Sub Topic: Internal Combustion Engines

10th U. S. National Combustion Meeting
Organized by the Eastern States Section of the Combustion Institute
April 23-26, 2017
College Park, Maryland

An assessment of CFD-based wall heat transfer models in piston engines

A. Sircar[1], C. Paul[1], S. Ferreyro-Fernandez[1], A. Imren[1], D.C. Haworth[1]

[1]Mechanical Engineering, Pennsylvania State University, USA
[*]Corresponding Author Email: author@university.edu

Abstract: The lack of accurate submodels for in-cylinder heat transfer has been identified as a key shortcoming in developing truly predictive, physics-based computational fluid dynamics (CFD) models that can be used to develop combustion systems for advanced high-efficiency, low-emissions engines. Only recently have experimental methods become available that enable accurate near-wall measurements to enhance simulation capability via advancing models. Initial results show crank-angle dependent discrepancies with respect to previously used boundary-layer models of up to 100%. However, available experimental data is quite sparse (only few data points on engine walls) and limited (available measurements are those of heat flux only). Predictive submodels are needed for medium-resolution ("engineering") LES and for unsteady Reynolds-averaged simulations (URANS). Recently, some research groups have performed DNS studies on engine-relevant conditions using simple geometries. These provide very useful data for benchmarking wall heat transfer models under such conditions. Further, a number of new and more sophisticated models have also become available in the literature which account for these engine-like conditions. Some of these have been incorporated while others of a more complex nature, which include solving additional partial differential equations (PDEs) within the thin boundary layer near the wall, are underway. These models will then be tested against the available DNS/experimental data in both SI (spark-ignition) and CI (compression-ignition) engines.

Keywords: wall-models, non-equilibrium, IC engines, URANS

1. Introduction

The broader goal of our current research is to develop predictive models for modern-day heavy-duty engines (both compression-ignition CI and spark-ignition SI). Such engines strive towards lesser pollutant emissions and higher efficiency. One way of improving the overall engine efficiency is reducing wall heat losses. These losses occur due to the high temperature gradient across the chamber walls which are maintained at moderate temperatures (about 500K) by a cooling fluid while combustion inside the chamber causes very high instantaneous temperatures (almost 2000K). If such losses could be reduced through better design, it would imply that a greater percent of the fuel (chemical) energy can go into generating power. In order to reduce wall heat losses, it is important to understand the mechanism of heat transfer at the walls. This mainly comprises two parts – convective and radiative. For the current work we are looking at the former while a future work involves exploring radiative heat transfer also. This is being done by implementing wall models for flow and heat transfer into a URANS (unsteady Reynolds Averaged Navier Stokes) based solver. There are a number of such models available in the literature, but there are great discrepancies (almost 100% [1]) amongst the predictions from such models. Further, available experimental data is sparse which makes validation of the models quite difficult. The main aim of this work is to be able to identify the different types of models, the approximations which go into their mathematical formulation, developing more robust models for engine-relevant conditions and find modern experimental data-sets from the literature to help validate these models under relevant operating conditions.

As mentioned above, it is important to understand the current state of wall models and what needs to be done in order to improve their predictive capabilities. Such models are required to mimic the physics of thermo-viscous boundary layers at the chamber walls. The grid for a URANS solver isn't adequate to resolve all the scales in the boundary layers, especially at high speeds which is typical of high-load operation. Typical boundary layer thickness in IC engines are of the order of 100 μm to 1000 μm under motored conditions and can vary depending on the level of swirl and firing [2]. The physical processes in the boundary layers of IC engines have great implications on heat exchange and combustion phasing [3]. Hence these are modeled using wall-functions, which can be derived from the thin boundary layer equations (reduced Navier Stokes equations in boundary layers) after making the following assumptions: - [4]

A1: Flow is parallel to the chamber walls with negligible flow normal to the walls
A2: Quasi-steady flow with negligible transients
A3: Constant density and transport properties in the boundary layer
A4: High Reynolds number flow, very thin laminar shear layer
A5: Zero pressure gradients along the flow
A6: No combustion and chemically inert mixture

The model which results from these assumptions is called the equilibrium wall-function model for the flow and the corresponding model (by analogy from low Mach number assumption) for temperature is known as the thermal wall-function model. It is found that such models usually under-predict wall heat losses compared to experimental measurements [5]. This can be explained by the fact that assumptions A1-A6 can be hardly expected to hold for today's engines. Ma et al. [6] have performed experiments using μ-PIV and LIF in a two-valve optical research engine (the TCC or Transparent Combustion Chamber) and showed that the boundary layer is driven by a pressure gradient which is affected by the piston motion to the extent that flow reversal is also possible locally. Hence, the flow is neither one-dimensional nor steady. Assumption A3 is strongly invalid too since there is a large temperature gradient near the wall and transport properties are inherently temperature-dependent. These arguments have led researchers to believe that these assumptions need to be relaxed. Hence, a wide range of models are available in the literature which relax some of these assumptions [7]. Among these some have been discussed in the next section. Since these equilibrium assumptions aren't sufficient to capture the dynamics of the boundary layers, non-equilibrium models have gained prominence and have been shown to better reproduce experimental results [6].

The other major limiting factor in understanding which models represent the physics of boundary layers in engines more accurately is the lack of good experimental data. Rakopoulos et al. [8] list a number of available experimental data from the literature. However, these studies report only the heat flux values at discrete locations on the cylinder head, liner and piston. This is not sufficient for model validation since we need to be able to compare with fields of data. Also, measurements of other quantities, like turbulence quantities, y+ values and turbulent Prandtl number, which go into a model for wall heat loss, are required to make a comprehensive analysis of model performance.

2. Models and Validation data

It is important to be able to validate the plethora of models available in the literature. For this purpose, two main data sets are being targeted for the current study – experimental measurements of heat flux and velocity fields in the TCC engine [9] and DNS (Direct Numerical Simulations) of the Morse engine by Schmitt et al. [10]. DNS results are quite good for model validation since they provide fields of heat fluxes, turbulence quantities (integral length scales), velocity etc. Figure 1 shows the schematic setup and the mesh for the DNS study in [10]. The initial conditions, boundary conditions and setup details are provided in [10]. For the DNS, the piston is initialized at TDC (Top Dead Center) and allowed to expand which draws in air from the plenum. On reaching BDC (Bottom Dead Center) the intake plenum is cut-off and high-resolution DNS is performed over 180degrees till the piston reaches TDC again. A wide range of data is provided in refs [10-13] for this DNS study.

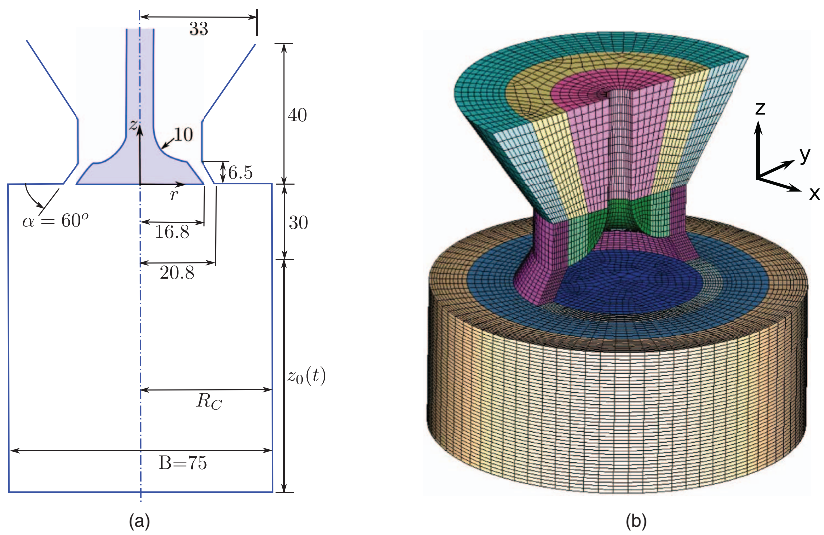

Figure 1: Main part of the domain: (a) schematic of the geometry (not to scale, all lengths in mm) and (b) the spectral element skeleton used in the simulations [11]

The results from the above DNS study is used to validate some of the models incorporated in the URANS context. OpenFOAM is used as the basic CFD code in which the wall-function models have been incorporated. The modelled energy equation (1) solved in OF2.3.x for reactive flows is solved for each finite volume cell while for wall cells the last term in the LHS represents the wall heat loss. This requires defining the turbulent thermal diffusivity α_t, which needs to be specified at the wall as a boundary condition.

$$\frac{\partial(\rho h)}{\partial t}+\nabla\,(\varphi h)+\frac{\partial\left(\rho\frac{1}{2}u^2\right)}{\partial t}+\nabla\left(\varphi\frac{1}{2}u^2\right)-\frac{dP}{dt}-\nabla^2\left(\left[\alpha+\alpha_t\right]h\right)=Q_{rxn} \qquad (1)$$

where φ is the mass flux in each is cell and Q_{rxn} denotes the chemical energy term.

$$\alpha_{t,w}=\frac{\mu_{t,w}}{\Pr_t} \quad \text{where the subscript w denotes the value at the wall} \qquad (2)$$

The in-built model in OpenFOAM considers the simple equilibrium wall-function model (2) with constant turbulent Prandtl number of 0.85. In order to incorporate some of the models available in literature which relax some of the assumptions A1-A5 (none of them consider flame-wall interactions) the implementation in OF2.3.x has been changed to some extent. The last term in the LHS of equation (1) is replaced by a wall heat loss term q_w for the wall cells. Table 1 lists the models from literature which have been incorporated in OF2.3.x.

Table 1: Heat-loss models from literature incorporated in OF2.3.x

Name of model	Heat Loss model	Comments
WernerWengle [14]	$q_W = \dfrac{\rho c_P u_\tau T \ln(T/T_W)}{C_{hw}\left\{7.843\tan^{-1}\left(0.0935 y^+\right)\right\}}$	$y^+ < 40$ Modeled τ_W for computing u_τ
Angelberger [15]	$q_W = \dfrac{\rho c_P u_\tau T_W \ln(T/T_W)}{\theta^+}$	Viscous sub layer $\theta^+ = \mathrm{Pr}\, y^+$ Turbulent layer $\theta^+ = \mathrm{Pr_t}\left(u^+ + P\right)$
Jayatilleke [16]	$T^+ = \dfrac{\rho c_P u_\tau (T_W - T)}{q_W}$	
	$T^+ = \mathrm{Pr}\, y^+ + \dfrac{1}{2}\rho \,\mathrm{Pr}\dfrac{u_\tau}{q_W} U_P^2$	If $y^+ < y^+$_thermal
	$T^+ = \mathrm{Pr_t}\left[\dfrac{1}{\kappa}\ln\left(Ey^+\right) + P\right] + \dfrac{1}{2}\rho\dfrac{u_\tau}{q_W} Q$	If $y^+ > y^+$_thermal
	$Q = \mathrm{Pr}_t U_P^2 + \left(\mathrm{Pr} - \mathrm{Pr}_t\right) U_C^2$	
	$P = 9.24\left[\phi^{3/4} - 1\right]\left[1 + 0.28 e^{-0.007\phi}\right]$	
	$\phi = \mathrm{Pr}/\mathrm{Pr}_t$	

The next target is to incorporate non-equilibrium wall models as described in [6]. These models solve the thin boundary layer equations (2D transient NS equations) on a grid which is laid between the last grid point (closest to the wall) in the main CFD mesh and the wall. This requires no additional modeling since it directly solves the governing equation, hence inherently removing assumptions A1-A5. Ma et al. [6] discusses the implementation of this model using the zonal approach and different turbulence closures. It is shown that this model works better in predicting wall heat loss under motored conditions for the TCC engine. The same will be validated in the OpenFOAM context with combustion.

3. Results and Discussion

The models discussed in Table 1 along with the OpenFOAM model (referred to as Constant Prt=0.85) are used to generate results for the compression stroke of the geometry shown in Figure 1. The LES and DNS of the same compression stroke by Mandanis et al. [13] are used for preliminary validation of these models. Figure 2 shows that these models predict the average pressure and temperature of the engine reasonably well. Figure 3 shows that there is a wide discrepancy in the total heat loss predictions. The average yPlus value doesn't change greatly among models thereby showing that the first grid point lies within the log-law region.

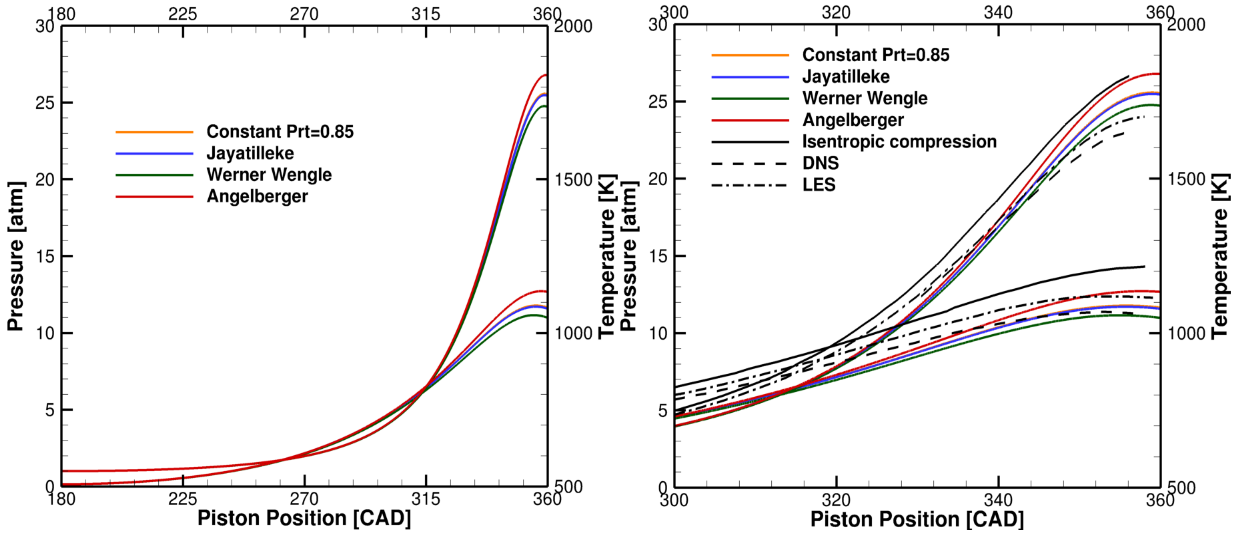

Figure 2: Predictions of average Pressure and Temperature from the models in Table 1

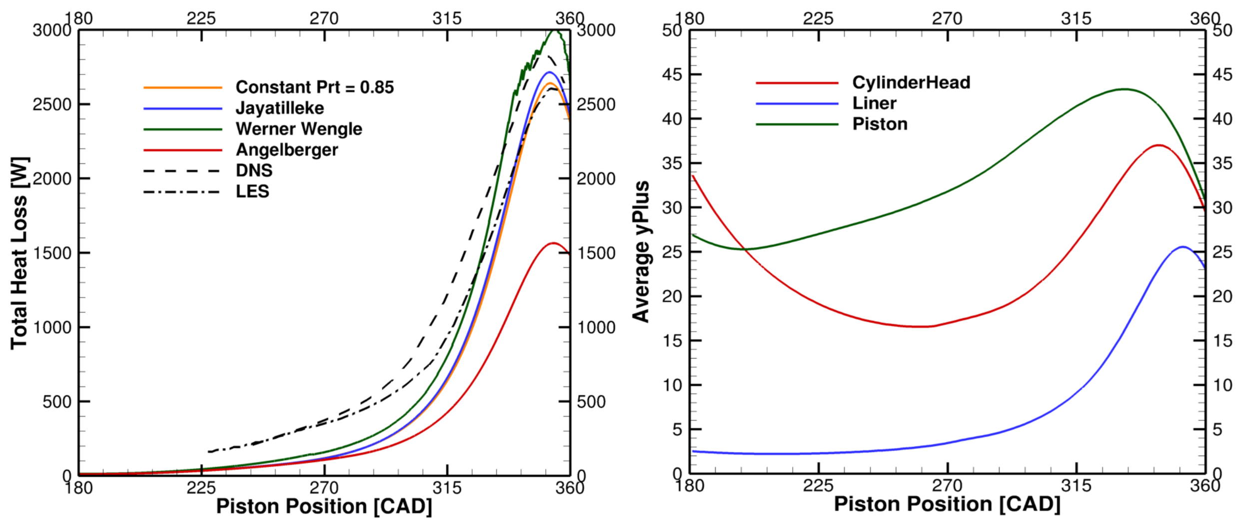

Figure 3: (left) Predictions of Total wall heat loss from the models in Table 1
(right) Variation of average yPlus values of the OpenFOAM model

4. Conclusions

These preliminary validation runs show that the prediction is in relatively good agreement except for the Angelberger model which predicts very low wall heat loss (similar to previous findings [5]). However, further comparisons are required of the turbulence quantities to be able to conclusively say anything about the actual performance of these models under fired conditions. Further it is expected that better results will be obtained with the non-equilibrium model even with the last grid point further away from the wall (higher yPlus). Future work includes incorporating the non-equilibrium model and removing assumption A6, i.e. considering combustion within the boundary layer leading to more complicated flame-wall interactions.

5. Acknowledgements

This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE) and the Department of Defense, Tank and Automotive Research, Development, and Engineering Center (TARDEC), under Award Number DE-EE0007278.

6. References

Journal article:
[1] A.Y. Alharbi, V. Sick, Investigation of boundary layers in internal combustion engines using a hybrid algorithm of high speed micro-PIV and PTV, Experiments in Fluids, 49:949-959, 2010.
[2] P.H. Pierce, J.B. Ghandhi, J.K. Martin, Near-wall velocity characteristics in valved and ported motored engines, SAE Paper 1992; : 920152
[3] J.E. Dec, Advanced compression-ignition engines – understanding the in-cylinder processes, Proc Combust Inst 2009; 32: 2727-2742
[4] Z. Han, R.D. Reitz, A temperature wall-function formulation for variable-density turbulent flows with application to engine convective heat transfer modeling, Int. J. Heat Mass Transf, 40(3), 613-625, 1997.
[5] S. Keum, H. Park, et al., Modeling of heat transfer in internal combustion engines with variable density effect, Int J Engine Res 2011; 12(6): 513-526
[6] P.C. Ma, T. Ewan, C. Jainski, L. Lu, A. Dreizler, V. Sick, M. Ihme, Development and analysis of wall models for internal combustion engine simulations using high-speed micro-PIV measurements, Flow Turbulence Combustion, 2017 98:283-309
[7] K.Y. Huh, I.P. Chang, J.K. Martin, A comparison of boundary layer treatments for heat transfer in IC engines, SAE Paper 900252, 1990
[8] C.D. Rakopoulos, G.M. Kosmadakis, E.G. Pariotis, Critical evaluation of current heat transfer models used in CFD in-cylinder engine simulations and establishment of a comprehensive wall-function formulation, Applied Energy 87 2010, 1612-1630
[9] P. Schiffman, S. Gupta, D. Reuss et al., TCC-III engine benchmark for large-eddy simulation of IC engine flows, Oil & Gas Science and Technology 2017; 71(1)
[10] M. Schmitt, C.E. Frouzakis, A.G. Tomboulides, Y.M. Wright, K. Boulochos, Direct numerical simulation of multiple cycles in a valve/piston assembly, Physics of Fluids 26, 035105, 2014
[11] M. Schmitt, C.E. Frouzakis, A.G. Tomboulides, Y.M. Wright, K. Boulochos, Direct numerical simulation of the effect of compression on the flow, temperature and composition under engine-like conditions, Proceedings of the Combustion Institute, 35 3069-3077, 2015.
[12] M. Schmitt, C.E. Frouzakis, A.G. Tomboulides, Y.M. Wright, K. Boulochos, Direct numerical simulation of the compression under engine relevant conditions: Local wall heat flux distribution, Int J of Heat and Mass Transfer, 92 718-731, 2016.
[13] C. Mandanis, M. Schmitt, J. Koch, Y.M. Wright, K. Boulouchos, Wall heat flux and thermal stratification investigations during the compression stroke of an engine-like geometry: A comparison between LES and DNS, Flow Turbulence and Combustion, 2016
[14] H. Werner, H. Wengle, LES of turbulent flow over a square rib in a channel, Advances in Turbulence, Vol 2 418-423, 1989.
[15] C. Angelberger, T. Poinsot, B. Delhay, Improving near-wall combustion and wall heat transfer modeling in SI engine computations, SAE 972881 113-130, 1997
[16] C. Jayatilleke, The influence of Prandlt number and surface roughness on the resistance of the laminar sublayer to momentum and heat transfer, Progress in Heat and Mass Transfer, 1:193-321, 1969