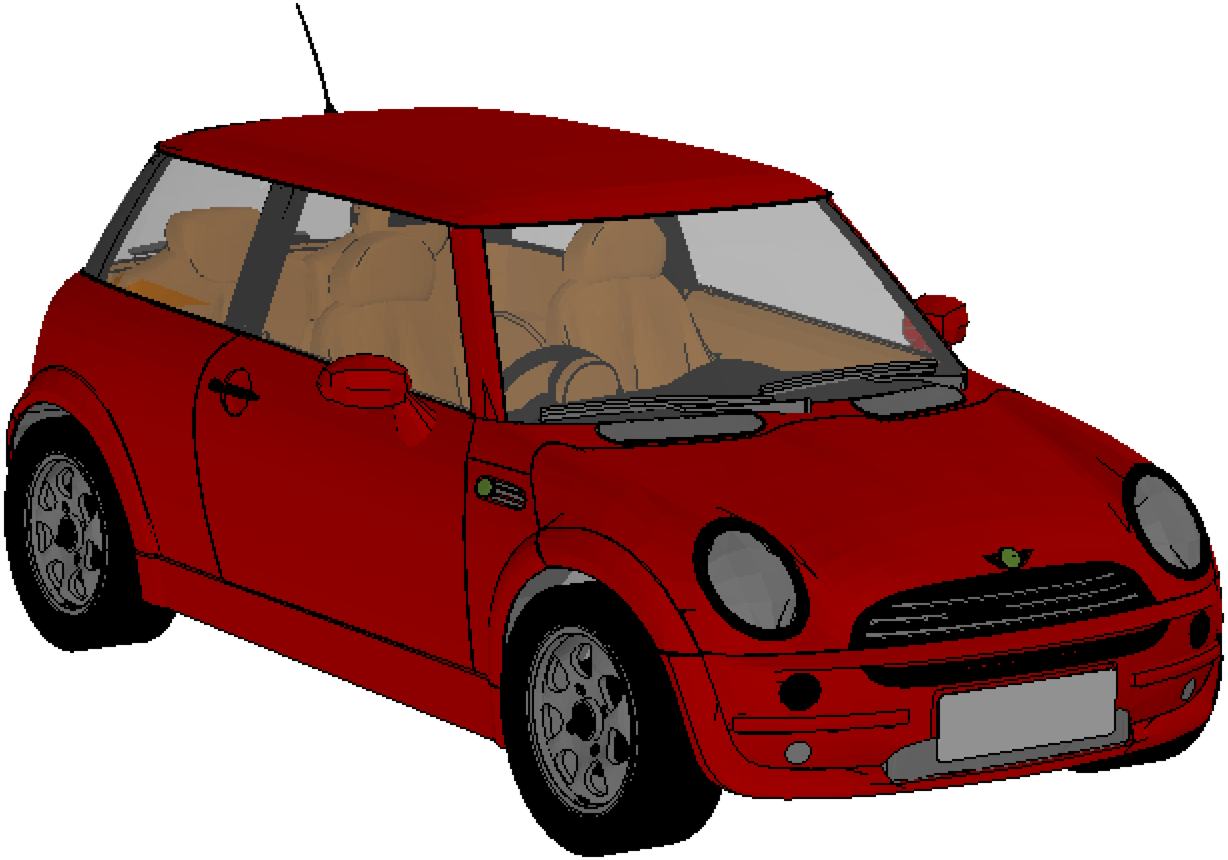
VECTIS CFD for Automotive application

Ricardo tools to meet the demands



VECTIS Incylinder Analysis

- **Introduction**
- What is VECTIS
- Incylinder analysis process
- Validation
- Examples

Introduction to Ricardo Software

- Trainer – Nick Tiney
- Product manager for VECTIS
- Worked for Ricardo since 1998
- Spent 5.5 years working for Ricardo in Japan, supporting VECTIS at Japanese OEM
- Spent 1.5 years in Prague office
- Now located in Shoreham-by-Sea Office in the UK

VECTIS Incylinder Analysis

- Introduction
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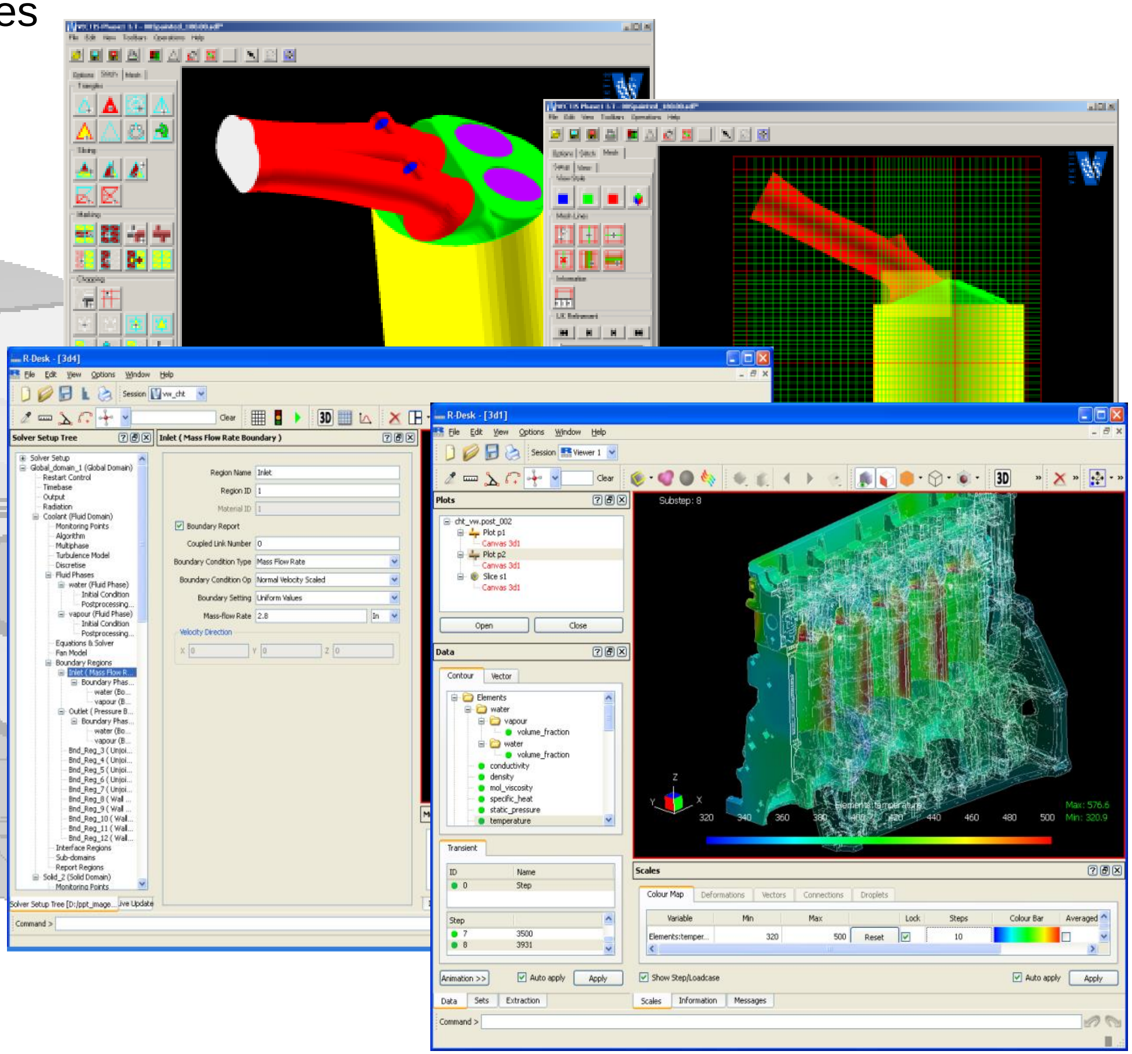
- Examples

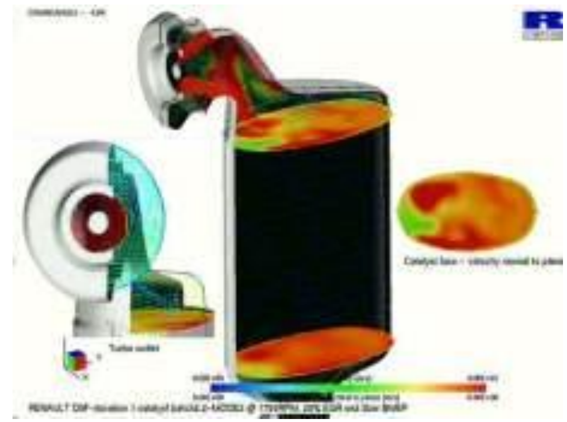
Ricardo have decades of experience in automotive engineering, fully supported by its own fluid and structural simulation software tools. VECTIS is Ricardo's 3D CFD tool.

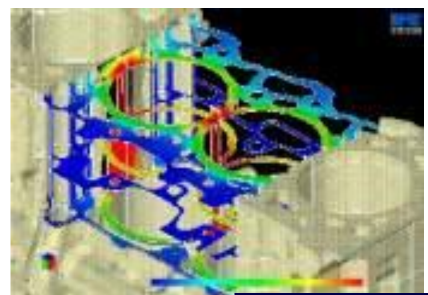
- VECTIS provides two CFD solvers developed specifically to address fluid flow simulations in the vehicle and engine industries
- VECTIS includes:
  - Pre-processor
    - Geometry import and repair
    - Control mesh setup
    - Mesh viewing
  - Automatic mesh generator
  - Solver and solver setup GUI
  - Post-processor
    - Extensive visualization and data extraction capability
    - Ensight translator
  - VECTIS to FE data translators

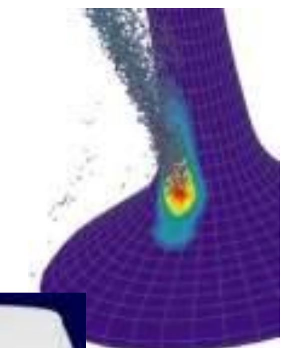


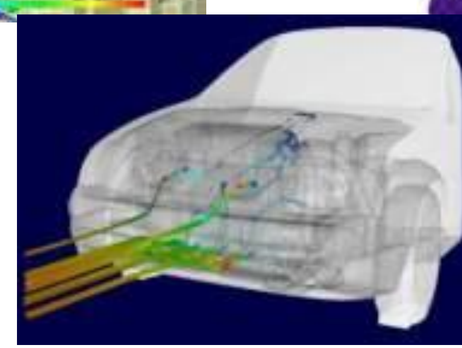
VECTIS: Capabilities

- Inlet manifold systems
- Exhaust manifold/catalyst systems
- **Combustion System Development**
  - **Diesel**
  - **Gasoline (G-Di)**
  - **Combustion modelling**
  - **Cold start**
- Coolant flows
  - Conjugate heat transfer
- Vehicle thermal management
  - Under-bonnet (under-hood flows)
- **Validation**
  - **In-cylinder flows**
  - **Fuel sprays**
  - Coolant flows
  - Catalysts
  - Under-bonnet (under-hood flows)



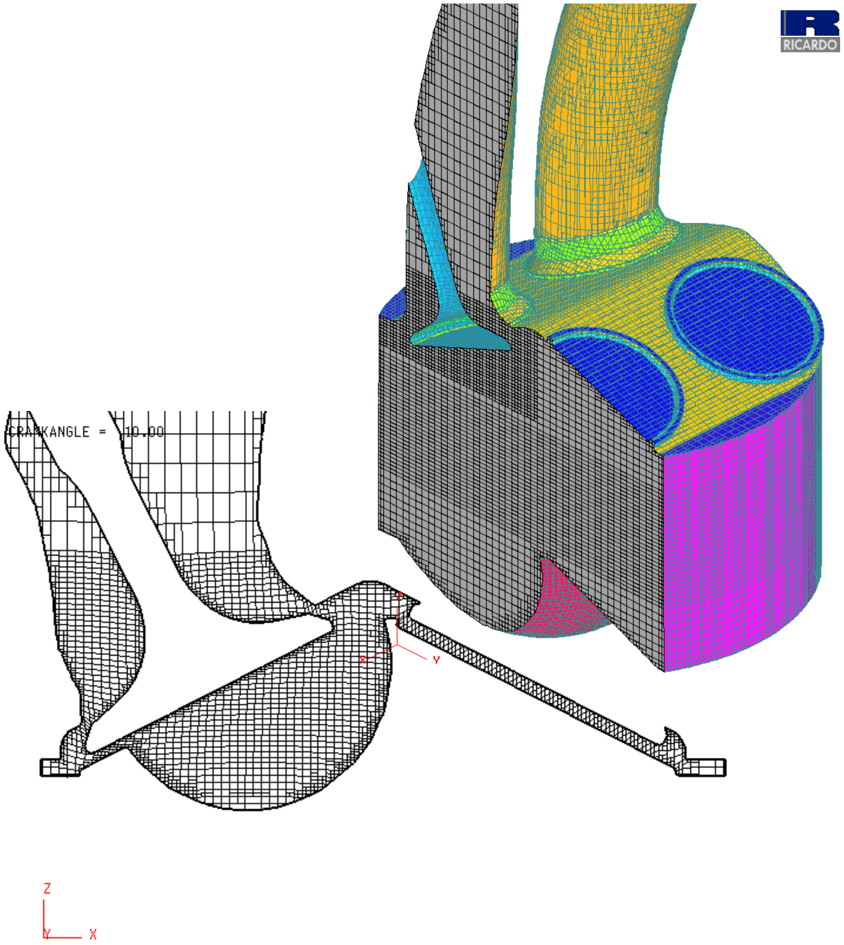






VECTIS: Automatic mesh generator

- VECTIS automatic hexahedral mesh generator allows for:
  - **Very quick CFD mesh generation using imported CAD geometry**
    - **Example - 5 million cell under bonnet (very high level of detail) mesh generation time typically 3 hours**
  - **Computational mesh based on chop cell approach**
    - **Original CAD geometry captured exactly**
  - **Local region and specific surface mesh refinement by cell sub-division**
    - **Accurate key flow detail modelled**



VECTIS Solver

- **BASICS**
- **3D, time-dependent or steady state, compressible or incompressible solution of the Navier-Stokes continuity and energy equations**
- **2nd order differencing, Stone and multigrid solvers for accurate and efficient numerical treatment.**
- **k-ε and RNG turbulence models**
- **User function capability allows for detailed boundary conditions and initial conditions and extraction of results as analysis is running**
- **Serial or multi CPU (parallel) analyses (automatic domain mesh decomposition)**
- **Time-dependent mesh distortion to capture motion of boundaries (e.g. Moving piston and valves in an IC engine)**
- **Spray atomisation, break up and interaction models**
- **Magnussen combustion model and Ricardo two-zone flamelet combustion model**
- **Direct coupling with Ricardo Software's one dimensional engine performance simulation code, WAVE**

VECTIS Incylinder Analysis

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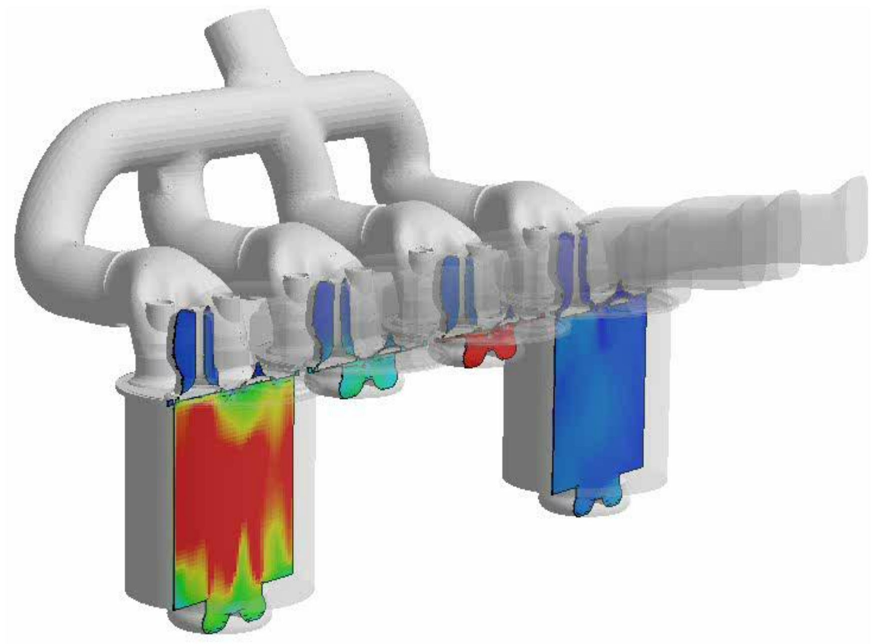
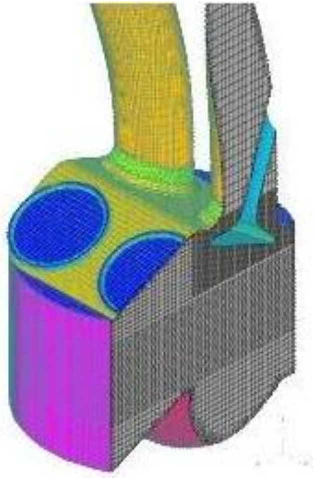
In-cylinder Analyses

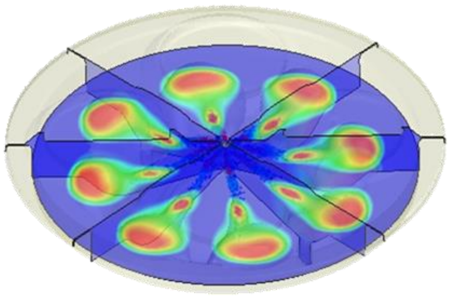
- Typical Engineering Use
  - Investigate air, fuel and combustion product species motion
  - Model port injection or direct injection sprays
  - Optimize combustion process
- VECTIS Advantages
  - Moving boundary and automatic meshing technique provides easy setup
    - Multi-cycle, multi-cylinder calculations
  - Discrete droplet modeling for sprays
  - Static and dynamic wall film capability
  - Auto-ignition and spark ignition models
  - Ricardo Two Zone Flamelet combustion model
  - Multiple Interactive Flamelet combustion
  - G-equation for pre-mixed combustion
  - Links to Ignition Progress Variable Libraries
    - for HCCI, Premixed and non-premixed combustion
  - Extensive internal validation programs

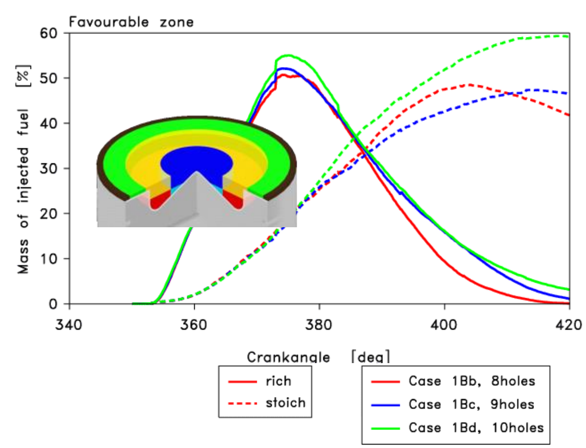




Combustion system development is key to the optimisation of the engine performance, fuel economy and emissions management

- Combustion System Development
  - Compare air motion, fuel spray interactions and combustion effects with different FIE types and combustion system designs
    - Diagnostic
      - Understanding engine responses
    - Predictive
      - Ranking potential combustion system designs
      - Optimising bowl/FIE geometry
      - Developing novel design/operating strategies
  - Advanced post-processing techniques developed to enable objective measurement of combustion system performance



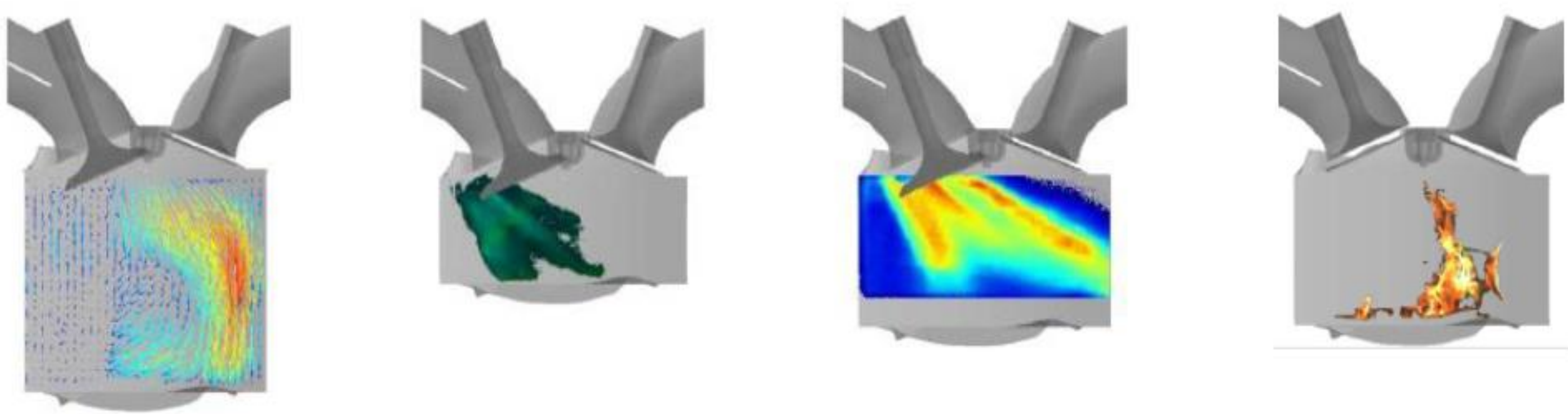


VECTIS incylinder
Gasoline Work flow

- The traditional workflow incylinder modelling is shown below
- Typically engineers will run several phases throughout the development process.
- Get each phase correct before moving on to the next phase

Cold flow › **Spray modeling** › **Mixture formation** › **Combustion**

Cold flow	Spray modeling	Mixture formation	Combustion
• Intake flow • Bulk charge movement	• Fuel Injection • Spray breakup	• Vaporization • Fuel distribution	• Flame propagation • Auto-ignition • Emission

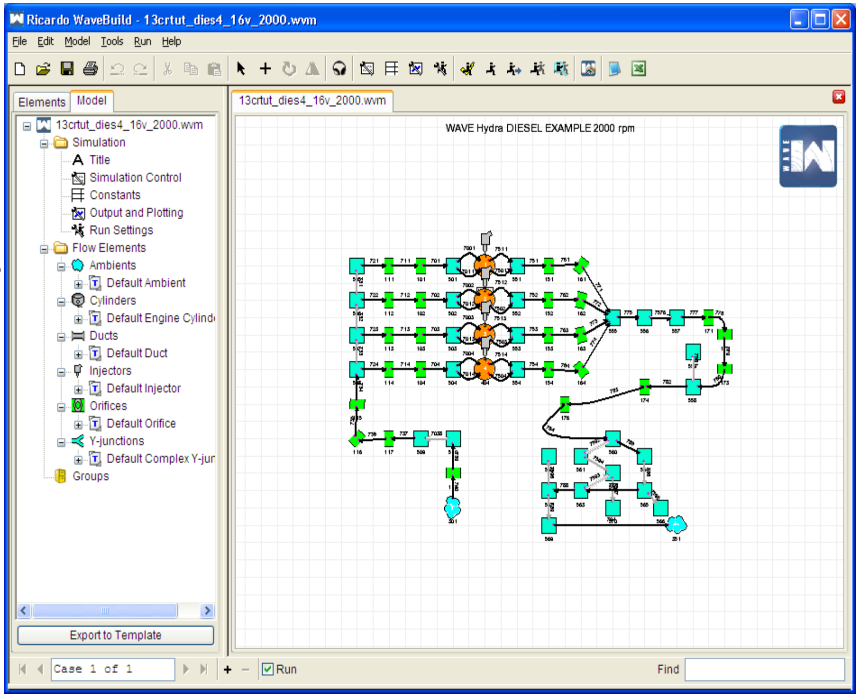


VECTIS incylinder
Setting up an in-cylinder analysis

- The in-cylinder is probably the most complex calculation to define in CFD
- For a good calculation we must define good values for the following
  - Gas input and output conditions
  - Spray modelling
  - Combustion modelling
  - Mesh motion – Piston and valves
  - Boundary temperature conditions

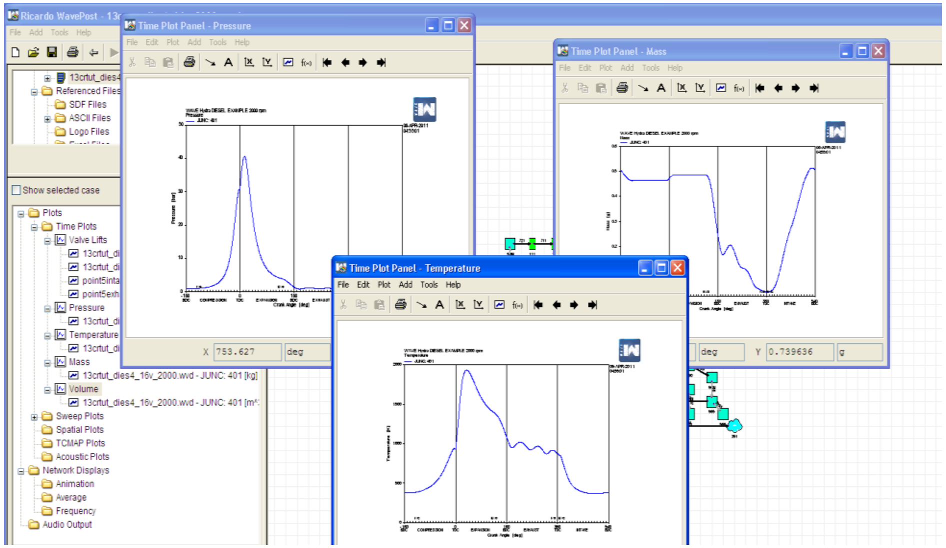
VECTIS incylinder
Setting up an in-cylinder analysis
Required data – initial boundary condition

- Typically the first step we perform is to obtain our inlet and outlet boundary conditions.
- Typically from a clean sheet design some performance studies will have been carried out using a 1D Gas dynamics product. In our case we will use Ricardo's WAVE 1D product



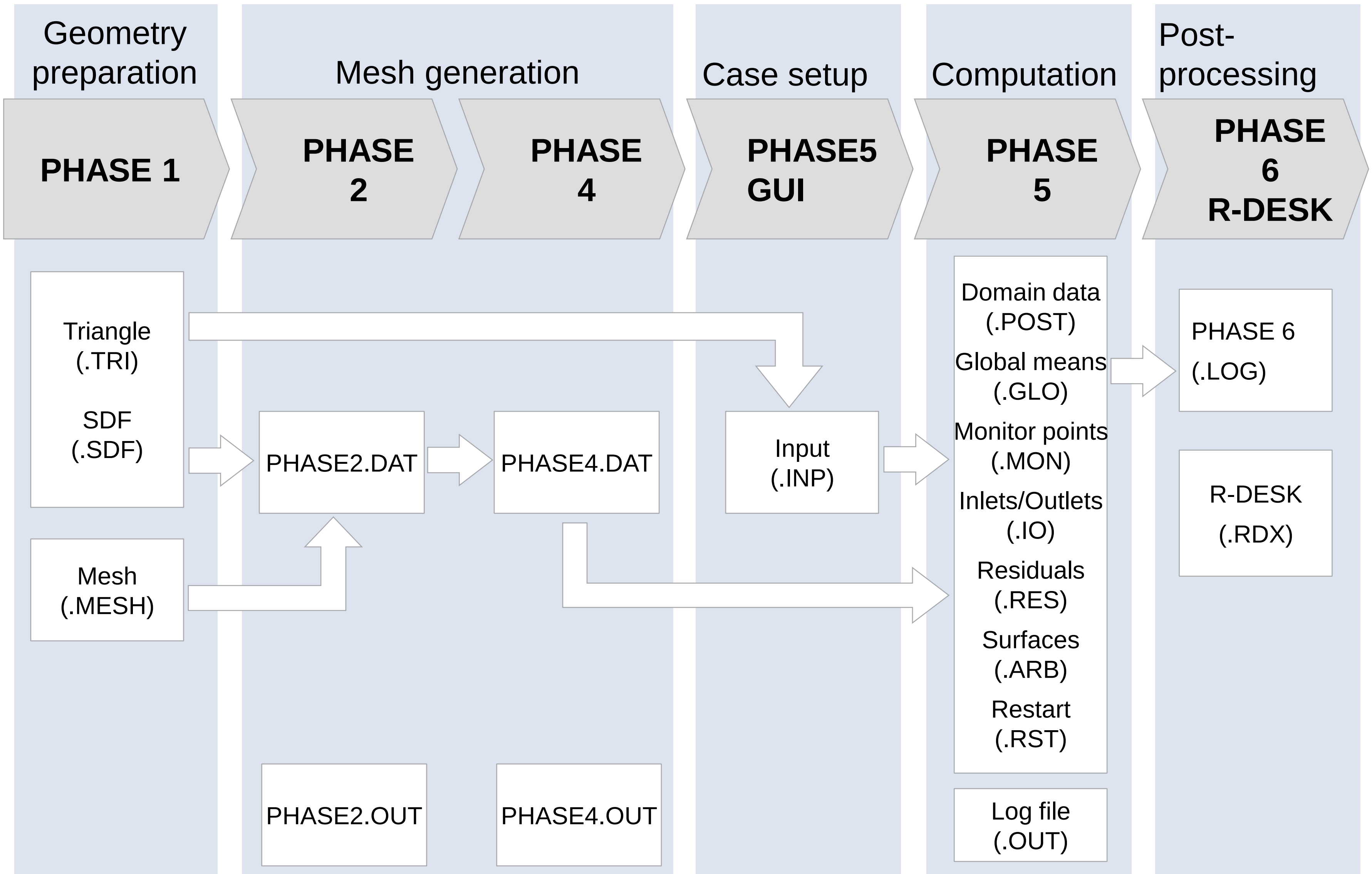
VECTIS incylinder
Setting up an in-cylinder analysis
Required data – initial boundary condition

- From this model we will extract
  - Valve motion curves
  - Inlet boundary conditions
    - Pressure, Temperature, Species
  - Outlet boundary conditions
    - Pressure, Temperature, Species
  - Wall boundary temperatures
    - Either defined from engineering judgement or from WAVE's own conduction model
  - Piston motion – Stroke, Rod length



  - [WAVE]

VECTIS incylinder
VECTIS work flow



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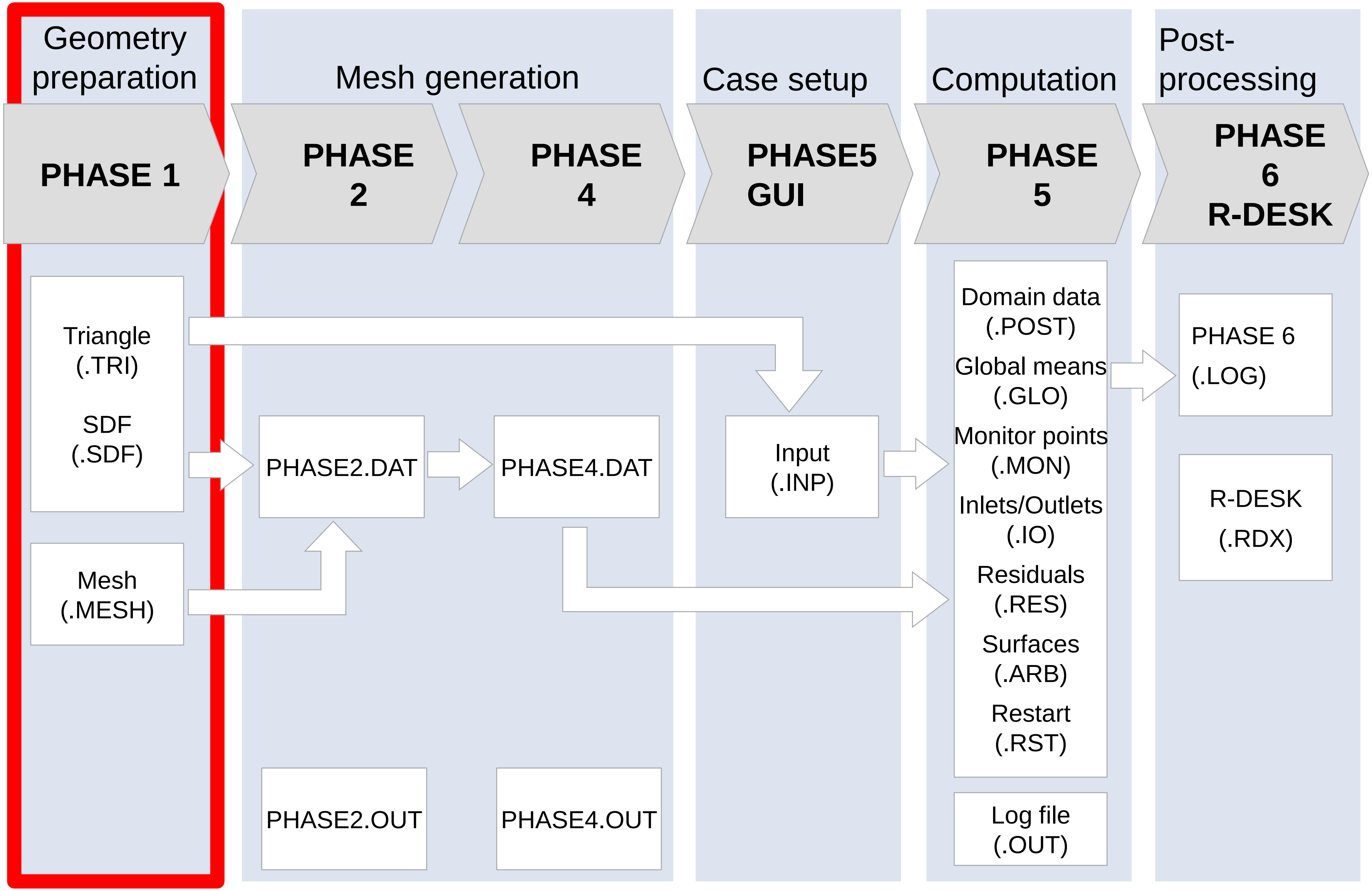
VECTIS incylinder
VECTIS work flow



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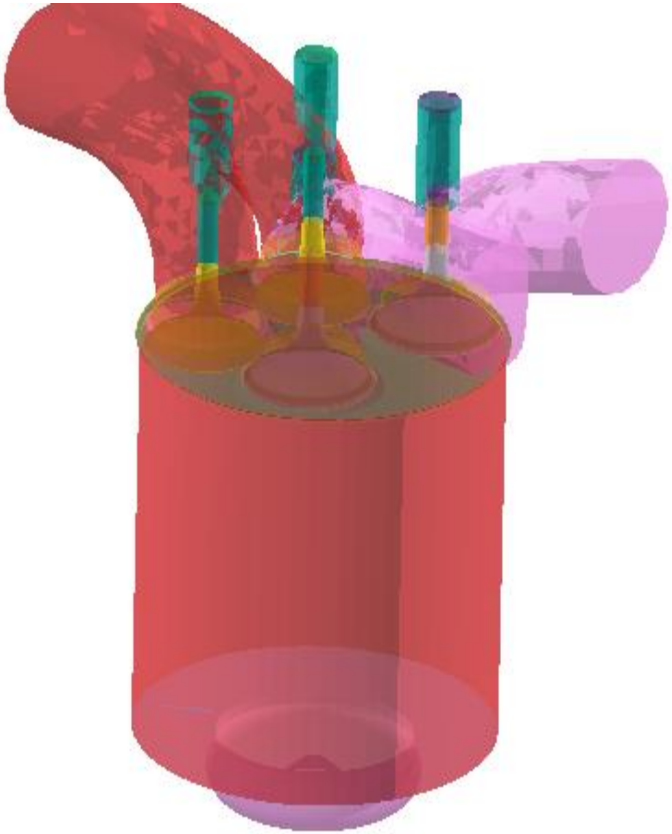
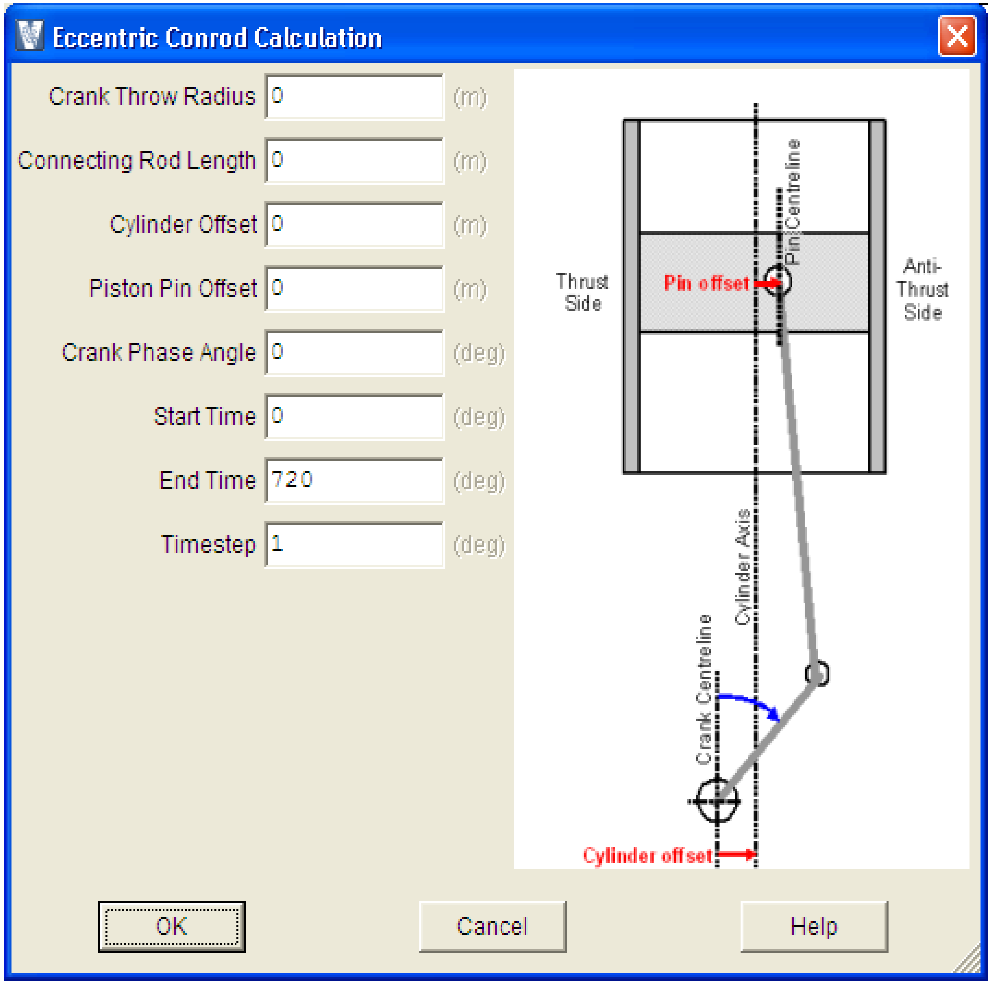
In-cylinder analysis
Geometry preparation

- The first step is to define the boundary types on the geometry
  - Inlet Ports
  - Exhaust Ports
  - Valves
  - Piston
  - Liner
- Any boundary that will have either motion different boundary condition attached to it
- PHASE1



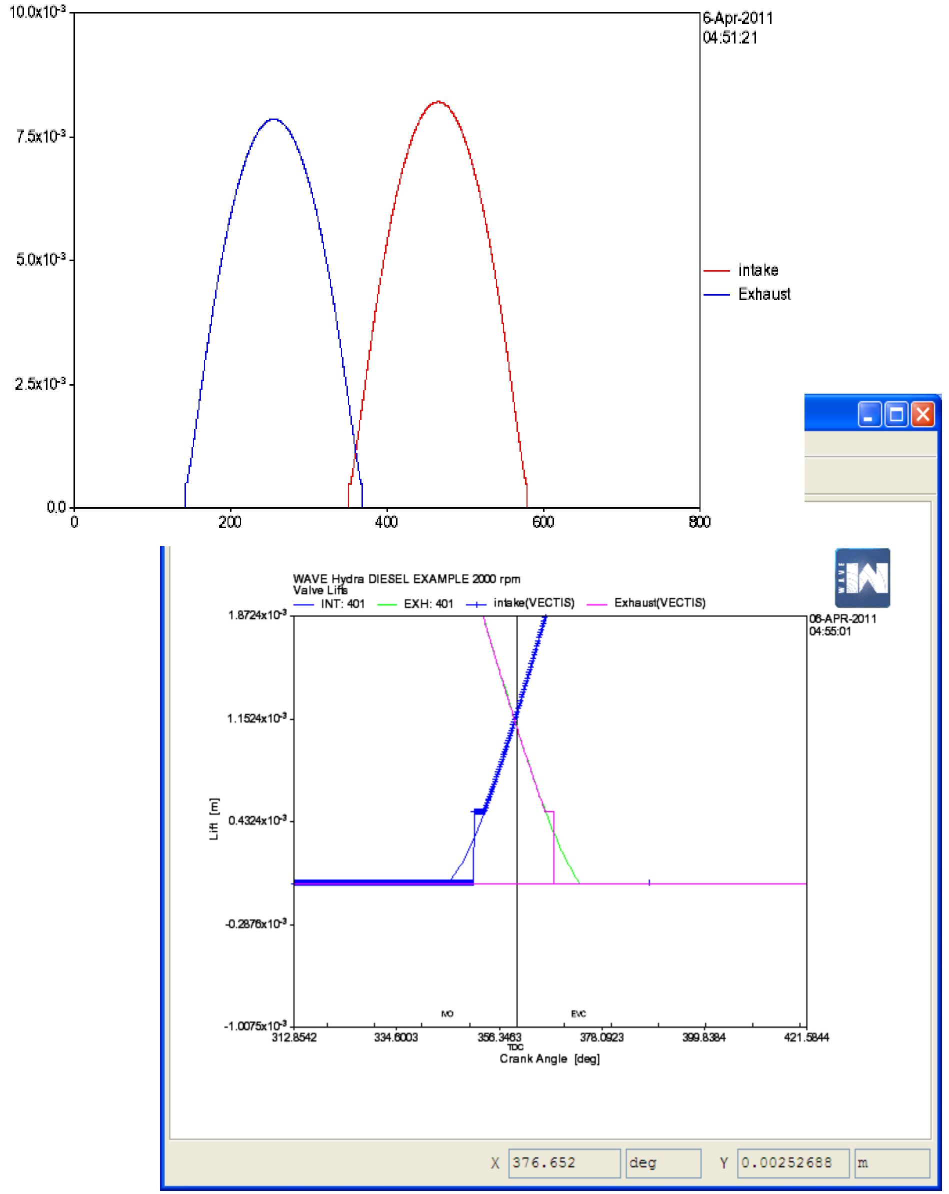
In-cylinder analysis- Geometry preparation
Boundary motion - Piston

- The in-cylinder piston motion can be defined with either a traditional piston motion or more complex settings can be defined in the eccentric conrod panel
- The boundary motion definition is saved to the geometry files so that PHASE5gui can access this data to allow faster setup times for the solver input file

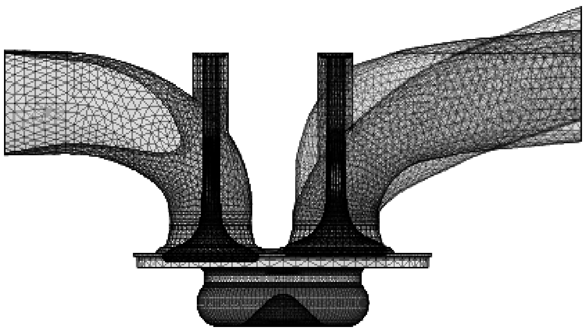


In-cylinder analysis- Geometry preparation
Boundary motion - Valves

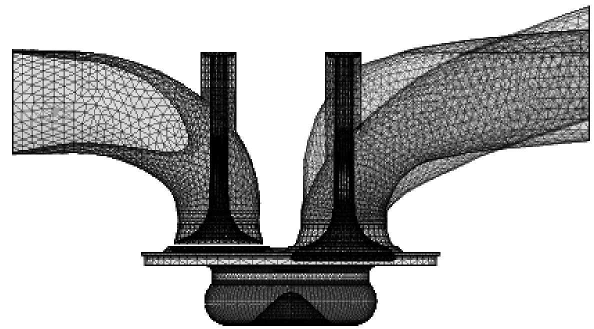
- The valve motion was extracted from the WAVE model
- In VECTIS we snapped the valves closed as we approach valve closing to avoid the need for many small cells in the valve gap
- Typically we snap the valves shut at about 0.2-0.3 mm
- This means we need to modify the WAVE data as shown
- The data is saves as Time-Displacement data



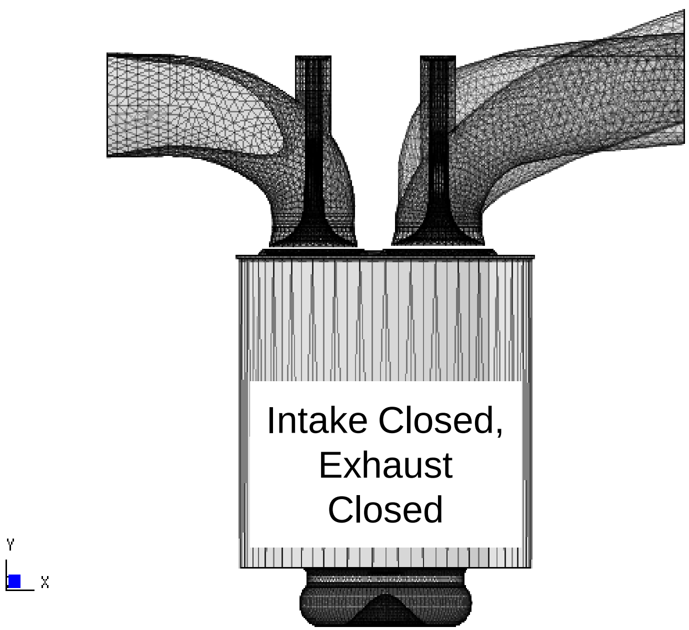
In-cylinder analysis- Geometry preparation
Topology and boundary painting



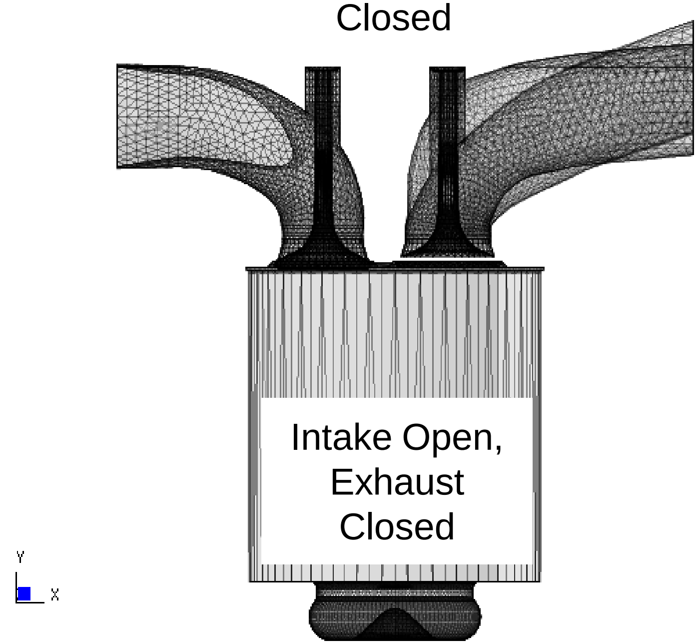
Intake Open, Exhaust Open



Intake Open, Exhaust Closed

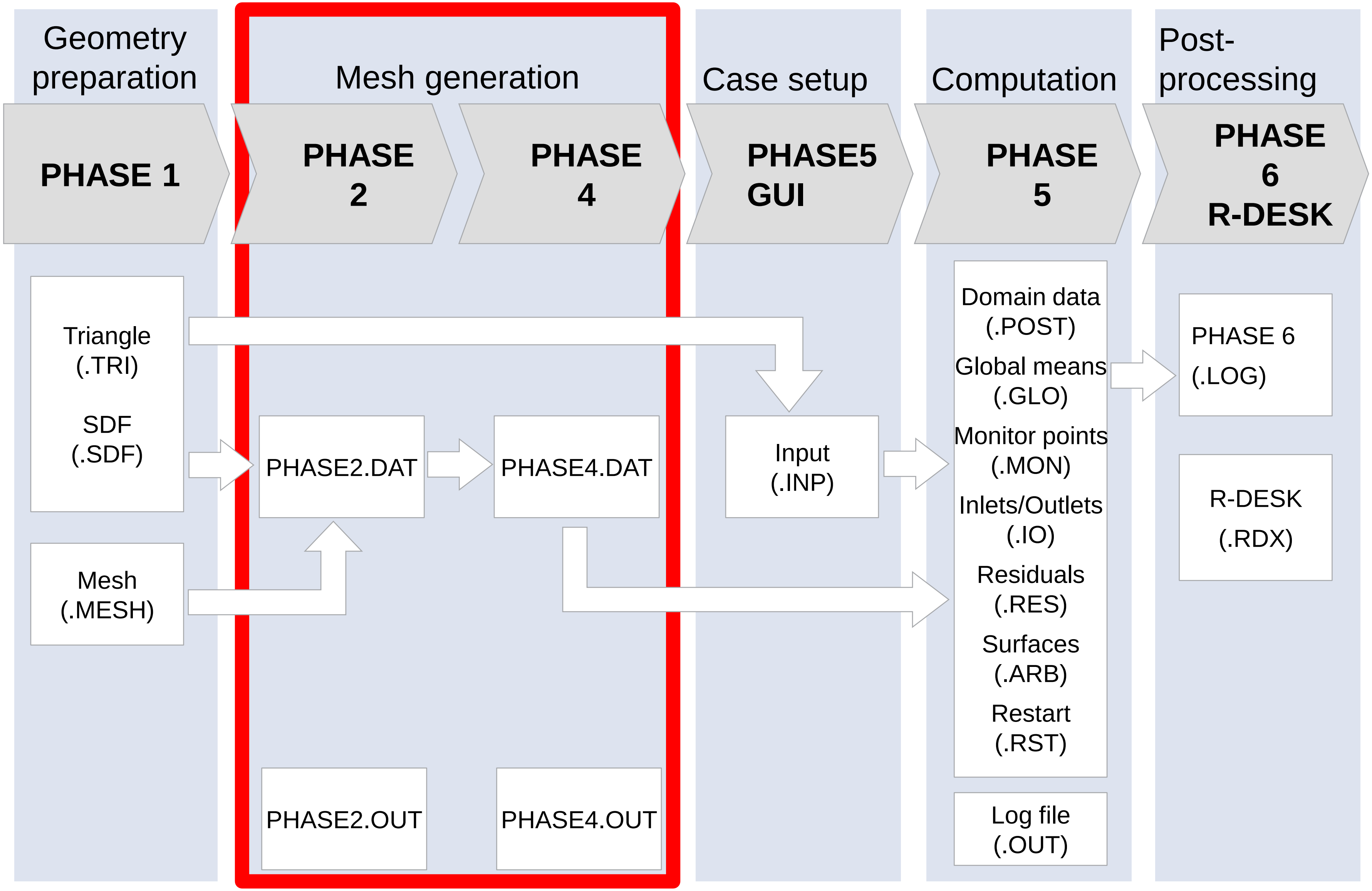


Intake Closed, Exhaust Closed



Intake Open, Exhaust Closed

VECTIS incylinder
VECTIS work flow



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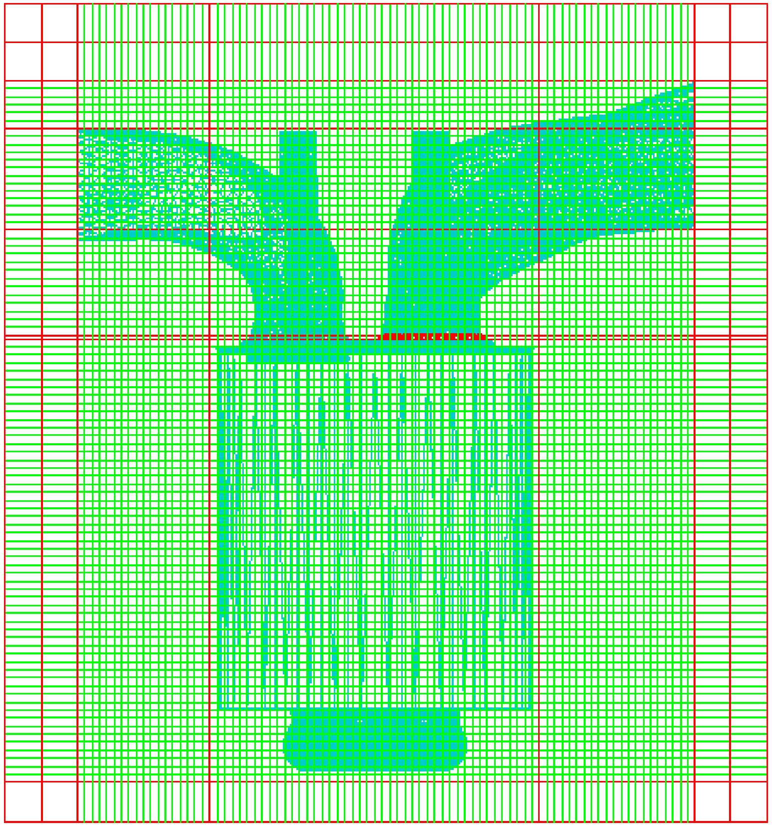
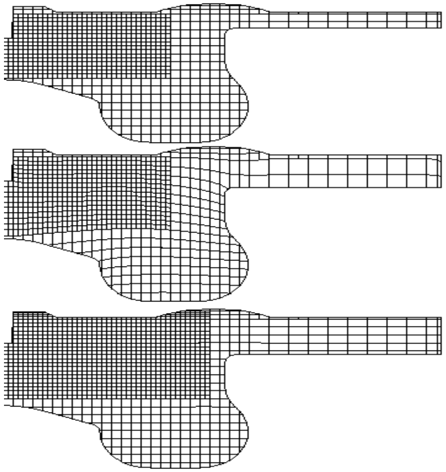
In-cylinder analysis
Creating the global mesh file

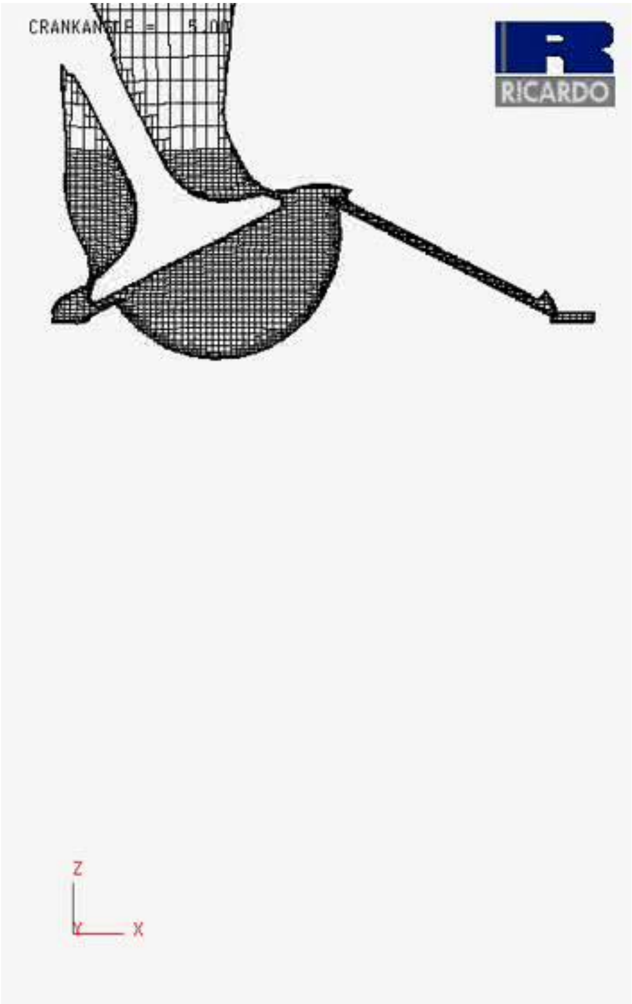
- There are several approaches which can be used here.
- In this example we have created one main global mesh file as show. This is defined to cover the geometry at its largest point i.e Bottom Dead Center
- Another mesh file is used as we approach the spray and combustion timings. This file has a localised mesh refinement block to increase the mesh density for this part of the calculation



In-cylinder analysis – Input file
Defining the mesh strategy

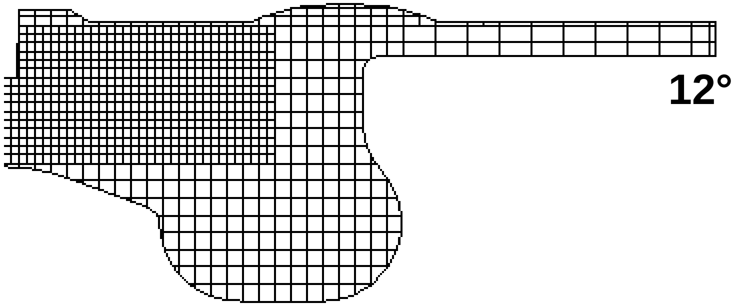
- The in-cylinder analysis will use an approach called cross-linking. This involves using multiple mesh files throughout the simulation
- This approach allows the mesh to distorted until a distortion limit is reached then solution is mapped on to new undistorted mesh
- This requires the user to create mesh files at certain crank-angle intervals
- [Mesh Strategy definition]

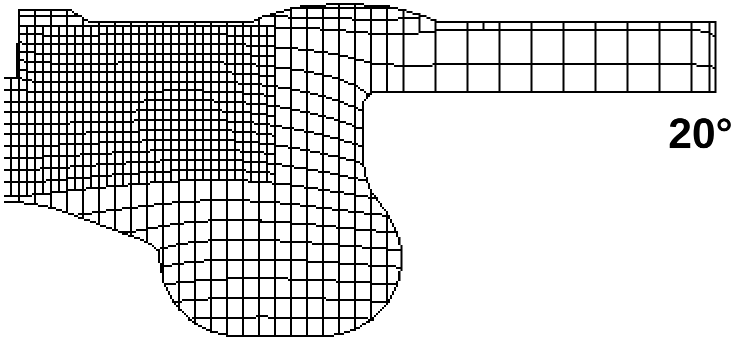


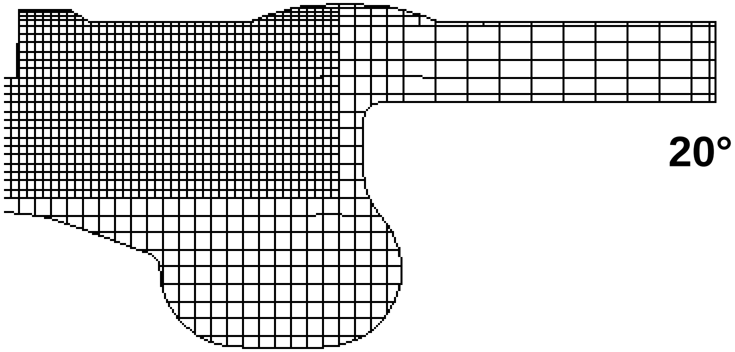


VECTIS Solver: Mesh Motion

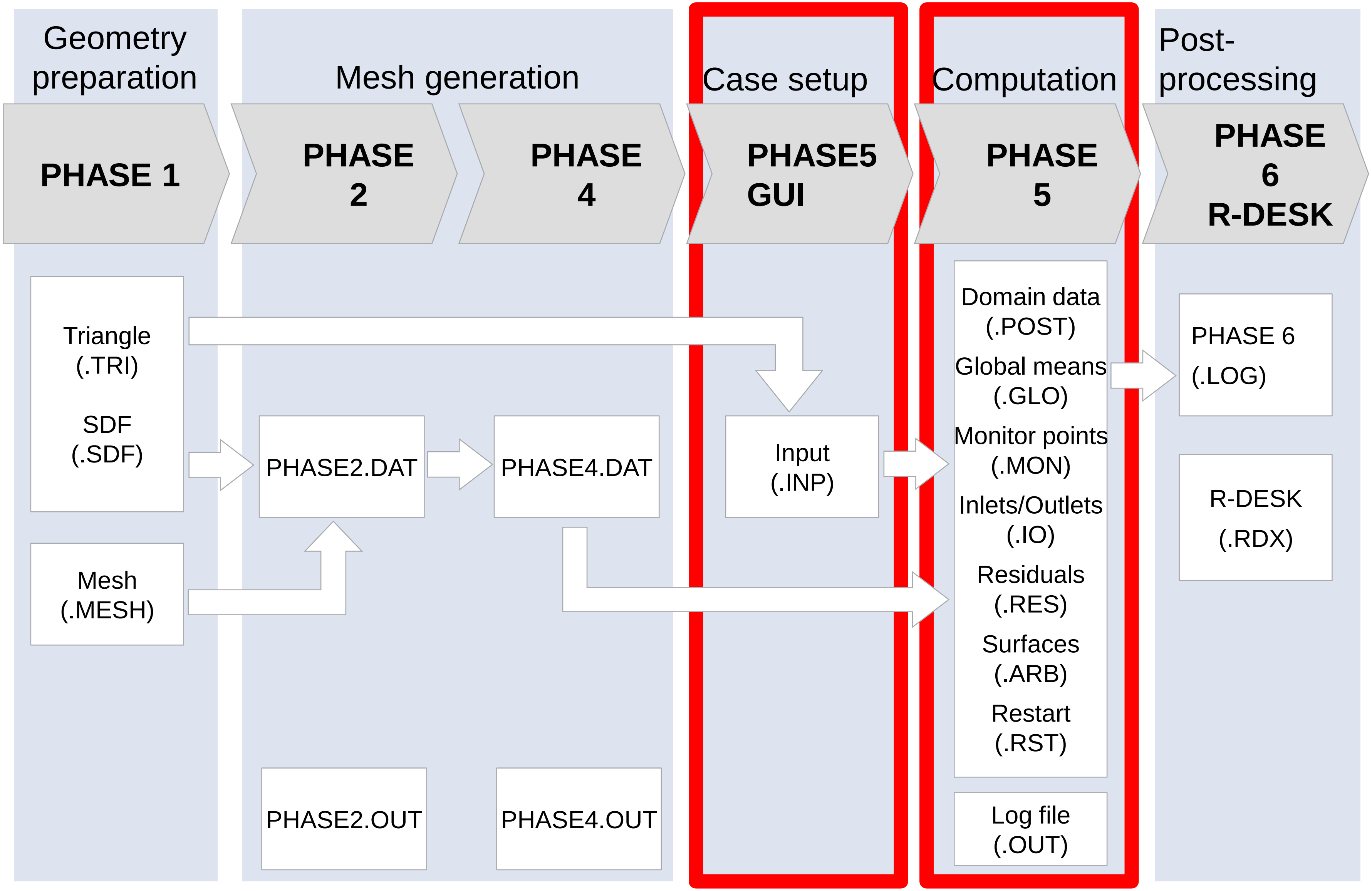
- **Initially Cartesian grid is distorted as piston (and valves if applicable) move**
- **Internal mesh structure automatically deforms in order to minimise distortion of each individual cell**
- **Solution re-zoned onto new Cartesian mesh when cell distortion criteria exceeded**







VECTIS incylinder
VECTIS work flow



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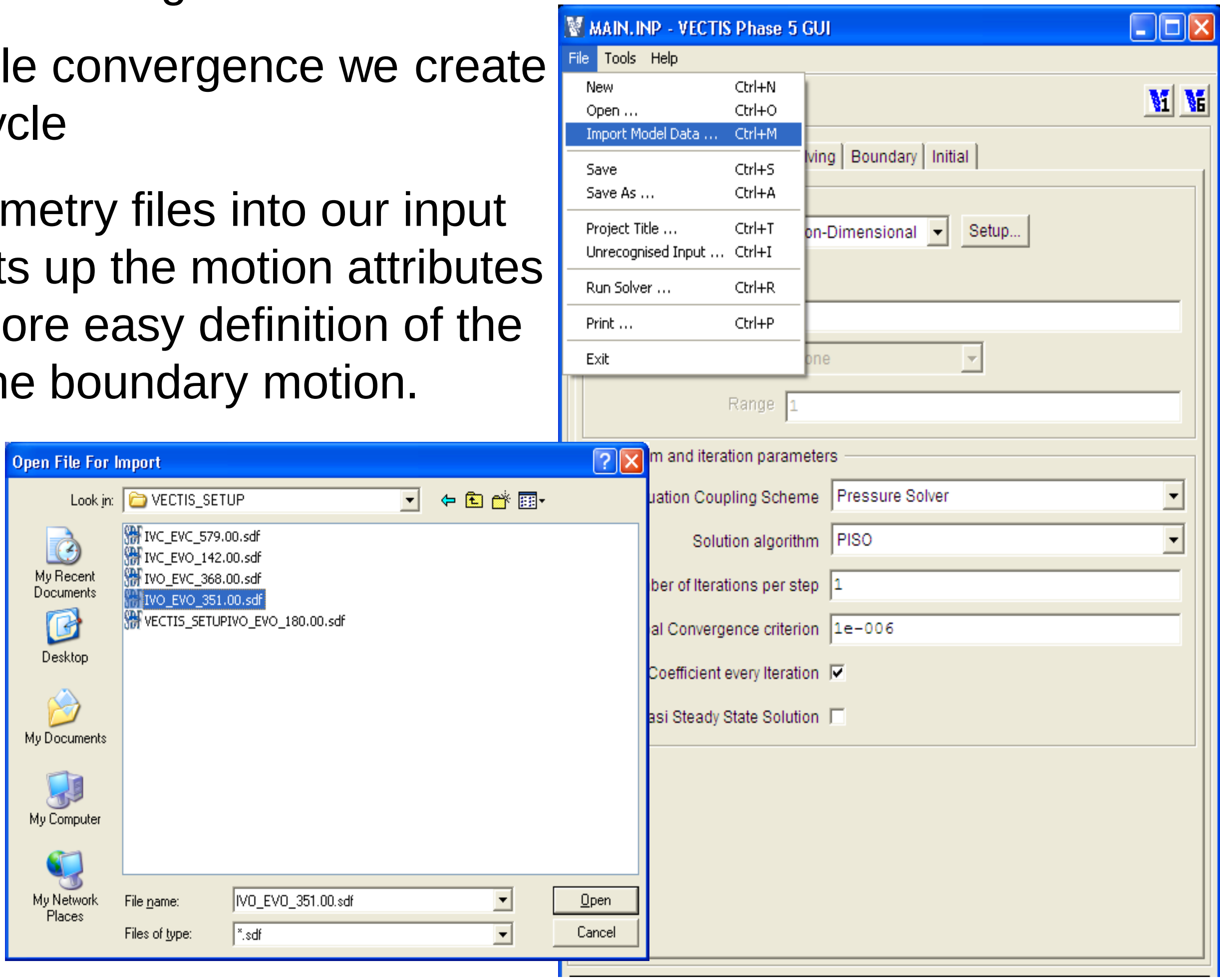
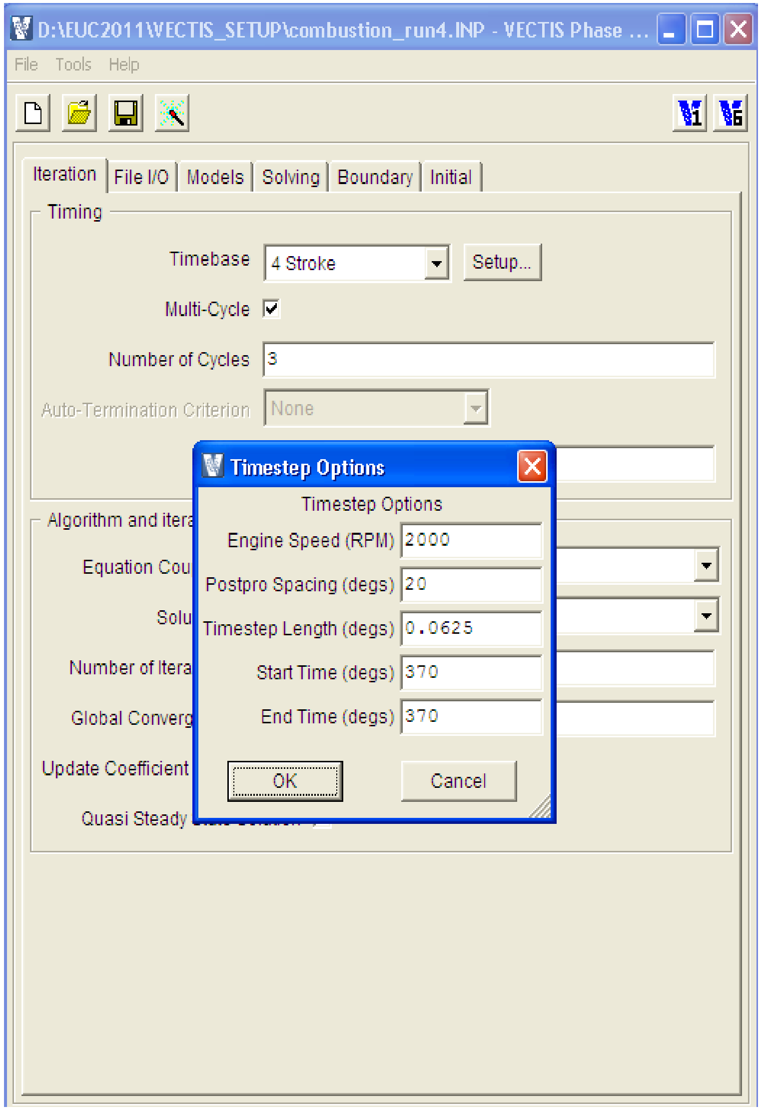
In-cylinder analysis – Input file
Multi-cycle calculation

- For these models we run for multiple cycles. We do this to obtain cycle to cycle convergence
- Once we have cycle to cycle convergence we create a POST file for 1 engine cycle
- We import our painted geometry files into our input file definition GUI. This sets up the motion attributes for the user will allow for more easy definition of the boundary conditions and the boundary motion.



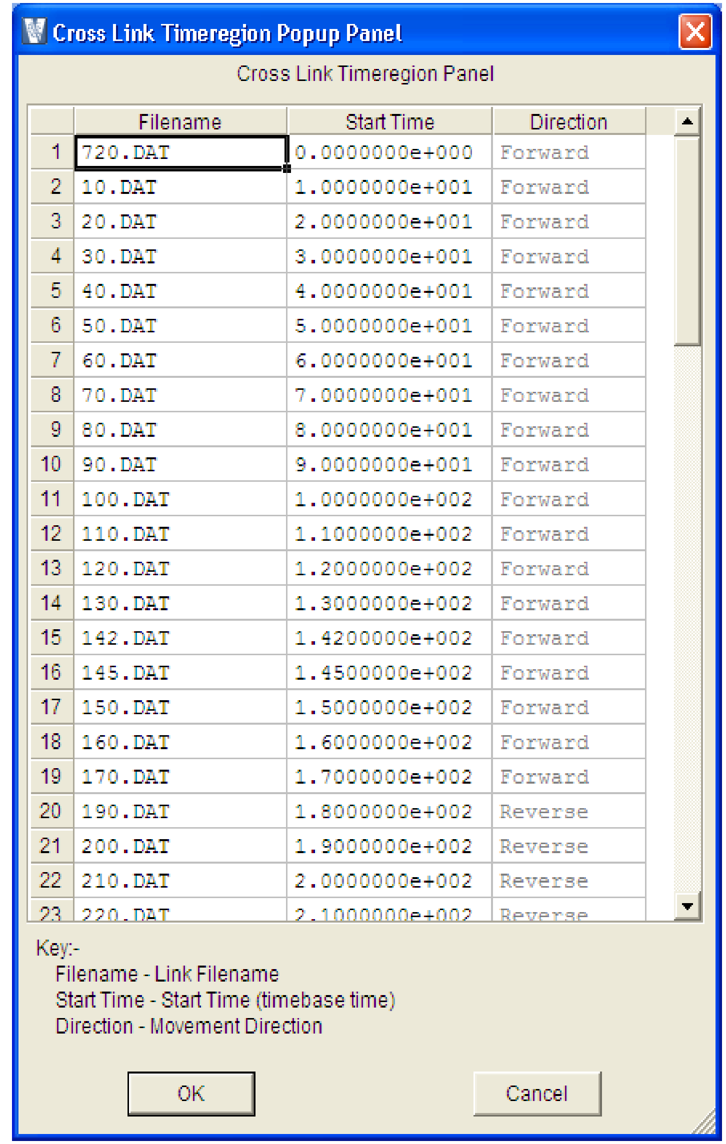
In-cylinder analysis – Input file
Engine speed and timestep

- Next the basic engine data must be defined
  - Engine speed
  - Engine combustion cycle
  - Start time
  - End time
  - Time step size
  - Post processing output
  - Number of cycles



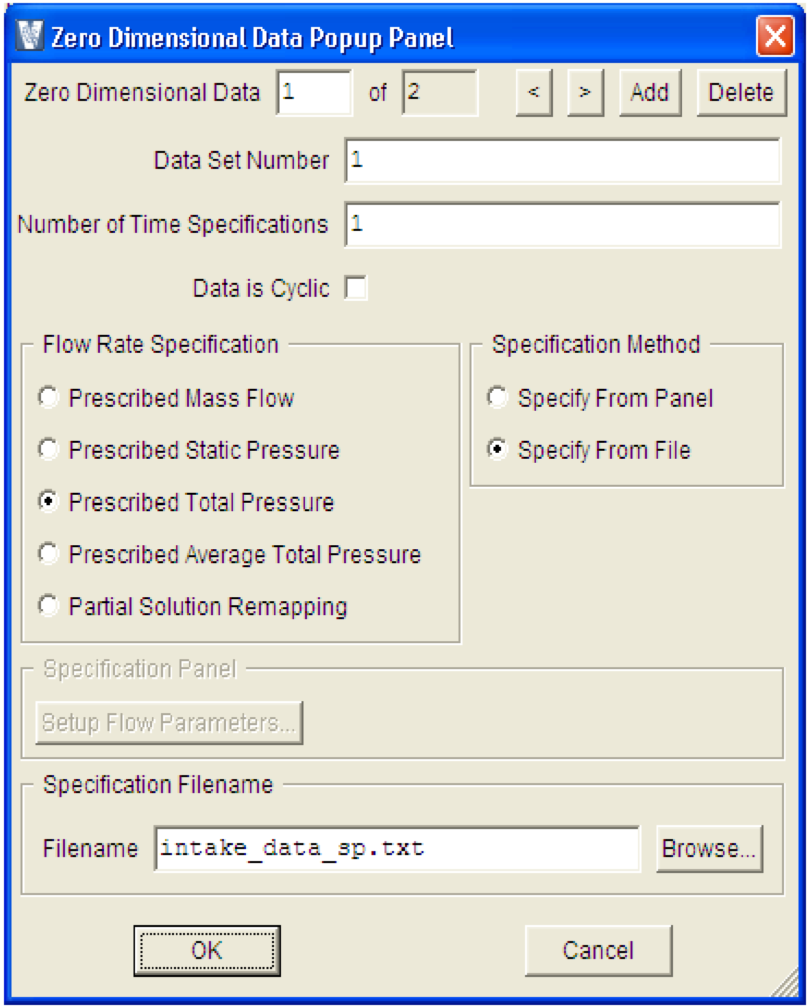
In-cylinder analysis – Input file
Defining the cross-linking

- The timing for changing from one mesh to another is defined in the cross-linking time region panel
- Each of the mesh files must be named along with their start time



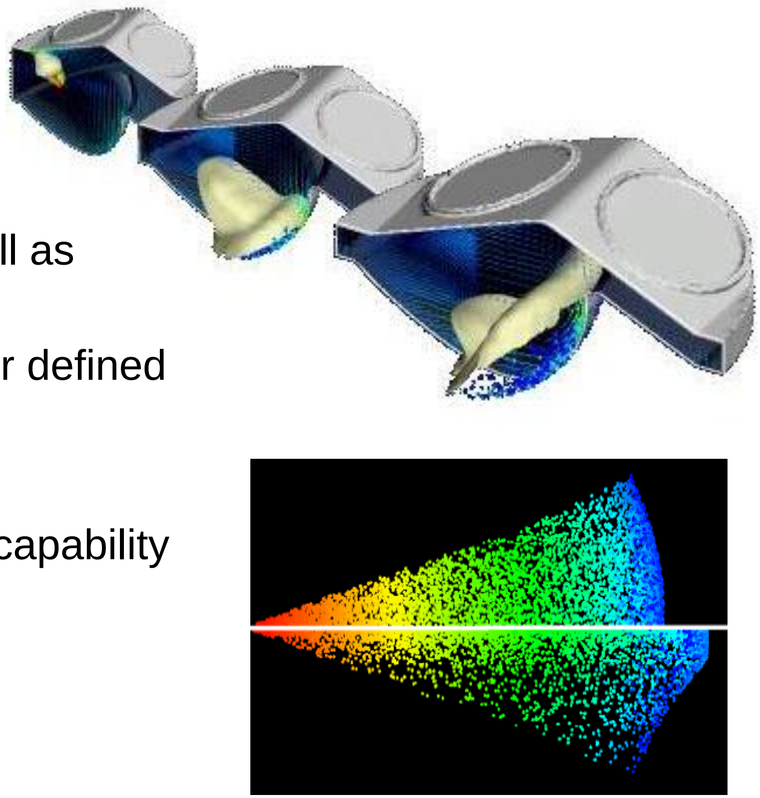
In-cylinder analysis – Input file
Boundary conditions

- **Inlet/Outlet**
  - The inlet and outlet boundary conditions must be defined via the inlet/Outlet panel and the Zero dimensional data panel show
  - The data is input with respect to time from the WAVE model
- **Wall Boundary**
  - The inlet and outlet boundary conditions must be defined via the inlet/Outlet panel and the Zero dimensional data panel show
  - The data is input with respect to time from the WAVE model



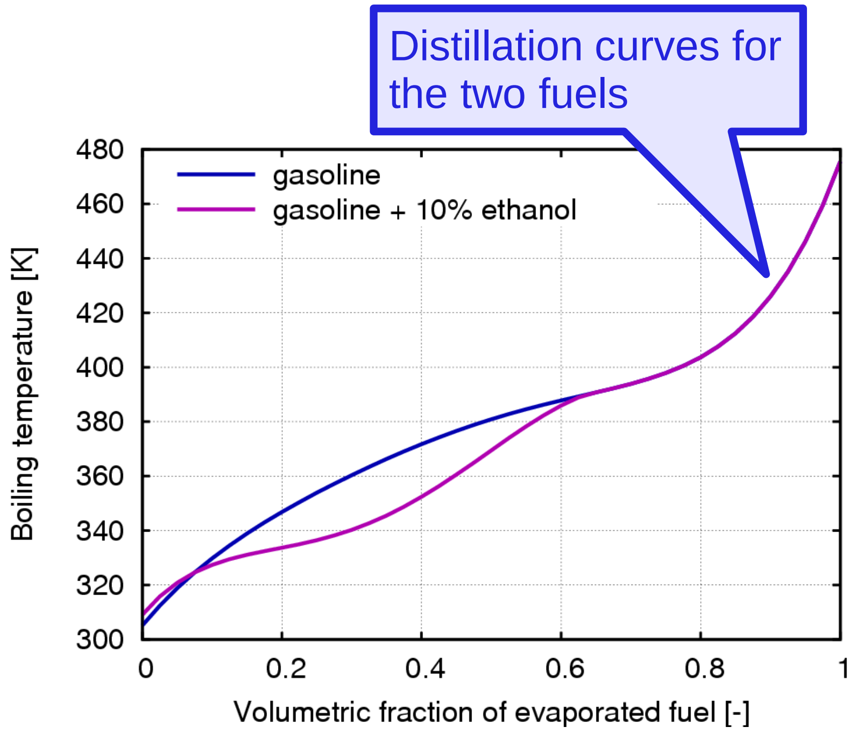
Spray modeling

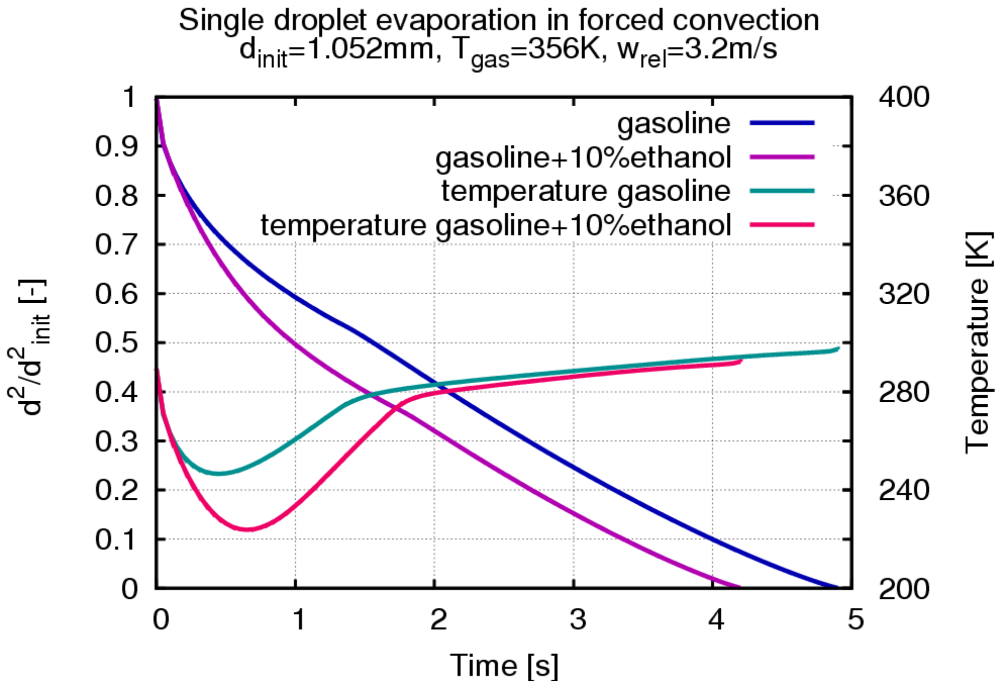
- Typical Engineering Use
  - Model port injection or direct injection sprays
- VECTIS Advantages
  - Discrete droplet modeling for sprays
    - Primary and secondary breakup models as well as droplet interaction
    - Extensive capability allows for modeling of user defined injector configurations
  - Static and dynamic wall film capability
    - User function initialisation and data extraction capability
  - Nozzle to discrete droplet primary breakup model



Spray modeling

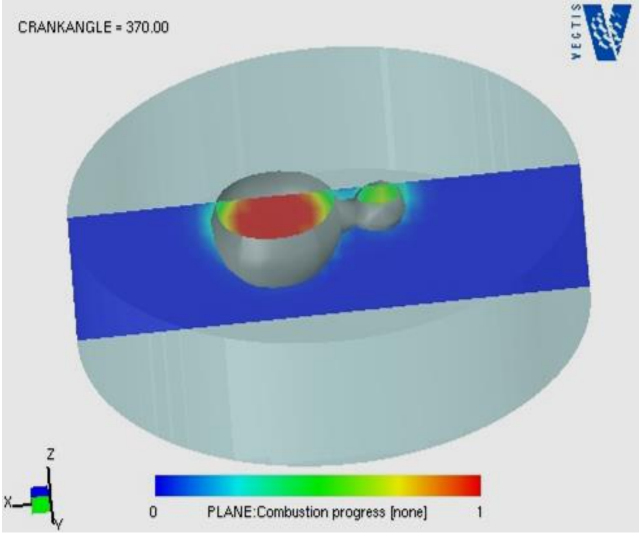
- Multi-component fuel for spray and wall-film
  - To reflect the real evaporation characteristics of multi-component fuels. Comparison of the evaporation of a gasoline droplet and a droplet from a mixture of gasoline and 10% of ethanol
- Fuels specified using the distillation data
- Allows modelling of alternative fuels, Ethanol, E85 etc





Combustion and emissions

- Advanced combustion models are available
  - For Non-premixed
    - Multi-Representative-Interactive-Flamelet (MIF) Model
    - Ignition progress variable model (IPV) library
  - For Premixed
    - G-Equation to determine flame front
    - Combustion with either RTZF or IPV library
    - Ignition with DPIK ignition model
      - Eliminate numerical diffusion
      - To predict correct ignition duration (block burnup time)
      - To achieve ignition size independent solution
  - HCCI/Premixed/Non-Premixed
    - Auto-ignition prediction from either Livengood-Wu, Shell model or more advanced IPV library model
    - Combustion with either RTZF or IPV library



In-cylinder analysis – Running the simulation

- On 16 CPU’s it typically takes about 14hrs to run 1 cycle with Spray and RTZF combustion
- During run time we generally watch
  - Residual values <1e-6
  - Convergence per time step
  - Maximum Courant number
  - Courant number trend
- The exact same approach can be used for multi-cylinder engines. The only difference is the amount of geometry topologies you will require for the meshing stage
- Post processing

VECTIS Incylinder Analysis

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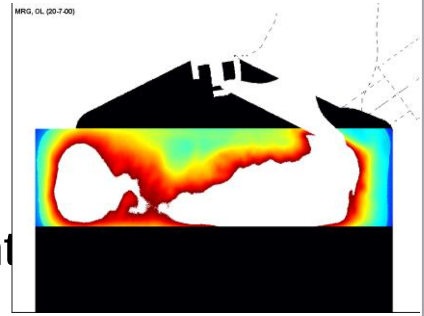
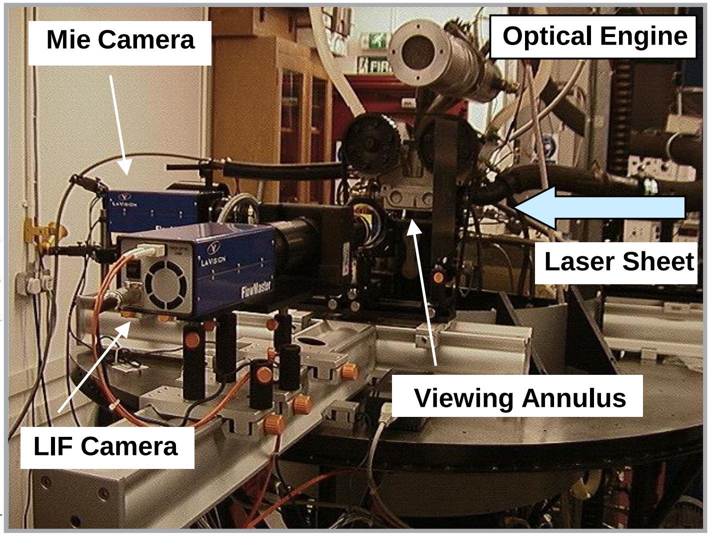
- Incylinder analysis process
- **Validation**
- Examples

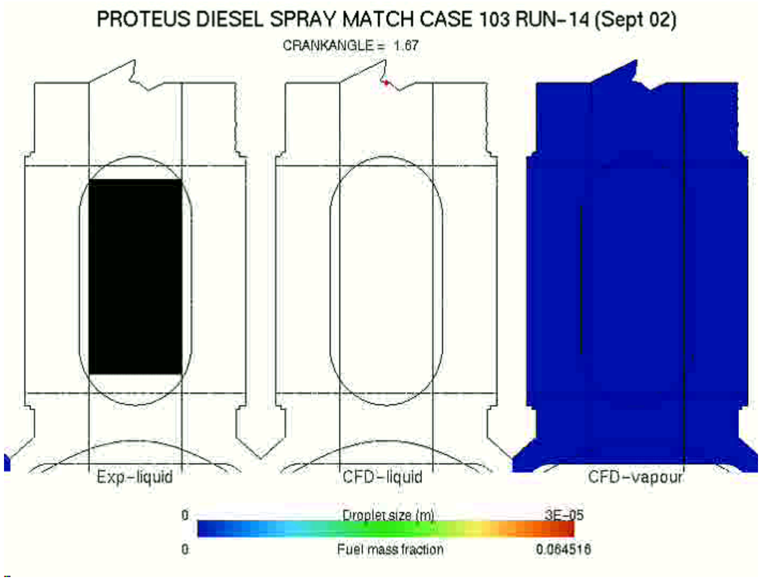
Fuel Spray Measurement and Validation

- Gasoline spray and mixture measurement
  - Quiescent fuel spray characterisation
  - MIE scattering measurements in motored engine
    - homogeneous operation
    - stratified operation
  - Quantitative LIF measurement



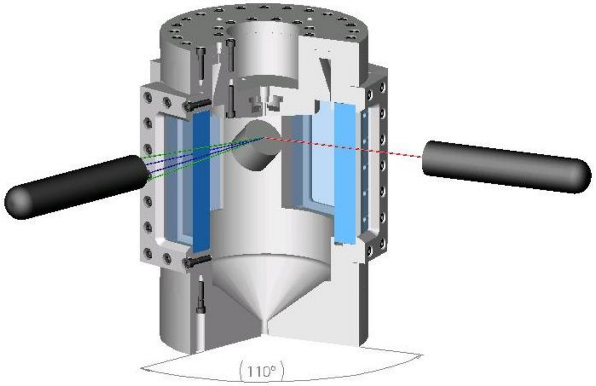


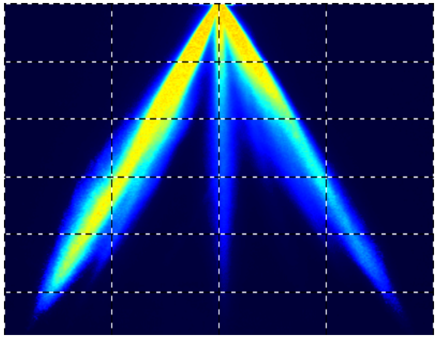
- Diesel spray and mixture measurement
  - Quiescent spray bomb characterisation
  - Ricardo Diesel spray rig
    - Provides cylinder conditions close to engine cylinder conditions

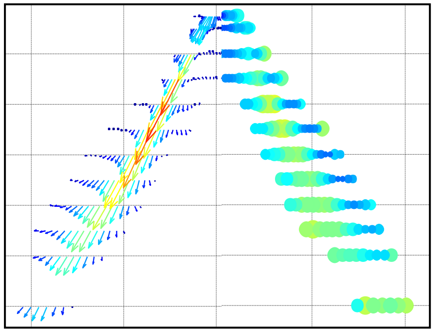


GDI Case Study – Injector Characterisation

- Fuel spray characterised using the phase doppler anemometry (PDA)
  - The PDA is able to determine the 3 components of the droplet velocity as well as the droplet size
  - The data gained is used to tune a 3D CFD model of the spray for use in further analysis







High pressure/high temperature rig

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- Introduction
- What is VECTIS
- Incylinder analysis process
- Validation
- **Examples**

VECTIS case study - Gasoline

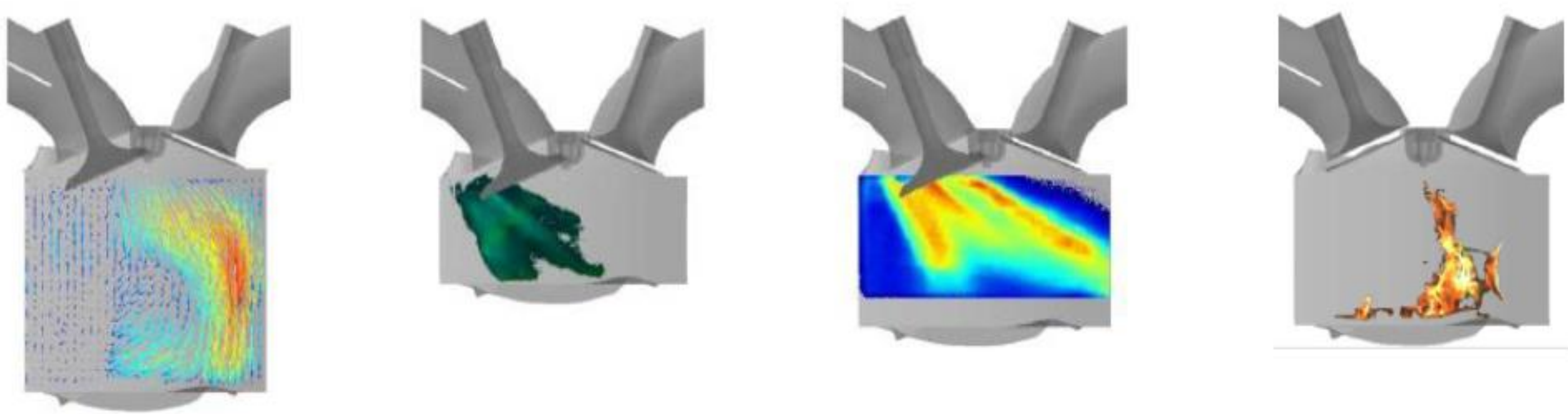
- Work performed by Volkswagen shows how VECTIS can be applied to todays advance engines
- New operating regimes require new advanced models for both Spray and Combustion. Today we will consider the problems in combustion

Cold flow
- Intake flow
- Bulk charge movement

Spray modeling
- Fuel Injection
- Spray breakup

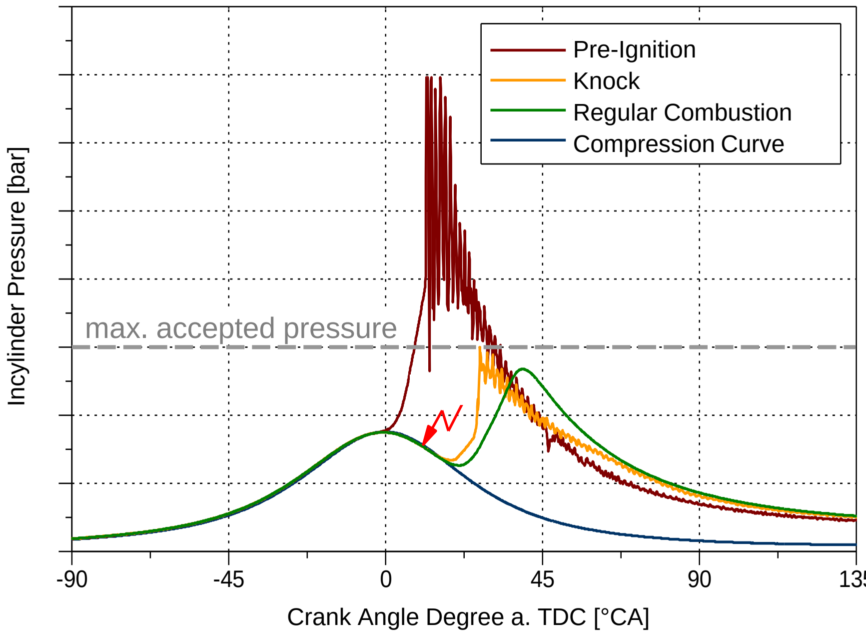
Mixture formation
- Vaporization
- Fuel distribution

Combustion
- Flame propagation
- Auto-ignition
- Emission



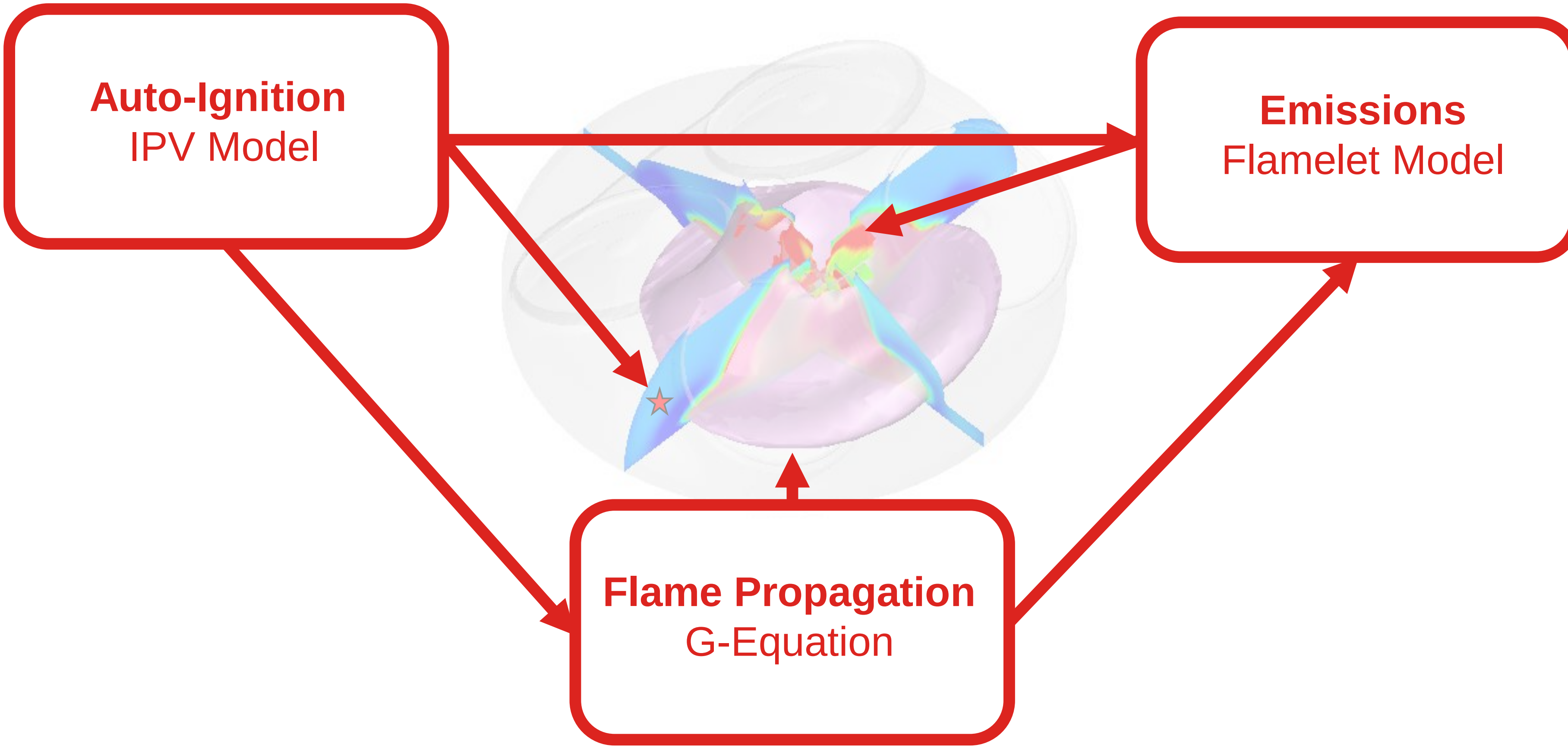
Motivation

- Today's car manufactures inevitably have to focus on the reduction of fuel consumption while maintaining high performance standards. In this respect, TSI® engines represent an appealing solution.
- The *downsizing* strategy involves an enhancement of the mean effective pressure and thus an increased knock tendency at low revolution and high loads. However, the knock tendency is sensitive to ethanol blends.

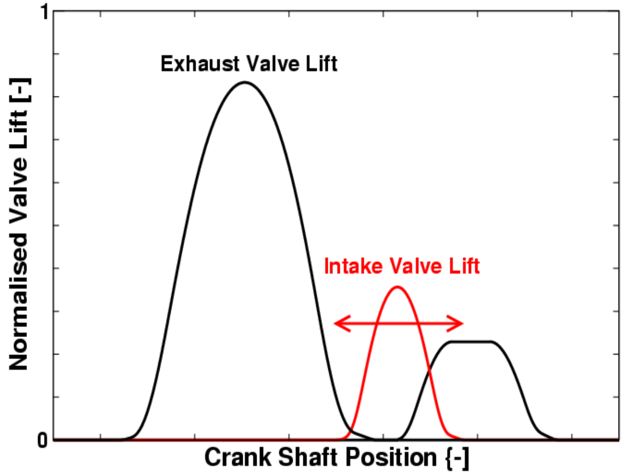


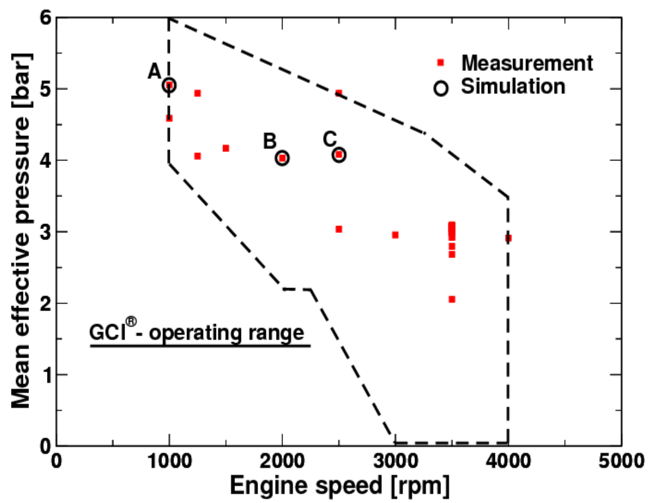
- Reference: Willand et al., Grenzen des Downsizing bei Ottomotoren durch Vorentflammungen, MTZ - Motortechnische Zeitschrift Ausgabe Nr.: 2009-05 , 2009

Method of Combustion Modeling



The Volkswagen GCI® Combustion System





- Source Picture: Steiger et al., GCI and CCS – Two new Combustion Systems of Volkswagen, 29. Internationales Wiener Motorensymposium, 2008
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- Source Valve lift profiles and engine characteristic: Willand et al., The Volkswagen GCI Combustion System for Gasoline Engines – Potentials and Limits in CO2 Emissions, 30.Internationales Wiener Motorensymposium, 2009
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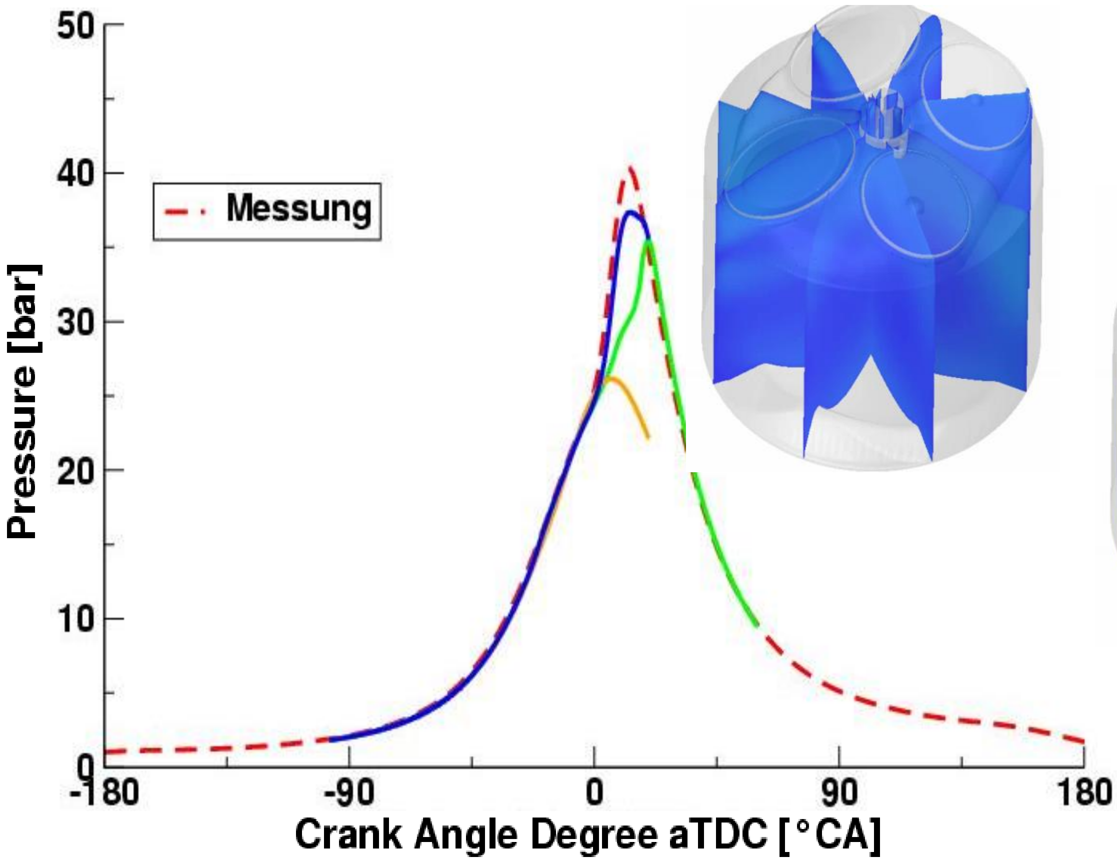
Exemplary Results for the Volkswagen GCI® Combustion System

Flame Propagation Model



Auto-ignition Model

Interaction of both Models

Conclusion

- The IPV Model represents a valid solution, in order to take into account detailed chemical processes into 3D-CFD.
- The presented approach allows to detect locally occurring auto-ignition phenomena in the combustion chamber, as well as to model their interaction with regular flame propagation, by keeping computational costs low.
- This method offers a key to model and thereby to address fuel specific issues, which are growing in importance for future engine development.

Combustion System Analysis – Prediction of Gasoline Combustion Stability

RICARDO

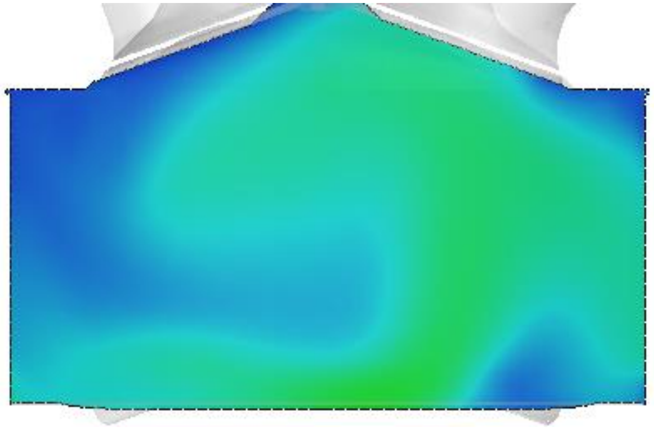
Objectives

- Prediction of combustion stability for gasoline and diesel engines under different operating conditions
  - Gasoline engine idle stability prediction
  - Diesel engine combustion stability prediction at light load operation

Gasoline Simulation Overview

- Combustion stability predictions require assessment of cycle-cycle variation for assessment of variation in IMEP
- Gasoline idle simulation approach
  - Assessment of combustion system sensitivity to changes in operating parameters in comparison to engine response data (i.e. AFR swing, timing swing, residual level) to assess sensitivity to changes in cyclic conditions
  - CFD simulation undertaken for multiple engine cycles with changes to operating parameters
  - Assessment of system robustness through comparison to guideline levels for variation
  - Development completed for direct simulation of multiple engine cycle simulation for direct assessment of changes in cycle-cycle conditions using coupled 1D/3D simulation tools

Residual mass fraction at 90°BTDC



Residual mass fraction at ignition

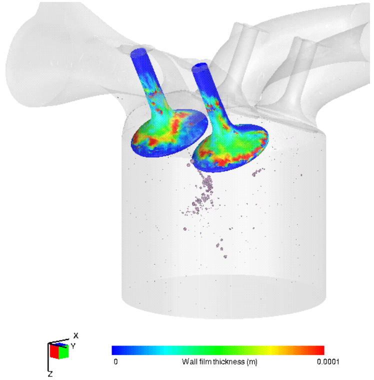
Combustion System Analysis –
Prediction of Cold Start HC Emissions

Objectives

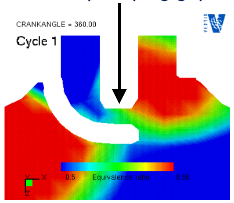
- Prediction of cold start mixture preparation and combustion prediction for development of cold start strategies, air motion and advanced technology assessment
  - Prediction of fuel spray, wall film generation and mixture preparation
  - Prediction of combustion during expansion stroke and within exhaust port, including SAI effect

Cold Start Simulation Overview

- Cold start mixture preparation required application of multiple cycle simulation incorporating prediction of spray, wall film generation, mixture preparation and combustion prediction
- Gasoline cold start simulation approach
  - Prediction of multiple engine cycles from start to review mixture preparation and wall film development
  - Assessment of mixture preparation and distribution for initial engine cycles
  - Prediction of combustion performance during cold operation to establish sensitivity to design parameters and ignition timing sensitivity
  - Combustion prediction within exhaust port possible with multiple cycle simulation



- Cycle 1 equivalence ratio ~ 0.55 at spark plug gap



- Cycle 2 equivalence ratio ~ 0.95 at spark plug gap