Computations of unsteady cavitating flow on wing profiles using a volume fraction method and mass transfer models

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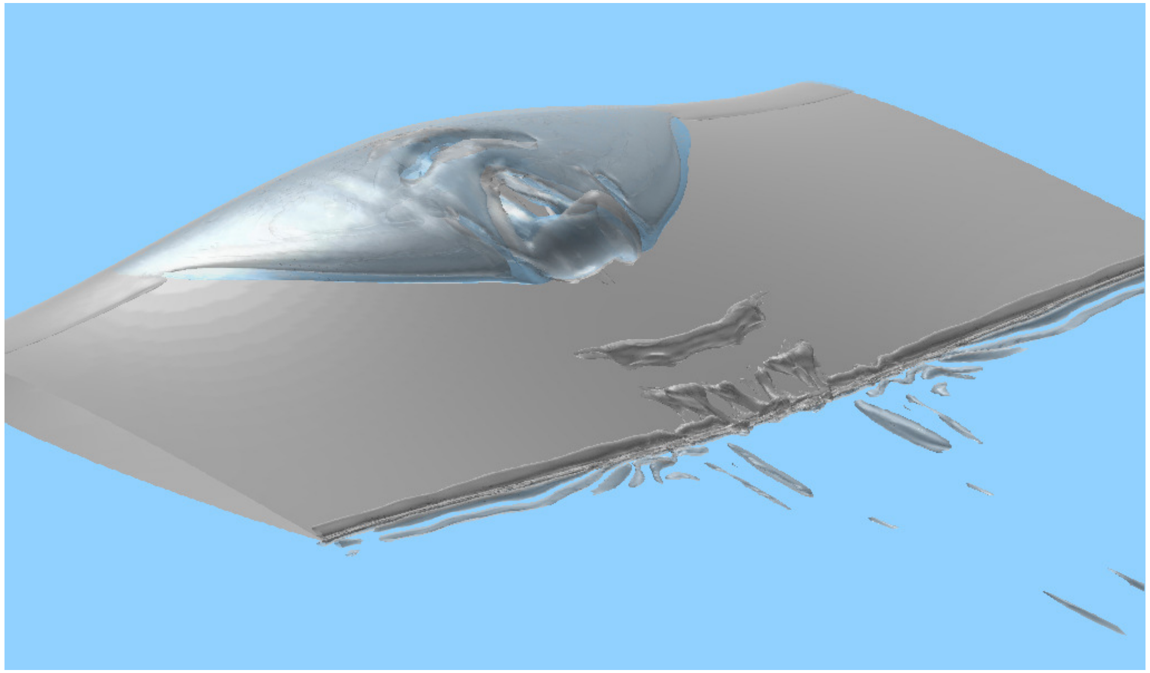


Objective

- To use LES, VOF and mass transfer models to simulate and understand the highly unsteady phenomena of cavitating flow
- Two mass transfer models, and two test cases are studied
- A modification of one of the mass transfer models is proposed
- A cavitation model is regarded as the entire set of equations including the general flow equations and the equations for mass transfer rate is referred to as mass transfer models.
- This work is sponsored by the Rolls Royce UTC, the EU project VIRTUE, the MarinLES program granted by the Swedish Defence Material Administration (FMV), and the Swedish Water Power Center (SVC)

Flow modeling, filtered equations

$$\begin{cases} \nabla \cdot \overline{\mathbf{v}} = S_\rho, \\ \partial_t (\rho \overline{\mathbf{v}}) + \nabla \cdot (\rho \overline{\mathbf{v}} \otimes \overline{\mathbf{v}}) = -\nabla \overline{\mathrm{p}} + \nabla \cdot (\overline{\mathbf{S}} - \mathbf{B}) \\ \partial_t \gamma + \overline{\mathbf{v}} \cdot \nabla \gamma = S_\gamma. \end{cases}$$

$\overline{\mathbf{S}}$ is the viscous stress tensor, $\mathbf{B}$ is the subgrid stress tensor

$$\rho = \gamma \rho_l + (1-\gamma)\rho_v$$
$$\mu = \gamma \mu_l + (1-\gamma)\mu_v$$

Surface tracking with Volume of Fluid

Source terms S_ρ and S_γ transfer mass, liquid↔vapour

No subgrid modeling (ILES) $\Rightarrow \mathbf{B} = 0$

Upwinding used to stabilize the flow, ~40%.

The Kunz mass transfer model

$$\gamma = \frac{Volume\ liquid}{Total\ volume}$$

Source terms

$$S_\rho = \dot{m}\left(\frac{1}{\rho_l} - \frac{1}{\rho_v}\right) \qquad S_\gamma = -\dot{m}\frac{\gamma\rho_v - \gamma\rho_l - \rho_v}{\rho_l \rho_v}$$

Specific mass transfer rate

$$\dot{m} = \dot{m}^+ + \dot{m}^-$$

Creation of vapour

$$\dot{m}^+ = \frac{C_{prod}\rho_v \gamma \min\left[0, \overline{p} - p_v\right]}{\rho_l U_\infty^2 t_\infty}$$

Destruction of vapour

$$\dot{m}^- = \frac{C_{dest}\rho_v \gamma^2 (1-\gamma)}{t_\infty}$$

The Sauer mass transfer model

$$\gamma = \frac{Volume\ vapour}{Total\ volume}$$

The Reyleigh equation yields the source terms

$$S_\rho = S_\gamma = \frac{3\gamma}{R} sign(P_v - P)\sqrt{\frac{2}{3}\frac{|P_v - P|}{\rho_l}}$$

$$R = \sqrt[3]{\frac{\gamma}{n_0\, 4/3\,\pi(1-\gamma)}}$$

where n_0 is the specific bubble density

The Sauer mass transfer model with a varying bubble density

- Here we propose to modify the Sauer mass transfer model with a varying bubble density
- n_0 is then derived from a separate LPT simulation
- We use a one-way coupling without particle-particle interaction, but including collisions with the surface
- The particles are injected randomly at every time step from a vertical plane upstream the wing
- The simulations are time-averaged for several through-flow times
- The resulting particle distribution is used to compute n_0

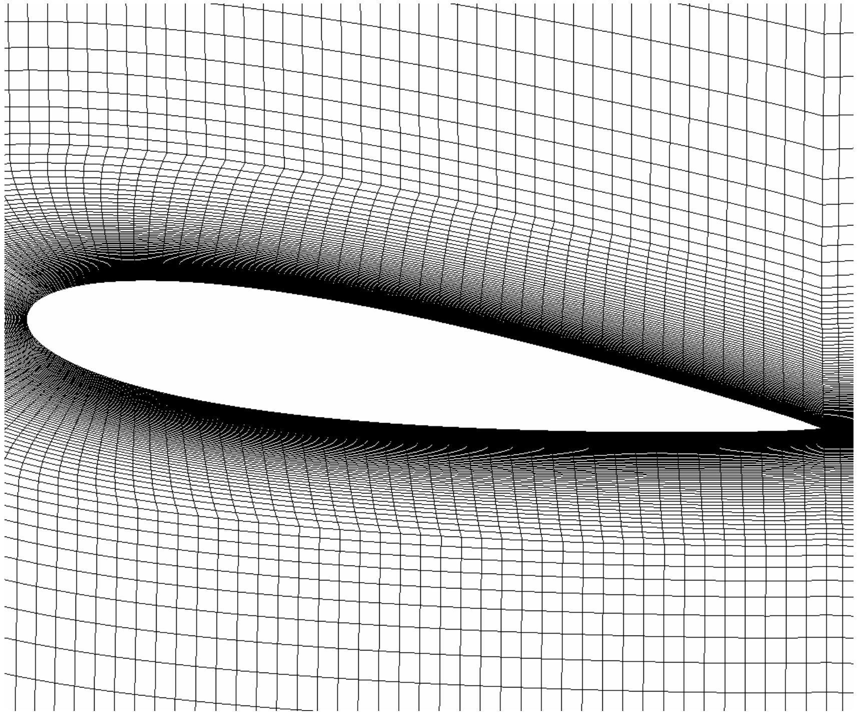
The OpenFOAM CFD solver

- The OpenFOAM OpenSource CFD solver has been used
- It can be downloaded from www.openfoam.org
- Patches and user contributions can be found at www.sourceforge.net (OpenFOAM-development)
- An OpenFOAM Turbomachinery Working Group has been established, which will develop OpenFOAM for turbomachinery applications. Maryse Page, Martin Beaudoin and Håkan Nilsson are organizing the group.

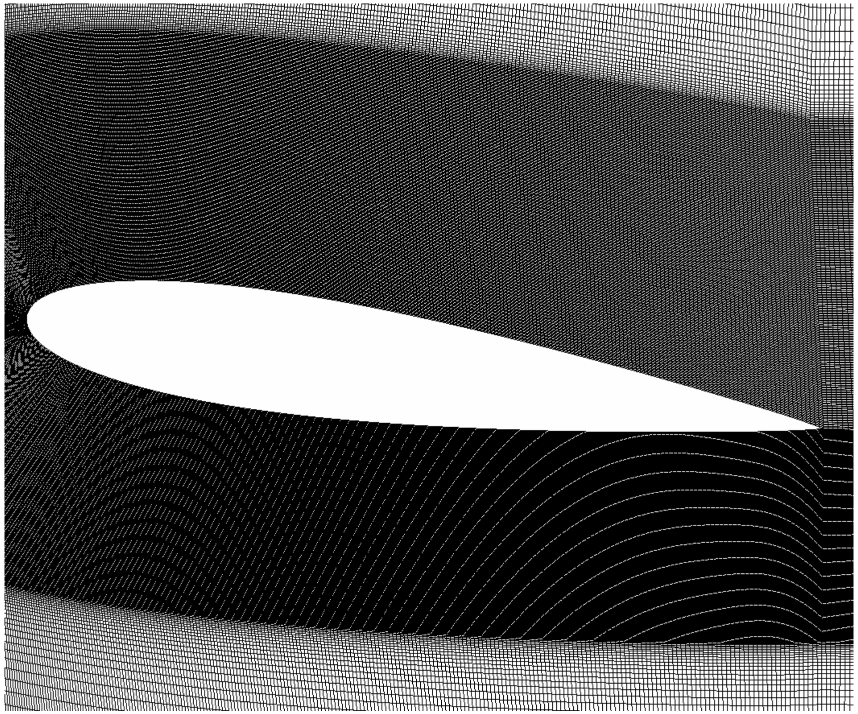
The NACA0015 test case

Experiments by Yakushiji. Re = 1,200,000, σ = 1.2
angle of attack is 8 degrees.

Coarse 2D grid, 21,000 cells



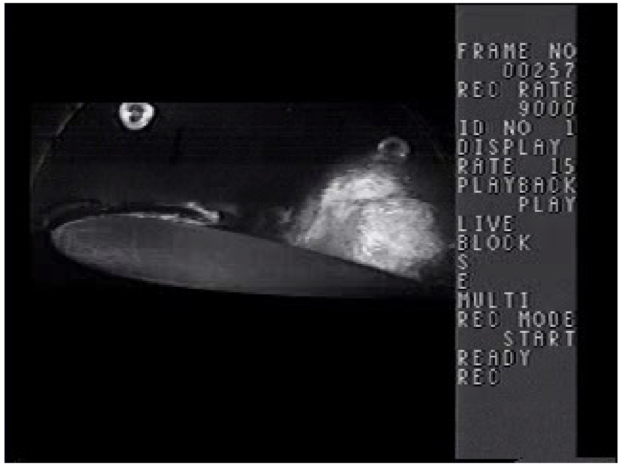
Fine 2D grid, 267,000 cells

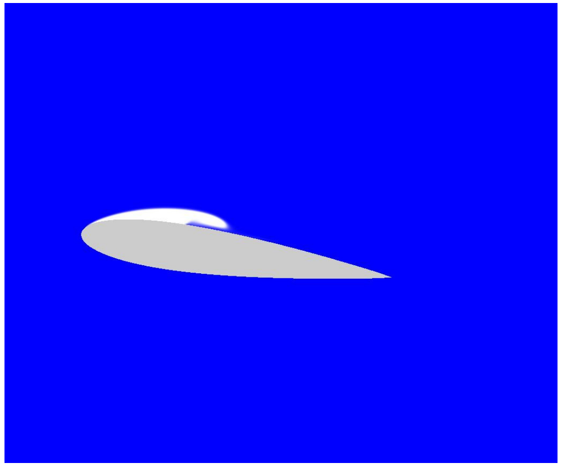


NACA0015 validation, fine mesh

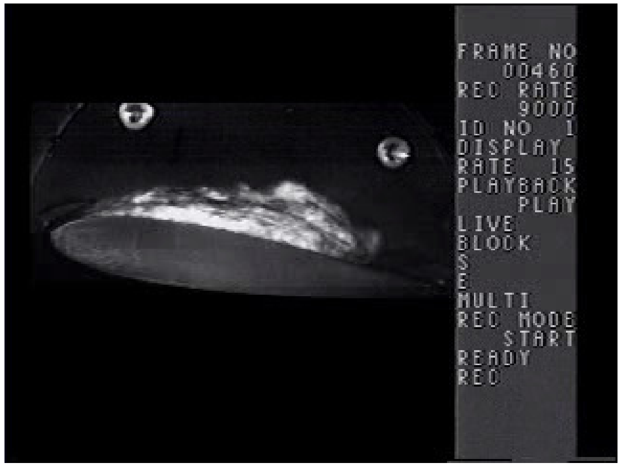
Kunz model, $t_{\infty}=0.1$, $U_{\infty}=10$, $c_{Prod}=10^{7}$, $c_{Dest}=1$

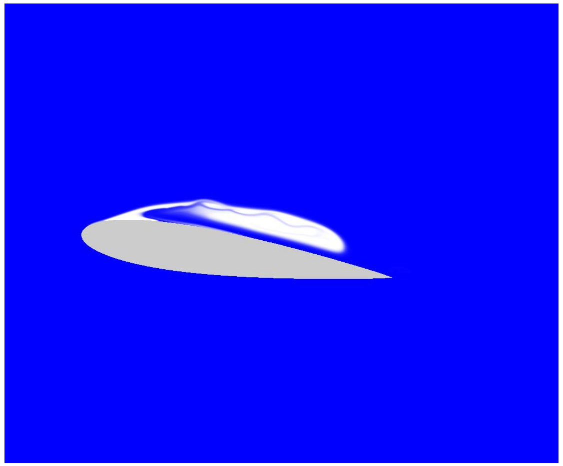
First cycle, growth of sheet cavity.





Re-entrant jet

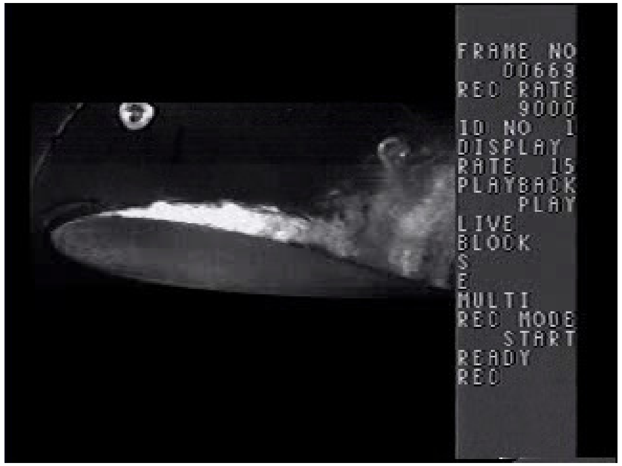


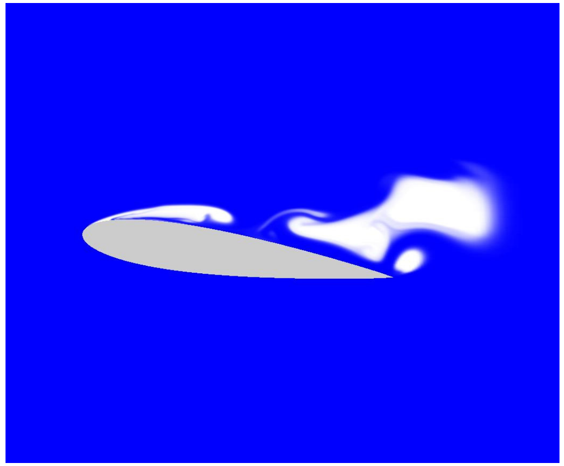


NACA0015 validation, fine mesh

Kunz model, $t_\infty=0.1$, $U_\infty=10$, $c_{Prod}=10^7$, $c_{Dest}=1$

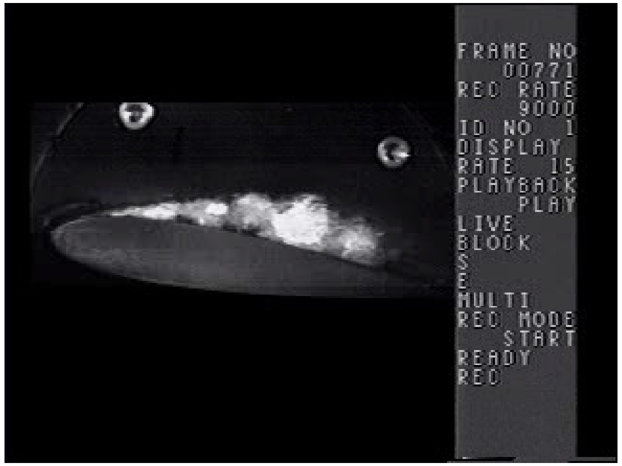
First sheet released, new sheet developing

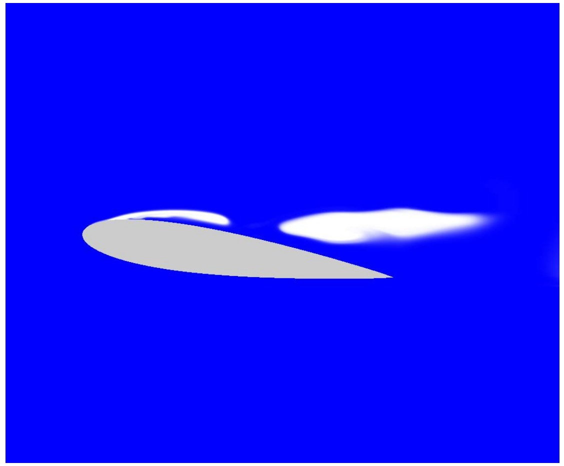




Second sheet released, new sheet developing

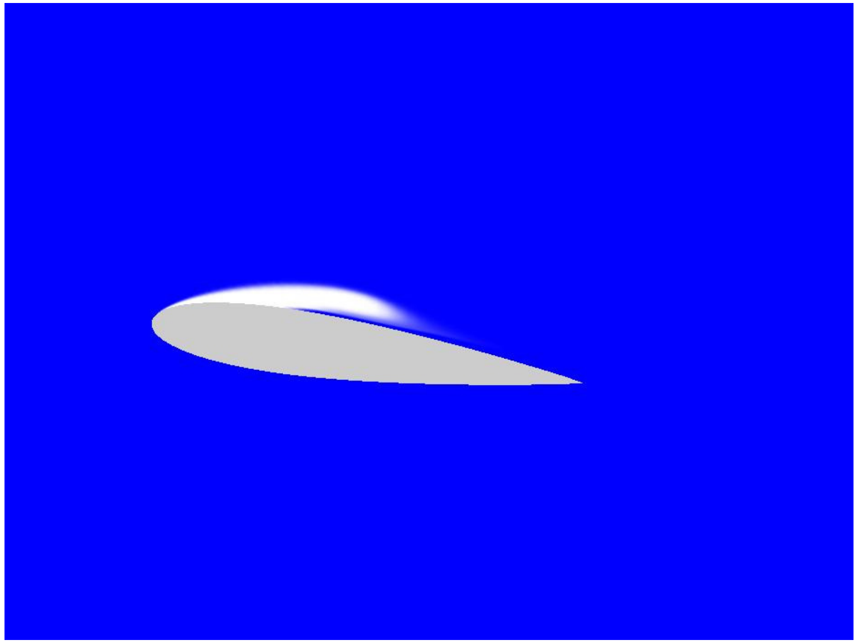
(periodic shedding)



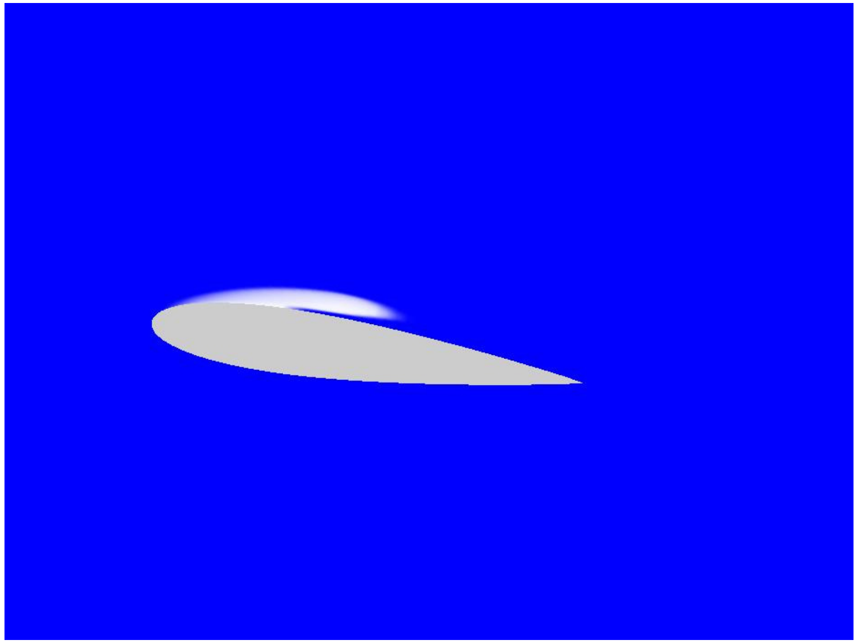


NACA0015 Kunz vs. Sauer, coarse grid, Growth of the first cycle

Kunz, $c_{Prod} = 10^7$, $c_{Dest} = 1$



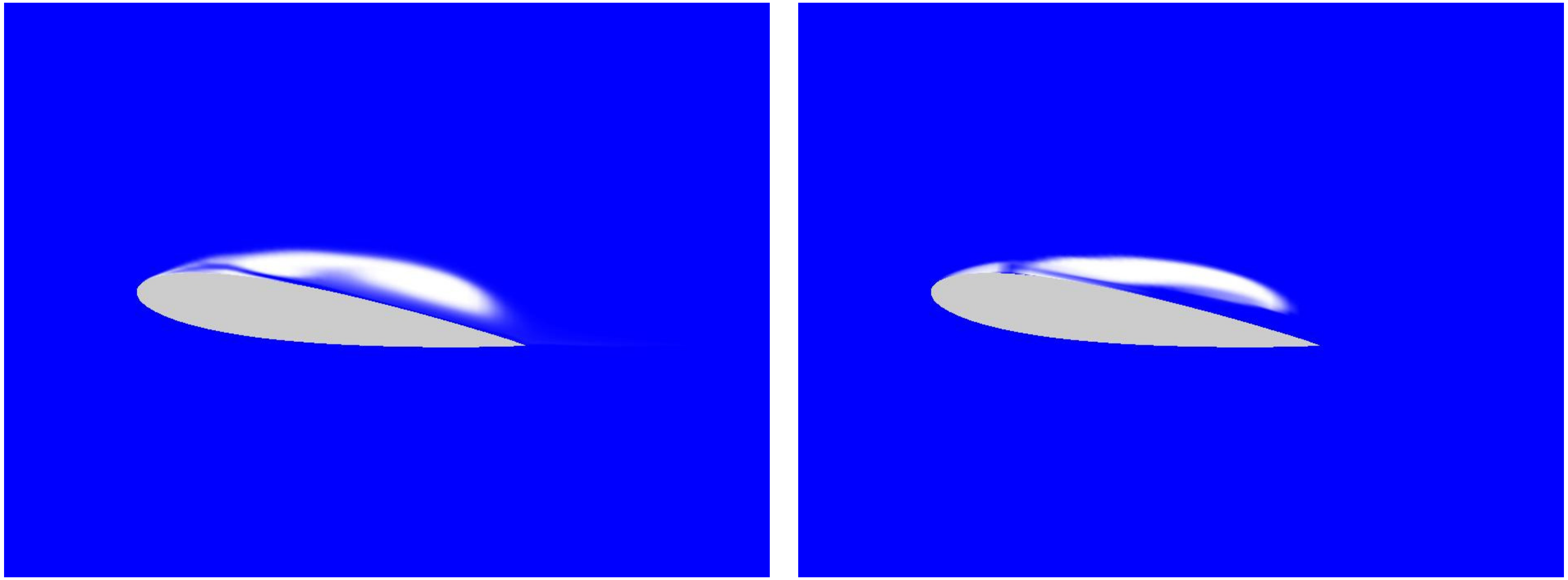
Sauer, $n_0=10^7$



NACA0015 Kunz vs. Sauer, coarse grid, Re-entrant jet in the first cycle

Kunz, $c_{Prod} = 10^7$, $c_{Dest} = 1$

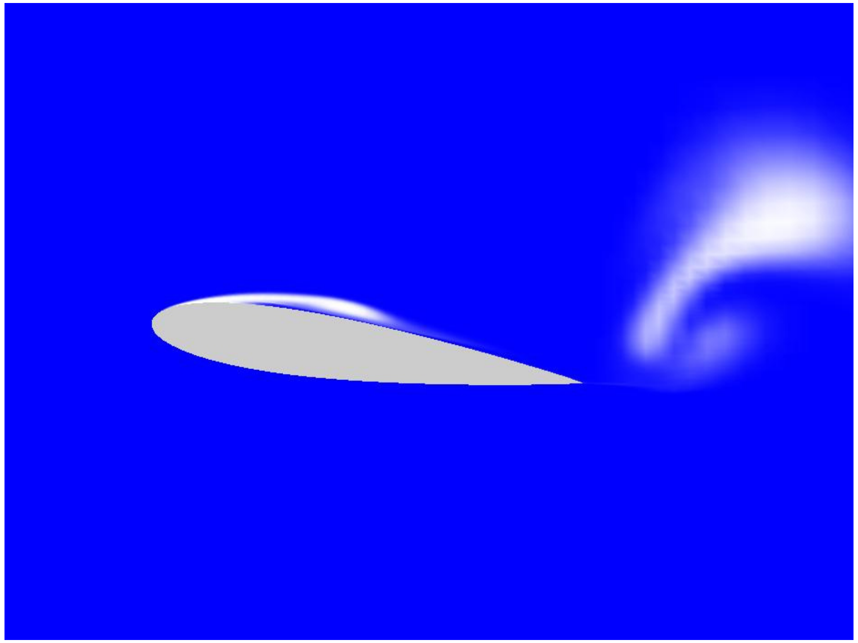
Sauer, $n_0 = 10^7$

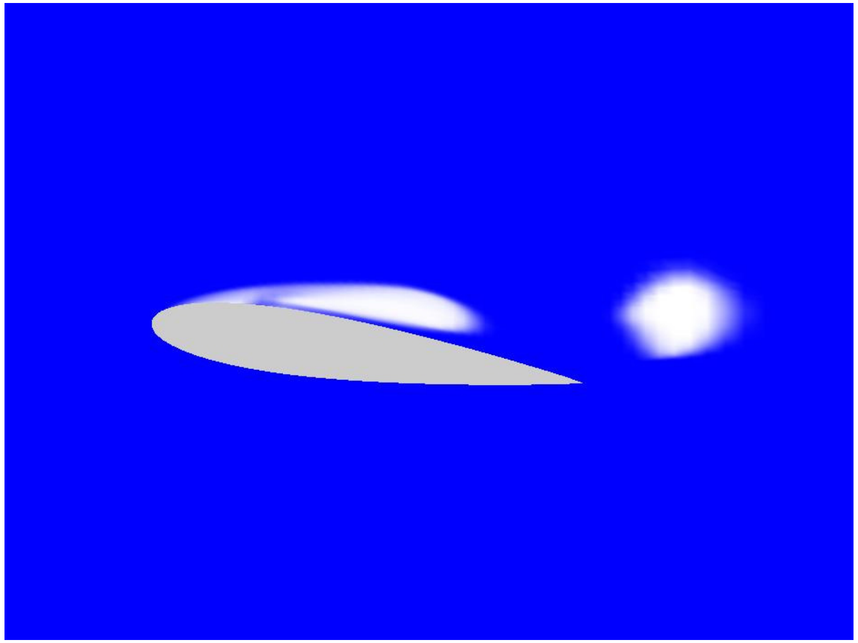


NACA0015 Kunz vs. Sauer, coarse grid, Growth of the second cycle

Kunz, $c_{Prod} = 10^7$, $c_{Dest} = 1$

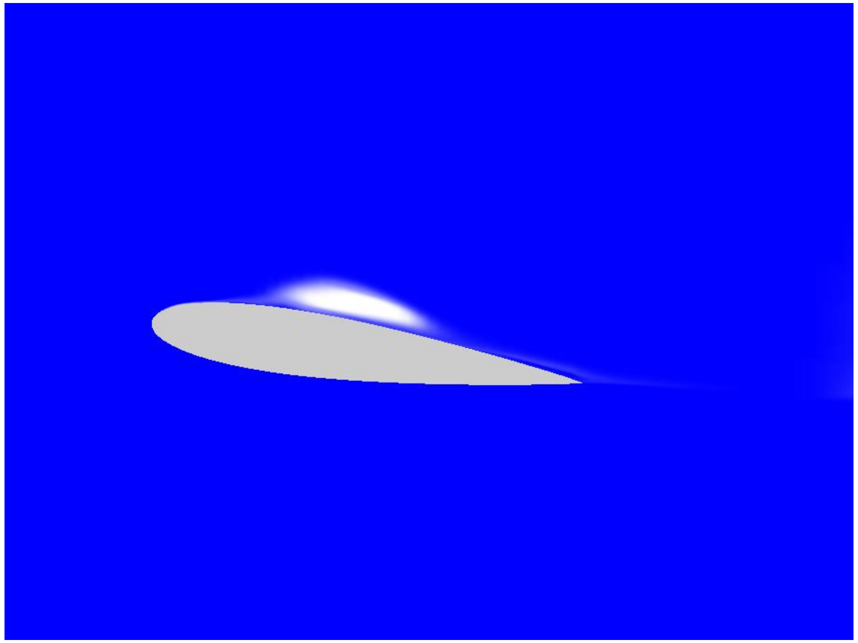
Sauer, $n_0 = 10^7$



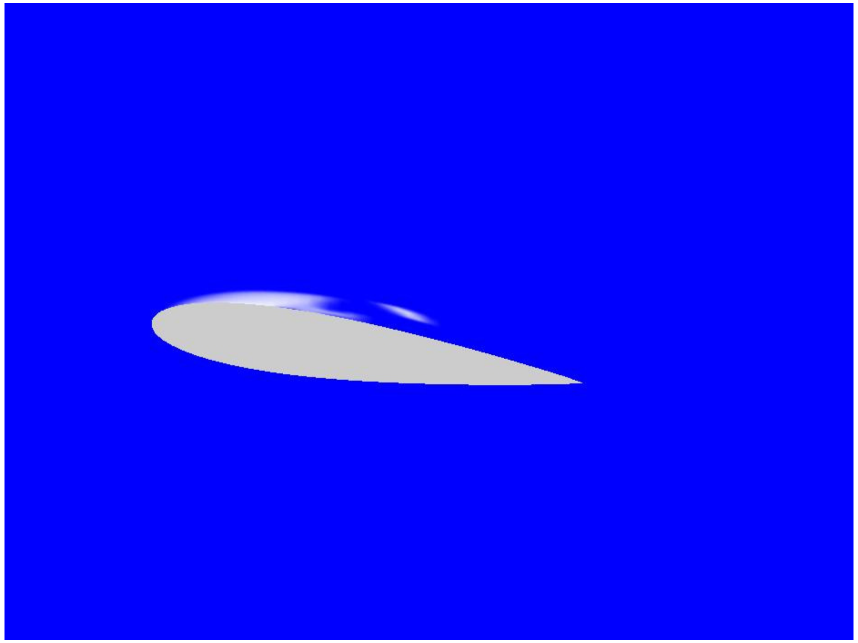


NACA0015 Kunz vs. Sauer, coarse grid, Re-entrant jet in the second cycle

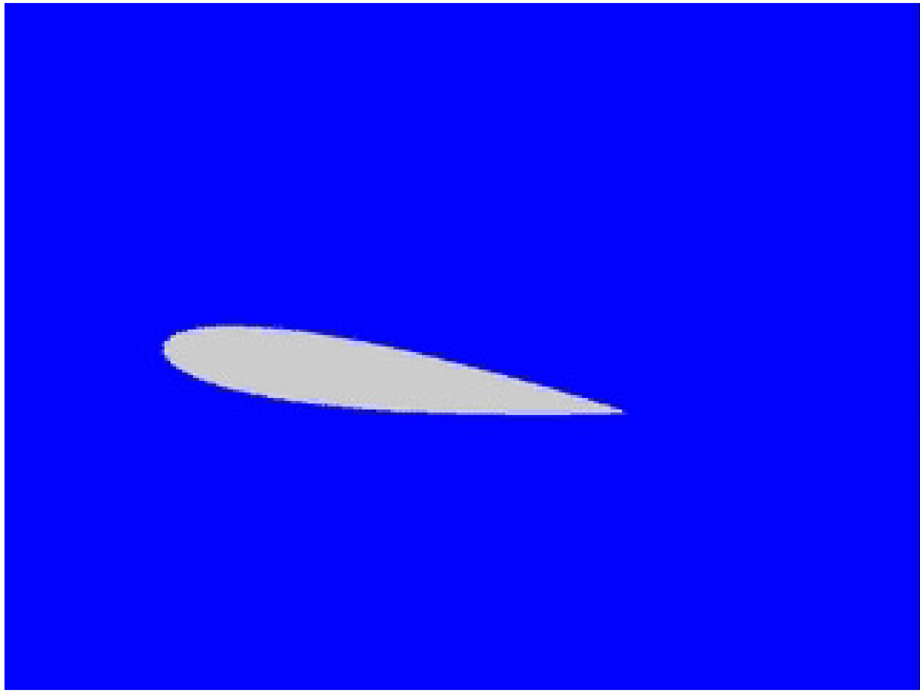
Kunz, $c_{Prod} = 10^7$, $c_{Dest} = 1$



Sauer, $n_0=10^7$



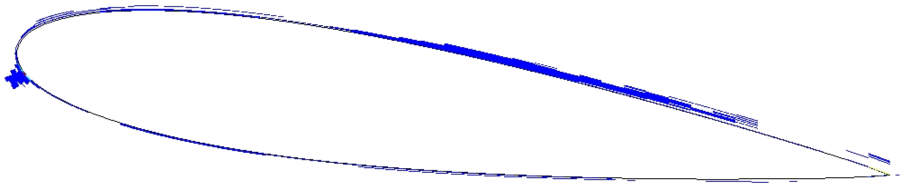
NACA0015 Kunz model



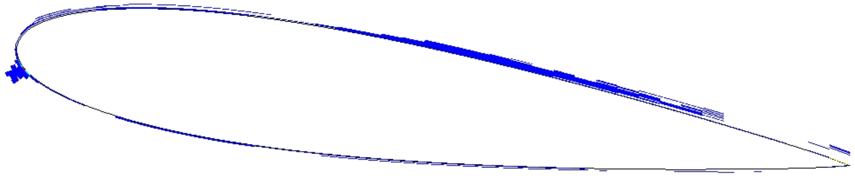
Preliminary LPT results,

Non-uniform nuclei distribution, Densities higher than inlet density are highlighted

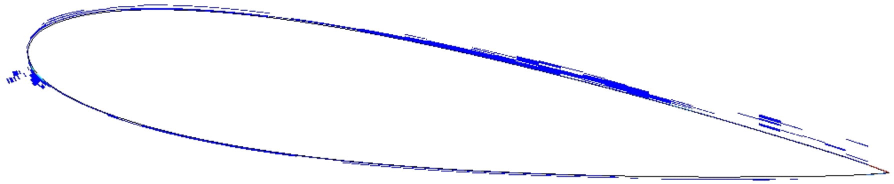
30 injections per time step ($n_0=4e^8$), $d=1\mu m$, $\rho_P=1 kg\ m^{-3}$



30 injections per time step ($n_0=4e^8$), $d=50\mu m$, $\rho_P=1 kg\ m^{-3}$



100 injections per time step ($n_0=1.4e^9$), $d=50\mu m$, $\rho_P=1 kg\ m^{-3}$



Conclusions from the 2D simulations

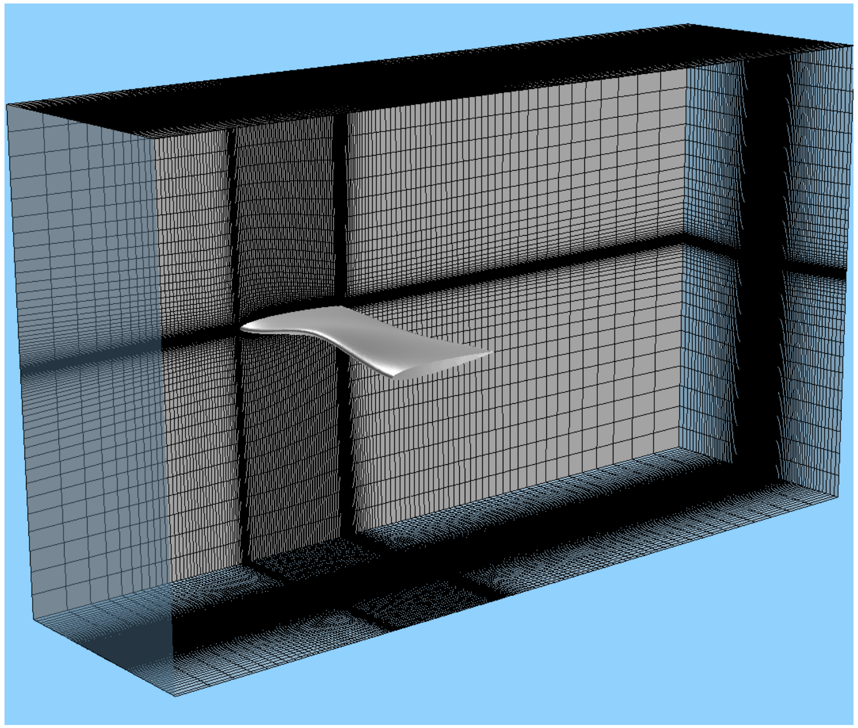
- Kunz’ model is rather insensitive to the production constant, but it should be as large as possible. Too high values are however numerically instable.
- A large Kunz destruction term makes the surface sharp, but destroys the cavity too early.
- The cavitation inception for the Sauer method occurs later than for the Kunz method. A non-constant nuclei distribution could be used to increase the cavitation inception at the leading edge suction side, without destroying the cavity too soon further downstream.
- Preliminary LPT simulations show an accumulation of cavitation nuclei at the leading edge suction side

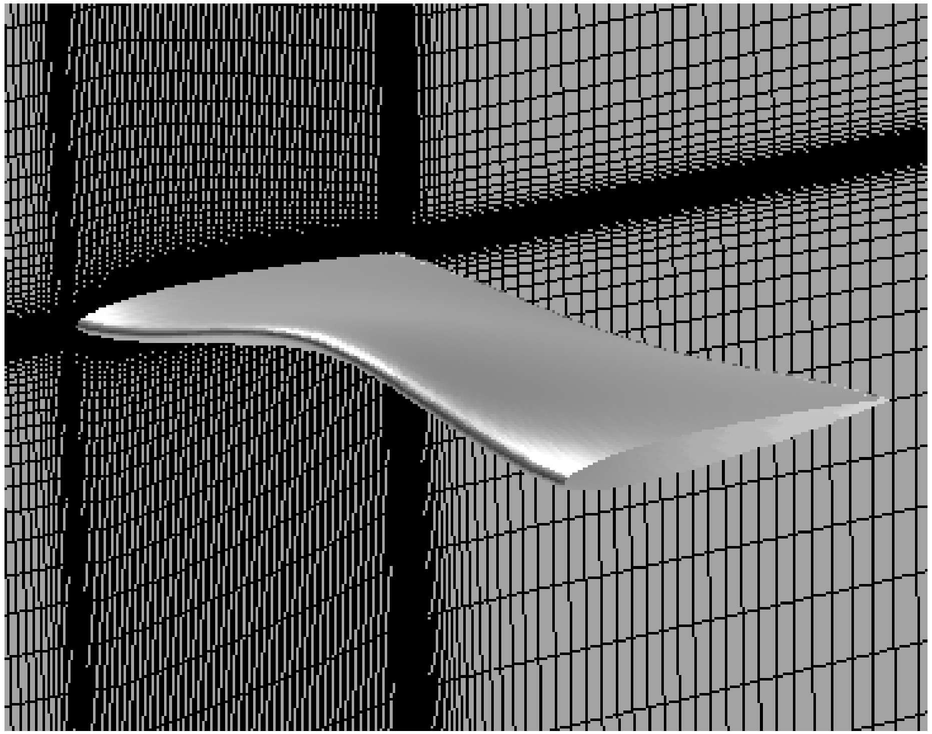
Twist11 – a NACA0009 with an 11 degree twist

Chord 150mm, spanwise extent 300mm

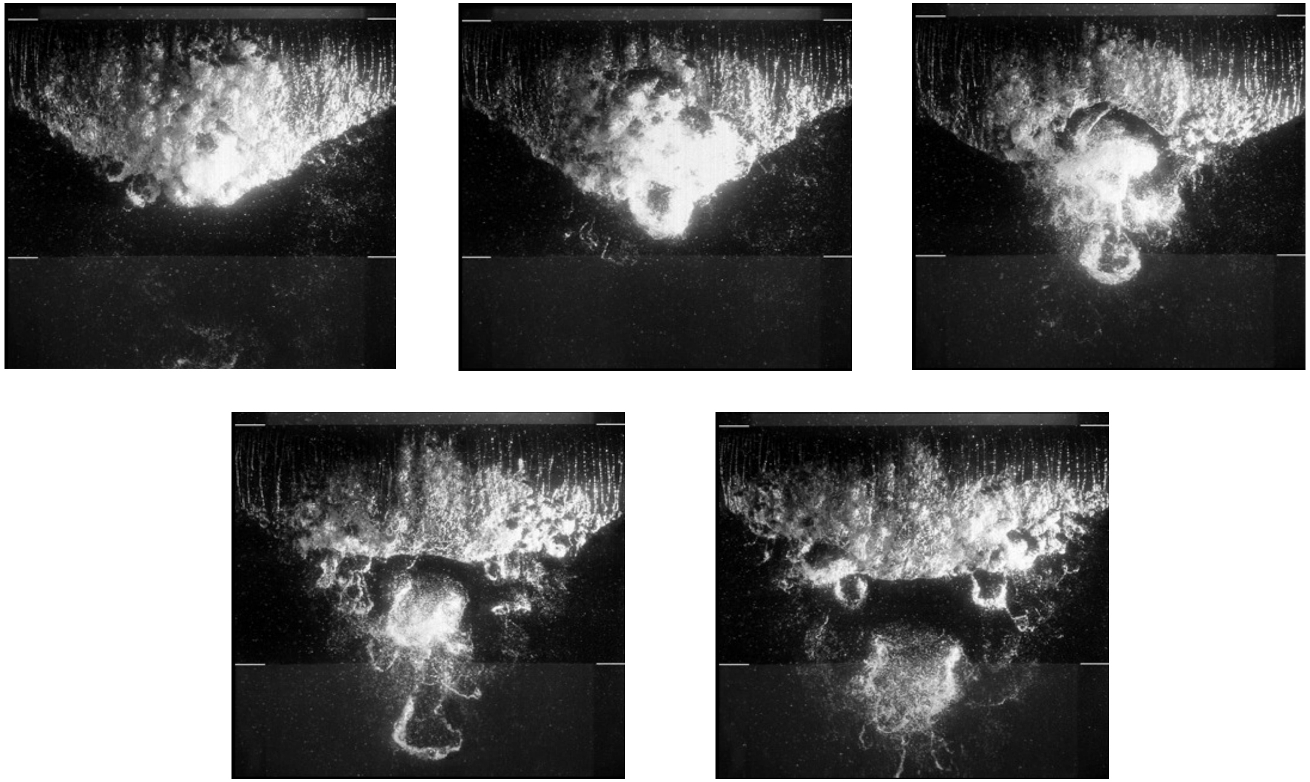
Angle of attack -2º (wall) to 9 º (center)

3,000,000 cells, symmetry mid-plane





Experimental observations (Twist8)

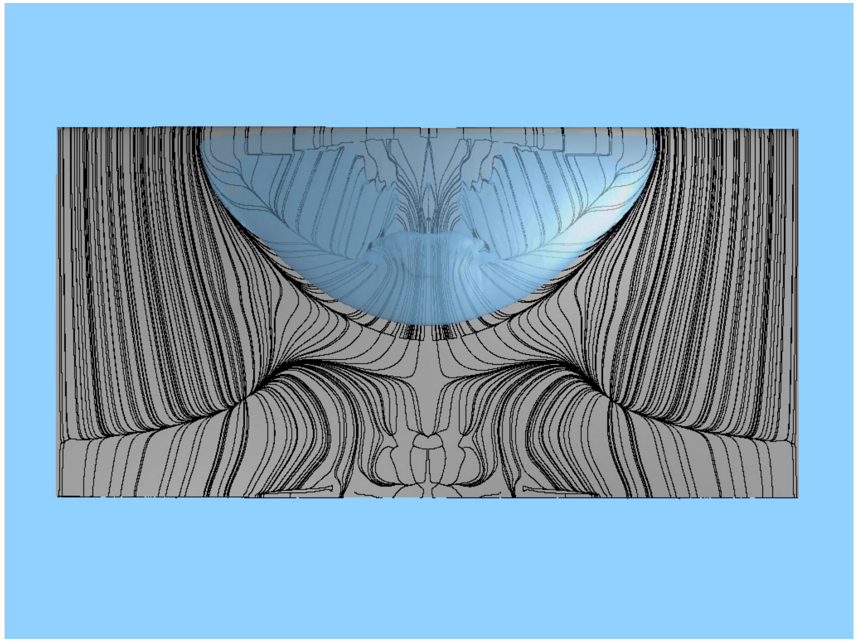


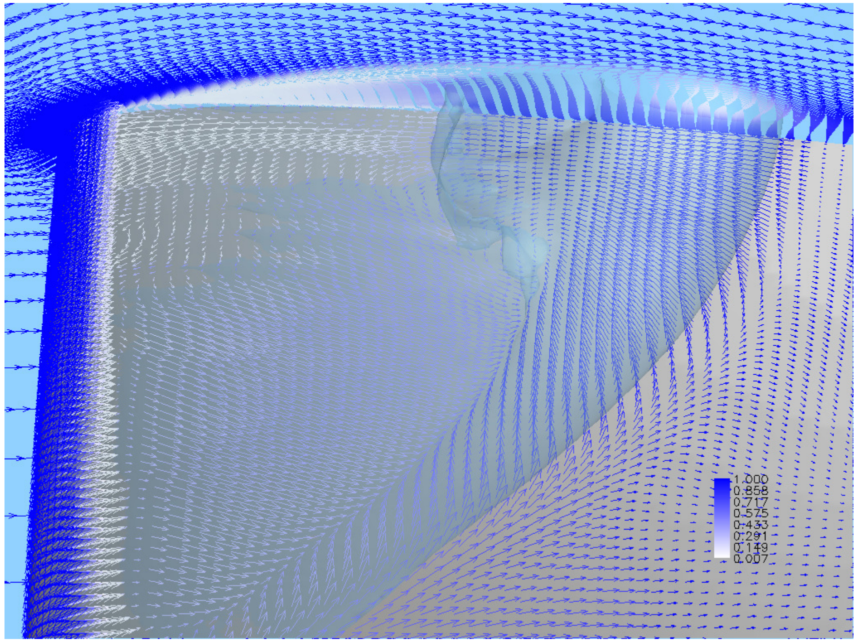
Experiments at V=4.96m/s, α=-1, σ=0.66, f=285,7 Hz

[5] Foeth, E.-J. and Terwisga, T., 2006, "The structure of unsteady cavitation.
Part I: Observation of an attached cavity on a three-dimensional hydrofoil", CAV2006, Wageningen, The Netherlands

Twist11 results, Kunz model

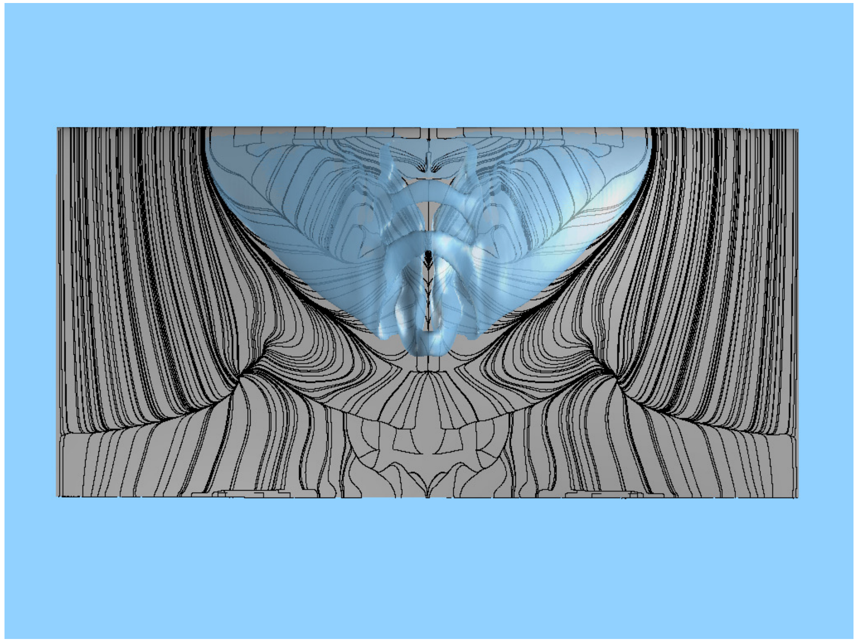
First cavitation cycle, maximum size,
side-jets collect fluid towards the center

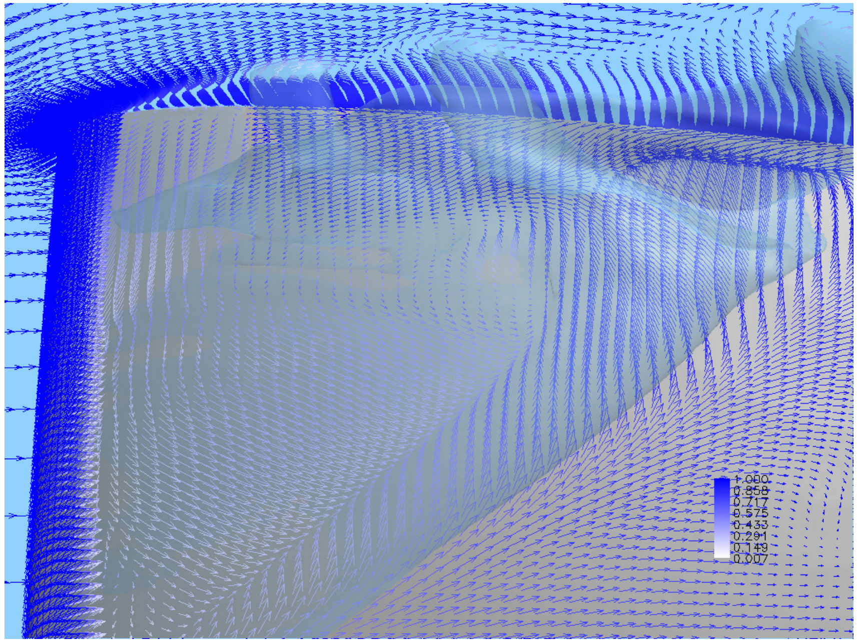




Twist11 results, Kunz model

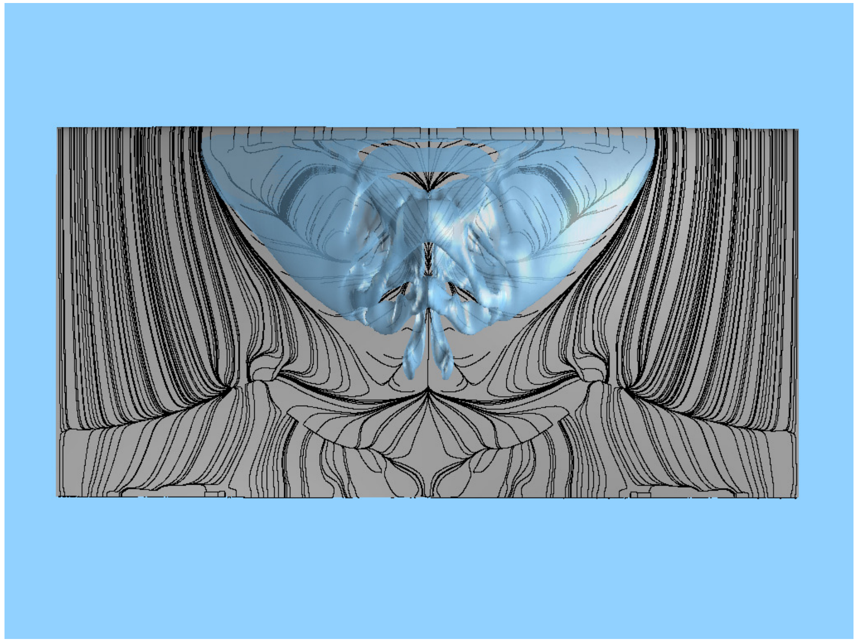
The side jets have formed a re-entrant jet
which has reached to the leading edge.
High-vorticity hair-pin vortices are being generated

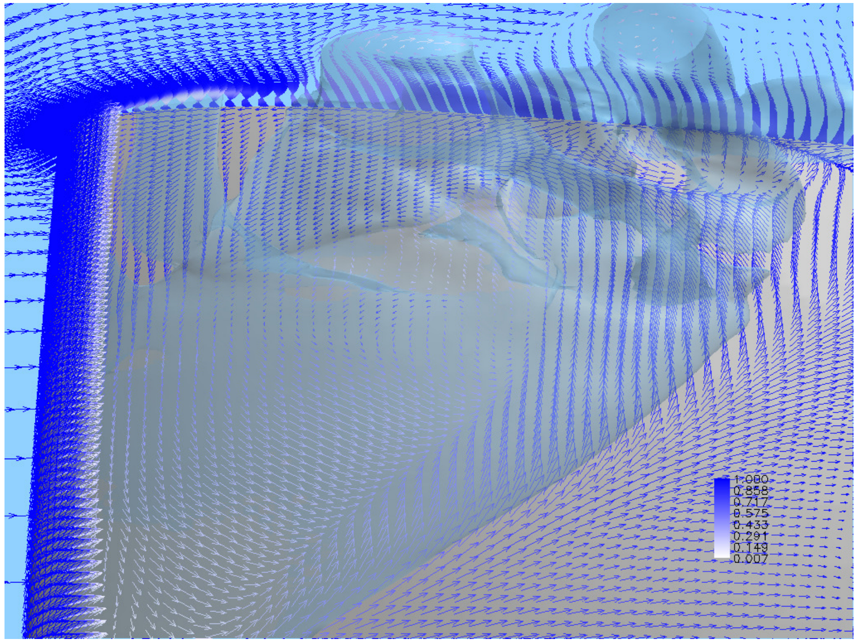




Twist11 results, Kunz model

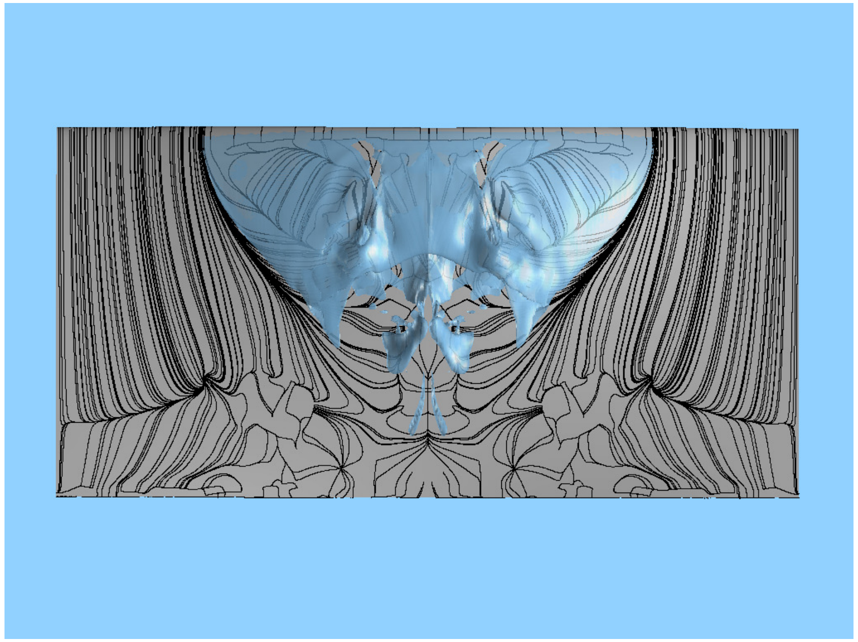
The cavity in the hair-pin vortex is being transported and a new sheet cavity is being formed

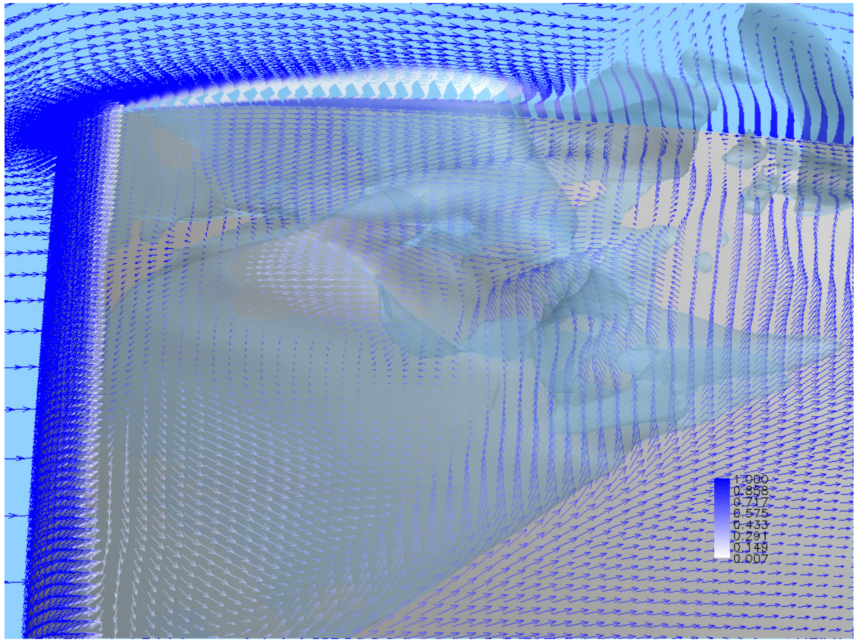




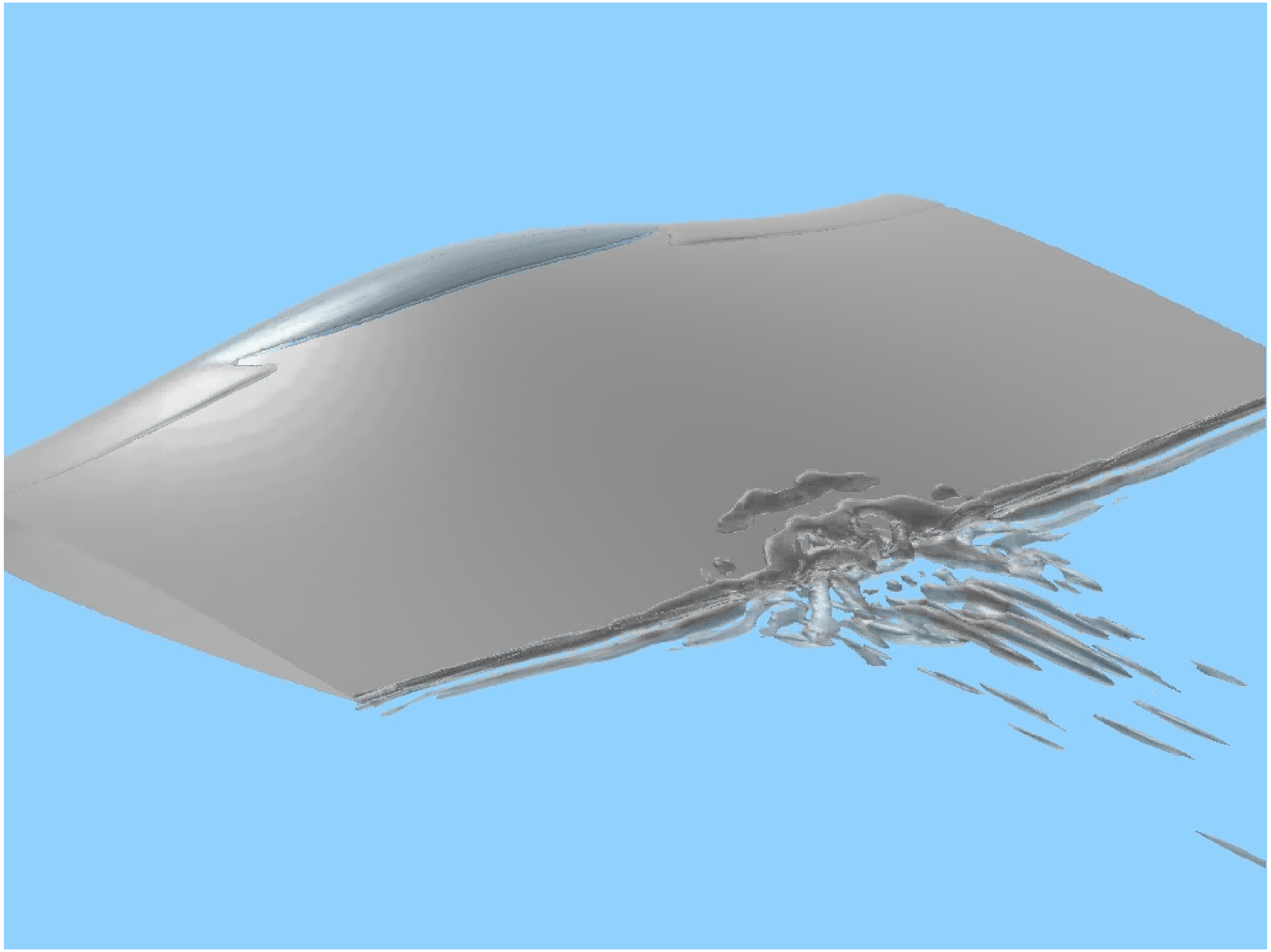
Twist11 results, Kunz model

The secondary vortices are being shed
and the new sheet cavity is almost fully developed





Twist11 results, Kunz model



Major conclusions

- The major physical phenomena are simulated qualitatively correct, and this can be used to understand the experiments better.
- The physics of side-entrant and re-entrant jets can be better understood using the simulations.
- The simulation results can be used together with experience to predict whether erosive cavitation will occur.
- The main limitation of the metod is its inability to model the switch from a convected sheet cavity to a bubble cloud.
- Real validation experiments exists, but can not be shown, due to publication rights.