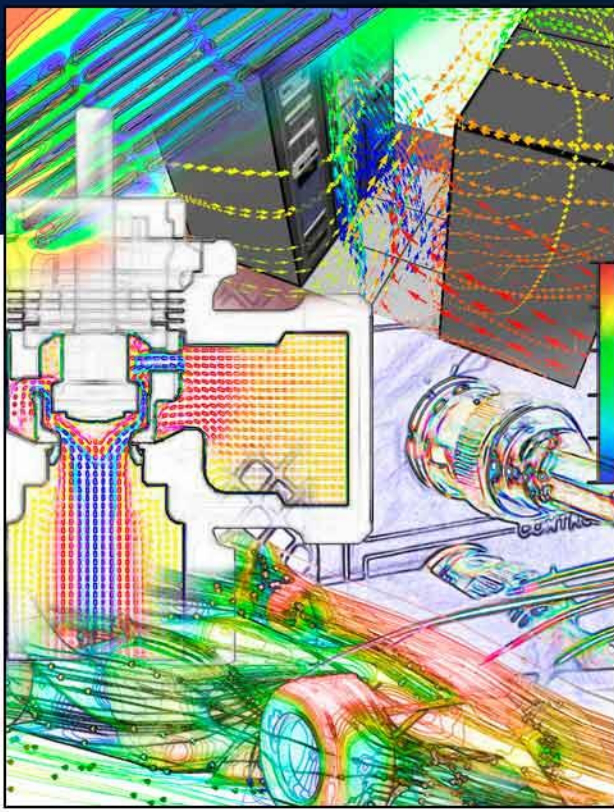
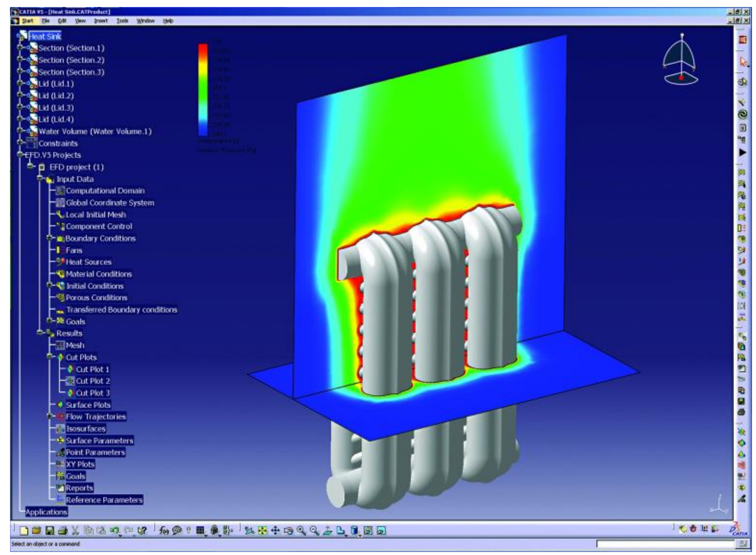


FloEFD Validation Examples

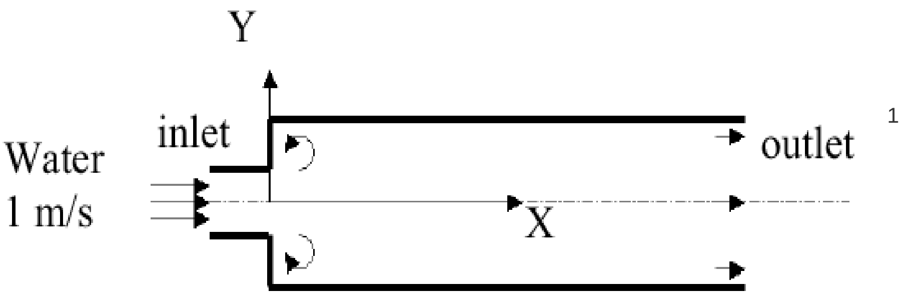


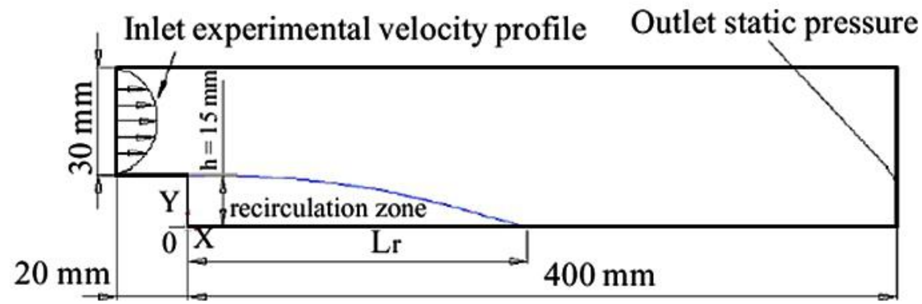
Mentor Graphics®

FloEFD Validation and Software Test Matrix

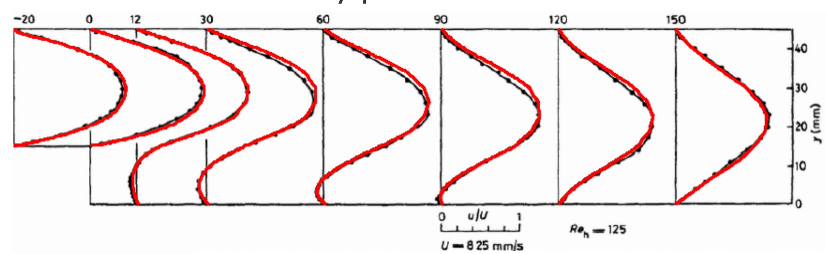
- Before the release of each version of FloEFD a suite of 300 test cases are run through the different CAD embedded versions of the software
- The test matrix ranges from simple 2D tests to industrial scale 3D benchmarks (see the following slides for a sample set of FloEFD validations)
- The validation suite includes many classical CFD benchmark cases including a wide range of flow turbulence scenarios and regimes suitable for a General Purpose CFD code
- The following slides illustrate some of the benchmarks each FloEFD release has to meet.

FloEFD Validation: Flow in 2D Channels with bilateral and unilateral expansions (Backward Facing Steps)

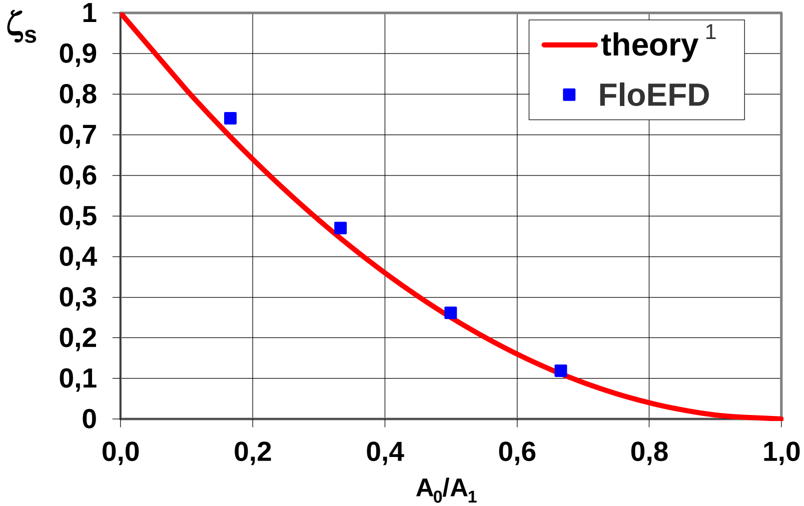




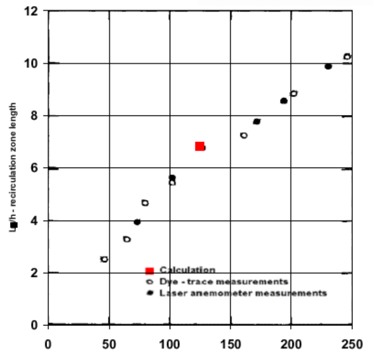
Velocity profiles[2]

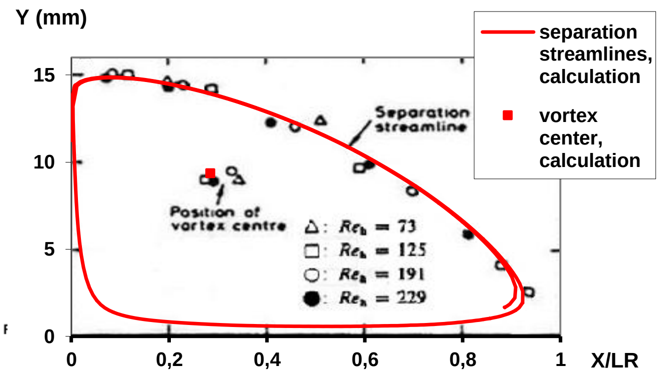


Resistance



[1]Idelchik, I.E., *Handbook of Hydraulic Resistance.* 2nd ed., McGraw Hill, New York, 1979

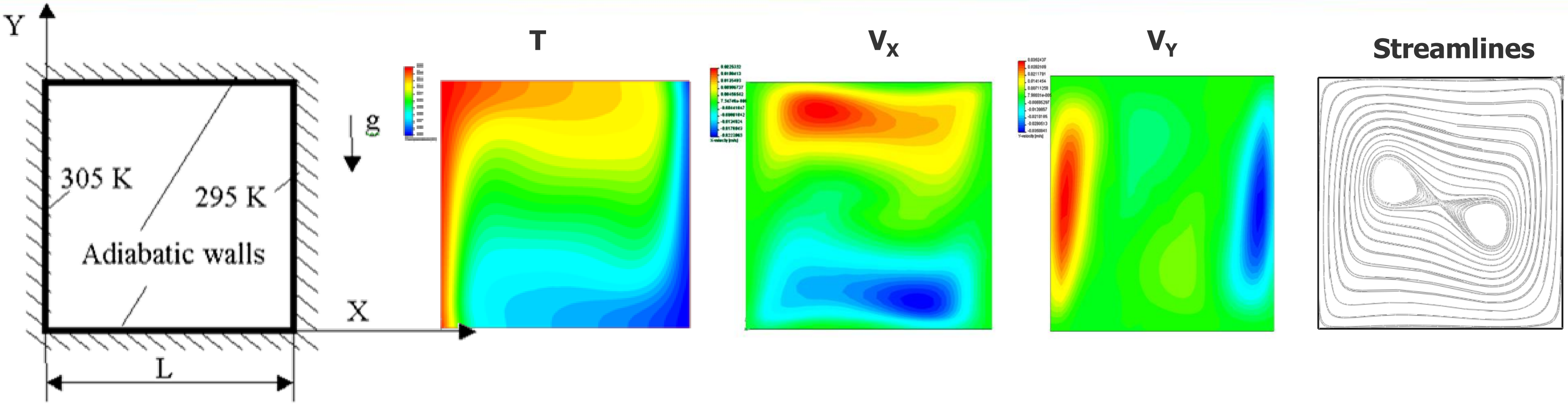


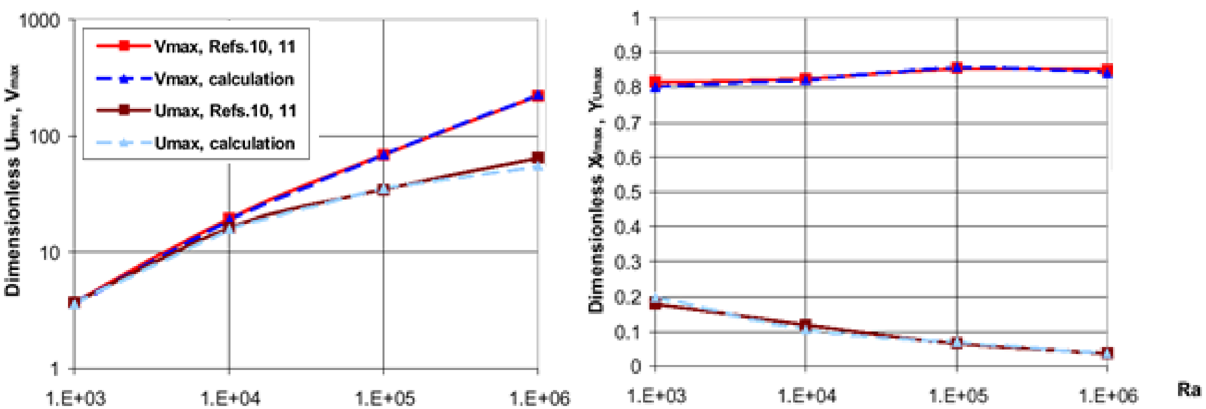


Recirculation zone

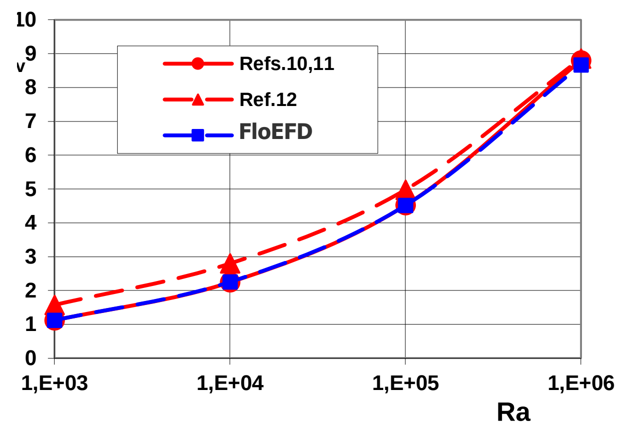
[2]Yanshin, B.I.: *Hydrodynamic Characteristics of Pipeline Valves and Elements. Convergen Sections, Divergent Sections and Valves.* "Mashinostroenie", Moscow, 1965

FloEFD Validation:
Natural Convection in a Square Cavity





Dimensionless Velocities vs. Rayleigh Number

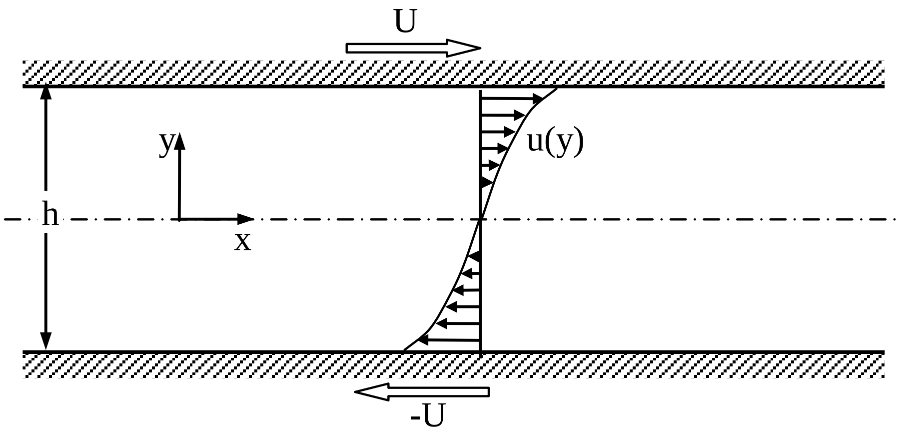


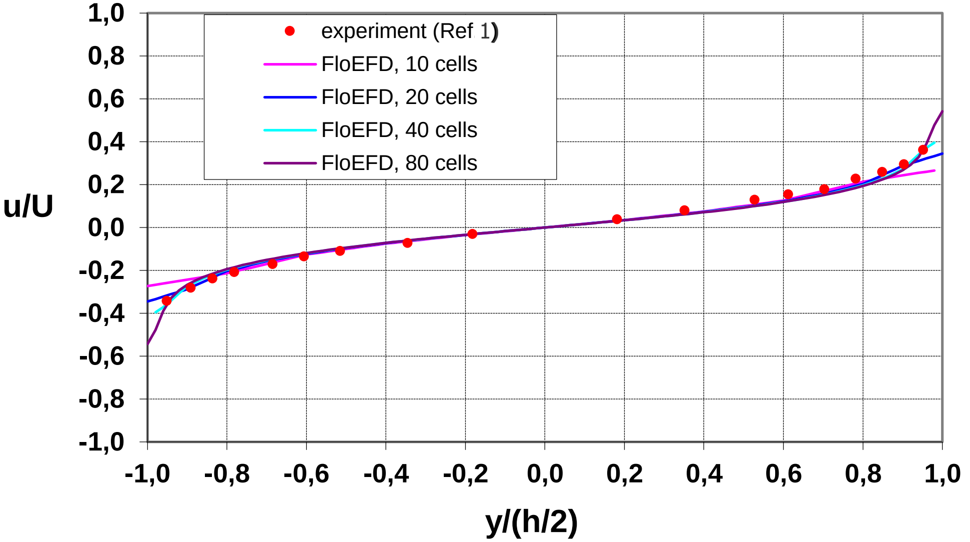
Nusselt number vs. Rayleigh number

References
10 Davis, G. De Vahl; Jones, I.P.: *Natural Convection in a Square Cavity: a Comparison Exercise.* Int. J. for Num. Meth. In Fluids, v.3, pp. 227-248 (1983)
11 Emery, A., Chu, T.Y.: *Heat Transfer across Vertical Layers.* J. Heat Transfer, v. 87, p. 110 (1965)
12 Denham, M.K., Patrick M.A.: *Laminar Flow over a Downstream Facing Step in a Two-Dimensional Flow Channel.* Trans. Instn. Chem. Engrs., v. 52, pp. 361-367 (1974)

FloEFD Validation: Couette Flow between Parallel Flat Plates at Re = 3.4×10^4

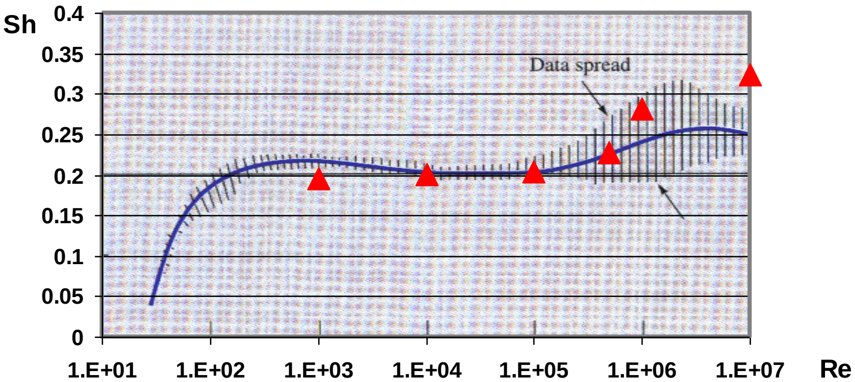
- A classical plane flow is one between two parallel infinite flat plates spaced at a distance *h* from one another and moving at velocity U in opposite directions ,
- Dimensionless velocity profiles for different meshes (10, 20, 40, 80 mesh cells across the channel) compare well with experimental data illustrating that with relatively coarse meshes good predictions can be expected when using FloEFD.



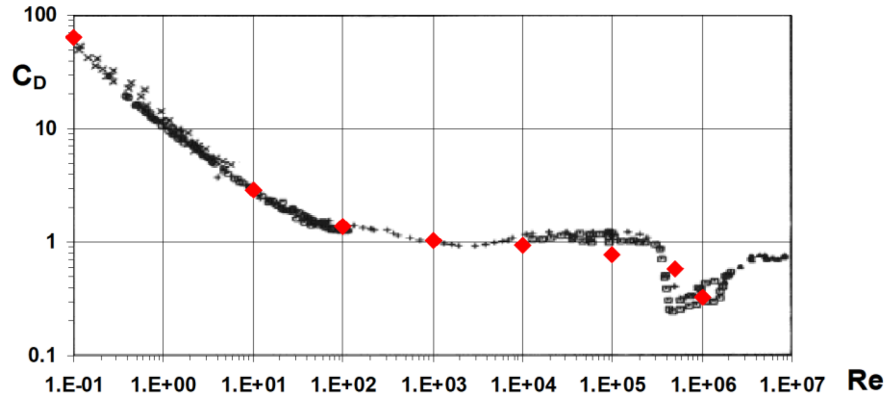


References
1. Schlichting, H. *Boundary-Layer Theory*. McGraw-Hill, New York, 1979.

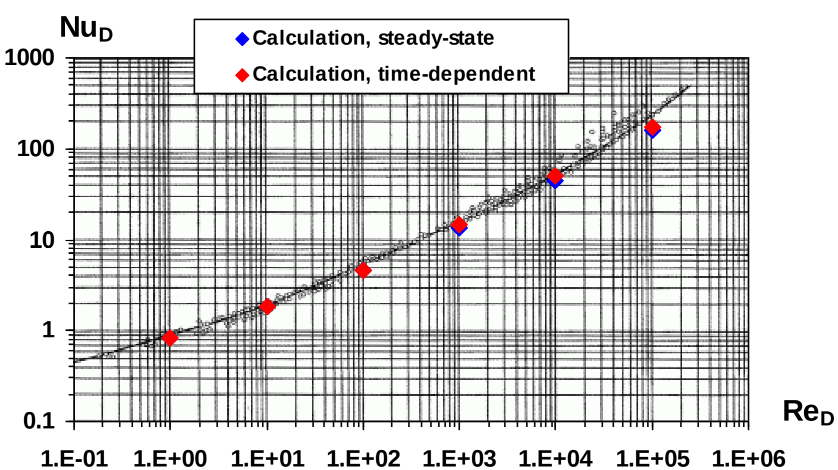
FloEFD Validation: Flow and Heat Transfer over a Circular Cylinder for Low Reynolds Numbers



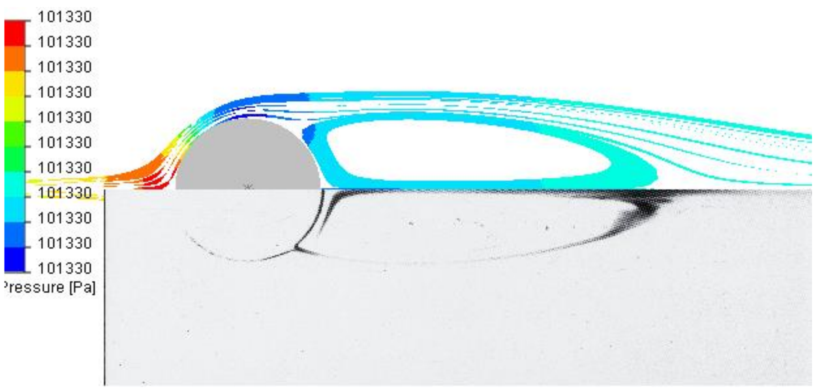
Strouhal Number *vs.* Reynolds Number (Ref 4)



Drag Coefficient *vs.* Reynolds Number (Ref 3)



Nusselt Number *vs.* Reynolds Number(Ref 6)

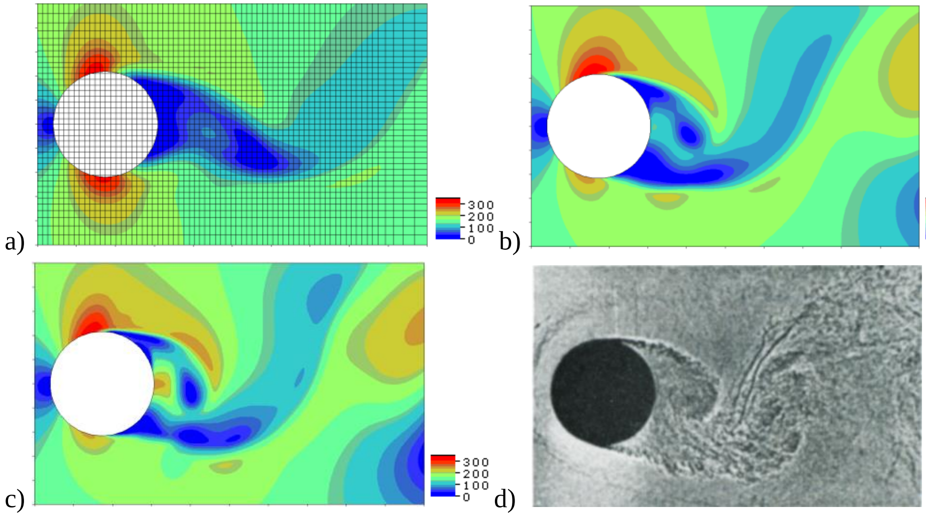


Flow Trajectories over and past a Circular Cylinder at Re=41: Qualitative Comparison with Experiment (Ref 9)

References
3. Panton, R.L., *Incompressible Flow.* 2nd ed., John Wiley & Sons, Inc., 1996
4. White, F.M., *Fluid Mechanics.* 3rd ed., McGraw-Hill, New York, 1994
6. Holman, J.P., *Heat Transfer. 8th ed.,* McGraw-Hill, New York, 1997
9. Davis, G. De Vahl: *Natural Convection of Air in a Square Cavity: a Bench Mark Numerical Solution.* Int. J. for Num. Meth. In Fluids, v. 3, pp. 249-264 (1983)

FloEFD Validation: Unsteady Vortex Shedding Flow over a Circular Cylinder at Re=3.7x10^5

- Predicted turbulent transient flow velocity fields over a circular cylinder calculated with FloEFD for different computational meshes having:
  - a) 20 quad cells per diameter,
  - b) 40 quad cells per diameter,
  - c) 80 quad cells per diameter, &
  - d) Similar real flow shadowgraph from Driver and Seegmiller (1985)



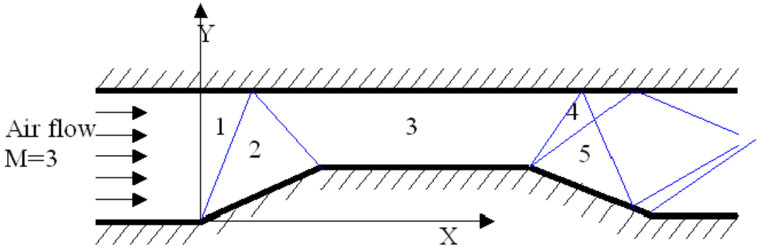
- Circular cylinder drag coefficients calculated with FloEFD in comparison with experimental data (Driver and Seegmiller 1985).

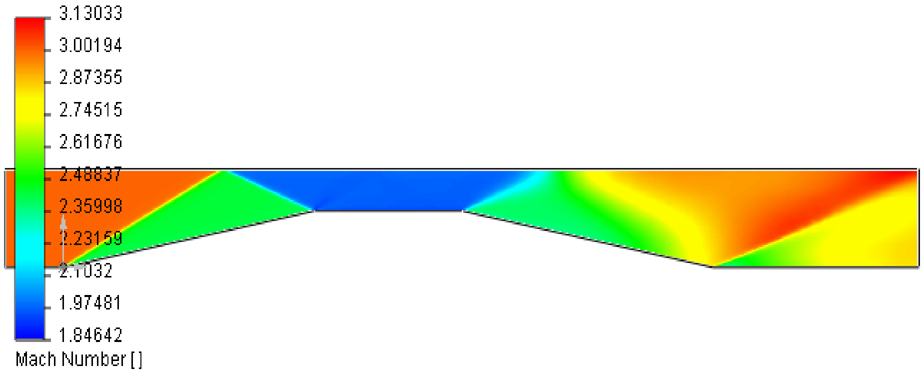
Mesh Density (cells per cylinder diameter)	C_d	Deviation from experimental data (%)	y^+_{max}
FloEFD, 20 cells per diameter	0.82	-18	650
FloEFD, 40 cells per diameter	0.95	-5	330
FloEFD, 80 cells per diameter	1.02	2	170
Experiment (Driver and Seegmiller 1985)	1.0	n/a	n/a

Driver, D.M. and Seegmiller, H.L. (1985). Features of a Reattaching Turbulent Shear Layer in Divergent Channel Flow. AIAA Journal, Vol. 23, p. 163.

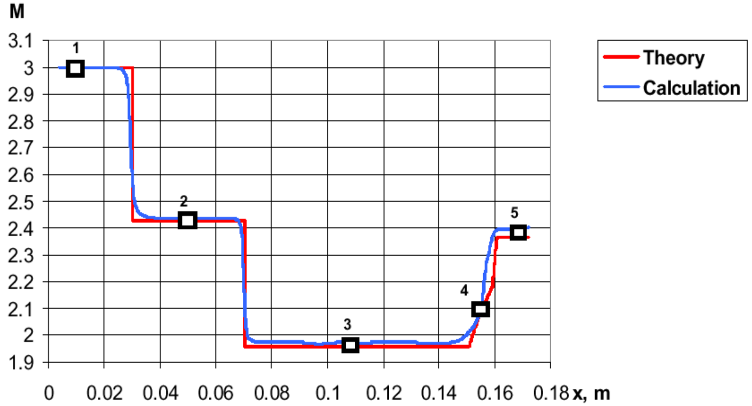
FloEFD Validation: Supersonic Flow in a 2-D Convergent-Divergent Channel

- Classical benchmark of air flow at inlet M=3 in a 2D (planar) convergent-divergent channel



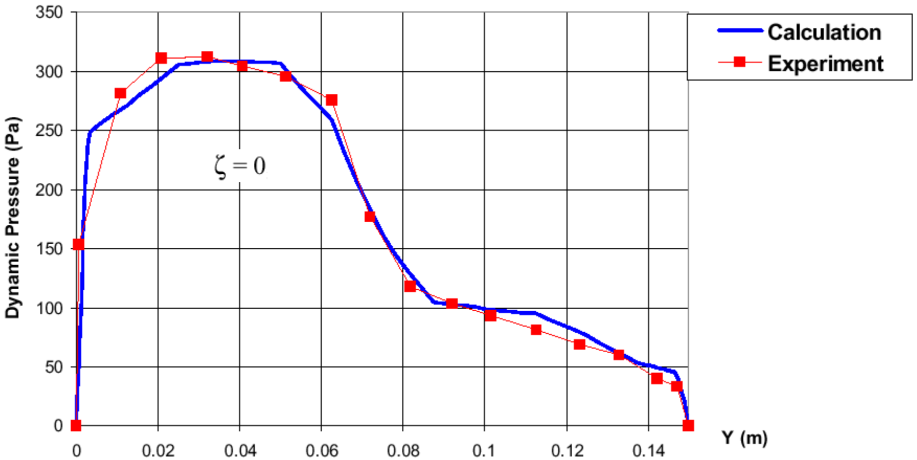


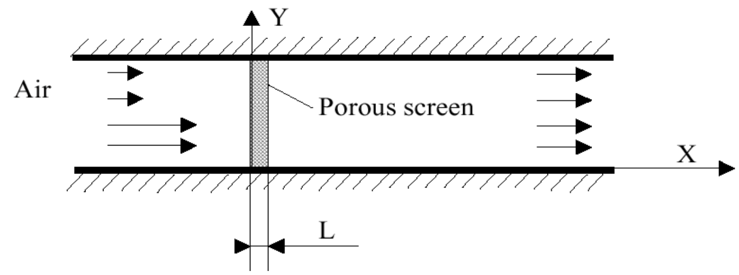
Reference Point	1	2	3	4	5
X ordinate (m)	0.0042	0.047	0.1094	0.155	0.1648
Y ordinate (m)	0.0175	0.0157	0.026	0.026	0.0157
Mach Number (Theory)	3.000	2.427	1.957	2.089	2.365
Mach Number (FloEFD)	3.000	2.429	1.965	2.106	2.380
Difference (%)	0.0	0.1	0.4	0.8	0.6

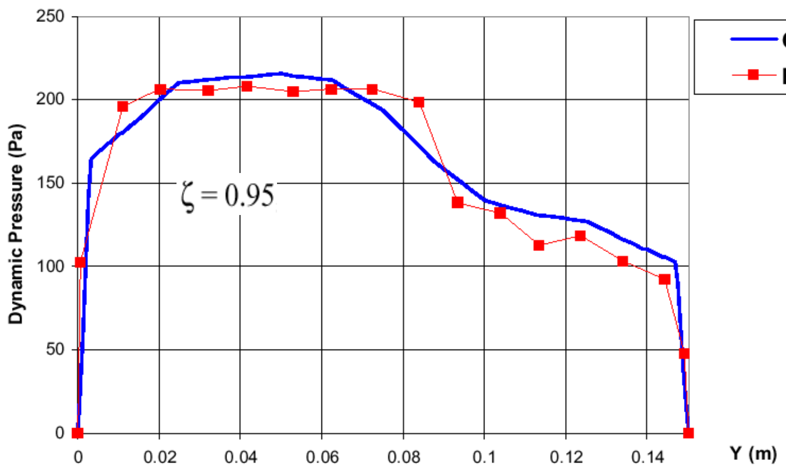


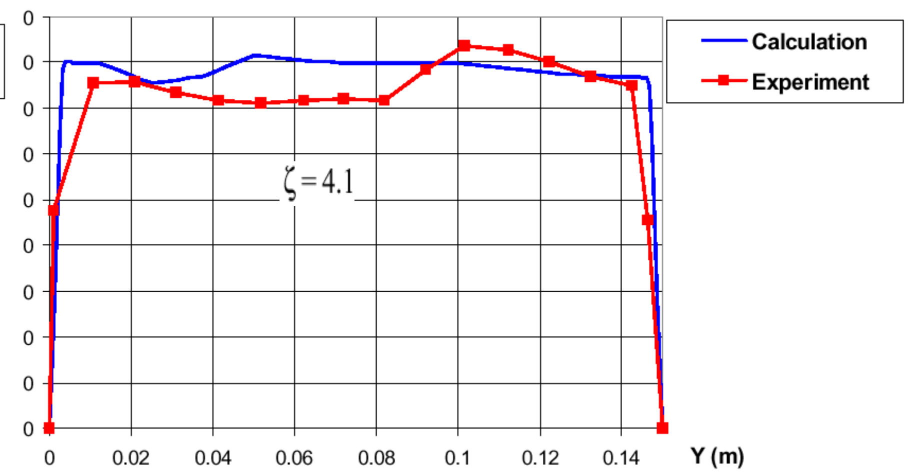
Mach number distribution

FloEFD Validation: Smoothing step-shaped velocity profile by a porous screen of different drag coefficient (ζ)



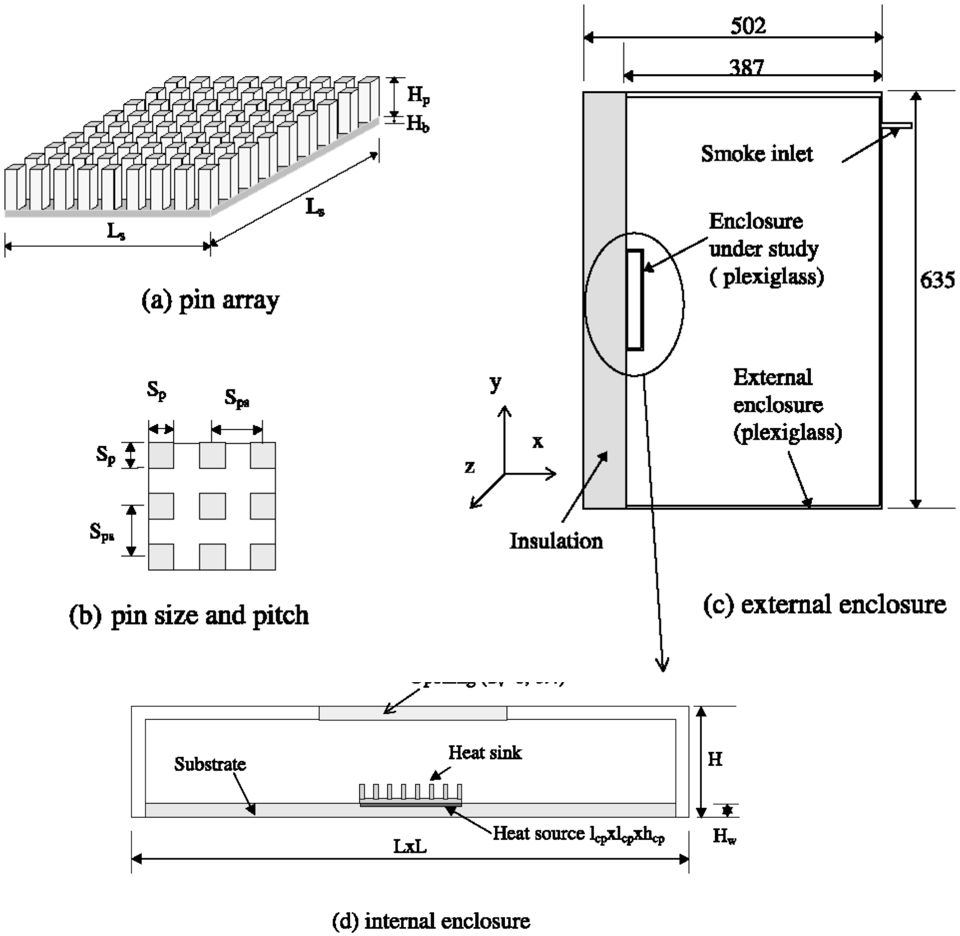






References
2. Panton, R.L., *Incompressible Flow.* 2nd ed., John Wiley & Sons, Inc., 1996

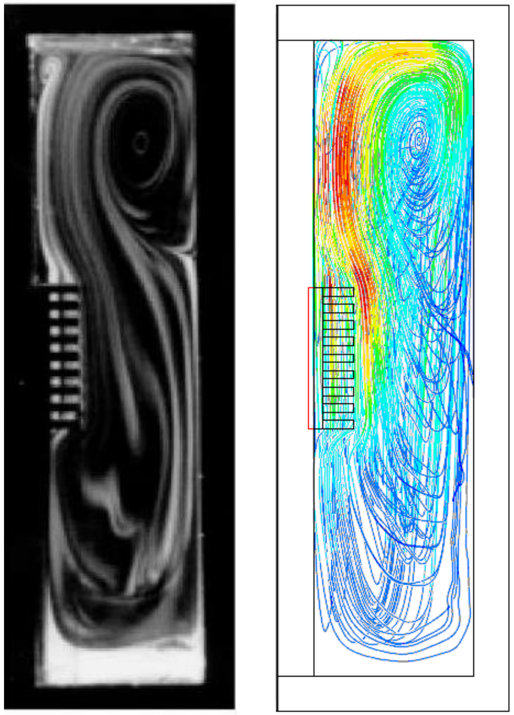
FloEFD Validation: Cooling a Pin-Fin Heat Sink Due to Natural Convection



$$R_{ja} = {}^{(T_{max} - T_{amb})}/_{Q}$$

$$R_{ja_{exp}} = 43^oC/W \text{ (Ref 14)}$$

$$R_{ja_{calc}} = 41^oC/W$$



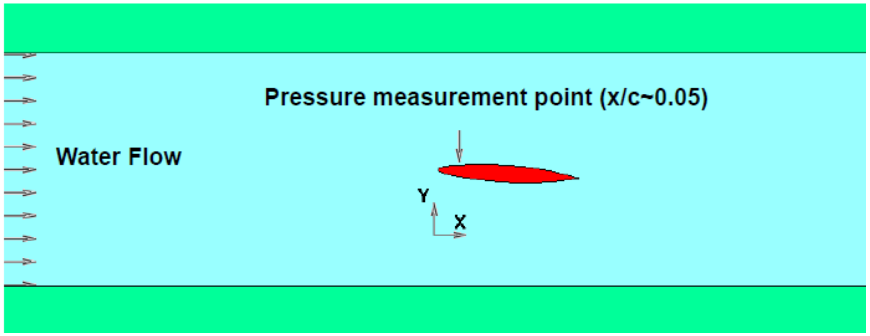
Flow Streamlines: Smoke Visualisation, left (Ref 19), FloEFD result, right

References

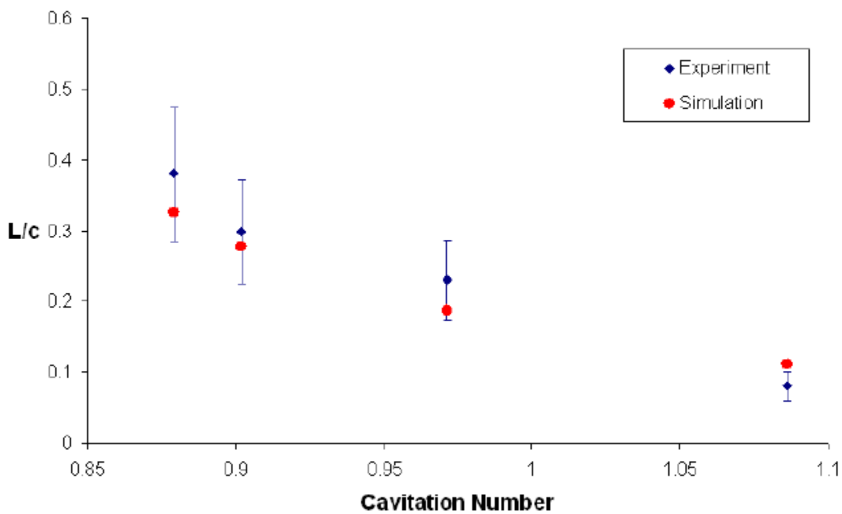
14. Enchao Yu, Yogendra Yoshi: *Heat Transfer Enhancement from Enclosed Discrete Components using Pin-Fin Heat Sinks* Int. J. of Heat & Mass Transfer, v. 45, pp. 4957-4966 (2002)

19. Jyotsna, R., Vanka, S.P.: *Multigrid Calculation of Steady, Viscous Flow in a Triangular Cavity.* J. Comput. Phsy., v. 122, pp. 107-117 (1995)

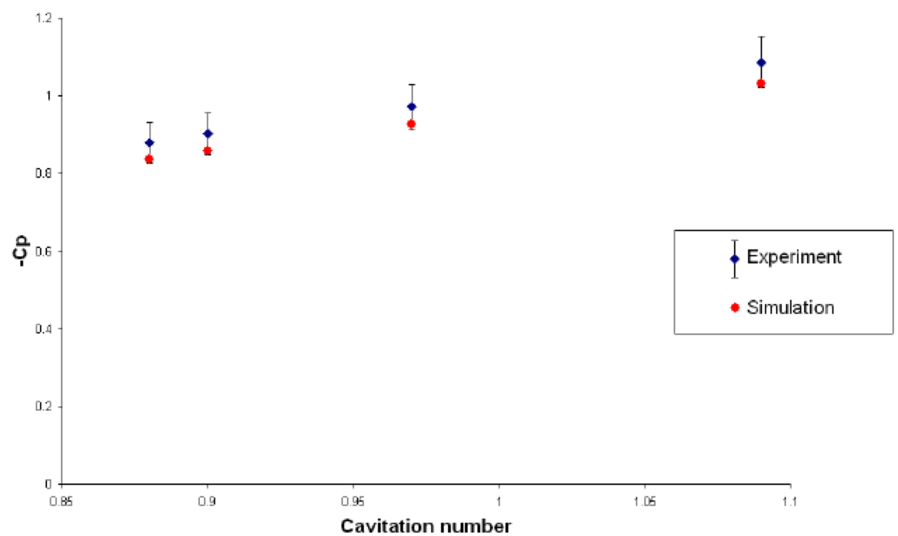
Caviatition on a Hydrofoil (1); Quantitative Comparison



Cavitation Number, $\sigma = \frac{P_\infty - P_v}{\frac{1}{2}\rho U^2}$

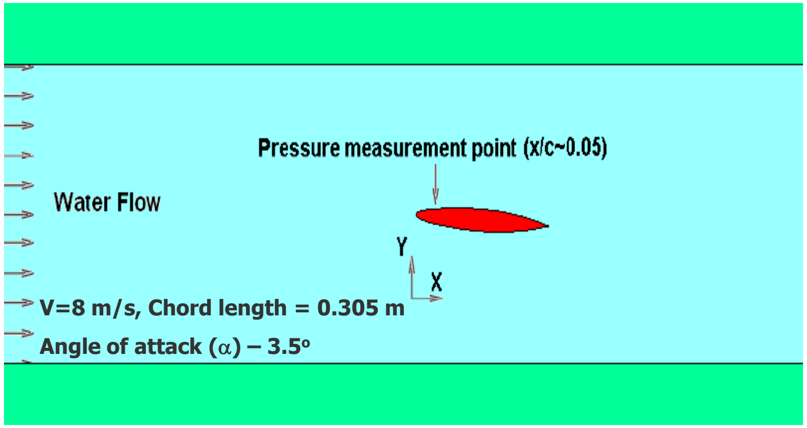


Cavitation Length *vs.* Cavitation Number



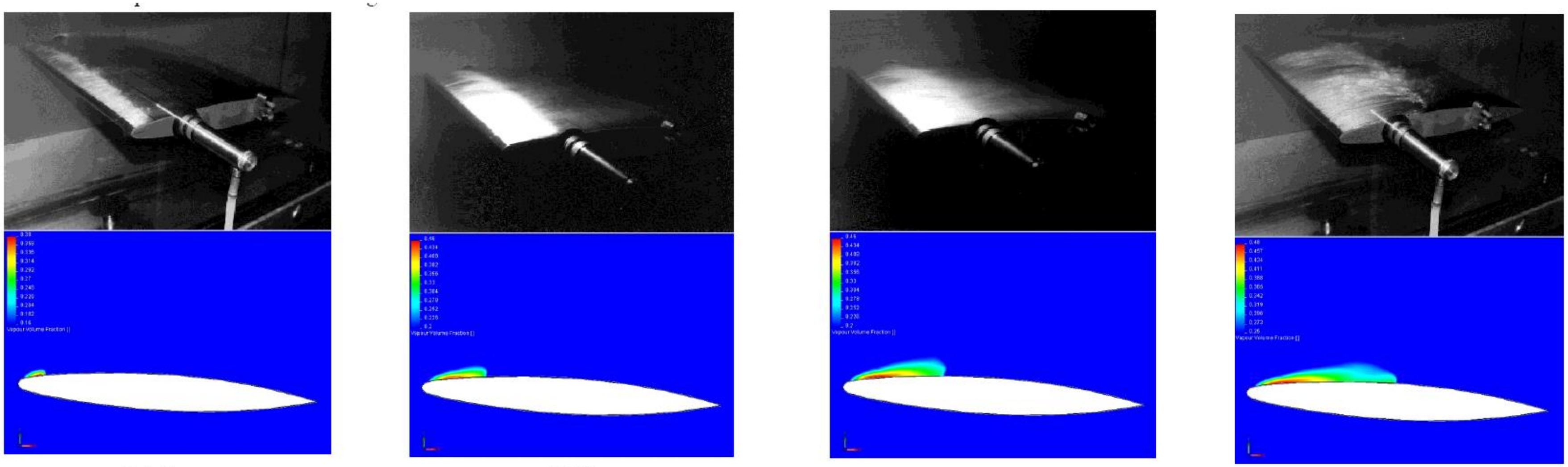
Pressure Coefficient *vs.* Cavitation Number

Caviatition on a Hydrofoil (2); Qualitative Comparison



Reference

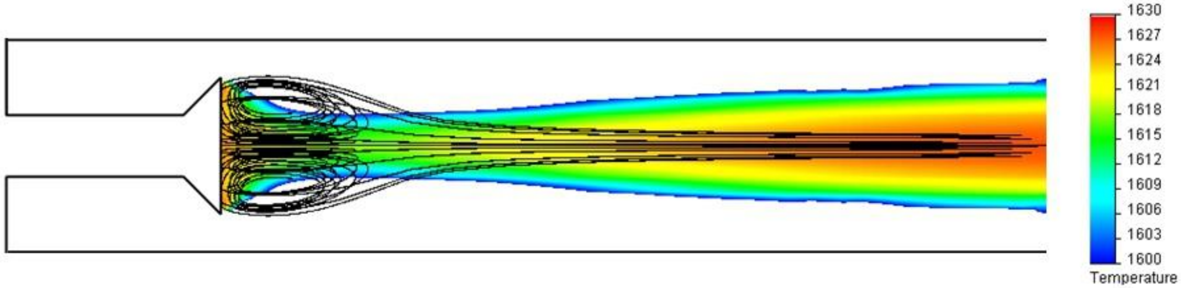
24. Wesley, H.B., Spyros, A.K.: *Experimental & Computational Investigation of Sheet Cavitation on a Hydrofoil.* Presented at 2nd Joint ASME/JSME Fluid Engineering Conference & ASME/EALA 6th International Conference on Laser Anemometry. The Westin Resort, Hilton Head Island, SC, USA August 13-18, 1995

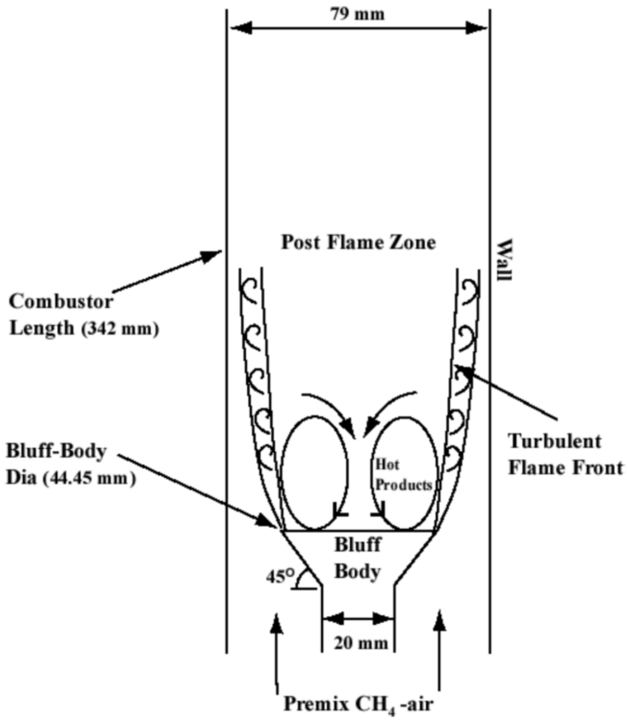


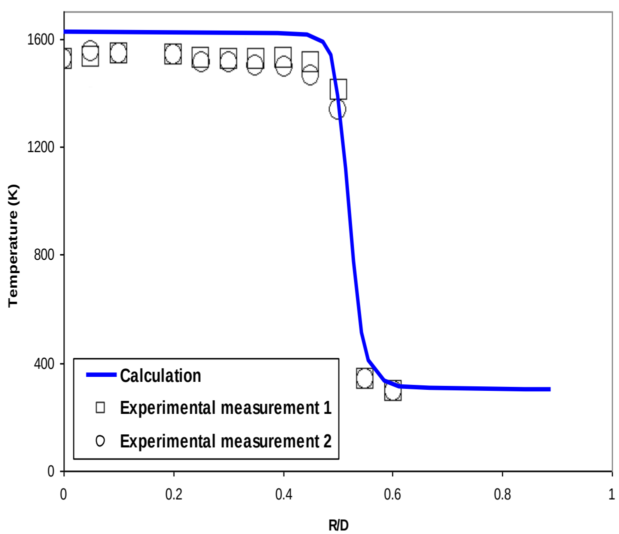
σ=1.1 σ=0.97 σ=0.9 σ=0.88

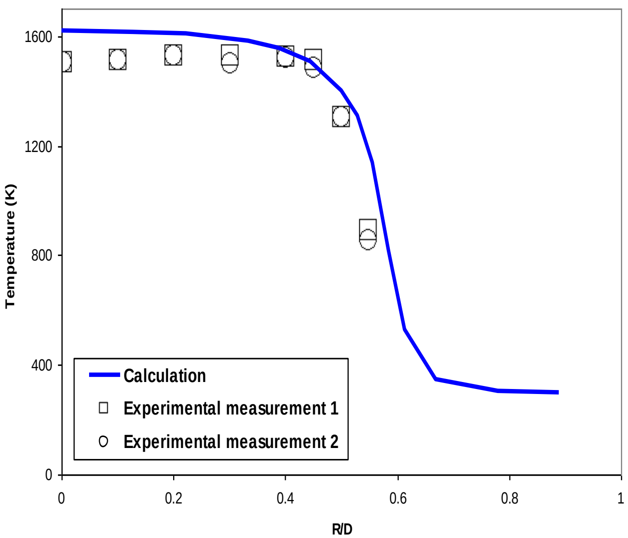
Combustion of a Premixed Methane/Air Mixture

Component	*Mass Fraction, %*
Fuel (Methane)	**3.29**
Oxidizer (Air)	**96.71**





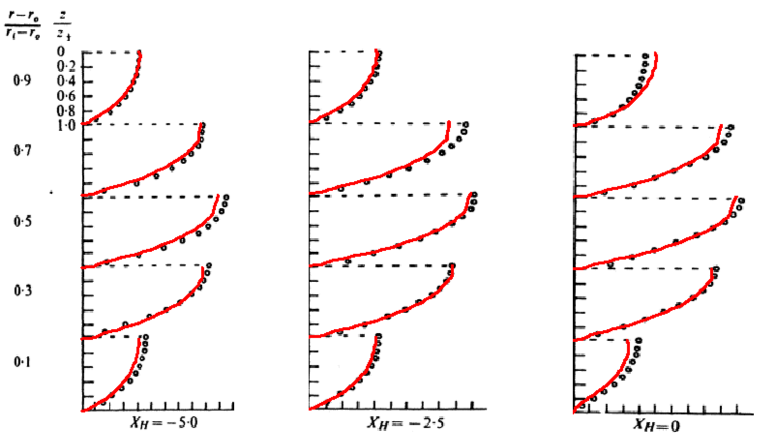


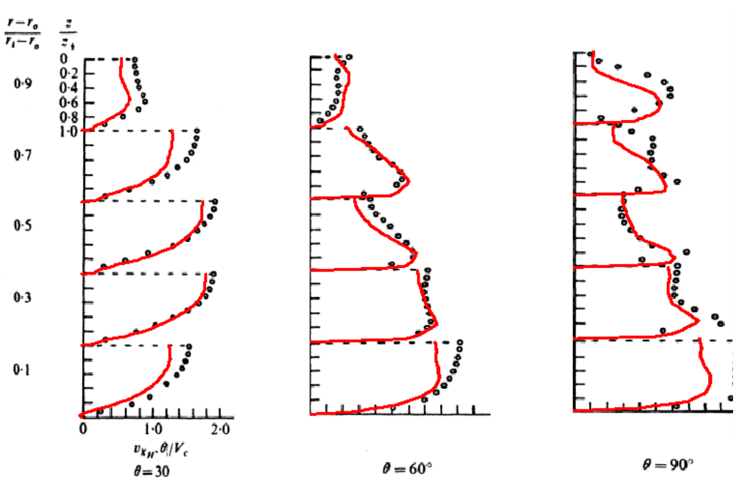


Reference

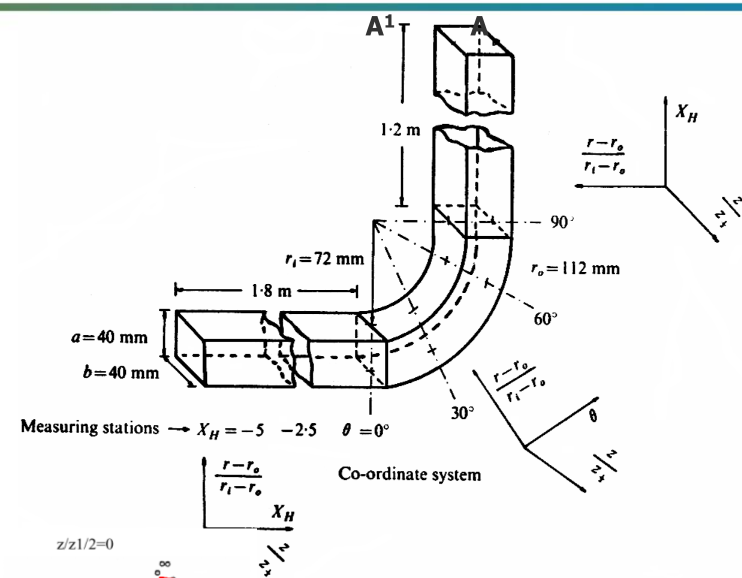
27. Nandula, S.P., Pitz, R.W., Barlow, R.S., Fiechtner, G.J., *Rayleigh/Raman/LIF Measurements in a Turbulent Lean Premixed Combustor"* AIAA 96-0937, 34th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 15-18, 1996

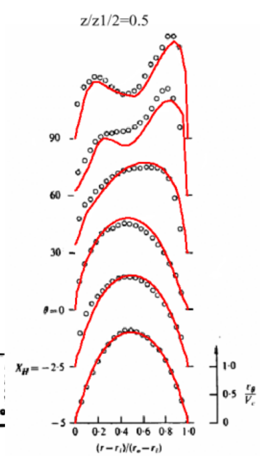
FloEFD Validation:
Flow in a 90º-bend of a 3D square duct

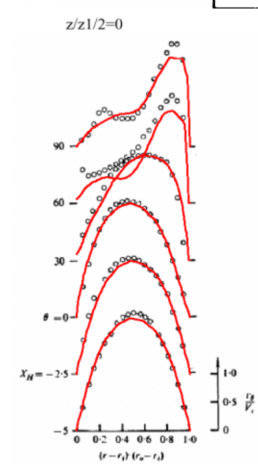


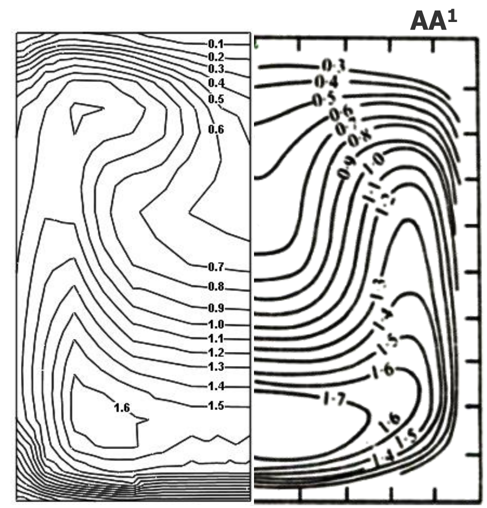


Velocity profiles at different cross sections in different longitudinal planes





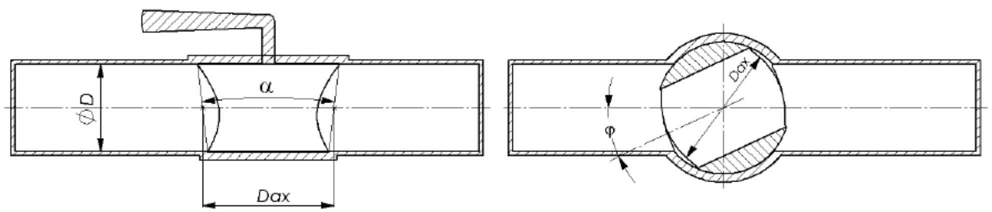


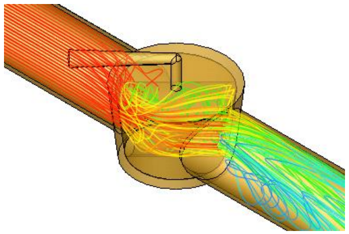


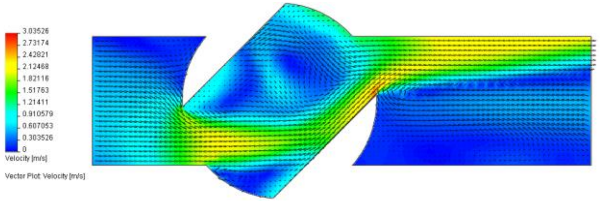
Reference

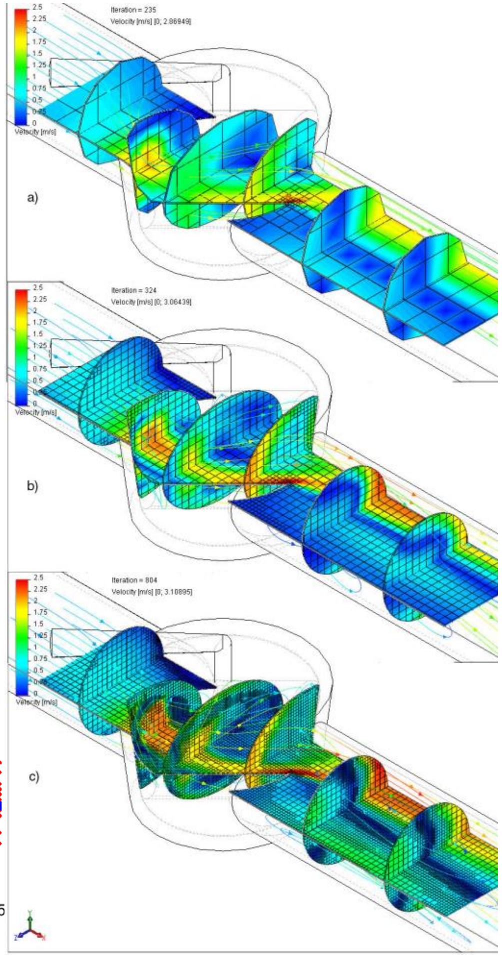
8. Van Dyke, Milton, *An Album of Fluid Motion*. The Parabolic Press, Stanford, California, 1982.

Flow through a Cone Valve

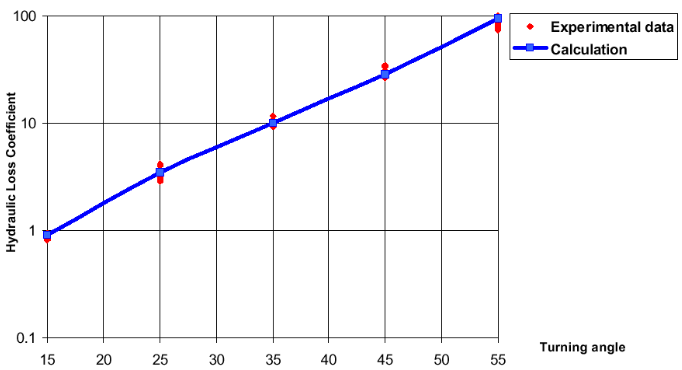




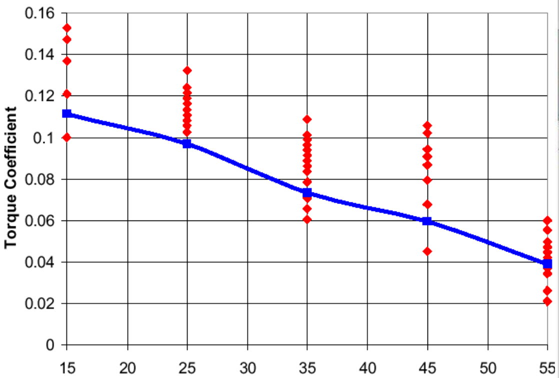




Hydraulic resistance coefficient



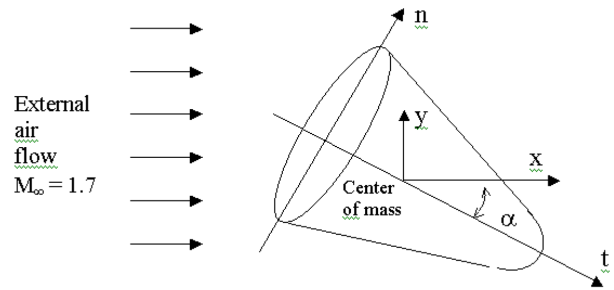
Torque coefficient

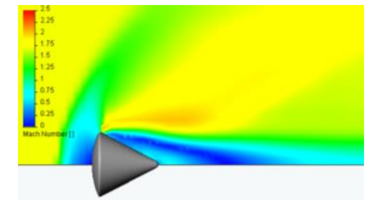


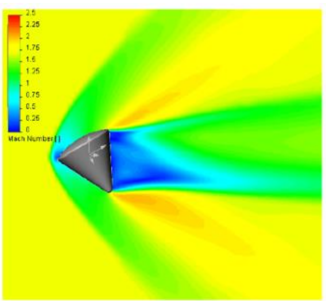
Reference
13. Yanshin, B.I.: *Hydrodynamic Characteristics of Pipeline Valves and Elements. Convergent Sections, Divergent Sections, and Valves*. "Mashinostroenie", Moscow, 1965.

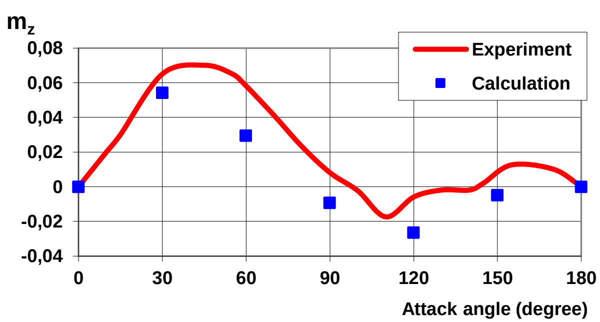
Supersonic Flow over a Segmental Conic Body

- Supersonic air flow at incident M=1.3 over a segmental conic body at different attack angles in the 0…180° range.

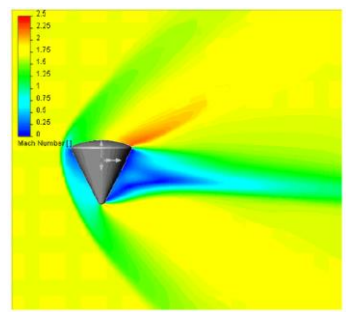


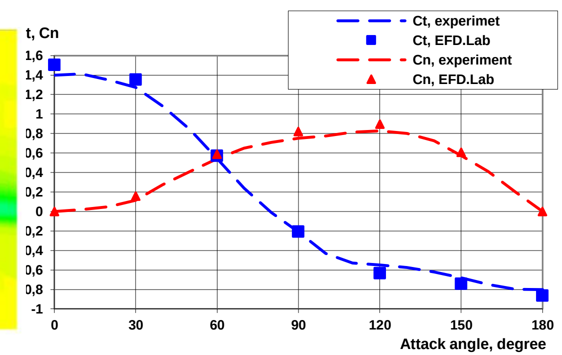






Aerodynamic torque coefficient vs. attack angle





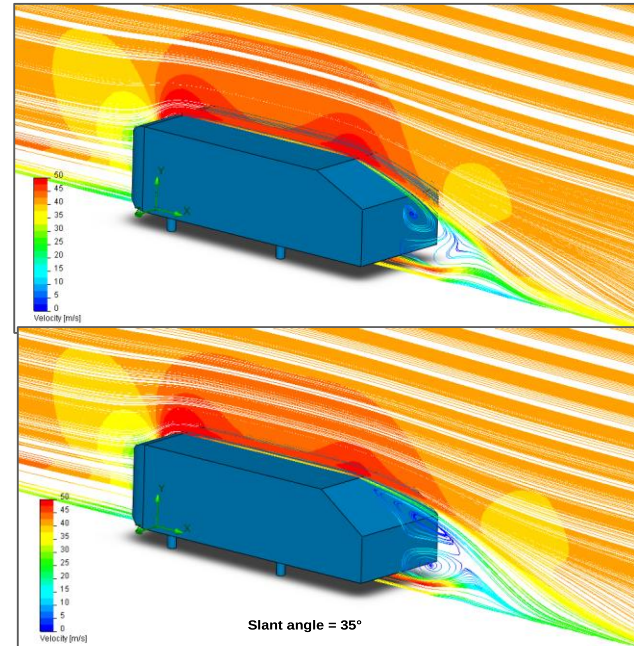
Aerodynamic drag coefficient *vs.* attack angle

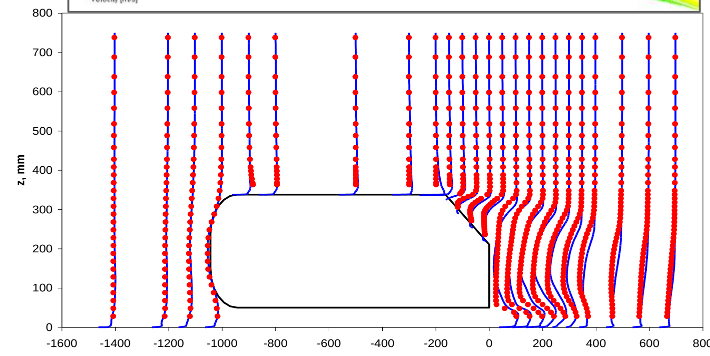
Reference

5. Artonkin, V.G., Petrov, K.P., *Investigations of aerodynamic characteristics of segmental conic bodies*. TsAGI Proceedings, No. 1361, Moscow, 1971 (in Russian).

Flow Around the Ahmed Car Body

Ahmed Body Slant Angle	$C_{d_{exp}}$	$C_{d_{FloEFD}}$	Absolute Difference	% Difference
25°	0.298	0.284	-0.014	-4.8
35°	0.257	0.274	0.017	6.6

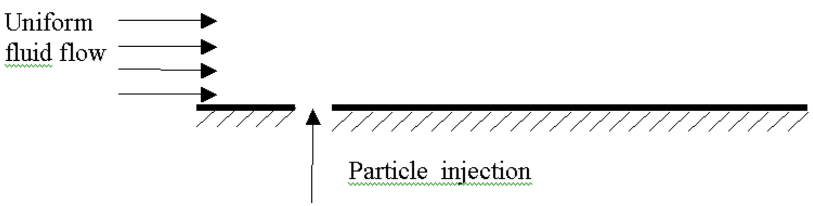




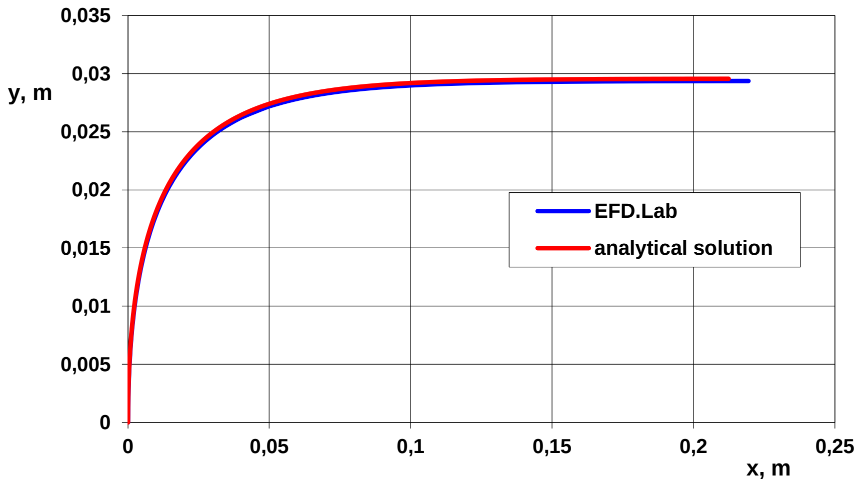
Reference
Lienhart, H., Stoots, C., Becker, S. *Flow and turbulence structures in the wake of a simplified car model (Ahmed model).* DGLR Fach Symp. der AG STAB, Stuttgart University, 2000.

Dispersed-phase flows (droplets and solid particles' trajectories)

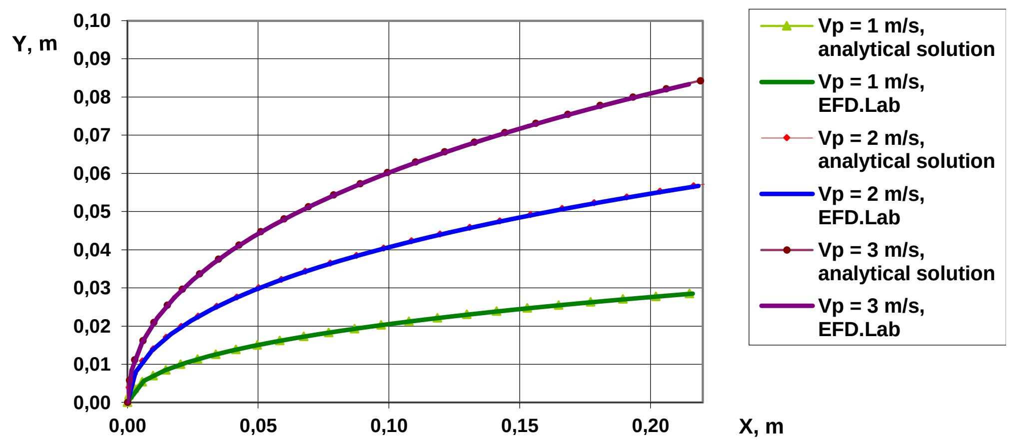
Injection of a particle into a uniform fluid flow field:



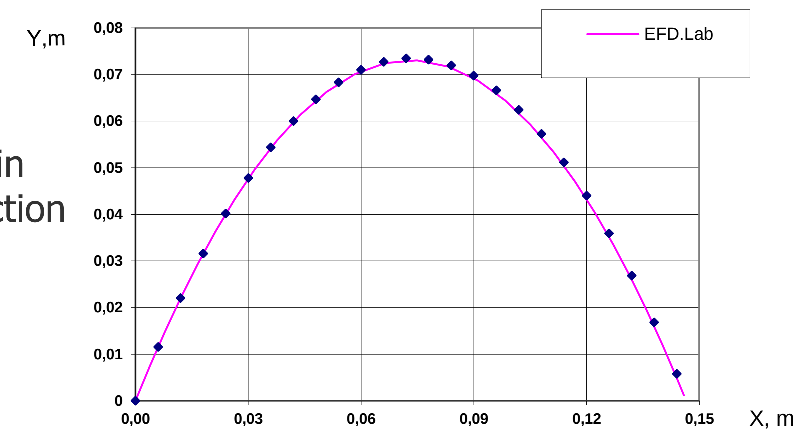
Re = 0.1



Re = 10^5

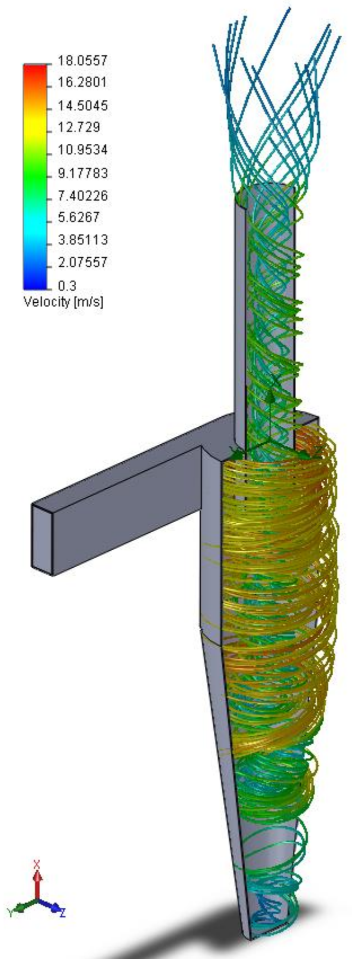


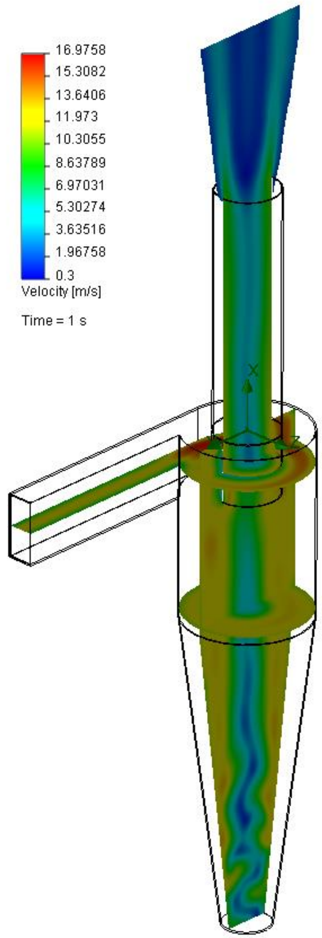
Particle trajectory in the Y-direction gravity

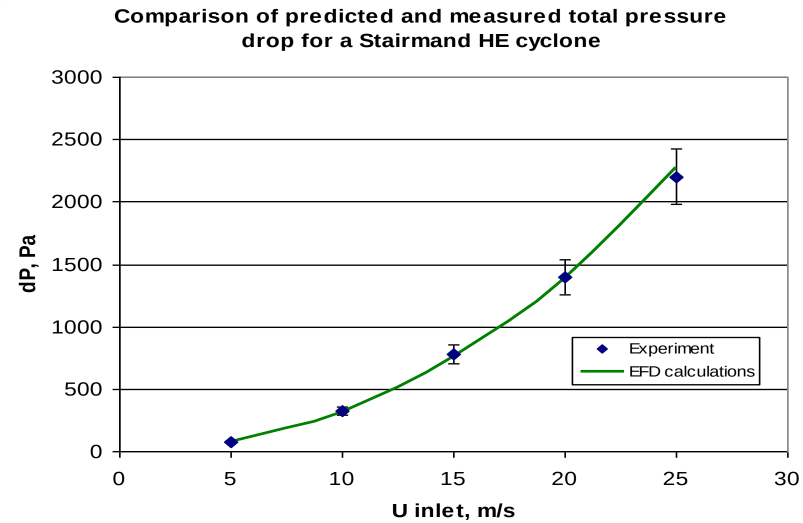


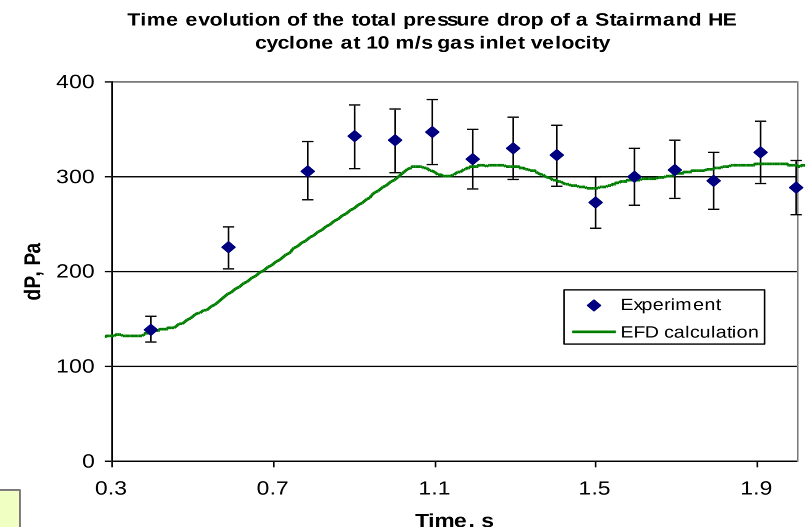
Reference
18. Henderson, C.B. *Drag Coefficients of Spheres in Continuum and Rarefied Flows.* AIAA Journal, v.14, No.6, 1976.

Stairmand High Efficiency Gas Cyclone (Non-isotropic swirling Flows)



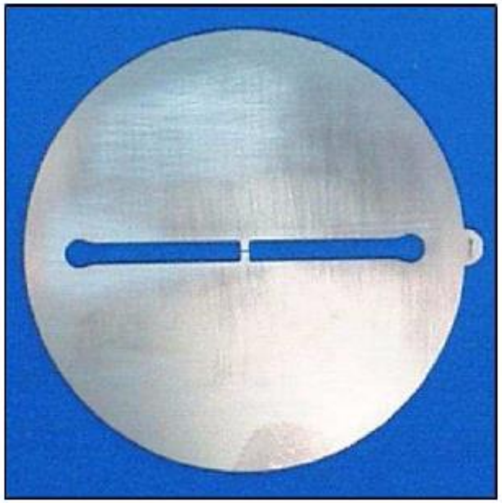






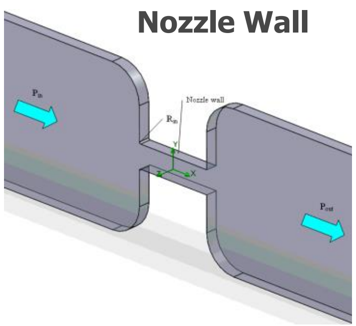
Reference
Griffiths, W.D., Boysan, F., 1996, *"Computational fluid dynamics (CFD) and empirical modelling of the performance of a number of cyclone samplers"*, J. Aerosol Sci, Vol 27, №2, 281-304

Fuel Injector Cavitation



Nozzle Wall

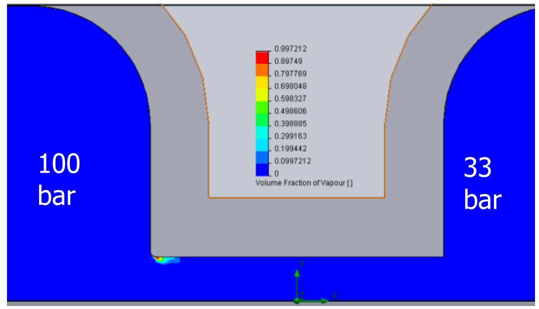
Inlet

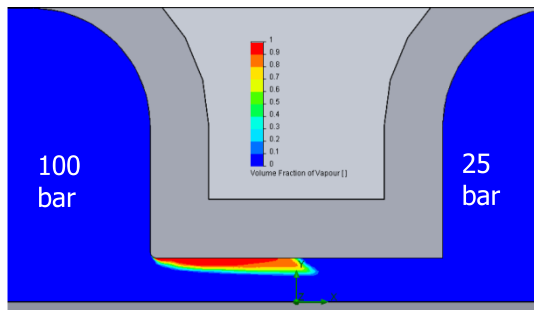


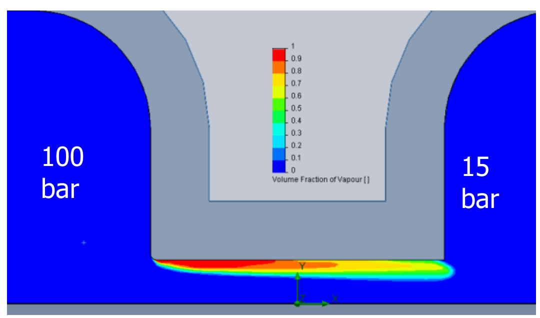
Outlet

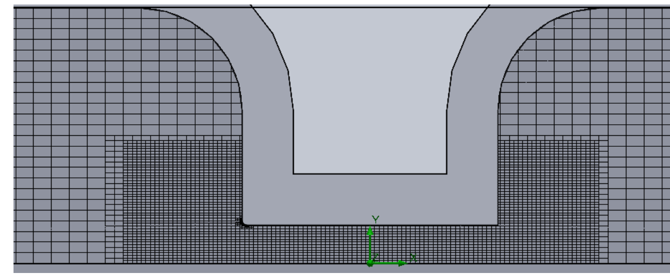
L=0.001 m, H=0.000299 m,

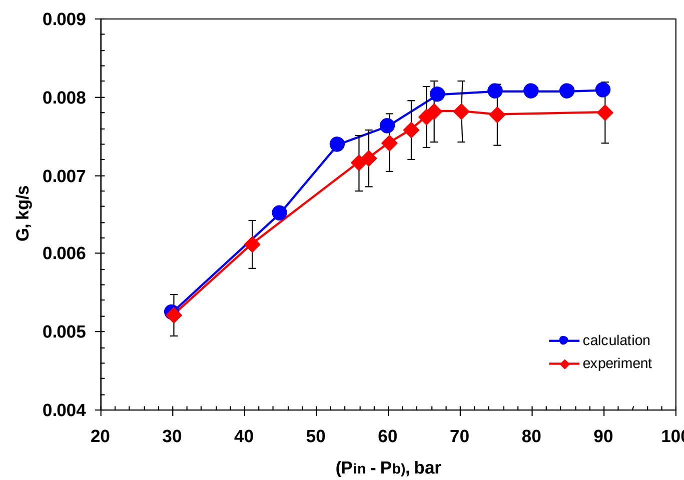
W=0.0003 m, Rin=0.00002 m











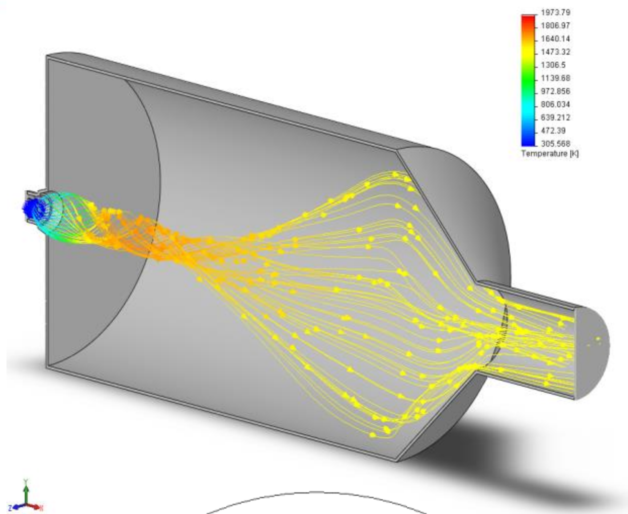
Mass flow rate through the injector versus pressure drop

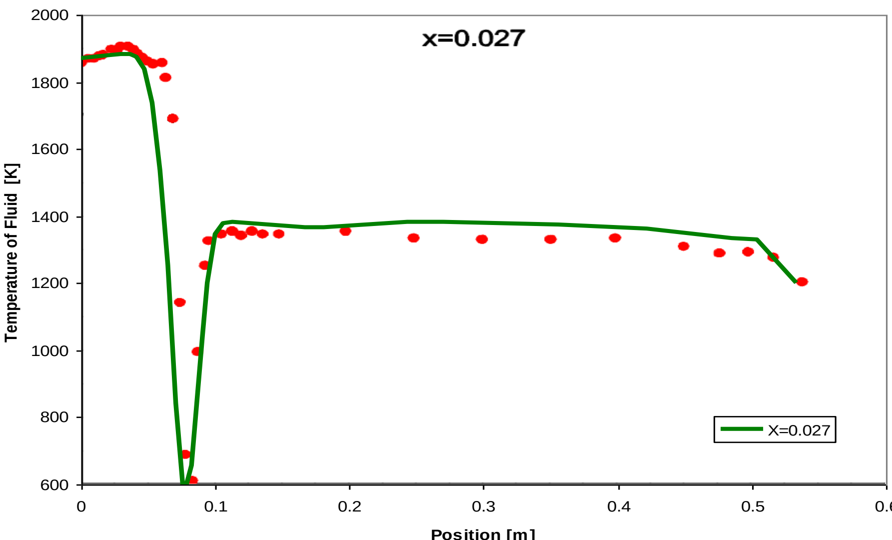
Reference

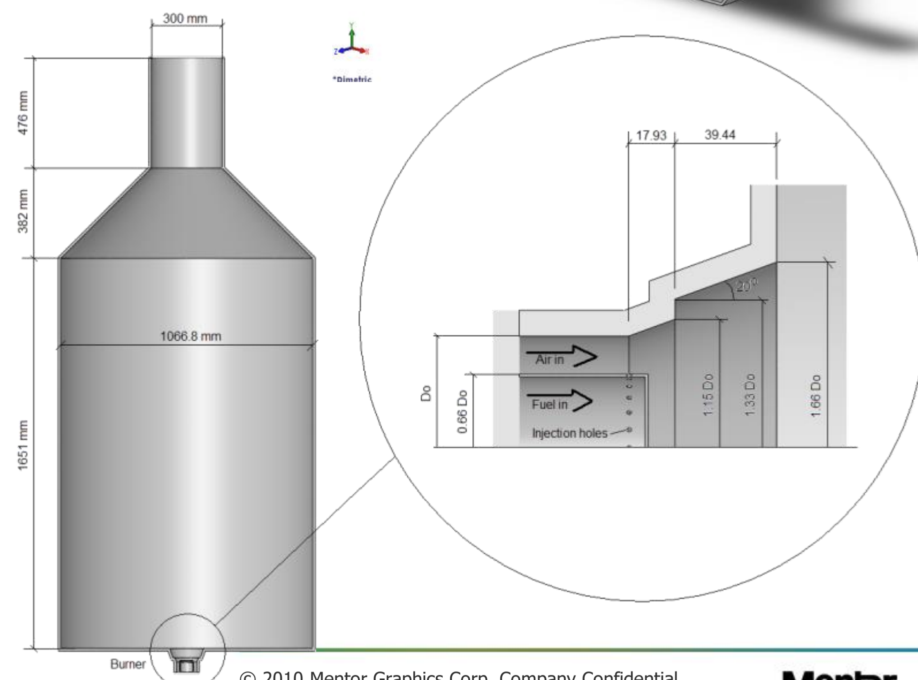
Winklhofer, E., Kull, E., Kelz, E., and Morozov, A., 2001, *"Comprehensive Hydraulic and Flow Field Documentation in Model Throttle Experiments Under Cavitation Conditions."* ILASS Europe 2001.

FloEFD Validation: Vortex Combustor Benchmark

- Modified equilibrium combustion model approach in FloEFD:
  - Combustion starts upon mixing (no pre-mixing)
  - "Limited Combustion Rate" option when premixed. Requires the separate simulation of an igniter to start the combustion simulation







Reference
Sayre A, N. Lallemant, J. Dugue, R. Weber, 1994, *Scaling Characteristics of Aerodynamics and Low-NOx Properties of Industrial Natural Gas Burners,* The Scaling 400 Study, Part IV: The 300 kW BERL Test Results, IFRF Doc No F40/y/11, The Netherlands.