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Numerical investigation of boundary layer flow and wall heat transfer in a gasoline direct-injection engine

Xueqi Fan, Zhizhao Che, Tianyou Wang *, Zhen Lu

State Key Laboratory of Engines, Tianjin University, Tianjin 300072, China

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Near-wall turbulent boundary-layer has a substantial impact on the wall heat transfer process in internal combustion engines, and ultimately affects the engine performance. However, the heat transfer processes are not well understood because of a lack of information on gas side velocity and temperature distribution. In the present study, the transient velocity and thermal boundary layers in a motored spark-ignition direct-injection engine are predicted using a Delay Detached Eddy Simulation Shear-stress Transport (DDES-SST) model. The near-wall ensemble-averaged and fluctuation velocity and temperature fields at the cylinder head are investigated throughout the compression stroke. The numerical results of the flow field in engine core region agree well with high-speed Two Dimensional Three Components-Particle Image Velocimetry (2D3C-PIV) experimental data. The simulated data show that boundary-layer separation occurs around the closing phase of intake valves and the turbulence in the near-wall region is anisotropic. The thickness of thermal boundary layer shows a non-monotonic variation with time. The dimensionless velocity profiles agree well with the law of the wall in the viscous sublayer but deviate from the log layer. The dimensionless temperature profiles tend to be uniform in the log-layer. The maximum local wall heat flux and heat transfer coefficient are 70 kW/m^2 and 200 W/(m^2 K) at top dead center (TDC), respectively. The spatial distribution of turbulent heat flux shows a strong link between the velocity and thermal boundary layers, and the peaks in the buffer layer occupy about 70–85% of the local wall heat flux, indicating that the forced convection heat transfer is the main heat transfer mechanism in internal combustion engines.

1. Introduction

In-cylinder turbulent flow has a substantial impact on air-fuel mixture formation and flame propagation in internal combustion engines (ICEs), and the turbulent boundary layer contributes a lot to the wall heat transfer which ultimately affects the engine efficiency, pollutant formation and component thermal stresses [1–3]. Therefore, quantitative prediction of local and transient heat transfer is important not only to accurate simulations but also to the optimization of ICEs [4]. Due to experimental limitations in measuring the velocity and temperature distribution in the near-wall region, the heat transfer processes are still not well understood [5]. Besides, the boundary layer flow in ICEs is influenced by the non-equilibrium turbulence due to high-speed reciprocating motion of the piston and the periodic opening and closing of the valves, so the current wall function models are not suitable for the complex conditions in engines [6]. Hence, understanding the details of ICE boundary layer flows and wall heat transfer is crucial for the design and optimization of ICEs.

Despite the importance of understanding wall heat transfer in ICEs, only a few studies have been focused on the near-wall turbulence flow compared with the flow structures in engine core region. Laser Doppler Velocimetry (LDV) was firstly applied to investigate the near-wall velocity filed in ICEs in 1980s [7]. Foster & Witze [8] measured as close as 60 μm from the cylinder head and found that the boundary layer thickness was less than 1 mm. Pierce et al. [9] conducted LDV with Particle Image Velocimetry (PIV) to measure the 3D velocity field on the cylinder head and proved that the boundary layer in ICEs was at least a 2D velocity field. Recently, high-speed micro-PIV and Particle Tracking Velocimetry (PTV) were applied in the near-wall region in ICEs, and greatly improved the measurement accuracy. Alharbi & Sick [10–13] measured as close as 45 μm from the cylinder head on a motored engine and observed reversal flows and millimeter vortex structures. Besides, they found that the dimensionless velocity profiles agreed well with the law of the wall in the viscous sublayer but deviated from the log layer. Jainski et al. [14] extended the

* Corresponding author.
E-mail address: wangtianyou@tju.edu.cn (T. Wang).

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above measurement to three different engine speeds and found that the thickness of the viscous sub-layer decreased as the engine speed increased. Koehler et al. [15] conducted time-resolved PIV (TR-PIV) to measure as close as 1.5 mm from the piston crown, but the experiment could only be carried out during the intake stroke because of the working fluid was water rather than air.

The thermal boundary layers in ICEs can be accessed by Schlieren photography, Coherent Anti-Stokes Raman Scattering (CARS) and Laser-Induced Fluorescence (LIF) techniques. Lucht et al. [16,17] measured the thermal boundary layer on the cylinder head using CARS, and found that the thermal boundary layer thickness in fired engine increased during the expansion stroke. Cundy and Sick [12,18,19] conducted LIF to measure the temperature distribution in the combustion chamber, and the results showed that the thermal boundary layer thickness was thinner than the results obtained by Lyford-Pike [20] using Schlieren photograph. They also observed thermal stratification on a cooled curved metal plate from the transient temperature fields. Tran et al. [21] observed the non-uniform temperature distribution in a Homogeneous Charge Compression Ignition (HCCI) engine by using LIF. Furthermore, the instant wall heat flux in ICEs was generally measured by thermocouples. Nijeweme et al. [22] found that the wall heat flux was influenced by the test location, engine speed, throttle setting and ignition time. Gingrich et al. [23] compared the instant heat flux on the piston crown under different combustion regimes. Ma et al. [24] measured the instantaneous heat flux on the cylinder head, the peak heat flux was about 60 kW/m^2 under motored condition at the engine speed of 500 rpm.

Since those experiments could only provide velocity and temperature distribution in limited areas, multi-dimensional simulations are necessary to solve the transient flow and heat transfer in ICEs. However, the wall models often used in Reynolds-Averaged Navier-Stokes (RANS) and Large-Eddy Simulation (LES) in ICEs are too simple and need to be refined [25]. The most widely used wall model is the classic equilibrium wall-function model derived by Prandtl [26]. Han and Reitz [4] improved this model by considering the density and turbulent Prandtl number variation in the near-wall region, and the improved model has also been widely used in multi-dimensional simulations in ICEs. After that, many researchers further improved the Han-Reitz heat transfer model in ICEs by considering the pressure work term [27], the variation of gas viscosity and turbulent Prandtl number [28,29] and the subgrid-scale (SGS) turbulent viscosity [30]. Ma et al. [31] conducted k-omega turbulence model with pressure gradient to solve the 2D unsteady velocity boundary layer under the experimental condition conducted by Jainski and Sick [11,14], the gas temperature was about 640 K at 330 CAD under motored condition at the engine speed of 800 rpm.

In addition to the wall-function models, hybrid LES/RANS method and Detached Eddy Simulation (DES) have been increasing popular to simulate in-cylinder flows. Jhavar et al. [32] solved the in-cylinder flow based on Very Large Eddy Simulation (VLES) and RANS k-ε model. Hasse et al. [33] conducted Shear-Stress Transport DES (SST DES) to simulate in-cylinder flow and the results agreed better with experimental data than the RANS approach. Hartmann et al. [34] investigated the velocity boundary layer at the intake valve seat based on SST DES model and observed flow separation in the near-wall region. Buhl et al. [35] investigated the velocity boundary layer on the piston crown during the intake stroke using Scale Adaptive Simulation Shear-stress Transport (SAS-SST) model, and the results showed that the boundary layer thickness varied strongly along the piston surface due to the large-scale tumble flow.

Direct numerical simulation (DNS) has been widely used to investigate the dynamics of the coherent structures and the physics of turbulent heat transfer within the turbulent boundary layers of simple geometry like channels, pipes and plates [36]. Shadloo et al. [37,38] investigated the effect of wall heat transfer on turbulent statistics and near wall behaviors in supersonic turbulent boundary layers under different wall conditions using DNS. The results showed that increasing the disturbance amplitude as well as perturbation frequency moved the laminar-to-turbulent transition upstream. Wu & Moin [39] simulated an incompressible, zero-pressure-gradient flat-plate boundary layer and observed that hairpin vortices developed into the downstream hairpin forests in the transitional region ($800 < Re < 1900$). However, DNS method is seldom used in ICEs because of the high CPU demand. Schmitt et al. [40–42] conducted DNS to simulate the boundary layer flow with wall heat transfer in an engine-relevant condition. The results showed that the velocity and thermal boundary layer thicknesses decreased towards top dead center, and the dimensionless velocity and temperature profiles deviated strongly from the law of the wall. The DNS data showed that the turbulent heat flux occupied almost 60% to 80% of total wall heat flux. These conclusions were significant but the simulation geometry was simplified without combustion chamber structure and moving valves, so it could not reflect the real boundary layer flow in ICEs.

In summary, the experiments could only access limited areas on wall surfaces in ICEs and there is a lack of simulation of velocity and thermal boundary layers in realistic engines to the authors' knowledge. The objective of the present study is to analyze the velocity boundary layer and thermal boundary layer together in a realistic engine, and provide a further understanding of wall heat flux and turbulent heat transfer in ICEs. The simulation setup and experimental validation are presented in Section 2. In Section 3, the evolution of velocity and thermal boundary layers during the compression stroke are described, the dimensionless velocity and temperature profiles are compared against the law of the wall, and local wall heat flux and heat transfer coefficient are predicted. Conclusions are drawn in Section 4.

2. Numerical method

2.1. Governing equations and turbulence modeling

Since the characteristic velocity in ICEs is on the order of 10 m/s, the in-cylinder flow can be described by the low Mach number compressible Navier-Stokes equations [31]. The compressibility of the fluid is ruled by the ideal gas law. The governing equations for mass, momentum and energy are as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \tag{1}$$

$$\rho\left(\frac{\partial u_i}{\partial t} + \nabla(u_i \cdot \boldsymbol{u})\right) = -\frac{\partial P}{\partial x_i} + \nabla(\mu \cdot gradu_i) + S_i \tag{2}$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T\right) = \frac{\partial P_0}{\partial t} + \nabla(\lambda \cdot \nabla T) \tag{3}$$

$$P_0 = \rho R T \tag{4}$$

where P is the hydrodynamic pressure, P_0 is the thermodynamic pressure, and the physical pressure is the sum of this two terms. c_p is the specific heat at constant pressure, μ is the dynamic viscosity and λ is the thermal conductivity. Among them [43],

$$\mu = 1.46 * 10^{-6} \frac{T^{1.5}}{T + 111} \tag{5}$$

$$\lambda = 2.089 * 10^{-3} \frac{T^{1.5}}{T + 111} \tag{6}$$