Advanced near-wall heat transfer modeling for in-cylinder flows

S. Šarić, B. Basara
AVL List GmbH

1 Abstract
Most of the existing wall heat transfer models employed for in-cylinder flow simulations are not capable of predicting the history and peak value of the heat flux. More comprehensive models that account for density and property variations rely mainly on the standard or low-Reynolds number variants of $k$-$\varepsilon$ turbulence model. Presently applied mesh resolutions already allow for first near-wall computational cells reaching the buffer or locally even viscous/conductive sub-layer, thus increasing importance of more sophisticated modeling of near-wall transport phenomena. The present approach relies on the $k$-$\zeta$-f turbulence model which is capable of capturing turbulent stress anisotropy near wall and predicting heat transfer with more fidelity. A compressible wall function of Han and Reitz is formulated in the framework of hybrid wall treatment. The model is validated against spark ignition (SI) engine heat transfer measurements. Predicted wall heat flux evolutions on the cylinder head exhibit very good agreement with the experimental data, being superior to similar numerical predictions available in the published literature.

2 Introduction
The existing wall heat transfer models (temperature wall functions) for in-cylinder flows are usually employed in conjunction with standard or low-Reynolds number variants of $k$-$\varepsilon$ turbulence model. Irrespective of complexity of the heat transfer model, its performance strongly depends on capability of the underlying turbulence model to capture near-wall transport phenomena. Numerous engine simulations, however, still employ a ‘standard’ modelling approach for turbulence (e.g. standard $k$-$\varepsilon$) and wall heat transfer (e.g. temperature wall function of Jayatilleke (1969)) models which do not account for near-wall effects (viscous and non-viscous), variable properties and increase of the turbulent Prandtl number. Consequently, this results in substantial under-predictions (log-law region) or over-predictions (viscous/conductive sub-layer) of wall heat transfer. The previous work pertinent to engine heat transfer modeling is scrutinized in the publications of Rakopoulos et al. (2010) and Nuutinen et al. (2014). Rakopoulos et al. (2010) have evaluated the most popular heat transfer formulations used in commercial and research computational fluid dynamics (CFD) codes. Under-predictions of the measured heat flux peak values by 35-50% revealed weakness of incompressible temperature wall functions, whereas the
model of Han and Reitz (1997) was found to be the best compromise between simplicity and accuracy. Apart from variable density effects already observed by Han and Reitz (1997) and Angelberger et al. (1997), Nuutinen et al. (2014) incorporated combined variable properties effects on heat transfer and near-wall turbulence modifications in their imbalance wall function. The present work is based on more advanced, k-ζ-f turbulence model which allows integration to the wall, with incorporated molecular and wall-blocking modifications (Hanjalić et al., 2004). Consequently, the model is capable of capturing turbulent stress anisotropy near wall and predicting heat transfer with more fidelity. Hybrid wall treatment in AVL FIRE® (2013) is extended to the temperature wall function of Han and Reitz. Predictive capability of the hybrid approach is validated against the spark-ignition (SI) engine heat transfer measurements of Alkidas and Myers (1982).

3 Modeling Approach

The k-ζ-f RANS model employed in the present work relies on the elliptic relaxation concept providing a continuous modification of the homogeneous pressure-strain process as the wall is approached to satisfy the wall conditions, thus avoiding the need for any wall topology parameter. The variable ζ represents the ratio \( \frac{v^2}{k} \) (\( v^2 \) is a scalar property in the Durbin’s \( v^2 - f \) model (1991), which reduces to the wall-normal stress in the near-wall region) providing more convenient formulation of the equation for ζ and especially of the wall boundary conditions for the elliptic function f. Hanjalić et al. (2004) demonstrated that the model is numerically very robust and more accurate compared to the simpler two-equation eddy viscosity models. Readers are referred to the original publications of Hanjalić et al. (2004), Popovac and Hanjalić (2007) and Basara (2006) for more specific details about the model developments.

Han and Reitz (1997) derived the compressible wall function

\[
T^+ = 2.1\ln y^+ + 2.5
\]

used to model the wall heat flux as

\[
q_w = \frac{\rho c_p \mu^* T \ln \frac{T}{T_w}}{2.1\ln y^* + 2.5}
\]

Note that the published model formulation was recommended for both turbulent and laminar regimes, i.e. irrespective of \( y^* \). Accordingly, among other authors, Rakopoulos et al. (2010) in their evaluation of the existing heat transfer models, point out validity of the wall function of Han and Reitz for all \( y^* \). Due to some ambiguities in the original publication, this model \( (T^+) \) is practically used irrespective of \( y^* \), relying on the advanced near-wall treatment applied only to the momentum and turbulent equations. Consistent implementation of the model would require consideration of the near-wall formulation of the temperature wall function. As discussed by Šarić and Basara (2015), the following two-layer formulation

\[
T_{nw}^+ = 7.415 \arctan(0.089 y^* - 0.093) + 0.685
\]

is used as a reference (Figure 1) for the model implementation in the framework of hybrid wall treatment.
This method blends the integration up to the wall (exact boundary conditions) with the high-Reynolds number wall functions, enabling well-defined boundary conditions irrespective of the position of the wall-closest computational node. The hybrid wall treatment employed here represents a somewhat simplified approach (AVL FIRE®, 2013). Whereas the original compound wall treatment of Popovac and Hanjalić (2007) includes the tangential pressure gradient and convection terms, a simpler approach utilizing the standard wall functions as the upper bound is used presently. Another departure from the original formulation is pertinent to the calculation of the dissipation rate as proposed by Basara (2006). Regarding a wavy profile in Figure 1 the blending function could certainly be tuned to yield smoother distribution in the buffer layer (e.g. $\Gamma_{\text{mod}} = 0.003(y^+)^4/(1+y^+)$. However, the same blending principle of Kader (1981) is intentionally retained and now extended to the compressible wall function of Han and Reitz which is implemented implicitly via effective enthalpy diffusion coefficients ($\mu y^+/T^+$). The hybrid model depicted in Figure 1 can be expressed as follows:

$$T^+_{\text{hyb}} = \text{Pr} y^+ e^{-\Gamma} + (2.1 \ln y^+ + 2.5)e^{-\frac{1}{T^+}}$$

(4)

with the blending coefficient (Kader,1981) as a function of the normalized distance to the wall:

$$\Gamma = 0.01 \frac{(\text{Pr} y^+)^4}{1 + 5 \text{Pr}^3 y^+}$$

(5)

4 Results

The hybrid model is validated against the experimental measurements of by Alkidas and Myers (1982) who investigated heat transfer in a premixed charge spark ignition (SI) engine. Employing the total enthalpy formulation for energy equation and using the ECFM3Z model (Colin and Benkenida, 2004, AVL FIRE®, 2013) to model combustion phenomena, a simple SI engine geometry was simulated (Šarić and Basara, 2015). In many practical engine simulations, the wall function of Jayatilleke (1969) is employed, moreover, this isothermal/incompressible wall function is often also used in conjunction with the standard k-ε turbulence model. Although the mean cylinder pressure can be reproduced (Figure 2a), heat transfer is substantially under-predicted as illustrated in Figure 2b. In this particular case, more advanced turbulence modeling and wall...
treatment \((k-\zeta-f-JT-hyb)\) brings certain benefit, however, the measured wall heat flux is still underpredicted by almost 50\%. Interestingly, if the same modeling is applied outside its applicability range (e.g. on meshes with \(y^+<10\), Figure 3a), one can observe better agreement with the measured data in Figure 3b. However, this behavior is fortuitous, resulting actually from turbulence and heat transfer over-predictions. This is caused by improper near-wall turbulence modeling (standard \(k-\epsilon\)) and deficiency of the wall function of Jayatilleke which cannot account for increase of the turbulent Prandtl number close to the wall \((y^+<10)\).

For the sake of illustration, Figure 4a compares the wall heat flux history predicted by the present model to the available experimental data at the radial location \(r=37.3\text{mm}\). Clearly, the hybrid model outperforms the standard Han and Reitz wall function. This behavior is expected if one examines the evolution of the near-wall \(y^+\) at this measuring location (Figure 4b), indicating that \(y^+\) resides in the buffer layer for \(CA\) larger than 0\(^\circ\). Since heat transfer is governed by temperature gradient and the enthalpy diffusion coefficient, being inversely proportional to \(T_{hyb}^\infty\), the results are consistent with the non-dimensional temperature profiles displayed in Figure 1. Although the two-layer formulation yields improved results as well, for the reasons explained before it is used here only as a reference in order to verify the hybrid model implementation. The present hybrid model
is evidently superior to the standard Han and Reitz wall function for cases involving fine mesh resolutions with non-dimensional wall distance $y^+$ ranging from the buffer region down to the viscous/conduction sub-layer. Predicted wall heat flux evolutions on the cylinder head exhibit very good agreement with the experimental data as documented in Figure 5.

Figure 4: Comparative assessment of different model formulations on the cylinder head surface at radial position $r=37.3\text{mm}$ (a) with the evolution of local $y^+$ at the cylinder head surface (b)

Figure 5: Improved predictions of wall heat fluxes employing the hybrid model formulation
5 Conclusions

The underlying hybrid wall treatment in AVL FIRE® was extended to the model of Han and Reitz and validated against the spark-ignition (SI) engine heat transfer measurements. The resulting hybrid model is superior to the standard Han and Reitz wall function for cases involving meshes with y⁺ ranging from the buffer region down to the viscous/conduction sub-layer. Predicted wall heat flux evolutions on the cylinder head exhibit very good agreement with the experimental data, clearly demonstrating potential advantages of the hybrid wall heat transfer approach in conjunction with the advanced turbulence model.

6 References


