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Research Paper

Influence of spatial and temporal distribution of Turbulent Kinetic Energy on heat transfer coefficient in a light duty CI engine operating with Partially Premixed Combustion

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HIGHLIGHTS

- Heat transfer coefficient for gasoline PPC is assessed.
- Heat transfer coefficient considers experimentally derived flow field parameters.
- High TKE levels at bowl periphery and center due to fuel injection and combustion.
- The greatest differences respect to motored case observed with single injection.

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ABSTRACT

Emission regulations together with the need of more fuel-efficient engines have driven the development of promising combustion concepts in compression ignition (CI) engines. Most of these combustion concepts, lead towards a lean and low temperature combustion potentially suitable to achieve lower emission and fuel consumption levels compared to conventional diesel combustion. In this framework, Partially Premixed Combustion (PPC) using gasoline as fuel is one of the most accepted concepts. There are numerous studies focused on studying concepts such as PPC from the emissions point of view. Nonetheless, there is a lack of knowledge regarding changes in heat transfer introduced by the use of these combustion concepts. It is worth noting that heat transfer can be considered as a key aspect behind possible engine performance improvements. Thus, the reliable estimation of this parameter is of considerable importance. Additionally, a better understanding of how events such as injection and combustion might affect heat transfer is also relevant.

To gain insight into gasoline PPC heat transfer coefficient, its evolution during late compression and early expansion were studied. In particular, this work aims to analyze Turbulent Kinetic Energy (TKE) spatial and temporal evolution influence on heat transfer coefficient. The analysis is based on experimental TKE maps derived from Particle Image Velocimetry (PIV) data. For the heat transfer coefficient estimation a modified Woschni correlation has been used. Results from several injection strategies and a reference motored case have been analyzed. It has been found that injection strategy has a considerable influence on the TKE field and hence on heat transfer coefficient evolution.

1. Introduction

Low Temperature Combustion (LTC) technologies, like Homogenous Charge Compression Ignition (HCCI) [1–3], Partially Premixed Combustion (PPC) [4,5] and Reactivity Controlled Compression Ignition (RCCI) [6–9] have been widely studied in the last decade because they are expected to achieve low engine-out emissions

Abbreviations: CA50, Crank Angle at 50% mass fraction burned; CA90, Crank Angle at 90% mass fraction burned; CAD, Crank Angle Degree; CI, Compression Ignition; EA, ensemble average; EOI, End of Injection; *h*, wall heat transfer coefficient; HCCI, Homogenous Charge Compression Ignition; LTC, Low Temperature Combustion; NOx, Nitrogen Oxides; PIV, Particle Image Velocimetry; PPC, Partially Premixed Combustion; RCCI, Reactivity Controlled Compression Ignition; SI, Spark Ignition; SOC, Start of Combustion; SOI, Start of Injection; TDC, Top Dead Center; TKE, Turbulent Kinetic Energy; V_c, characteristic velocity; V_{module}, module of velocity in the vertical plane; V_{tang}, tangential component of velocity.

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along with high thermal efficiency. In this context, gasoline PPC has received increasingly attention due to its potential for simultaneously reducing fuel consumption and NOx emissions in gasoline Spark Ignition (SI) engines, and its capability to avoid soot and NOx emissions in CI diesel engines. Several experimental and numerical investigations of this combustion type have been performed over the recent years. PPC is achieved by controlling the injection events, inlet temperature and pressure, and composition of the fuel-air mixture, so that it ignites close to Top Dead Center (TDC). It is similar in nature to HCCI, with significantly early fuel injection in the cycle and a combustion process that occurs as a sequence of auto-ignition events. The main difference between HCCI and PPC is that the goal of PPC is to control auto-ignition timing with moderately early fuel injections ($\sim$20 CAD bTDC) by manipulating the in-cylinder charge stratification level.

PPC is highly dependent on the level of in-cylinder fuel stratification at the start of combustion (SOC). Recent work performed by Izadi et al. [10] focused on investigation of combustion stratification using single injections. They concluded that combustion stratification is low and almost independent of start of injection (SOI) for early injections, while there is a remarkable reverse correlation between combustion timing and stratification level for the late injections (-45 to -12.5 CAD). Lee and Reitz [11] investigated characteristics of PCCI with single early injection. Their results demonstrated that combustion performance and emissions are strongly affected by injection timing. They also indicated that spray targeting at the surface of piston bowl directly influenced emissions formation. Spray targeting point, which was located near the edge of piston bowl, was considered as the optimum in PCCI combustion through different engine operating conditions because the squish flow would promote mixture preparation when spray is injected at this location.

Multiple injection strategies with early injection pulses are usually employed to promote different levels of fuel stratification. Early study [12] on combustion stratification using different injection strategies had shown that the combustion following triple injection is more homogeneous compared to single and double injection. Manente et al. [13] employed triple pulse injections to control excessive fuel stratification that causes unacceptable pressure rise rates in a heavy duty diesel engine. They operated the engine at various loads using fixed SOI timings for the three pulses. Kalghatgi et al. [14] tested the effectiveness of triple injection on controlling heat release rates as well as improving engine performance in a small-bore diesel engine fueled with RON84 gasoline. Sellnau et al. [15–17] applied a triple-injection method to improve fuel economy in a light duty (LD) diesel engine operated with RON91 gasoline at 6 bar IMEP. They also showed that a triple injection strategy allowed the use of lower injection pressures compared to single and double-injection strategies.

Studies on multiple injection strategies conducted with experimental fluid dynamics have rarely been reported. The systematic study by the authors [12,18] in the field of experimental fluid dynamics has focused on in-cylinder flow pattern and temporal evolution of turbulence level under PPC conditions.

In view of the potential of PPC and aiming at a more comprehensive study of this combustion mode, the analysis of wall heat transfer coefficient is of particular importance. It has been reported that wall heat transfer affects in-cylinder physical phenomena such as droplet evaporation, auto-ignition and flame-wall interaction [19]. Therefore, wall heat transfer has a deep impact on the overall engine performance. On the one hand, heat losses through cylinder walls reduce energy available to be converted into useful mechanical work affecting indicated efficiency. On the other hand, changes in gas and surface temperature due to heat transfer might also affect pollutant formation [20].

The aim of the current work is to gain insight into heat transfer under PPC operating conditions. To that end, a modified Woschni correlation is used to estimate wall heat transfer coefficient. The modified correlation is not only a function of thermodynamic conditions, but also of the in-cylinder velocity and TKE fields. By using experimental data measured by means of high-speed PIV [12] TKE can be derived from the velocity field. Temporal and spatial TKE distribution and its influence on the heat transfer coefficient is studied. The analysis is carried out for three injection strategies (i.e. single, double and triple injection) as well as for a reference case under motored conditions.

2. Experimental setup

2.1. Experimental facility

Experiments were performed in a Bowditch-designed single-cylinder engine modified from a Volvo D5 LD diesel engine.

Table 1 shows the engine specifications. Due to the large top ring-land crevice required for side-view imaging, the geometric compression ratio of this optical engine is lower than the target of 16, typical of PPC combustion systems. The engine further allows the intake swirl to be adjusted by a swirl control valve. It was operated at a swirl ratio of 2.6 through this work. A Bosch common rail fuel injection system and a 5-hole solenoid Bosch injector were used for fuel injection.

2.2. PIV measurement system

An Nd: YLF diode pumped dual cavity laser from Dantec Dynamics (model type: DualPower 30-1000) was used as the light source. Its wavelength is 527 nm and can reach a maximum 30 mJ power per pulse at a running repetition rate of 1 kHz. At 800 rpm engine speed the laser operates at 2.4 kHz with 13 mJ energy per pulse. The light sheet created by the optics unit was aligned with the injector tip installed in the optically accessible engine. The engine is equipped with a production-like optical piston and an optical cylinder liner with height of 25 mm shown in Fig. 1. The light sheet was focused in the area between the injector tip and the liner inner surface with a height of around 3 cm through the field of view.

Titanium Dioxide (TiO_2) powder was used as PIV seeding particles, which have a mean particle diameter from 2 to 3 μm and a density of 4260 kg/m^3. Assuming Stokes drag, the particle time constant (τ_s) representing the response time to changes in the flow

Table 1
Engine and injection system specifications.

Engine base type	Volvo D5
Number of cylinders	5
Number of valves	4
Bore	81 mm
Stroke	93.2 mm
Connecting rod	147 mm
Displacement	0.48 L
Compression ratio (metal configuration)	1:16
Compression ratio (optical configuration)	1:11.3
Swirl ratio	2.6
Fuel injection	
Type	Common Rail
Fuel injector type	Solenoid
Hydraulic flow	360 cc/30 s @ 100 bar
Umbrella angle	140°
Orifice diameter	0.159 mm
Number of holes	5
Hole conicity	1.5