Simulation of Internal Combustion Engines

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Application and Motivation

Engine designers have to comply with stringent emission regulations, where in-cylinder phenomena are of key importance for efficient and clean combustion. Research single cylinder engines with optical access are used to study in detail spray formation, in-cylinder aerodynamics or combustion. However, providing optical access may lead to unfavorable modifications to the geometry of the engine, which makes it less representative to its corresponding series production engine.
CFD can reduce time and cost during the development phase and help in better understanding pollutant formation.

CFD can be used to assist the experiment. Fields of interest are the following:

- Cyclic dispersion
- Pollutant formation
- Parametric studies

Engine Geometry

- Single cylinder SI-engine, naturally aspirated, with canted valves and flat piston
- Fast pressure transducers in the cylinder and in intake and exhaust ports
- Large-scale windows provide access for laser-optical measurements of the flow field, mixture formation, ignition and combustion
- Bore/Stroke: 84 /90mm

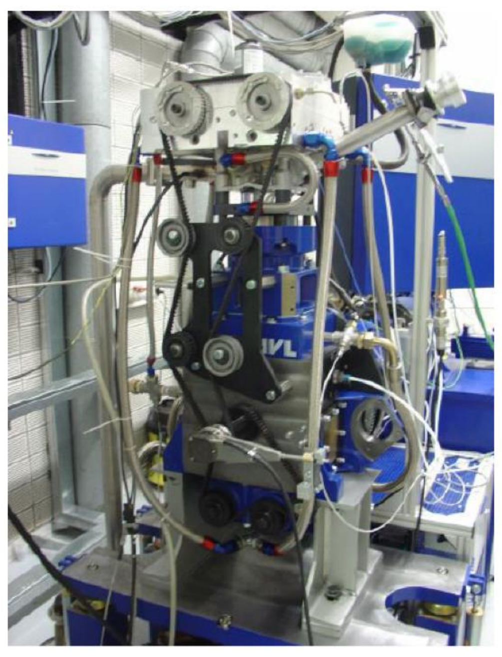


Figure 1: Research Engine at IVG

Modeling Approaches

CFD applied to IC engines is challenged by:

- 3D transient turbulent flow field
- Different lengths and time scales
- Time dependent boundary conditions
- Complex geometries
- Moving boundaries

Two different approaches are applied:

- LES on structured equidistant grids with immersed boundaries for moving obstacles integrated in the in-house code PsiPhi [1]
- RANS on unstructured moving grids using OpenFOAM [2]

RANS vs. LES

RANS (Reynolds Average Navier Stokes)

Ensemble average: Introducing the Reynolds Decomposition to the Navier-Stokes Equation.

Assuming of having infinitesimal many engine test benches and carrying out the same test at the same time and averaging them. $\phi = \bar{\phi} + \phi'$

$\bar{\phi}$	Deterministic component:	explicitly simulated
ϕ'	Stochastic component:	correlations are applied for it and replaced by model

LES (Large Eddy Simulation)

Favre filtering of the Navier-Stokes equation with a low-pass filter. Flow structures bigger than the cut-off length of the filter are resolved. The energy transfer to the residual fluctuations (sub grid scales) is modeled.

$$\phi = \tilde{\phi} + \phi''$$

$\tilde{\phi}$ Density weighted average

ϕ'' Favre fluctuation

No distinguish between deterministic and stochastic's.

RANS and LES equations appear to be the same
BUT different physical interpretation!

References

[1] A. Kempf, PsiPhi in-house Code
[2] OpenCFD. OpenCFD release OpenFOAM, 2013.
[3] H. Jasak and Ž. Tukovic. Automatic Mesh Motion for the Unstructured Finite Volume Method. Transactions of FAMENA, 30 (issue 2), 2007.
[4] Gambit, http://www.ansys.com/, 04/2013
[5] snappyHexMesh, OpenCFD. OpenCFD release OpenFOAM, 2013.
[6] Blender, http://www.blender.org/, 04.2013
[7] H. G. Weller, G. Tabor, A. D. Gosman, and C. Fureby. Application of a flame-wrinkling LES combustion model to a turbulent mixing layer. Proc. Combust. Inst. 27, page 899 907, 1998.
[8] H. Forrer and M. Berger; Flow simulations on Cartesian Grids involving Complex Moving Geometries; Proceedings of 7th International Conference on Hyperbolic Problems, Zurich, Switzerland (1998).
[9] A. P. Morse, J. H. Whitelaw, and M. Yianneskis. Turblent low measurements by Laser Doppler Anemometry in a motored reciprocating engine;Technical report, ImperialCollege London (1978)

LES in IC-Engine Simulations

There are many complex, physical phenomena related to engine operation such as knocking, mixture formation, turbulent combustion or ignition. The knowledge of these topics is important in order to improve the engine performance. The application of LES in engine simulations is very promising because it allows to simulate complicated flow behaviors correctly in different length scales with a reasonable computational cost.

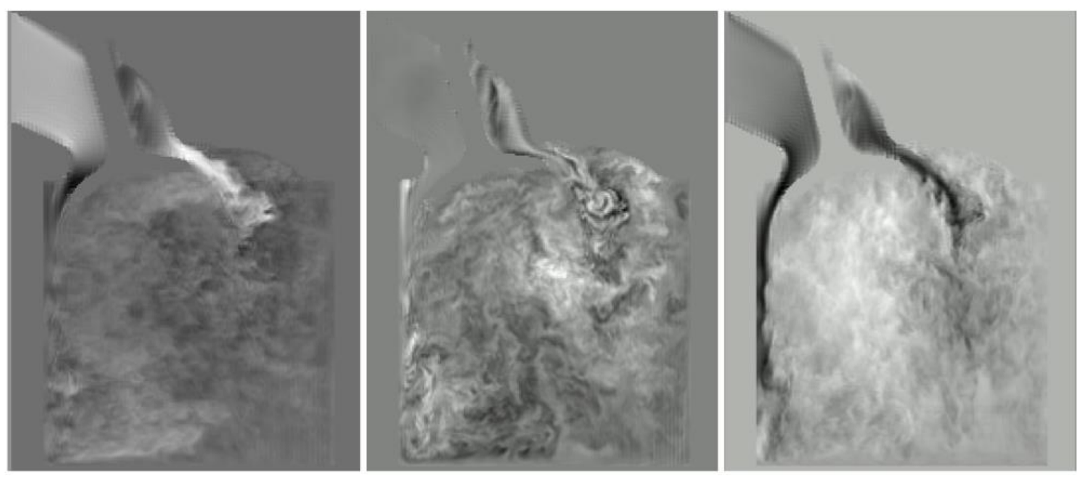


Figure 2: The axial, radial, and tangential velocity fields during the intake stroke of a four valve single cylinder engine.

LES – Moving Boundaries

Lagrangian particles are utilized to describe the moving objects in IC engine simulations. Moving geometries such as intake, exhaust valves, and piston are formed by different particle groups where different motion functions are applied for the motion of the objects. The velocity of the solid cells at the boundary are computed according to equation [8]:

$$\underline{V}_s = 2\underline{V}_p - \underline{V}_f$$

V_s is the velocity vector of the solid cell, V_f is the velocity vector of the fluid cell, and V_p is the velocity vector of the particle.

$$\frac{\partial P}{\partial \underline{x}} = -\rho \underline{a}_p$$

The pressure gradient at the moving boundaries is computed from the acceleration of the moving particles [8].

LES of a stationary Valve Engine

A simplified engine with an axis-centered valve is employed for the validation of the LES approach. The engine configuration is taken from Whitelaw et al. [9]. In this test case, the central valve is fixed and only the piston moves.

Validation with the experiment at a centerline 10 mm underneath the valve (see Figure 4)

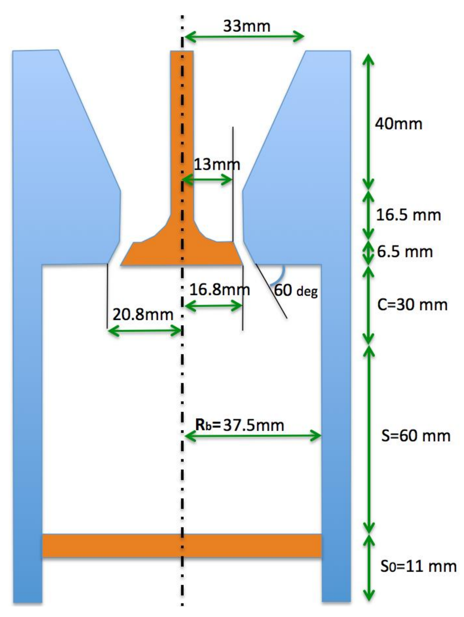


Figure 3: Simplified engine with fixed valve

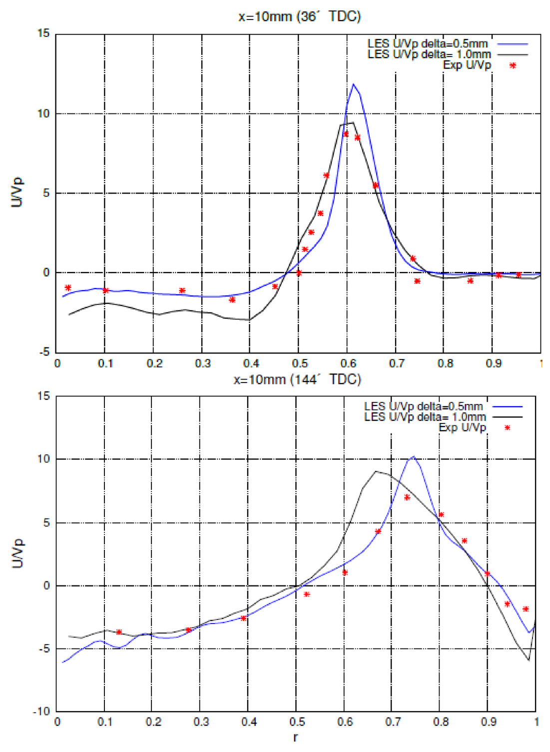


Figure 4: Mean radial profile of axial velocity at 36 CAD and 144 CAD after TDC, x=10mm

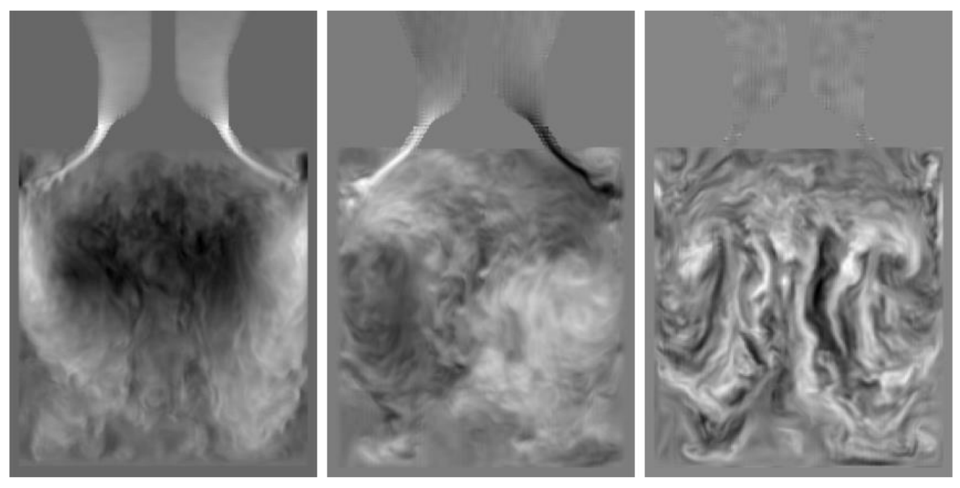


Figure 5: The axial, radial, and tangential velocity field during the intake stroke of a simplified engine with fixed axisymmetric valve.

RANS – Mapping approach for full cycle

The engine is represented by several unstructured grids, which have to cope with piston and valve motion. Within this time window, the grid exhibits good mesh quality. The internal grid points of the mesh are automatically moved by Jasak's method [3]. Valve closure is achieved by decoupling the ports from the combustion chamber.

Different Configurations (see Figure 6)

1. Intake port attached, exhaust port detached
2. Intake and exhaust ports detached
3. Intake port detached, exhaust port attached
4. Intake port and exhaust port attached

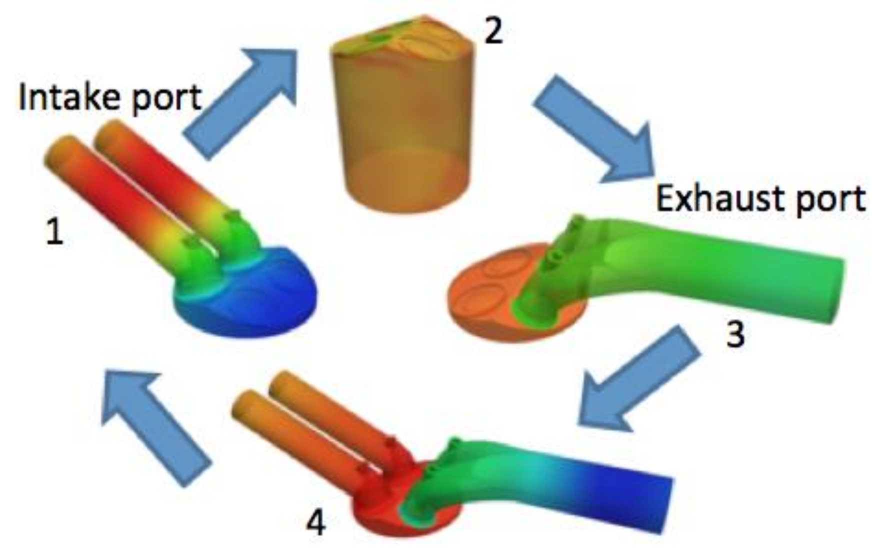
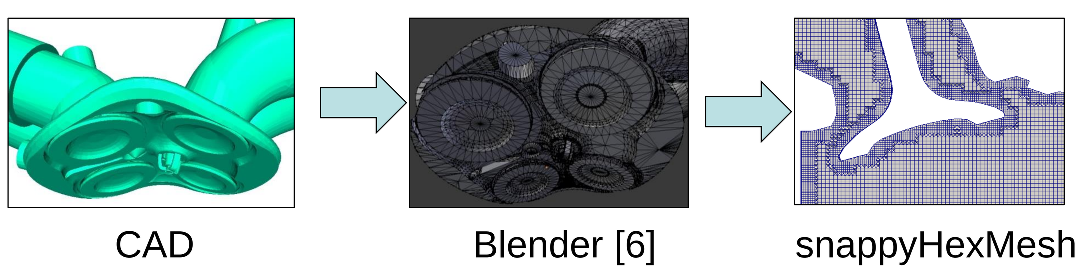


Figure 6: Engine configurations colored by pressure.

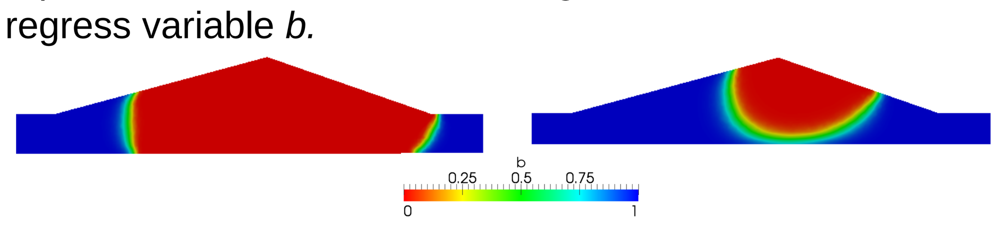
RANS – Mesh generation

Grids are generated with Gambit [4] or with snappyHexMesh [5]. The former tool creates automatically hexahedral meshes for arbitrary complex geometries described by triangulated surfaces (STL file). STL's are cleaned with Blender and valves and piston positions adjusted for the mapping approach.

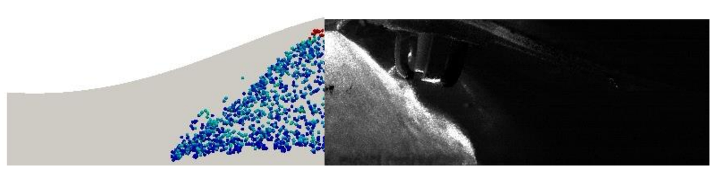


RANS – Combustion and Fuel Injection

- Flame Surface Density approach for flame front propagation [7]. Progress of combustion is modelled by a transport equation for the flame wrinkling coefficient and a reaction regress variable *b*.



- The spray is modeled by Lagrangian particles and the gaseous phase within the Eulerian field



RANS – Flow Field

The compressible Favre-averaged Navier–Stokes equations are solved and closed with the k-Epsilon turbulence model. Time varying boundary conditions for the pressure are imposed at intake and exhaust ports provided by the experiment. Exhaust and intake stroke were simulated before.
Figure 6 shows a comparison of the flow field in the central symmetry plane of the simulation against 100 phased locked PIV images for the compression stroke. The engine was motored at a speed of 1000 rpm .

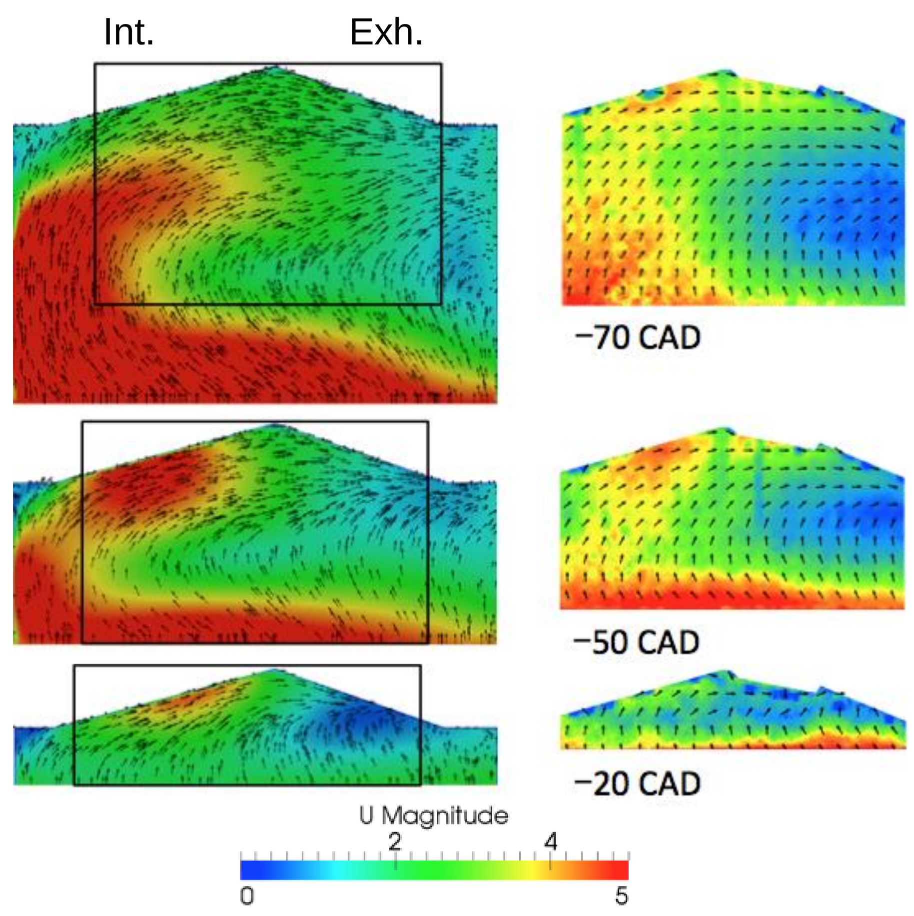


Figure 7 Comparison of velocity magnitudes fields [m/s] from simulation (left) and experiment (right)