Investigation of an IC Engine Intake Flow Based on Highly Resolved LES and PIV

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Overview

- Introduction
- Engine setup / experimental studies / numerical setup
- Comparison experiment vs. simulation
- Investigation of intake jet
- Summary
Introduction

- Intake jet is the main contributor to in-cylinder charge motion
- Intensive optimization process of the port during engine development
- Simple setup but a highly complex flow field

Multitude of phenomena:

A) Vortex shedding
B) Flow separation
C) Turbulent intake jet
D) Recirculation zones
E) Wall reattachment
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Engine Setup

**Numerical domain**

CAD model of numerical domain

**Experimental data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>CMOS 2560 x 2160 px</td>
</tr>
<tr>
<td>Laser</td>
<td>Nd:YAG at 532nm and 30 mJ/pulse</td>
</tr>
<tr>
<td>Light sheet thickness</td>
<td>0.5-0.9 mm</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Interrogation window</td>
<td>32x32 px; 725 x 725 µm²</td>
</tr>
<tr>
<td>Snapshots</td>
<td>2700 images from 9 data sets</td>
</tr>
</tbody>
</table>
Experimental studies

Visualization of normalized velocity

\[ |\langle \mathbf{u} \rangle|_{no} = \frac{|\langle \mathbf{u} \rangle|}{v_{char}} \quad v_{char} = \frac{\dot{m}}{\rho A_C} \]

\[ h: \text{ valve lift} \]
\[ s: \text{ valve gap height} \]
\[ \gamma: \text{ valve seat angle} \]
\[ A_C: \text{ cross sectional area} \]
\[ d_{AC}: \text{ mean diameter } A_C \]
\[ d_i: \text{ inner valve face diameter} \]
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Strong curvature towards cylinder head
Experimental studies

Visualization of normalized velocity

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Curvature inverts with increasing valve lift and mass flow.
Experimental studies

Visualization of normalized velocity

Flow structure differs strongly with varying mass flow and valve lift

\[ |\langle u \rangle|_{no} = \frac{|u|}{v_{char}} \]

\[ v_{char} = \frac{\dot{m}}{\rho A_C} \]

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Numerical Setup

Numerical approach:
- ANSYS CFX R16.0
- 2\textsuperscript{nd} order in time and space

<table>
<thead>
<tr>
<th></th>
<th>Coarse</th>
<th>Medium</th>
<th>Fine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodes</td>
<td>$5.7 \times 10^6$</td>
<td>$25.1 \times 10^6$</td>
<td>$155.1 \times 10^6$</td>
</tr>
<tr>
<td>Elements</td>
<td>$15.3 \times 10^6$</td>
<td>$74.4 \times 10^6$</td>
<td>$493.4 \times 10^6$</td>
</tr>
<tr>
<td>$\Delta x_{chamber}$</td>
<td>$1.0 \ mm$</td>
<td>$0.5 \ mm$</td>
<td>$0.25 \ mm$</td>
</tr>
<tr>
<td>$\Delta x_{refined}$</td>
<td>$0.5 \ mm$</td>
<td>$0.25 \ mm$</td>
<td>$0.125 \ mm$</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>$6 \ \mu s$</td>
<td>$3 \ \mu s$</td>
<td>$1.5 \ \mu s$</td>
</tr>
<tr>
<td>CPU</td>
<td>144</td>
<td>288</td>
<td>3000</td>
</tr>
<tr>
<td>CPU\textsubscript{h}</td>
<td>$1 \times 10^4$</td>
<td>$7 \times 10^4$</td>
<td>$1 \times 10^6$</td>
</tr>
</tbody>
</table>

Applied turbulence models:
- DES-SST (hybrid model)
- Sigma (state of the art LES model)

Investigated cases:
- DES $\rightarrow$ DES-SST on medium mesh
- SC $\rightarrow$ Sigma on coarse mesh
- SM $\rightarrow$ Sigma on medium mesh
- SF $\rightarrow$ Sigma on fine mesh
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Comparison – Velocity Field

Instantaneous velocity magnitude at valve middle plane

- Identical flow field topology
- Increasing level of resolved turbulence with increasing grid resolution
Comparison – Velocity Field

- Good agreement in general flow structure between all results
- Small differences at the left and the right intake jet for simulation
- Deviations between PIV and simulations at the orientation of the right jet
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Detect jet centerline

Goals:
- Extraction on the intake jet
- Comparison to:
  - 2D jet
  - Planar jet
  - Curved jet
Jet – Centerline Methodology

→ Detect jet centerline

1. Definition of a geometrical reference point (intake valve seat)
Detect jet centerline

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2. Construction of an evaluation line perpendicular to the intake valve seat
Jet – Centerline Methodology

Detect jet centerline

1. Definition of a geometrical reference point (intake valve seat)
2. Construction of an evaluation line perpendicular to the intake valve seat
3. Shift of evaluation line parallel to the intake valve seat (1x valve lift)
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→ Detect jet centerline

1. Definition of a geometrical reference point (intake valve seat)
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4. Maximum velocity on the shifted evaluation line defines the centerline starting point ($x_0$)
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2. Construction of an evaluation line perpendicular to the intake valve seat
3. Shift of evaluation line parallel to the intake valve seat (1x valve lift)
4. Maximum velocity on the shifted evaluation line defines the centerline starting point ($x_0$)
   i. Calculation of centerline (by integration)
   ii. Definition of an adapted coordinate system $Y^* - Z^*$
   iii. Normalization of velocity by characteristic velocity $v_{char}$
Jet – Centerline Methodology

- Detect jet centerline
  - Extraction of the intake jet
  - Transformation of velocity components based on the adapted coordinate system
    - Streamwise velocity component
    - Normal velocity component
  - Evaluation of velocity profiles (based on streamwise velocity)
  - Comparison to
    - 2D jet
    - Planar jet
    - Curved jet
Jet – Trend and Curvature

Jet centerline

Centerline curvature
Jet – Trend and Curvature

- Similar results for simulation
- Deviations to experiment
Almost identical starting point for simulations
Position of experimental starting point differs
Small deviations for $Y^* < 0$ between simulation and experiment

\[ \Rightarrow \text{reason for deviation between simulation and experiment in jet centerline?} \]

Almost identical curvature for all results for $0 < Y^* < 3$:

Strong differences in curvature for $Y^* > 3$
- Small deviations for $Y^* < 0$ between simulation and experiment
  → reason for deviation between simulation and experiment in jet centerline?
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Small deviations for $Y^* < 0$ between simulation and experiment
→ reason for deviation between simulation and experiment in jet centerline?
Almost identical curvature for all results for $0 < Y^* < 3$:
Strong differences in curvature for $Y^* > 3$
Jet – Trend and Curvature

Small deviations in the valve gap increase along the jet centerline

- Small deviations for $Y^* < 0$ between simulation and experiment → reason for deviation between simulation and experiment in jet centerline?
- Almost identical curvature for all results for $0 < Y^* < 3$:
- Strong differences in curvature for $Y^* > 3$
Jet – Zone Identification

Schematic representation of a planar intake jet [1]

In general 2 zones on centerline
– Potential core (constant velocity)
– Decay zone

Schematic representation of ICE intake jet

No classical potential core due to axisymmetric geometry \(\rightarrow\) Expectation:
– 1\(^{\text{st}}\) Zone: Decrease by \(r^{-1}\)
– 2\(^{\text{nd}}\) Zone: Decay

Jet – Zone Identification

Zone I:
- Increasing velocity
- Low RMS level

Zone II (end at $\langle u_c \rangle_{no} \sim 0.6$):
- Moderate velocity decrease
- Increasing RMS

Zone III:
- Strong velocity decay
- Decreasing RMS

Ensemble-averaged and normalized streamwise velocity
Jet – Zone Identification

Ensemble-averaged and normalized streamwise velocity

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- Increasing velocity
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Zone II (end at $\langle u_c \rangle_{no} \sim 0.6$):
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Classical jets and ICE intake jets are hardly comparable
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- Investigation of a steady state flow bench configuration
  - 3 meshes
  - 2 turbulence models
- Comparison to experiment
- Applying an ad-hoc post-processing to investigate the intake jet
  - Intake jet orientation differs between PIV and simulation
  - 3 Zones on jet centerline were identified

Conclusion:
- Flow field differs strongly with varying mass flow and valve lift  
  (preliminary experimental studies)
- Small deviations of the flow field within the valve gap lead to large deviations 
  of the intake jet within the combustion chamber
- Strong differences between classical and ICE intake jet
Thank you for your attention!