CFD predictions of aerodynamics and mixing in ultra-low NOx lean combustion grid plate flame stabilizer

JOSÉ RAMÓN QUIÑONEZ ARCE, DR. ALAN BURNS, PROF. GORDON E. ANDREWS.
SCHOOL OF CHEMICAL AND PROCESS ENGINEERING, UNIVERSITY OF LEEDS, UK.

<PMJRQO@LEEDS.AC.UK>

José Ramón Quiñonez Arce, Dr. Alan Burns, Prof. Gordon E. Andrews, Dr. N. A. Al-Dabbagh. University of Leeds

Introduction

Nitrogen Oxides
NOx ($NO + NO_2$)

NOx emissions from boilers are required to be reduced to ultra-low NOx levels, in many areas of the World including Europe and the USA.

The EU Ecodesign regulations for small residential gas boilers, require NOx to be less than 56 mg_{NOx}/kWh from 26th Sept 2018. For natural gas (NG) with a CV of 50 MJ/kg this is 13.9 g_{NOx}/GJ and an emission index of 0.78 g_{NOX}/kg_{fuel} and this converts to 27ppm NO_x at 0% oxygen. In the USA some areas of California have NOx reglulations at <5ppm at 0% oxygen.

For gas turbines for power generation NOx regulations <25 ppm at 15% oxygen have been in existence for many years, but currently requirements are <10ppm in many areas of the World and in California <2.5 ppm (<8.8 ppm at 0% oxygen).

The rapid mixed grid mix design investigated in this work has been shown capable of meeting these ultra-low NOx requirements.

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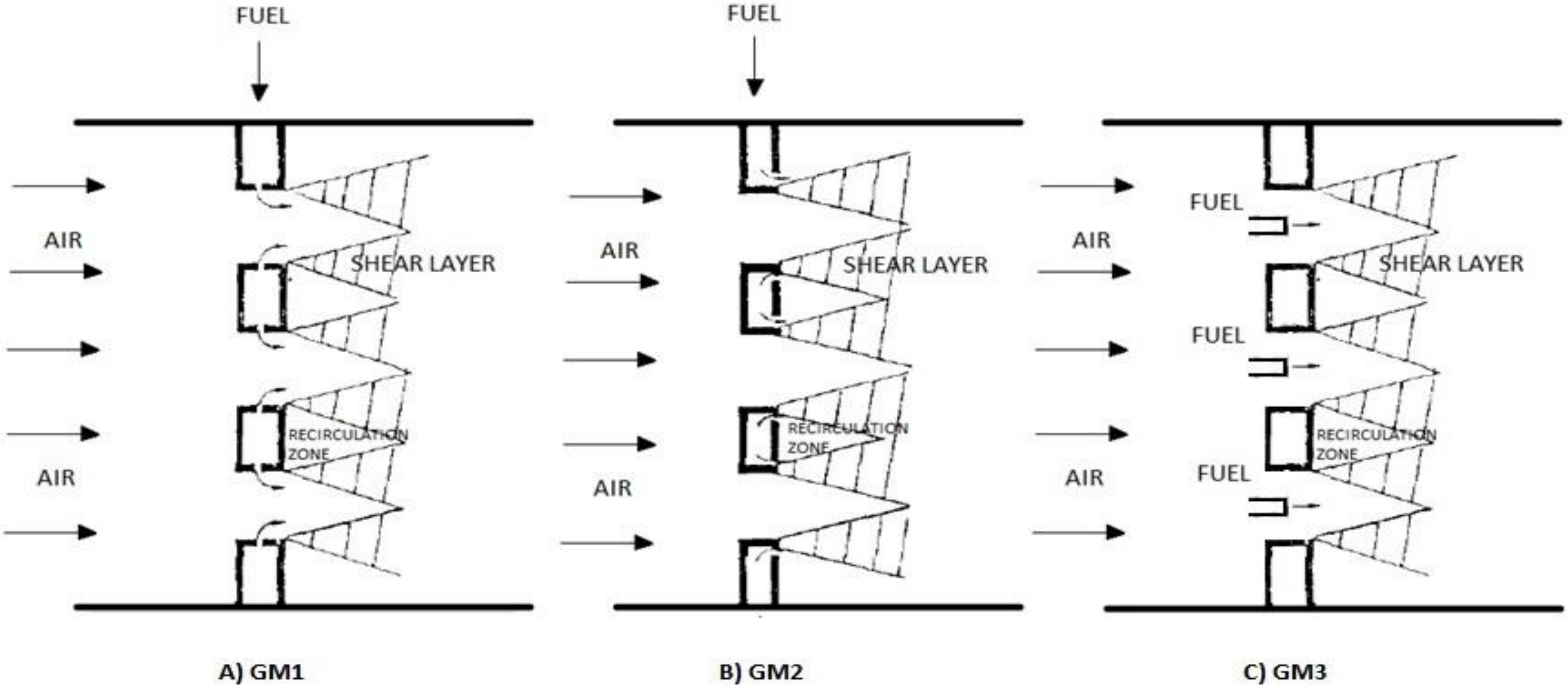

Grid mix jet shear layer fuel injection: GM1- 8 radial inward equally spaced fuel jets from the wall of the jet; GM2 - annular fuel injection slot around each shear layer jet hole. (Andrews, G.E. and S.A.R. Ahmed, 2008) GM3 new fuel injection considering a fuel insert in the centreline (FLOX burners)

GE hydrogen combustor

GM1

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Funke, H. H-W. et al. U. Aachen and Krebs, W. and Wolf, E. Siemens Energy
Experimental characterization of low NOx micromix prototype combustors for industrial gas turbine applications. ASME GT2011-45305, 2011.
Low NOx for hydrogen containing fuels.

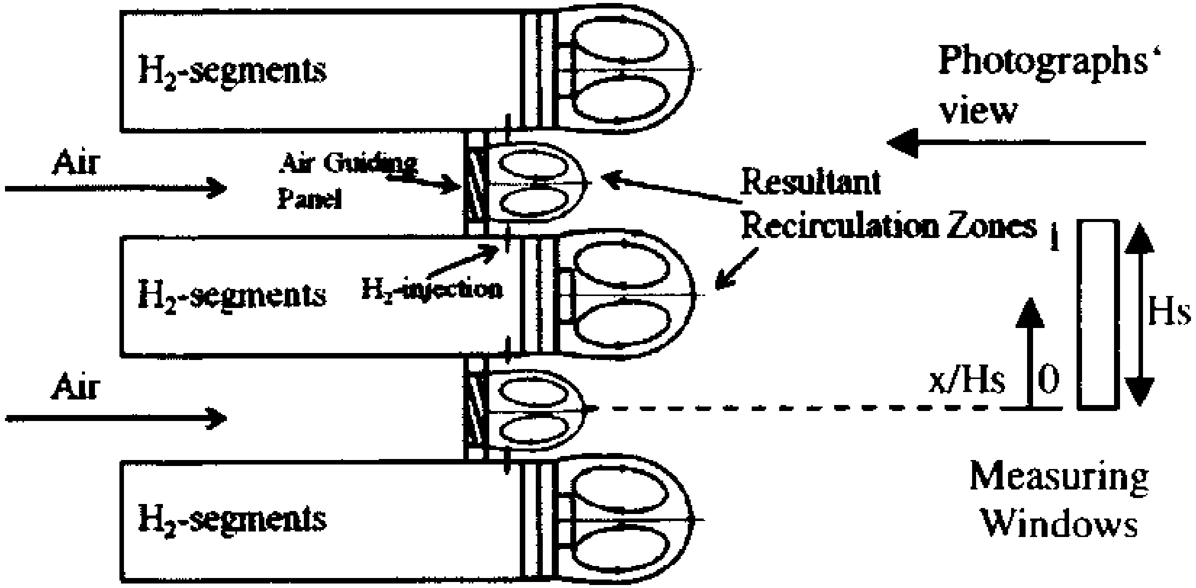


Figure 2: Resultant Recirculation zones

ASME GT2012-69913 York, et a., GE Energy and GE Global Research
Development and testing of a low NOx Hydrogen Combustion System for HDGT

GM1

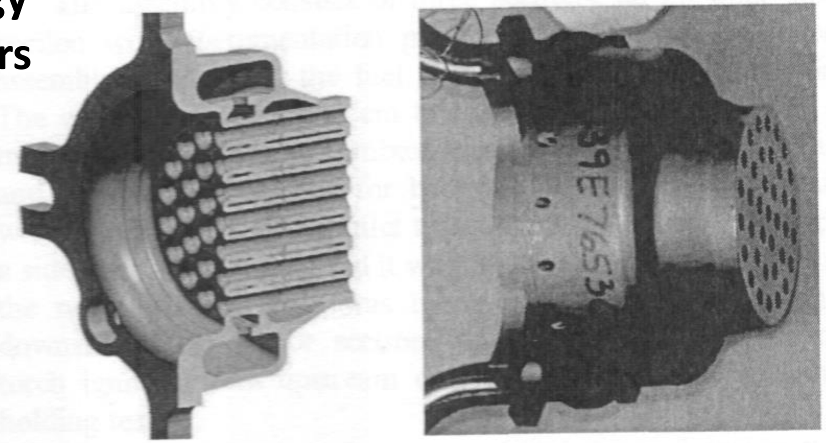
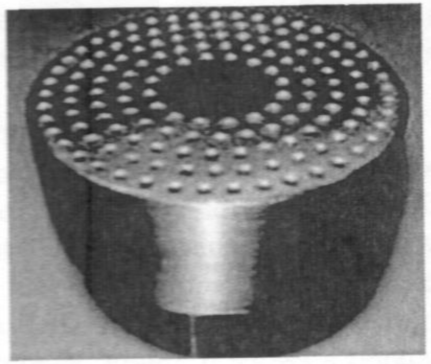


Figure 2. Model cross-section and photograph of small multi-tube mixer for high-hydrogen fuel.

20.3 bar 650K 63.5mm dia
Combustor Grid plate stabiliser



MT mixer

Figure 3. Larger scale multi-tube mixer used for single nozzle rig flame operability testing.

HITACHI Multicluster combustor **GM3**

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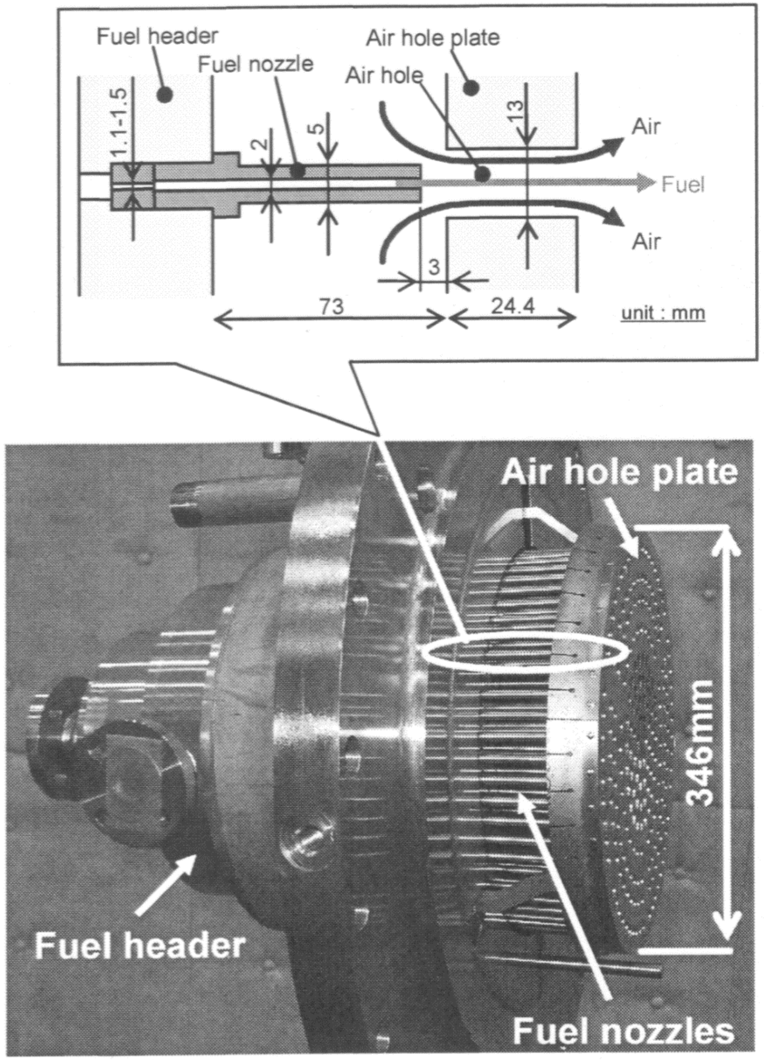
ASME Paper GT2007-27737, Hitachi



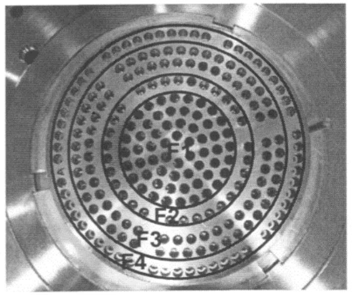
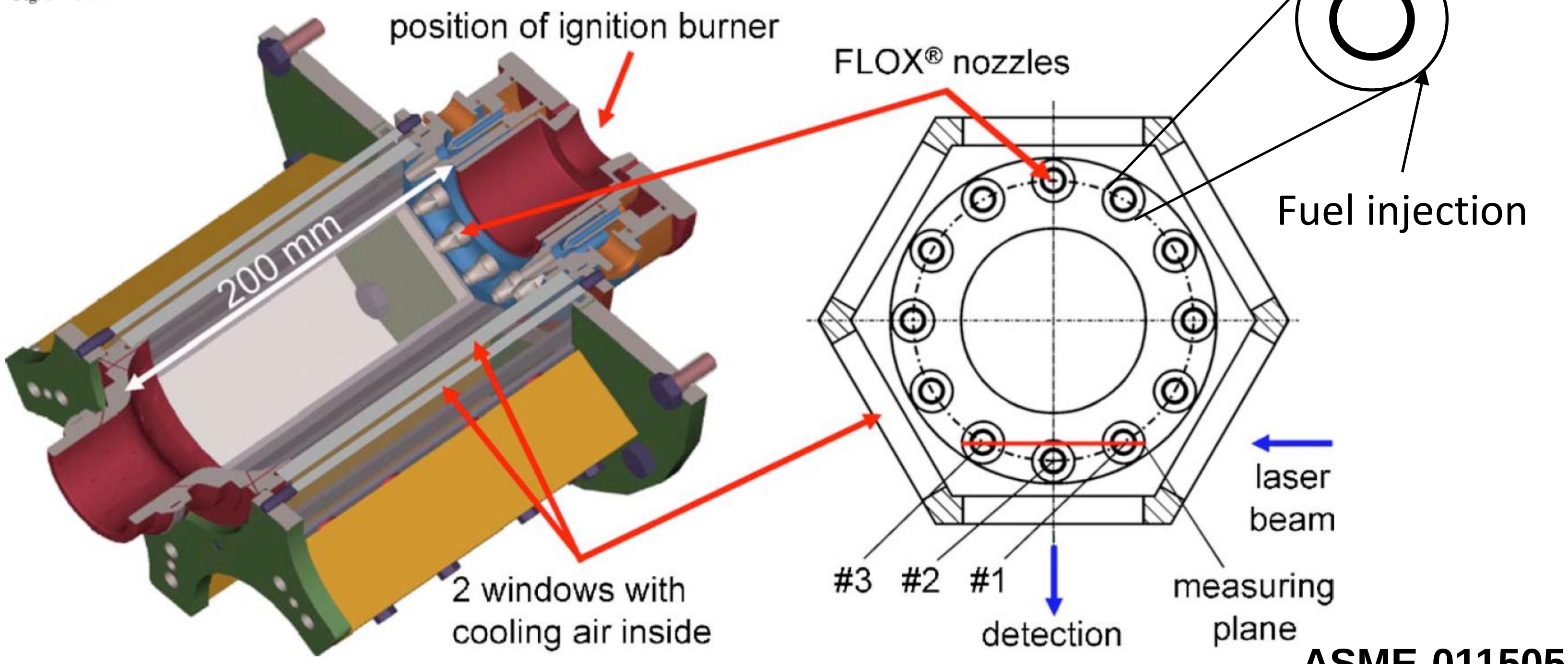


Fig. 2 Cluster Nozzle Burner

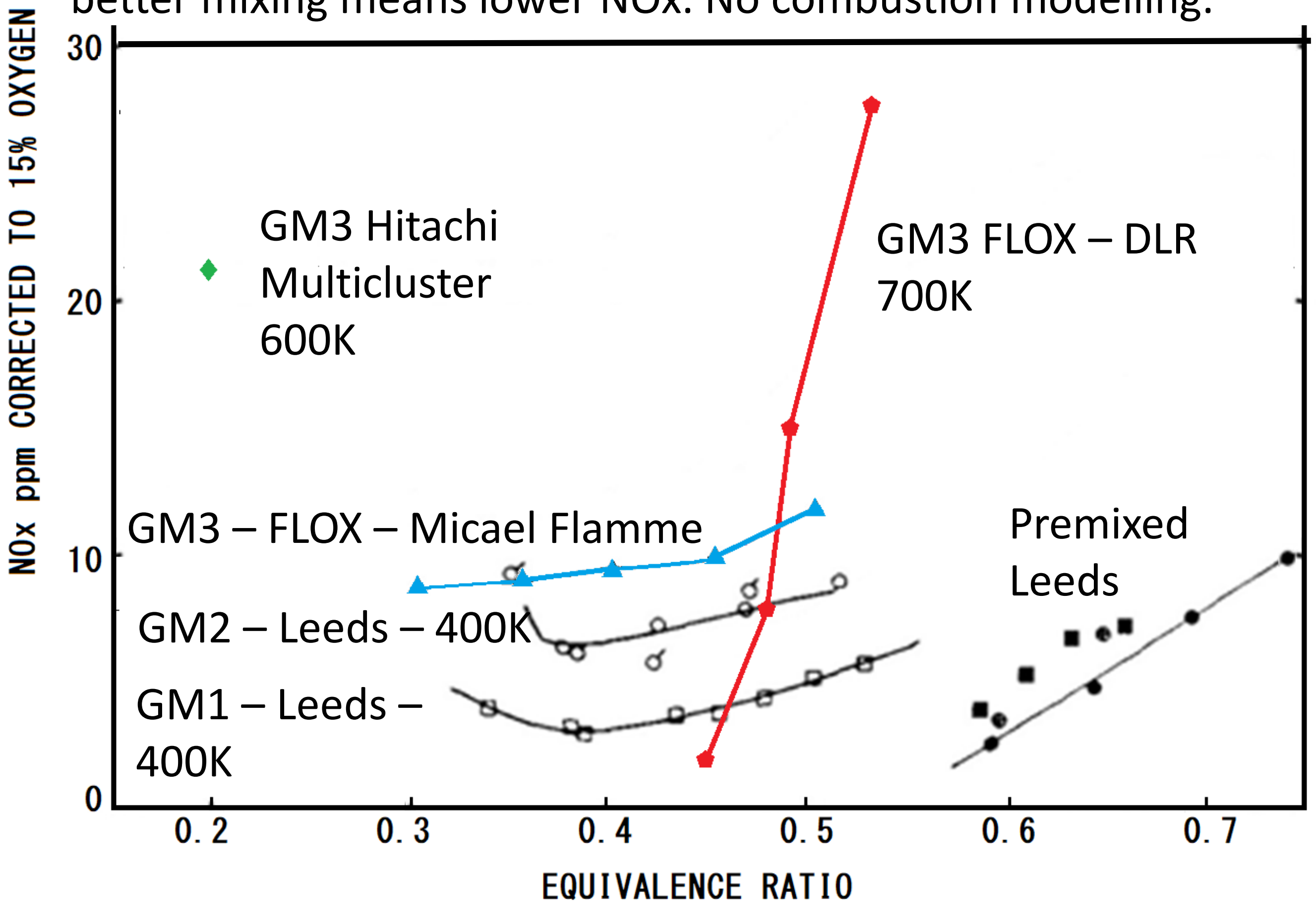
Fuel staged cluster nozzle burner of Hitachi in a 3MW GT.

FLOX technology **GM3**



ASME-011505

Comparison of experimental measurements in the literature for the impact of the method of fuelling a grid plate flame stabiliser. Comparison with fully premixed combustion.
This CFD investigation models the mixing of fuel and air, as better mixing means lower NOx. No combustion modelling.



NOx corrected to 15% oxygen as a function of equivalence ratio at 400K *(Al-Dabbagh, N.A., G.E. Andrews, and R. Manorharan, 1984 6th ISABE Paris*

FLOX BURNER data points
"New combustion systems for gas turbines (NGT)"
Michael Flamme (2004)

DLR data points (ASME GT2007-27337)

HITACHI Multicluster burner data points
(ASME GT2007-27737)

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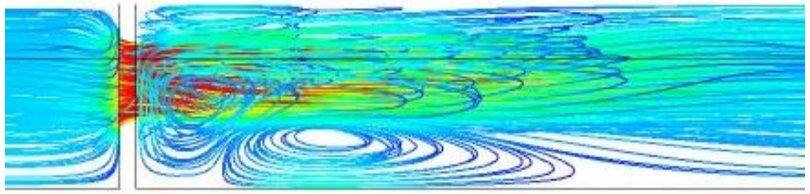

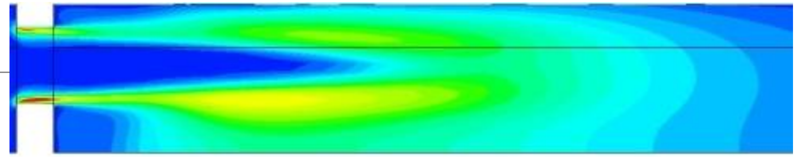

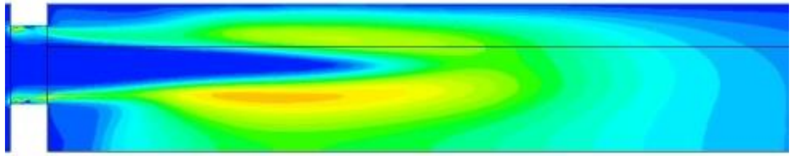

Computational Fluid Dynamics

ANSYS CFX version 17.2

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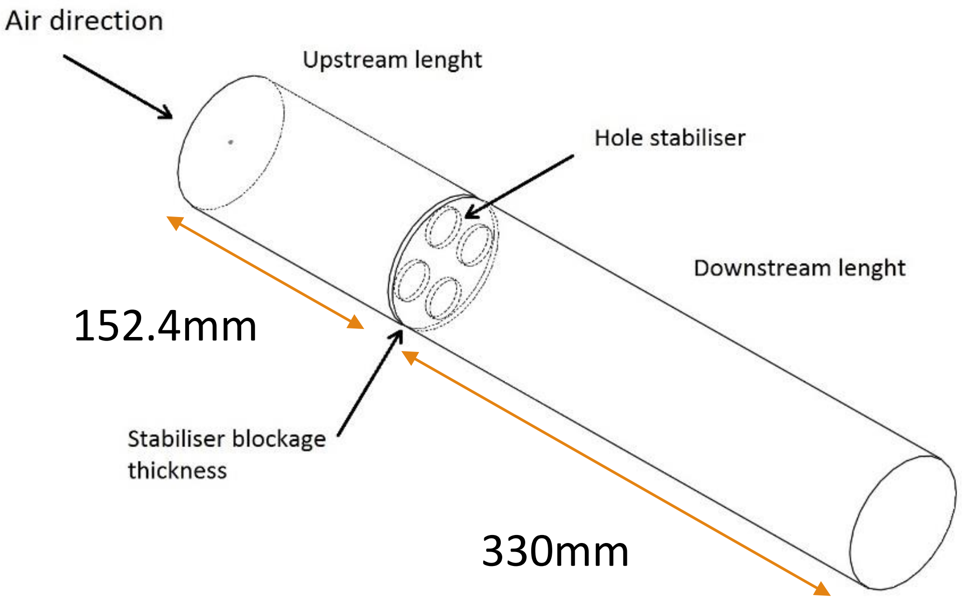
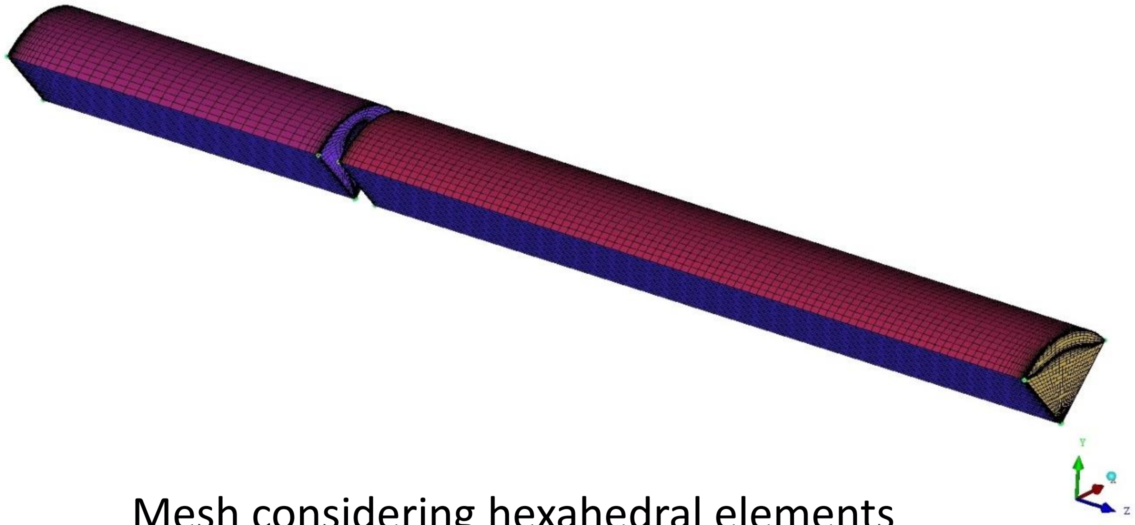
Software and computational methods





Mesh considering hexahedral elements and a fine boundary layer at the wall

Aerodynamics

Boundary Conditions	Value
Mach number	0.047
Combustion Intensity	20 MW/m^2 per bar
Air inlet temperature	400°K
Air inlet mass flow rate	0.0786 kg/s
Air inlet velocity	18.84 m/s
Fuel Inlet temperature (mixing)	288K
Fuel inlet mass flow rate (mixing)	0.0006298 kg/s
Reference Pressure	1 ATM
Outlet pressure (19.27 & 19.62mm geometries)	122.58 Pa
Outlet pressure (22.44mm geometry)	61.29 Pa
Convergence Criteria	RMS: 1×10^{-6}

Mixing

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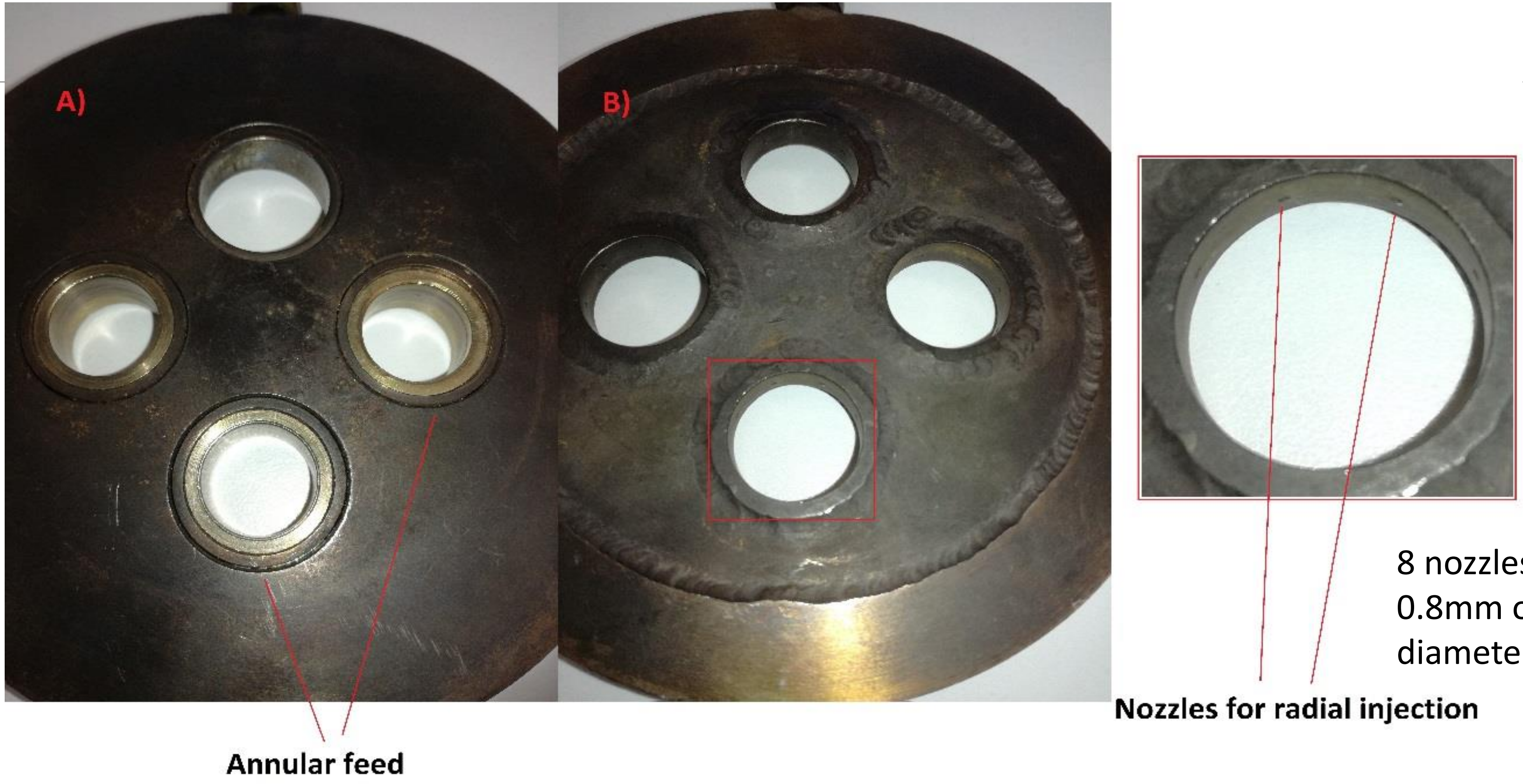
0.3mm for annular gap



8 nozzles of 0.8mm of diameter

Equations

$$\dot{m} = C_D A_2 (2\rho\Delta P)^{0.5} \longrightarrow C_D = \frac{1}{K^{0.5}} * \frac{1}{\beta} \qquad (1)$$

$$1/C_C = 1/C_D + \beta \qquad (2)$$

$$K = \frac{\Delta \mathrm{P}}{0.5\, \rho_{air} {U_{air}}^2} \qquad (3)$$

Ward Smith formulae

$$K = \left[\frac{1}{0.608\beta(1-\beta^{2.6})\left(1+\left(\frac{t}{d}\right)^{3.5}\right)+\beta^{3.6}} - 1\right]^2 \qquad (4)$$

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Results for aerodynamics

			Modelling		Experiment		Ward Smith formulae	
Turbulent model	Mesh Quality	Number of nodes	CD	CC	CD	CC	CD	CC
KE								
	Finer	5,974,098	0.741	0.632	0.747	0.628	0.738	0.621
	Fine	2,189,768	0.768	0.653	0.747	0.628	0.738	0.621
	Medium	834,828	0.78	0.663	0.747	0.628	0.738	0.621
	Coarse	254,410	0.78	0.665	0.747	0.628	0.738	0.621
SST								
	Finer	5,974,098	0.731	0.621	0.747	0.628	0.738	0.621
	Fine	2,189,768	0.748	0.634	0.747	0.628	0.738	0.621
	Medium	834,828	0.765	0.65	0.747	0.628	0.738	0.621
	Coarse	254,410	0.761	0.646	0.747	0.628	0.738	0.621

Mesh independence study for the one hole 19.27mm hole stabiliser diameter geometry

			Modelling		Experiment		Ward Smith formulae	
Turbulent model	Mesh Quality	Number of nodes	CD	CC	CD	CC	CD	CC
KE								
	Medium	2,700,000	0.735	0.616	0.747	0.628	0.738	0.621
	Coarse	1,300,000	0.748	0.629	0.747	0.628	0.738	0.621

Mesh statistics for a four-hole 19.27mm hole diameter stabilizer geometry

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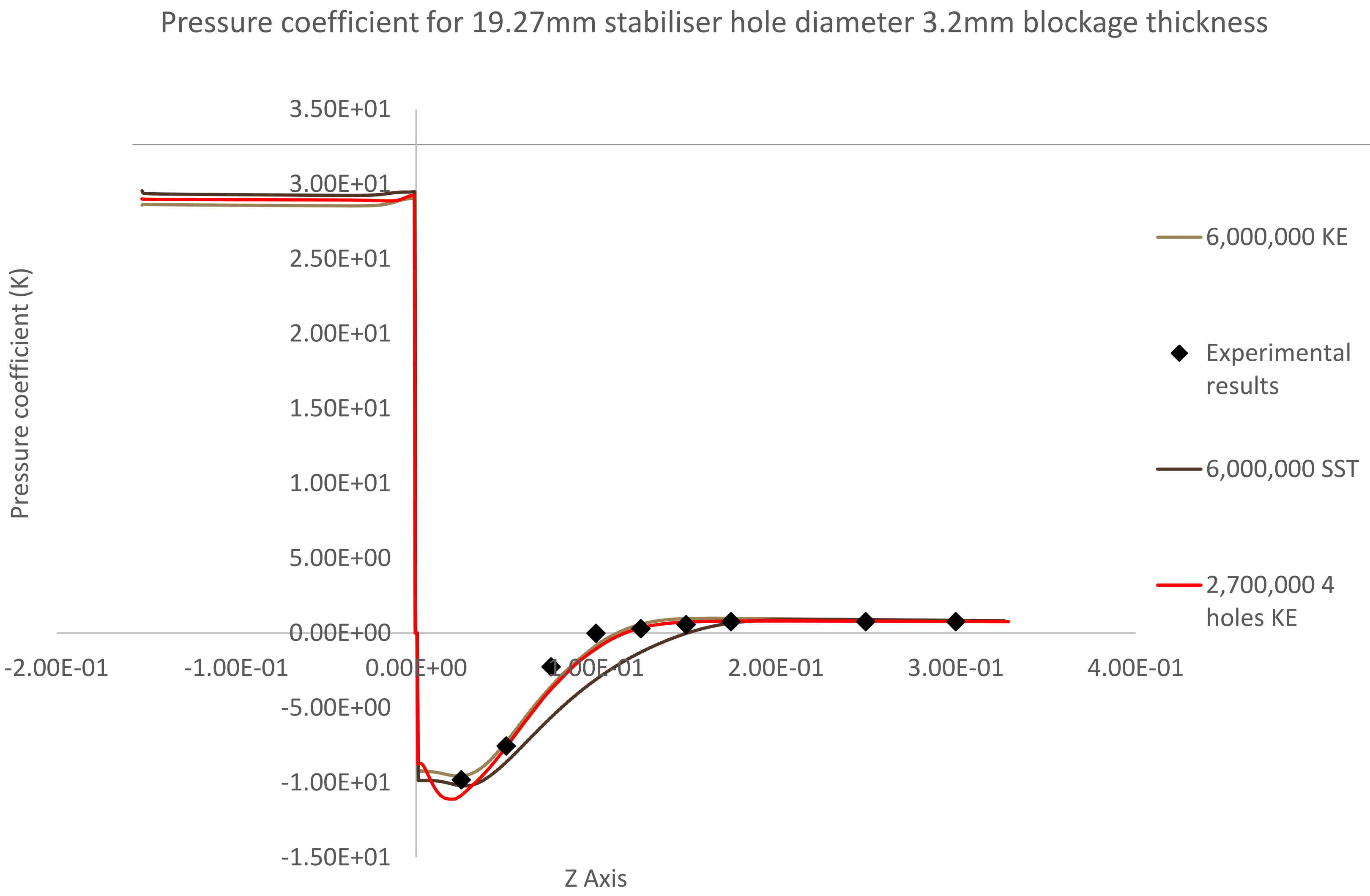

Pressure coefficient for the 19.27mm hole stabiliser geometry, considering best mesh qualities for one and four holes, and the different turbulence models

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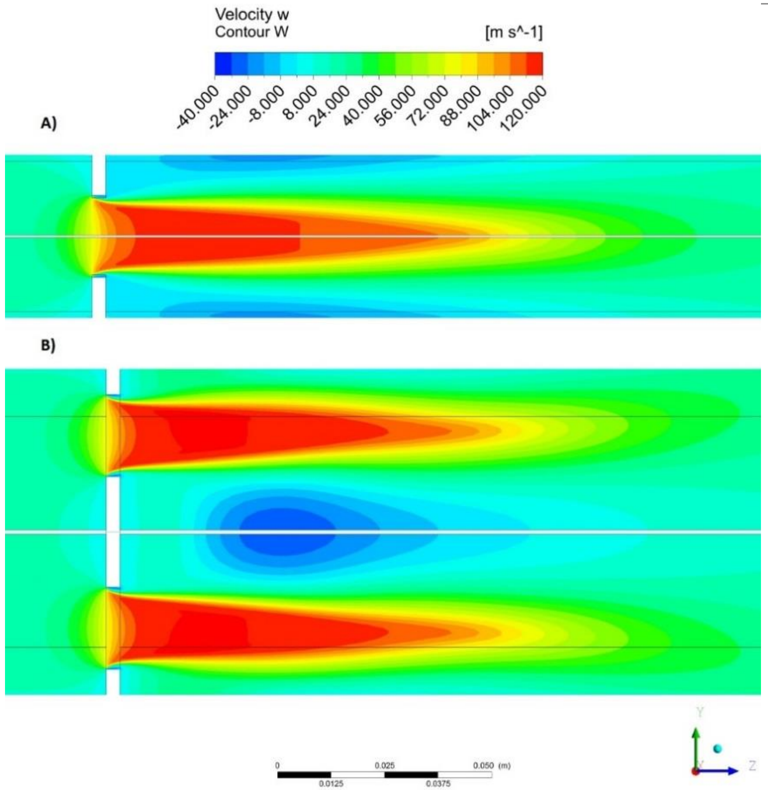
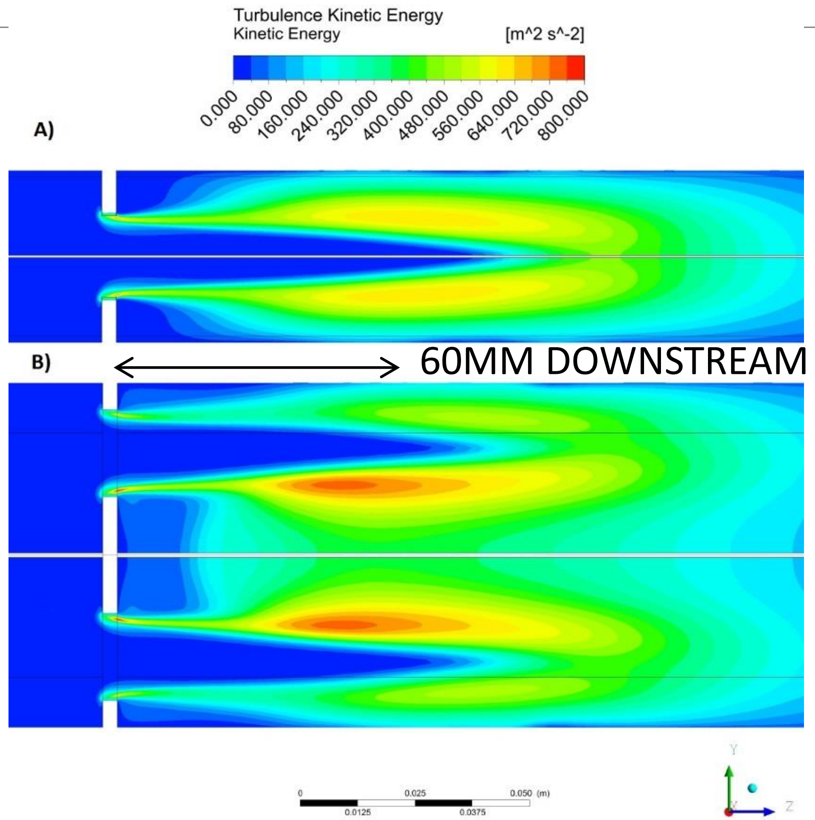
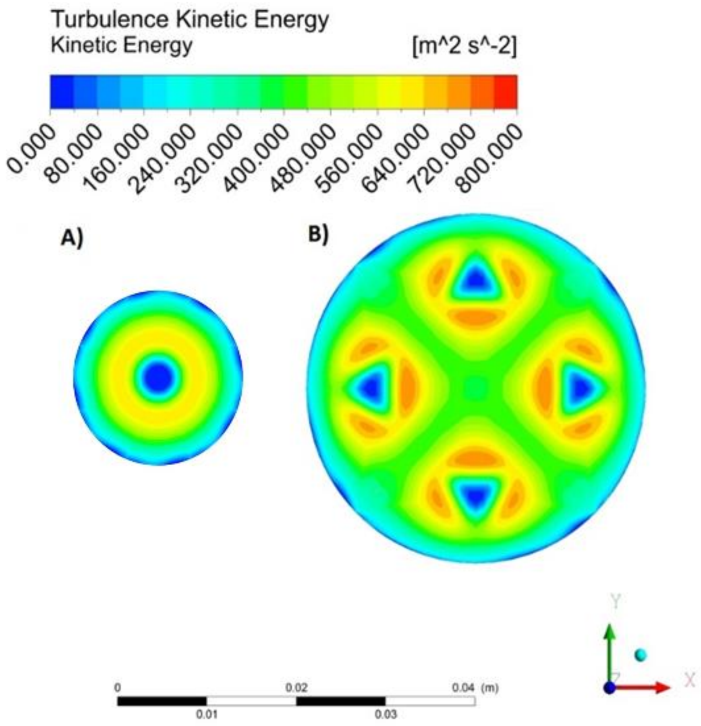
Velocity contours for A) one hole. B) 4 holes 19.27mm stabiliser's hole diameter geometry



Turbulence kinetic energy contours for A) one hole. B) 4 holes 19.27mm stabiliser's hole diameter geometry



Plane at 60mm downstream of the combustor for Turbulence kinetic energy contours for A) one hole. B) 4 holes 19.27mm stabiliser's hole diameter geometry



The total mass flow at 25mm downstream the contraction is 0.026 kg/s and **the recirculating mass is 0.00622kg/s. (24%)** This is the biggest recirculation zone.

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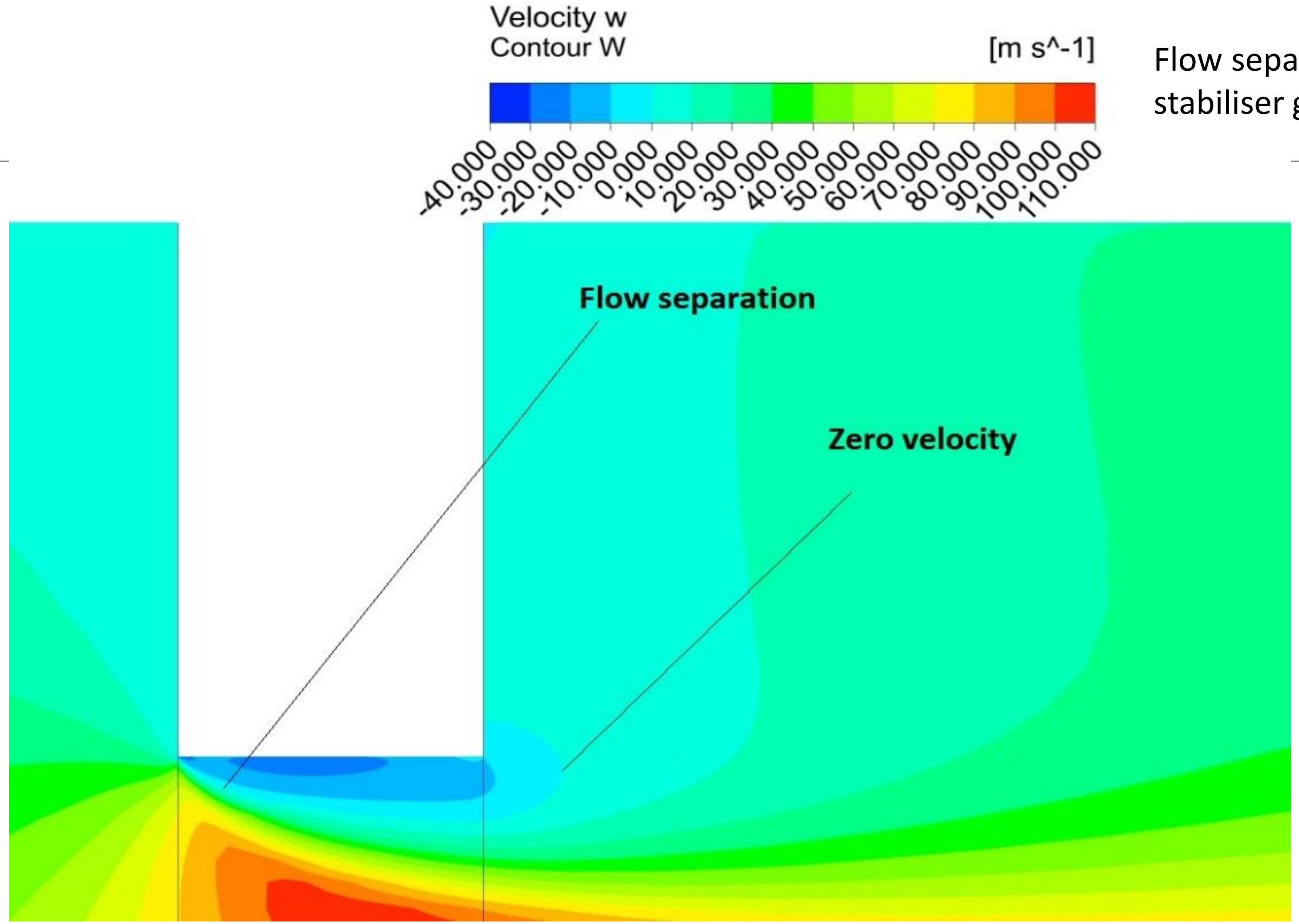
Flow separation and zero velocity for stabiliser geometry

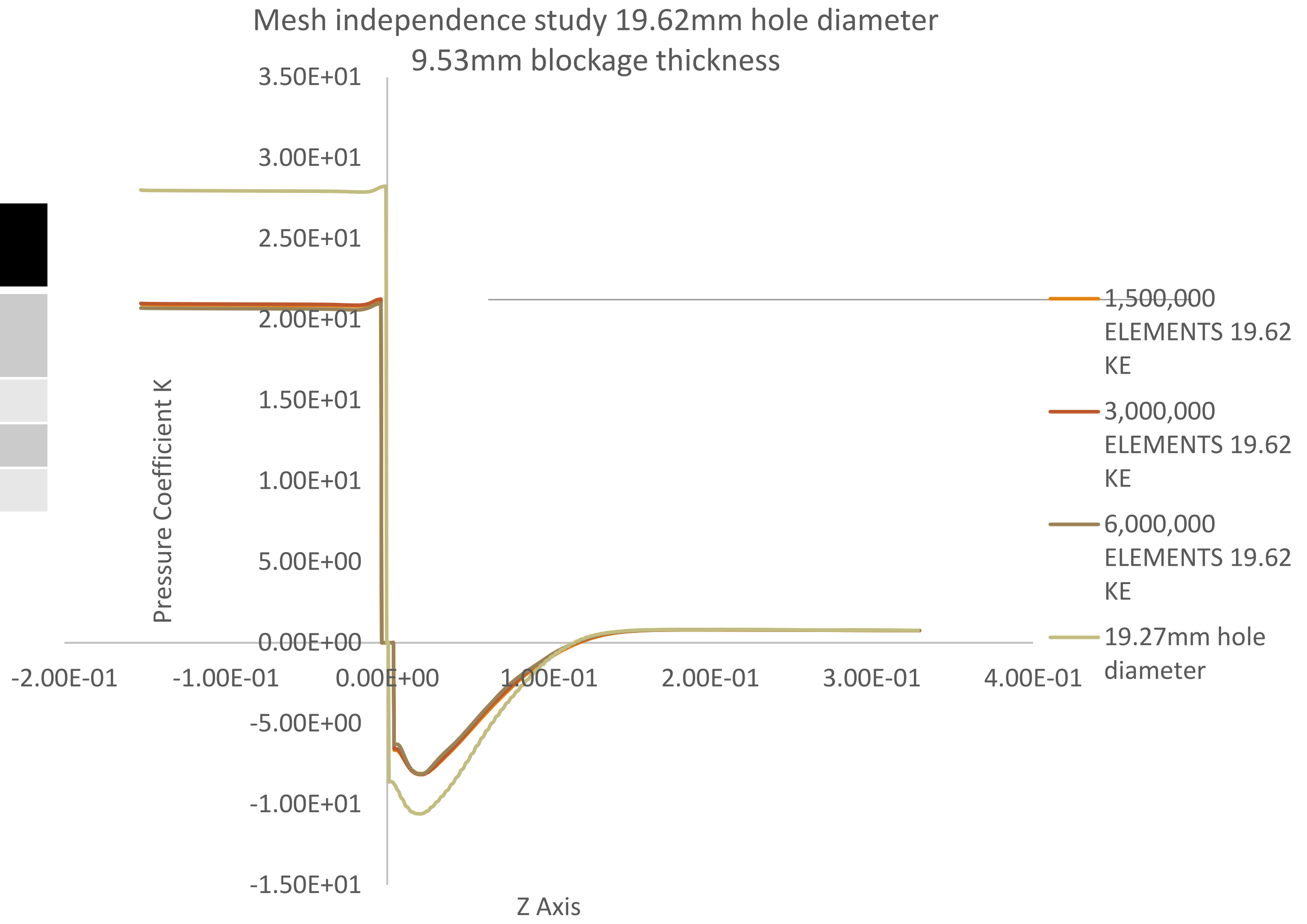


Mesh statistics for a four-hole 19.62mm stabiliser's hole diameter 9.53mm stabilizer thickness

		Model		Experiment		Ward Smith formulae	
Mesh Quality	Number of nodes	CD	CC	CD	CC	CD	CC
Fine	6,000,000	0.845	0.703	0.969	0.804	0.811	0.672
Medium	2,700,000	0.839	0.699	0.969	0.804	0.811	0.672
Coarse	1,300,000	0.841	0.7	0.969	0.804	0.811	0.672

The pressure coefficient calculated from Equation (4) is K=21.678 considering $\beta = 0.265$.

The thicker plate geometry has a lower pressure loss due to the shape of the geometry and the size of the hole



Mesh independence study for the Pressure Loss coefficient along the Z axis for the 19.62mm stabiliser's hole diameter and comparison with 19.27mm hole stabiliser diameter.

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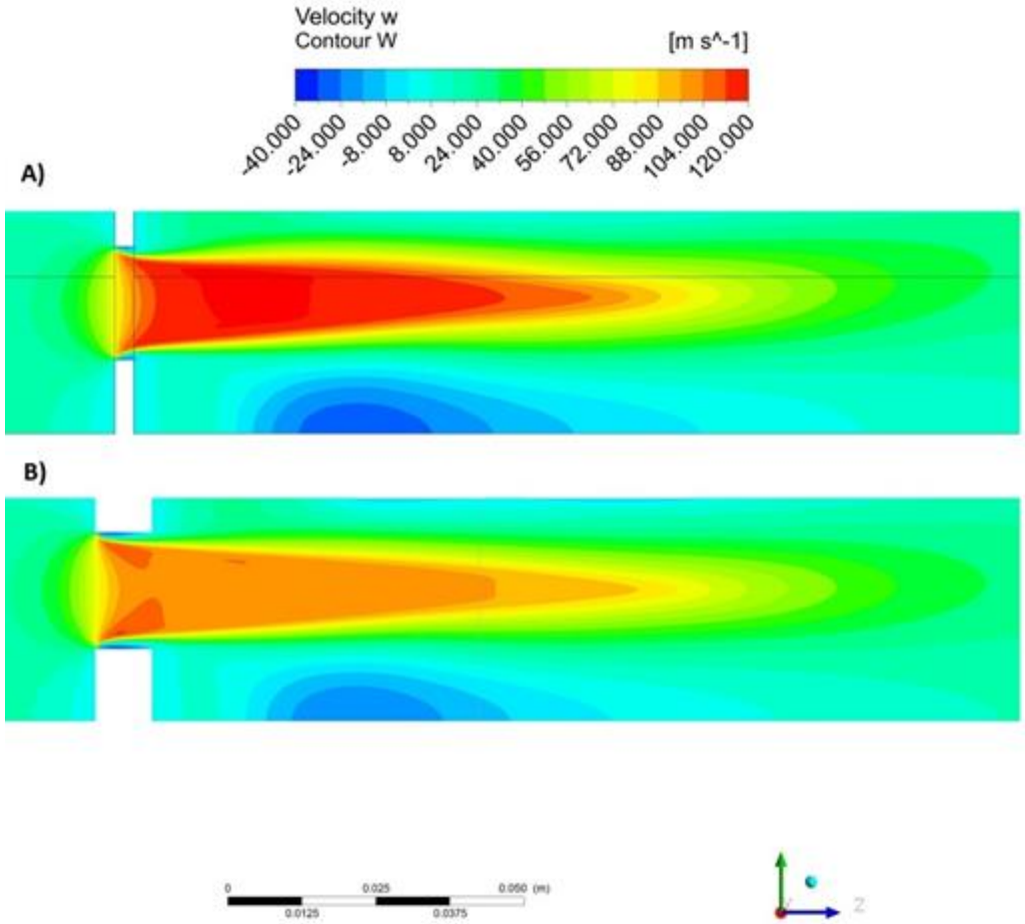
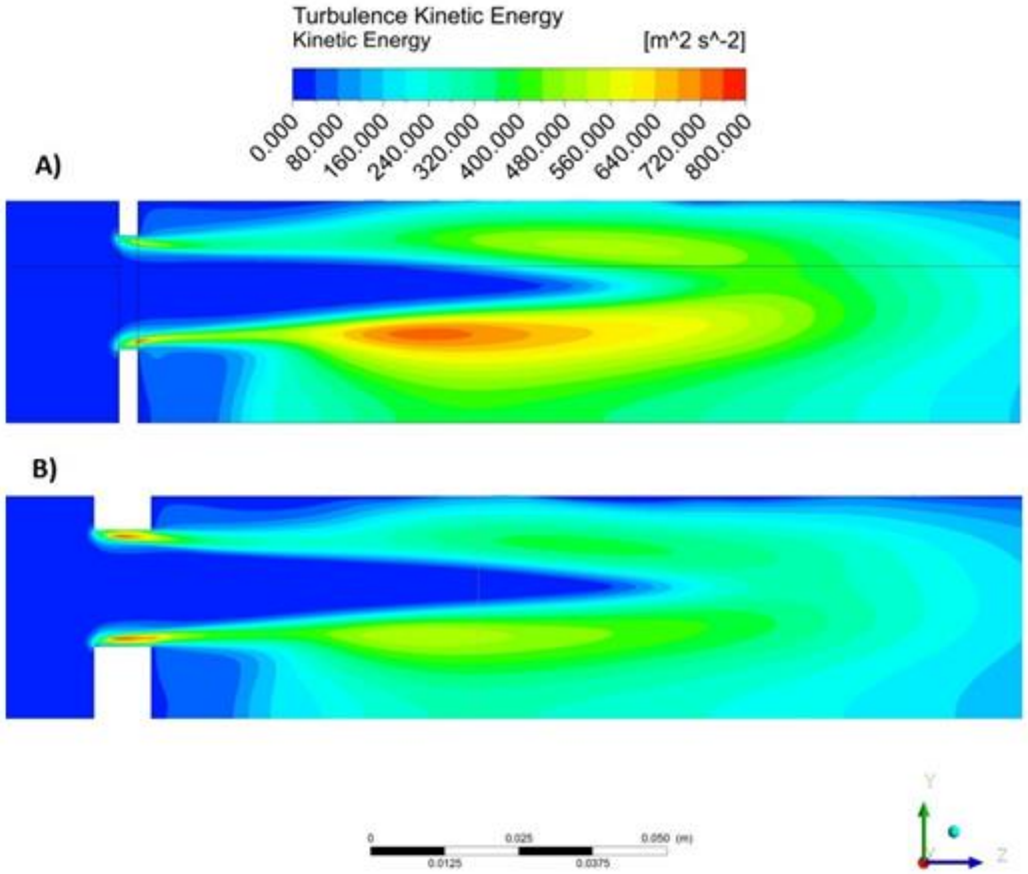
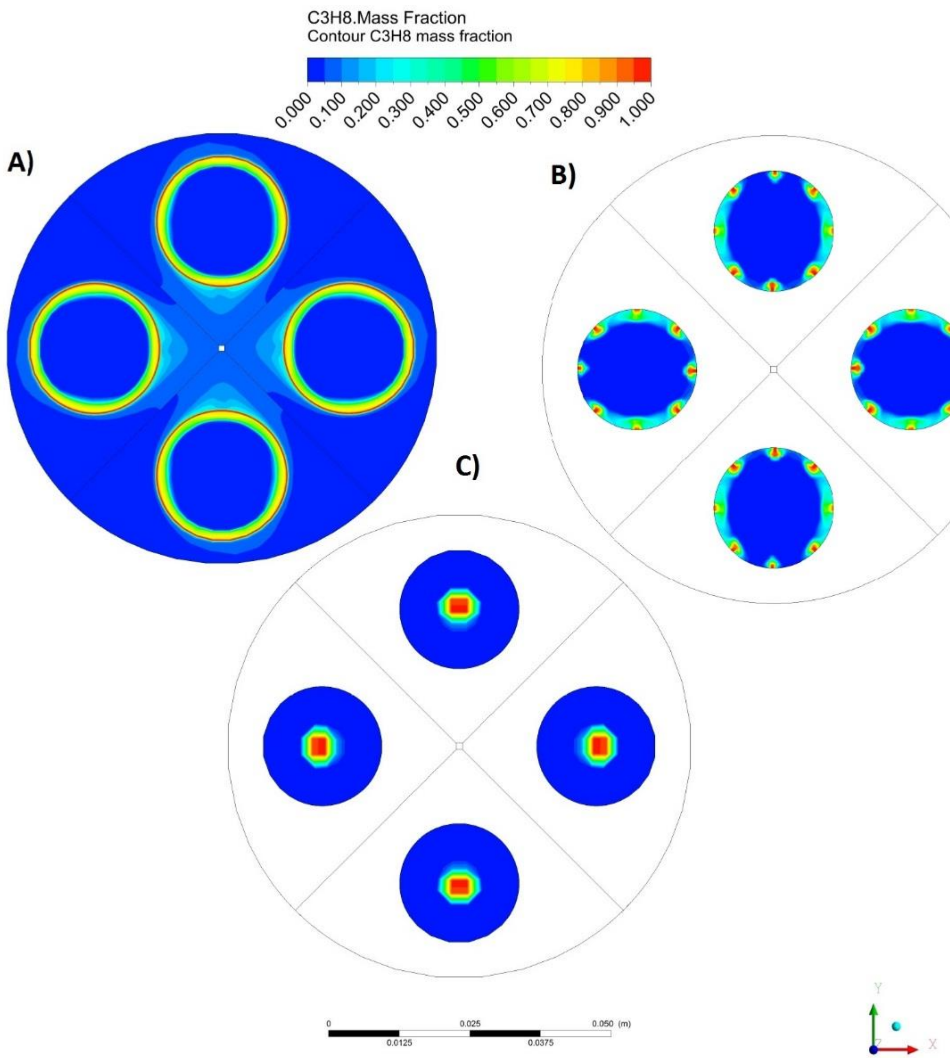
Comparison of the 19.27 mm stabiliser's hole diameter with 3.2mm blockage thickness and the 19.62mm with 9.53mm blockage thickness

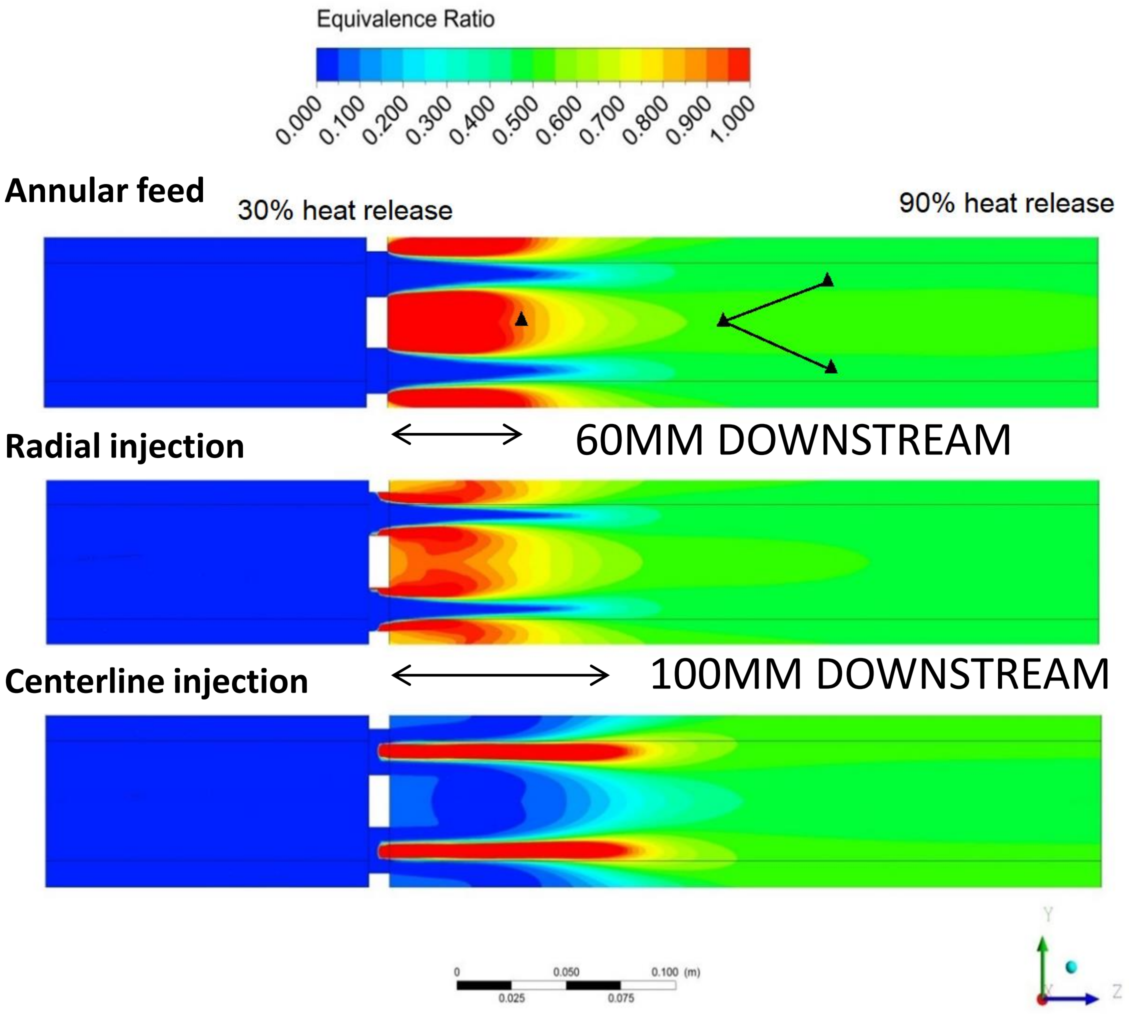


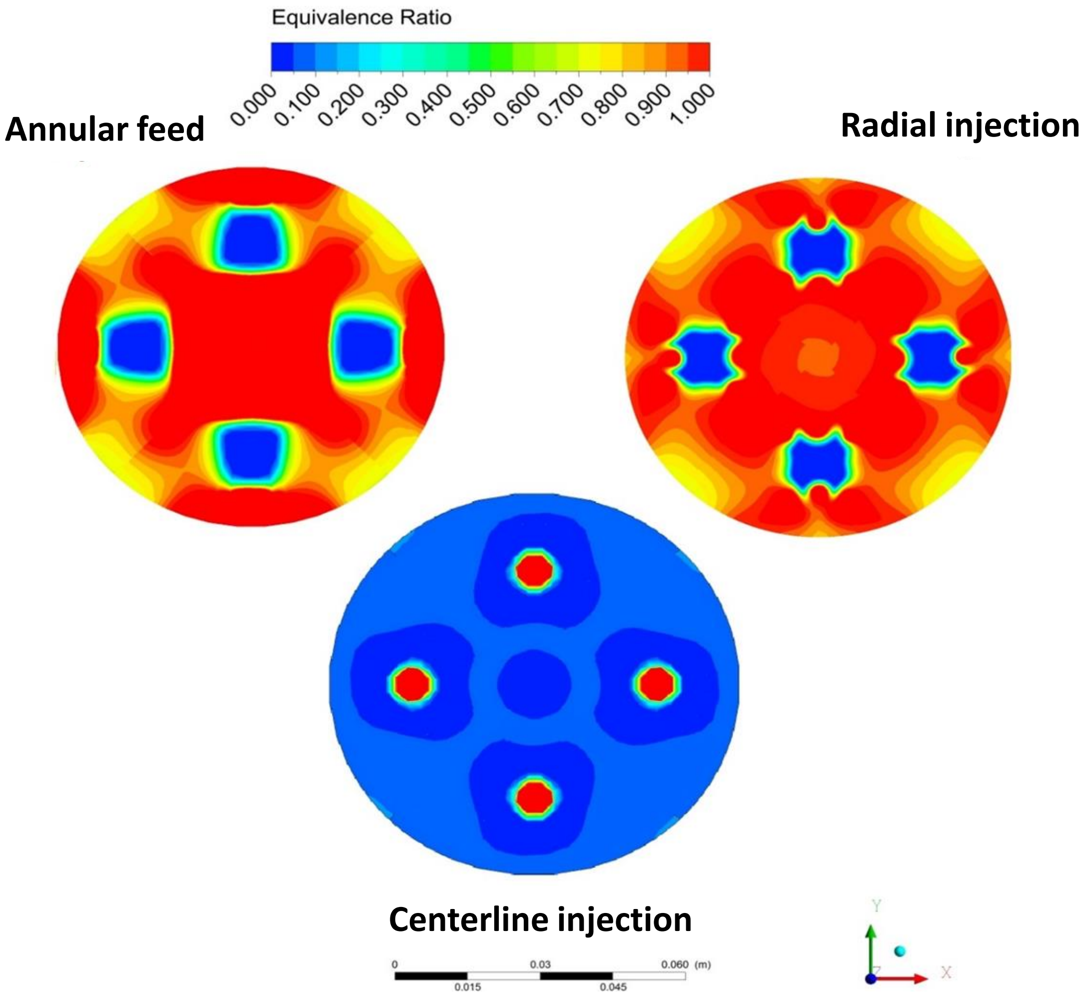




Results for mixing

Results in mass fraction for radial injection. A) Annular feed. B) Radial injection. C) Centreline injection.





For the radial injection the **propane mixes faster** than in the other two cases, and this will produce lower NOx (considering half stoichiometric)

Equivalence Ratio contours 60mm downstream

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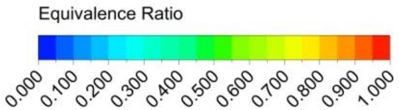
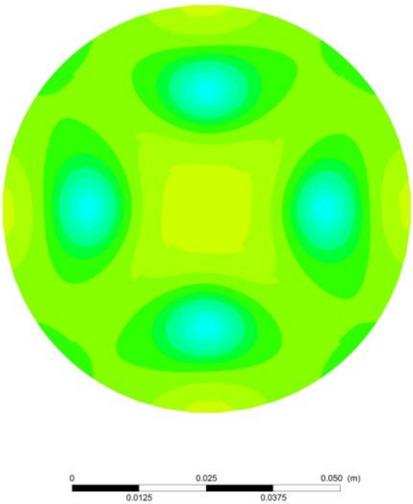
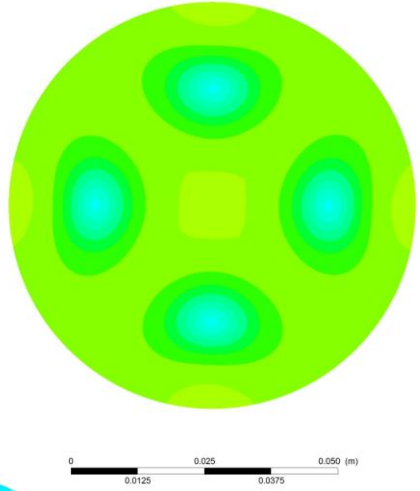
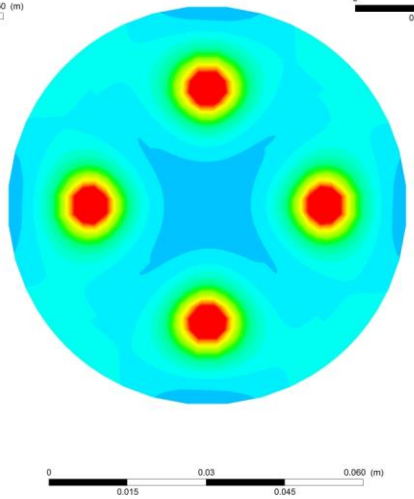


Annular feed



Radial injection





Centerline injection

Equivalence Ratio contours 100mm downstream

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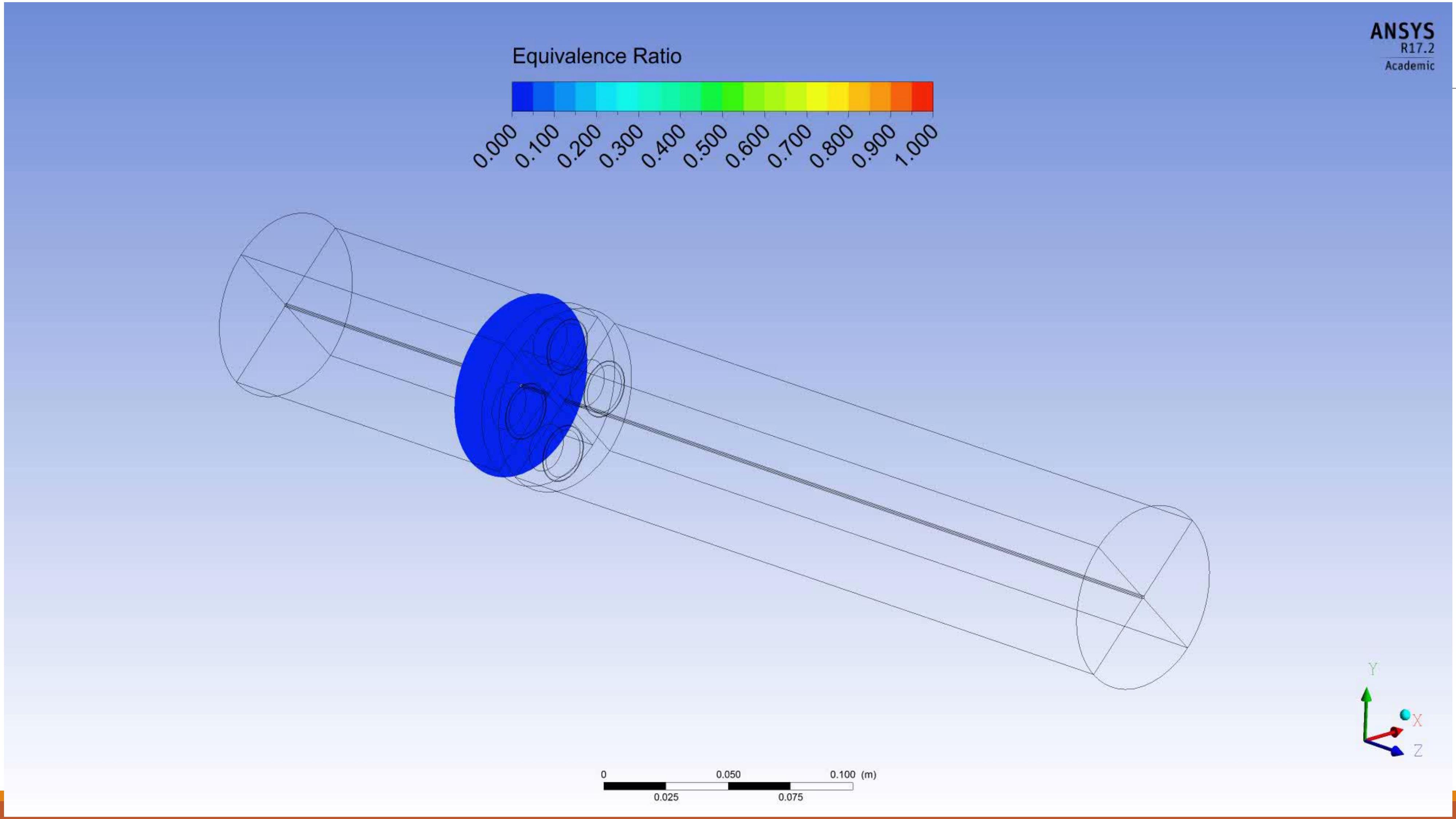
Equivalence ratio for the three types of fuel injection

Annular feed



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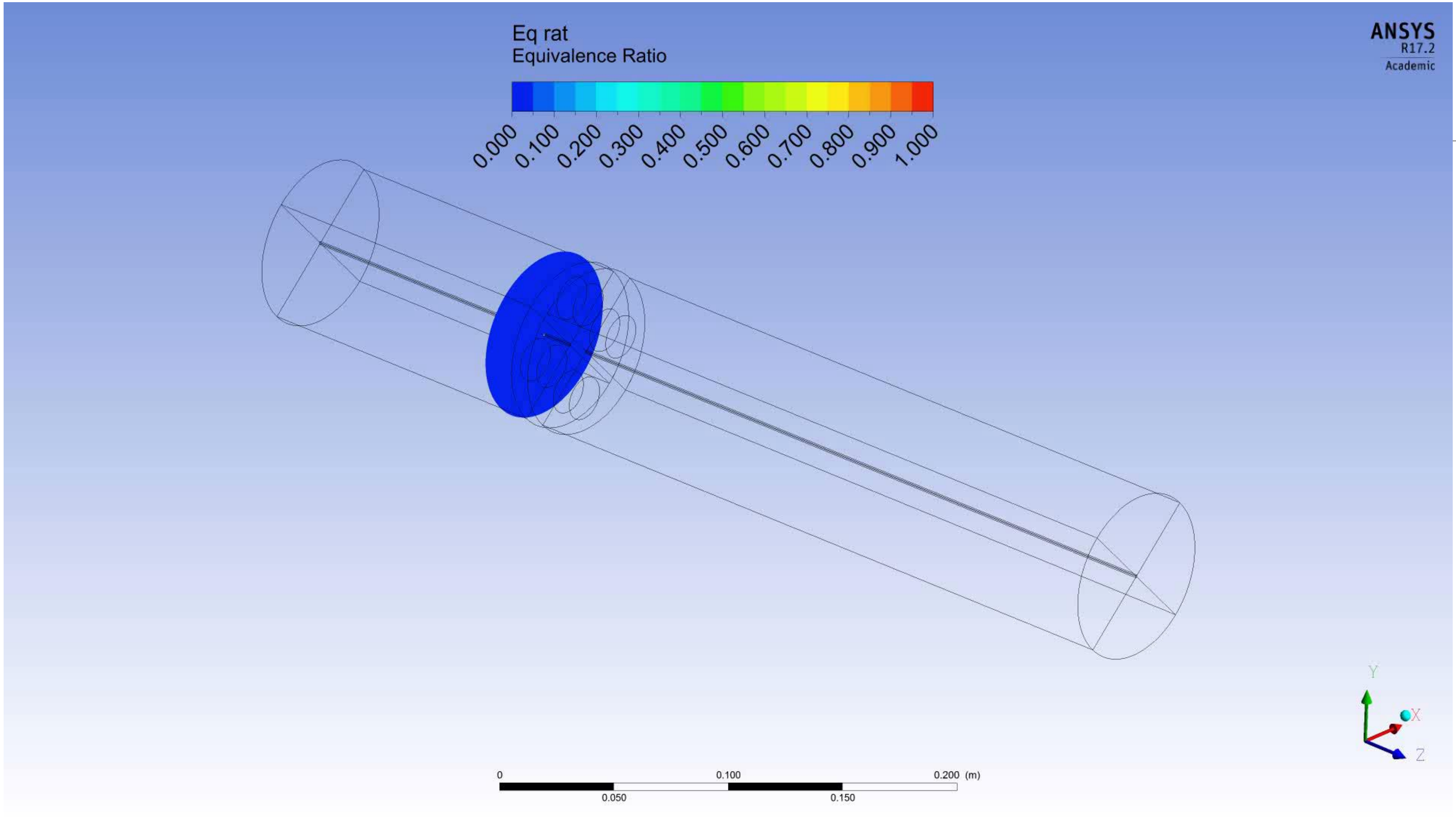

Radial injections

Centerline

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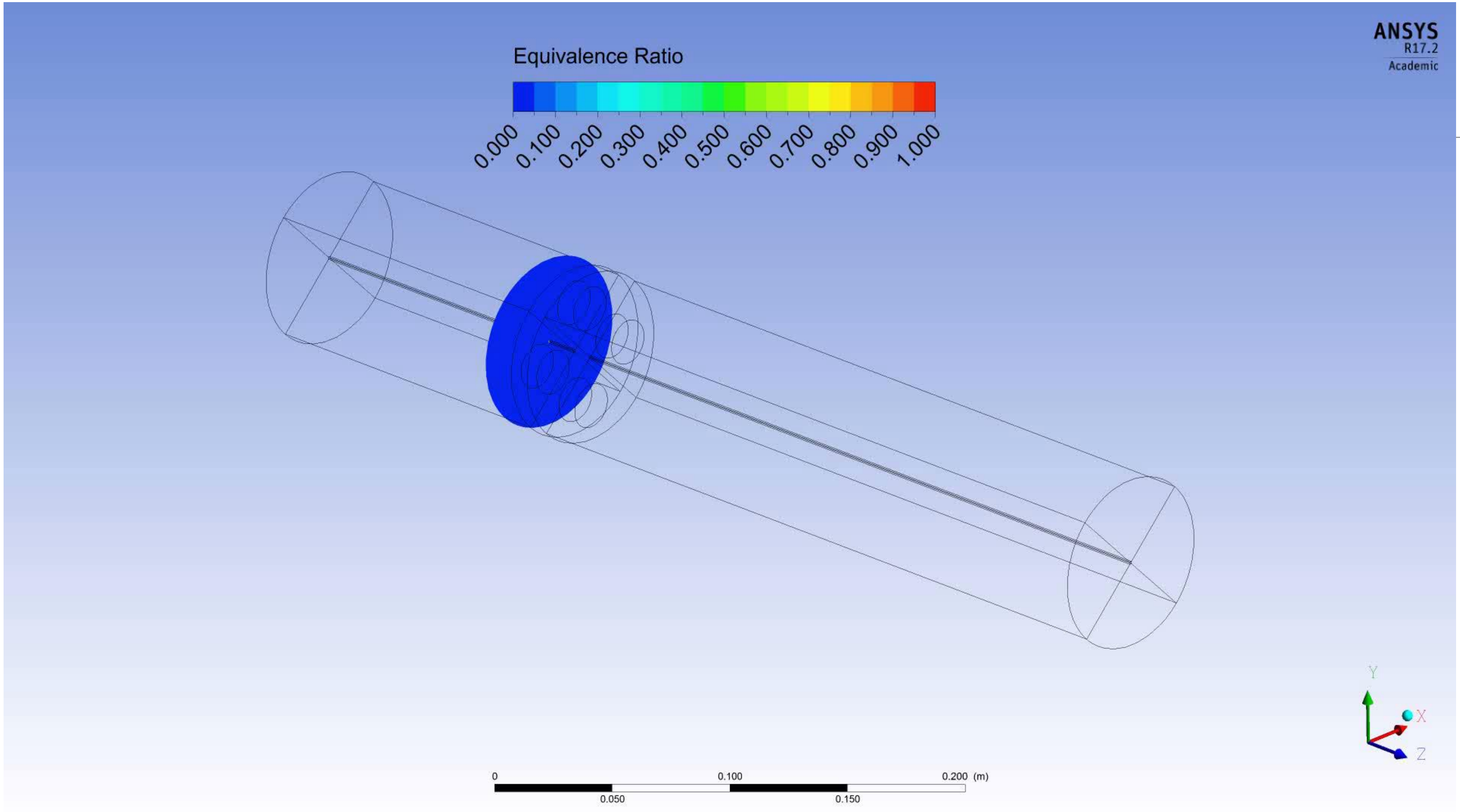
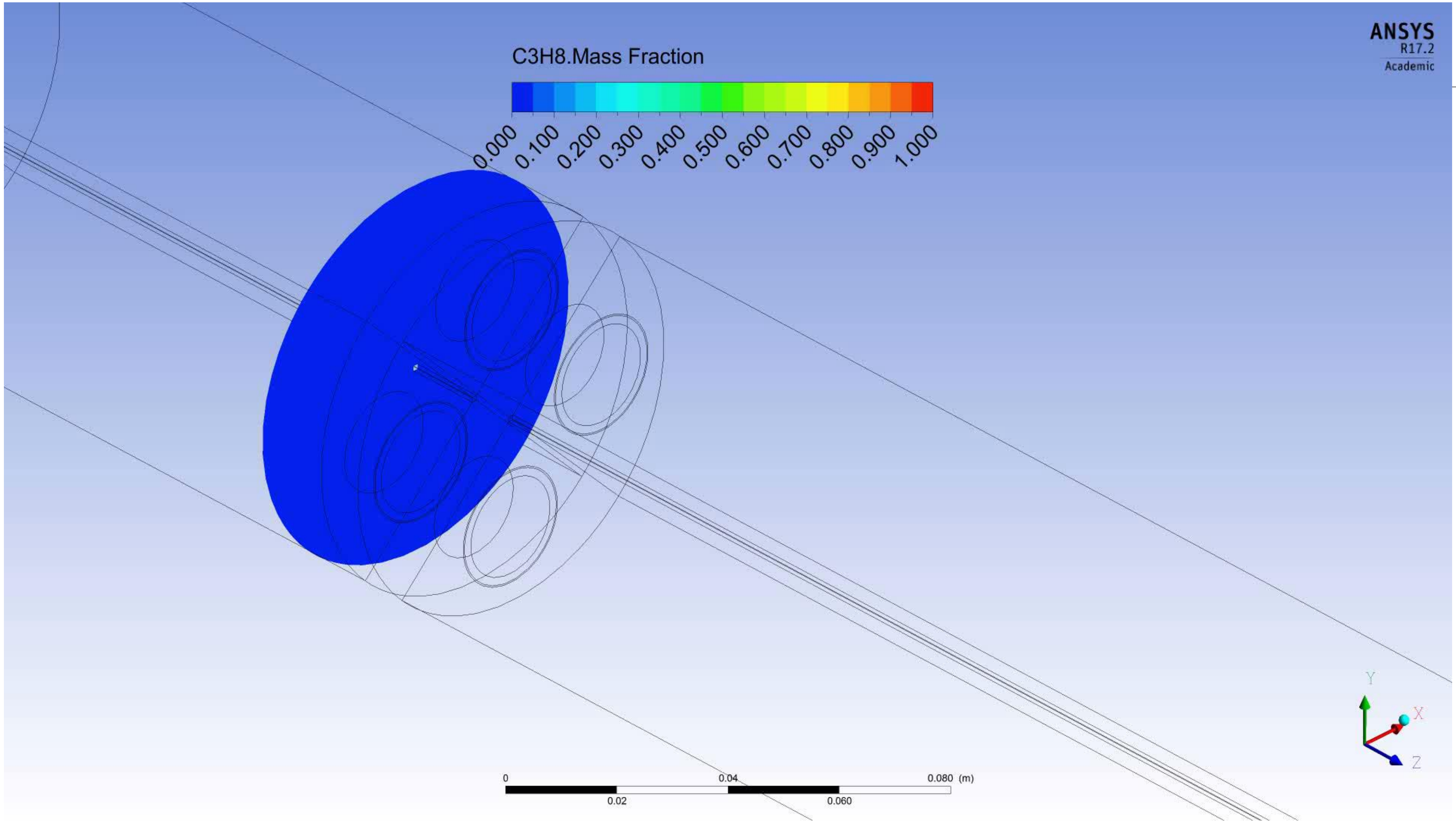


Mass fraction for the three types of fuel injection



Annular feed

Radial injections

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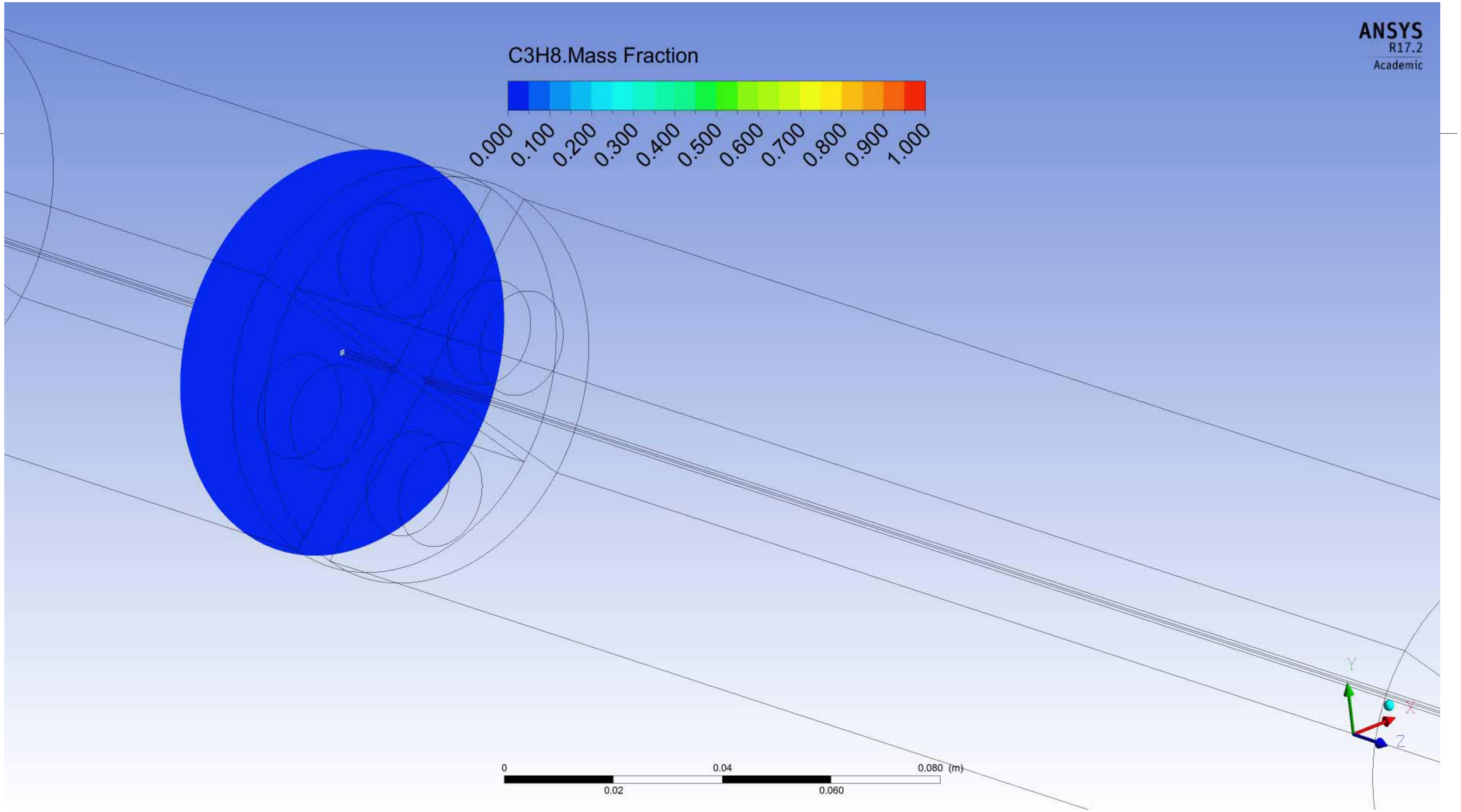

Centerline

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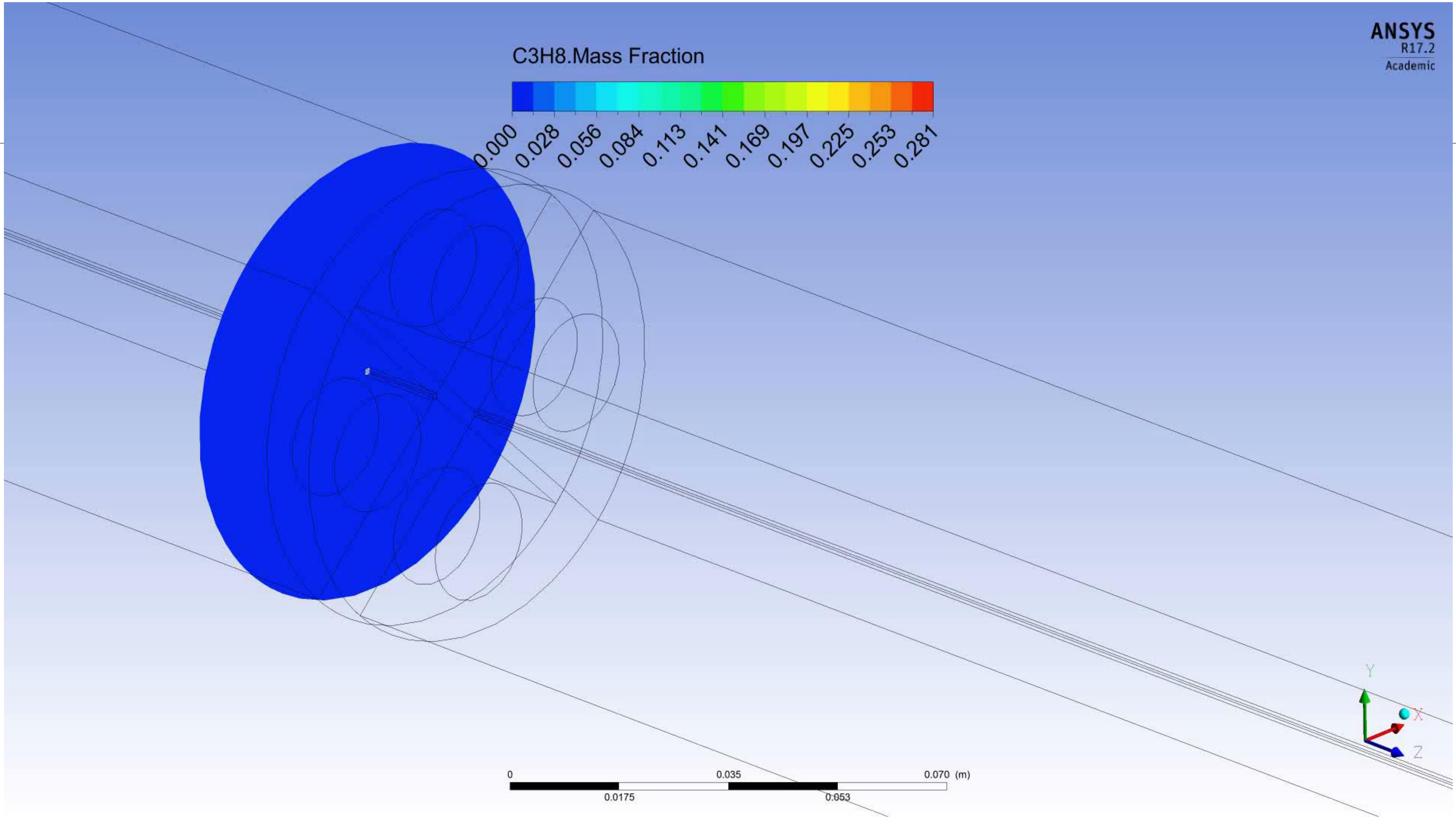

Conclusions

- The results for the aerodynamics for two combustor flame stabilizer were evaluated, they were taken from the thesis "Emissions and stability of gas turbine combustors with rapid fuel and air mixing" from N. A. Al-Dabbagh (1982) considering one and four holes, as well as a thin and a thick blockage.
- There were evaluated three methods of fuel injections prior combustion
- The obtained predictions for the aerodynamics using simulation showed very good agreement with the experimental results from the thesis
- The radial injection showed to produce a quicker mixing than in the annular feed and the centreline injection so that the NOx emissions will be lower.
- It was shown that it is possible to predict NOx levels by simply looking at fuel and air mixing.

For your attention, Many thanks!