INVESTIGATION OF FLUID FLOW IN A NOZZLE WITH SUDDEN EXPANSION

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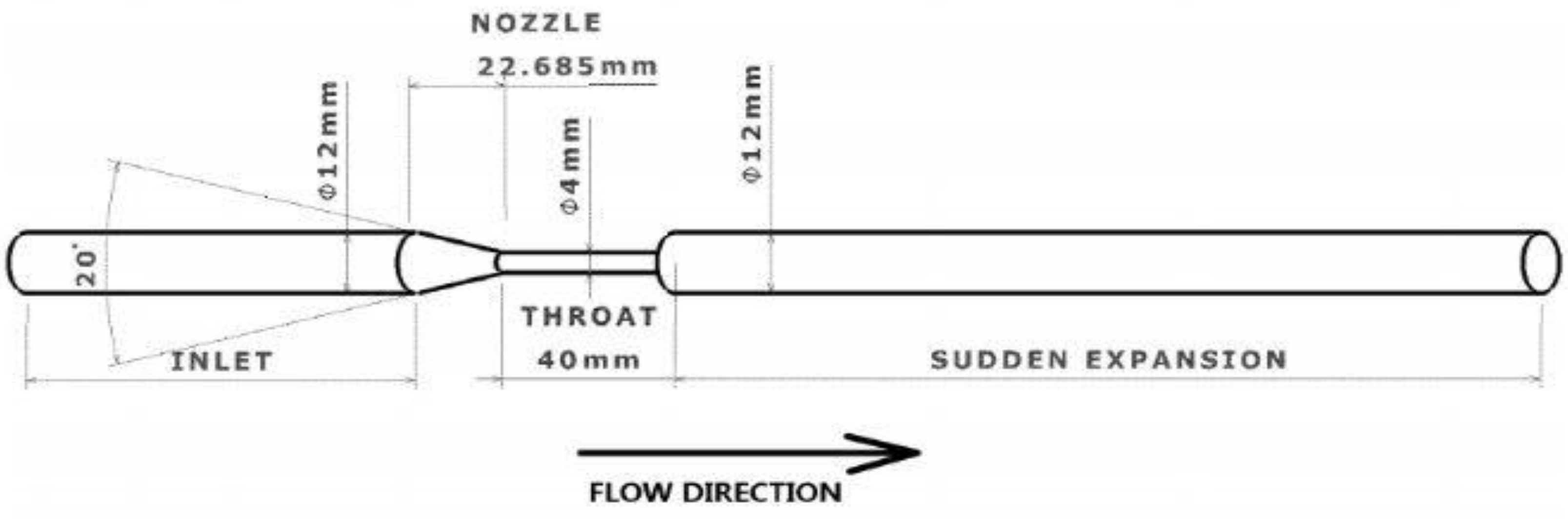
PROJECT INTRODUCTION

- Food & Drug Administration has proposed a standard nozzle geometry to serve as benchmark for CFD Simulations
- The CFD codes simulate blood flow through the nozzle.
- Discrepancies with experimental results at Separation zone. (Reference: *FDA Benchmark Medical Device Flow Models for CFD Validation. Malinauskas RA1, Hariharan P, Day SW, Herbertson LH, Buesen M, Steinseifer U, Aycock KI, Good BC, Deutsch S, Manning KB, Craven BA.)*

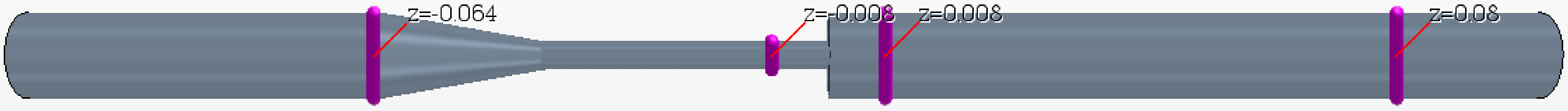


PROJECT OBJECTIVES

- Create the geometry and prepare suitable mesh
- Simulate the model for Reynolds number of 5000 based on nozzle diameter.
- Compare results for various turbulence models.
- Validate CFD approaches against several series of FDA's multi-laboratory experiments.
- Suggestions to improve model.

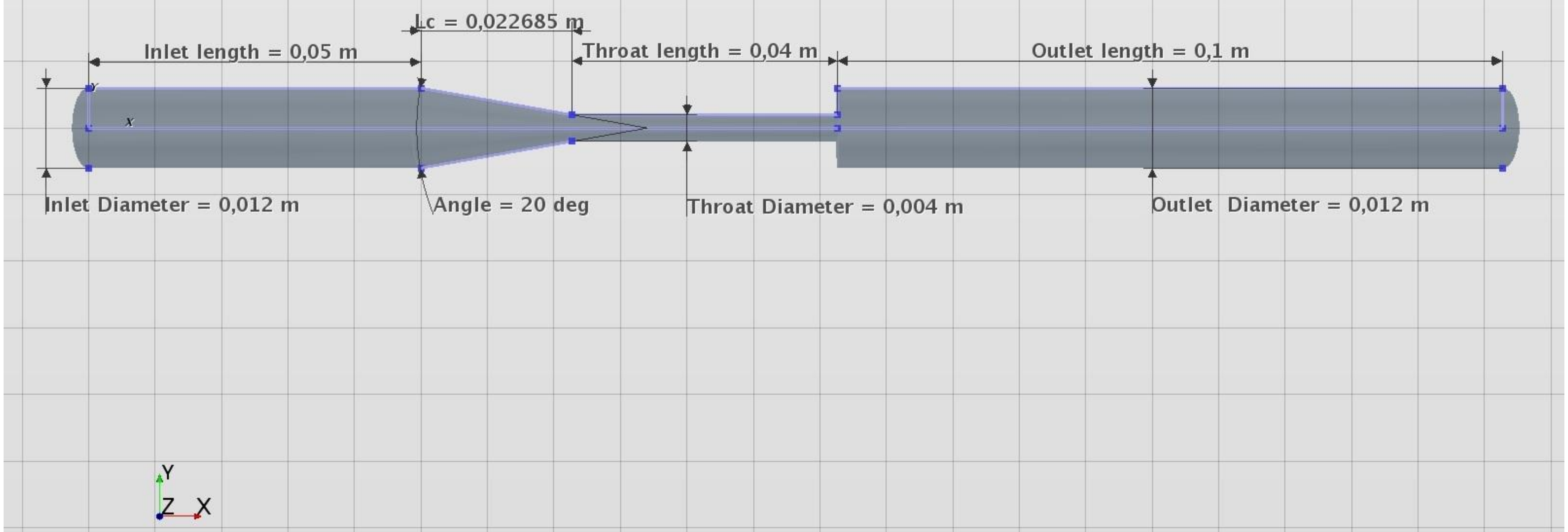
SIMULATION VALIDATION

- Axial velocity at four positions along the length
- Velocity profile along the length of the model
- 3 experimental results compared.
- For RANS model, FDA inter-laboratory gathered 28 CFD groups and 2 were able to match experimental centreline velocity for turbulent flows. (Reference: *Stewart SF, Paterson EG, Burgreen GW, Hariharan P, Giarra M, Reddy V, Day SW, Manning KB, Deutsch S,Myers MR, et al.. Assessment of CFD Performance in Simulations of an Idealized Medical Device: Results ofFDA's First Computational Interlaboratory Study. Cardiovasc. Eng. Technol. 2012; 3(2):139–160, doi:10.1007/s13239-012-0087-5.)*



Axial positions considered for comparision with experimental data

NOZZLE DIMENSIONS (CAD MODEL)



NOZZLE MESH

Meshers used:

- Surface Remesher
- Automatic Surface Repair
- Polyhedral Mesher
- Prism Layer Mesher

1mm cells

```
-----------------------------------------------------
--- Computing statistics in Region: Region_radial_profile 2
-----------------------------------------------------
-> ENTITY COUNT:
   # Cells: 94975
   # Faces: 449940
   # Verts: 306278
-> EXTENTS:
   x: [0.0000e+00 , 2.1269e-01 ] m
   y: [-5.9821e-03, 5.9821e-03 ] m
   z: [-5.9789e-03, 5.9789e-03 ] m
-> MESH VALIDITY:
   Mesh is topologically valid and has no negative volume cells.
-> FACE VALIDITY STATISTICS:
Minimum Face Validity: 1.000000e+00
Maximum Face Validity: 1.000000e+00
        Face Validity <  0.50          0    0.000%
0.50 <= Face Validity <  0.60          0    0.000%
0.60 <= Face Validity <  0.70          0    0.000%
0.70 <= Face Validity <  0.80          0    0.000%
0.80 <= Face Validity <  0.90          0    0.000%
0.90 <= Face Validity <  0.95          0    0.000%
0.95 <= Face Validity <  1.00          0    0.000%
1.00 <= Face Validity              94975  100.000%
-> VOLUME CHANGE STATISTICS:
Minimum Volume Change: 1.336430e-02
Maximum Volume Change: 1.000000e+00
         Volume Change <  0.000000e+00            0    0.000%
0.000000e+00 <= Volume Change <  1.000000e-06      0    0.000%
1.000000e-06 <= Volume Change <  1.000000e-05      0    0.000%
1.000000e-05 <= Volume Change <  1.000000e-04      0    0.000%
1.000000e-04 <= Volume Change <  1.000000e-03      0    0.000%
1.000000e-03 <= Volume Change <  1.000000e-02      0    0.000%
1.000000e-02 <= Volume Change <  1.000000e-01   1356    1.428%
1.000000e-01 <= Volume Change <= 1.000000e+00  93619   98.572%
```

0.5 mm cells

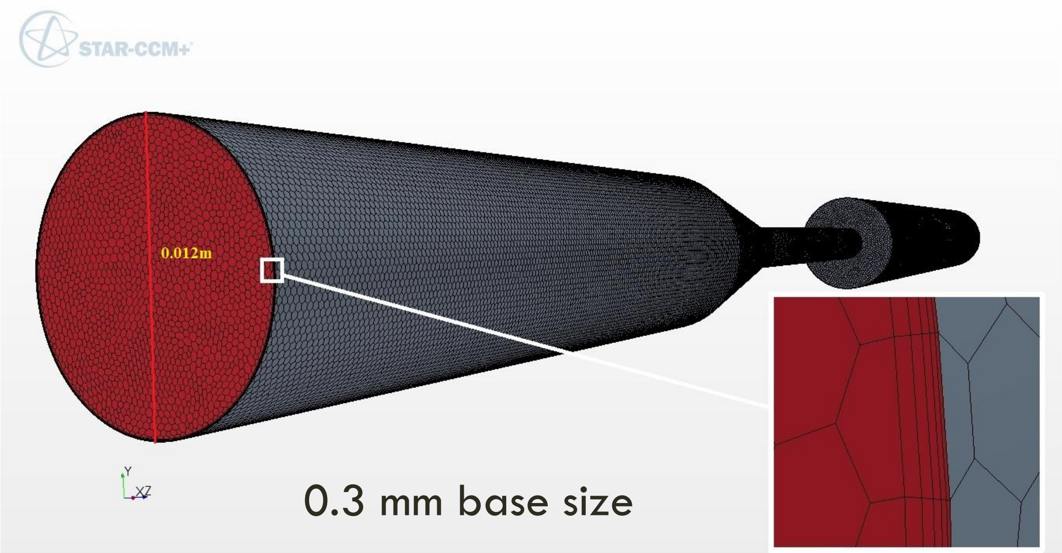
```
-----------------------------------------------------
--- Computing statistics in Region: Region_radial_profile 2
-----------------------------------------------------
-> ENTITY COUNT:
   # Cells: 295760
   # Faces: 1524150
   # Verts: 1105448
-> EXTENTS:
   x: [0.0000e+00 , 2.1269e-01 ] m
   y: [-5.9940e-03, 5.9940e-03 ] m
   z: [-5.9956e-03, 5.9956e-03 ] m
   Setting pro-STAR cell IDs on Region_radial_profile 2 starting at 1
-> MESH VALIDITY:
   Mesh is topologically valid and has no negative volume cells.
-> FACE VALIDITY STATISTICS:
Minimum Face Validity: 1.000000e+00
Maximum Face Validity: 1.000000e+00
        Face Validity <  0.50          0    0.000%
0.50 <= Face Validity <  0.60          0    0.000%
0.60 <= Face Validity <  0.70          0    0.000%
0.70 <= Face Validity <  0.80          0    0.000%
0.80 <= Face Validity <  0.90          0    0.000%
0.90 <= Face Validity <  0.95          0    0.000%
0.95 <= Face Validity <  1.00          0    0.000%
1.00 <= Face Validity             295760  100.000%
-> VOLUME CHANGE STATISTICS:
Minimum Volume Change: 1.006561e-02
Maximum Volume Change: 1.000000e+00
         Volume Change <  0.000000e+00            0    0.000%
0.000000e+00 <= Volume Change <  1.000000e-06      0    0.000%
1.000000e-06 <= Volume Change <  1.000000e-05      0    0.000%
1.000000e-05 <= Volume Change <  1.000000e-04      0    0.000%
1.000000e-04 <= Volume Change <  1.000000e-03      0    0.000%
1.000000e-03 <= Volume Change <  1.000000e-02      0    0.000%
1.000000e-02 <= Volume Change <  1.000000e-01   3692    1.248%
1.000000e-01 <= Volume Change <= 1.000000e+00 292068   98.752%
```

0.3 mm cells

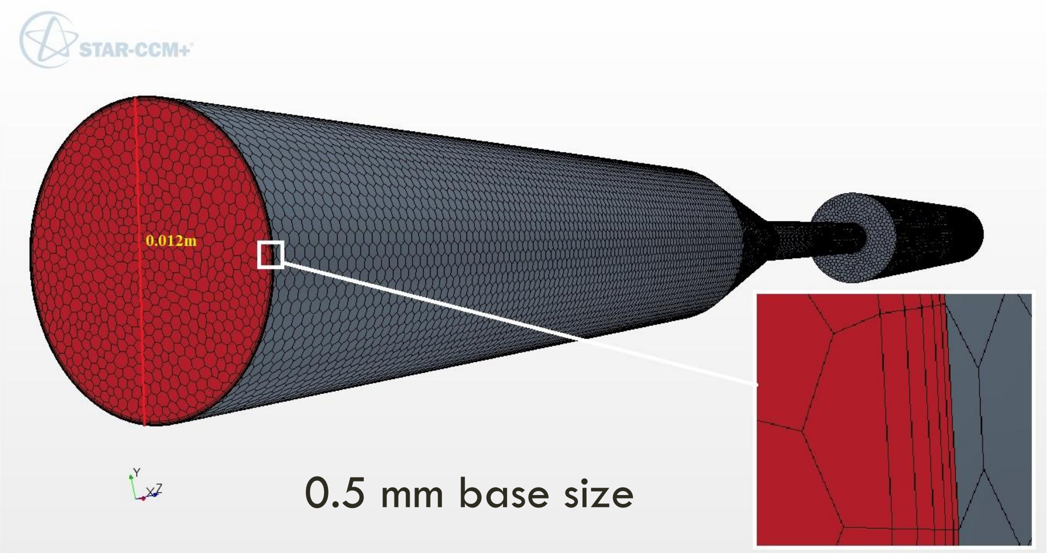
```
-----------------------------------------------------
--- Computing statistics in Region: Region_radial_profile 2
-----------------------------------------------------
-> ENTITY COUNT:
   # Cells: 960973
   # Faces: 5331761
   # Verts: 4058441
-> EXTENTS:
   x: [0.0000e+00 , 2.1269e-01 ] m
   y: [-5.9983e-03, 5.9983e-03 ] m
   z: [-5.9978e-03, 5.9978e-03 ] m
   Setting pro-STAR cell IDs on Region_radial_profile 2 starting at 1
-> MESH VALIDITY:
   Mesh is topologically valid and has no negative volume cells.
-> FACE VALIDITY STATISTICS:
Minimum Face Validity: 1.000000e+00
Maximum Face Validity: 1.000000e+00
        Face Validity <  0.50          0    0.000%
0.50 <= Face Validity <  0.60          0    0.000%
0.60 <= Face Validity <  0.70          0    0.000%
0.70 <= Face Validity <  0.80          0    0.000%
0.80 <= Face Validity <  0.90          0    0.000%
0.90 <= Face Validity <  0.95          0    0.000%
0.95 <= Face Validity <  1.00          0    0.000%
1.00 <= Face Validity             960973  100.000%
-> VOLUME CHANGE STATISTICS:
Minimum Volume Change: 1.249391e-03
Maximum Volume Change: 1.000000e+00
         Volume Change <  0.000000e+00            0    0.000%
0.000000e+00 <= Volume Change <  1.000000e-06      0    0.000%
1.000000e-06 <= Volume Change <  1.000000e-05      0    0.000%
1.000000e-05 <= Volume Change <  1.000000e-04      0    0.000%
1.000000e-04 <= Volume Change <  1.000000e-03      0    0.000%
1.000000e-03 <= Volume Change <  1.000000e-02      2    0.000%
1.000000e-02 <= Volume Change <  1.000000e-01  11079    1.153%
1.000000e-01 <= Volume Change <= 1.000000e+00 949892   98.847%
```

Mesh Base Size	Cells	Faces	Vertices	No. of Prism Layers
0.3 mm	960,973	5,331,761	4,058,441	5
0.5 mm	295,760	1,524,150	1,105,448	5
1.0 mm	94,975	449,940	306,278	5

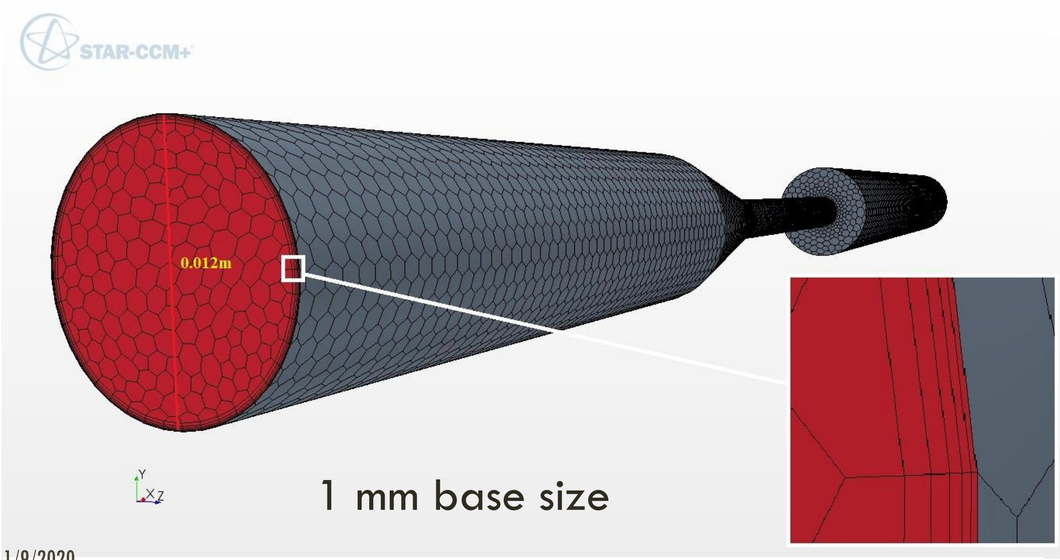
NOZZLE GEOMETRY (MESH VIEW)



0.3 mm base size



0.5 mm base size



1 mm base size

Total length

PHYSICS MODELS

Common in all simulation runs:

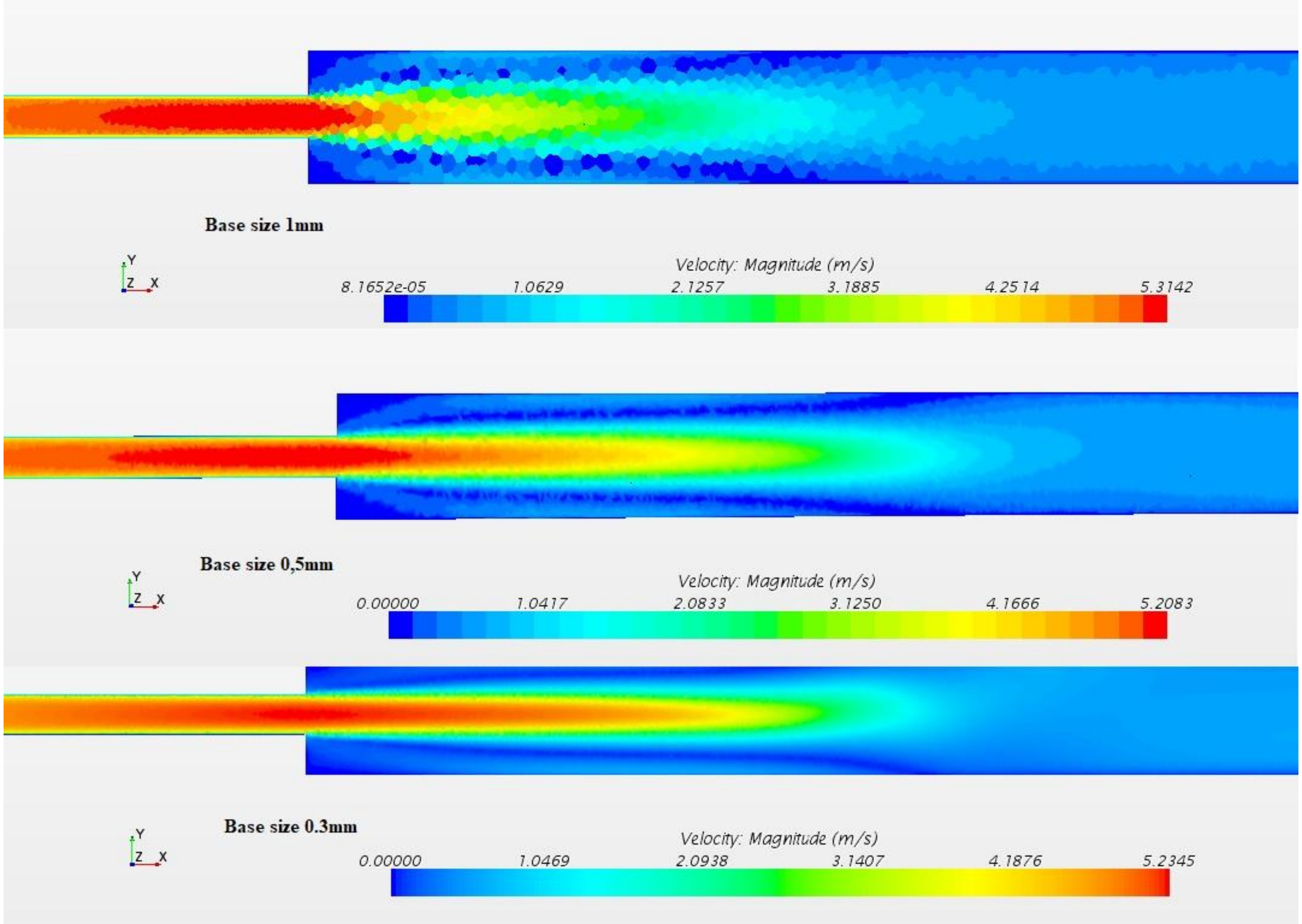
- Steady-state, Three-dimensional, Constant Density, Liquid
  - Liquid density: 1056 kg/m^3
  - Liquid viscosity: 0.0035 Pa-s
- Turbulent, Segregated Flow

Three Turbulence Models tested:

- Realizable two layer k-Epsilon Turbulence
- Low Reynolds Number k-Epsilon Turbulence
- K-Omega SST (Menter) Turbulence

SIMULATION RUN GRID

Turbulence Models → Mesh Base Size ↓	Regular k-Epsilon	Low Re k-Epsilon	K-Omega SST
0.3 mm	√	√	√
0.5 mm	√	√	√
1.0 mm	X	√	√

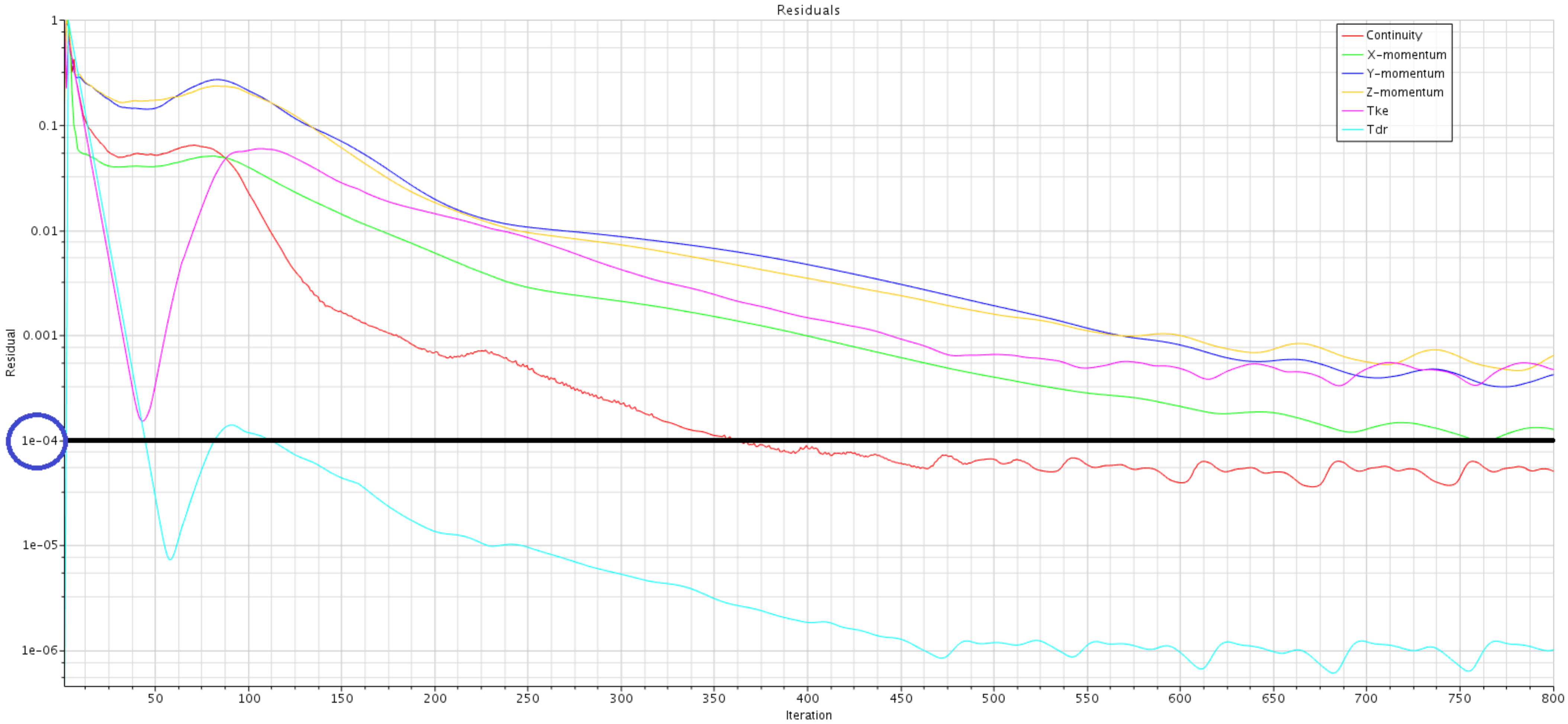

Base size 1mm
Y
Z X
Velocity: Magnitude (m/s)
8.1652e-05
1.0629
2.1257
3.1885
4.2514
5.3142
Base size 0,5mm
Y
Z X
Velocity: Magnitude (m/s)
0.00000
1.0417
2.0833
3.1250
4.1666
5.2083
Base size 0.3mm
Y
Z X
Velocity: Magnitude (m/s)
0.00000
1.0469
2.0938
3.1407
4.1876
5.2345

PHYSICS MODELS

Initial Condition Parameters	Values	Units
Turbulence Intensity	5.52	%
Turbulence Length Scale	0.000456	m
Turbulence Velocity Scale	1.8413307	m/s

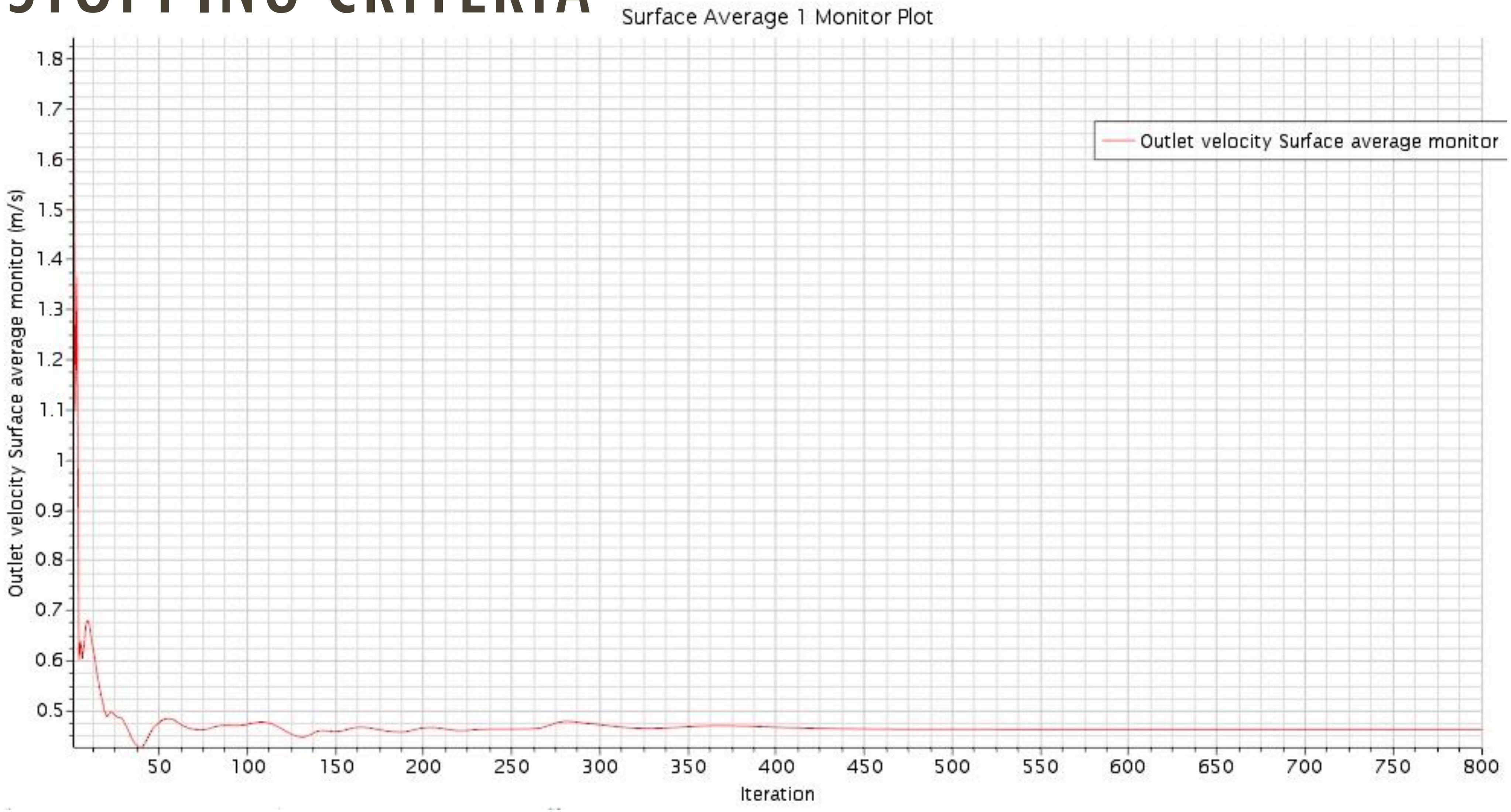
Boundary Condition Parameters	Values/Formulae	Units
Inlet Velocity Profile	Fully-developed (Poiseuille) flow	m/s
Outlet Pressure (Gauge)	0.0	Pa
Nozzle Walls	No-slip (Wall) Condition	--

STOPPING CRITERIA



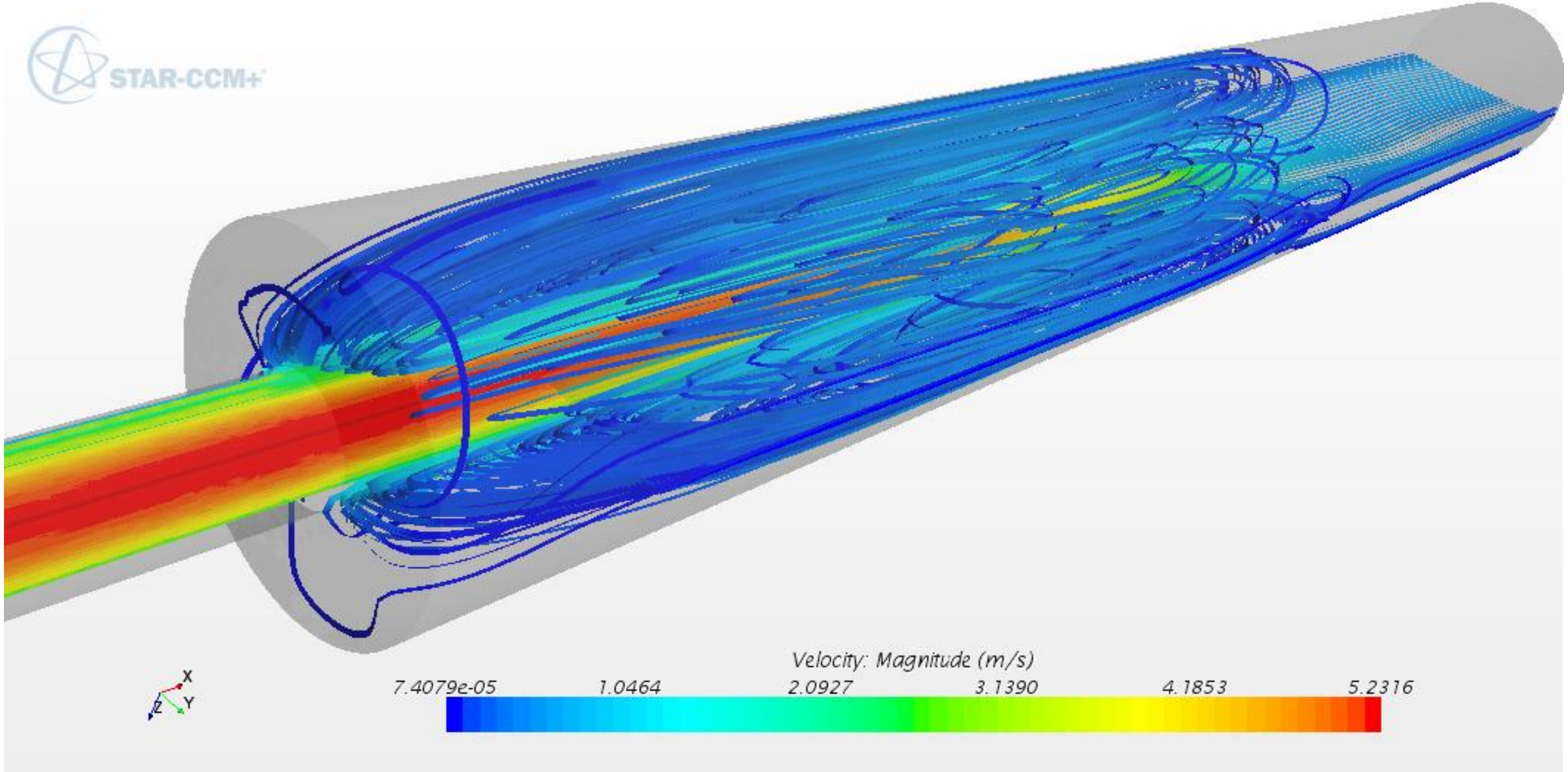
Continuity Residual limit = 1e-04 [0.3 mm mesh size k-eps low Re]

STOPPING CRITERIA

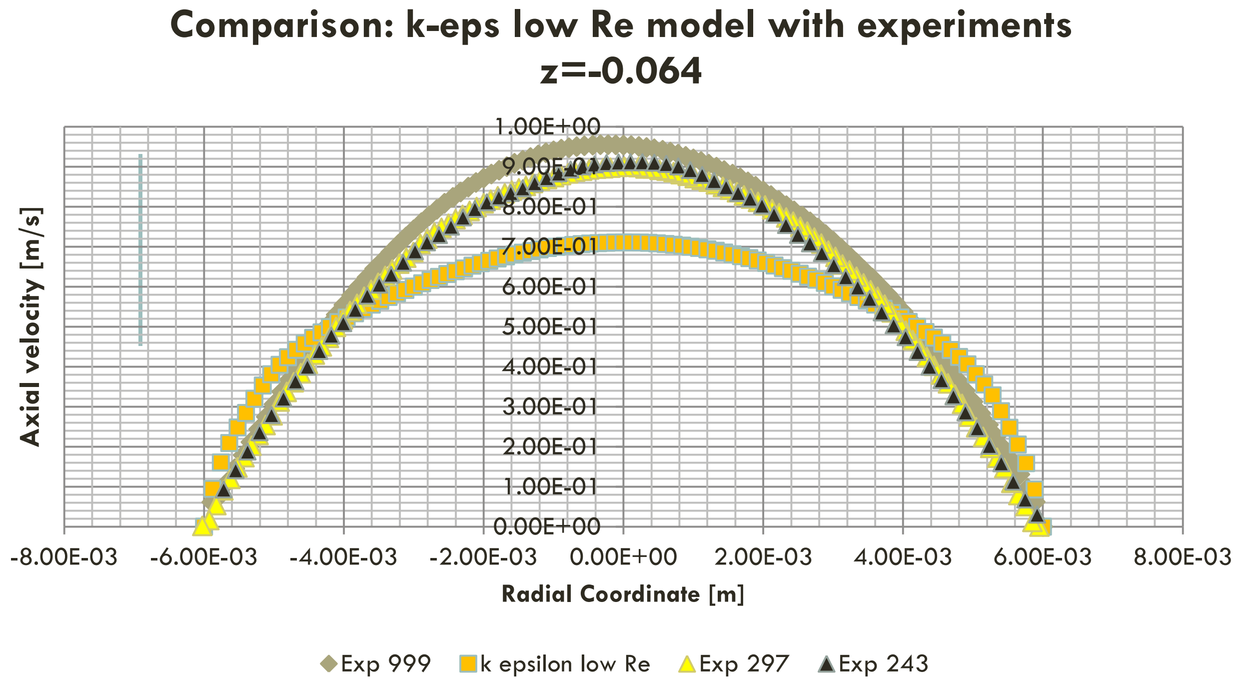


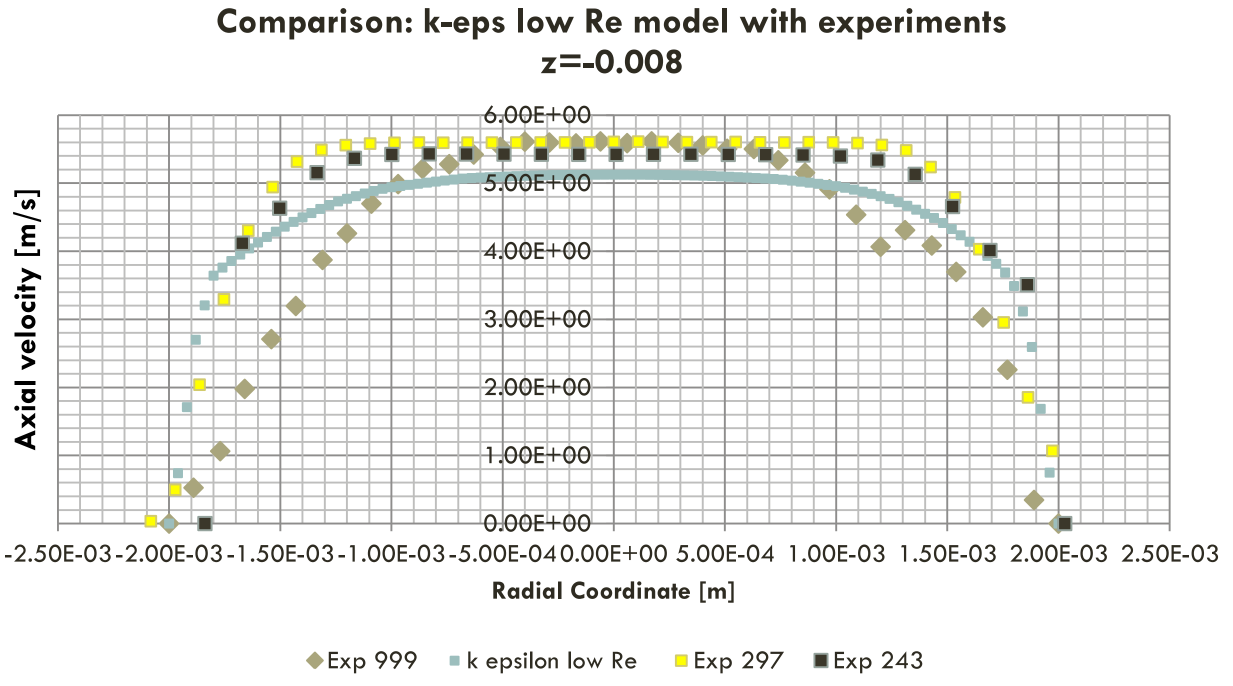
Average outlet velocity monitor to verify stability, due to fluctuating residuals

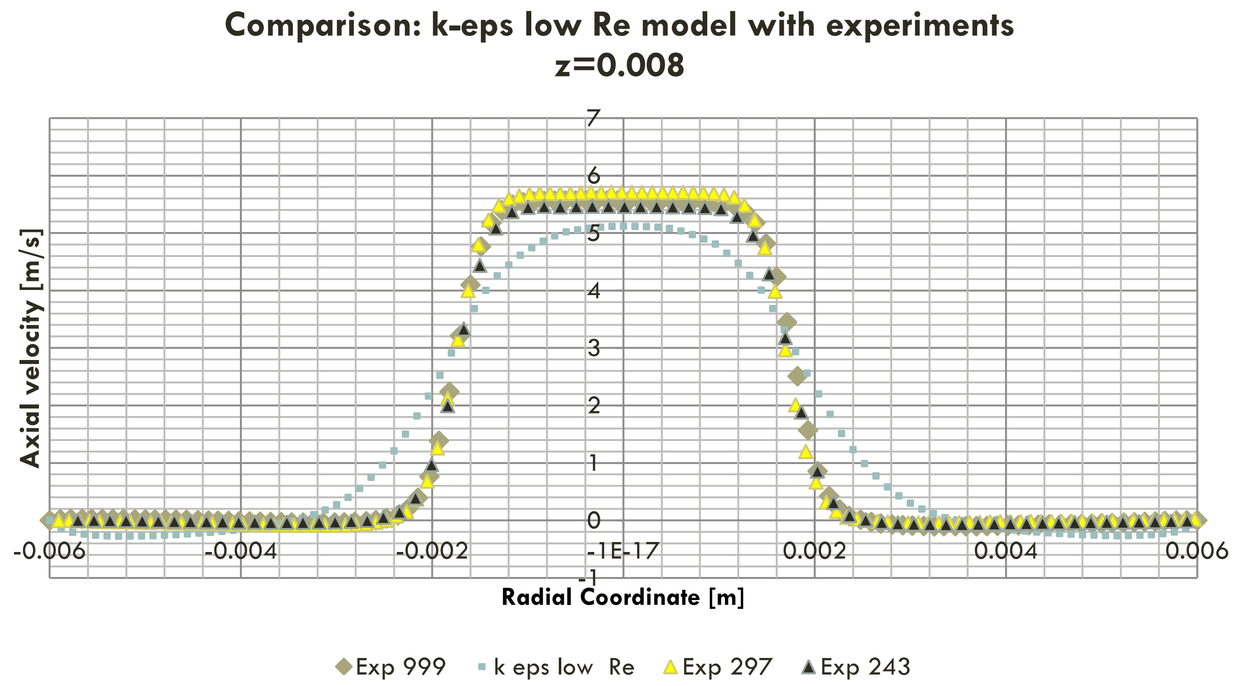
SIMULATION RESULTS

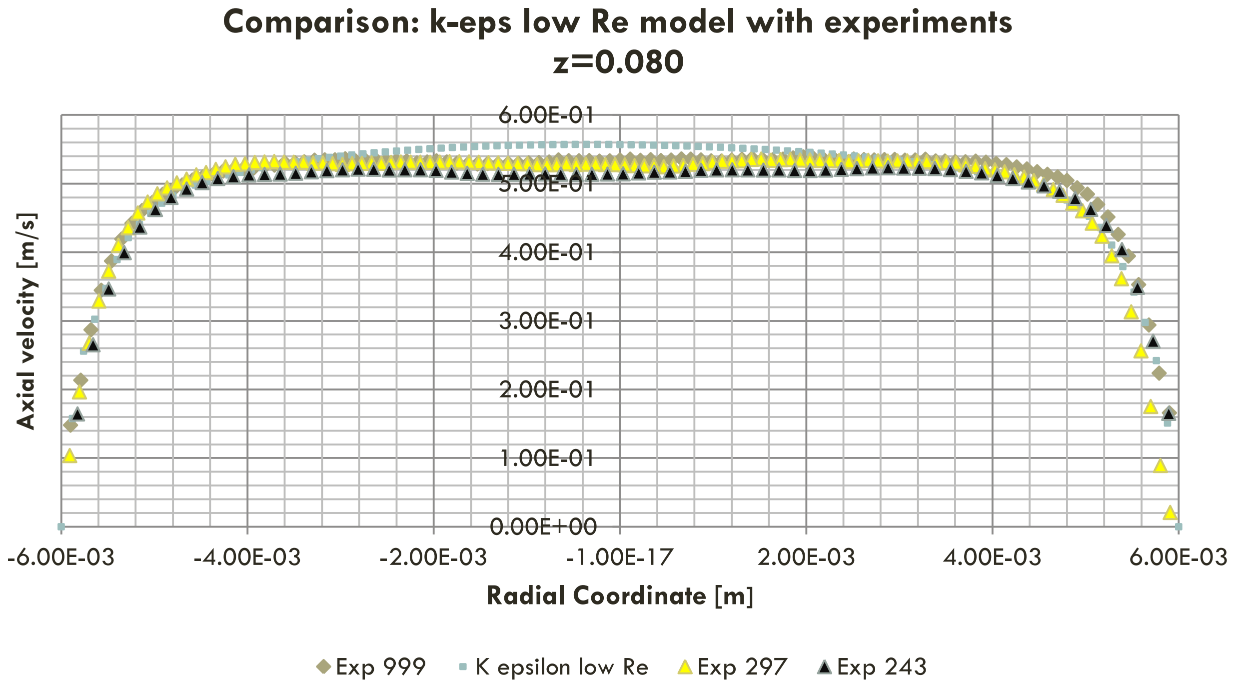


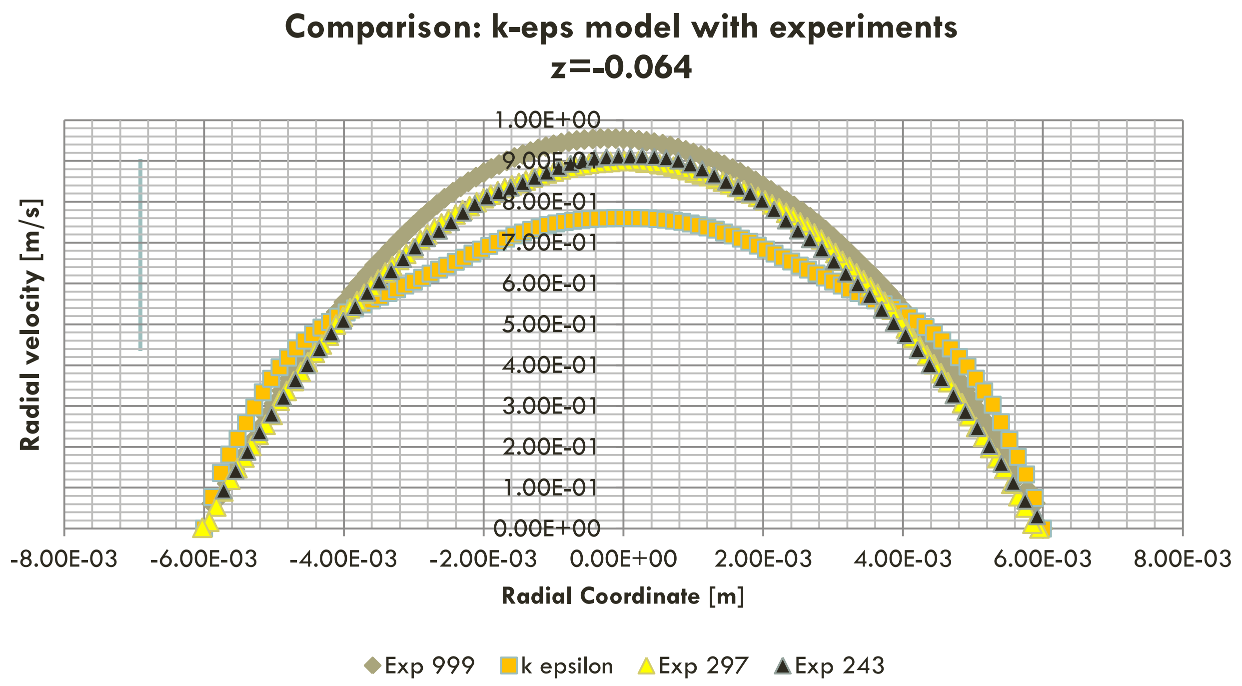
Streamline Scene of Velocity Magnitude – 0.3 mm mesh (k-Omega SST)

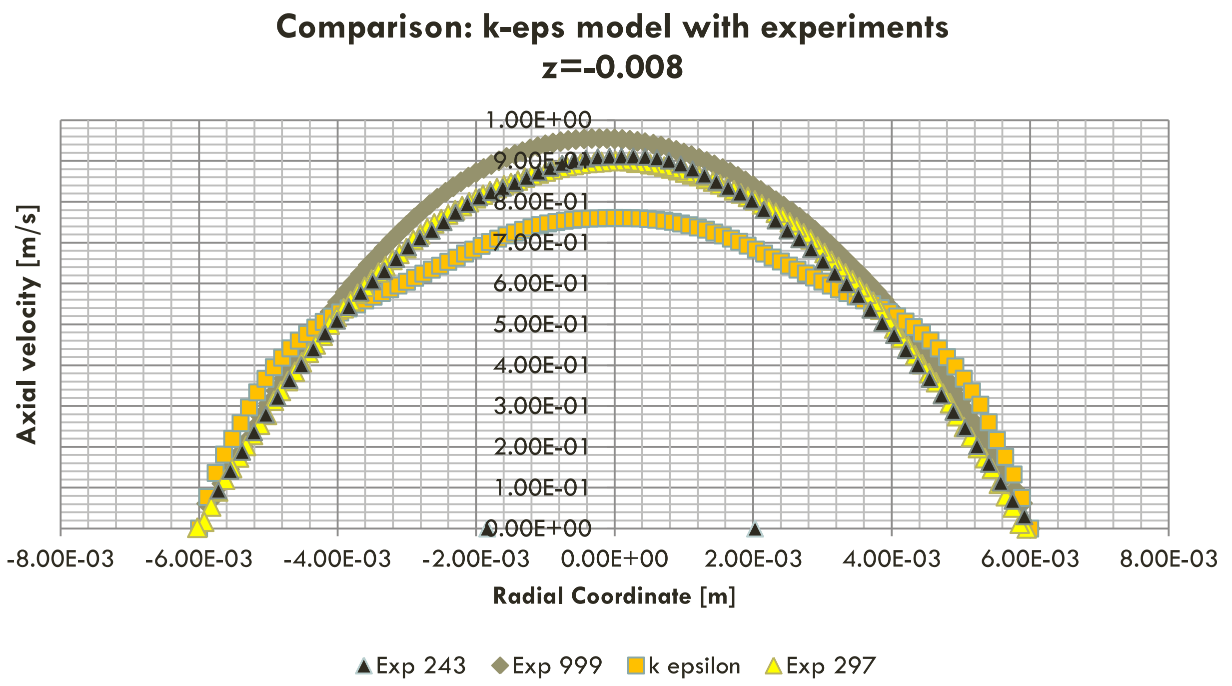

Comparison: k-eps low Re model with experiments
z=-0.064
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k epsilon low Re
Exp 297
Exp 243

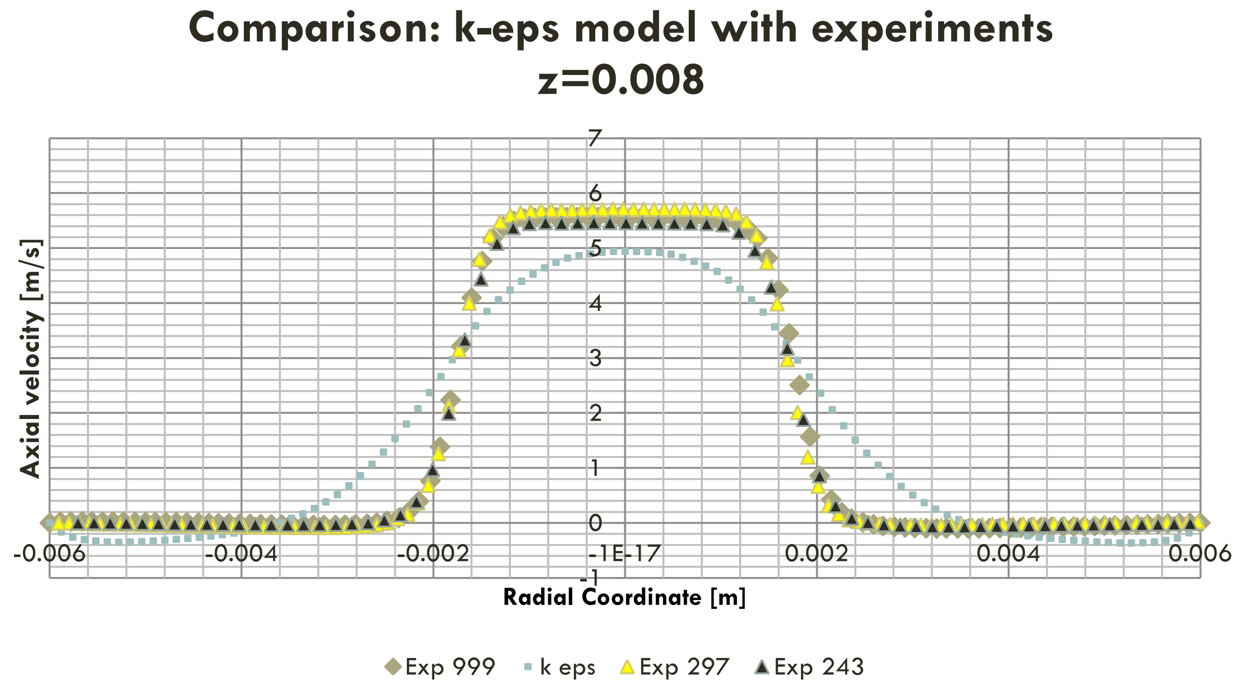

Comparison: k-eps low Re model with experiments
z=-0.008
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k epsilon low Re
Exp 297
Exp 243

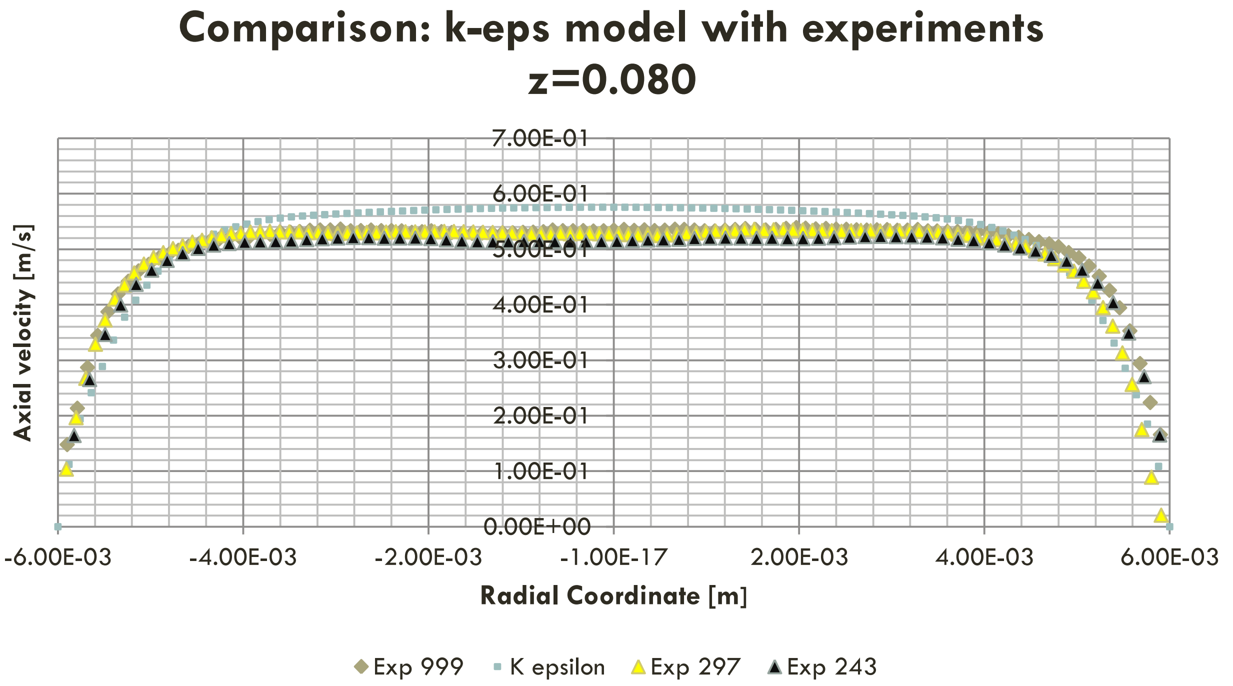

Comparison: k-eps low Re model with experiments
z=0.008
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k eps low Re
Exp 297
Exp 243

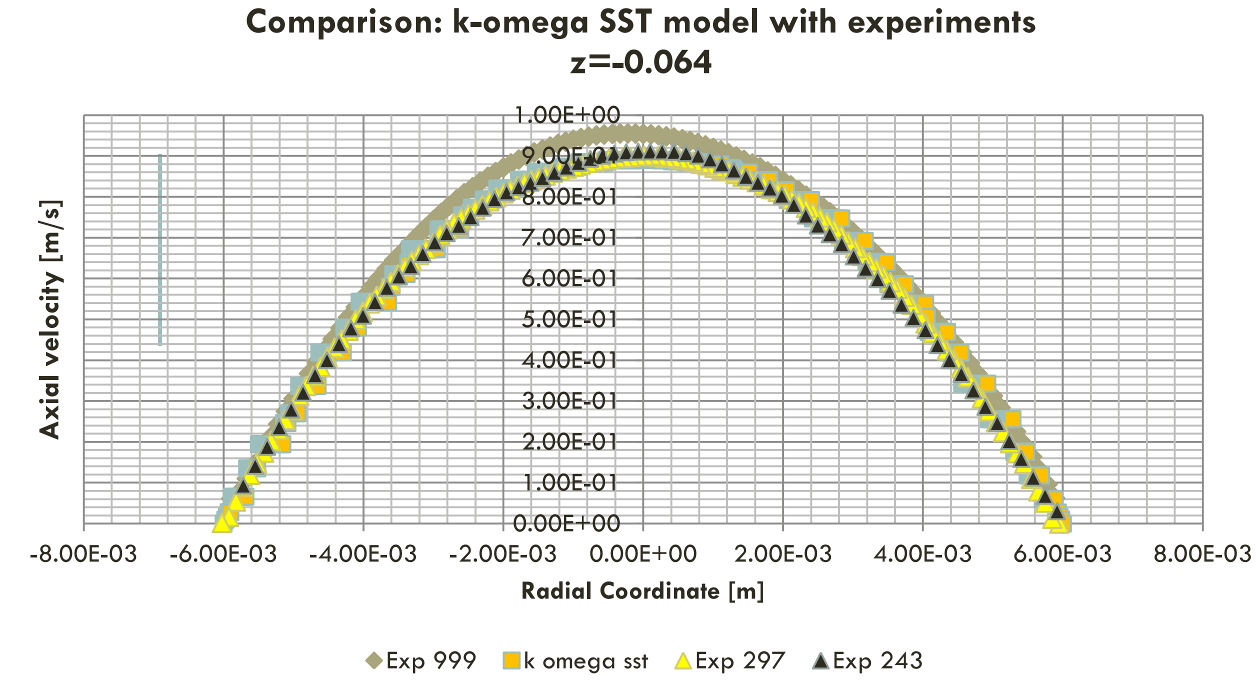

Comparison: k-eps low Re model with experiments
z=0.080
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
K epsilon low Re
Exp 297
Exp 243

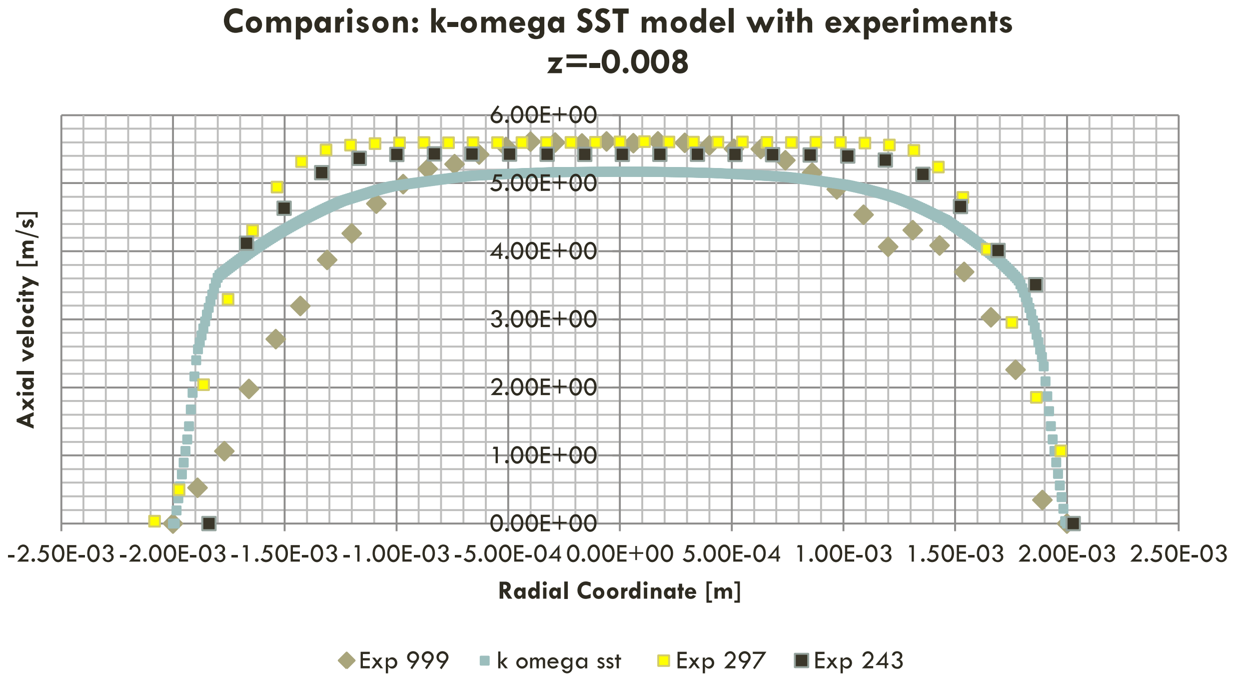

Comparison: k-eps model with experiments
z=-0.064
Radial velocity [m/s]
Radial Coordinate [m]
Exp 999
k epsilon
Exp 297
Exp 243

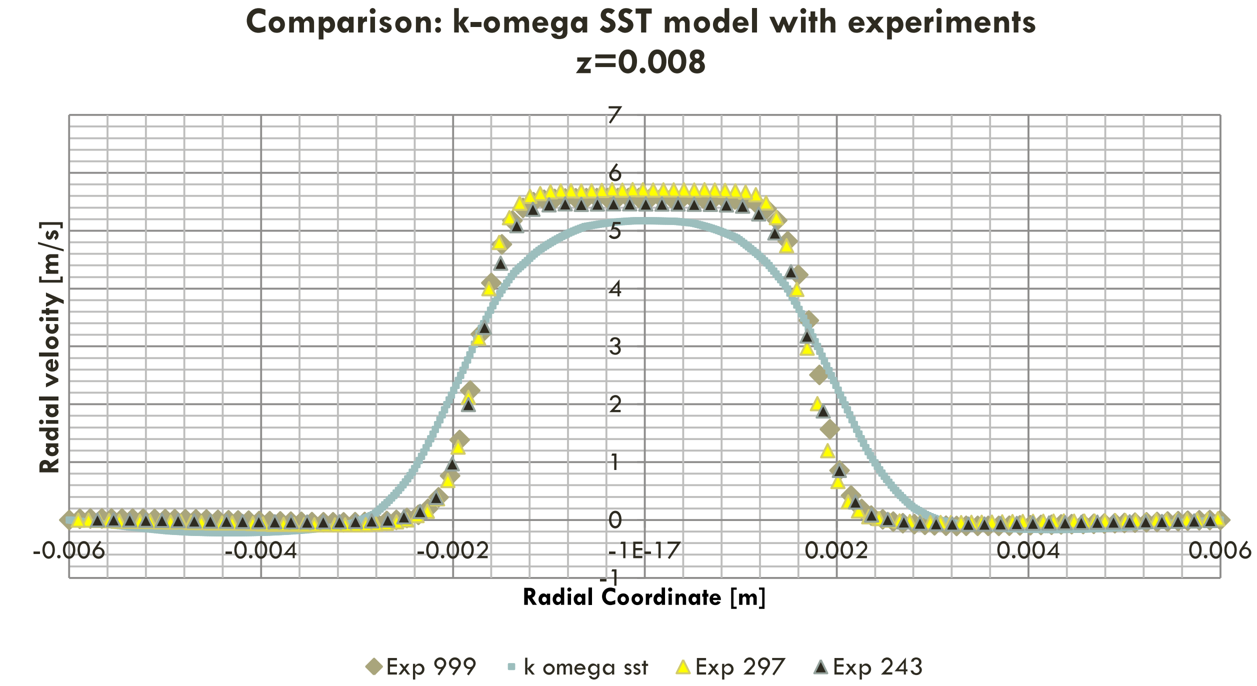

Comparison: k-eps model with experiments
z=-0.008
Axial velocity [m/s]
Radial Coordinate [m]
Exp 243
Exp 999
k epsilon
Exp 297

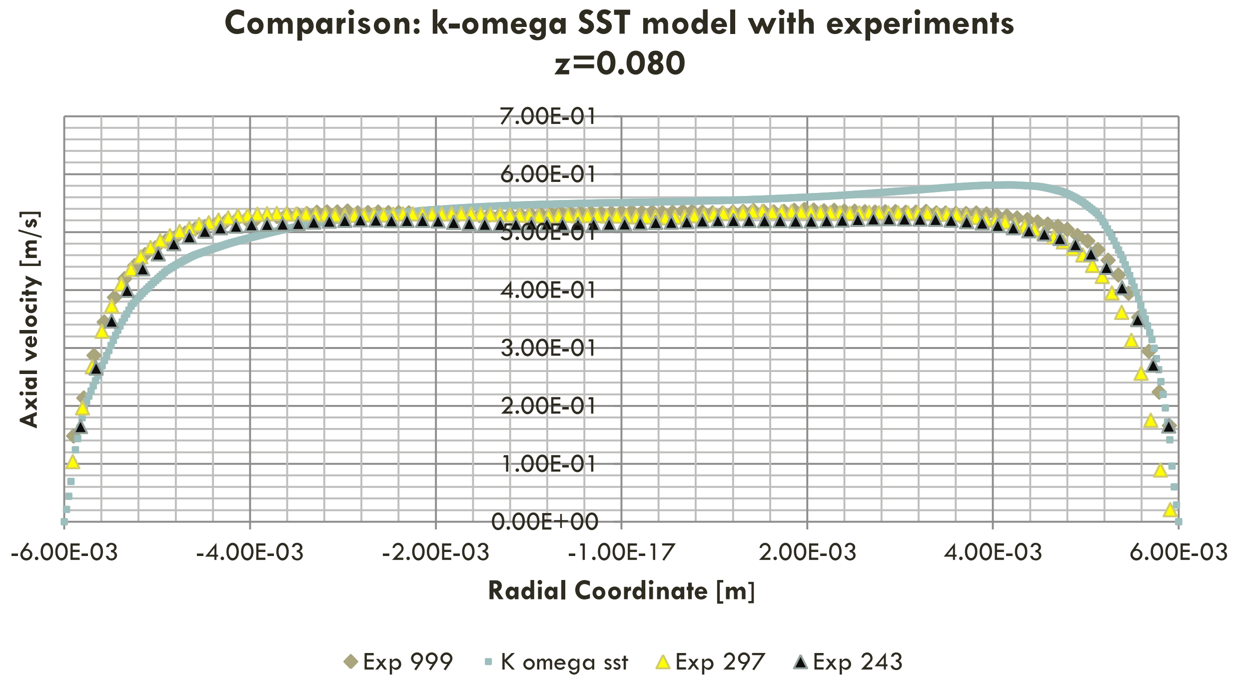

Comparison: k-eps model with experiments
z=0.008
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k eps
Exp 297
Exp 243


Comparison: k-eps model with experiments
z=0.080
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
K epsilon
Exp 297
Exp 243

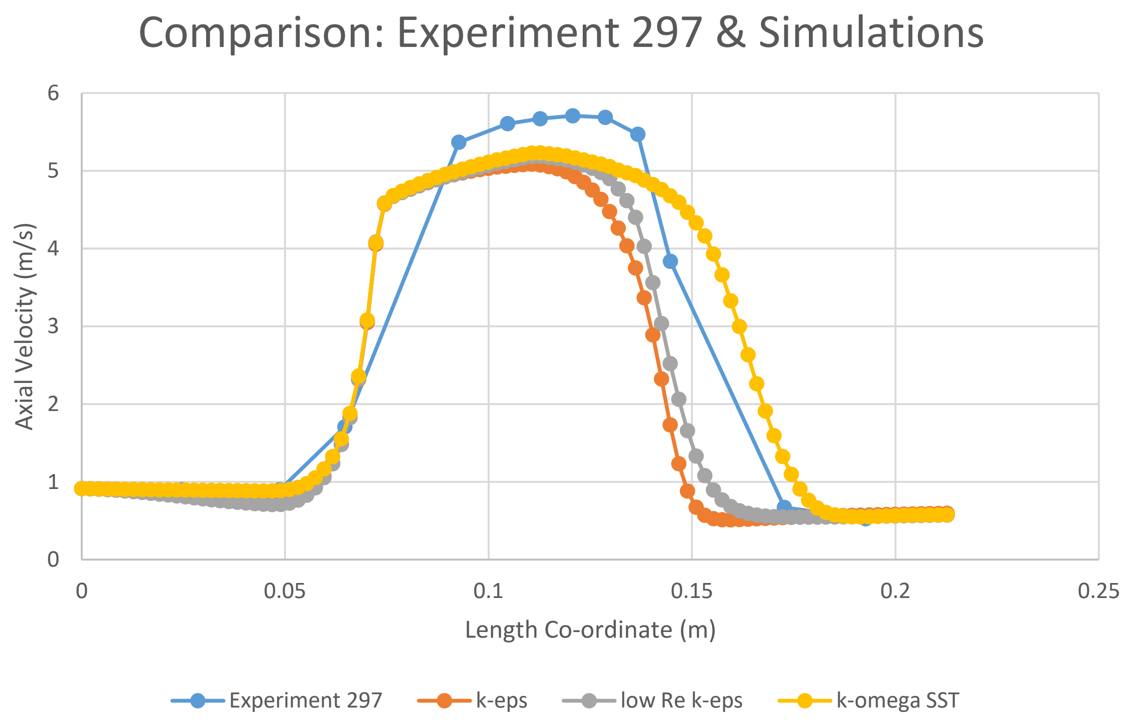

Comparison: k-omega SST model with experiments
z=-0.064
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k omega sst
Exp 297
Exp 243

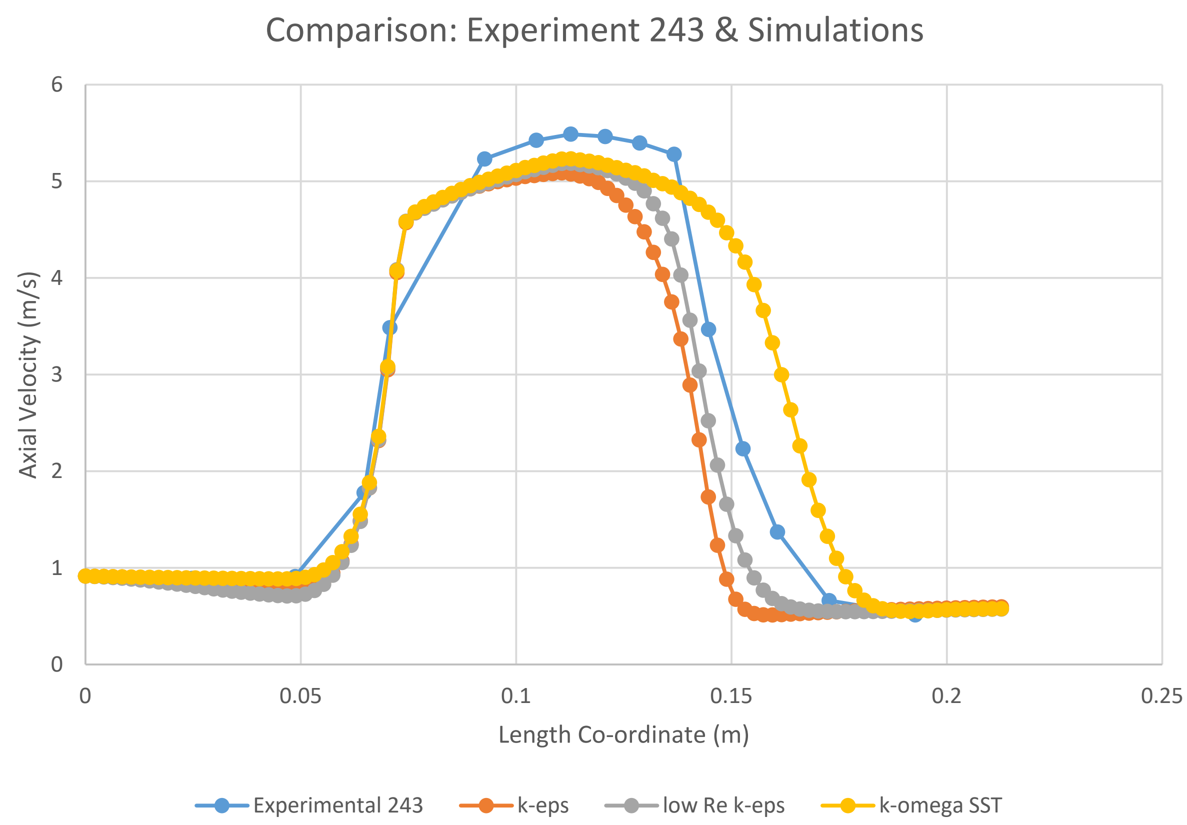

Comparison: k-omega SST model with experiments
z=-0.008
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
k omega sst
Exp 297
Exp 243

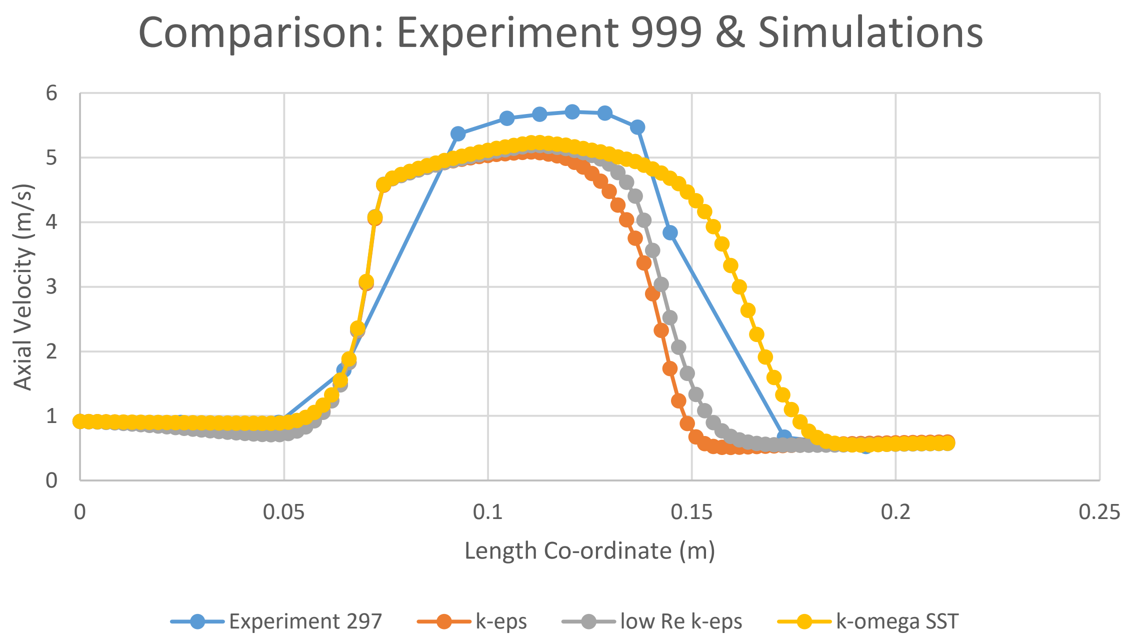

Comparison: k-omega SST model with experiments
z=0.008
Radial velocity [m/s]
Radial Coordinate [m]
Exp 999
k omega sst
Exp 297
Exp 243


Comparison: k-omega SST model with experiments
z=0.080
Axial velocity [m/s]
Radial Coordinate [m]
Exp 999
K omega sst
Exp 297
Exp 243

SIMULATION RESULTS







ANALYSIS & DISCUSSION

Experimental Sources of Errors:

- Fluid property measurements
- Inlet Disturbances : Stagnation Chamber

Computational Sources of Errors:

- Modelling errors
- Discretisation errors
- Iteration errors

ANALYSIS & DISCUSSION

Parameter selected for Grid Resolution Study: Peak Axial Velocity (m/s) at z=0.008 section

Experimental Values (m/s) : 5.7103, 5.46552, 5.56682 for 3 datasets respectively

Turbulence Models → Mesh Base Size ↓	Low Re k-Epsilon	K-Omega SST	Experimental Values (3 datasets)
0.3 mm	5.12659	5.18024	5.7103
0.5 mm	4.99482	5.03773	5.46552
1.0 mm	4.52439	4.59811	5.56682

CONCLUSION

The small mesh size (0.3 mm) with k-Omega SST turbulence model comes closest to simulating the experimental flow fields in a benchmark nozzle

Simulation results can be even more closely calculated to experimental values for mesh sizes smaller than 0.3 mm, dependent on computational & memory limitations

REFERENCES

1. https://nciphub.org/publications/43/2 - Webpage for experimental datasets
2. Hariharan, Prasanna, et al. "Multilaboratory particle image velocimetry analysis of the FDA benchmark nozzle model to support validation of computational fluid dynamics simulations." *Journal of biomechanical engineering* 133.4 (2011): 041002.
3. Zmijanovic, Vladeta, et al. "About the numerical robustness of biomedical benchmark cases: interlaboratory FDA's idealized medical device." *International journal for numerical methods in biomedical engineering* 33.1 (2017): e02789.