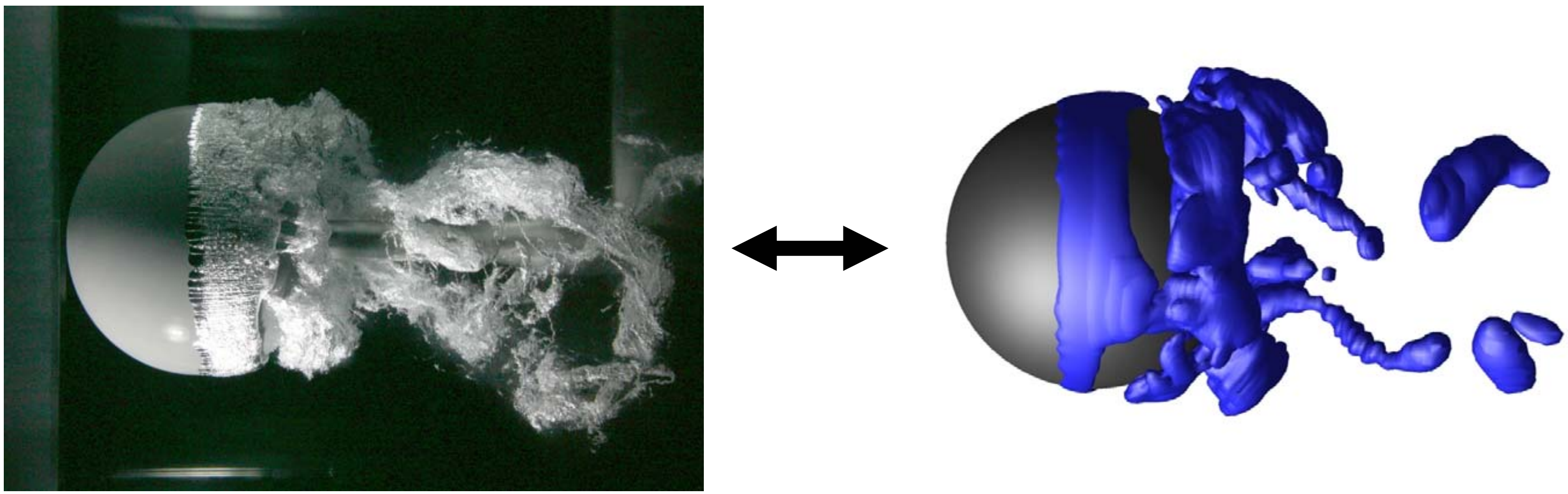
Technische Universität München
Lehrstuhl für Fluidmechanik – Fachgebiet Gasdynamik
Univ.-Prof. Dr.-Ing. habil. G. H. Schnerr

Modelling and Computation of Dynamic Phase Transition of Liquids - Compressible Flows with Cavitation -



Michael Mihatsch
JASS 2009
09.03.-19.03.2008, St. Petersburg, Russia

Outline

Introduction	Important numbers
	Physical effekts
Modeling	**CATUM**
	Cavitation **T**echnische **U**niversität **M**ünchen
Numerical results and validation	- Spherical body:
	- Hydrofoil
	- Prismatic body – cavitation erosion

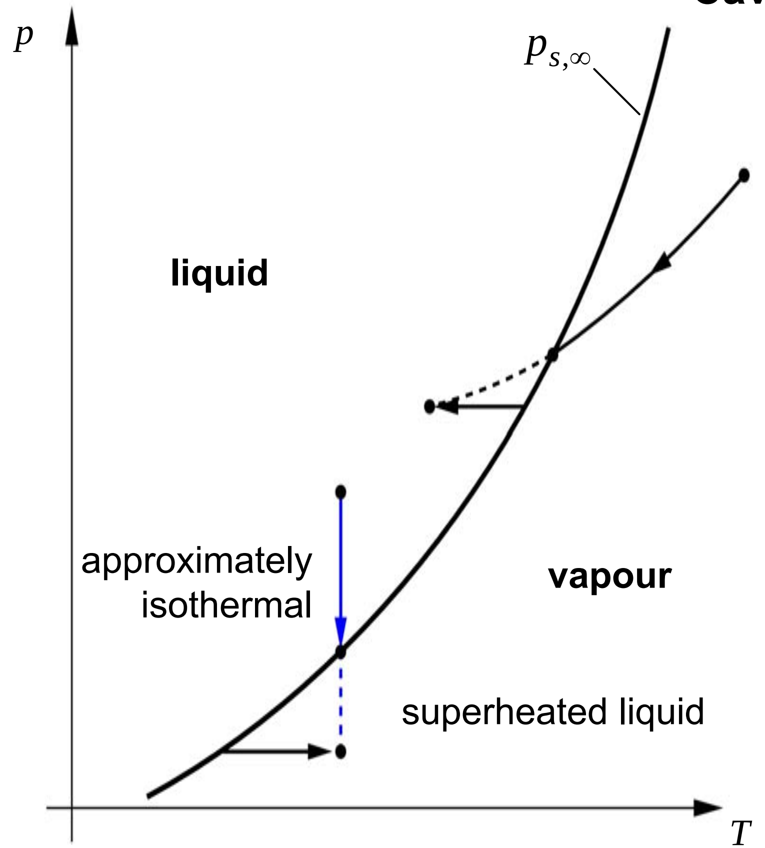
Physics of cavitating flows

initially single-phase liquid fluid	$p_l \approx O(1\text{-}10^3$ bar), $T \approx 300\text{-}400$ K
	$p_v \approx O(10^{-2}\text{-}1$ bar)
	$\rho_v \approx O(10^{-2}\text{-}1\ kg/m^3)$
	$\rho_l \approx O(10^3\ kg/m^3)$
void fraction	$0 \leq \alpha \leq 1$
speed of sound	$c \approx O(1\text{-}10^3\ m/s)$
strong variation of the Mach number	$M \approx O(0\text{-}10^1)$

Dominating

- **strong density variation** $\rho_l/\rho_v \approx 10^4$
- **strong variation of speed of sound** $c_l/c_{min} \approx 10^3$
- **coexistence of compressible and weak compressible flow regimes**
- formation of violent shocks in collapse region
- **intense noise, vibration and erosion**

Cavitation dynamics



$p_{s,\infty}$ coexistence of phases
equilibrium

- - - - - metastable
time scale of flow

1. Process

Depressurization - evaporation
increase of volume - 1 : 50000
displacement of liquid fluid
instability

2. Process

collapse
implosion of bubbles and cavitation patterns
violent shocks
erosion

Compressibility

local very low wave speed $c \leq 10$ m/s
stiffness because of coupling
with regimes of $c \approx 1500$ m/s

Nucleation

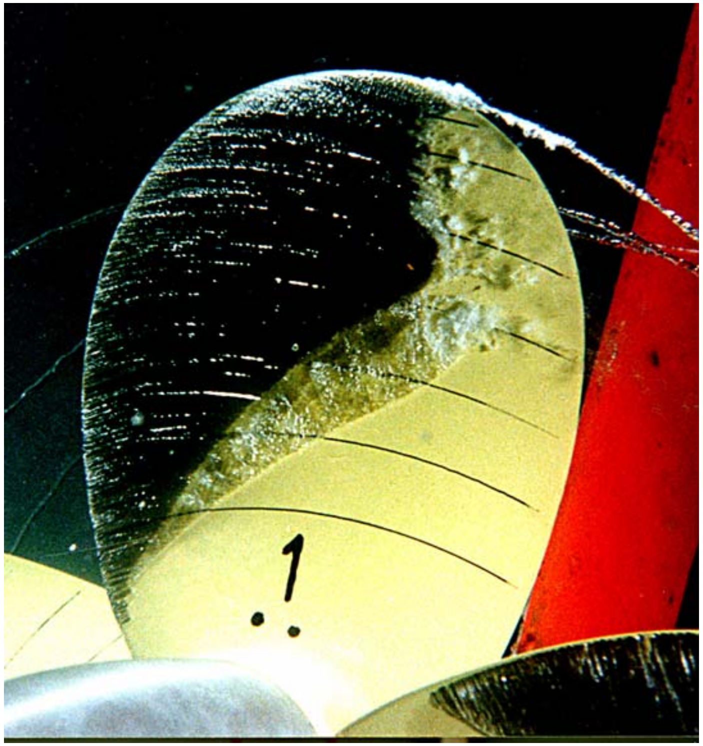
Homogeneous	**Heterogeneous**
Nucleus consists of molecules	Impurities like dissolved gas or crevices at walls or particles act as nucleus
Exclusive hom. nucleation allows high surface tention and highly metastable states	
Only important with pure water	Dominant in most technical applications

Cavitation phenomena

Bubble and cloud cavitation

Sheet and cloud cavitation

Supercavitation



Vortex

cavitation

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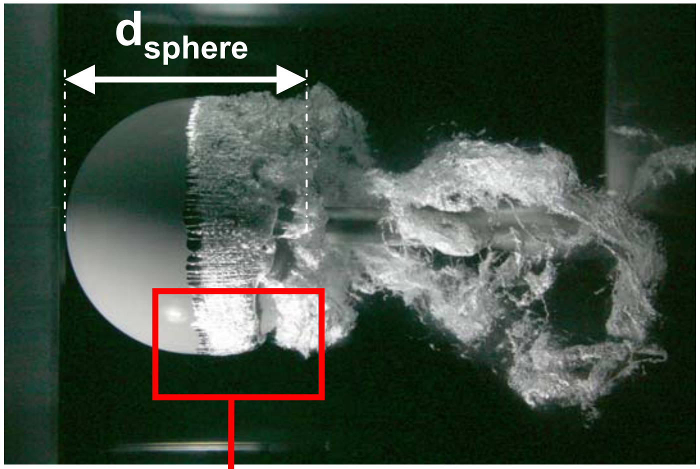
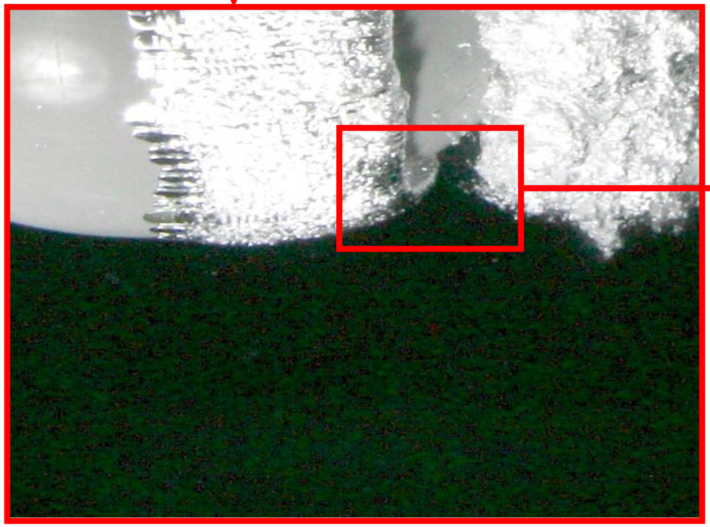
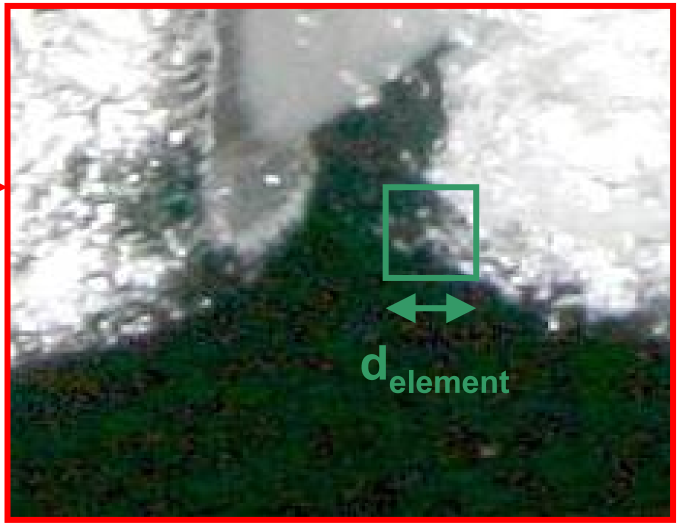
Size of cavitation structures



Sphere diameter $d_{sphere}=1{,}5\ 10^{-1}$ m

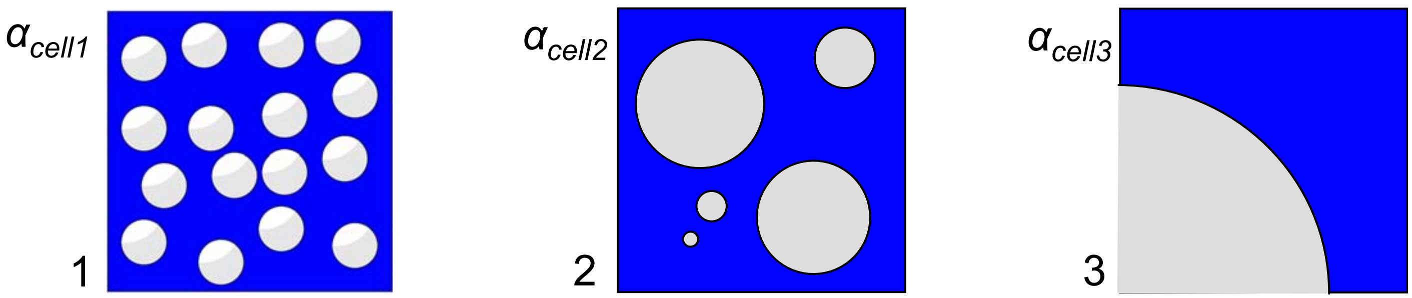
Size of a fluidemement $d_{element}=5{,}2\ 10^{-3}$m





Two-phase flow properties via integral averages per cell

Vapor volume fraction per cell $\alpha_{cell} = \dfrac{V_{vapor,\,cell}}{V_{cell}}$



$\alpha_{cell1} = \alpha_{cell2} = \alpha_{cell3}$

subgrid scale structures → integral average properties (FVM)

$$\overline{\rho} = \frac{1}{V_{cell}} \int_{V_{cell}} \rho \cdot dV \qquad \overline{\rho u} = \frac{1}{V_{cell}} \int_{V_{cell}} \rho u \cdot dV \qquad \overline{\rho E} = \frac{1}{V_{cell}} \int_{V_{cell}} \rho E \cdot dV$$

Stable thermodynamic conditions → constitutive relations (EOS) determine cell variables $\overline{p}$, $\overline{T}$

$$\Rightarrow \quad \overline{\rho} = \overline{\rho}(\overline{p},\overline{T}) \qquad \overline{e} = \overline{e}(\overline{p},\overline{T})$$

Thermodynamic Equilibrium Conditions - Substitute EOS

- "Equation of state" for liquid water: modified Tait "EOS" (thermal and caloric EOS for pure liquids)

$$\overline{p}\left(\overline{\rho},\overline{T}\right)=\left(B+p_{sat}\left(\overline{T}\right)\right)\cdot\left(\frac{\overline{\rho}}{\rho_{l,sat}\left(\overline{T}\right)}\right)^{n}-B$$

$$e_l\left(\overline{T}\right)=c_{vl}\cdot\left(\overline{T}-T_{ref}\right)+e_{l,ref}$$

- EOS of pure water vapour: perfect gas law (thermal and caloric description of pure vapour)

$$\overline{p}\left(\overline{\rho},\overline{T}\right)=\overline{\rho}\cdot R_v\cdot\overline{T}$$

$$e_v\left(\overline{T}\right)=c_{vv}\cdot\left(\overline{T}-T_{ref}\right)+e_{v,ref}+l_v$$

For water: $B \approx 3.3 \cdot 10^8$ *Pa*, $n \approx 7.15$, reference state *ref*.: expected mean temperature (293.15 K).

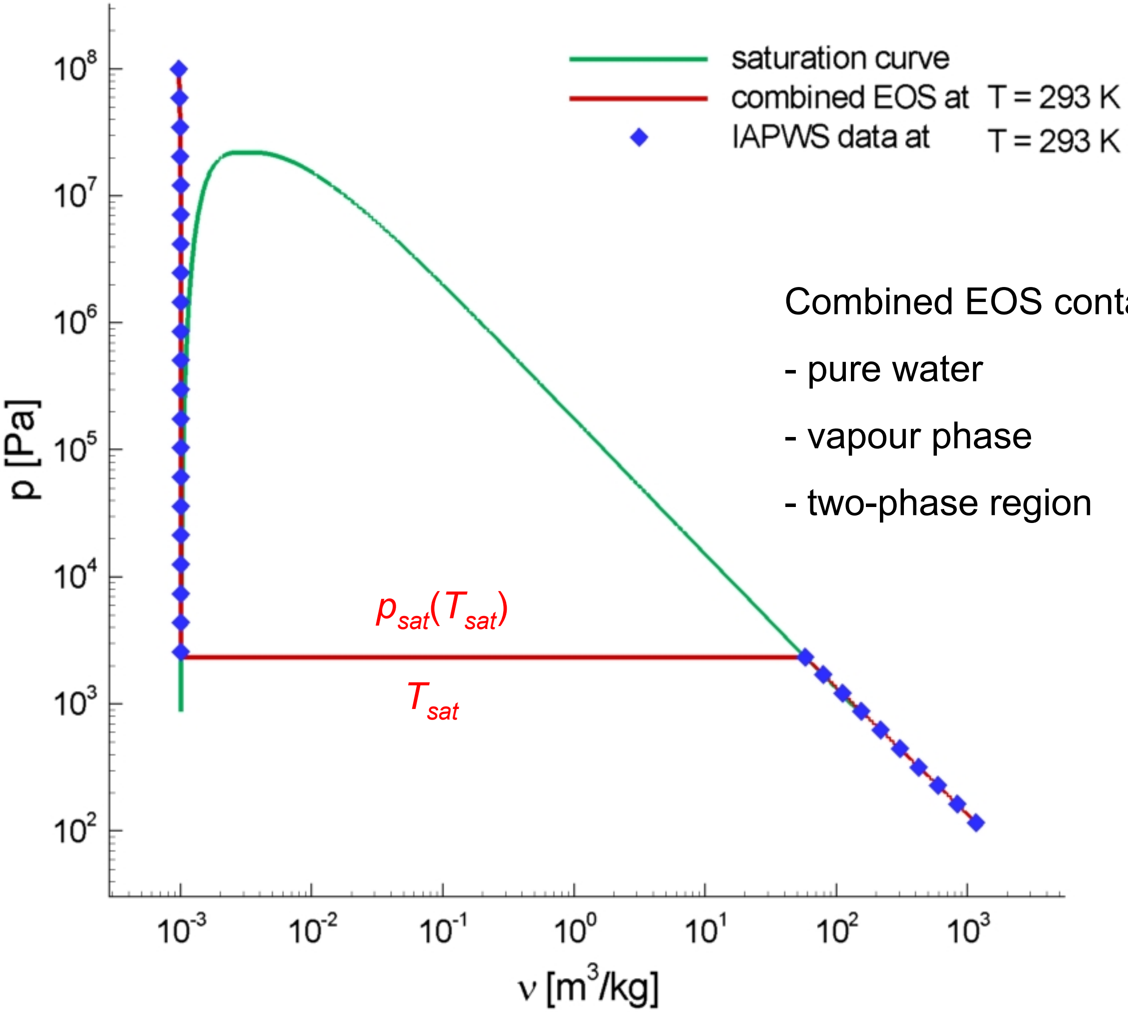
-EOS for saturated water/vapour: saturation conditions **– Oldenbourg polynomials**
(conditions for saturated mixture of water and water vapour for a void fraction α)

$$\overline{p}=p_{sat}\left(\overline{T}\right)$$

$$\overline{\rho}=\alpha\cdot\rho_{v,sat}\left(\overline{T}\right)+\left(1-\alpha\right)\cdot\rho_{l,sat}\left(\overline{T}\right)$$

$$\overline{\rho e}=\alpha\cdot\rho_{v,sat}\left(\overline{T}\right)\cdot e_v\left(\overline{T}\right)+\left(1-\alpha\right)\cdot\rho_{l,sat}\left(\overline{T}\right)\cdot e_l\left(\overline{T}\right).$$

Thermodynamic model - EOS



Combined EOS contains relations for:

- pure water → modified Tait equation
- vapour phase → ideal gas law
- two-phase region → saturation conditions

CATUM - Cavitation **T**echnische **U**niversität **M**ünchen

Finite volume Method

Compressible, frictionless, unsteady flows -> Euler equations

Grid: structured hexagonal cells

Flux function: density based

Solver: mod. Riemann solver

2nd order accurate

explicit

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Numerical results and validation

- Spherical body
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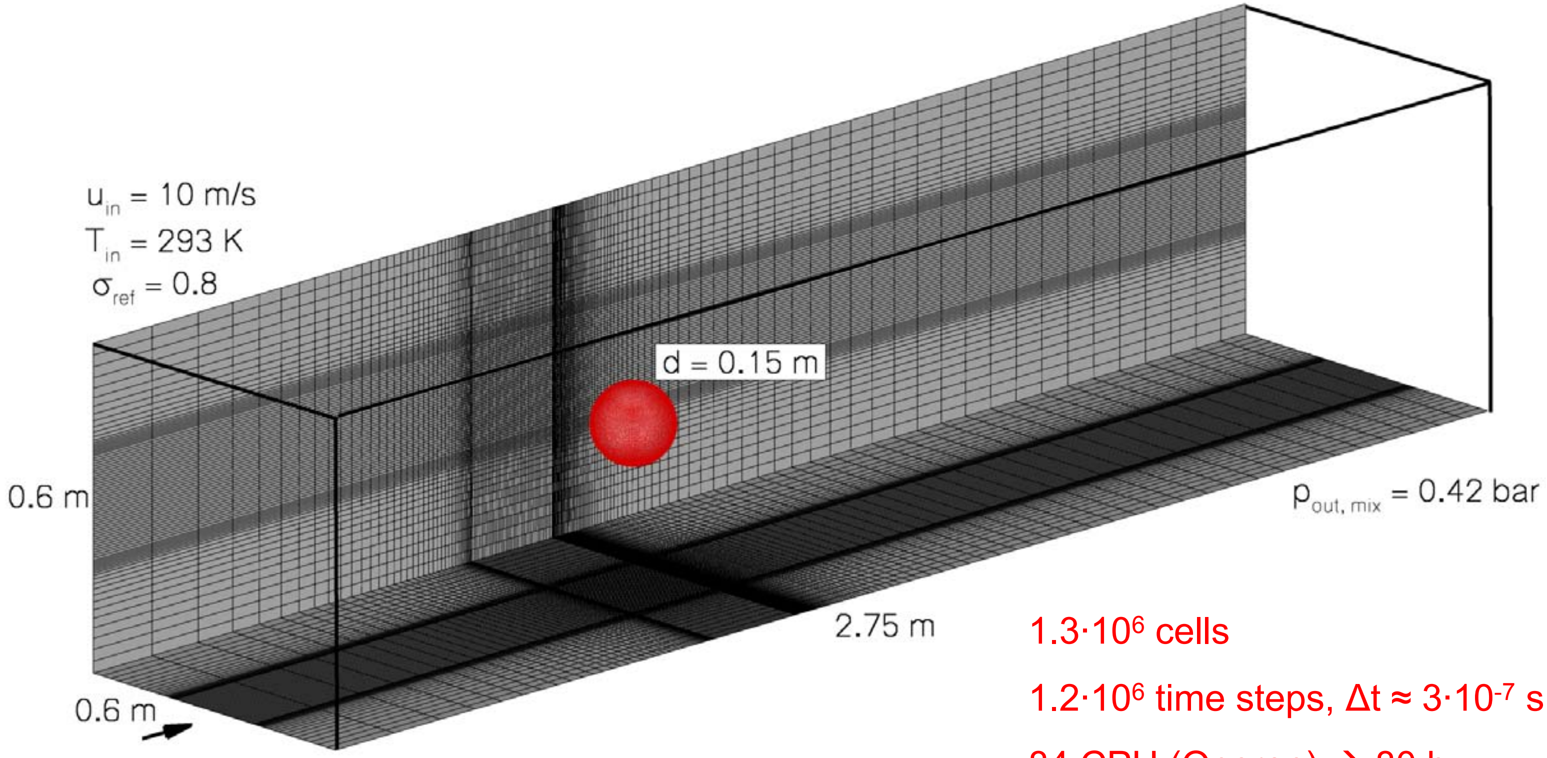
Numerical results – application: two-phase flow

3-D simulation of Branders experiment of cavitation around a sphere



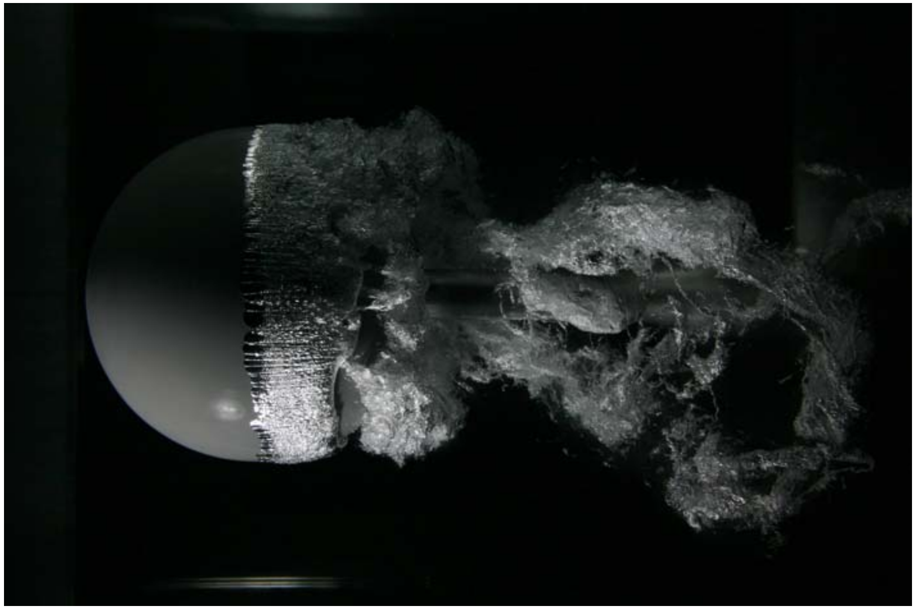
$1.3 \cdot 10^6$ cells

$1.2 \cdot 10^6$ time steps, $\Delta t \approx 3 \cdot 10^{-7}$ s

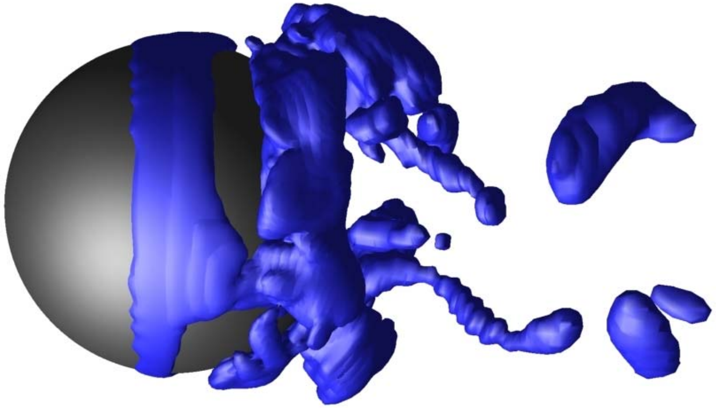
84 CPU (Operon) → 80 h.

Numerical results – application: two-phase flow

Comparison of two-phase structures experiment/simulation

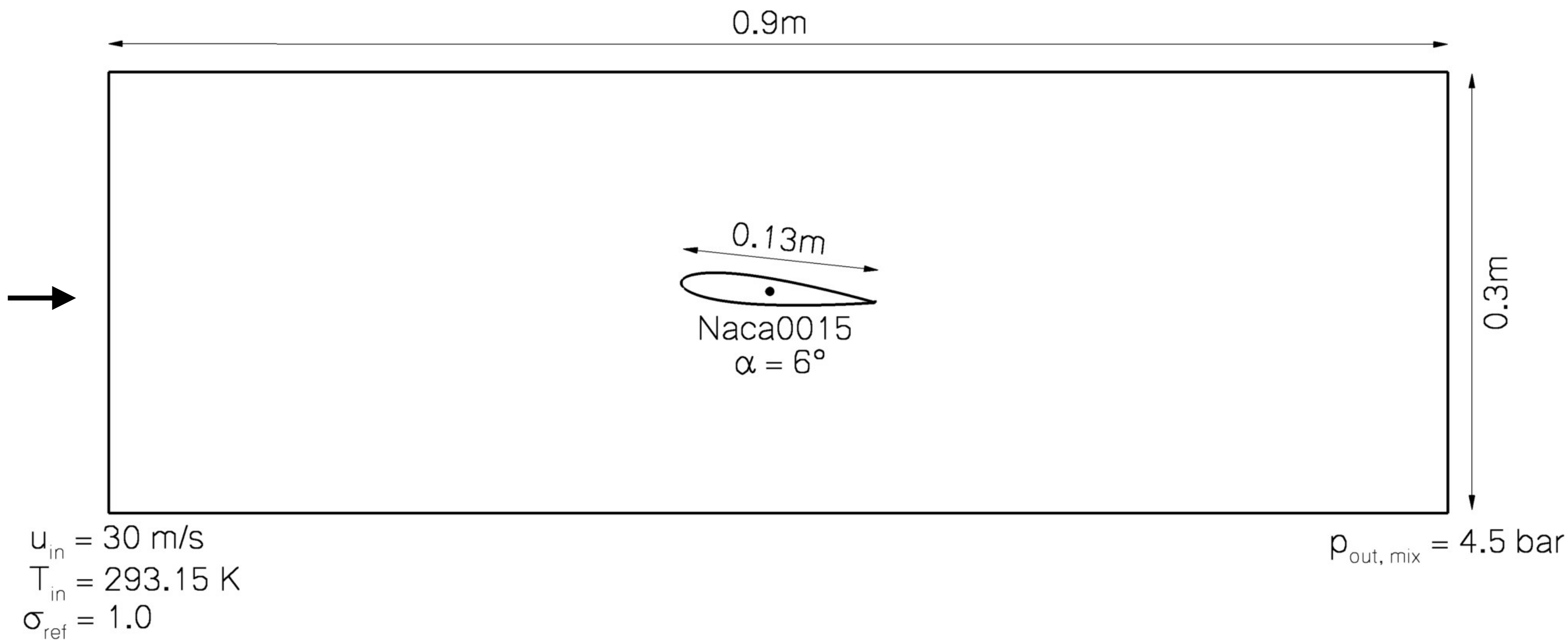


Experiment: Brandner, P. A., Walker, G. J., Niekamp, P. N. and Anderson, B., "An Investigation of Cloud Cavitation about a Sphere." In: 16th Australasian Fluid Mechanics Conference, 2 – 7 December 2007, Crown Placa, Gold Coast, Australia, 2007.



Simulation CATUM: Isosurfaces α=0.05, one instant in time.

Numerical results – 2-D hydrofoil

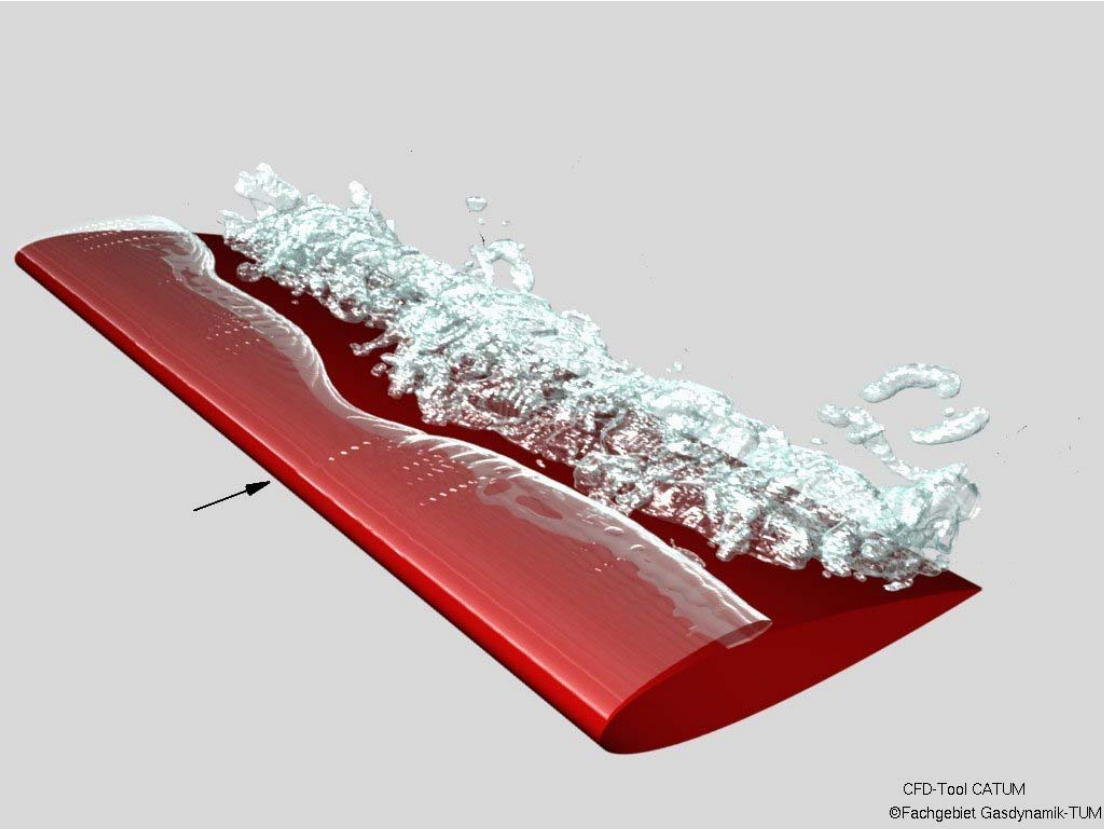


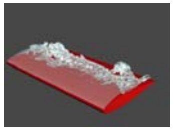
3-D simulation – span/channel width 0.3 m

$2.4 \cdot 10^7$ cells

$6 \cdot 10^5$ time steps, $\Delta t \approx 5 \cdot 10^{-8}$ s,

Numerical results – 2-D hydrofoil





f_{zyklus} = 100 Hz,

$\Delta t_{movie} = 3 \cdot 10^{-2}$ s

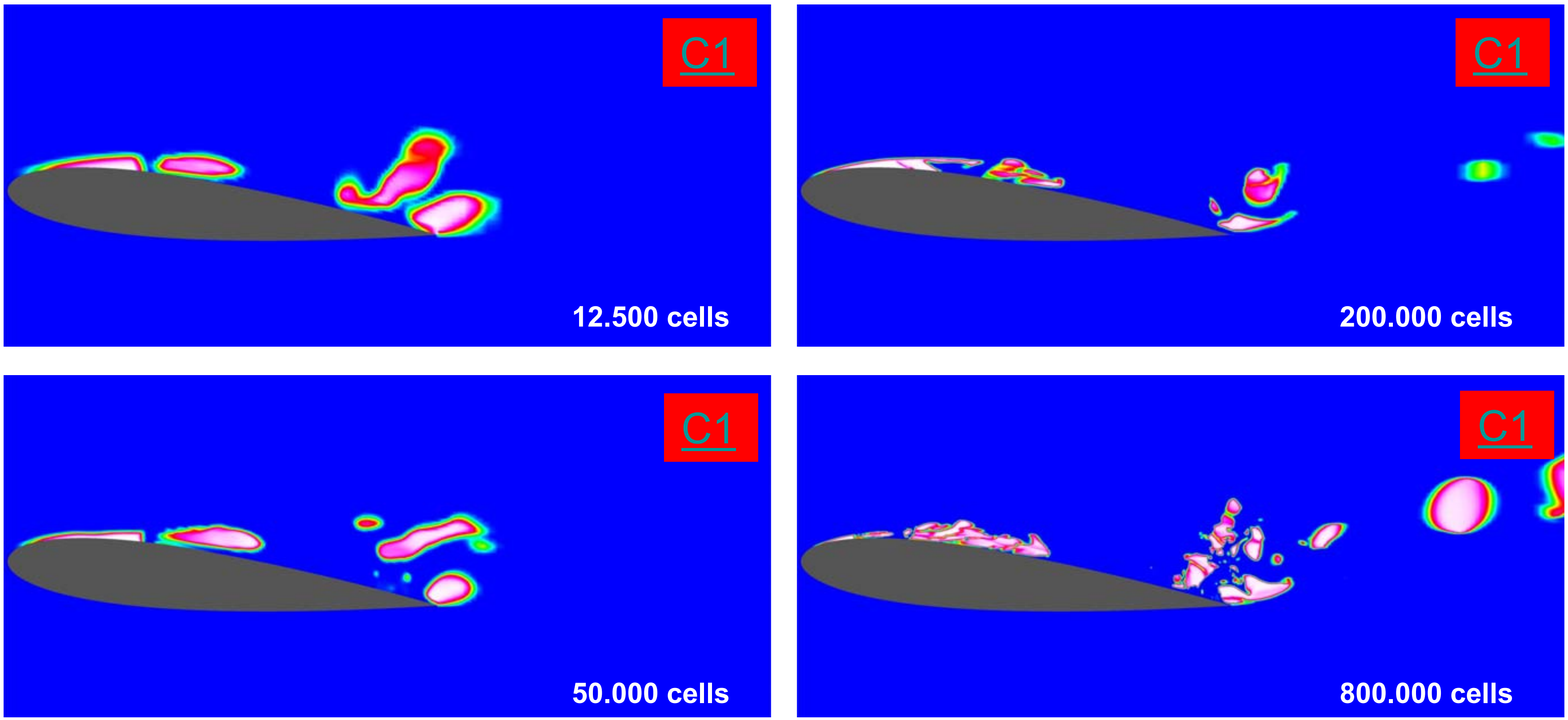
$2.4 \cdot 10^{7}$ cells,

$6 \cdot 10^{5}$ time steps, $\Delta t \approx 5 \cdot 10^{-8}$ s,

96/192 CPU (lx64a Opteron) → 500 h

Numerical results – fragmentation of two-phase flow

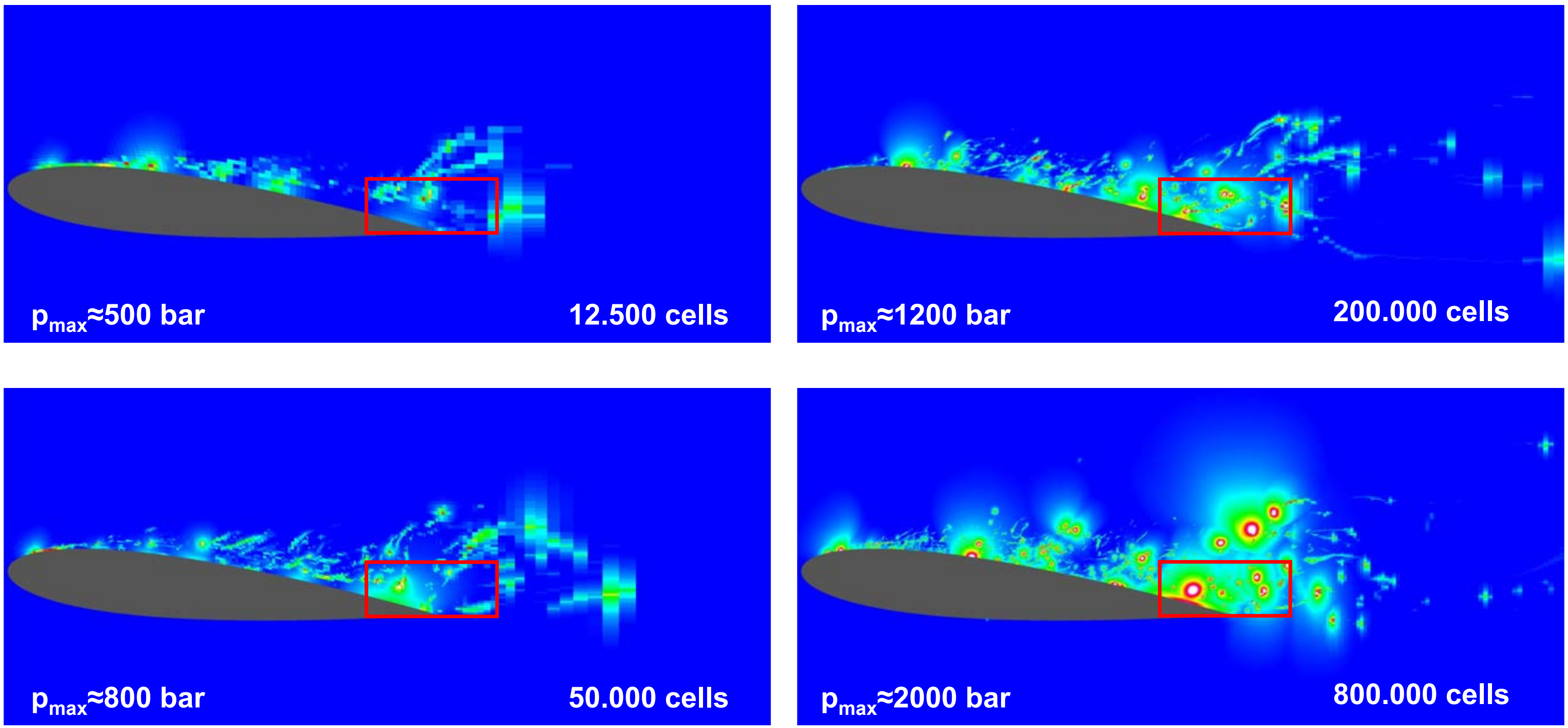
2-D cavitation on 2-D hydrofoil



Effect of the spatial resolution on the structures of the vapor volume fraction α

Numerical results – fragmentation of two-phase flow

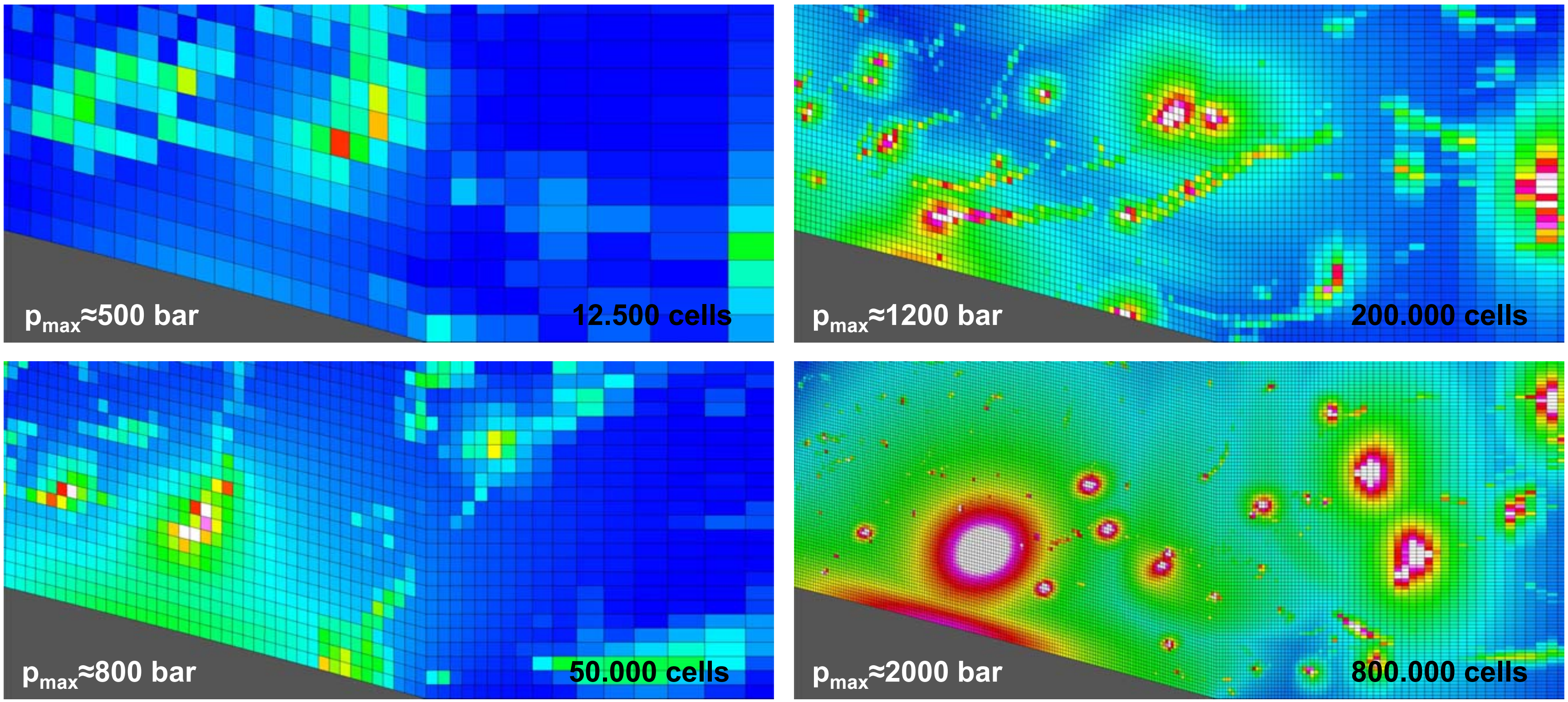
2-D cavitation on 2-D hydrofoil



Effect of the spatial resolution on the instantaneous maximum loads –
pressure footprint over one cycle

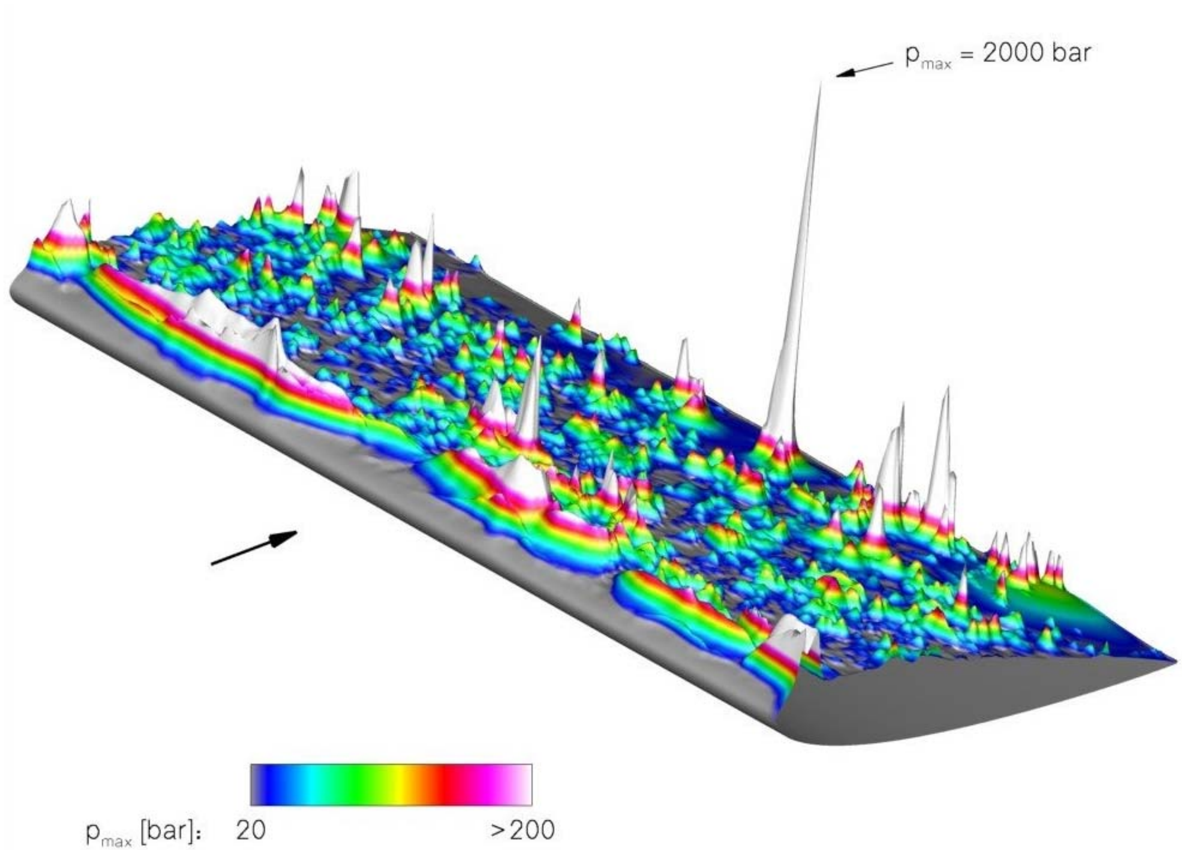
Numerical results – fragmentation of two-phase flow

2-D cavitation on 2-D hydrofoil



Effect of the spatial resolution on the instantaneous maximum loads – pressure footprint over one cycle, **zooms of previous pictures**

2-D hydrofoil – maximum pressure



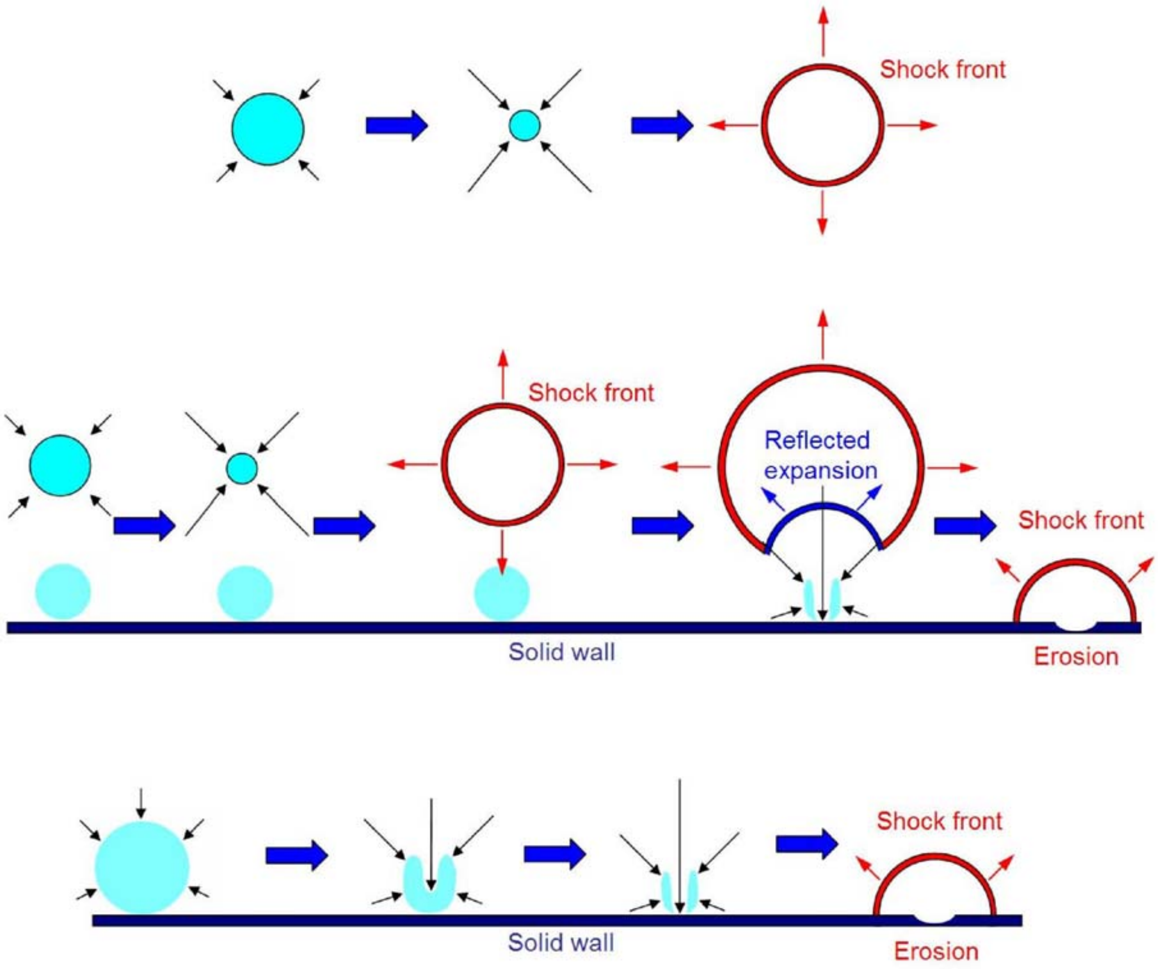
Collaps induced maximum pressure on the suction side - $p_{max} \approx 2000$ bar

Analysed time: one period with $\Delta t_{zyklus} = 10^{-2}$ s

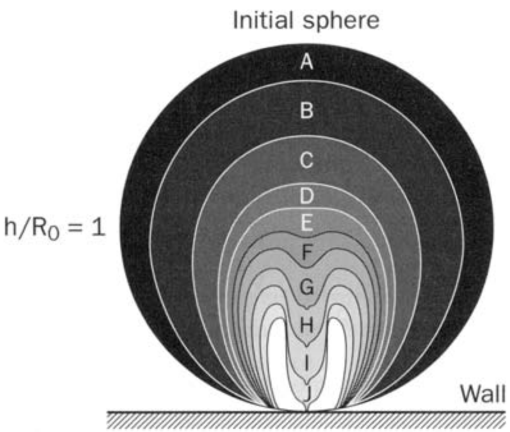
Cavitation erosion

Kuiper, G. - **MARIN** Maritime Research Institute - The Netherlands

Driving mechanisms of cavitation erosion

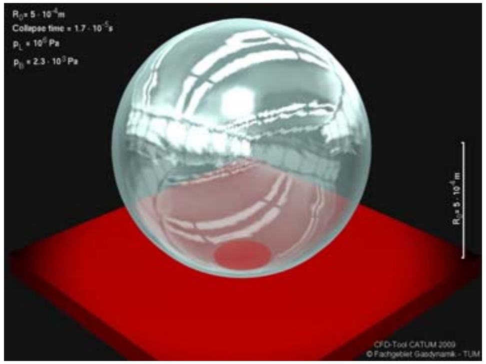


Single bubble collapse with wall interaction

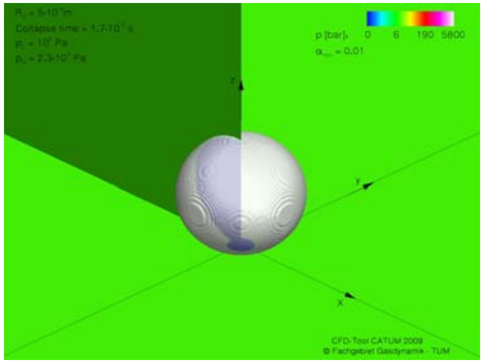


J.P. Franc, J.M. Michel:
„Fundamentals of Cavitation“, 2004

M4



M5



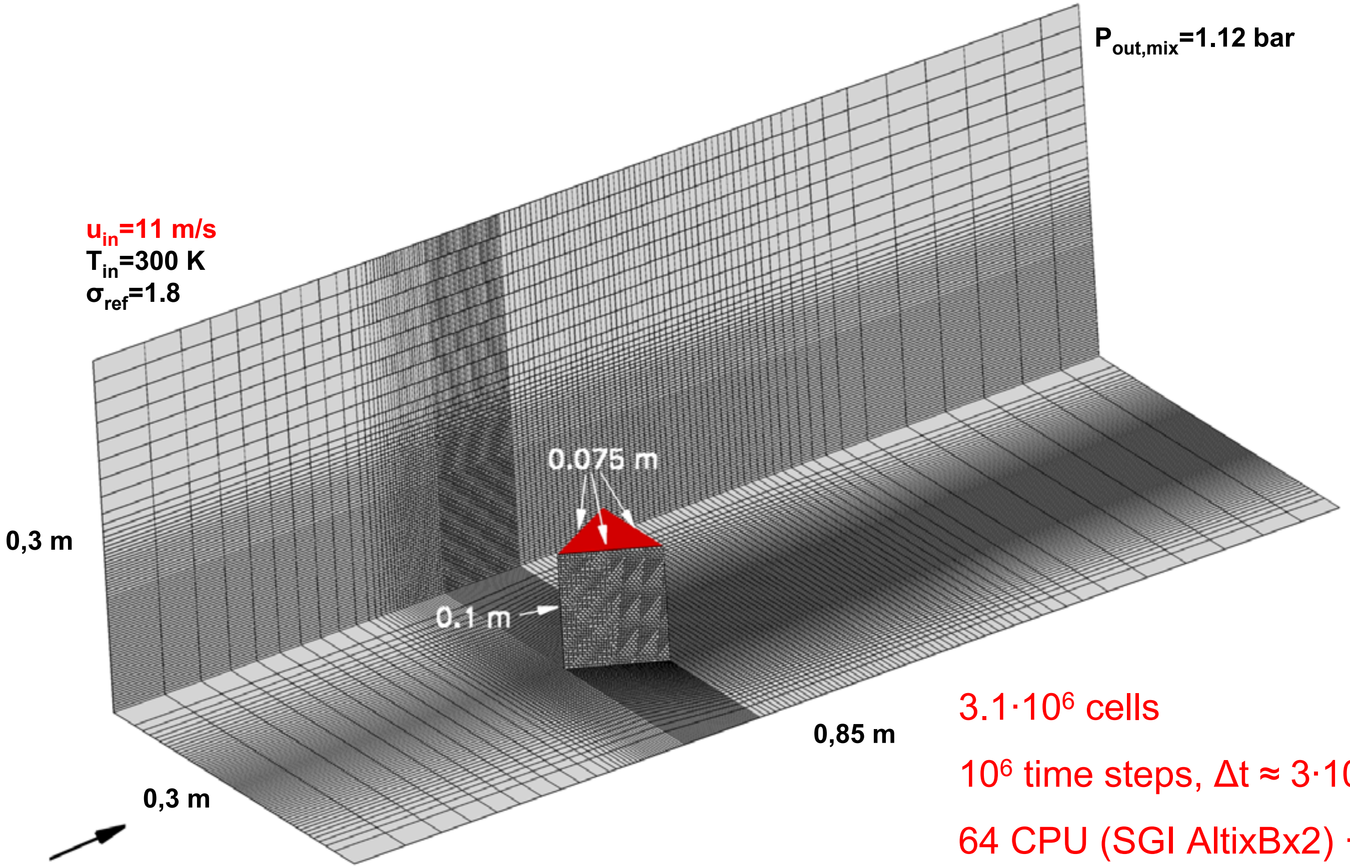
Simulation CATUM

Initial radius R_0=0.5 mm, time step $\Delta t_{CFD}=6.0 \cdot 10^{-9}$ s, collapse time $1.7 \cdot 10^{-5}$ s,

Initial pressures p_{liquid}=10.0 bar, p_{bubble}=0.023 bar , T=293 K, water/vapor

Numerical results – Erosive two-phase flow

3-D simulation of the “Obernach-experiment” on cavitation erosion



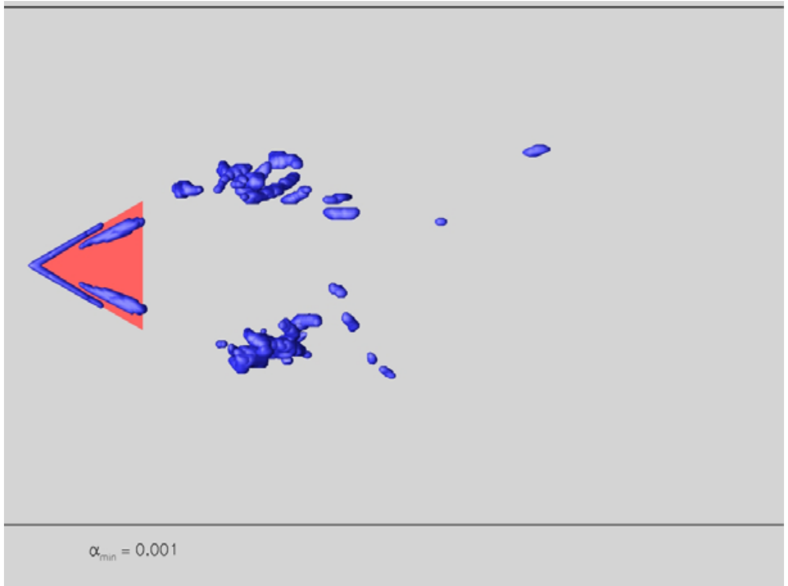
$3.1 \cdot 10^6$ cells

10^6 time steps, $\Delta t \approx 3 \cdot 10^{-7}$ s

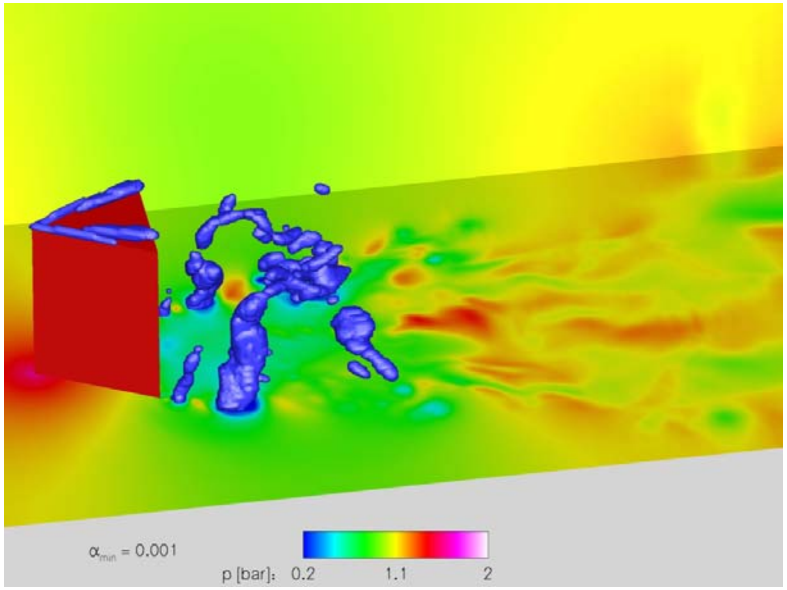
64 CPU (SGI AltixBx2) → 240 h.

Numerical results – Erosive two-phase flow

Dynamic phase-transition and related pressure field



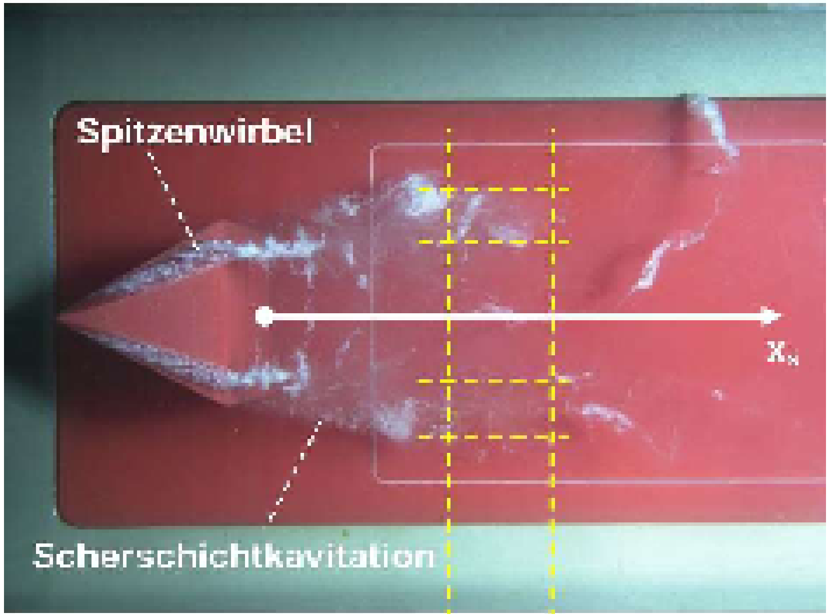
Top view: Two-phase regions, Δt_{Movie}=0.17 s.

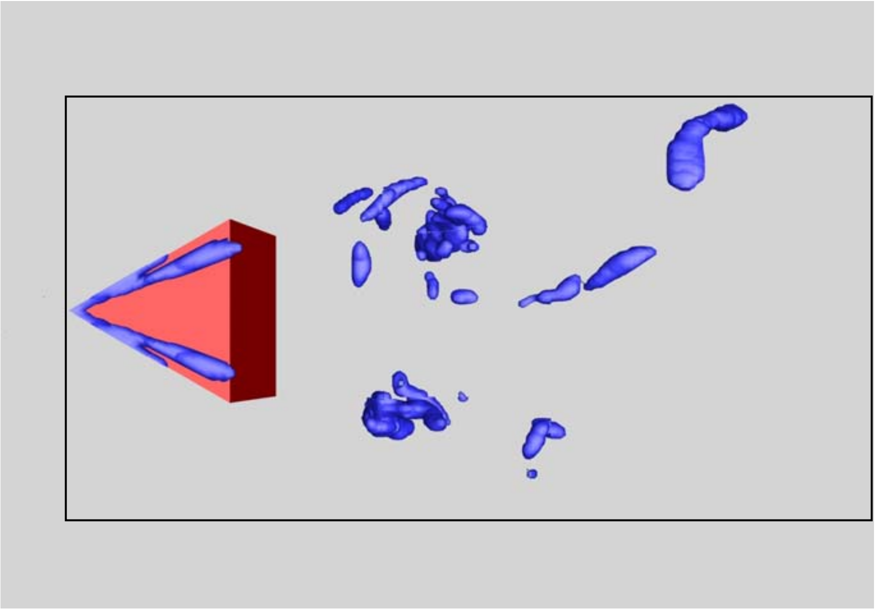


Perspective view: Two-phase regions and static pressure at the walls, Δt_{Movie}=0.17 s.

Numerical results – Erosive two-phase flow

Comparison of two-phase structures experiment/simulation



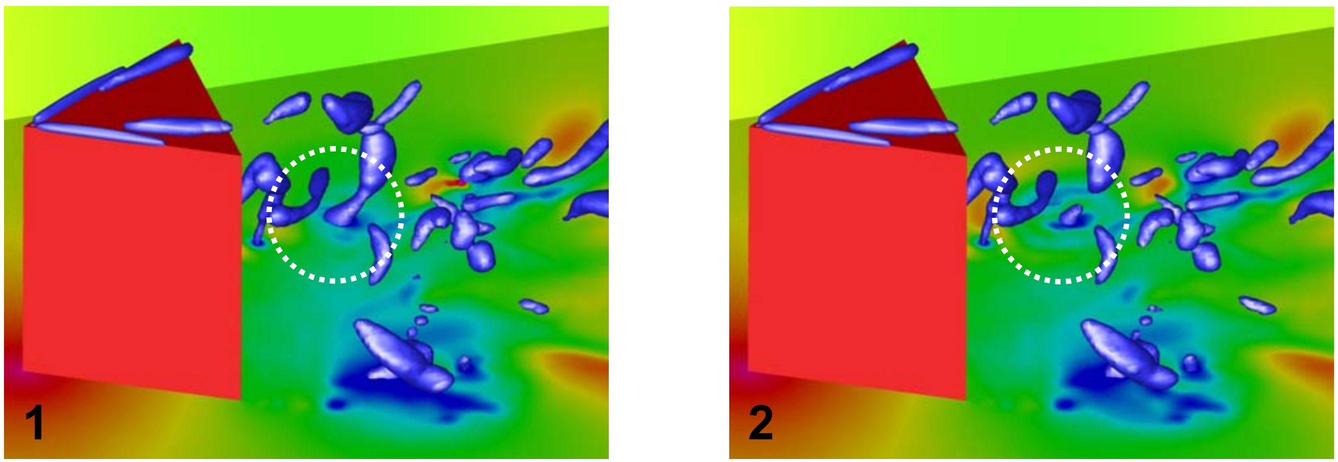


Experiment: Huber R., Geschwindigkeitsmaßstabseffekte bei der Kavitationserosion in der Scherschicht nach prismatischen Kavitatoren, Berichte des Lehrstuhls und der Versuchsanstalt für Wasserbau und Wasserwirtschaft, Hrsg. Univ.-Prof. Dr.-Ing. Th. Strobl, Nr. 102, 2004.

Simulation CATUM: Isosurfaces α=0.01, one instant in time.

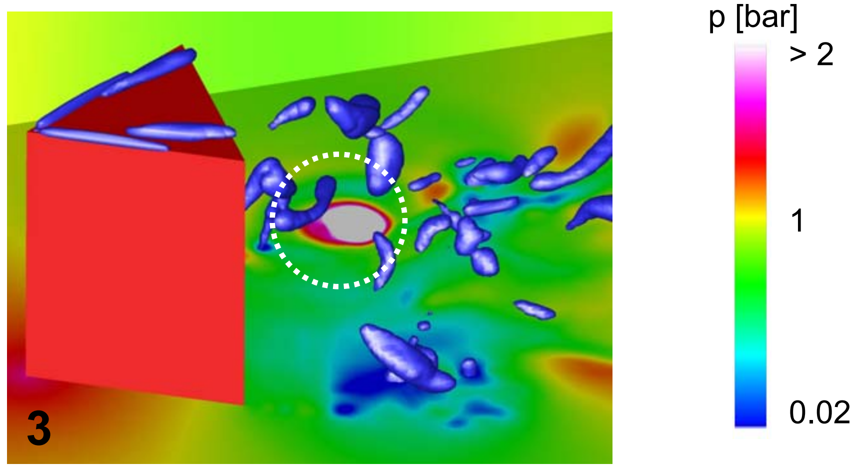
Numerical results – Erosive two-phase flow

Fragmentation of two-phase structure, collapse, shock formation



$\Delta t_{1\rightarrow 2}=1.17\cdot 10^{-4}$ s

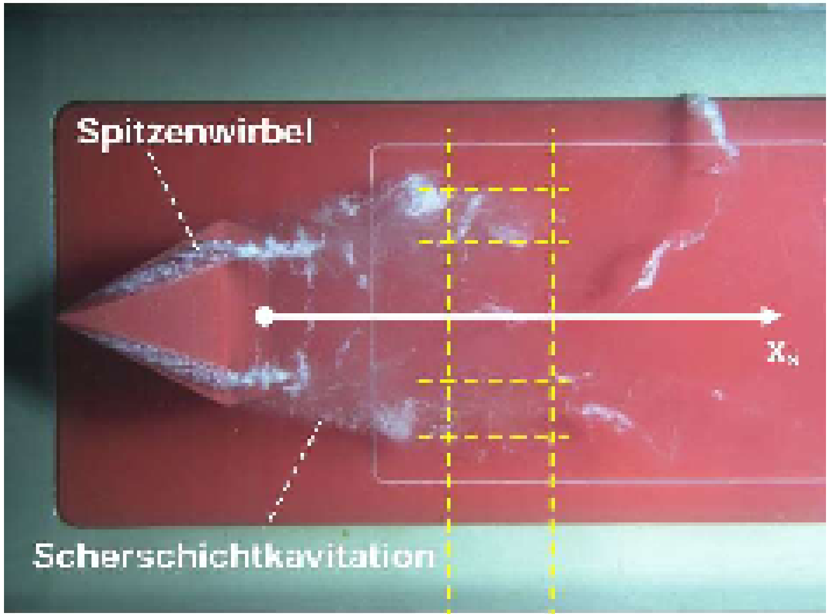
$\Delta t_{2\rightarrow 3}=0.58\cdot 10^{-4}$ s

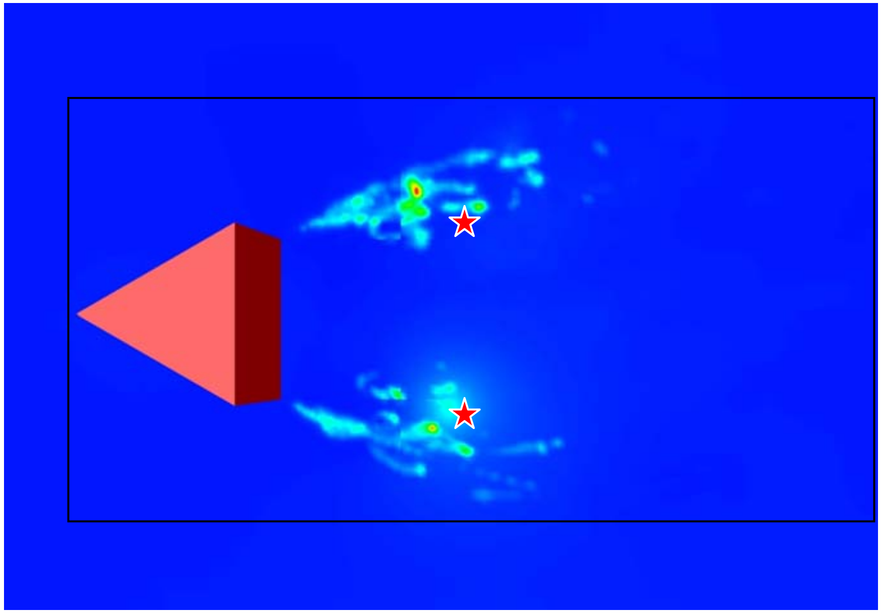


p_{max} = 65 bar

Numerical results – Erosive two-phase flow

Areas of intense erosion (experiment) - maximum pressures (simulation)





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Simulation CATUM: Collapse induced maximum pressure at the bottom wall of the numerical test-section, analysis interval 0.058 seconds. Stars indicate the barycenters (experimental) of the erosion ares.

Discussion