# Project Update: Heat Transfer and Internal Flow in Reciprocating Compressors

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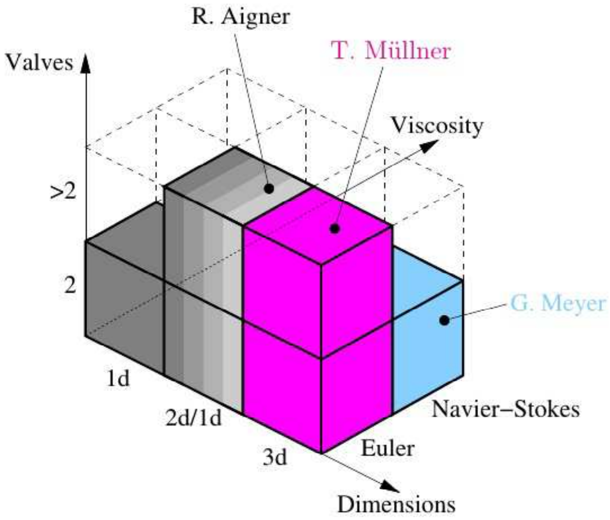
## Outline

1. Flow3D
2. Heat Transfer
3. Examples, Mesh study
4. Instructions and file structure
5. Conclusions

# Program family Compressor1D/2D/3D



# Changes since April 2015

- A bug in the "valve dynamics" has been eliminated.
- The graphical representation of the flow properties on the side walls has been improved.
- Preliminary version of the PhD-thesis of Thomas Müllner is available.
- http://www.fluid.tuwien.ac.at/EFRC_Projects

# Flow 3D

Features

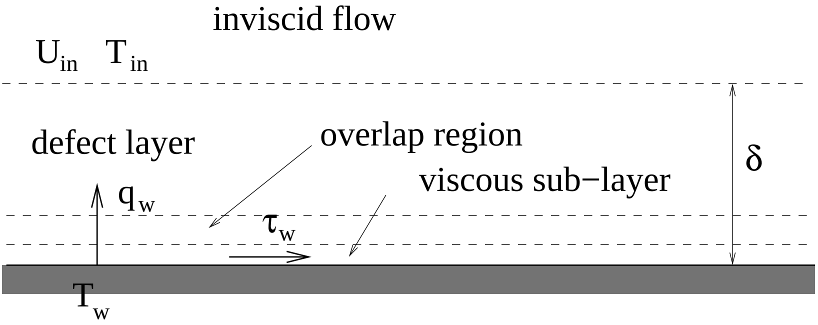
- Flow 3D simulates the **inviscid gas flow**, described by the Euler equations, in the cylinder and in the valve pockets and the motion of the valve plates.
- Cylinder: structured mesh
  mesh is characterized by th number of grid points in radial direction
  dynamic layering along cylinder axis.
  Solver: Roe's method for structured grids
- Unstructured mesh. A meshed reference valve pocket is given.

  $$\text{cone} + \text{cylinder}$$
- A posteriori calculation of heat transfer coefficients. for each face as function of the crank angle.

# Turbulent Boundary Layer

- defect layer: $u = U_{in} - u_\tau f'(y^+ Re_\tau)$
- overlap region: $u = u_\tau \left(\frac{1}{\kappa} \ln y^+ + C_2\right)$
- viscous sub-layer $u = u_\tau f(y^+)$

$$u_\tau^2 = \frac{\tau_w}{\rho}, \quad y_+ = \frac{y u_\tau}{\nu}, \quad Re_\tau = \frac{u_\tau \delta}{\nu}$$



# Turbulent Boundary-Layer

Assumption: High-Reynolds number attached boundary layer flow.
see: Schlichting/Gersten.

- friction law:

$$\frac{U}{u_\tau} = \frac{1}{\kappa} \ln \frac{u_\tau \delta}{\nu} + C^+ + \frac{2\Pi(x)}{\kappa} \approx \frac{1}{\kappa} \ln \frac{u_\tau \delta}{\nu} + C^+$$

- friction velocity

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

- friction coefficient:

$$c_f = \frac{2\tau_w}{\rho U^2} = 2\frac{u_\tau^2}{U^2}$$

- von Karman constant: $\kappa = 0.40$
- unknown boundary layer thickness $\delta$.

# The Boundary-Layer Thickness

Options:

a) solve boundary-layer equations (finite volume method)
b) solve boundary-layer equations with integral method for $\delta$
c) estimate boundary layer thickness for each face.- Implemented

# Heat Transfer

- logarithmic temperature profile in overlap region implies:

$$\frac{T_\infty - T_w(x)}{T_\tau(x)} = \frac{1}{\kappa_\theta} \ln \frac{u_\tau \delta}{\nu} + C_\theta^+(\mathrm{Pr}) + \tilde{C}_\theta(x)$$

friction temperature

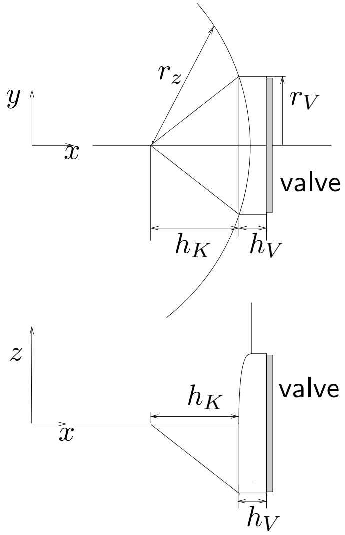
$$T_\tau = -\frac{\bar{q}_w}{\rho c_p u_\tau}$$

$$\kappa_\theta = 0.47, \quad C_\theta(\mathrm{Pr}) = 13.7\mathrm{Pr}^{2/3} - 7.5, \quad \mathrm{Pr} > 0.5$$

- Reynolds analogy

$$St = \frac{\bar{q}_w}{\rho c_p (T - T_\infty) U} == \frac{c_f/2}{\kappa/\kappa_\theta + \sqrt{\frac{c_f}{2}} D_\theta(x, \mathrm{Pr})} \approx \frac{\kappa_\theta}{\kappa} \frac{c_f}{2}.$$

# Valve Pocket



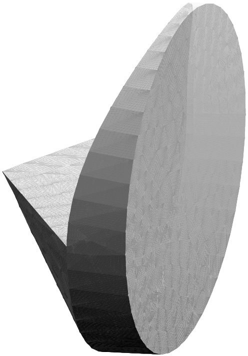

Parameters of valve pocket:

cylinder radius $r_Z$

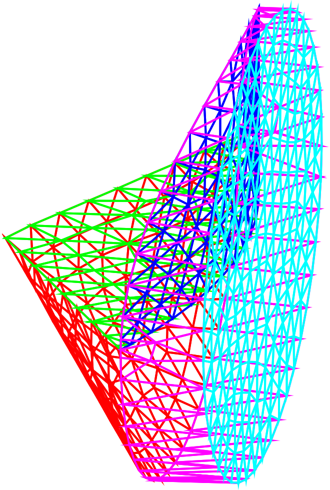
valve radius $r_V$

cone height $h_K$

height of valve cylinder $h_V$



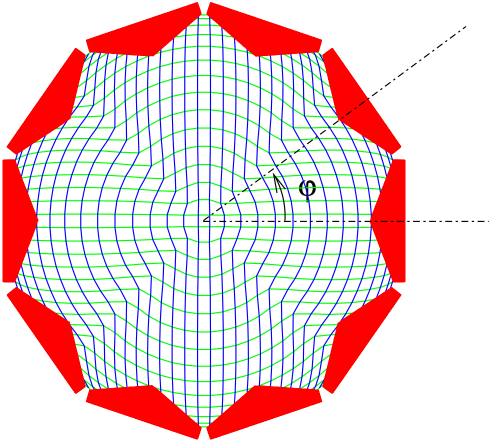
# Mesh on Surface of Valve Pocket



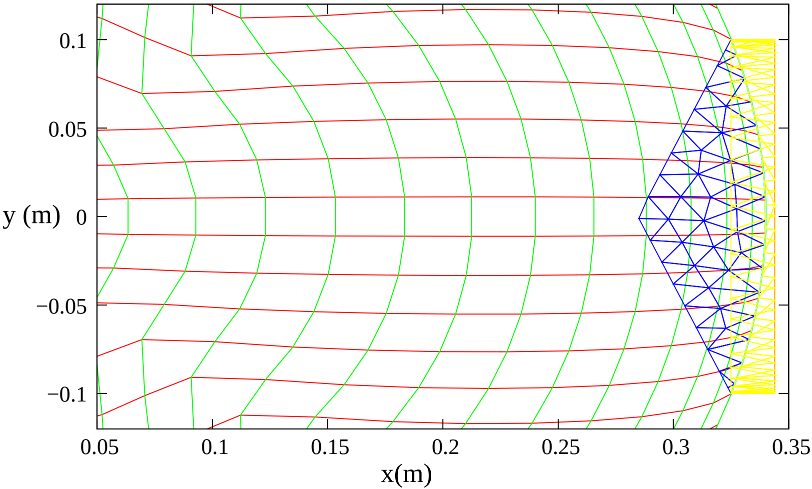
# Structured Mesh in Cylinder

grid defined by number of cells along cylinder radius

position of valve defined by angle $\varphi$ of valve axis



# Connecting Surface

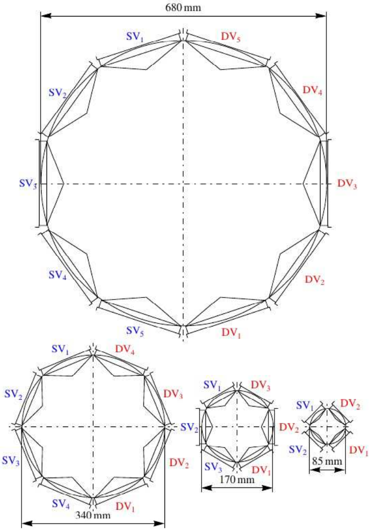



Surface connecting cylinder and vale pocket (blue)

# Program

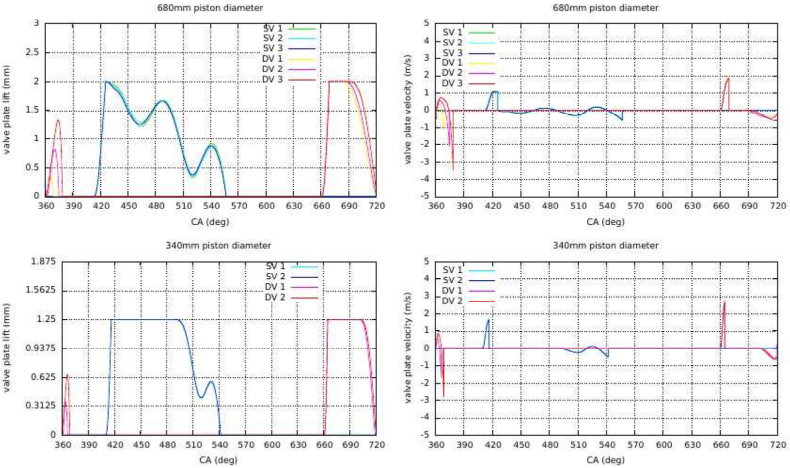
- Euler solver on structured grid, delivered 2012, source code available.
- Euler solver on unstructured grid integrated in executable euler.exe delivered April 22rd,2015
- Coupling algorithm structured/unstructured mesh integrated in euler.exe delivered April 22nd,2015
- A posteriori calculation of heat transfer coefficients.
- No meshing tool for valve pockets is provided. Referent valve pocket is delivered. For other geometries a *.msh file has to be created with NETGEN. But additional information concerning the boundary condition is needed.
- GUI April 22nd,2015

# Test examples

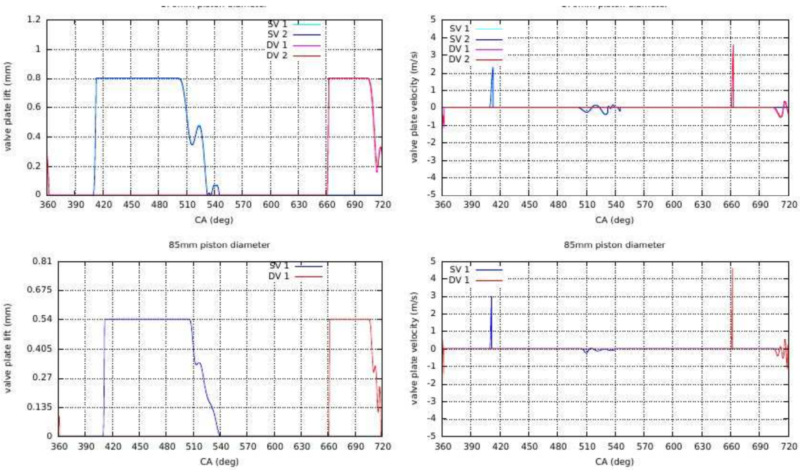



| Case | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| speed rpm | 800 | 800 | 800 | 800 |
| $\rho_s$ (kg/m$^3$) | 1 | 4 | 16 | 64 |
| $p_s$ (bar) | 1 | 4 | 16 | 64 |
| $p_d$ (bar) | 4 | 16 | 64 | 256 |
| $d_P$ (mm) | 680 | 340 | 170 | 85 |
| # Suc./Dis. V. | 5/5 | 4/4 | 3/3 | 2/2 |
| stroke /mm) | 150 | 150 | 150 | 150 |
| $d_V$ (mm) | 200 | 125 | 80 | 54 |

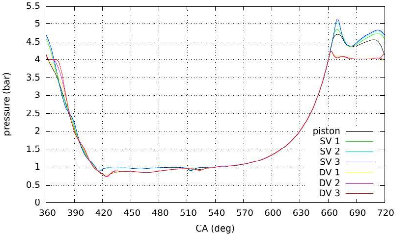
# Valve lift, Cases 1 & 2

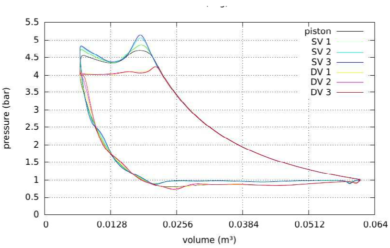


# Valve lift, Cases 3 & 4

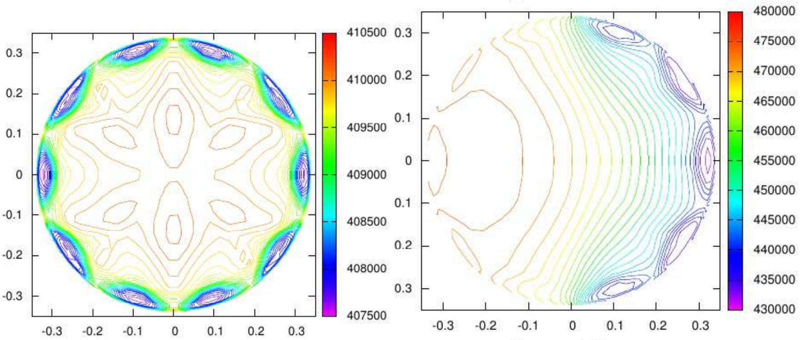


# Pressure, Case 1



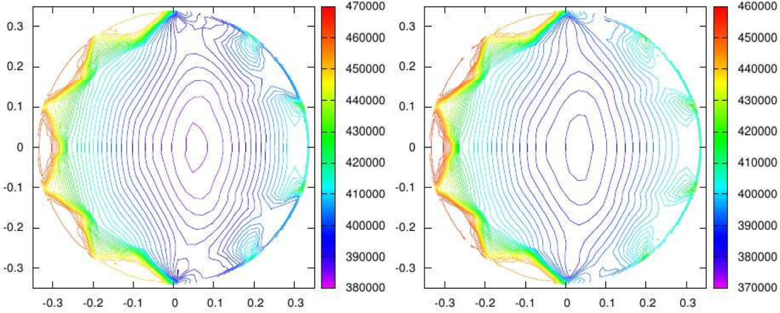
# Pressure at opening of DVs




(a) $\varphi = 301°$

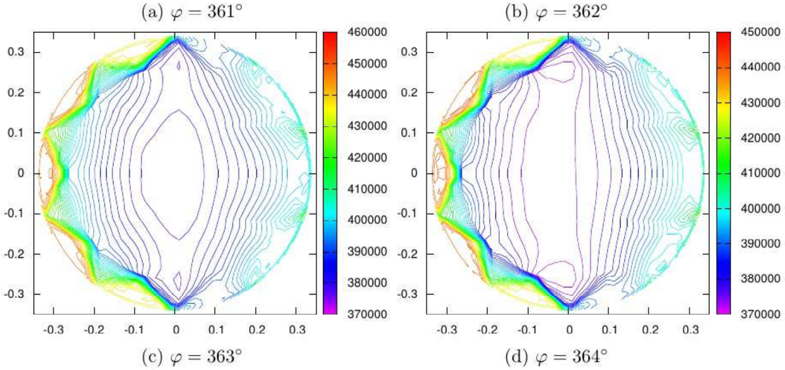
(f) $\varphi = 306°$

# Internal Pressure Waves Pressure at Dead Center

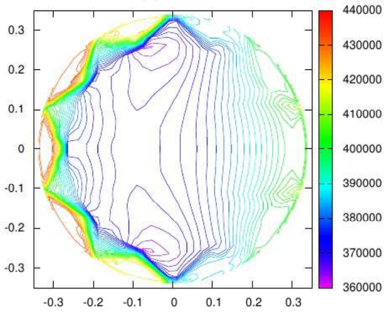



(a) $\varphi = 361°$ (b) $\varphi = 362°$

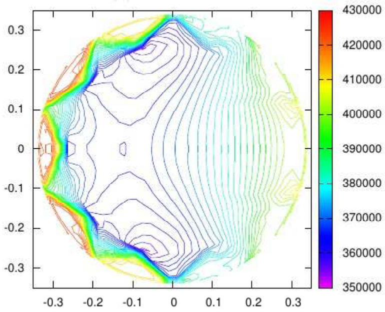
# Internal Pressure Waves Pressure at Dead Center



# Internal Pressure Waves Pressure at Dead Center

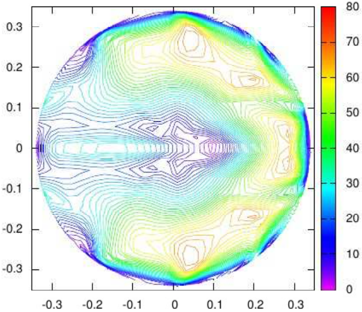



(e) $\varphi = 365°$

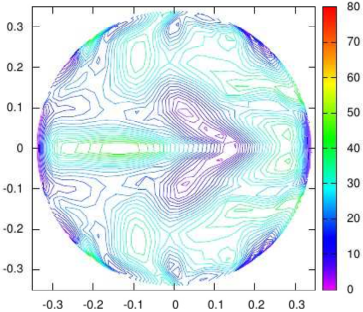



(f) $\varphi = 366°$

# Velocity Magnitude at Piston

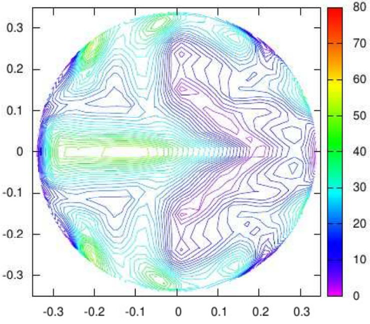



(a) $\varphi = 385°$

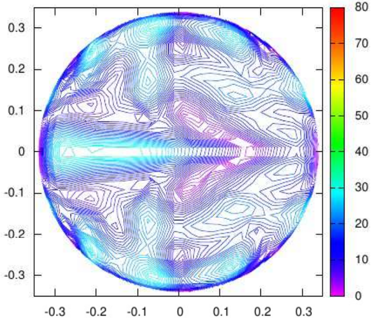



(b) $\varphi = 390°$

# Velocity Magnitude at Piston

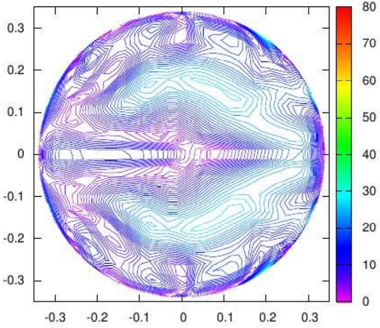



(c) $\varphi = 395°$

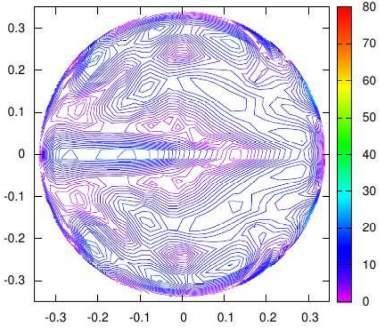



(d) $\varphi = 400°$

# Velocity Magnitude at Piston

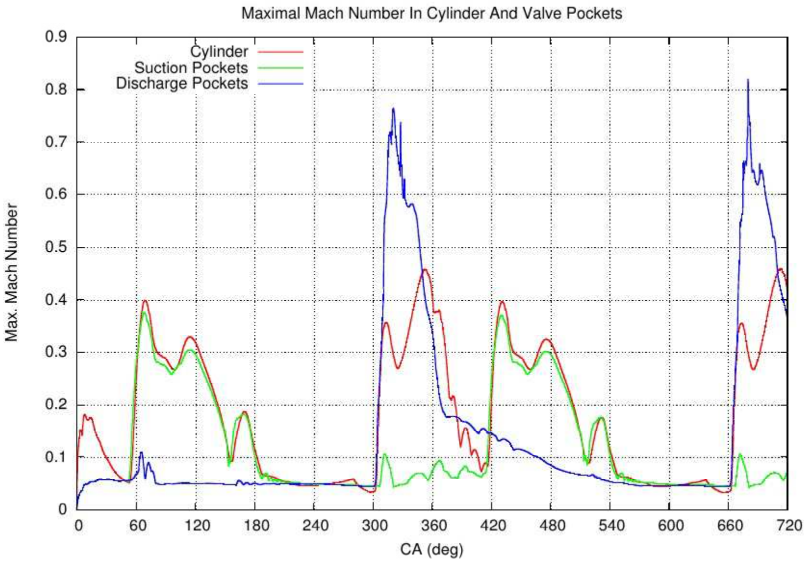



(e) $\varphi = 405°$

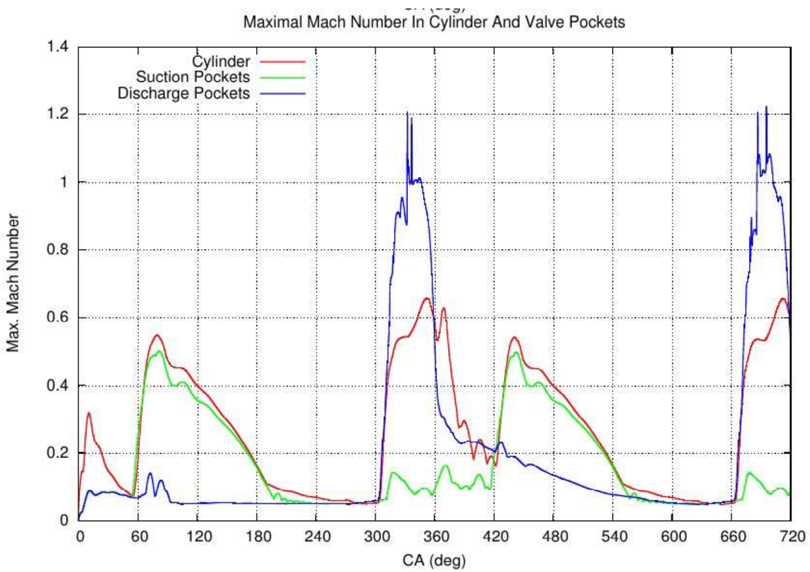



(f) $\varphi = 410°$

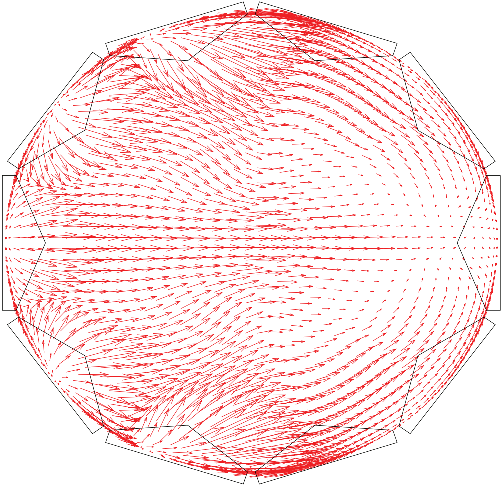
# Maximal Mach number 800 rpm



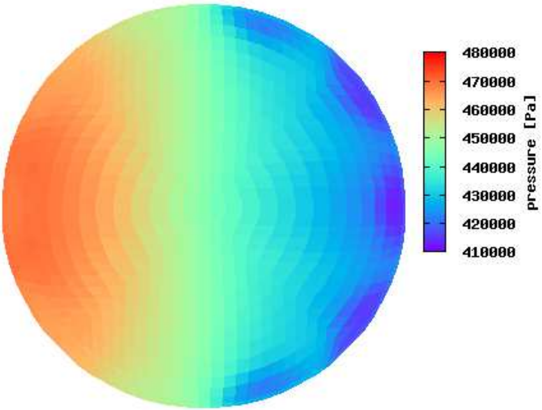
# Maximal Mach number 1200 rpm



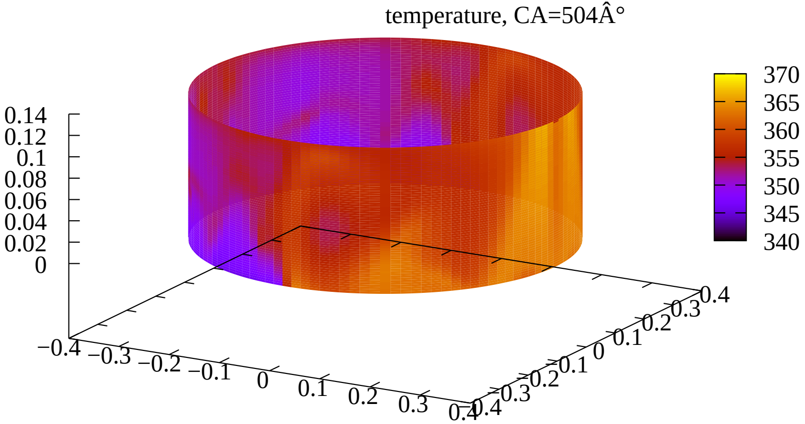
# Velocity at Piston CA=420°



# Pressure at piston CA=306°



# Temperature at side wall CA=504°



# Example 2 valve compressor

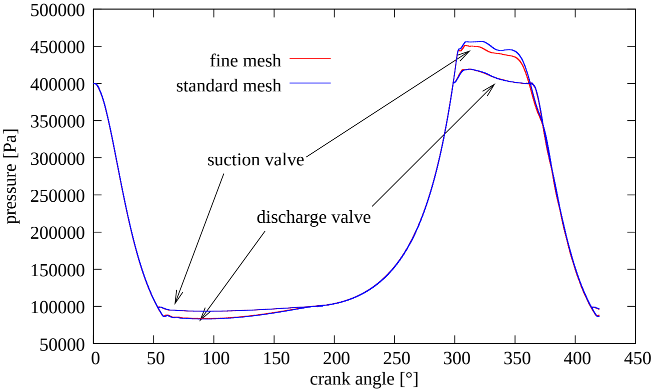
| | 2-valve comp. |
|---|---|
| Piston diameter $d_P$ (m) | 0.220 |
| Minimal gap between $z_{\min}$ (m) | 0.00150 |
| Crank radius $r$ (m) | 0.045 |
| Con-rod length $L$ (m) | 0.300 |
| Crank shaft speed omega (rpm) | 980 |
| Ratio of specific heat capacities $\gamma$ | 1.4 |
| Suction pressure $p_s$ (bar) | 1.0 |
| Discharge pressure $p_d$ (bar) | 4.0 |
| Suction density $\rho_s$ $(\mathrm{kg/m^3})$ | 1.0 |

# Mesh refinement

A new reference mesh with halves all edges has been created for comparison, not delivered.

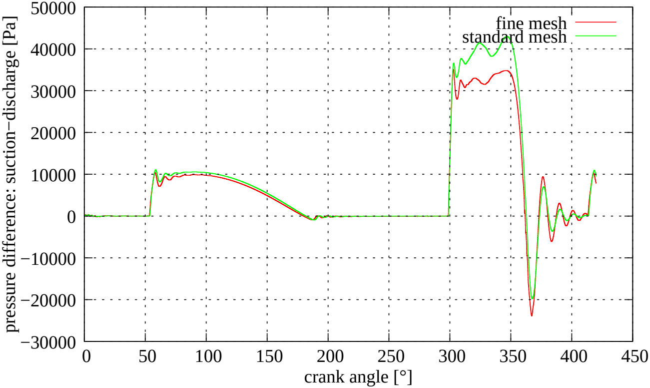
| cells along radius | mesh in valve pocket | comp. time $CA = 420^\circ$ |
|---|---|---|
| 15 | standard | 10 h 23 min |
| 30 | standard | sing. at $CA = 9^\circ$ |
| 30 | fine | 81 h 48 min |

# Pressure



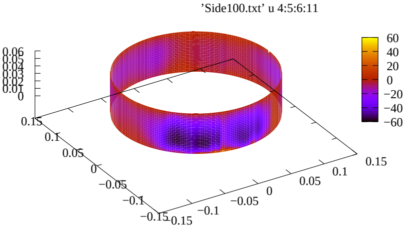

fine mesh, standard mesh

# Pressure difference

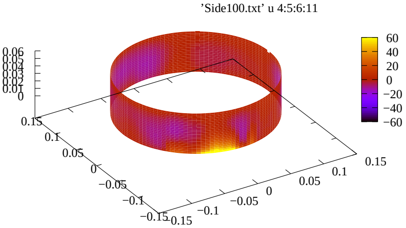



fine mesh, standard mesh

# Vertical velocity CA=100° - Intake



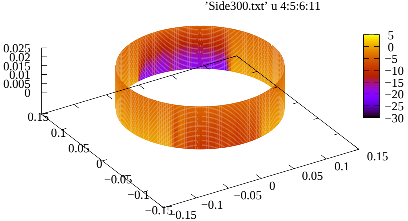

fine mesh

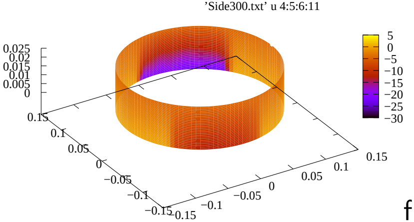



standard mesh

Grid dependence of flow field ⇒ Grid dependence of heat transfer coefficient during intake!

# Vertical velocity CA=300° - Discharge



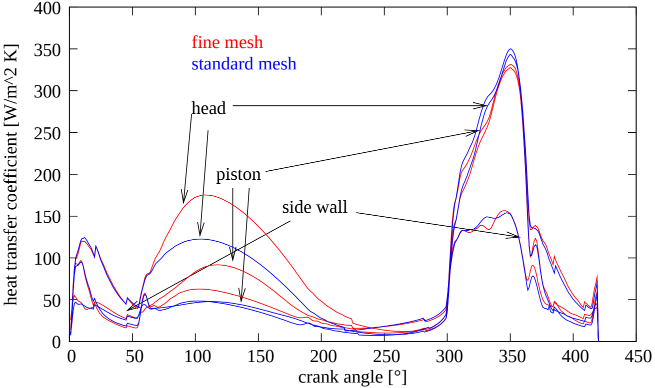

fine

mesh

standard mesh

Flow field grid independent during discharge ⇒ No grid dependence of heat transfer coefficient during discharge!

# Heat transfer coefficients



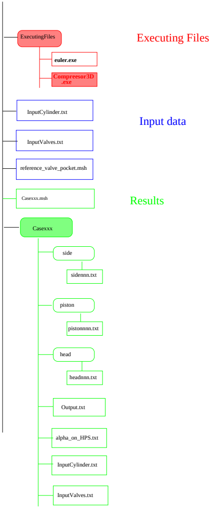

fine mesh, standard mesh

HTCs depend on grid during intake, grid independent otherwise.

# File Structure

GUI: Compressor3D.exe resides in Executing Files.
It creates the files InputCylinder.txt InputValves.txt and puts them into the right place.
It creates the Output directory Casexxx and its sub-directories.
It calls euler.exe which writes the output data in the corresponding directories.

Output.txt Valve data and some global data for every times step.
sidennn.txt, pistonnnn.txt, headnnn.txt velocity, density pressure for each surface cell at crank angle nnn.
alpha_on_HSP.txt Heat transfer coefficients for head, piston side wall as function of crank angle.



# Instructions

- Download setupComp3D.exe from http://cddlab2.fluid.tuwien.ac.at/EFRC/Compressor3D/Version04
- Install Compressor3D by executing setup3D.exe
- Start Compressor3D: (Switch to Compressor3D/ExecutingFiles and run Comp3D.exe)
- Define the Compressor data or read an the Input data files (2 Files needed: InputCylinder.txt, InputValves.txt)
- Define a case name and run the program (11 hours for two complete cycles on my laptop).
- Display the data
- The data can be accessed in the files Output.txt and headnnn.txt, sidennn.txt, pistonnnn.txt (see file structure)

# Conclusions

| Flow in cylinder | Flow in valve cage | Heat transfer |
| --- | --- | --- |
| proposal | | |
| inviscid 3D | inviscid 1D | boundary-layer along cylinder walls |
| delivered | | |
| inviscid 3D | inviscid 3D | boundary-layer along cylinder walls |

File download:

http://www.fluid.tuwien.ac.at/EFRC_Projects

# Recommendation

- For detailed analysis: Commercial CFD program (license costs are of the order of this project) not pre-competitive.
- We have reached, what can be done by a one person project.
- alternative pre-competitive approach: Open source CFD software: OpenFoam.