HYBRID URANS-LES METHOD FOR INTERNAL COMBUSTION ENGINE APPLICATIONS

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PLAN

- Introduction of common turbulence modeling approaches
- Consistent hybrid turbulence model for ICE flows: HTLES
- Validation on three cases
  - Attached boundary layer: Channel flow
  - Highly separated flow: Hill flow
  - Flow downstream a fixed valve: Steady Flow Rig
- Conclusions and perspectives
INTRODUCTION
Huge interest to benefit from the simulation tools by developing accurate modeling approaches with affordable cost

DNS: Solve Navier-Stokes equations for all turbulent length & time scales => expensive

Solution: Limit the resolved scales by using turbulence modeling

2 commonly used approaches:

- All turbulent motions are modeled
- Large framework
- Affordable
- Compatible with wall-functions
- Provides only phase averages

Possible solution

Use URANS near the wall and LES inside the domain

Affordable accurate scale resolving simulation

Buhl et al. [1]

HYBRID MODEL FOR ICE FLOWS

HYBRID TEMPORAL LARGE EDDY SIMULATION (HTLES)
The original k-ω SST URANS model where all turbulent motions are modelled:

\[
\frac{d}{dt}(\rho k_{tot}) = P - \rho k_{tot} \omega + D \quad \text{(Eq. 1)}
\]

where \( k_{tot} \) is the energy relative to integral scales.

HTLES transforms the k-ω SST URANS model (Menter et al. [2]) to hybrid model.

The model switches automatically between URANS & LES depending on the grid resolution.

\[
\frac{d}{dt}(\rho k_m) = P_m - \rho \frac{k_m}{T} + D_m \quad \text{(Eq. 2)}
\]

\( k_m \) is the energy relative to the grid resolution.

For hybrid model: HTLES

\[
T = \frac{r}{1 + \left(\frac{C_{\varepsilon 2}}{C_{\varepsilon 1}} - 1\right)} \left(1 - r \frac{C_{\varepsilon 1}}{C_{\varepsilon 2}}\right) \times \frac{k_{tot}}{\varepsilon} \quad \text{(Eq. 3)}
\]

\[ r \text{ is defined as } \frac{k_m}{k_{tot}} \text{ that has to be modelled.} \]

By making the dissipation term in the energy equation sensitive to the temporal filter width \( T \).

\[ T = r \frac{C_{\varepsilon 2}}{C_{\varepsilon 1}} - 1 \text{ that has to be modelled.} \]

MODELING THE RATIO R

- \( r \) varies between 0 and 1:

\[
0 \quad \text{DNS} \quad \text{Scale resolving mode} \quad 1 \quad \text{URANS}
\]

- The ratio \( r \) is modelled using the multi-scale approach by comparing (Manceau et al. [3]):

\[
r = \min \left( 1, \frac{1}{\beta} \left( \frac{U_c \varepsilon}{k_{\text{tot}}^{3/2}} \right)^{2/3} \left( \frac{\omega_c}{\beta} \right)^{2/3} \right)
\]

(Eq.4)

- The wall-distance is added to the model using the Elliptic Blending framework [4] which:
  - Forces the URANS mode near the wall
  - Guarantees a smooth transition between URANS and LES regions near the wall


PRESENTATION OF THE CFD SOLVER

- Cell centered CFD code based on Finite Volume methods
- Multiphysic solver: Turbulence – Diphasic flows – Combustion – Chemistry ...
- Automatic meshing for mobile geometries
  - Hexahedral mesh with cut-cell Technique
  - Automatic mesh refinement (AMR)

(Converge CFD presentation video)
HTLES results

HTLES PHYSICAL VALIDATION & COMPARISON WITH URANS/LES

Channel flow

- $Re_\tau = 1\,000$
- Attached boundary flow

Hill flow

- $Re_h = 10\,595$
- Separated flows & reattachment
- Recirculation

Steady flow rig

- $Re_D = 30\,000$
- Complex & industrial flow
- Realistic engine configuration
REMARKS:

- All simulations use the same setup:

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<th>URANS</th>
<th>Hybrid</th>
<th>LES</th>
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<td>Models</td>
<td>k-(\omega) SST</td>
<td>HTLES</td>
<td>(\sigma)-model</td>
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<td>Automatic wall function</td>
<td>Werner &amp; Wengle wall function</td>
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- Focus only on the single impact of the models on the results.
**CHANNEL FLOW SETUP**

- **Case setup:**
  - Height of the Channel $L_y = D = 25$ mm
  - Length of the Channel $L_x = 10 \times D$
  - Width of the Channel $L_z = 2 \times D$

- Grid size is set to 0.5 mm in the 3 directions (500x50x100)

- $y^+ \approx 30$

**Reference data: DNS data of Moser et al. [5]**

**Q-criterion iso-surface given by HTLES simulation**

COMPARISON OF THE VELOCITY PROFILES

Results:
- LES combined with wall-function over-estimates the flow rate
- URANS and HTLES give accurate flow rate compared with DNS-data
HILL FLOW
COMPARISON OF HTLES TO URANS AND LES

Q-criterion iso-surface given by HTLES simulation
HILL FLOW SETUP

• Hill height $h = 28$ mm
• Length of the domain $L_x = 9h$
• Height of the domain $L_y = 3.035h$
• Depth of the domain $L_z = 4.5h$

• $Re_h = 10595$
• Reference data: well-resolved LES data (Temmerman et al. [6])

QUALITATIVE ANALYSIS: MEAN VELOCITY STREAMLINES

- URANS: limited accuracy
  - Recirculation length is overestimated
  - The center of the recirculation is shifted away from the hill
- HTLES: close results to the reference
  - Recirculation length is close to the reference
  - Good location of the recirculation center
MEAN AXIAL VELOCITY PROFILES OVER THE ALTITUDE

- URANS shows discrepancies with the reference data.
- HTLES gives accurate results in term of:
  - Separation location
  - Reattachment location
  - Farfield velocity profiles
MEAN TOTAL TURBULENT ENERGY PROFILES ALONG THE ALTITUDE

- URANS under-estimates the turbulent kinetic energy profiles
- HTLES gives satisfactory kinetic energy profiles compared to the reference data
STEADY FLOW RIG

Q-criterion iso-surface given by HTLES simulation
STEADY FLOW RIG SETUP

- References: LDA measurements [7]

Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Fluid</td>
<td>N2</td>
</tr>
<tr>
<td>$Re_D$</td>
<td>30000</td>
</tr>
<tr>
<td>Mass flow rate (Kg/s)</td>
<td>0.055</td>
</tr>
<tr>
<td>$U_{inlet}$ (m/s)</td>
<td>65</td>
</tr>
<tr>
<td>Outlet pressure (atm)</td>
<td>1</td>
</tr>
</tbody>
</table>

Introduction

Hybrid model: HTLES

Results

Conclusions & perspectives

MESHING STRATEGY

30 < \( y^+ \) < 100

Total cells = 1M4
QUALITATIVE ANALYSIS: MEAN VELOCITY STREAMLINES

- Close results between HTLES and LES
- The first recirculation at the cylinder head is the same in the 3 simulations
- The second recirculation length given by URANS is bigger than HTLES and LES predictions
MEAN VELOCITY PROFILES ALONG THE RADIUS

velocity profiles are compared at two positions

- LDA measurements
  - k-ω SST (URANS)
  - σ model (LES)
  - HTLES (HYBRID)

Good agreement with LDA measurements: velocity magnitudes are well located and estimated

LES and HTLES show the same radial profiles at 20 mm

URANS simulations underestimate the radial velocity at \( r/R \in [0.6; 1] \)

URANS overestimates the axial velocity in the core region

LES and HTLES show better assessment of the axial velocity at 70 mm

20 mm

70 mm
MEAN VELOCITY PROFILES ALONG THE RADIUS ARE BETTER PREDICTED BY HTLES AND LES

- All the simulations show good agreements of velocity magnitudes
- LES and HTLES enhance slightly prediction of the radial velocity at 20 mm at the recirculation region
MEAN VELOCITY PROFILES ALONG THE RADIUS ARE BETTER PREDICTED BY HTLES AND LES

- URANS over-estimates the axial velocity in the core region
- LES and HTLES show better results of the axial velocity at 70 mm than the URANS
MEAN VELOCITY PROFILES ALONG THE RADIUS ARE BETTER PREDICTED BY HTLES AND LES
The head loss is over-predicted by LES simulation.

The head loss is predicted correctly by HTLES and URANS simulations.
CONCLUSIONS AND PERSPECTIVES

- Consistent hybrid model was derived from $k$-$\omega$ SST model
- HTLES gave very good results compared to the reference data in three situations
  - Attached boundary layers: channel flow
  - Highly separated flow: hill flow
  - Simplified ICE configuration: steady flow rig
- Results showed that HTLES combines the advantages of URANS and LES
  1. Accurate prediction of the attached boundary layer flows by using URANS near the wall
  2. Good predictions of separated flows by using the scale resolving mode far from walls
  3. Fluctuation predictions as accurate as LES
- Perspectives:
  - Explore the mesh dependency of the method
  - Extend the method to time-dependent flows and apply it to unsteady in-cylinder flows