Lean Burn Gas Engine with a Pre-Chamber Ignition System: Grid Independence Study and Design Optimization

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Lean Burn Gas Engine with a Pre-Chamber Ignition System: Grid Independence Study and Design Optimization

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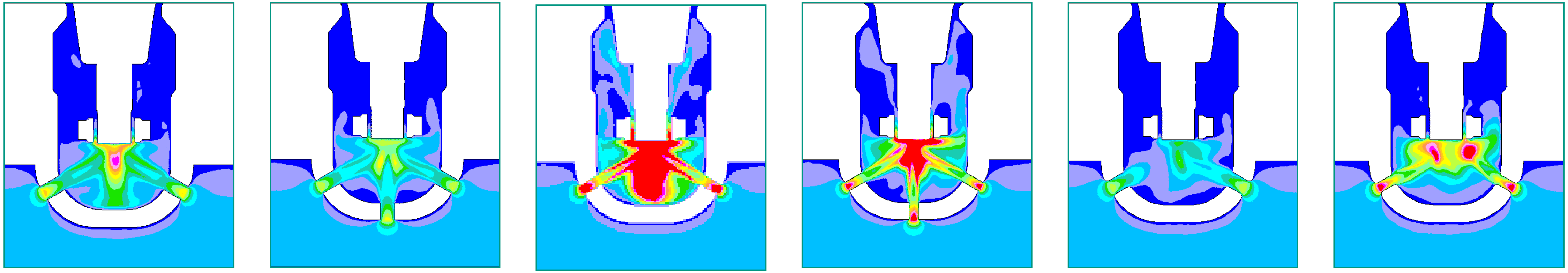
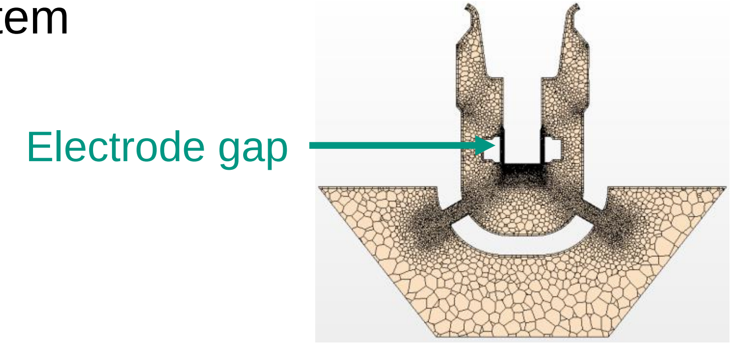


Introduction

Objectives and Challenges

- The passive pre-chamber ignition systems offers an attractive solution for the lean burn gas engines by providing following benefits:
  - Lean operation leads to lower CO_2 and NO_x emissions
  - Multiple ignition locations leads to faster combustion with combustion stability (less cycle to cycle variations)
  - Shorter flame travel towards crevices leads to lower UHC and unburnt CH_4 emissions
  - Higher efficiency in heavy duty operations
- To achieve these benefits, a detail investigation of the charge motion and flame development inside the pre-chamber ignition system is required
  - Experimental investigation ➔ difficult to investigate optically due to small sizes
  - Numerical investigation ➔ best possible alternative
- Pre-chambers requires local refinement, especially between electrodes and holes and thus requires an individual Grid Independence Study (GIS) of the Pre-chamber ignition system



Objectives:

- Grid Independence Study (GIS) of the Pre-chamber ignition system
- Optimization of the Pre-chamber ignition system geometry

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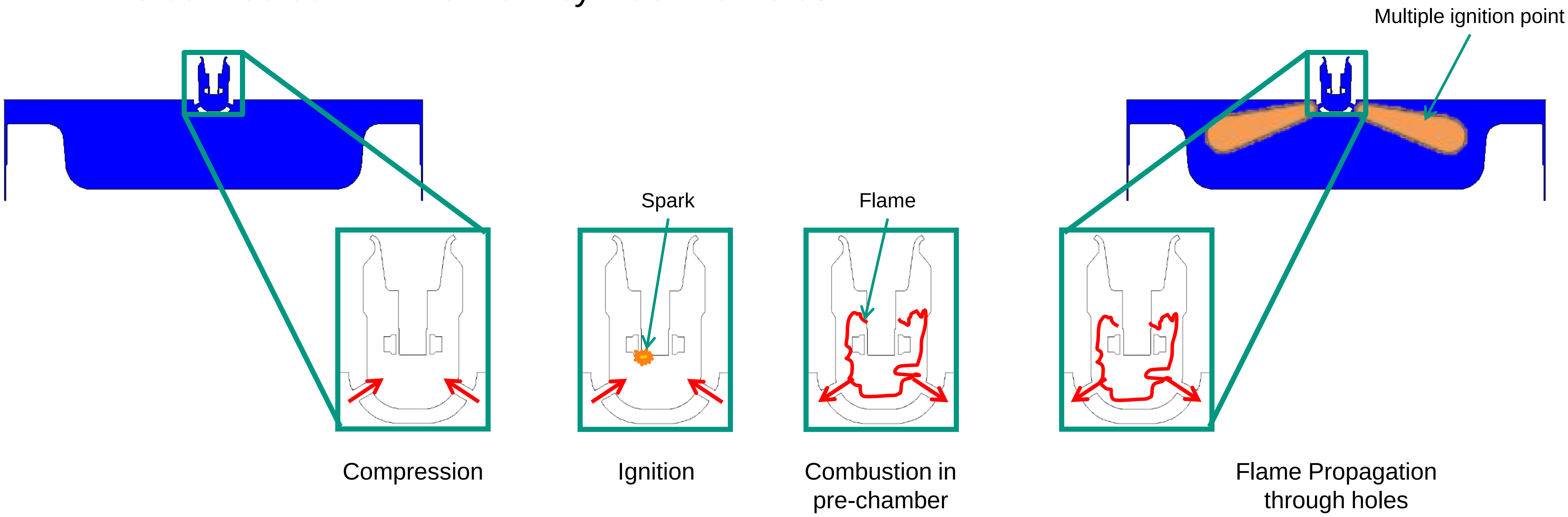
Introduction

Operation of a Pre-Chamber Ignition System

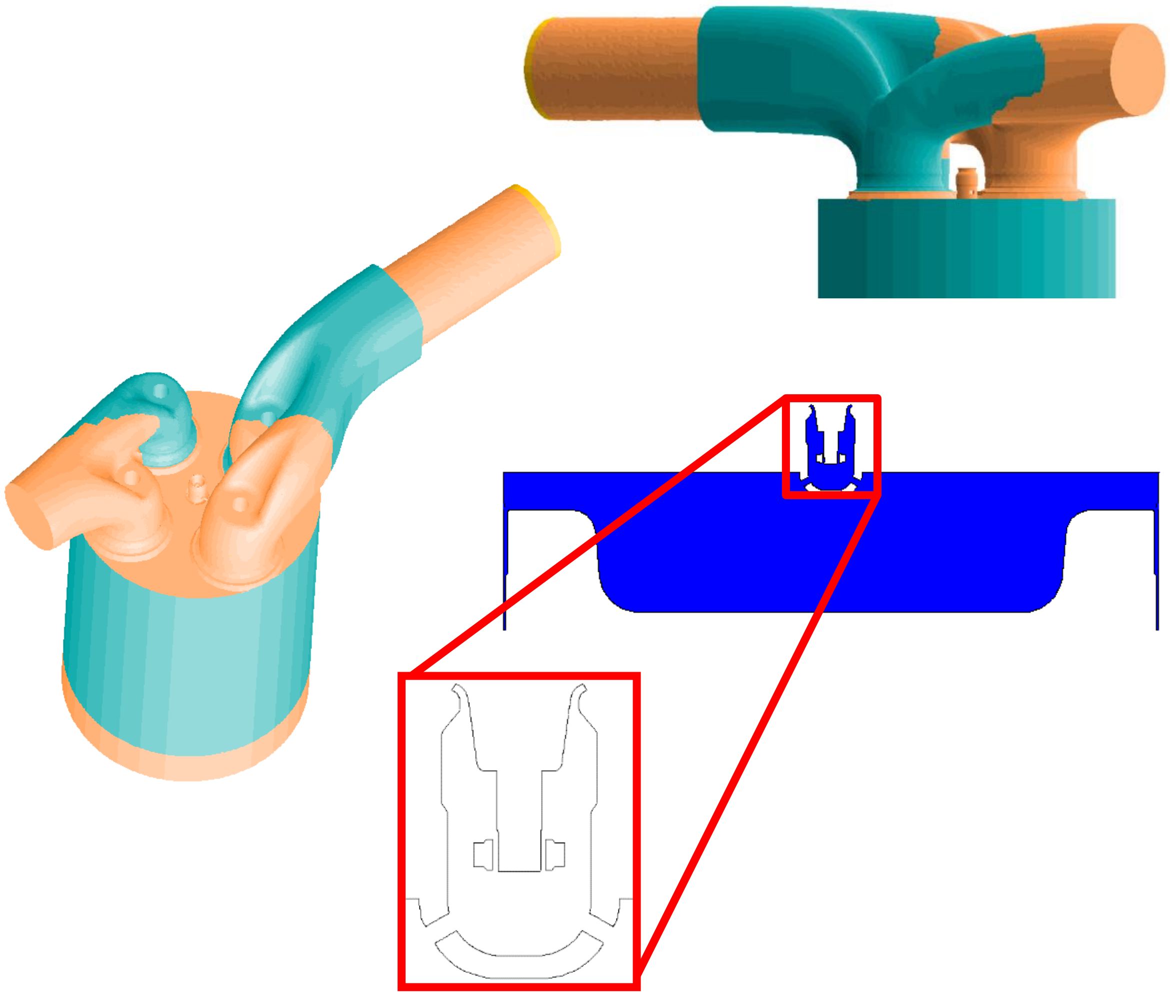
- A pre-chamber is an enclosed volume with spark plug enclosed in it (and sometimes pilot fuel injection system - only in active type).
- It is connected with the main cylinder via holes



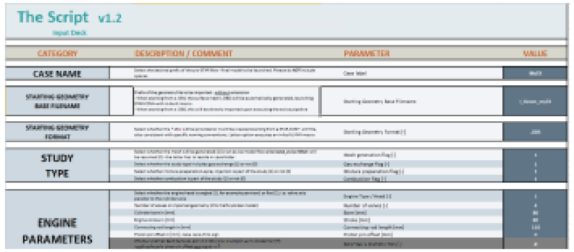
Introduction
Engine and Simulation Description

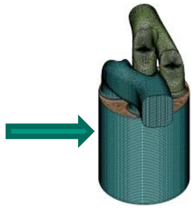
Parameter	Dimension/Configuration
Type	Single-cylinder heavy-duty engine
Displacement	2 litres
Compression ratio	12.5
Bore x Stroke	130mm x 150mm
Pre-chamber/main chamber volume ratio	0.5 %
Speed	1500 rpm
Valves	2 intake, 2 exhaust
Fuel	Natural gas (premixed)

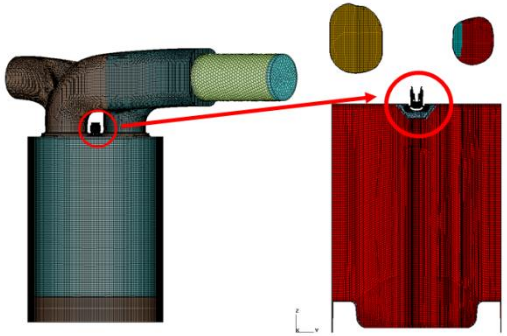
Parameter	Model
Software	Star CD es-ice v4.30
Turbulence Model	k-ε RNG turbulence model
Wall function	Grumo-Unimore



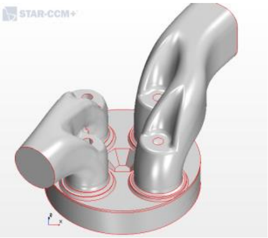
Introduction
Workflow







3D automatische Vorlage und die Querschnitte des Zylindermodells



CREO
Engine negative volume CAD model

Star CCM+
Surface preparation, surface meshing

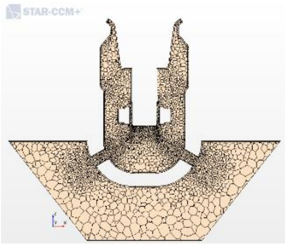
Siemens Star CD
moving mesh generation with Siemens automatic tool „TheScript“

Star CCM+
3D meshing for static parts (e.g. pre-chamber, inlet pipe etc)

Siemens Star CD
Boundary conditions input and numerical setup

Automatic mesh generation helps to reduce time of mesh generation (15 hours to 4 hours) and human effort and also at the same time increases accuracy.

With the use of static pieces, one can use the same movable mesh for different geometries of pre-chamber ignition systems. This process ensures same effect of inlet charge motion during intake valve open.



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Introduction

Validation Process

Engine

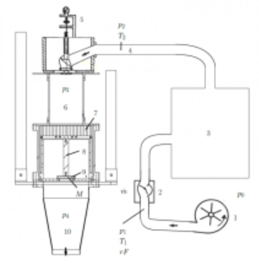
Engine Test Bench
Pressure measurement (intake, exhaust, cylinder), Temperature measurement (intake and exhaust), wall temperature

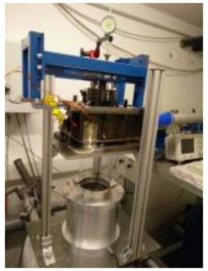
Swirl Measurement Test Bench
Swirl coefficient measurement

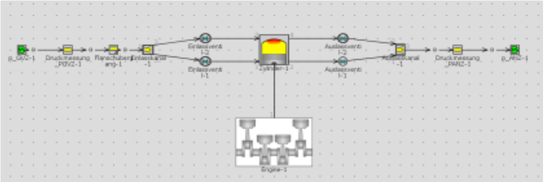
BREMO
Pressure curve analysis

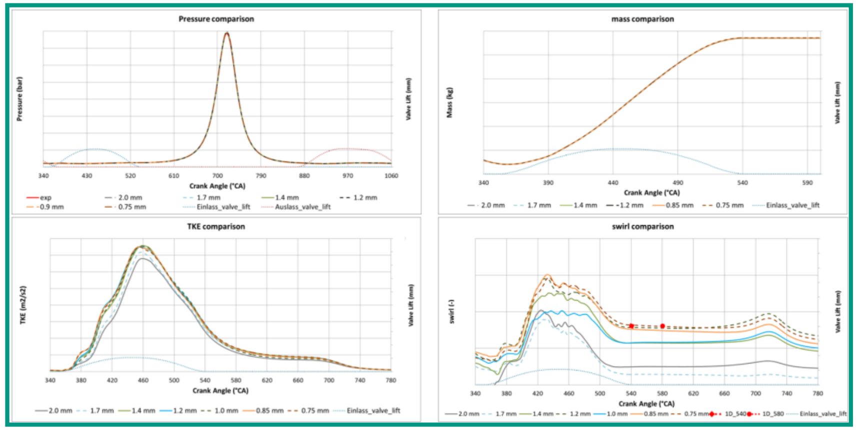
GT Power
Swirl, trapped mass calculation, p_{zyl}

Siemens Star CD
p_{zyl}, m_{zyl}, TKE, swirl









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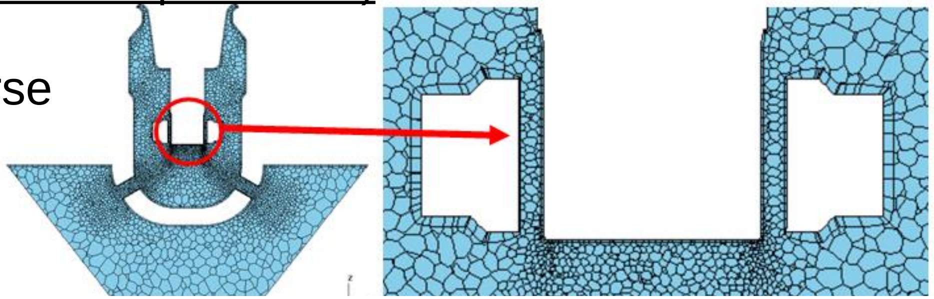
Grid Independence Study (GIS): Pre-Chamber Ignition System

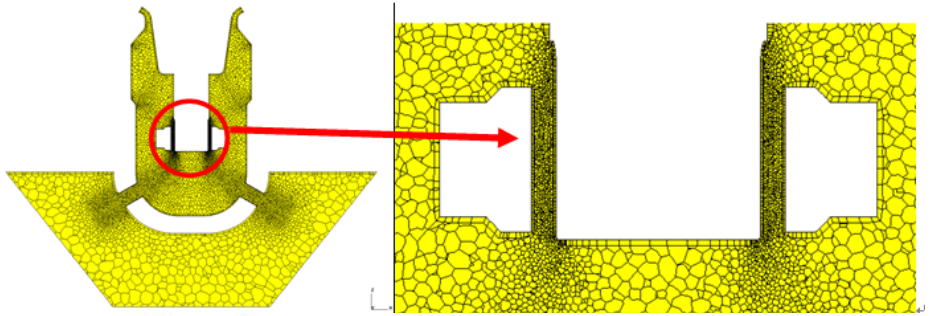
Simulation Settings

GIS is required to find the minimum grid size after which convergence (variation) of result becomes small (within some acceptable limit)

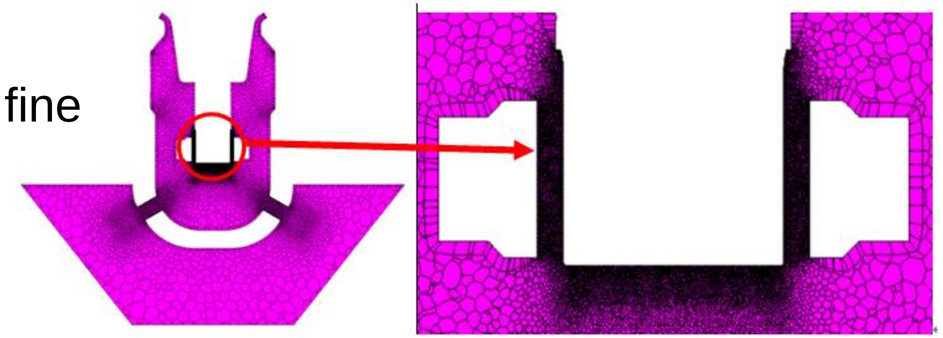
Coarse



Fine



Very fine

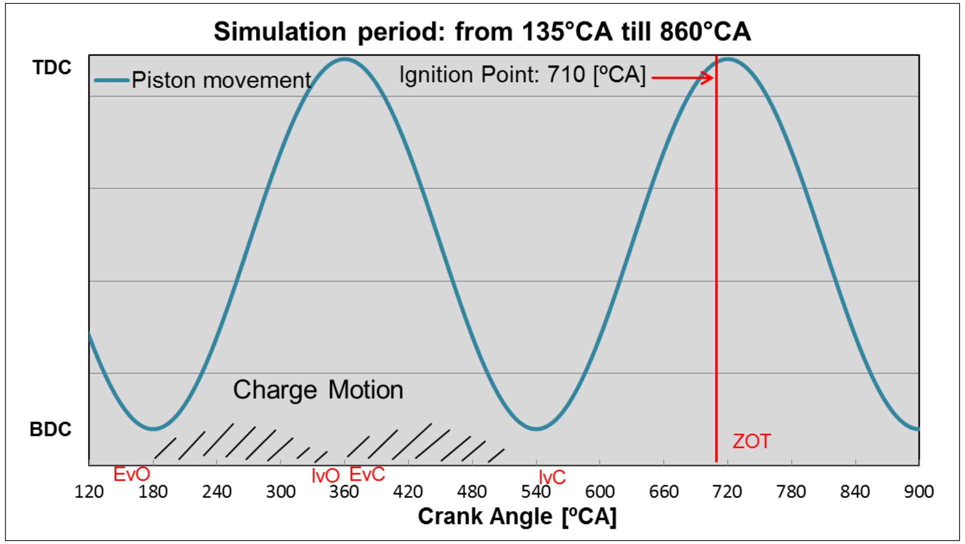


Title	Coarse	Fine	Very fine
Total number of cells in Pre-chamber	175,000	670,000	2,400,000
Cells in the electrode gap	5	10	20
Cells in the holes along the diameter	10	20	30
Timestep (°CA)	0.1	0.05	0.01
Simulation run time (CPU hours)	8800	19200	115200

Simulation is started before exhaust valve opening to analyse the effect of scavenging inside the pre-chamber ignition system

Initial mass distribution

Gas	Mass fraction
N_2	0,7252
O_2	0,0849
H_2O	0,07837
CO_2	0,10062
CH_4	0,00049
HCHO	0,00271
CO	0,00027
NO_X	0,00744



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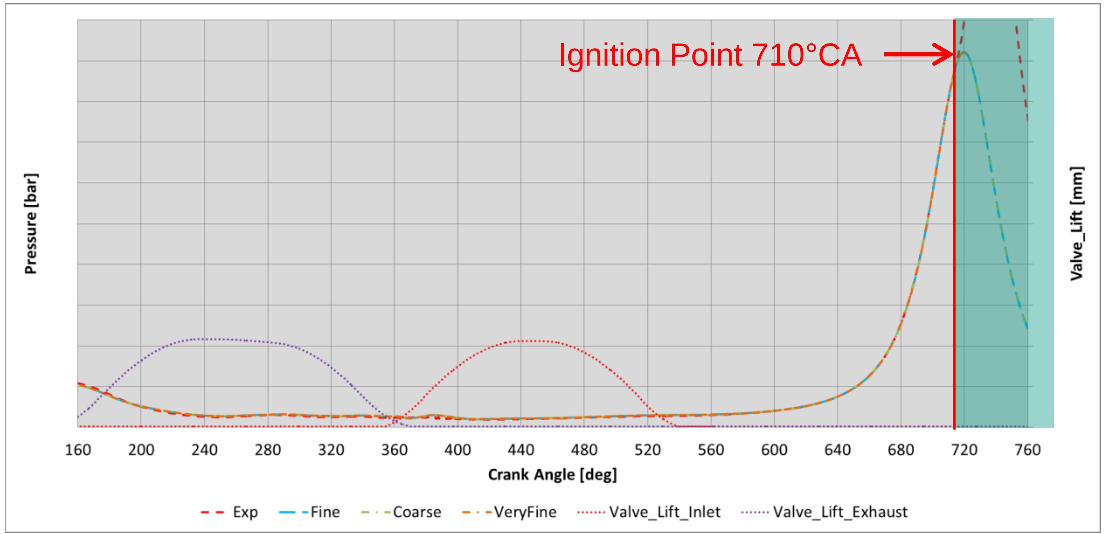
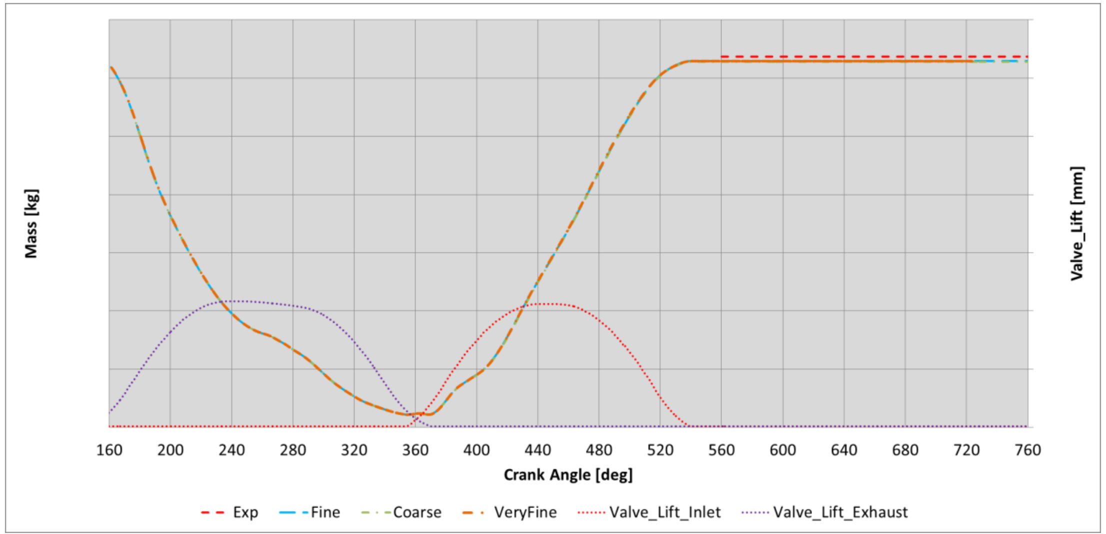
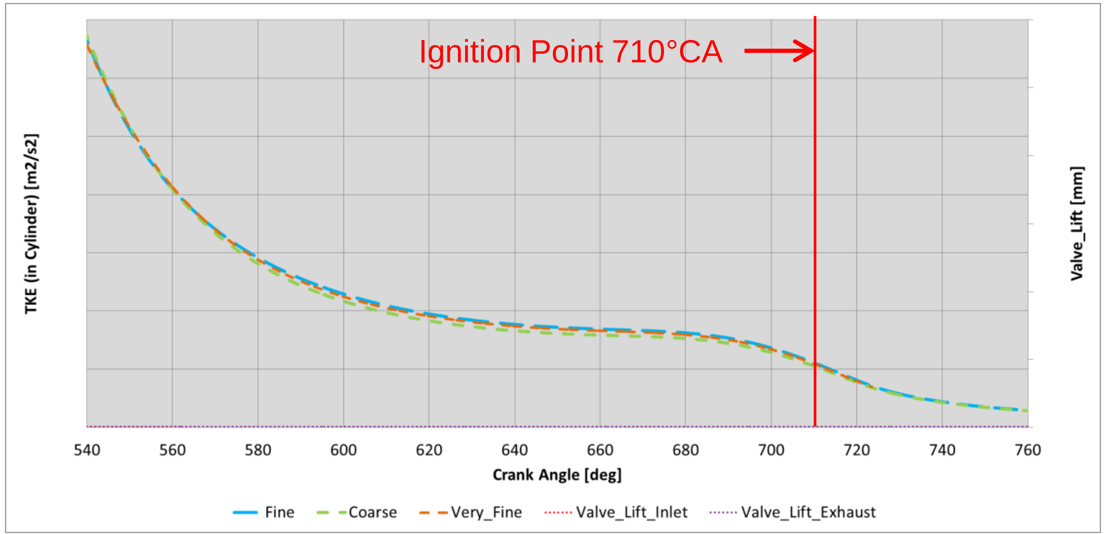
Grid Independence Study (GIS): Pre-Chamber Ignition System

Results



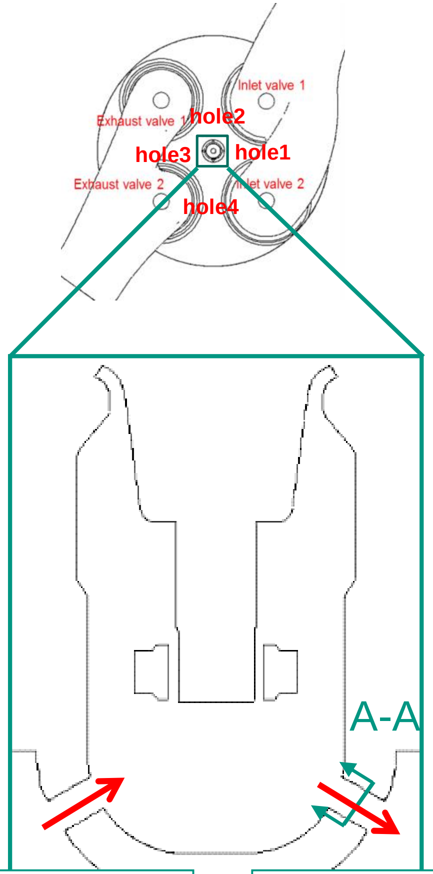




Results from simulation until 710 °CA (Ignition point) are comparable with the experimental results. Not much variations in the cylinder parameters

Grid Independence Study (GIS): Pre-Chamber Ignition System

Results: Comparison of velocity profile in the holes



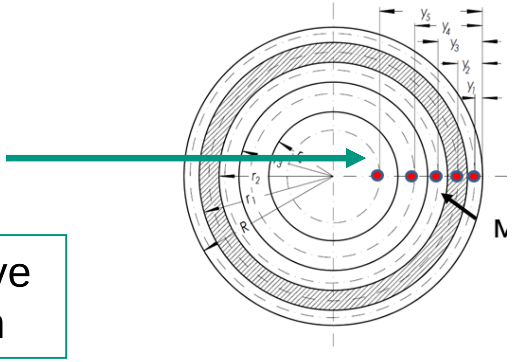
\+ positive direction

\- negative direction

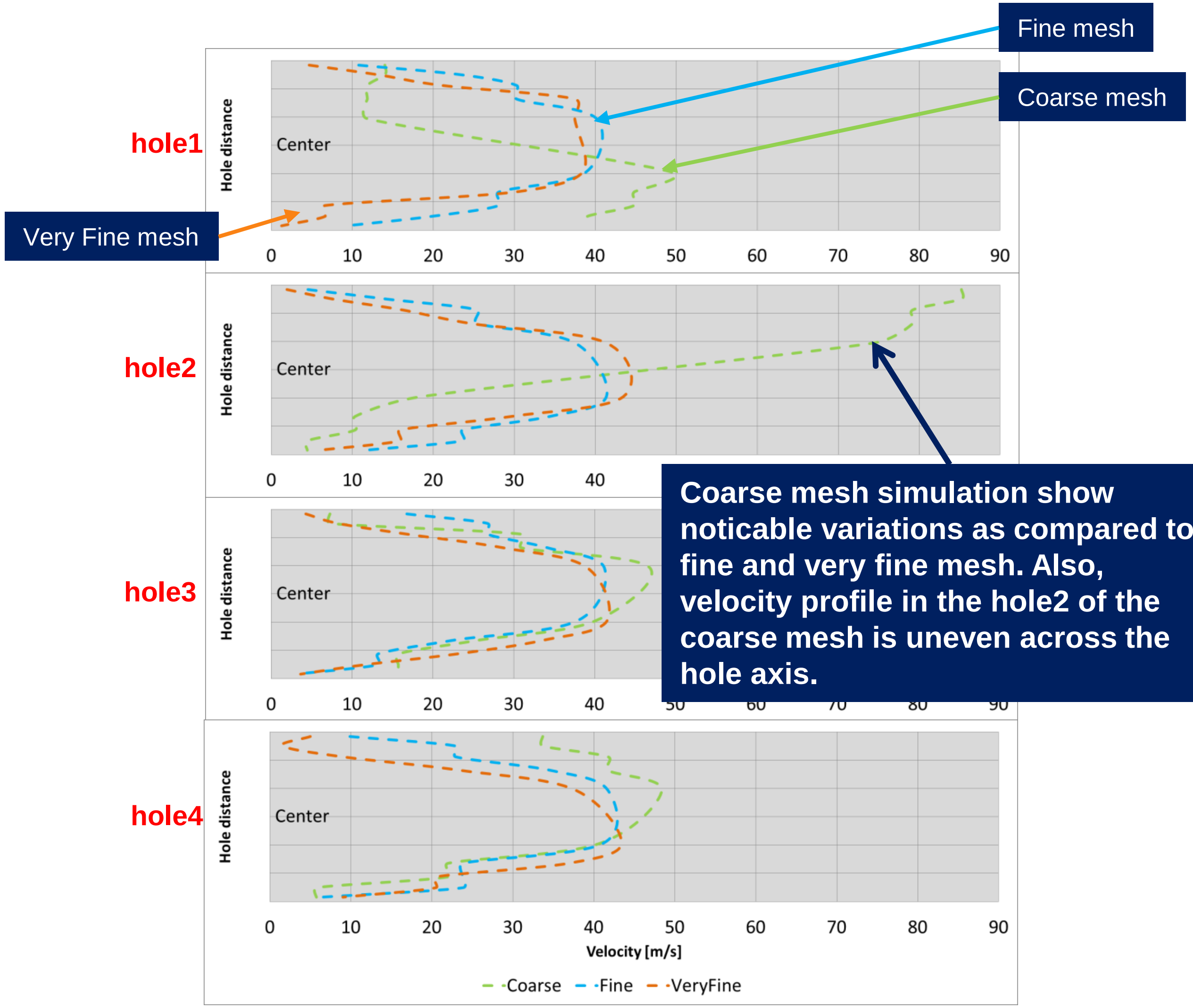
Wall distance of the measuring points in the centerline method according to DIN EN 12599

y/D bei 5 Messstellen	Wert
y_1/D	0.026
y_2/D	0.082
y_3/D	0.146
y_4/D	0.226
y_5/D	0.342

Section: A-A



Arrangement of the measuring points along the center line



Coarse mesh simulation show noticable variations as compared to fine and very fine mesh. Also, velocity profile in the hole2 of the coarse mesh is uneven across the hole axis.

Grid Independence Study (GIS): Pre-Chamber Ignition System

Results

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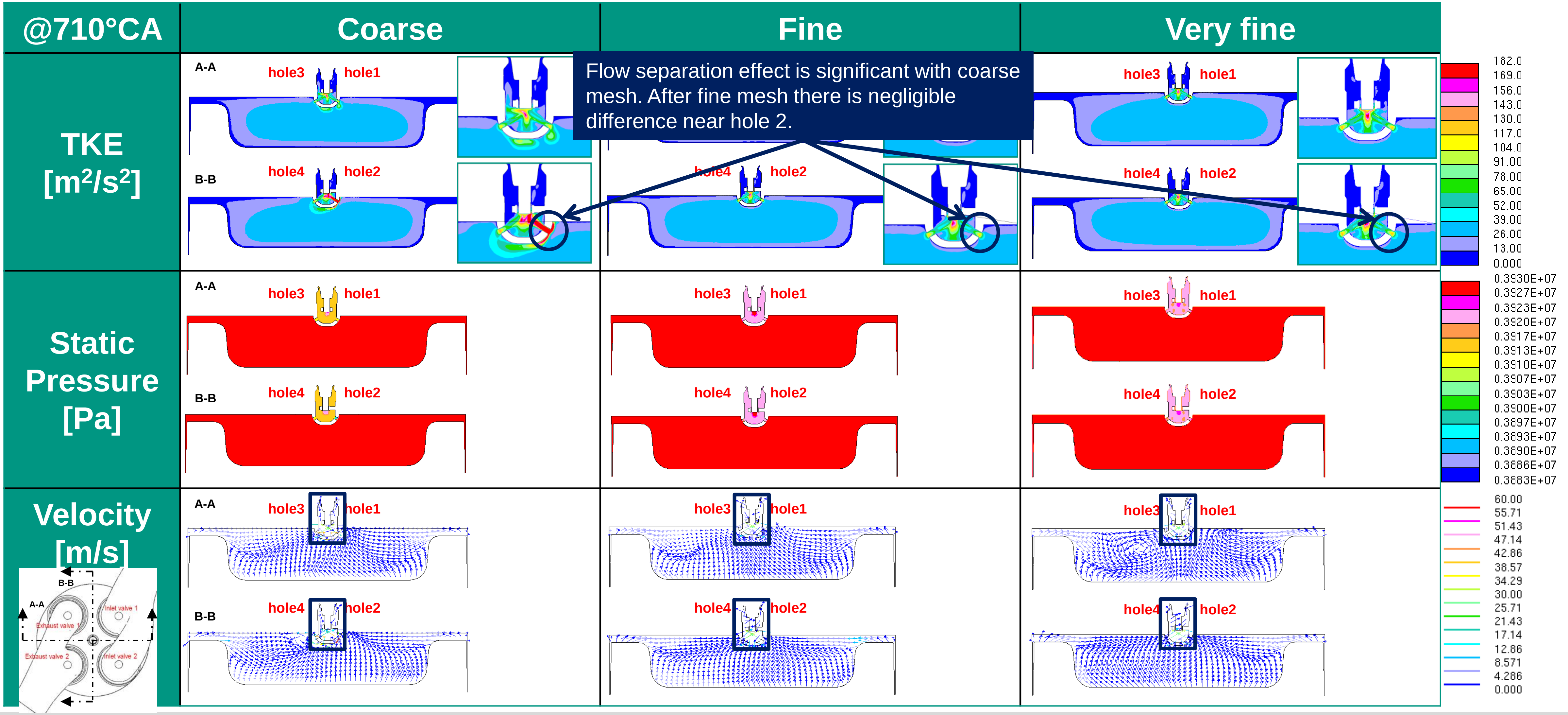

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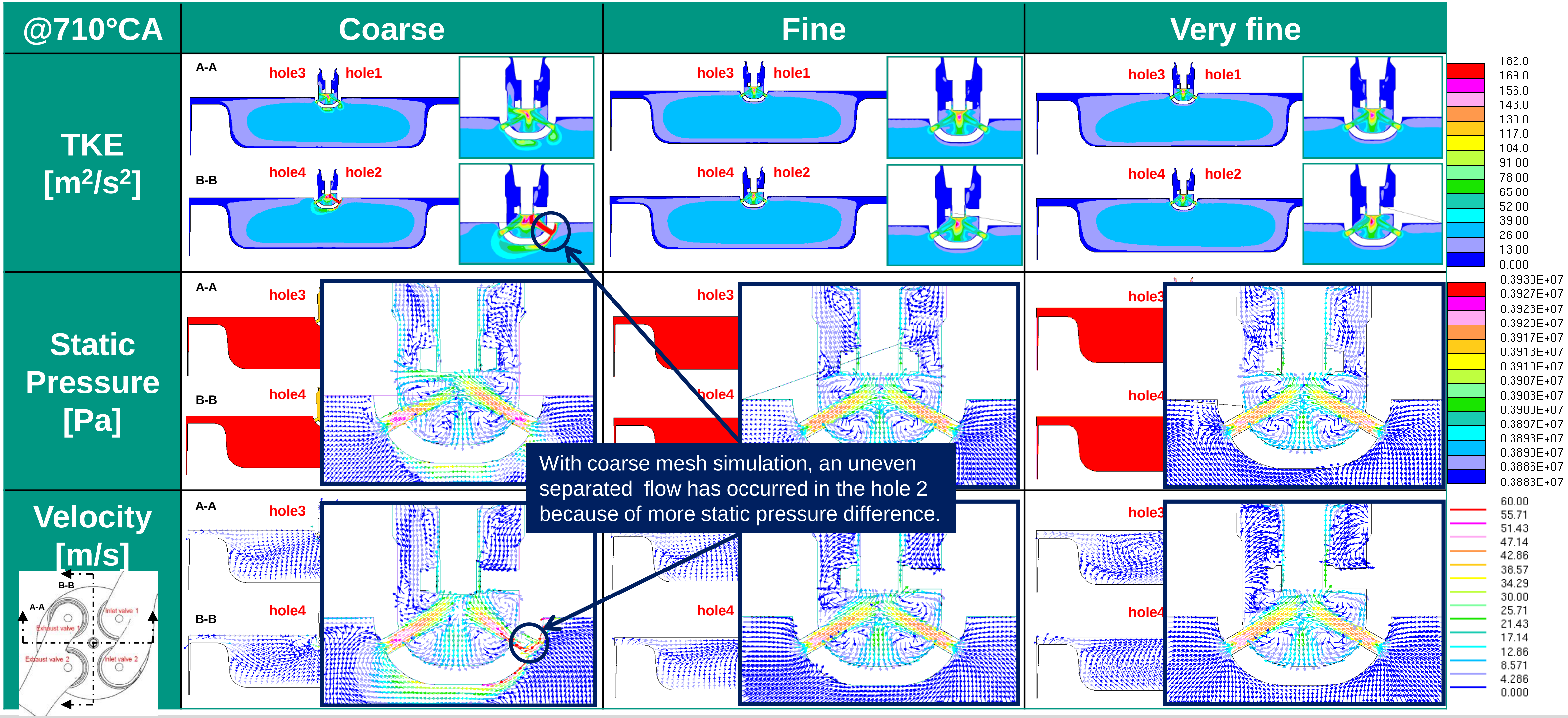
Grid Independence Study (GIS): Pre-Chamber Ignition System

Results



Grid Independence Study (GIS): Pre-Chamber Ignition System

Results

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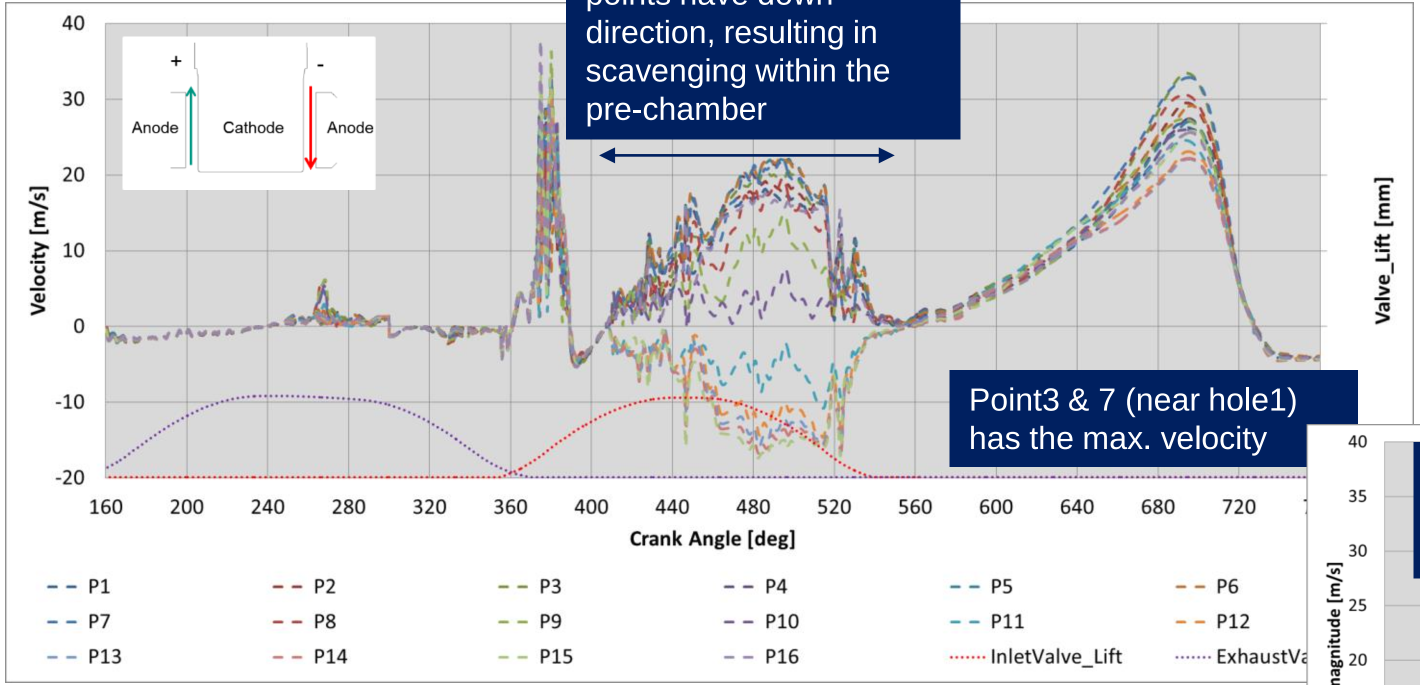
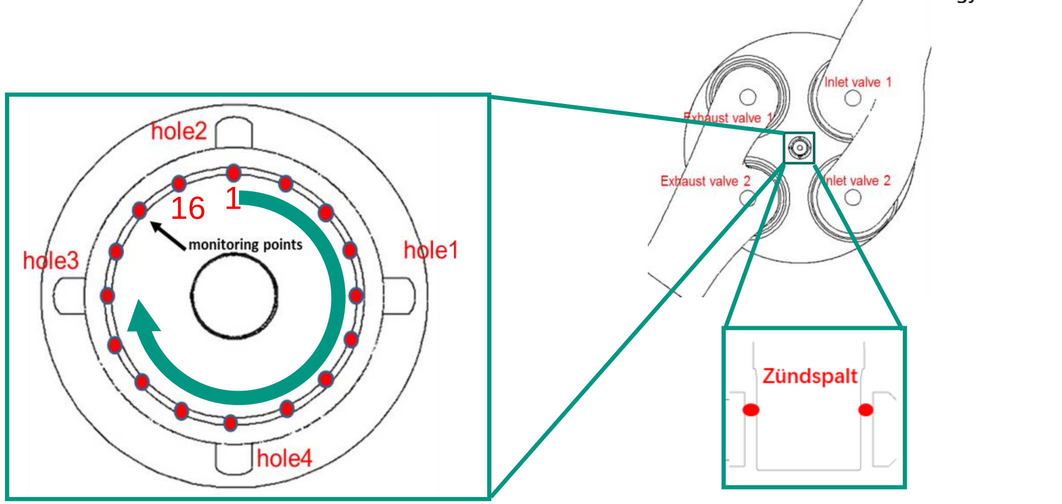
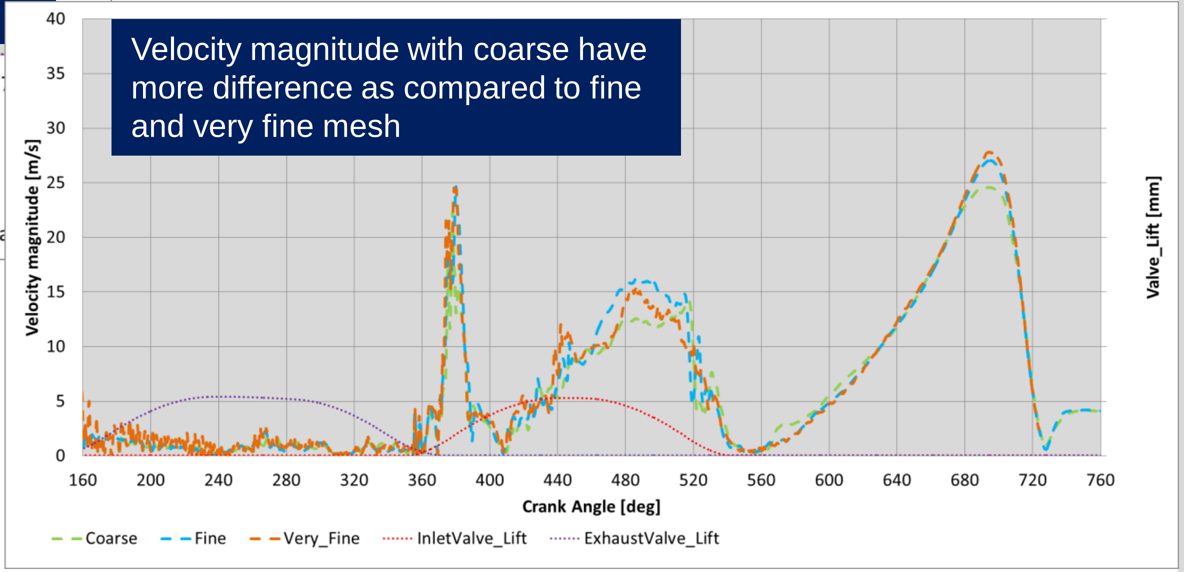
Points near inlet valves have up direction velocity while away points have down direction, resulting in scavenging within the pre-chamber



Point3 & 7 (near hole1) has the max. velocity



Velocity magnitude with coarse have more difference as compared to fine and very fine mesh



Grid Independence Study (GIS): Pre-Chamber Ignition System

Results

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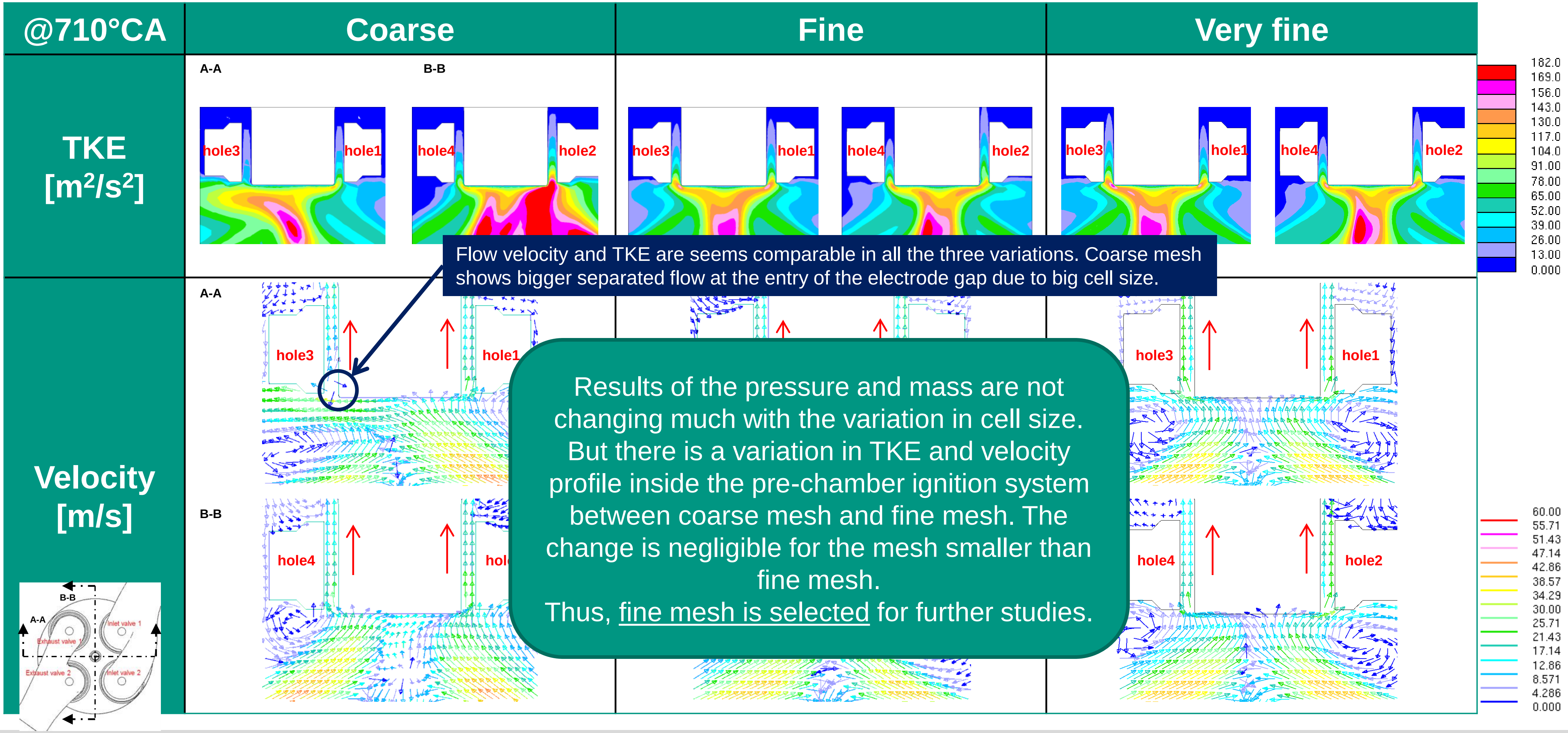

Flow velocity and TKE are seems comparable in all the three variations. Coarse mesh shows bigger separated flow at the entry of the electrode gap due to big cell size.

Results of the pressure and mass are not changing much with the variation in cell size. But there is a variation in TKE and velocity profile inside the pre-chamber ignition system between coarse mesh and fine mesh. The change is negligible for the mesh smaller than fine mesh.
Thus, fine mesh is selected for further studies.

Optimization of the Pre-Chamber Geometry

Geometries

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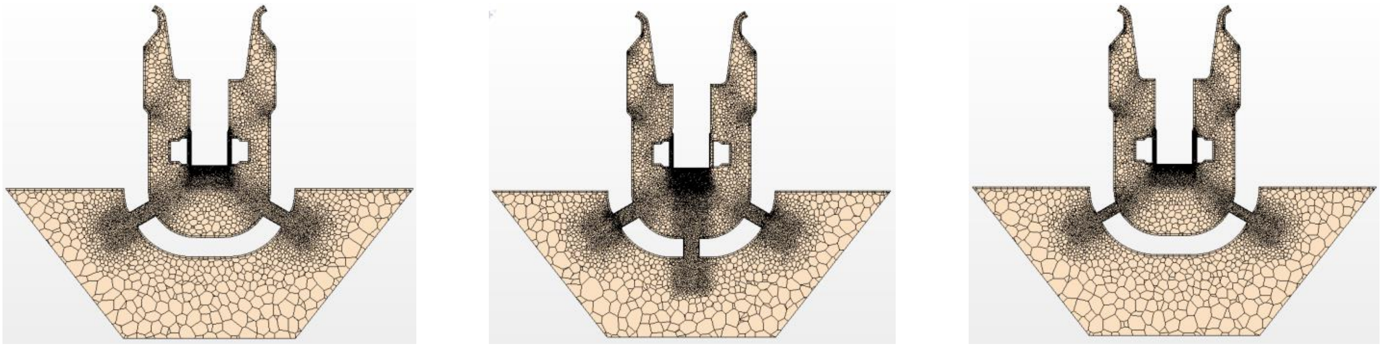
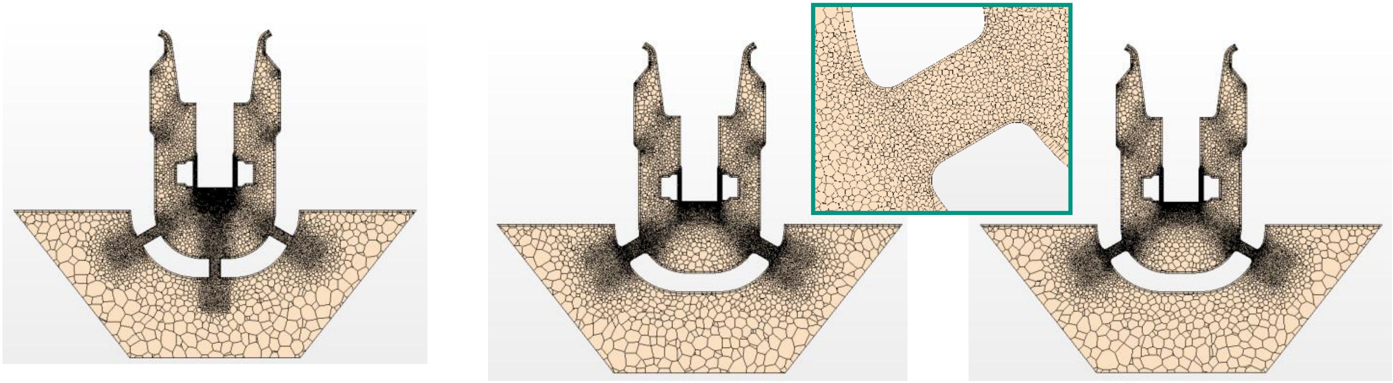
5 different geometries along with the original geometry are analyzed in order to create the flow conditions for consistent and fast flame kernel development and flame propagation inside the pre-chamber ignition chamber



Original	VK1 (5 holes)	VK2 (4 small holes)



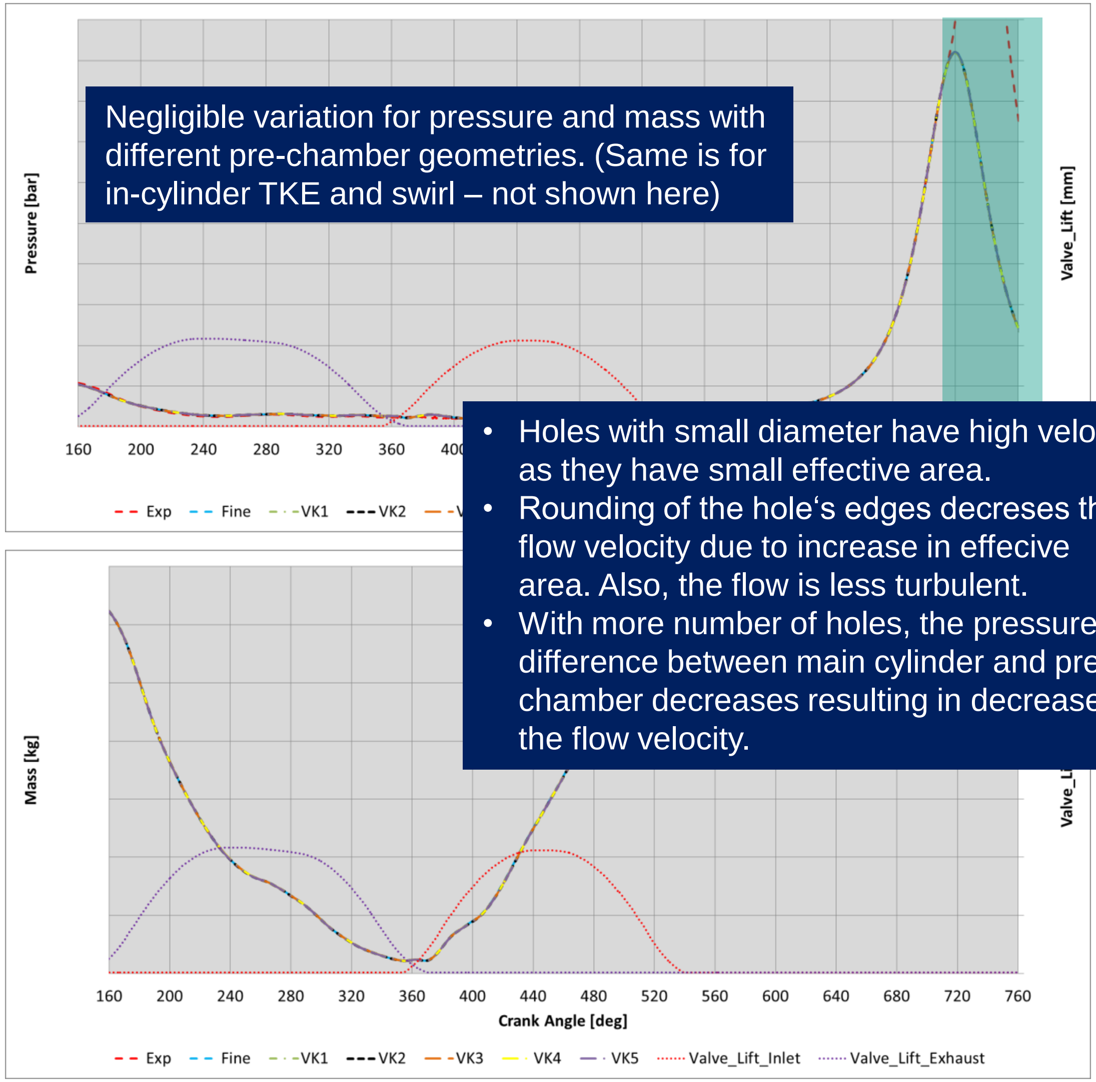
VK3 (5 small holes)	VK4 (4 holes with round edges)	VK5 (4 small holes with round edges)

<u>Targets:</u>

- flow velocity should not be very high, so that it shears the flame kernel or very less in the electrode gap (no standard value available)
- High Turbulent Kinetic Energy(TKE) in the Pre-chamber but <u>low TKE in the electrode gap</u>
- Low residual exhaust gas in the Pre-chamber, especially in the electrode gap

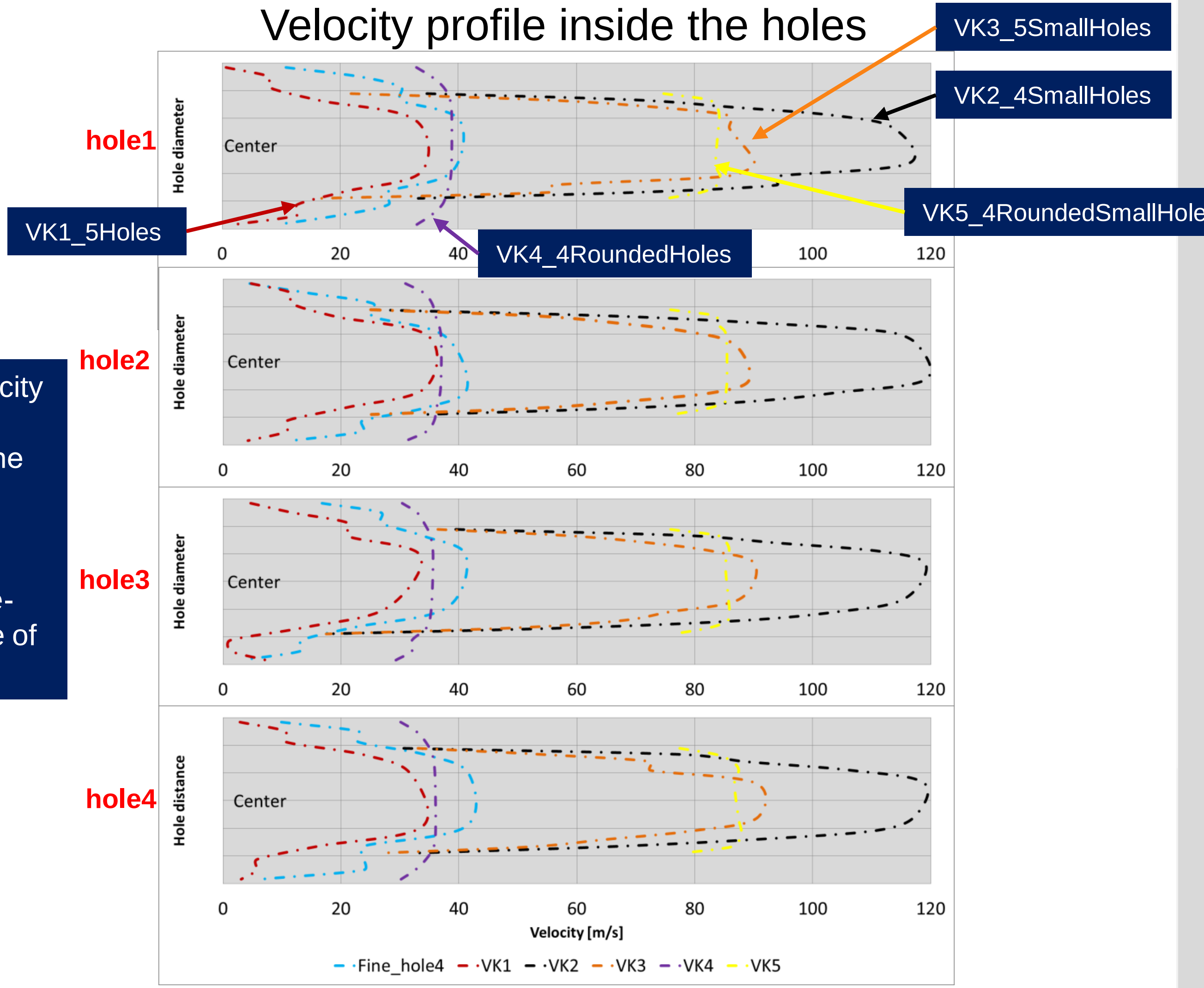
Optimization of the Pre-Chamber Geometry

Results: Comparison of velocity profile in the holes



Negligible variation for pressure and mass with different pre-chamber geometries. (Same is for in-cylinder TKE and swirl – not shown here)

- Holes with small diameter have high velocity as they have small effective area.
- Rounding of the hole's edges decreases the flow velocity due to increase in effecive area. Also, the flow is less turbulent.
- With more number of holes, the pressure difference between main cylinder and pre-chamber decreases resulting in decrease of the flow velocity.



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Optimization of the Pre-Chamber Geometry
Results

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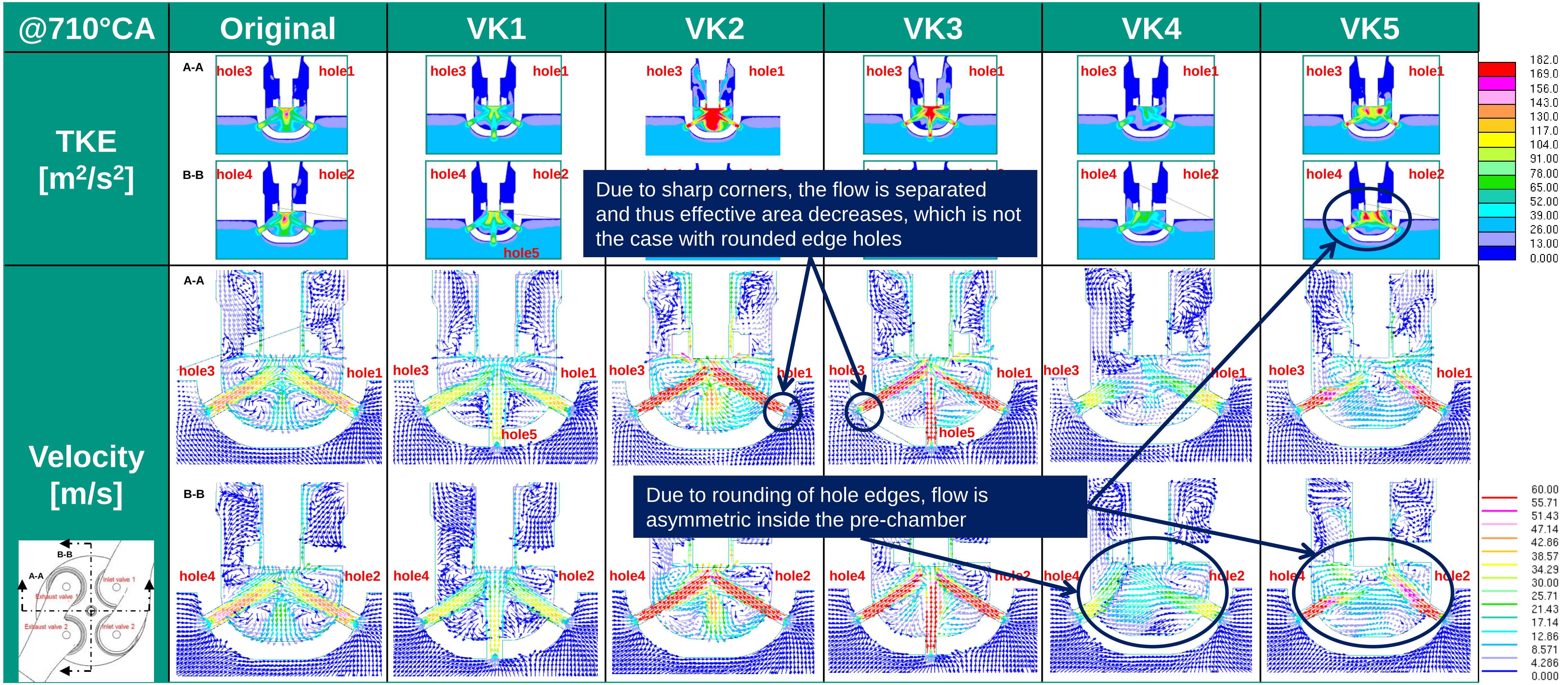
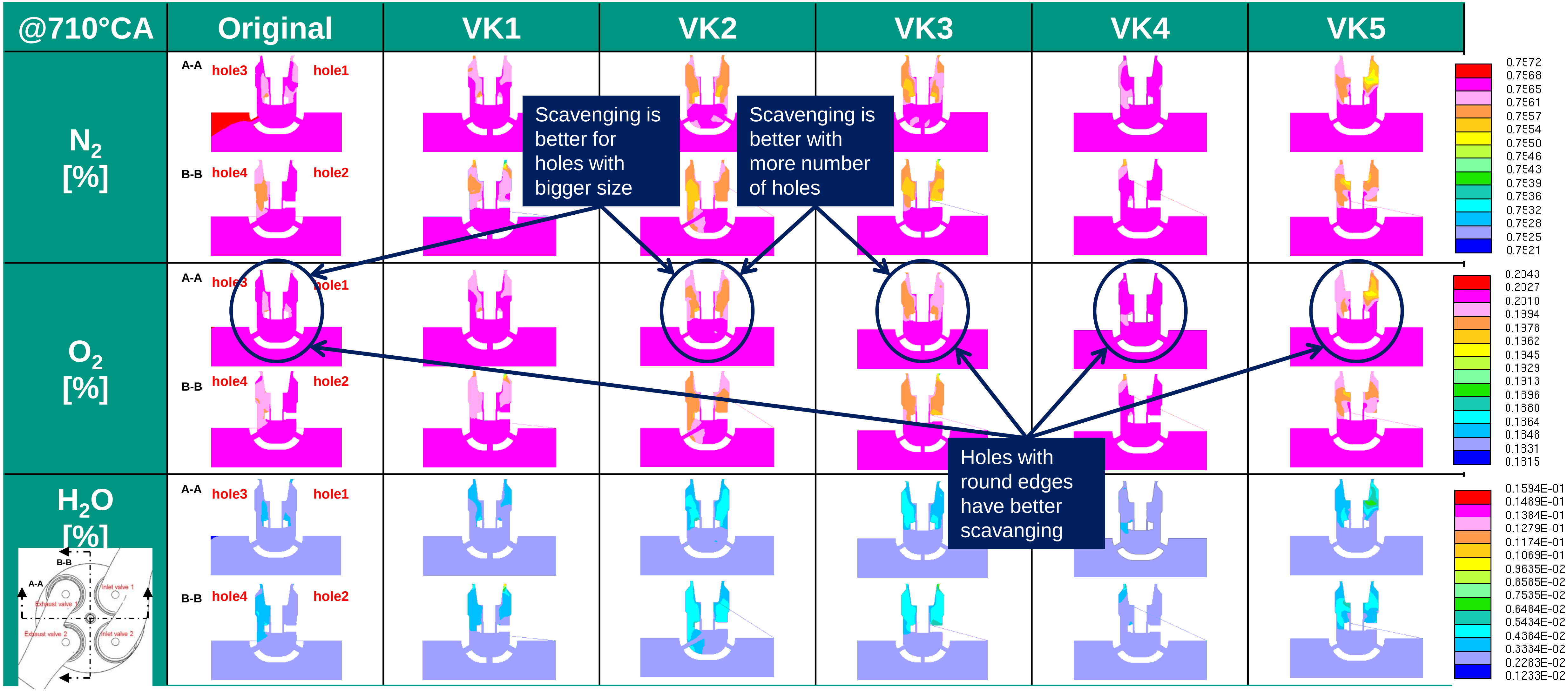
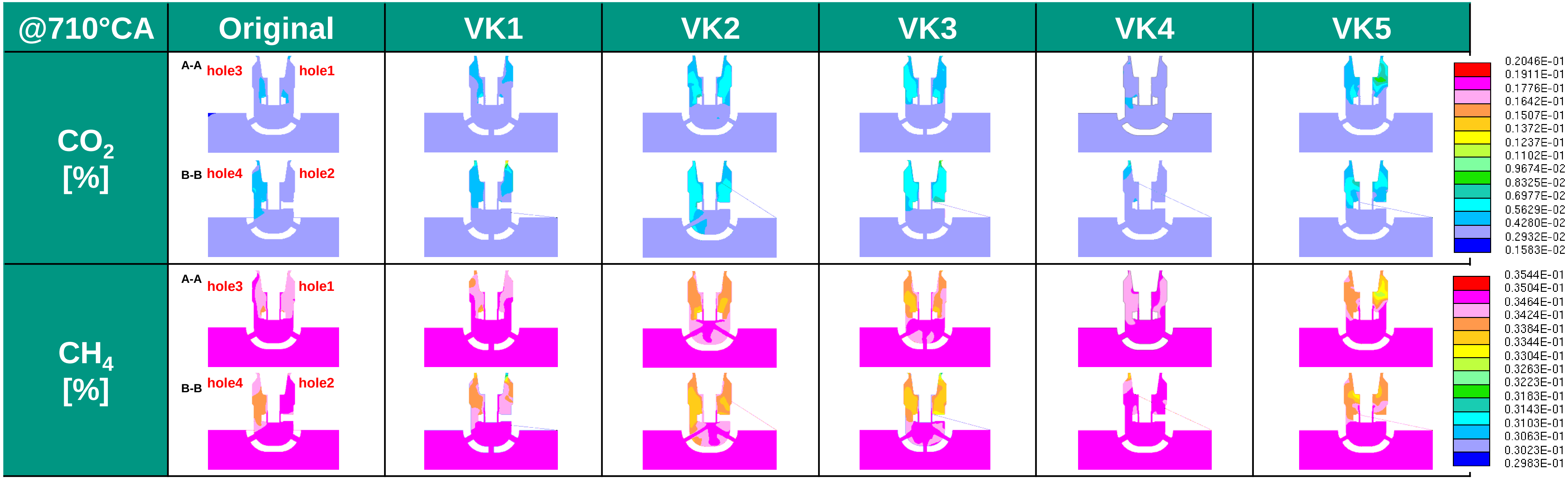


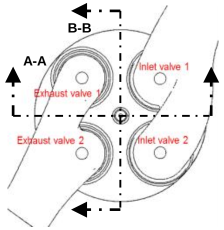
Optimization of the Pre-Chamber Geometry

Results



Optimization of the Pre-Chamber Geometry
Results





Scavenging in the electrode gap is similar for all the geometries as the flow from the holes is directed toward the electrode gap which pushes the residuals towards the upper area of pre-chamber.

Optimization of the Pre-Chamber Geometry

Results

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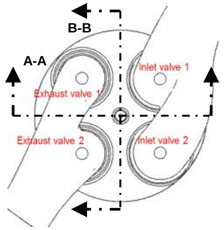
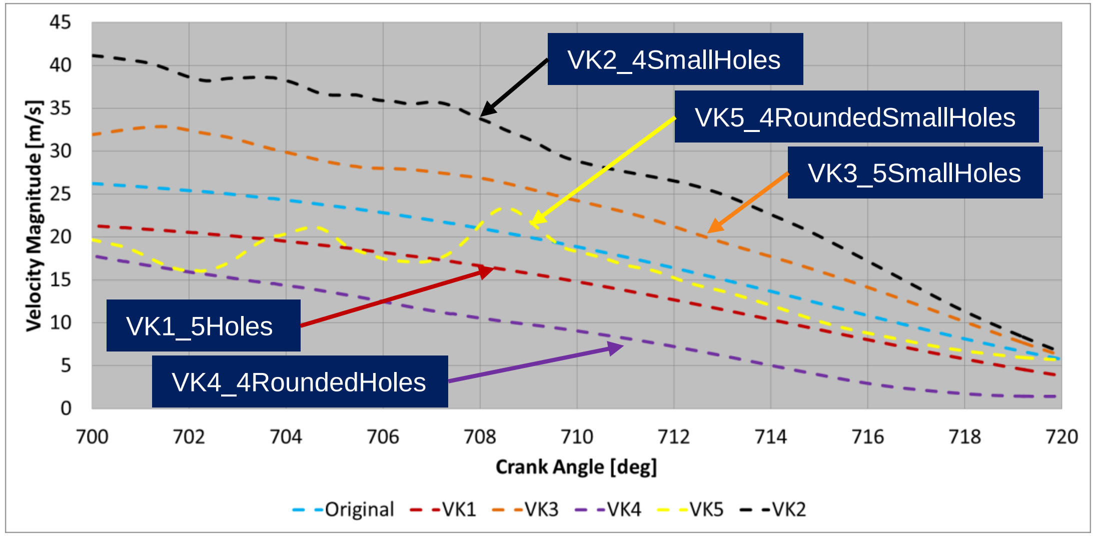
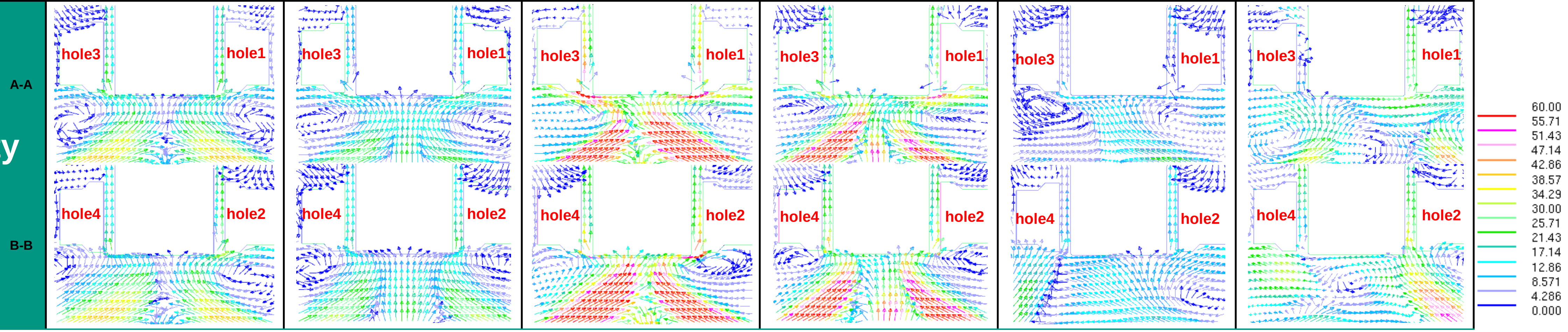




Scavenging in the electrode gap is similar for all the geometries

@710°CA	Original	VK1	VK2	VK3	VK4	VK5
Velocity [m/s]						



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Summary

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- 3D simulation results are validated with the experimental results.
- A new workflow of static mesh for pre-chamber ignition system is developed and presented.
- GIS of the pre-chamber ignition system applied successfully. Coarse mesh shows insufficient accuracy of the velocity. Fine mesh with 10 minimum cells in the electrode gap and 20 cells in the holes is required to accurately calculate the flow.
- Optimization study shows the influence of hole diameter, number of holes and hole edges on the TKE, velocity and residuals inside the pre-chamber and between the electrodes.

Geometry	Velocity in the holes (more)	Velocity in the electrode gap (less)	TKE in the pre-chamber (more)	Residual in the pre-chamber (less)
Original	0	0	0	0
VK1_5Holes	-	+	-	0
VK2_4SmallHoles	+	-	+	-
VK3_5SmallHoles	+	-	+	-
VK4_4RoundedHoles	-	+	-	+
VK5_4RoundedSmallHoles	+	0	+	-

- Further investigation of the pre-chamber geometry like tangential holes, holes axis angle etc. is required.

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THANK YOU!