Extension and Validation of the CFX Cavitation Model for Sheet and Tip Vortex Cavitation on Hydrofoils

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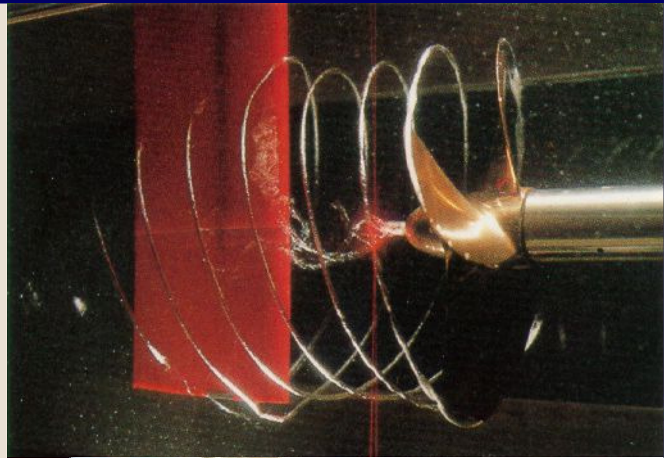
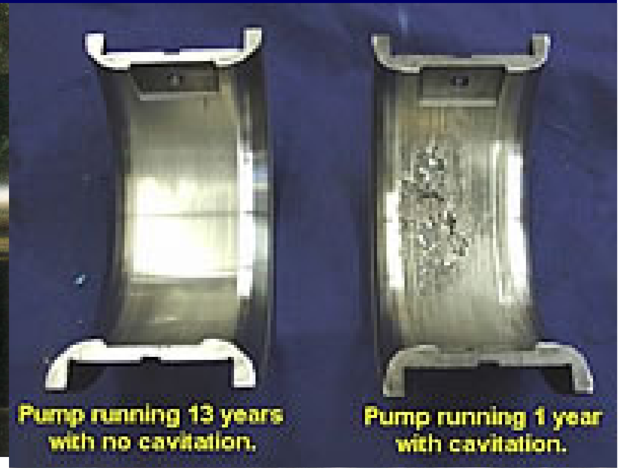
Overview

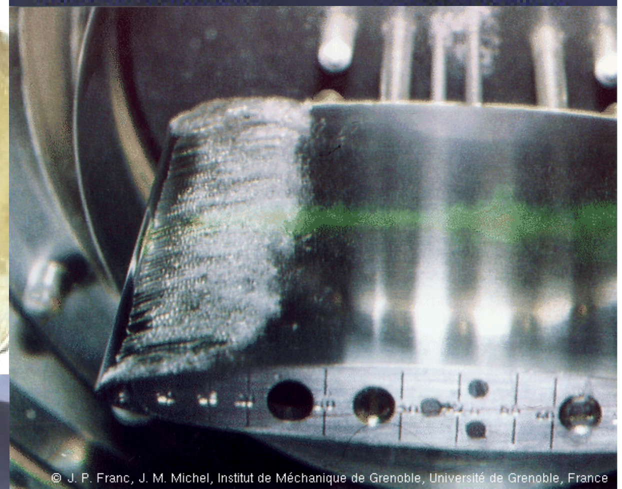
- Introduction
- Cavitation project
  - Goals
  - Cavitation model
  - Testcases
- Results
  - Testcase set-up
  - Validation studies
- Summary

Cavitation on Pumps, Propellers & Hydrofoils

- Cavitation phenomena
- Propeller
  - Tip vortex cavitation
- Hydrofoil
  - Sheet & cloud cavitation





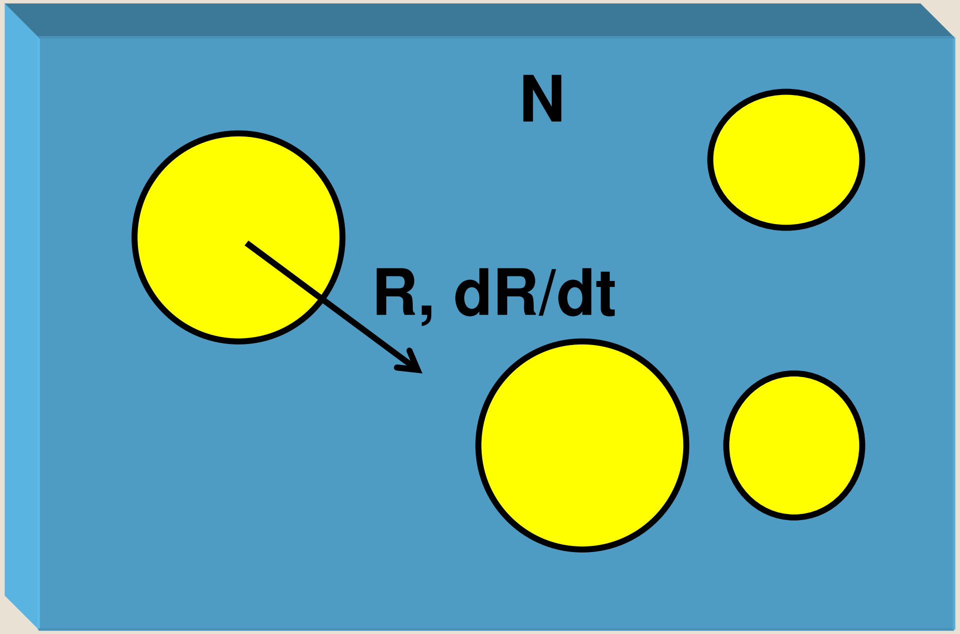


Cavitation Project

- Title
  - Investigation of higher order pressure fluctuations and its influence on ship stern, taking into account cavitation at propeller blades
- Project partners
  - SVA Potsdam, ANSYS Germany
- Duration
  - July 2005 to June 2008
- Funded by German Ministry of Education and Research (BMBF)
- Main issues
  - CFD & experiments for ship propeller cavitation
  - Cavitation including transient effects
  - Cavitation induced pressure fluctuations and interaction with ship stern

Cavitation Model-Rayleigh-Plesset Equation

- **Interfacial mass transfer**



$$\Gamma_{lv} = \dot{m}_{lv} A_{lv}$$

$$\dot{m}_{lv} = \frac{dm_v}{dt} = \rho_v \frac{dR}{dt}$$

$$\frac{dR}{dt} = \sqrt{\frac{2}{3} \frac{P_v - P}{\rho_l}}$$

Cavitation Model-Rayleigh-Plesset Equation

$$\Gamma_{lv} = F_{vap} \frac{3\alpha_{nuc}(1-\alpha_v)}{R} \rho_v \sqrt{\frac{2}{3}\frac{P_v - P}{\rho_l}} \quad \text{if } P < P_v$$

$$\Gamma_{vl} = -F_{con} \frac{3\alpha_v}{R} \rho_v \sqrt{\frac{2}{3}\frac{P - P_v}{\rho_l}} \quad \text{if } P > P_v$$

- **Modified interfacial area density for vapourisation**
- **$F_{vap} = 50$, $F_{con} = 0.01$**
- **$\alpha_{nuc} = 5 \times 10^{-4}$**

Turbulent Pressure Fluctuations

Pressure fluctuations in the (U)RANS equations:

$$P = \overline{P} + p'$$

Where

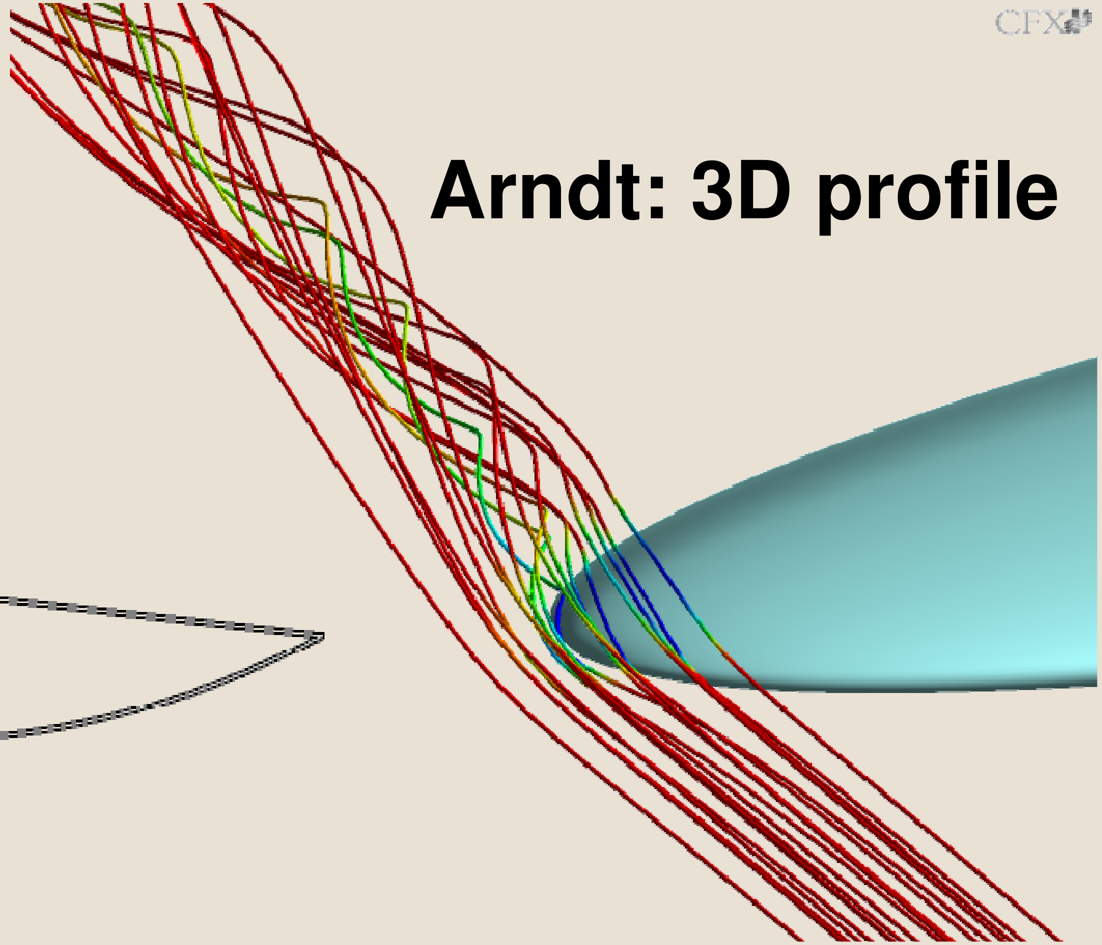
$$\tilde{p} = \sqrt{\overline{p'^2}} \sim CAV_{coef}\,\rho(1-\alpha_v)k = \frac{1}{2}CAV_{coef}\,\rho(1-\alpha_v)(\overline{u'^2}+\overline{v'^2}+\overline{w'^2})$$

Therefore:

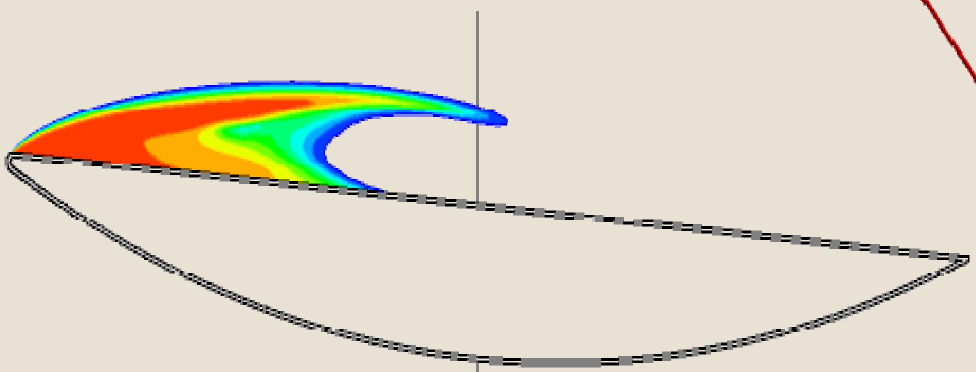
$$\frac{dR}{dt} = \sqrt{\frac{2(P_v - \overline{P} - \tilde{p})}{3\rho_l}}$$

$$CAV_{coef} = 0.39$$

Project Testcases



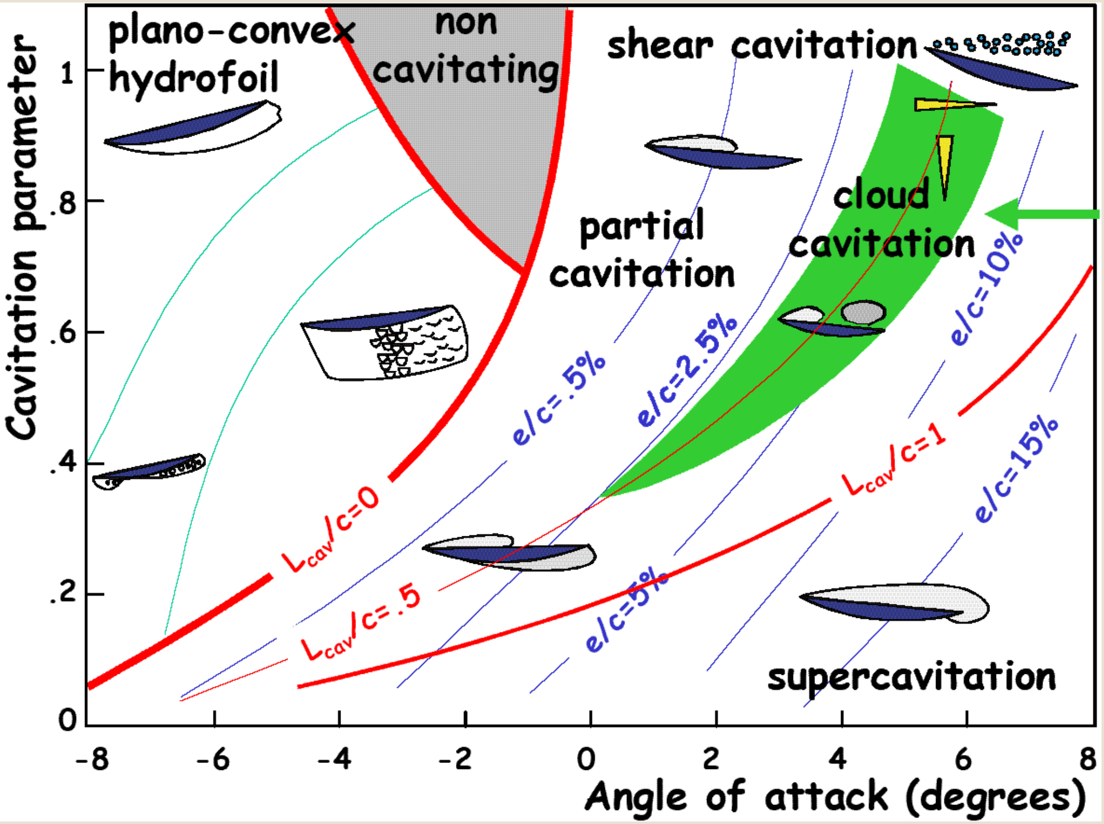
Arndt: 3D profile

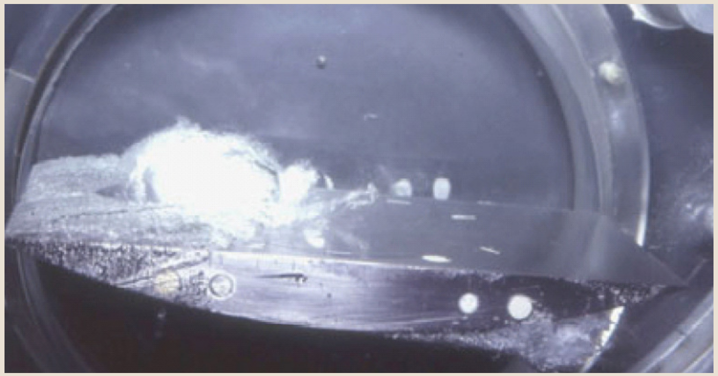


Le: 2D profile

Le Profile

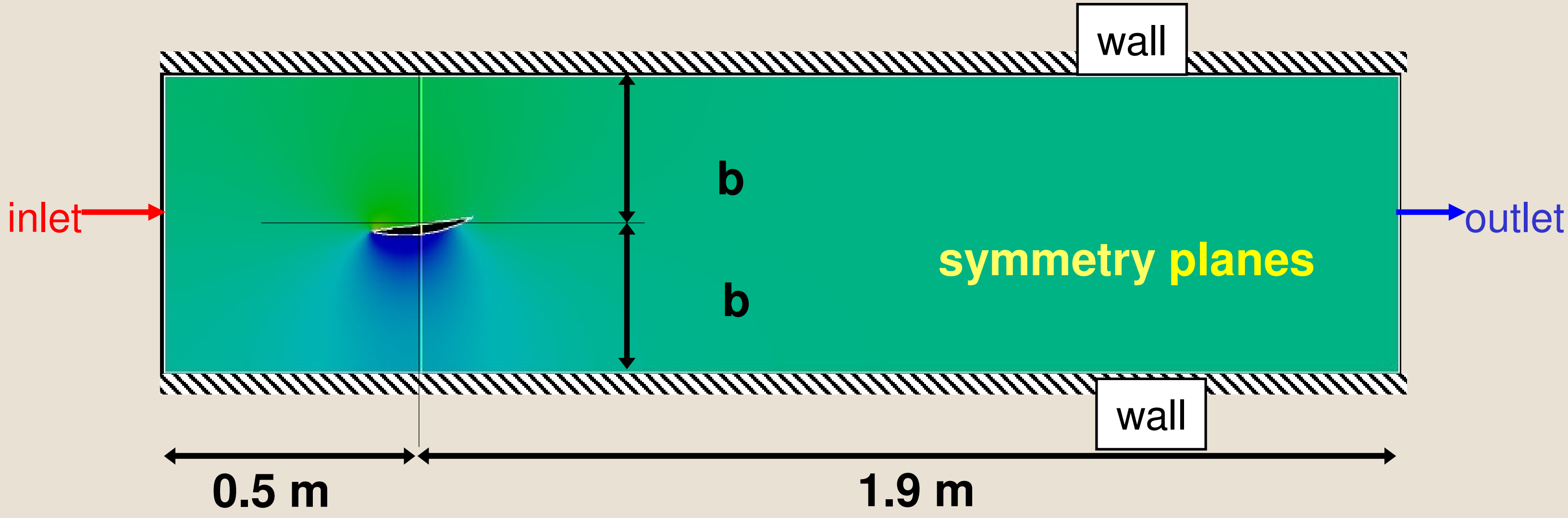
- **Measurements of Le et al. (1993) & Franc (2001)**
  - **Two-dimensional profile**
  - **Different cavitation phenomena**





$$\sigma = \frac{P_\infty - P_v}{0.5 \rho v_\infty^2}$$

Set-up: Boundary Conditions



- Inlet: Specified velocity (from Reynolds number)
- Walls: Free slip
- Outlet: Static pressure for entrainment

Meshing: Grid Hierarchy

- ICEM CFD HEXA
  - Geometry rotation for different angle of attack
- 2d refinement between grids by scale factor 2×2

Grid	Coarse(2)	Medium(3)	Fine(4)
Number of nodes	56,452	224,264	893,986
Number of elements	27,840	111,360	445,440
Minimum grid angle	41°	38°	43°
First layer distance y [μm]	10	5	2.5
Average y^+	4	2	1

Validation: Cavitation Length

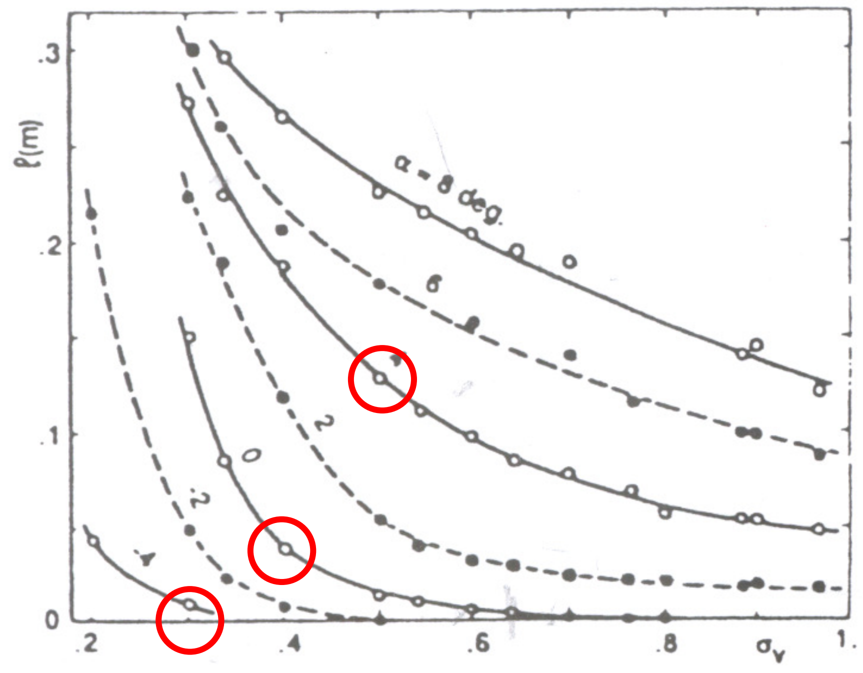
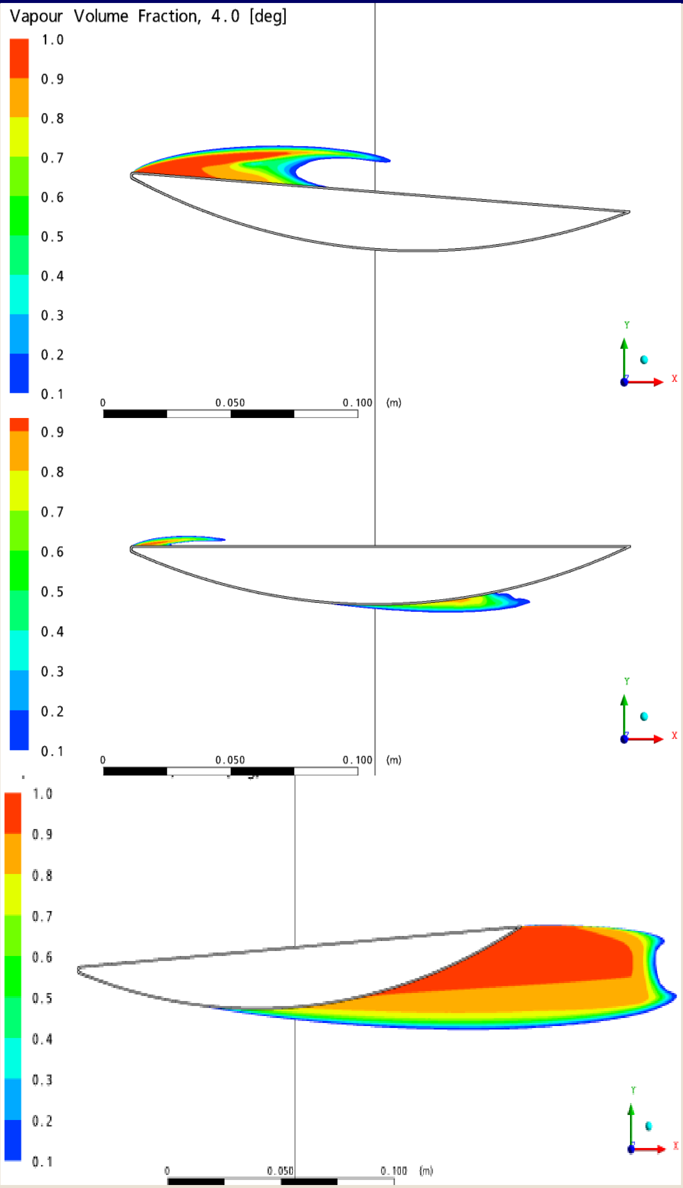


Fig. 5 Cavity length versus cavitation number

C_0=0.198m

- Transient simulations, time averaged data



α=4°

σ=0.5

α=0°

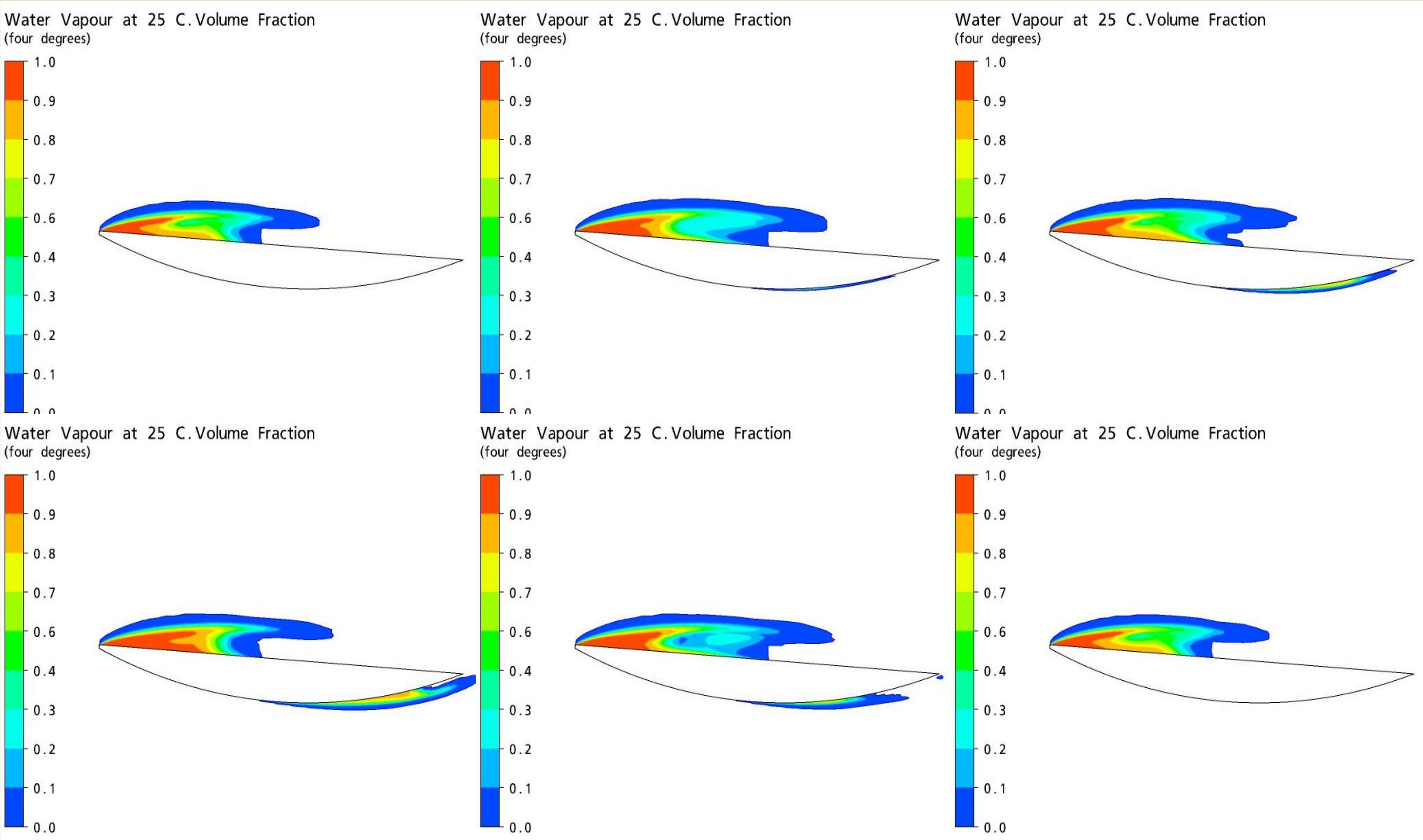
σ=0.4

α=-4°

σ=0.3

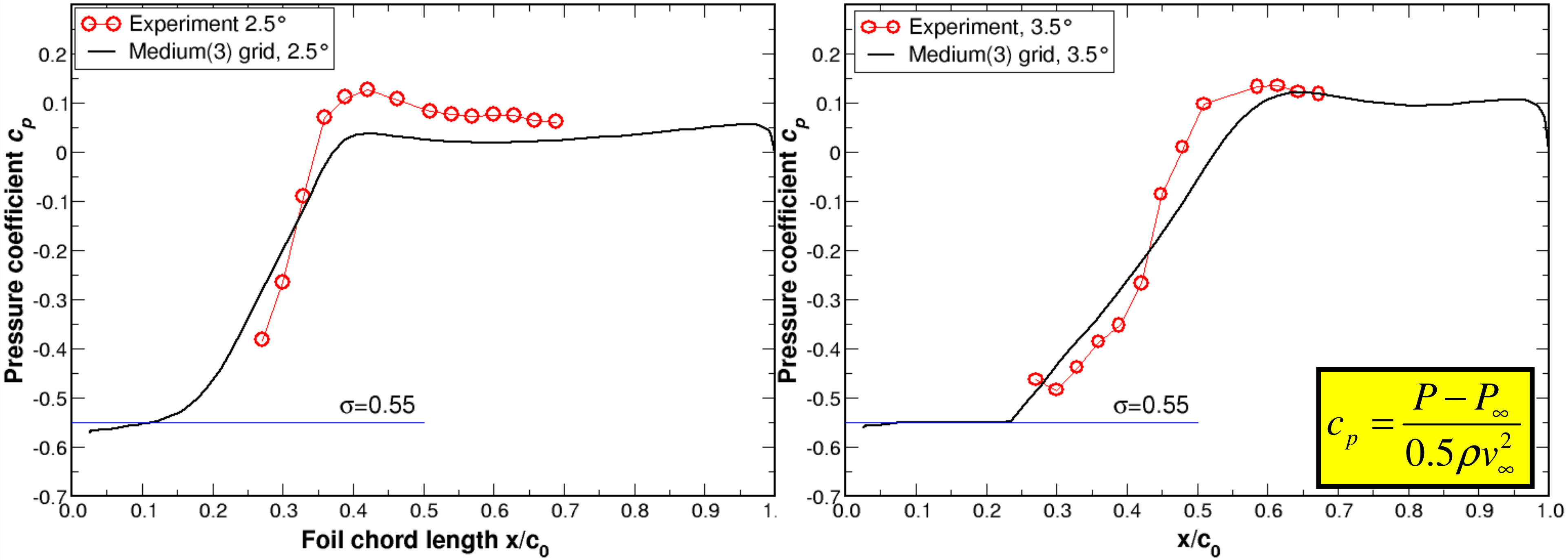
Validation: Cavitation Length

- **Transient simulation , $\alpha=4°$, $\sigma=0.5$**



Validation: Pressure Distribution

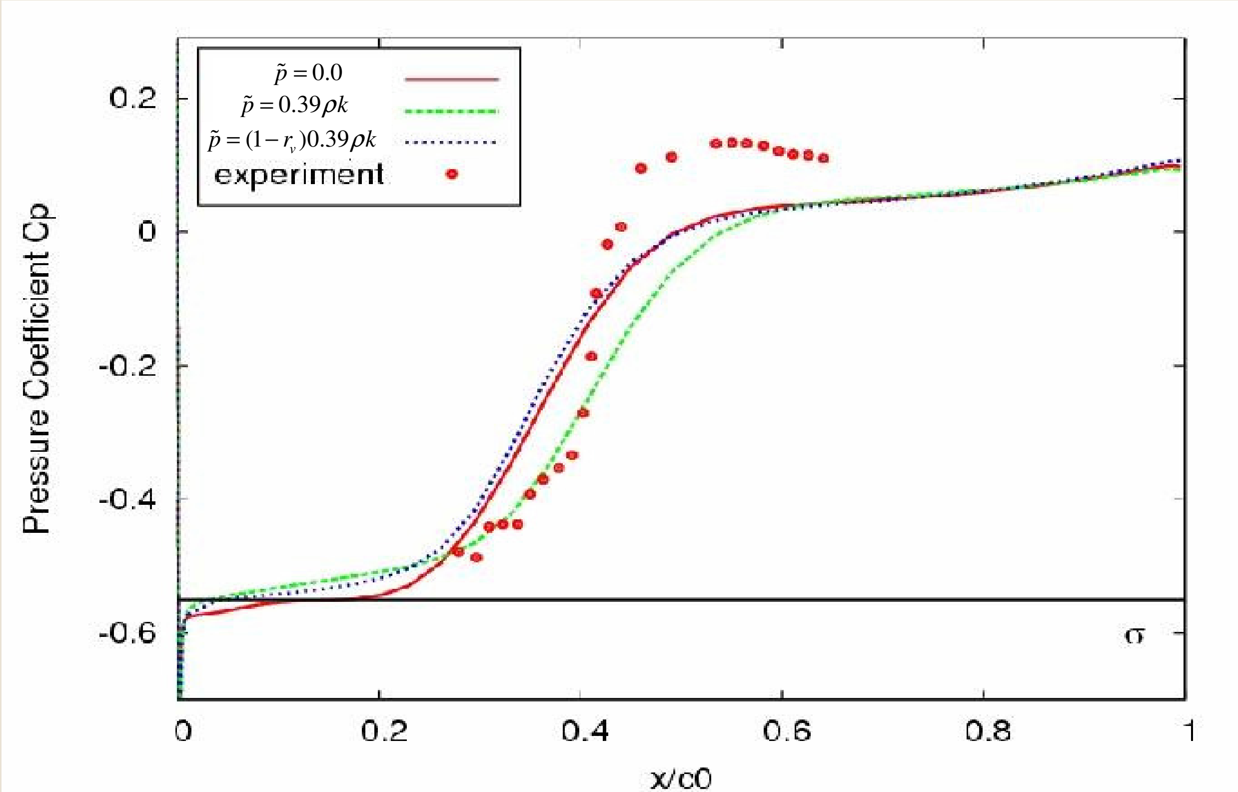
- **Pressure coefficient distribution on foil upper side**
- **Angle of attack: α=2.5° and α=3.5°**



- **Transient simulations, time averaged data**

Validation: Pressure Distribution

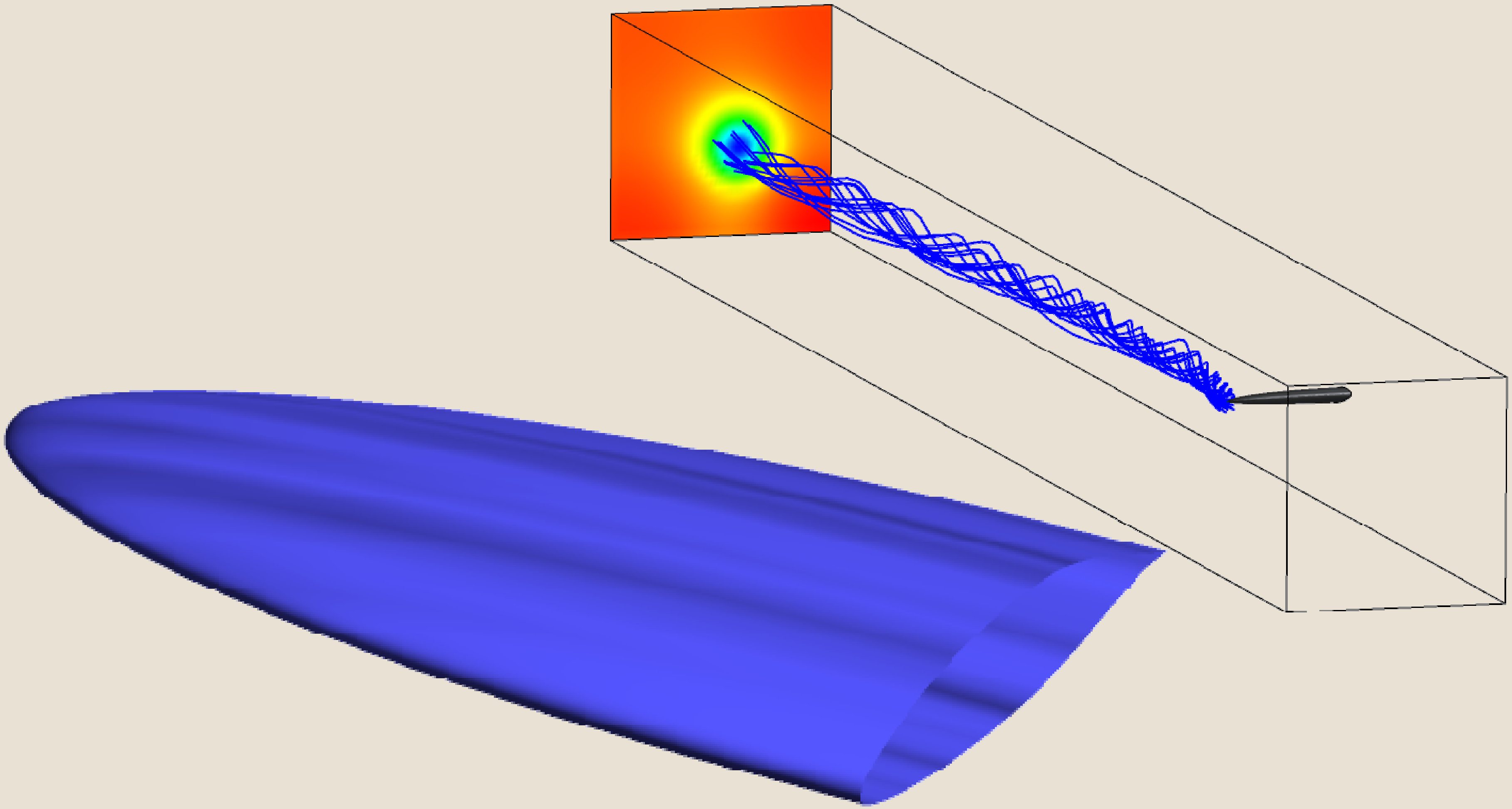
- **Pressure coefficient distribution on foil upper side**
- **Angle of attack: α=3.5°, σ=0.55**



- **Transient simulations, time averaged data**

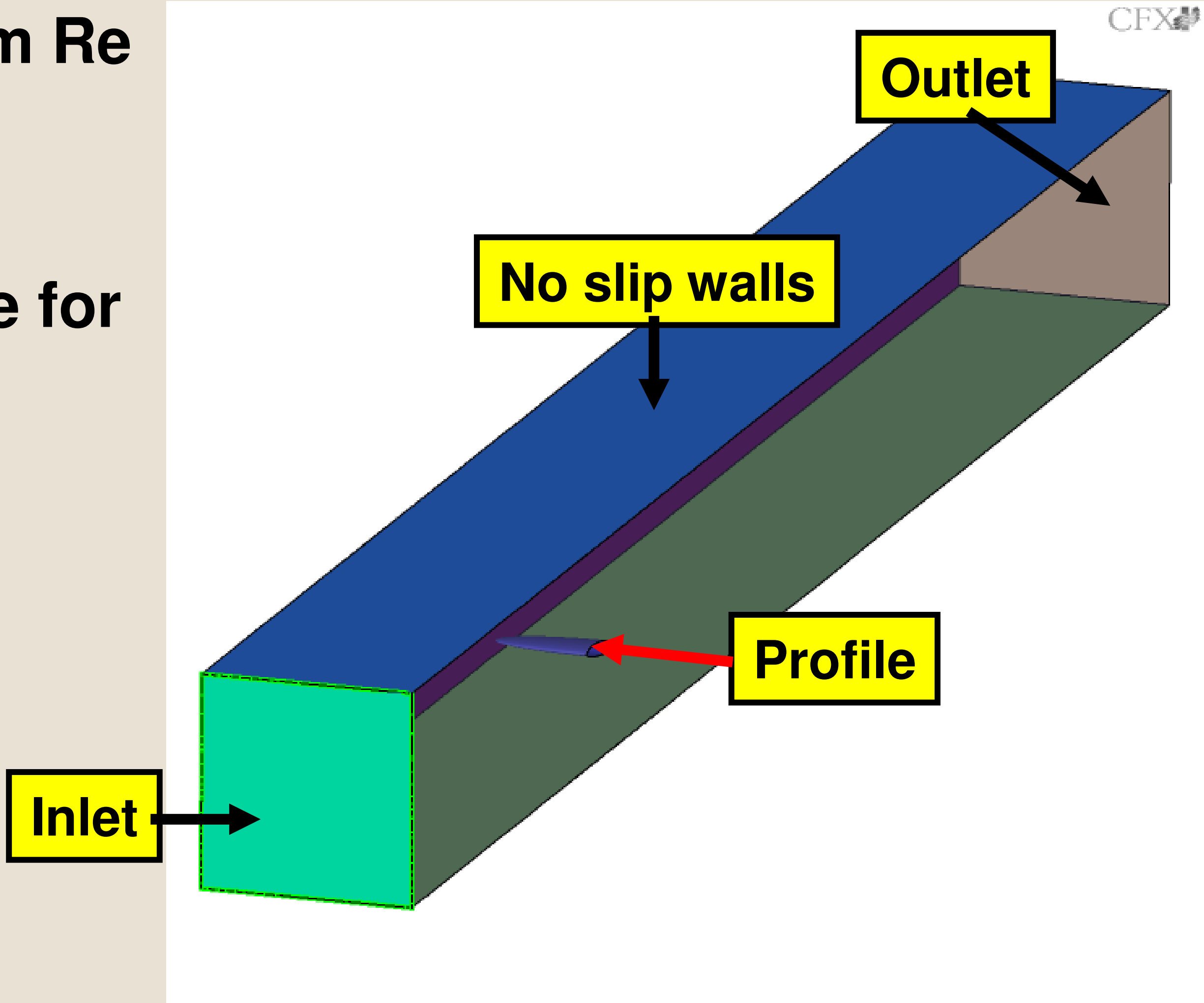
Arndt Profile

- **Measurements by Arndt, R.E.A. and Dugue (1992)**



Set-up: Boundary Conditions

- Inlet
  - Computed from Re number
- Outlet
  - Static pressure for entrainment
- Walls
  - No slip



Meshing: Topology

- ICEM CFD structured meshes
  - C-Grid type grid around foil surface
  - Quarter O-Grid between C and O-Block connection at blade tip

Meshing: Grid Hierarchy

- **Boundary layer resolution**
  - Relation of first cell spacing to y+ value

$$\Delta y = L\sqrt{80}\,\mathrm{Re}_L^{-13/14}\,\Delta y^+$$

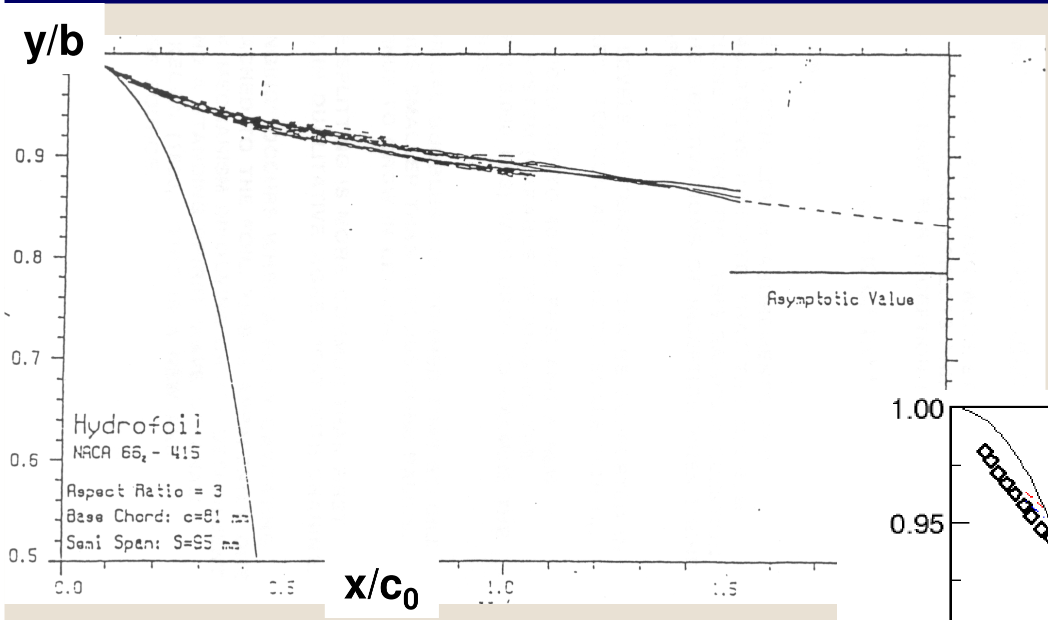
- **Scaling factor between grids ~** $\sqrt[3]{4}\times\sqrt[3]{4}\times\sqrt[3]{4}$

Grid	Coarse (1)	Medium (2)	Fine (3)
Number of nodes	358,519	1,394,862	5,442,459
Number of elements	341,596	1,352,603	5,337,217
Minimum grid angle	21°	21°	21°
First layer distance y [μm]	30	15	7.5
Average y^+	14.3	7.1	3.6

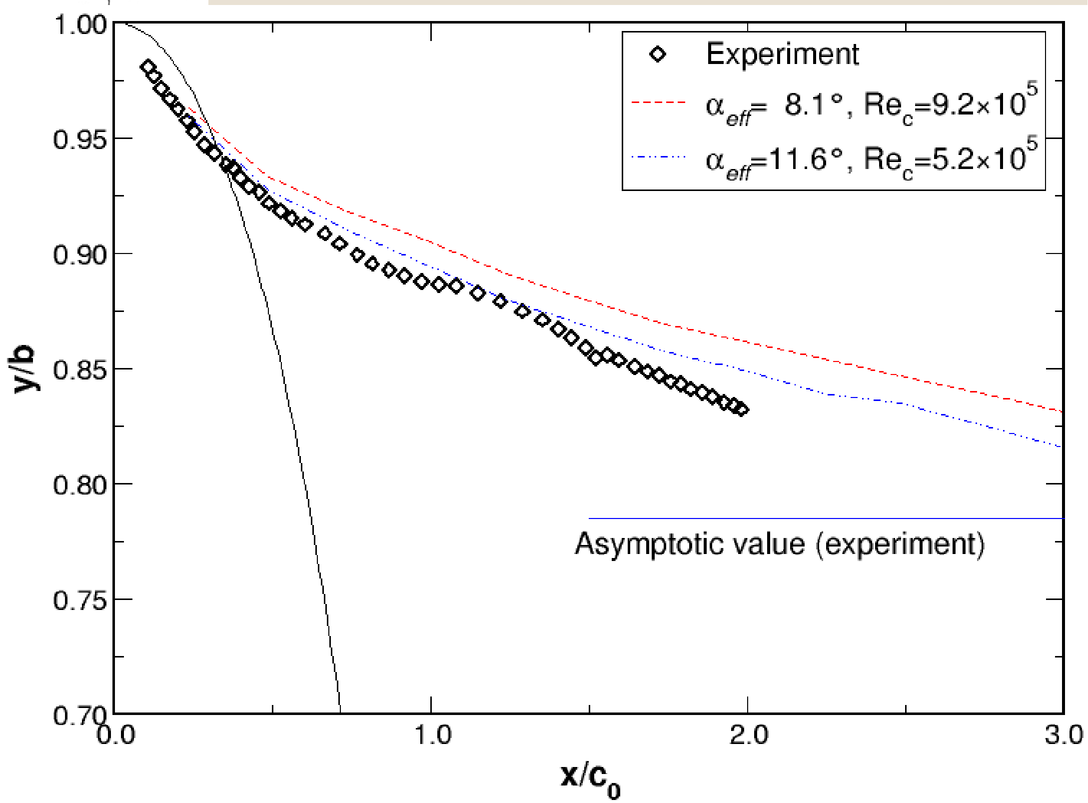
Set-up: Physical Models

- Spatial discretization
  - High Resolution for hydrodynamic system
  - Upwind / High Resolution for k-ω equations
- Time integration
  - 2nd order Backward Euler
- Two-phase flow
  - Water, water vapour
- Mass transfer
  - Rayleigh-Plesset cavitation model
- Turbulence
  - SST, SST with Curvature Correction, BSL-RSM

Validation: Tip Vortex Trajectory

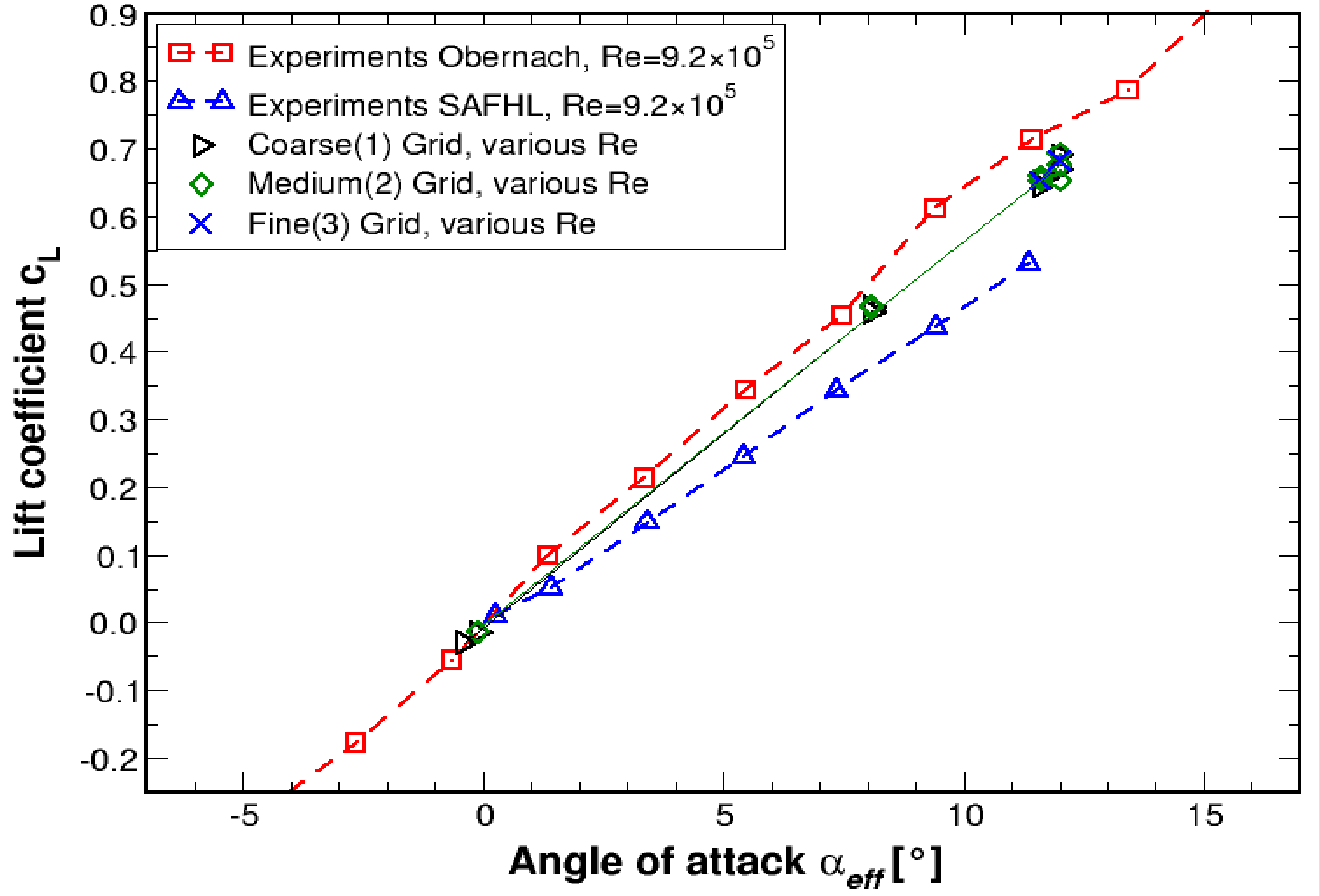


- **Multiple measurements:**
  - **Various Re numbers**
  - **Various angle of attack**



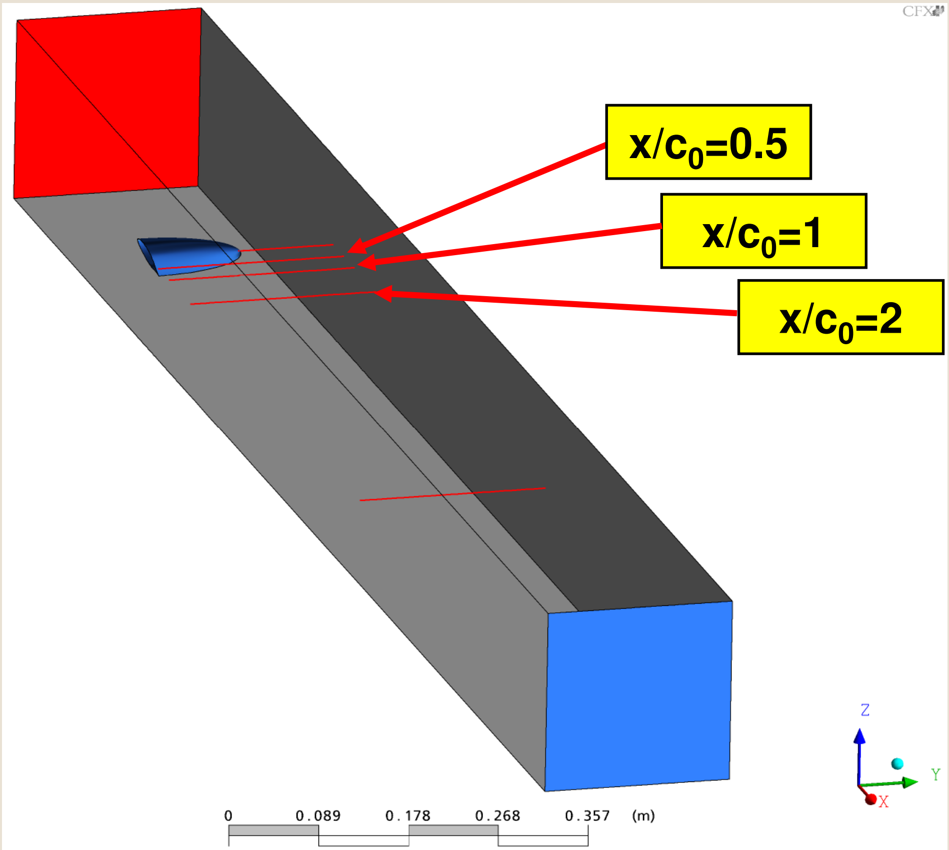
Validation: Lift Curve

- Lift coefficients vs. Effective angle of attack (α-α_0)
- Experiments: Re_c=9.2×10^5, Simulation: various Re_c



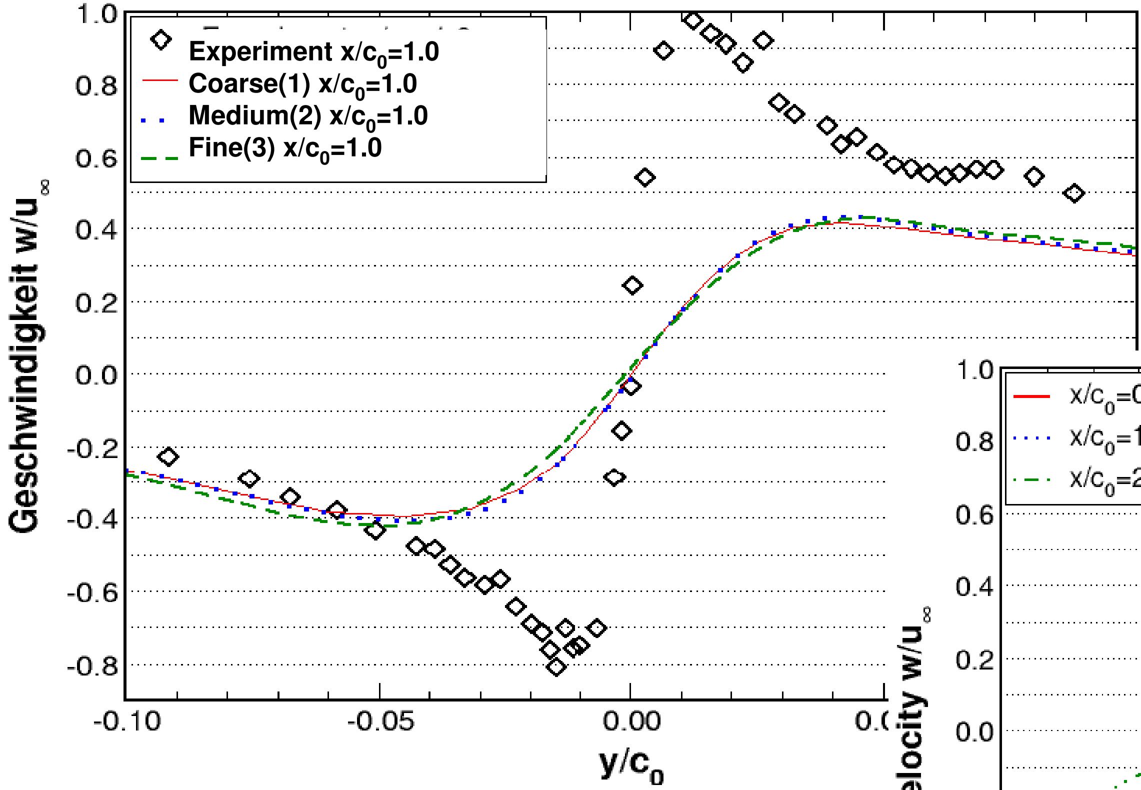
Validation: Tip Vortex Velocity

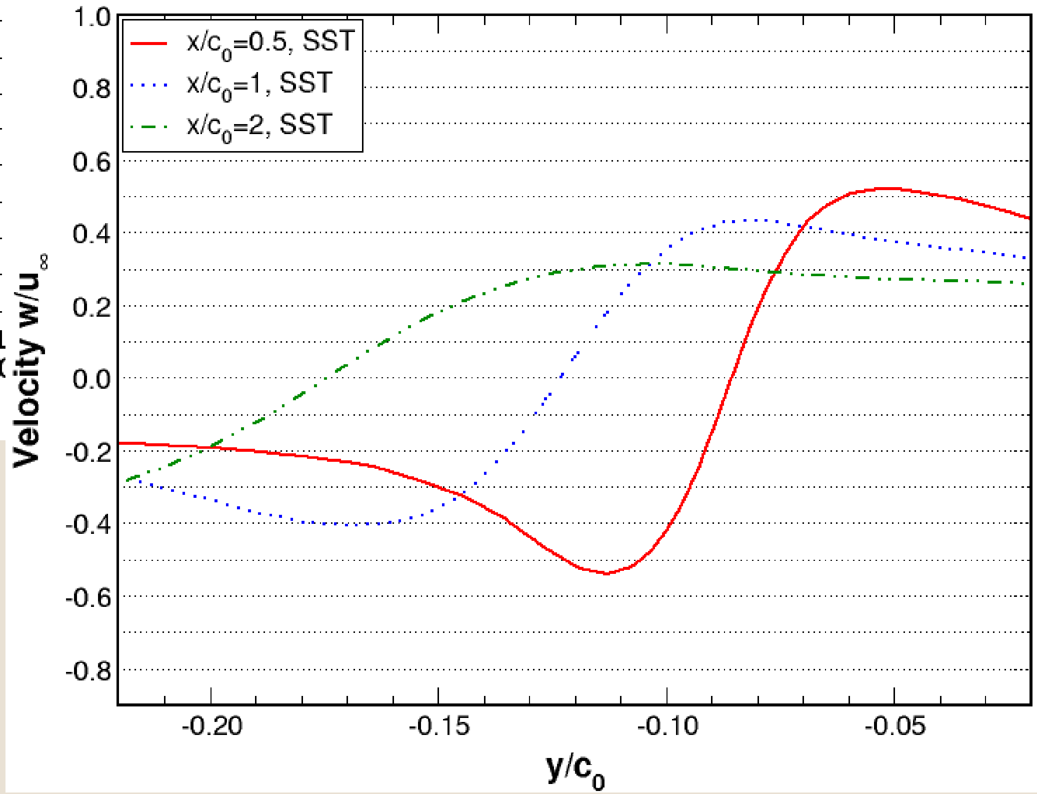
- **Measurement planes**
  - Evaluation of vortex velocity at plane perpendicular to flow at x/c=0.5, 1.0, 2.0 behind hydrofoil



Validation: Tip Vortex Velocity

$\alpha_{eff}=12°$, $Re=5.2\times10^5$





Vortex velocity distributions

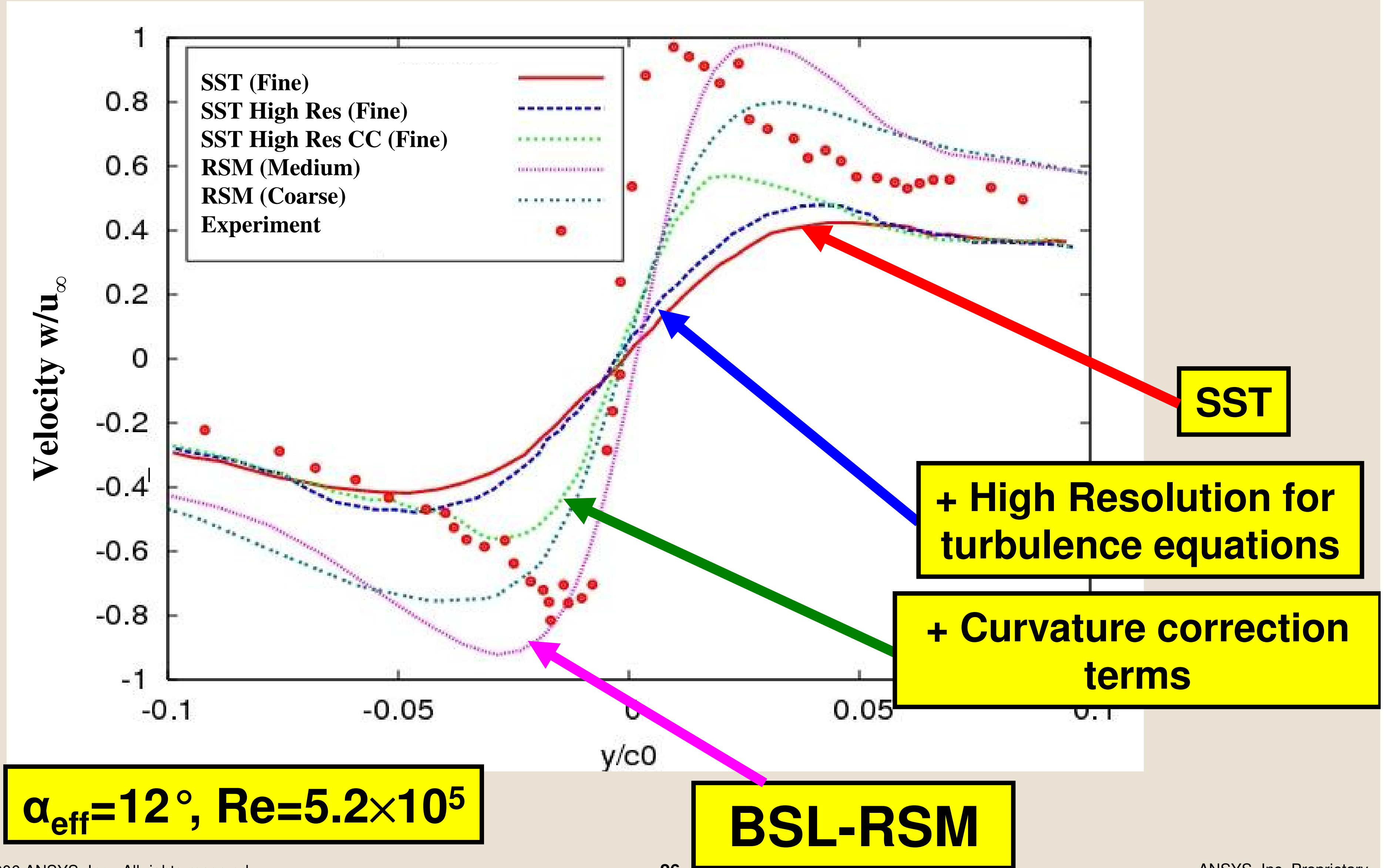
Cavitation inception in core of tip vortex

Validation: Tip Vortex Velocity

Turbulence model variation:

- Standard SST model
- Spatial discretization
  - High Resolution for all equations except turbulence
  - High Resolution for all equations
- Curvature correction
  - Turbulence strongly affected by swirl and streamline curvature
  - Effects are not accounted for in standard 2-equation model
  - Additional terms in SST turbulence equations
- BSL-RSM model
  - One equation for each stress tensor component

Validation: Tip Vortex Velocity

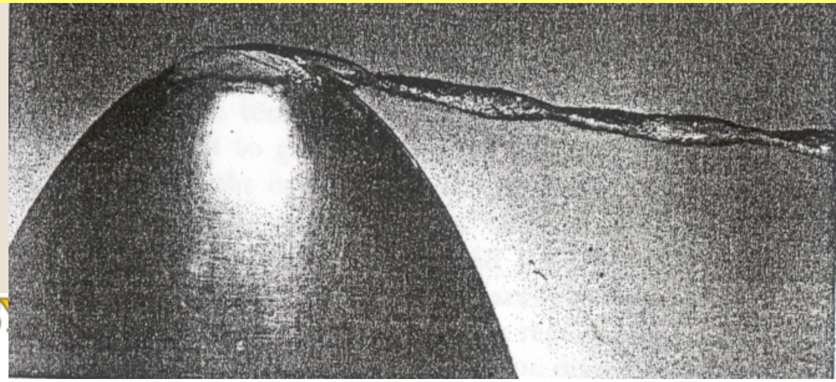


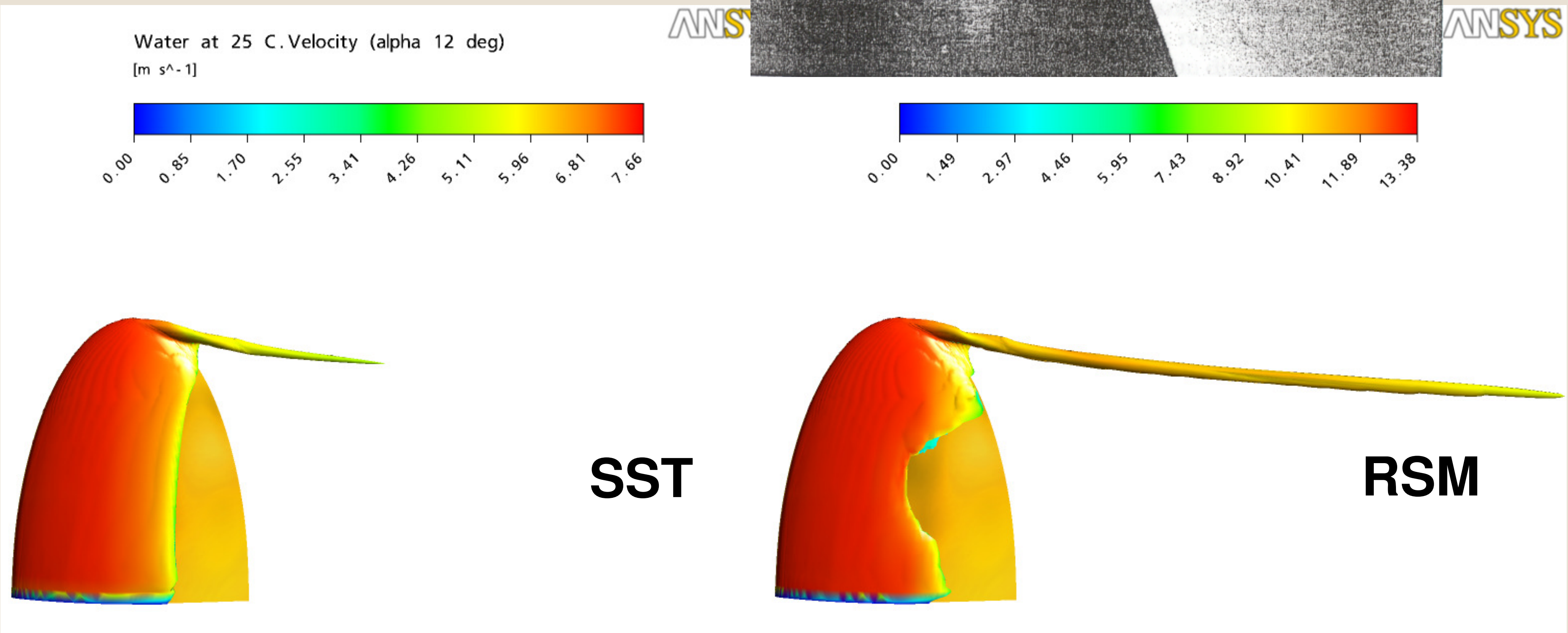
α_{eff}=12°, Re=5.2×10^5

Tip Vortex Vapour volume fraction

- Medium grid
- $Re=5.2x10^5$
- $\alpha_{eff}=12°, \sigma=0.58$

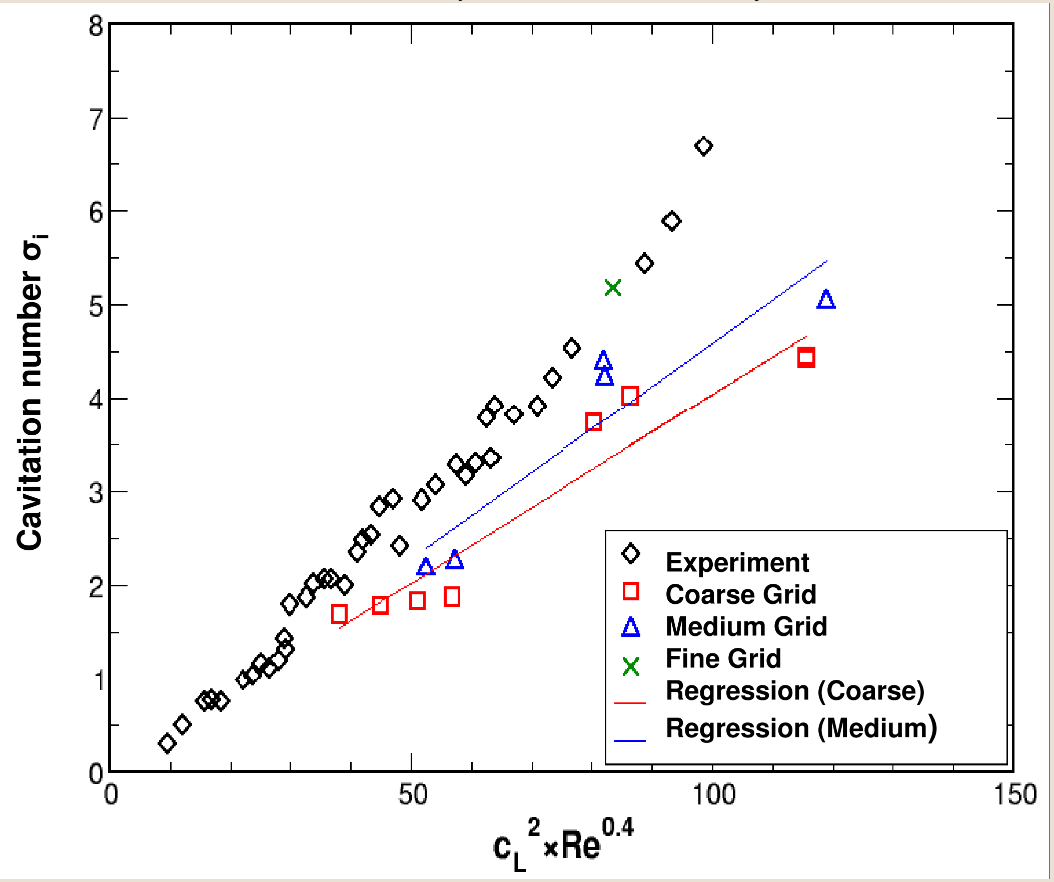
$\alpha_{eff}=9.5°, \sigma=0.58, Re=5.2x10^5$





Validation: Cavitation Inception

- **Arndt & Dugue (1992), Arndt et al. (1991) ⇒**
  - **Cavitation inception vs. lift, correlation for model scaling:** $\sigma_i \propto 0.063\, c_l^2\, \mathrm{Re}^{0.4}$



Summary

- SVA Potsdam & ANSYS Germany cavitation project (BMBF)
- ANSYS CFX cavitation model
- Validation test cases for hydrofoil cavitation:
  - Le et al. → 2d hydrofoil cavitation
  - Arndt et al. → tip vortex cavitation
- Work in progress
  - Isolated propeller P1356
  - Non condensible gas cavitation
  - Ship propeller with ship stern.
    - Rotor-Stator interface
    - Influence of the turbulence model

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CFX

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ICEM CFD

Thank You!