel wall film. A variety of studies have been carried out on the injection strategy and wall film formation in gasoline engines.

Lee et al. [5] analyzed the macroscopic spray behavior and atomization performance of the multi-hole DISI gasoline injector using a high-pressure injection strategy through spray visualization, droplet size and velocity measurements using a PDPA (phase Doppler particle analyzer) system. Spray, air entrainment, branch-like structures and droplet detachment are observed in the atomization process of gasoline. In addition, jet-to-jet interactions increase as injection pressure rises in multi-hole sprays. Measurements of droplet size and velocity using PDPA equipment have shown that the spray head period becomes shorter as the injection pressure increases because of rapid spray development. Also, the fuel atomization and mixing performance are improved because of larger momentum exchange between the fuel spray and ambient gas. Schulz et al. [6] visualized the wall film formation in a constant-volume chamber using a laser induced fluorescence technique to quantitatively compare wall film formation for various conditions because the wall film is a cause of soot and hydrocarbon emissions in the DISI engine. They reported that about half of the injected fuel was deposited as a wall film at low wall temperature depending on initial warm-up conditions, but the evaporation characteristics improved as temperature increased. However, a small amount of the fuel film still existed when injection began at the early stage of the intake stroke. As the distance between the nozzle and the wall increased, the amount of fuel in the fuel film decreased, and the film thickness decreased because of improved atomization with the use of a high-pressure injection strategy. To reduce the formation of the wall film, which determines the exhaust characteristics, an appropriate injection strategy should be selected depending on the engine operating conditions.

Various studies have been carried out on the spray behavior and wall film formation when applying high pressure injection strategies [7–9]. However, there is a limit to predicting the wall impingement phenomena depending on the piston movement and spray development in the cylinder under various engine operating conditions. It is possible to visualize in-cylinder spray behavior and mixture formation processes using an optical engine. However, it is hard to take clear spray images

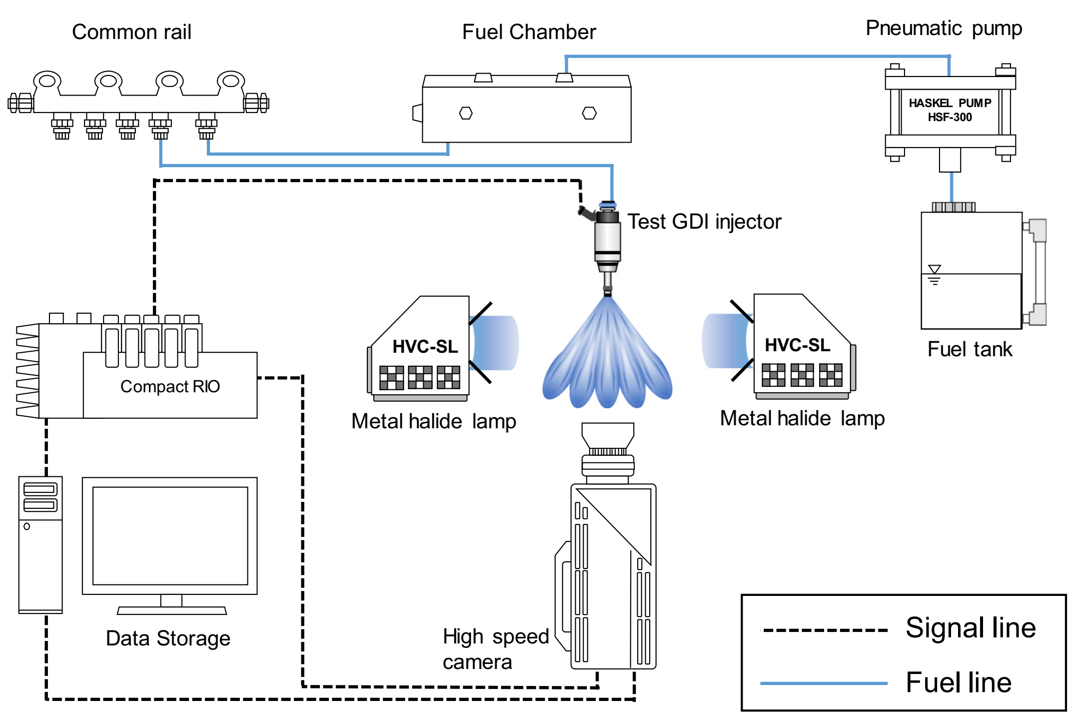

Fig. 1. Experimental apparatus for spray visualization.