LES of a Spark-Ignition Engine using different Combustion Models

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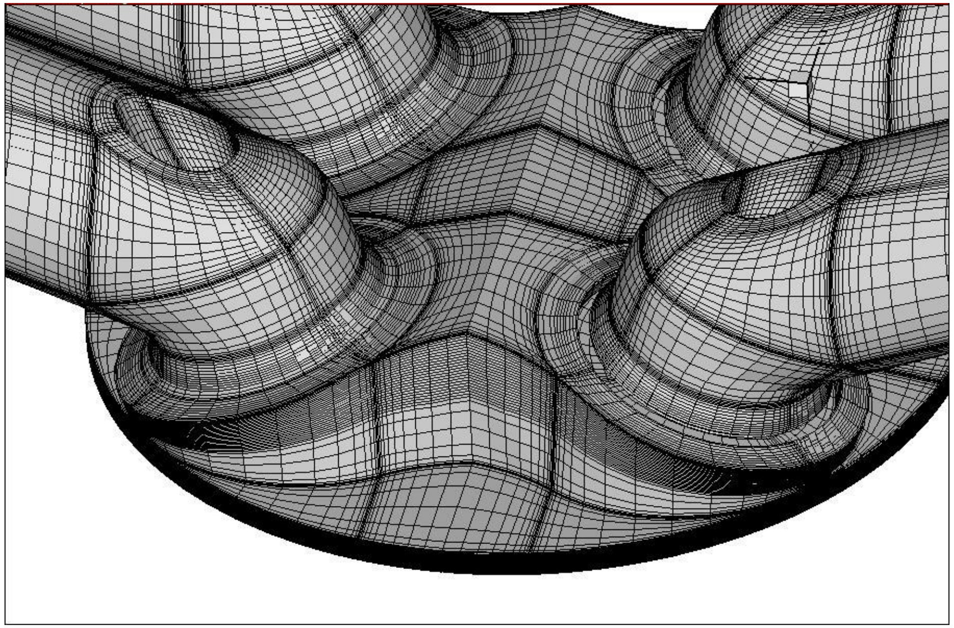


Karlsruher Institut für Technologie

Outline of the presentation

- Motivation
- Numerical procedure used for ICE
- Combustion and subgrid-scale models
- Setup of the Rotax engine
- Numerical analysis of the Rotax engine
- Conclusions and future work

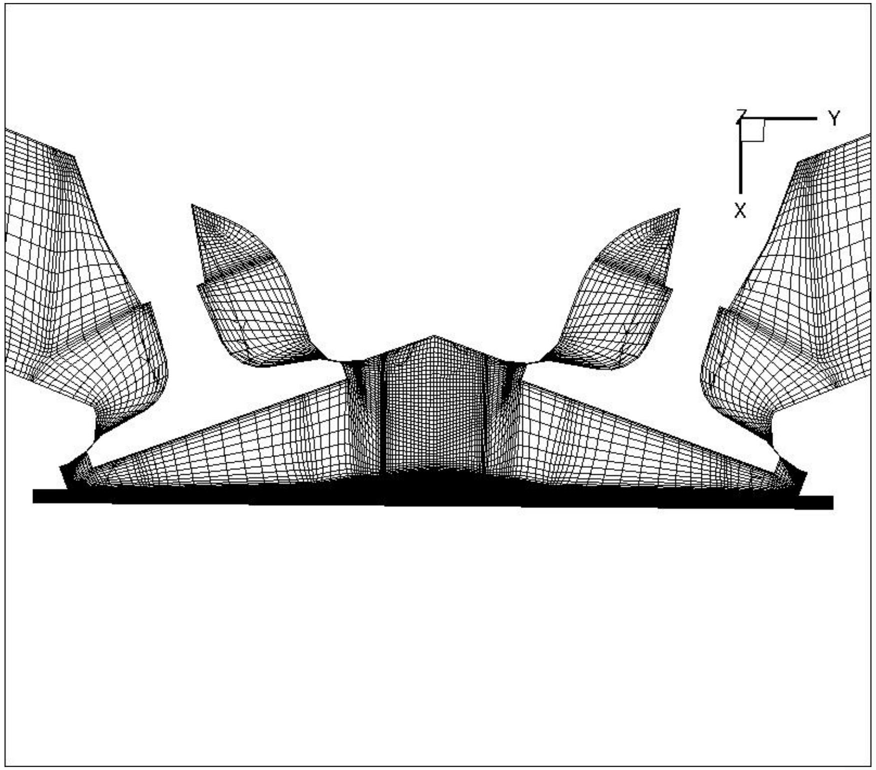
Motivation

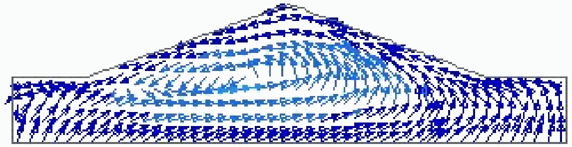
- The analysis of ICE by LES should help in understanding details of the flow field and combustion better than RANS.
- LES and the experiments from IFKM should complement each other in understanding the complex physics in the ICE.
- Suitable subgrid-scale and combustion model especially for ICE must be used.
- Modifications for wall proximity effects and variable pressure and temperature have to be taken into account.
- The influence of mesh resolution on turbulence and combustion should be investigated
- A modified Rotax one cylinder engine with four-valve and with port fuel injection (premixed) has been analyzed.

Numerical procedure for the simulation of ICE

- Flow solver: in-house developed SPARC
- Compressible Navier-Stokes equations
- Subgrid scale model: HPF-Smagorinsky, Miles
- Progress variable model (Schmid et al.) and Flame Surface Density (Poinsot et al.) models have been used
- 3D – blockstructured finite volume method
- Curvilinear coordinates system
- Discretization in space: 4rd order central difference scheme
- Time integration: 2nd order dual time stepping, $\Delta t=2\cdot10^{-6}$ s
- Parallelization by message passing interface (MPI)

Numerical procedure for the simulation of ICE





Euler method

Euler-Lagrange method

Combustion and Subgrid-scale models for ICE

- Subgrid-scale models for complex flows must be self adapting to flow field and locally formulated.
- Dynamic models are accurate for these flows, but averaging procedure is difficult for moving grids.
- The averaging procedure is done in space or time. These makes little sense on moving and deforming grids.
- High-pass filtering is obtained by subtracting low-pass filtered quantities from unfiltered ones

HPF-Smagorinsky reads (Stolz 2003):

$$H * \overline{u} = (I - G)^{N+1} * \overline{u}$$

$$\tau_{ij} - \frac{\delta_{ij}}{3}\tau_{kk} = -2\left(c_s^{HPF}\Delta\right)^2 \left|S(H * \overline{u})\right| \cdot S_{ij}(H * \overline{u})$$

Extension of the combustion model of Schmid et al. for ICE

Schmid et al. progress variable model is a simple but relatively accurate combustion model proposed for RANS calculations

$$\frac{\partial \rho\Theta}{\partial t} + \frac{\partial(\rho u_i \Theta)}{\partial x_i} - \frac{\partial}{\partial x_i}\left(D_t \frac{\partial \Theta}{\partial x_i}\right) = S_\Theta$$

$$S_\Theta = 4.96 \cdot \frac{\varepsilon}{k}\left(\frac{S_l}{\sqrt{{}^{2}\!/\!_{3}\,k}} + \left(1 + Da_t^{-2}\right)^{-1/4}\right)^2 \cdot \Theta \cdot \left(1 - \Theta\right) \cdot \rho_u$$

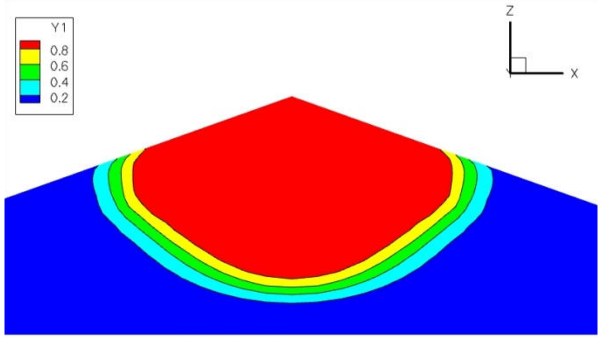
For LES k and ε must be replaced by subgrid-scale quantities:

$$k = u'^2 = \left(c_{comb} \cdot \Delta \cdot \left|S_{ij}(\overline{u})\right|\right)^2 \qquad \varepsilon = \frac{k^{3/2}}{\Delta}$$

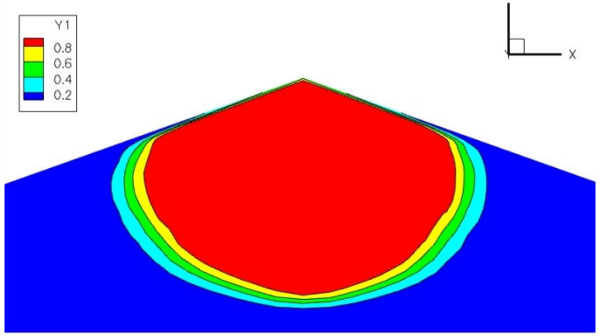
The constant c_{comb} =0.06 has been calibrated using the bomb experiments of Abdel-Gayed et al. for propane/air mixtures

Extension of the combustion model of Schmid et al. for ICE

Progress variable models have severe difficulties when applied to flames close to walls



Prediction of the flame front without ITNFS



Prediction of the flame front with ITNFS

Intermittent Turbulent Net Flame Stretch (ITNFS) of Meneveau and Poinsot has been combined with Schmid et al. combustion model.

$$\frac{1}{\tau_{turb}} = \Gamma_K\left(\frac{u'}{S_l}, \frac{l_t}{\delta_l}\right)\cdot\frac{u'}{\Delta}$$

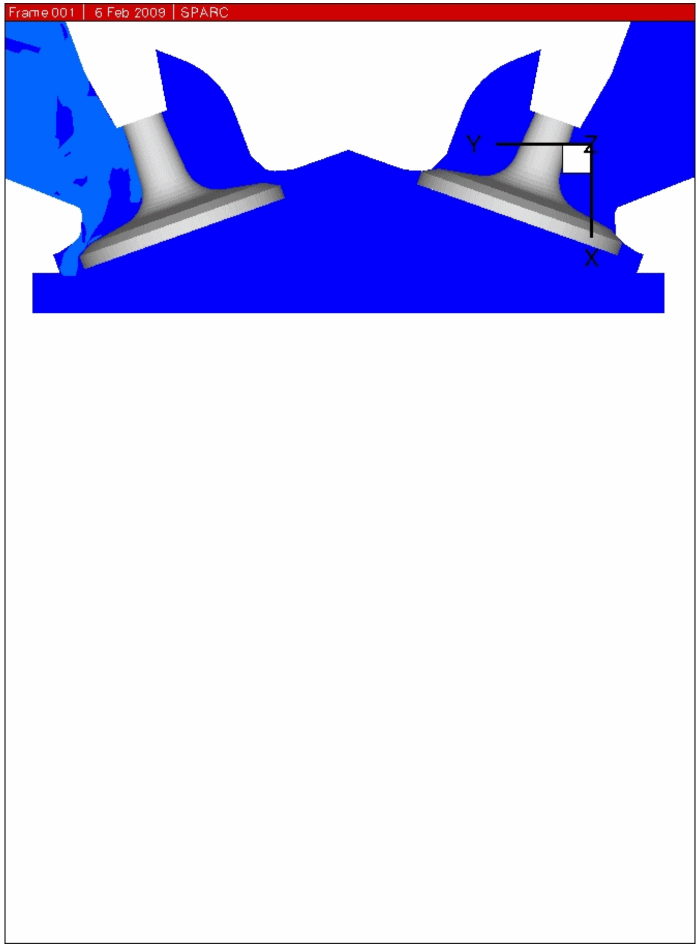
Reduction of the turbulent velocity fluctuations by Van Driest wall damping term.

$$u' = (1-\exp^{\frac{-y^+}{25}})\cdot c_{comb}\cdot\Delta\cdot\left|S_{ij}(\overline{u})\right|$$

Mixing model for the fuel-air ratio

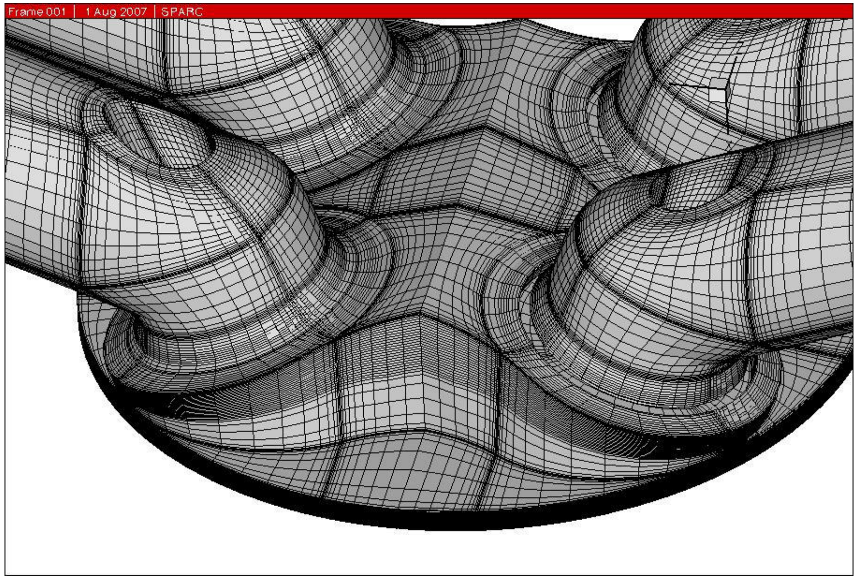
A transport equation for the fuel-air mixture ϕ is proposed for the modelling of the flow of fuel-air mixture into the cylinder:

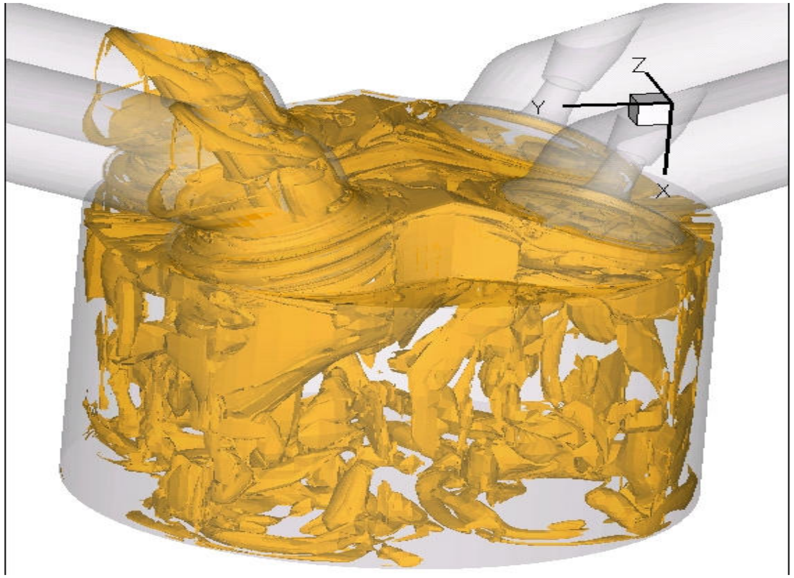
$$\frac{\partial \rho\phi}{\partial t}+\frac{\partial(\rho u_i\phi)}{\partial x_i}-\frac{\partial}{\partial x_i}\left(D_t\,\frac{\partial\phi}{\partial x_i}\right)=0$$



Setup for the Rotax engine

- Four-valve engine with a stroke and bore of 83mm x 100 mm and compression ratio of 11.5.
- Engine speed Ω_{cs}=2000 rpm, load = 100%
- The equivalence ratio was Φ=1.12 of the fuel-air mixture.

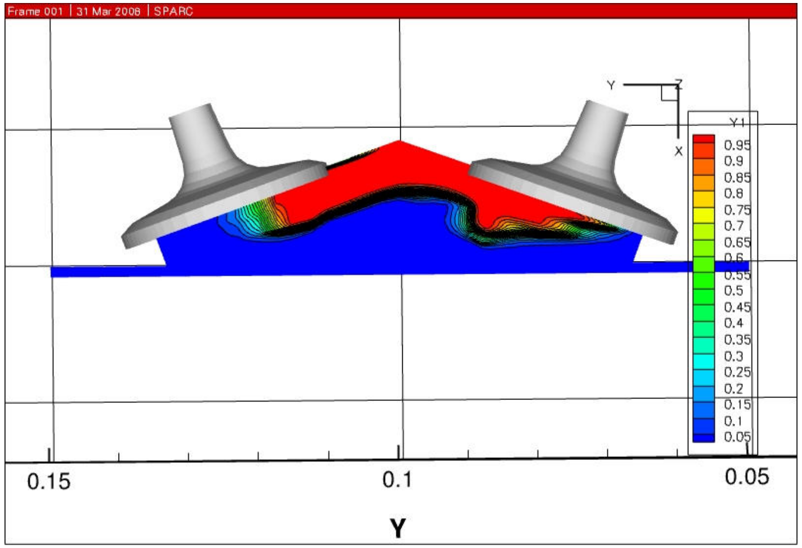


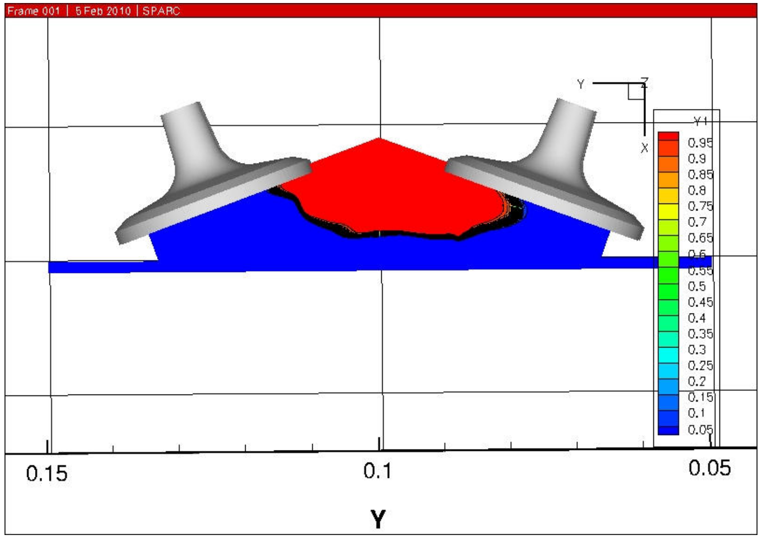


Isocontours of Q-criterion

Setup for the Rotax engine

- Full compressible calculation with dual time stepping ($\Delta t = 2*10^{-6}$ s).
- Laminar burning velocity according to Metghalchi and Keck
- Variable c_p, γ, R_{gas} with JANAF tables calculated
- $1*10^6$ and $8*10^6$ mesh points in about 1452 blocks
- Results have been obtained with Schmid et al. model, Flame Surface Density combustion model of Poinsot et al.



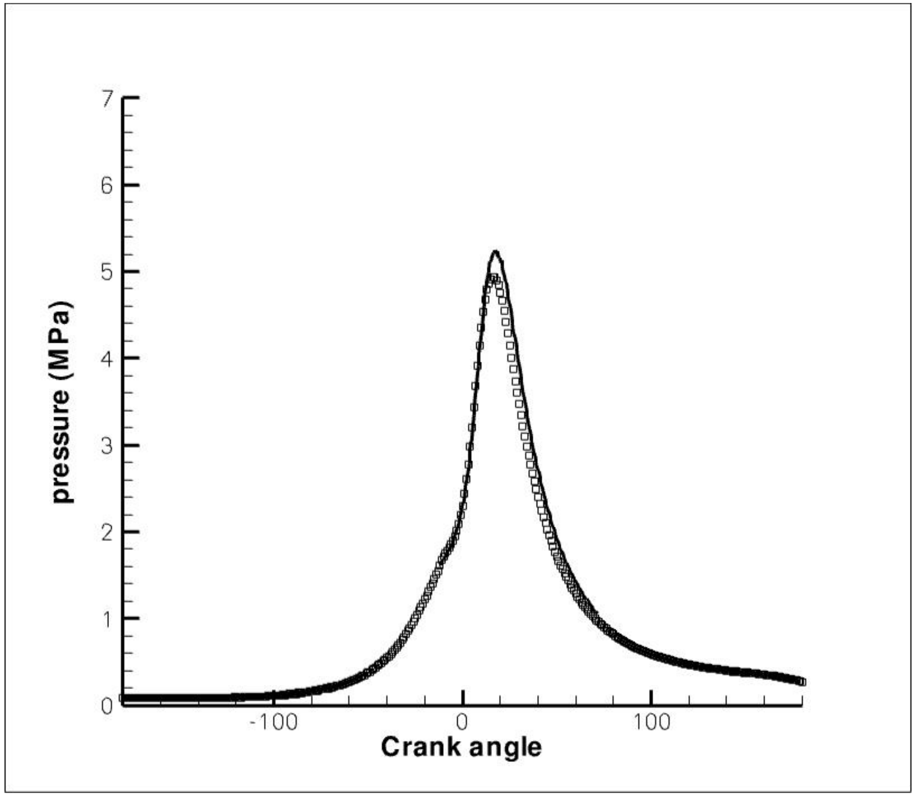


Flame front on coarse mesh
(Schmid et al.)

Flame front on fine mesh
(Schmid et al.)

Mixing model for the fuel-air ratio

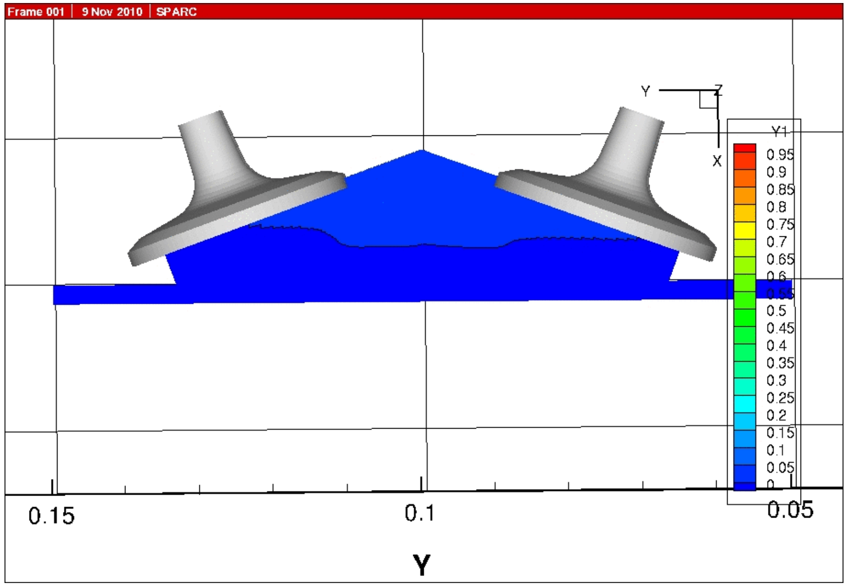
Solution with transport equation for the fuel-air mixture ϕ



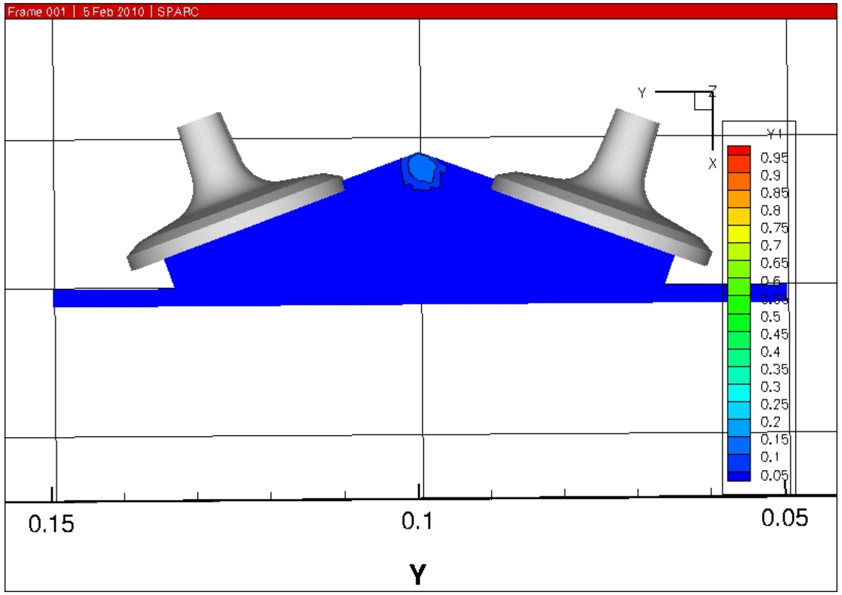
Cylinder pressure calculated

LES of the Rotax engine at full load

Flame front predicted with Flame Surface Density model and Progress variable model (on 8 *10^6 points)



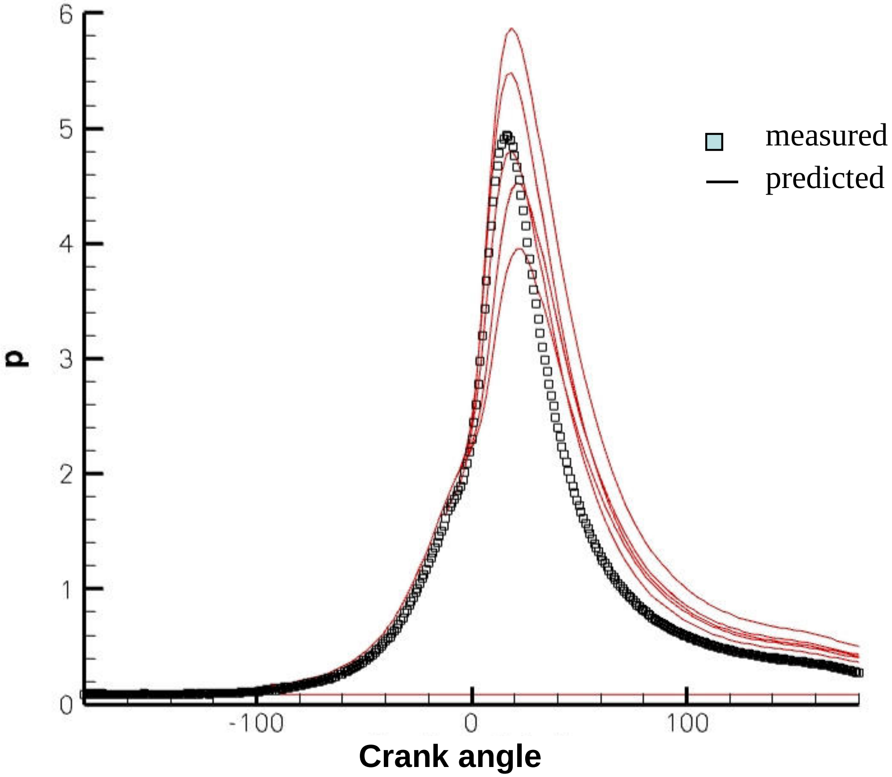
Flame front with Flame Surface Density (Poinsot et al) model



Flame front with Schmid et al model

LES of the Rotax engine with Schmid et al. model

- In the first 5 cycles the pressure is variable due to start up process.
- Later the variations becomes very small.
- The reason is the suppression of the pressure waves moving up and down in the intake and exhaust pipes by unsuitable boundary conditions.



Cylinder pressure calculated

Conclusions and future work

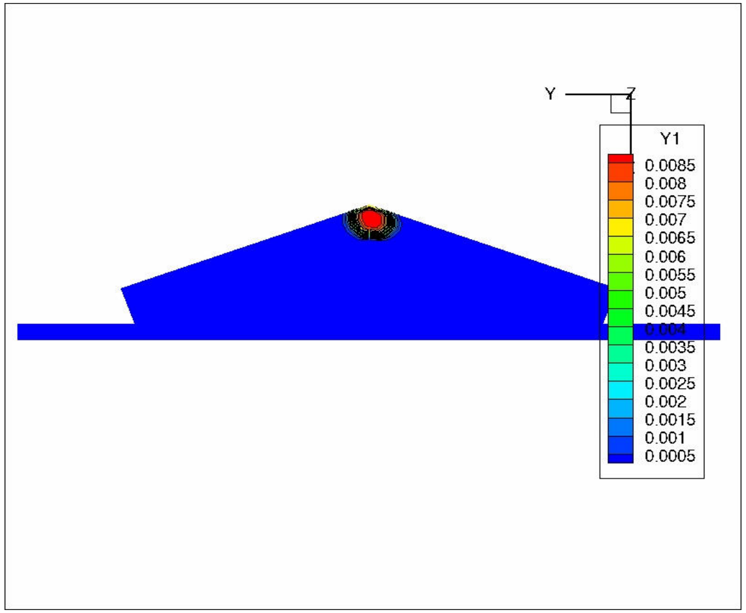
- The progress variable model of Schmid et al. has been modified for LES and extended to account for wall proximity effects (ITNFS).
- A transport equation for the fuel-air ratio has been proposed and used.
- Calculations on different fine meshes (same combustion model) shows a strong dependence on the solution.
- The flame front progressing into the combustion chamber shows differences between FSD and Schmid et al. model.
- The cyclic variations calculated with the Schmid et al. model becomes too small after the start-up process.
- First computations with FSD gives stronger dependence of speed of the heat release rate with turbulence

Future developments:

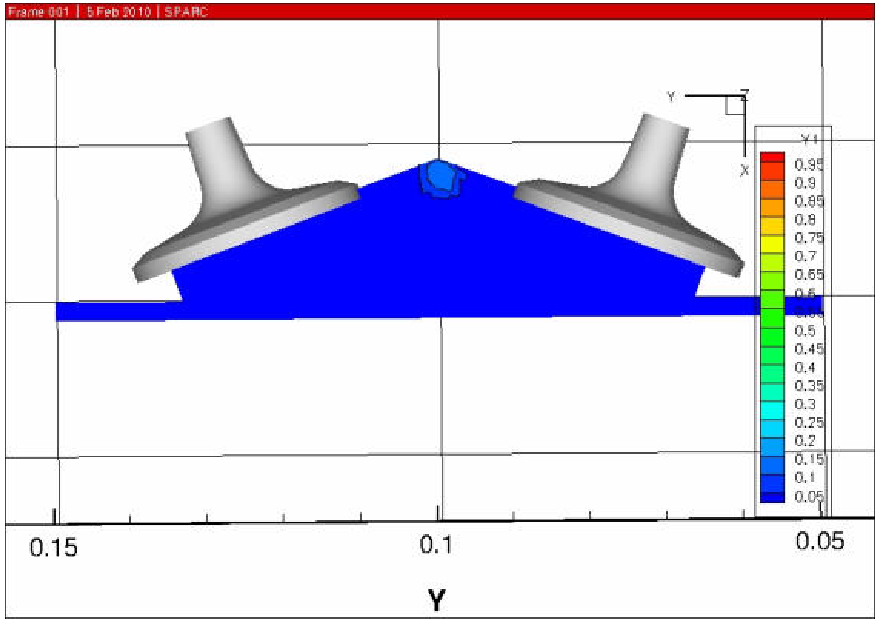
- The REDIM combustion model will be extended (ITT) and used next.
- Investigations will be extended for the analysis of Direct Injection engines.

LES of the Rotax engine at full load

Flame front predicted with Flame Surface Density model and Progress variable model (on 8 *10^6 points)



Flame front with Flame Surface Density (Poinsot et al) model



Flame front with Schmid et al model