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Full Length Article

Combined effects of piston bowl geometry and spray pattern on mixing, combustion and emissions of a diesel engine: A numerical approach

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ABSTRACT

In the present work the combine effects of spray angle and the piston bowl geometry on mixing, combustion and emission characteristics of a direct injection diesel engine have been analyzed numerically. The piston bowl geometry is one of the most important factor that affect the air fuel mixing and combustion and emissions in a direct injection diesel engine. Four spray angles 150°, 155°, 160° and 165° and three different piston bowl geometries namely Toroidal Re-entrant Combustion Chamber (TRCC), Toroidal Combustion Chamber (TCC) and the baseline Hemispherical Combustion Chamber (HCC) have been considered for the same compression ratio of 17.5 and with same chamber volume for all three cases. To simulate the in-cylinder flow and combustion computational fluid dynamics (CFD) modeling based AVL FIRE code was performed and experimental results of the baseline hemispherical bowl were used to validate the numerical model. Simulation results show that spray angle significantly affects the mixing and combustion process for all three bowl geometries and the engine having TRCC type of combustion chamber gives better performance.

1. Introduction

The internal combustion (IC) engines play a dominant role in the fields of transportation of goods and passengers, powering agricultural equipment and industrial applications. Diesel engines are preferred for heavy-duty usage as they can develop more power at lesser fuel consumption. Although the direct injection diesel engine is a better choice among internal combustion engines as a prime mover considering fuel economy and exhaust emissions. Therefore the efforts are being put to improve them further to meet future stringent demands of fuel economy and pollution. In diesel engines, there is a strong relationship between air fuel mixing process and combustion since both the processes occur simultaneously. The most important phenomena are the fuel atomization, collision and break-up of fuel droplets, their momentum, energy and mass exchange with the air and the droplet-wall interaction. The fluid dynamics in diesel engine is highly transient accompanied by the piston bowl configuration, which make it one of the most important aspects for designing combustion chamber. Therefore, proper understanding of the effect of the piston bowl shape on the air fuel mixture and thus how it affects the combustion process is required in order to maintain outstanding engine performance and reduce exhaust emissions.

The performance and emission characteristics of compression ignition (CI) engines mainly depend upon the combustion process. Combustion of fuel in diesel engines depends on the efficient fuel atomization, to increase the surface area of the fuel in order to attain improved air-fuel mixing and increased evaporation rates. The reduction in the average droplet diameter increases the heat release rates, facilitates ignition, provides excellent vaporization and thereby improves combustion efficiency and reduces the pollutant emissions [1]. When there is swirl in the in-cylinder air, the swirl–squish interaction produces a complex turbulent flow field at the end of compression. This interaction is much more intense in re-entrant combustion chamber geometries [2]. The primary factor, which controls the diesel combustion, is formation of mixture. The mixture formation is controlled by the characteristics of the injection system, the nature of air swirl, the turbulence in cylinder, and the spray characterization [3]. Venkateswaran et al. [4] investigated the effect of re-entrant bowl geometry on the engine performance and combustion efficiency of a turbocharged engine at full load conditions. Their result shows that the swirl and Turbulent Kinetic Energy with bowl geometry having more re-entrance which is much higher than baseline bowl and it produces better combustion and hence better engine performance is found than the baseline bowl which is effective in lowering ISFC and soot emission. Li et al. [5]

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Table 1
Technical specifications of the engine.

Engine type	4-Stroke, Single Cylinder, Water cooled, Diesel Engine
Bore	87.5 mm
Stroke	110 mm
Length of connecting rod	234 mm
Compression ratio	17.5
Rated Speed	1500 RPM
Rated power	5.2 @1500 RPM
Number of nozzle hole	3
Outlet diameter of hole	0.3 mm
Fuel Injection System	Direct Injection
Injection timing	23° bTDC
Injection Pressure	210 bar
Combustion chamber	Hemispherical
Intake valve opening (IVO)	4.5° before TDC
Intake valve closure (IVC)	35.5° after BDC
Exhaust valve opening (EVO)	35.5° before BDC
Exhaust valve closure (EVC)	4.5° after TDC

investigated the effects of piston bowl geometry on combustion and emission characteristics of a diesel engine fueled with biodiesel under medium load condition. It shows that Omega Combustion Chamber (OCC) bowl geometry is more effective combustion chamber shape in forming strong squish in a short time. As a result, the performance of OCC is better than that of Hemispherical Combustion Chamber (HCC) and Shallow depth Combustion Chamber (SCC) from medium to high engine speeds. Besides these, the concentration of CO is found low due to well mixed mixture. Risi et al. [6] adopted optimization procedure to the geometric features of the different shape of combustion chamber for same bowl volume and squish-to-bowl volume ratio so that the optimum compression ratio can be investigated for all chambers. The spray injection angle was also considered as a variable parameter. The result shows that to reduce NOx emissions, the combustion chamber should be narrow and deep with a shallow re-entrance and a low protuberance on the cylinder axis while spray should be oriented towards the bowl entrance. Corcicone et al. [7] reported that the re-entrant combustion chamber has been widely used in high-speed direct injection (HSDI) diesel engines. The re-entrant bowl with higher levels of air velocity and turbulent kinetic energy at the time of injection gives the best performance. The nozzle, which injects the fuel into the regions of higher turbulent kinetic energy, lowers the smoke emission levels. Rakopoulos et al. [8] reported that the quasi-dimensional model with the proposed simplified air motion model is capable of capturing the physical effect of combustion chamber geometry and speed on the in-cylinder velocity and temperature field, while needing significantly lower computing time compared to the more detailed and accurate CFD model. They also added that the CFD model is more suitable when detailed simulation of the in-cylinder geometry is required and the way the corresponding transport phenomena are affected. Lim and Min [9] investigated the effect of injection timing, spray angle of the injector and the piston bowl shape on wall impingement and soot emissions. They reported that wall impingement was minimized and soot emissions were reduced with the modification of the spray angle and piston bowl shape.

The above literatures show that rare studies have been carried out on the effects of bowl geometry along with spray pattern on the combustion process and emission formation of a diesel engine. Therefore, to have better understanding the gap, it is very important to address the fuel air mixing and the combustion process of a diesel engine with different bowl geometries at different spray angles. The goal of the present study is to enhance the fuel atomization through effective spray and formation of air fuel mixture inside the combustion chamber by modifying chamber geometry.

2. Experimental approach

2.1. Experimental setup

In this study, a four stroke single cylinder 5.2 kW direct injection water cooled diesel engine with Hemispherical Combustion Chamber (HCC) was used. The engine was equipped with eddy current dynamometer (Make: Saj Test Plant Pvt. Ltd) for load measurement. The engine is also synchronized to a crank angle sensor (Make-Kubler-Germany, Model 8.3700.1321.0360) for measuring the position and speed of the crankshaft. The engine was operated at a rated constant speed of 1500 rpm. A piezoelectric pressure transducer (Make: KISTLER) was used to measure in-cylinder pressure. The detailed technical specifications of the engine are given in Table 1. An AVL DiGAS 444 exhaust gas analyzer is used to measure the emission from the engine. The schematic diagram of engine experimental setup is shown in Fig. 1.

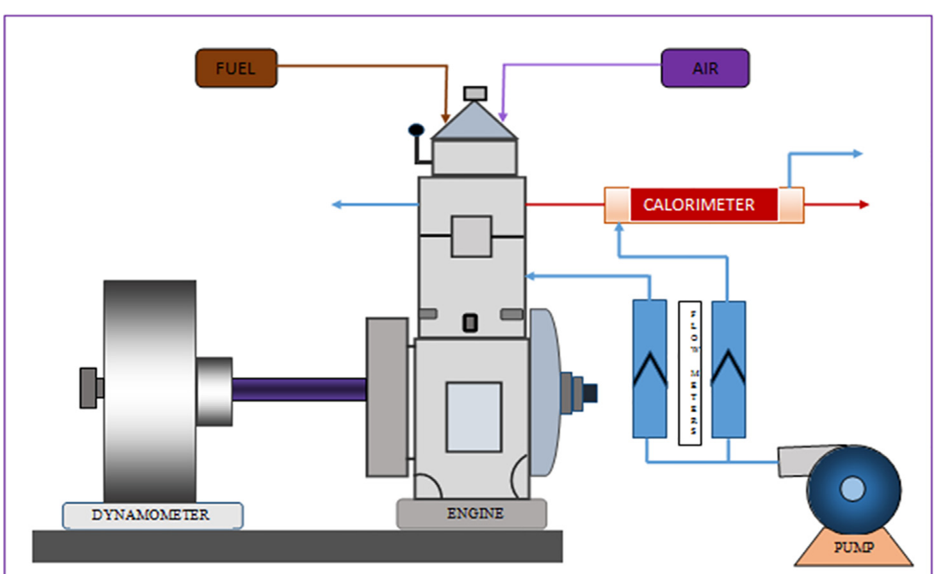

Fig. 1. Schematic diagram of engine experimental setup.