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Numerical assessment of wall modelling approaches in scale-resolving in-cylinder simulations

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ABSTRACT

Wall modelling in internal combustion engines (ICEs) is a challenging task due to highly specific boundary layers and a dynamically changing flow environment. Recent experimental (Jainski et al., 2013, Renaud et al., 2018) and direct numerical simulation (DNS, Schmitt et al., 2015a) studies demonstrate that scaled near-wall velocity and temperature profiles in ICEs deviate considerably from the law of the wall. Utilising the DNS data, the present paper focusses on benchmarking a scale-resolving approach with a 1-D non-equilibrium wall model (HLR-WT, Keskinen et al., 2017) in ICE-like flows. Specific emphasis is put on the compression stroke using different grids and two additional wall-modelled large eddy simulation (WMLES) reference approaches. The standard wall law based WMLES-1 produces highly grid-dependent under-prediction of wall fluxes, to which WMLES-2 (Plensgaard and Rutland, 2013) and HLR-WT, employing engine-targeted wall treatments, yield considerable improvement. Differences between the improved methods are noted in detailed metrics. Throughout the compression stroke, HLR-WT provides a good match to the DNS in scaled mean boundary layer profiles for both velocity and temperature. With relevance to local heat flux distribution, the characteristic impingement-ejection process observed in the DNS is qualitatively replicated with WMLES-2 and HLR-WT. The non-equilibrium formulation of the latter allows for slight improvements in terms of local heat transfer fluctuation predictions. In contrast, coarse near-wall grids appear to be detrimental for such predictions with all approaches. The study provides evidence on the potential of the HLR-WT and WMLES-2 approaches in ICE near-wall flow prediction, advocating further investigations in more realistic engine configurations.

1. Introduction

1.1. Background

Near-wall fluid flow processes and wall heat transfer have a substantial influence on internal combustion engine (ICE) charge conditions such as temperature and flow turbulence. With the concurrent prospect of high thermal efficiency and low emissions, ICE research and development is increasingly focussed on modern, sensitive concepts such as lean combustion, homogeneous charge compression ignition (HCCI) or reactivity controlled compression ignition (RCCI) (Reitz, 2013). Hence, the understanding and predictive analysis of such modern concepts benefits from the comprehension and accurate prediction of near-wall processes.

Modern computational methods (direct numerical simulation, DNS; large eddy simulation, LES) aim at the description of temporally and spatially resolved turbulent flow fields and associated flow processes such as heat transfer and combustion. For DNS (depicting all turbulent scales), computational time dependence on pressure p, rotational speed n and stroke S scales with $p^3n^3S^6$ in ICE simulations (Frouzakis et al., 2017), leading to remarkable increases for large supercharged engines operated at high speeds. Although DNS will likely remain prohibitively expensive for engineering simulations in the near future (particularly if multi-cycle statistics are required), LES (resolving turbulent scales

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larger than a filtering threshold) has gained a firm standing as a complement to the widespread Reynolds-averaged (RANS) technique.

However, wall boundary layers pose a considerable challenge to LES (cf. Pope, 2004): for accurate predictions of near-wall turbulence and heat transfer, near-wall grid resolution is required to approach DNS standards. In ICEs, LES quality has been discussed by di Mare et al. (2014) who present, among other metrics, the popular estimators based on modelled turbulent kinetic energy and modelled viscosity. However, conventional near-wall metrics such as scaled tangential resolution are less frequently studied. Considering the complexity of ICE flows, it may not be straightforward to adopt near-wall criteria established for flat-plate boundary layers (e.g. Choi and Moin, 2012). In fact, in-cylinder wall-resolved LES investigations are scarce and unaffordable computational costs are associated with high Reynolds numbers and complex engine configurations (Misdariis et al., 2015).

Wall-modelled LES (WMLES; referring here to wall stress models) and hybrid LES/RANS methods (cf. Larsson et al., 2016 for taxonomic perspectives) represent some of the primary avenues for alleviation of the near-wall issue (see reviews of Piomelli, 2008; Sagaut et al., 2013; Larsson et al., 2016; Chaouat, 2017). Interest in such scale-resolving methods has also been raised within the engine research community (Hasse, 2016). However, knowledge of the functionality of different approaches is not extensive in the ICE context, where wall modelling advances are not frequent and clear research gaps have been previously identified (Rutland, 2011). Many groups have applied models based on the law of the wall or closely related correlations (e.g. Vermorel et al., 2009; Enaux et al., 2011; Misdariis et al., 2015; Truffin et al., 2015; Schiffmann et al., 2016) while engine-targeted algebraic models have also been adapted for WMLES (Plensgaard and Rutland, 2013). Conversely, some contemporary studies consciously disregard wall treatment (in favour of straightforward linear gradient approximations), stating either modelling difficulty (Nguyen et al., 2016) or the known departures from typical wall law (equilibrium) assumptions (He et al., 2017). In general, near-wall flows or wall heat transfer are only rarely a focal component of ICE-related LES papers.

In-cylinder flows differ considerably from channel or pipe flows, wherein the law of the wall, for both wall shear stress and convective heat transfer, can often be considered to be an acceptable approximation (White, 2006). As revealed by particle image velocimetry (PIV) measurements (Jainski et al., 2013) and DNS (Schmitt et al., 2015a), scaled near-wall velocity and temperature profiles in ICEs deviate from the law of the wall substantially. Such variations are also influenced by engine operating conditions (Renaud et al., 2018) or local flow regions dominated by (i) wall-parallel and (ii) stagnating contributions (Buhl et al., 2017b). Renaud et al. (2018) found near-wall velocity profiles to resemble accelerated boundary layers following impingement. Such an impinging flow type is well-known for local variation of scaled profiles (Hattori and Nagano, 2004). ICE wall models should hence be applicable to many types of flows in highly dynamic in-cylinder conditions. For RANS, improved wall models accounting for considerable near-wall material property variations were introduced by Han and Reitz (1997) and Angelberger et al. (1997). Later on, further advances have been made in complex flows (e.g. Craft et al., 2002; Popovac and Hanjalic, 2007; Suga et al., 2013; Nuutinen et al., 2014). Non-equilibrium models have recently been advocated in experimentally based ICE near-wall layer investigations (Ma et al., 2017a; 2017b) and have become a frequent topic in recent WMLES studies not specifically pertaining to engines (Kawai and Larsson, 2013; Park and Moin, 2014; Yang et al., 2015).

1.2. Study objectives

Based on the literature survey, there is a research gap in wall modelling for scale-resolving ICE simulations. The recent DNS work on engine-like flows (Schmitt et al., 2014a; 2014b; 2015a; 2015b; 2016a; 2016b; Schmitt and Boulouchos, 2016) provides a unique opportunity to benchmark various approaches. Here, existing methods are assessed by implementing algebraic WMLES methodologies based on standard wall laws (WMLES-1) and engine-targeted models (WMLES-2). In addition, an approach with a non-equilibrium wall model aimed at ICE flows (HLR-WT), recently investigated in canonical flows (Keskinen et al., 2017), is further assessed here. Simulations comprise three consecutive stages: (I) cold, multi-cycle reciprocating flow, (II) fuel-air intake, and (III) charge compression, while stage III is the main focus of the present work. The objectives of this study are stated as follows:

1. Comparing with the DNS data, assess the predictive ability of the approaches in terms of mean quantities such as global wall heat transfer.
2. Examine how the specific near-wall profiles found in the DNS are reproduced with the methods.
3. Analyse how focal physical near-wall mechanisms observed in the reference results are replicated in the present simulations.
4. Investigate result sensitivity to grid variations both in the core flow and in the near-wall region.

The paper is structured so that turbulence modelling and near-wall methodologies are presented in Section 2, while the present engine-like test case setting and utilised computational grids are reported in Section 2.7. Results in Section 3 convey a brief overview of stages I to III followed by volume-averaged quantities in the compression stroke. Observations are then gradually taken to a more detailed level, highlighting approach and grid-specific differences not easily evidenced through averaged metrics. Finally, a discussion attempts to convey relevant practical aspects to the investigation.

2. Methodology

2.1. Governing equations

The present simulations consist of three stages (I-III) explained in detail in Section 2.7. While stage I is based on an incompressible formulation (see Keskinen et al., 2017), we next explain the methodology used herein for the compressible intake (II) and compression (III) processes. The simulations provide numerical solutions to the filtered compressible mass, momentum, energy and species transport equations. Utilising density-weighted ($\tilde{\cdot}$) and non-density-weighted ($\hat{\cdot}$) filtering notations, the governing equations read in Cartesian coordinates with the Einstein notation:

$$\frac{\partial \hat{\rho}}{\partial t} + \frac{\partial (\hat{\rho}\tilde{u}_j)}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (\hat{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial (\hat{\rho}\tilde{u}_j\tilde{u}_i)}{\partial x_j} = -\frac{\partial \hat{p}}{\partial x_i} + \frac{\partial \hat{\tau}_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}^r}{\partial x_j} \tag{2}$$

$$\frac{\partial (\hat{\rho}\tilde{h})}{\partial t} + \frac{\partial (\hat{\rho}\tilde{u}_j\tilde{h})}{\partial x_j} = \frac{\partial \hat{p}}{\partial t} - \frac{\partial}{\partial x_j}\left(\hat{q}_j + q_j^r\right) + \tilde{u}_j\frac{\partial \hat{p}}{\partial x_j} + (\hat{\tau}_{ij} + \tau_{ij}^r)\frac{\partial \tilde{u}_i}{\partial x_j} \tag{3}$$

$$\frac{\partial (\hat{\rho}\tilde{Y}_m)}{\partial t} + \frac{\partial (\hat{\rho}\tilde{u}_j\tilde{Y}_m)}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\hat{f}_{j,m} + f_{j,m}^r\right) \tag{4}$$

where $\hat{\rho}$, $\tilde{u}$, $\hat{p}$, $\tilde{h}$ and $\tilde{Y}_m$ refer to the density, velocity, pressure, static enthalpy and species mass fraction, respectively, whereas quantities $\hat{\tau}_{ij}$, $\hat{q}_j$ and $\hat{f}_j$ respectively correspond to the viscous stress tensor, heat flux vector and species flux vector. Unresolved (residual) quantities are modelled in the residual stress tensor τ_{ij}^r, residual heat flux vector q_j^r and residual species flux vector f_j^r, expressed here with an eddy-viscosity model