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Review

Direct numerical simulation of the compression stroke under engine relevant conditions: Local wall heat flux distribution

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ABSTRACT

The distribution of the heat flux on the walls in a closed cylinder during the compression of a non-reactive hydrogen–air mixture is investigated using data from a direct numerical simulation (DNS) of the compression stroke under engine relevant conditions. It is found that the relation of the temperature field with the local heat flux distribution depends strongly on the distance from the wall. The strong correlation of the two quantities within the viscous sublayer deteriorates with increasing distance from the wall; in the outer layer they become uncorrelated. In contrast the flow in the wall-normal direction transports hot gases towards and cold gases away from the wall and the velocity in the wall-normal direction is correlated to the heat flux distribution also further away from the wall. A local flow away from the wall results in a lower and more uniform heat flux while flow towards the wall result in significantly higher and strongly fluctuating heat fluxes. Ejection streams localized in the near-wall region are found to be responsible for the highly fluctuating heat flux distributions. The joint PDF distributions of wall-normal velocity and temperature with the heat flux collapse when scaled by density-weighted wall-normal units, which can be used to model the heat flux distribution within coarser RANS and LES cells and may therefore provide a promising basis for future engine wall heat transfer models.

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1. Introduction

Despite its importance, relatively little is known about velocity and thermal boundary layers and wall heat flux distribution in internal combustion engines (ICEs). With respect to the flow, this is mainly due to the limited experimental insight concerning the ICE near-wall region, which is restricted to single points (Laser Doppler Velocimetry [1]) and small 2D slices (near-wall Particle Image Velocimetry (PIV) [2]). The thermal boundary layers in ICEs can be accessed pointwise by means of Coherent Anti-Stokes Raman Scattering (CARS) measurements [3,4]. However, according to Lucht et al. [4] CARS is not sufficient to measure the gas-phase temperature gradient at the wall to better than a factor of two. In addition, instantaneous measurements of the wall temperature can be performed on single points using thermocouples (e.g. [5]), or on optically-accessible surface segments based on phosphor coated materials (e.g. [6]).

3D-Computational Fluid Dynamics (CFD) calculations in ICEs compute the flow and temperature fields in the whole domain and thus can provide the local wall heat flux at all engine walls. However, the typical mesh resolutions used in Reynolds Averaged Navier Stokes (RANS) and Large Eddy Simulations (LES) calculations in engines are too coarse to resolve the thin boundary-layer structure and hence special treatment is required to approximate the boundary layers and the wall heat flux.

The boundary layers are commonly modeled using wall functions as proposed by Patanker and Spalding [7], which are based on the law-of-the-wall. The approach, which was initially developed for the boundary layer in steady, incompressible and fully-developed flows in smooth pipes/channels at moderate Reynolds numbers, is nonetheless employed in very different conditions and applications. According to Nijeweme et al. [8] the main assumptions implicit in the standard wall-function treatment of Patanker and Spalding [7] are: (a) steady flow, (b) incompressible flow, (c) essentially one-dimensional flow, such that gradients of velocity and scalar quantities are only normal to the wall, (d) small pressure gradients, (e) turbulence in local equilibrium and (f) linear turbulence length scale variation with the distance from the wall. It is obvious that under realistic engine conditions most of these assumptions are violated. In order to reduce modeling errors, Han and Reitz [9] improved the standard wall function approach in the RANS context by taking gas density variations into account; the required model constants were derived by fitting the experimental data presented of Kays [10], who investigated fully-developed boundary layers in steady tube or duct flows. The modeled heat transfer showed satisfactory agreement compared to experimental data in a premixed combustion engine. Angelberger [11] also improved the standard wall functions for RANS by considering the effect of temperature and thereby density gradients within the boundary layer, and proposed a model for the influence of near-wall flame quenching. The model was compared to the global 0D heat transfer model of Woschni [12] on a four-valve spark-ignited engine and reasonable agreement was found. Chang et al. [13] on the other hand reported significant differences of the Woschni correlation compared to experimentally-derived heat fluxes.

Nijeweme et al. [8] discussed the law-of-the-wall assumptions for heat transfer models in ICEs based on the one-dimensional energy equation. The convective flow normal to the wall created by the density changes in the boundary layer was found to be very important for the accurate description of wall heat transfer. In addition, the time-varying pressure term was shown to increase the wall heat transfer during compression and shift the heat flux peak towards earlier times. The models by Han and Reitz [9] and Angelberger et al. [11] do not account for the convective flow resulting from density variations, since they still utilize a constant density approximation to derive the analytical wall function. The model of Keum et al. [14] avoided the constant density approximation and the model constant were derived by matching the heat release rate against the experimental data of Alkidas and Myers [15]. However, the assessment of the model performance is difficult, since only comparisons with heat fluxes derived based on the standard wall function approach were reported.

Modeling of engine wall heat transfer using RANS faces the drawback that as a consequence of averaging only the mean flow field is available, although the instantaneous flow field is crucial for the derivation of the local wall heat flux distribution. LES solves directly for the large scale instantaneous velocities, but a large number of cells would be required to resolve the steep velocity and thermal gradients in the boundary layers. Thus also in LES engine calculations the boundary layers need to be modeled. However, according to Rutland [16], the available approaches are not well developed. In the recent work of Plengsaard and Rutland [17] an improved wall model was proposed by extending the one of Han and Reitz [9] to LES using the Werner–Wengle model [18]. The latter calculates wall shear stresses assuming an instantaneous tangential velocity in the first near-wall cell in phase with the wall shear stress to update the friction velocity that appears in the heat flux equation used in [9]. Although LES provides improved agreement with experimental heat flux data in comparison to RANS, significant deviations from the experimental data persist. The recent work of Nuutinen et al. [19] further improved the wall-function approach by accounting for the effects of variable density, multicomponent transport property variations and convection. An imbalance wall function based on the work of Popovac and Hanjalic [20] was introduced, which takes into account departures of the flow field from wall-parallel mean velocities. The model was validated against the strongly-heated pipe flow investigated experimentally by Shehata and McEligot [21] and numerically via DNS by Bae et al. [22] and good agreement was found. In addition, model validation with data from a pancake engine showed an improved agreement compared to the model of Angelberger [11].

In summary, since experimental methods can only partly access the ICE near-wall regions fundamentally little is known about velocity and thermal boundary layers in ICEs [5]. As a consequence, the wall models in 3D-CFD ICE simulations are mainly based on the law-of-the-wall. However, in the works of Alharbi et al. [23], Jainski et al. [2] and Schmitt et al. [24], strong deviations of ICE boundary layers compared to the law-of-the-wall are reported and thus according to Rutland [16] the predictive capabilities of present wall modeling approaches in ICEs are limited.

The aim of this study is to provide an improved physical understanding and validation data for the ICE wall heat transfer using DNS. In a previous study using the same DNS dataset, emphasis was placed on the description and analysis of the averaged boundary layer profiles [24]. In contrast, this work focuses on the local distribution of the wall heat flux and its correlation with the velocity and temperature fields, which can be valuable for wall models in LES engine calculations with their instantaneous description of the velocity field.

2. Numerical method

2.1. Governing equations and solver

The low-Mach number form of the conservation equations [25] are integrated in time based on the highly-efficient parallel spectral element (SEM) solver Nek5000 [26]. In SEM, the solution is