Modelling of two phase flow and application in industries

Third Workshop Micro-Macro Modelling and Simulation of Liquid-Vapour Flows

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- Motivation
- Cavitating flow – how does it look?
- Modelling of two phase flow
- Validation methods
- Simulation of two phase flow
- Summary

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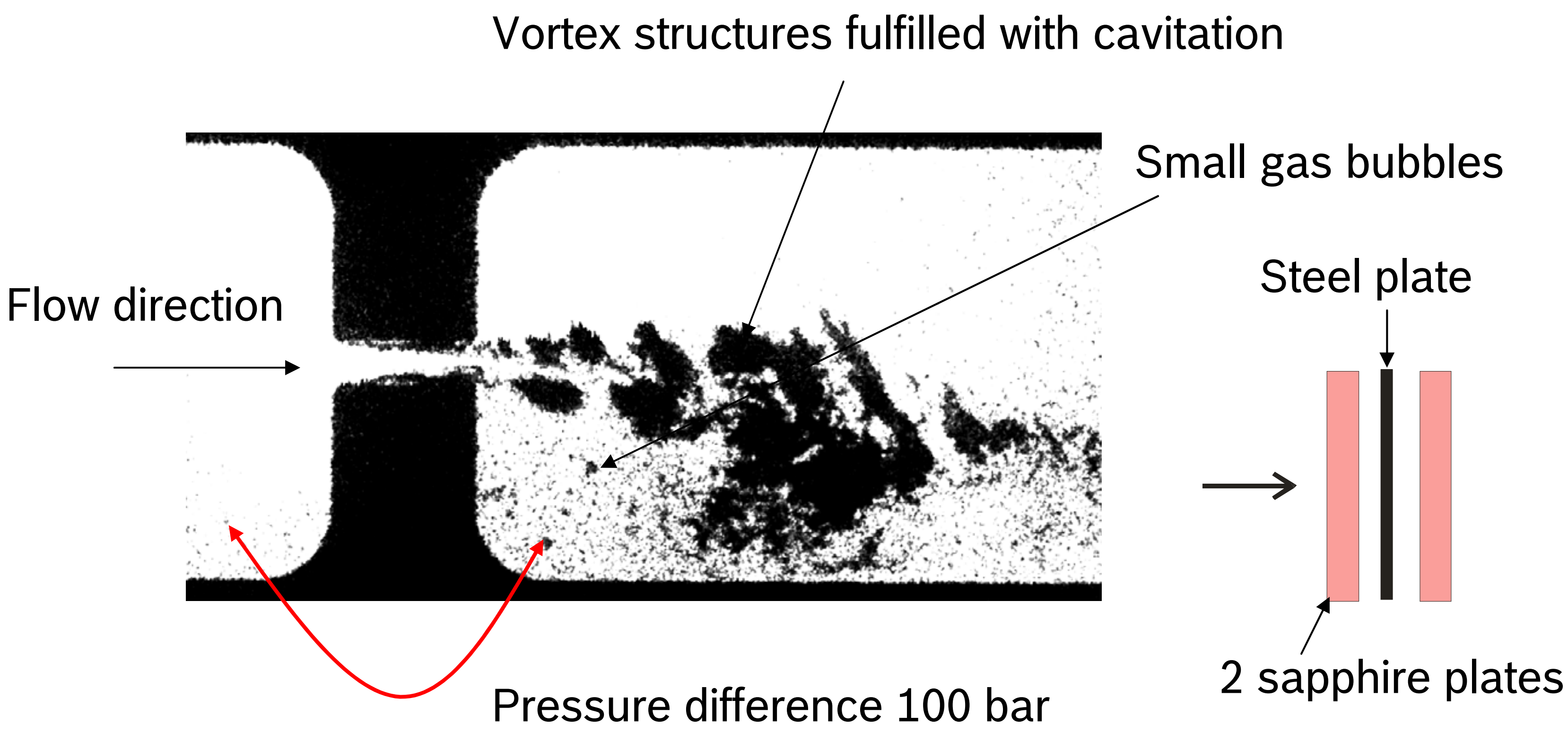
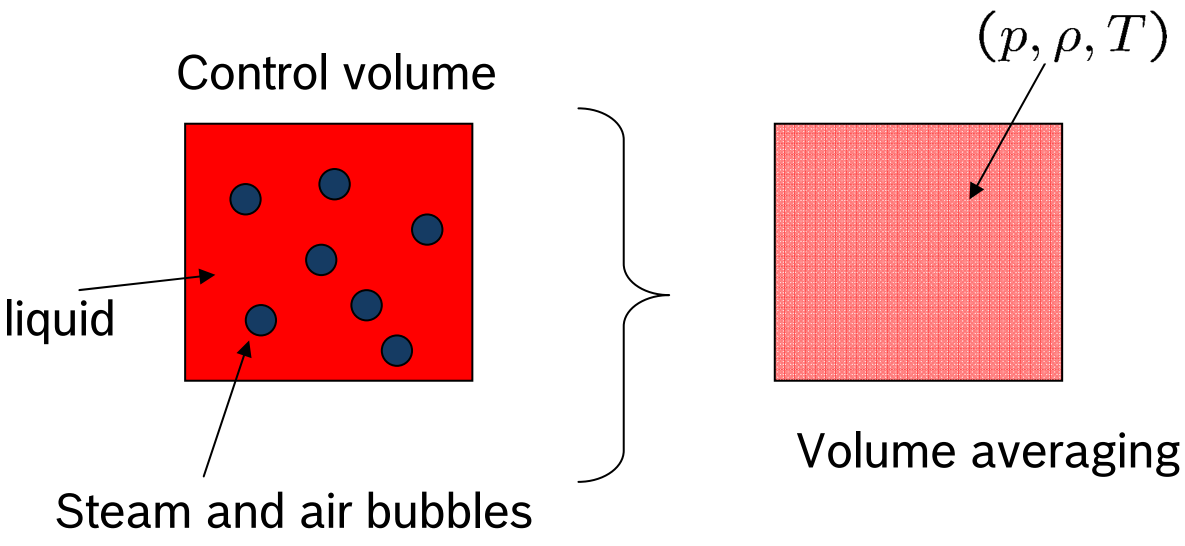
Modelling of cavitating flow

Cavitating channel flow: transmitted light methods, exposure time 5 ns



Modelling of cavitating flow

Modelling of cavitating flow



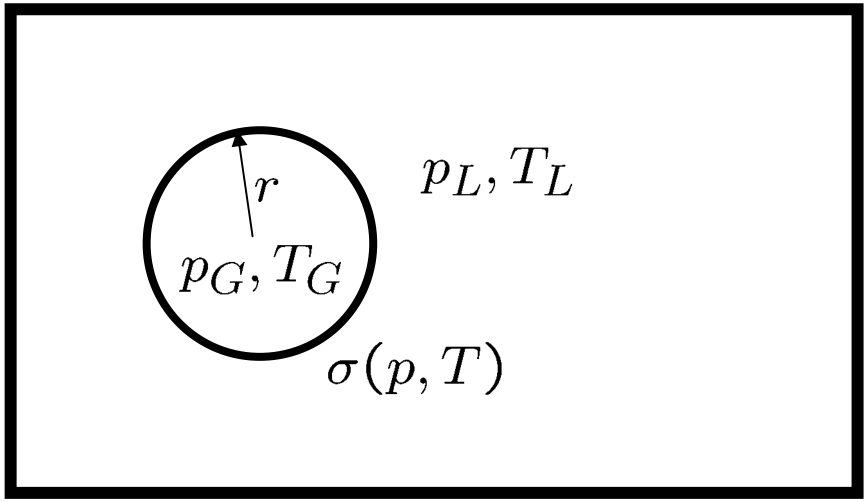
$$\mu = \frac{m_G}{m}$$

$$\epsilon = \frac{V_G}{V}$$

Assumptions:

- homogeneous flow (no slip between both phases)
- both phases have a common pressure
- both phases have a common temperature

Modelling of cavitating flow



Surface tension $\sigma(p, T)$

$$p_L \to p$$

$$T_L \to T$$

Mechanical equilibrium $p_G = p_L + \frac{2\sigma}{r} > p_L$

Pressure inside the bubble leads to delay of evaporation and condensation

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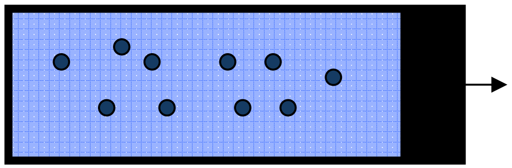
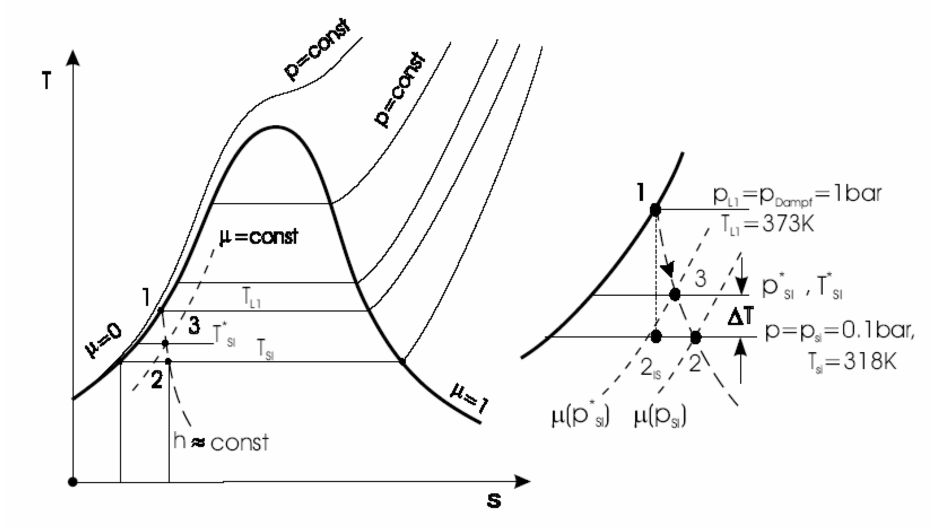
Modelling of cavitating flow

Model for equilibrium procedures = source term for flow equations

Cylinder with a piston



$$\frac{d\mu}{dt} = -\frac{1}{\Delta h}\left(\frac{dh'}{dp} - \frac{1}{\rho'}\right)\frac{dp}{dt}$$



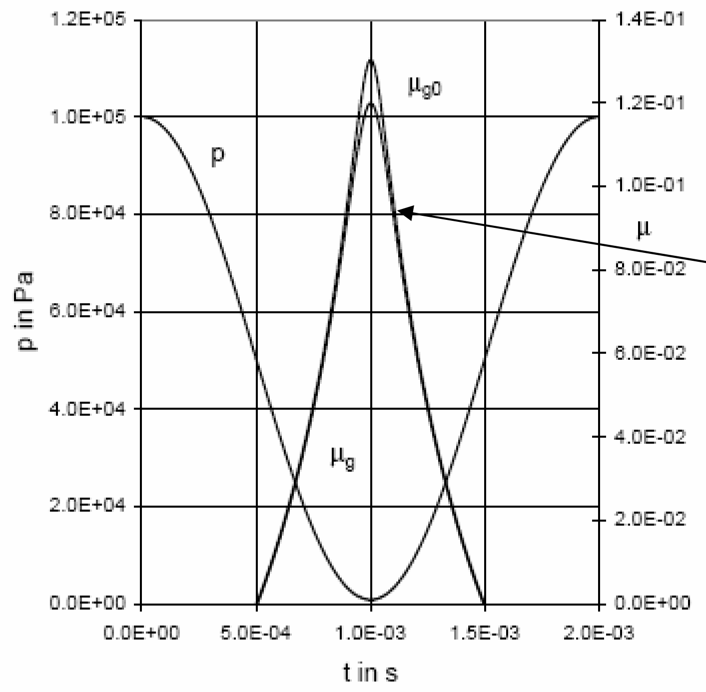
$$\frac{\mathrm{d}\mu}{\mathrm{d}t} = -\frac{1}{\left(r_{verd} + \frac{2\sigma}{3 r_B \rho_B}\right)}\Bigg\{\left[\frac{\mathrm{d}h'}{\mathrm{d}p} - \frac{1}{\rho'} + \left(\frac{c_{pG}}{c_{pv}}x + \mu\right)\frac{\mathrm{d}h''}{\mathrm{d}p} - (x+\mu)\frac{\mathrm{d}h'}{\mathrm{d}p}\right.$$

$$\left. - \left(\frac{x}{\rho_B} + \frac{\mu}{\rho''}\right) + \frac{x+\mu}{\rho'} - \frac{2\sigma}{3 r_B \rho_B^2}(x+\mu)\frac{\mathrm{d}\rho_B}{\mathrm{d}p}\right]\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{\dot{q}}{\rho A} + v\,F\Bigg\}$$

Reduction

Modelling of cavitating flow

Results



Given pressure distribution

$$p(t)$$

Computed mass fraction

Fluid properties for Water

Modelling of cavitating flow

Non-equlibrium models

Both phase have different heat capacity $T_G \neq T_L$

$$\frac{\mathrm{d}T_L}{\mathrm{d}t} = -\frac{1}{(1-x-\mu)c_{pL}}\left\{\left(h_{Bv} - h_{EL} + \frac{2\sigma}{3r_B\rho_B}\right)\frac{\mathrm{d}\mu}{\mathrm{d}t} + \left[\left(\frac{c_{pG}}{c_{pv}}x + \mu\right)\frac{\mathrm{d}h_{Bv}}{\mathrm{d}p}\right.\right.$$
$$\left.\left. - \left(\frac{x}{\rho_G} + \frac{\mu}{\rho_v}\right) - \frac{2\sigma}{3r_B\rho_B^2}(x+\mu)\frac{\mathrm{d}\rho_B}{\mathrm{d}p}\right]\frac{\mathrm{d}p}{\mathrm{d}t} - \frac{\dot{q}}{\rho A} + v\,F\right\} + \frac{T_L\alpha_L}{\rho_L c_{pL}}\frac{\mathrm{d}p}{\mathrm{d}t}\,,$$

$$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \frac{3\alpha_w(T_L - T_G)}{\left(h_{Bv} + \frac{2\sigma}{3r_B\rho_B}\right)\rho_v r_B}\left(\frac{\rho_v}{\rho_G}x + \mu\right) - \frac{1}{\left(h_{Bv} + \frac{2\sigma}{3r_B\rho_B}\right)}\left[\left(\frac{c_{pG}}{c_{pv}}x + \mu\right)\frac{\mathrm{d}h_{Bv}}{\mathrm{d}p}\right.$$
$$\left. - \left(\frac{x}{\rho_G} + \frac{\mu}{\rho_v}\right) - \frac{2\sigma}{3r_B\rho_B^2}(x+\mu)\frac{\mathrm{d}\rho_B}{\mathrm{d}p}\right]\frac{\mathrm{d}p}{\mathrm{d}t}\,,$$

$$\frac{\mathrm{d}r_B}{\mathrm{d}t} = \frac{r_B}{3(x+\mu)}\left[\frac{\mathrm{d}\mu}{\mathrm{d}t} - \left(\frac{x+\mu}{\rho_B}\right)\frac{\mathrm{d}\rho_B}{\mathrm{d}p}\frac{\mathrm{d}p}{\mathrm{d}t}\right].$$

$$\boxed{\alpha_w(t, T_G, \cdots)}$$

Coupling liquid-steam (heat transfer coefficient)

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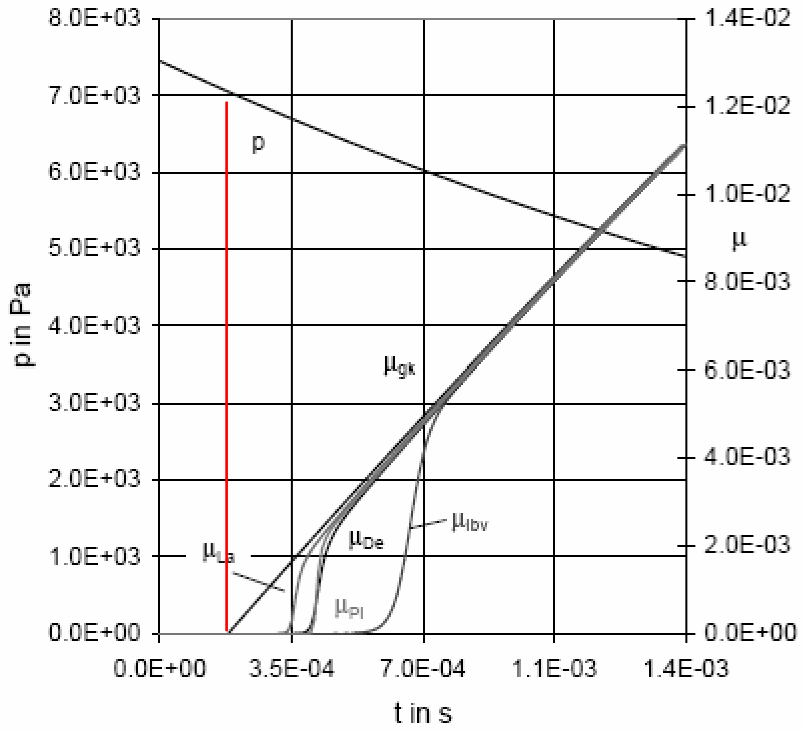
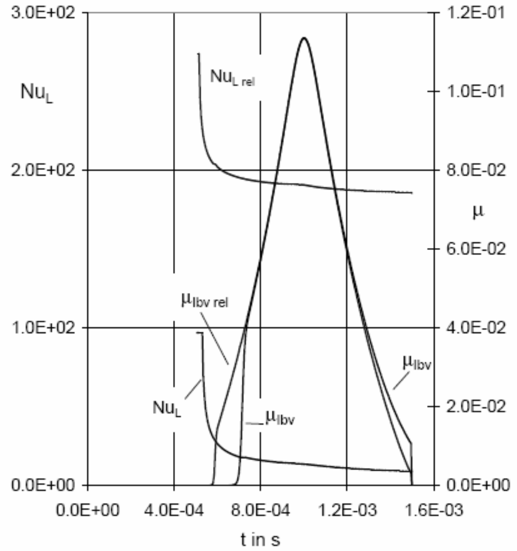
Modelling of cavitating flow



Different evaporation models

Name	Differentialgleichung
Plesset	$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \frac{18}{\pi r_B^2} Ja \lvert Ja \rvert a_L \, \mu$
Labunzov	$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \frac{18}{\pi r_B^2} Ja \lvert Ja \rvert a_L \, \mu \left[1 + \frac{1}{2} \left(\frac{\pi}{6 \lvert Ja \rvert} \right)^{2/3} + \frac{\pi}{6 \lvert Ja \rvert} \right]$
Dergarabedjan	$\frac{\mathrm{d}\mu}{\mathrm{d}t} = \frac{3\pi}{4 r_B^2} Ja \lvert Ja \rvert a_L \, \mu$



$$v_G \neq v_L$$

Modelling of cavitating flow

Rayleigh-Plesset equation[1]

$$r_B \frac{d^2 r_B}{dt^2} + \frac{3}{2}\left(\frac{\mathrm{d}r_B}{\mathrm{d}t}\right)^2 = \frac{p_B - p_\infty}{\rho_L}$$

Linearization of the R.-P.- Model:

$$(\dot{r}_B)^2 = \frac{2}{3}\frac{p_B - p_\infty}{\rho_L}$$

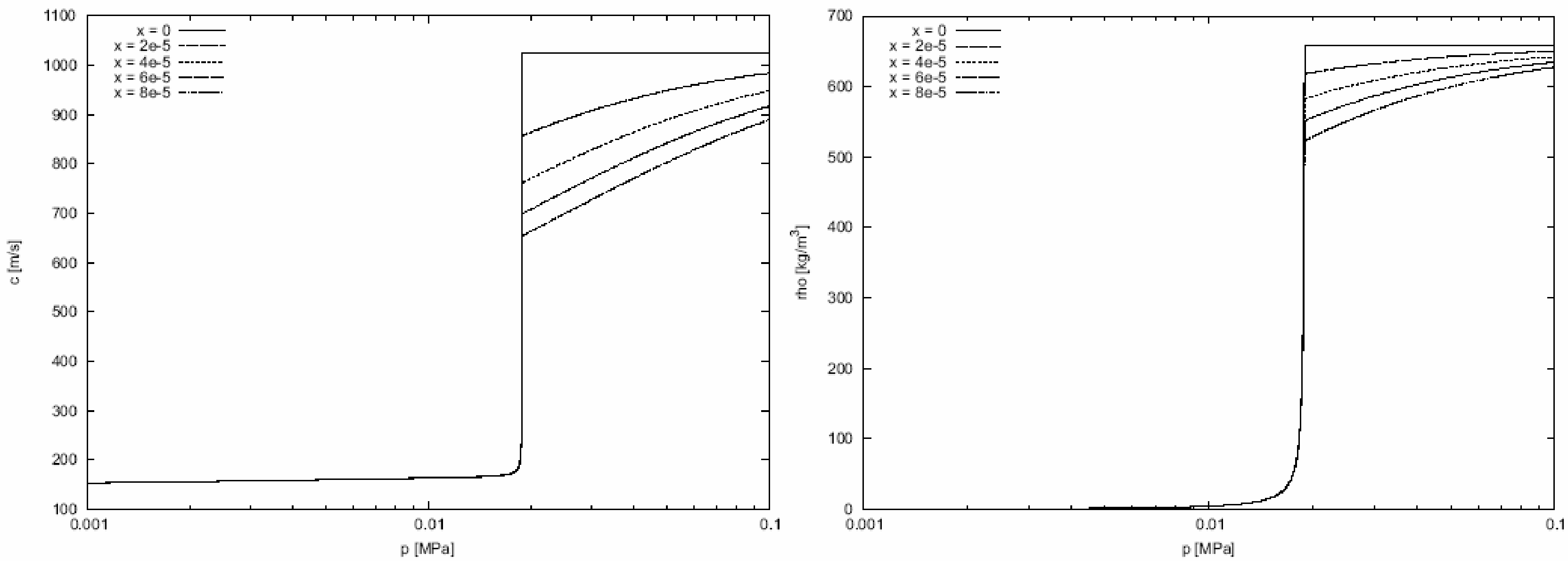
Pressure far away from cavitation (???)

No evaporation or condensation term

1: z.B: Dissertation M. Voß: „Numerische, theoretische und experimentelle Untersuchungen zur Kavitationsblasendynamik", Uni Göttingen 2002

Modelling of cavitating flow

Barotropic model for cavitating flow with unsolved air



- Homogeneous two-phase flow
- Definition of thermodynamic path (isothermal or isentropic)
- Density is a function of pressure

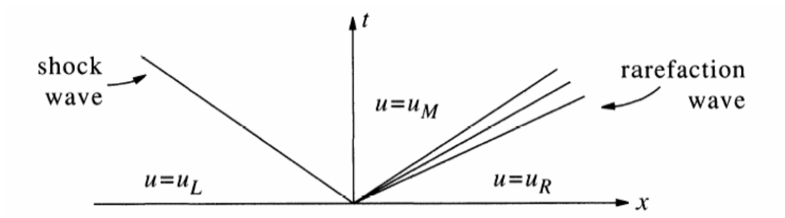
Modelling of cavitating flow

Transition: Liquid <-> Steam

Convex EOS

Pure liquids: Water, N-Heptan

Classical solution of Riemann-Problems



Non convex EOS

Multi component fluids: Gasoline Diesel, hydraulic fluids

many different complex combinations

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Modelling of cavitating flow

Flow equations

1.
$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial z} = 0 \qquad \rho = \rho(p, T_0)$$

Barotropic flow

2.
$$\frac{\partial (\epsilon \rho_G)}{\partial t} + \frac{\partial (\epsilon \rho_G v)}{\partial z} = \Gamma \qquad \Gamma = \rho \frac{d\mu}{dt}$$

Homog.
Two-phase flow

$$\frac{\partial \rho v}{\partial t} + \frac{\partial (\rho v^2 + p)}{\partial z} = -\rho v F$$

Momentuum
equation

→ Full compressible approach with all well known problems

Friction models include transient flow phenomenae (e.g. IET)

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Modelling of cavitating flow

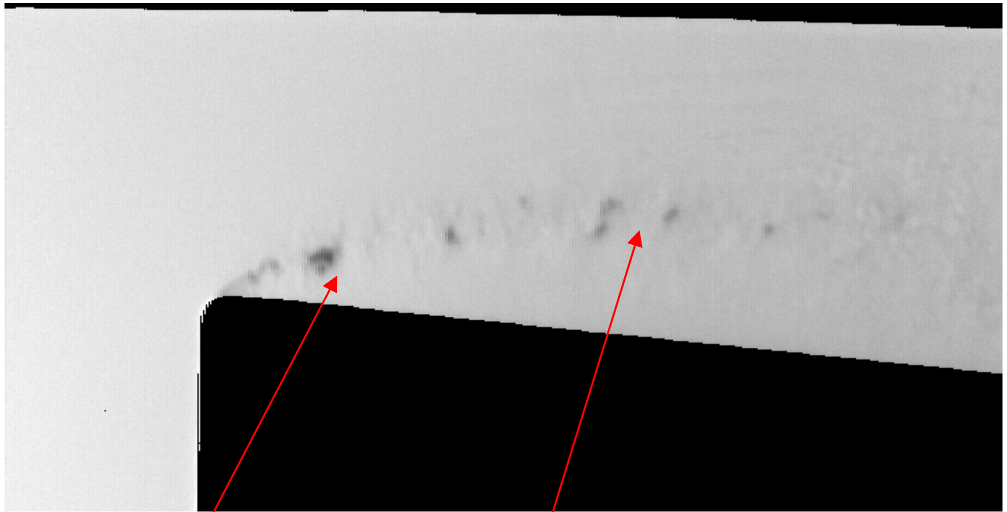
Problems:

- Low Mach-number problem
- Cavitation generates shock waves with high frequencies (MHz)
- Wave propagation due to initial conditions
- non convex EOS
- No typical Riemann solutions (composite waves)
- Question: which numerical scheme resolves the difficult structures?
- Reflecting pressure waves on boundaries of computational area

Experimental analysis of cavitating flow

Experimental validation of cavitating flow

Of interest: Critical Cavitation Point



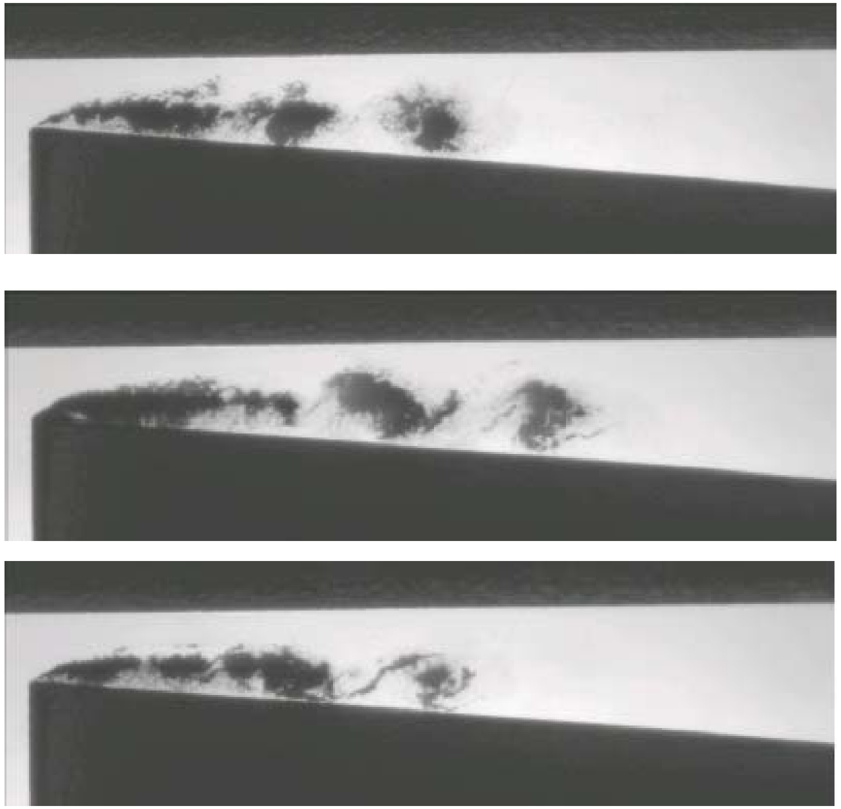
Transmission
Exposure time 10 ns
with high-pressure
flash lamp

Inlet pressure: 100 bar
Outlet pressure: 60 bar

Weak cavitation   Vortex structure, shear layer

Experimental analysis of cavitating flow

Flow around a step in a channel



t_1

100 ms

t_2

100 bar – 50 bar

t_3

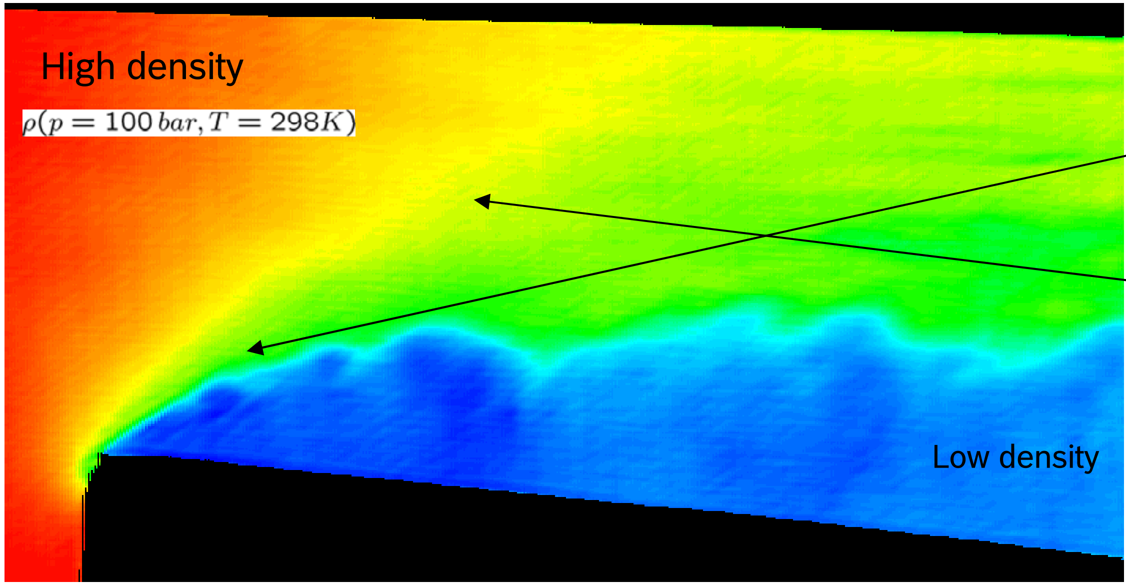
10 ns Exposure time

High transient flow

Experimental analysis of cavitating flow

Digital interferometry as a result of classical and holographic interferometry

Experimental results



Inlet pressure: 100 bar
Outlet pressure: 60 bar

Optical measurement of density field, exposure time 400 ns, depth averaged
-> computing of pressure and temperature fields

Additional step: Using LIF for local velocity fields

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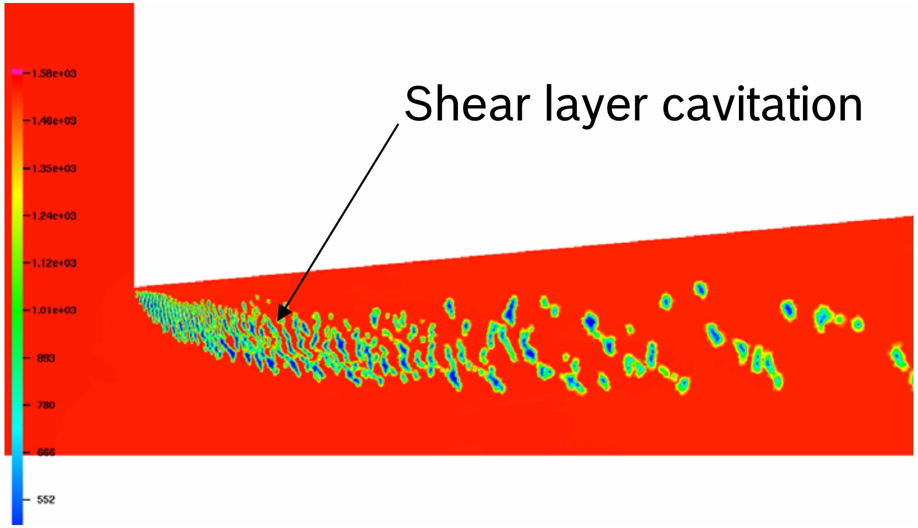
Simulation of cavitating flow

Two dimensional numerical scheme based on the solution of Riemann problems



$k-\omega$-turbulence model

Movie

Inlet: 76 bar
Outlet: 16 m/s

+

$$\frac{1}{\Delta x}\int_{x_{j-\frac{1}{2}}}^{x_{j+\frac{1}{2}}}\mathbf{u}(x,t^{n+1})dx = \frac{1}{\Delta x}\int_{x_{j-\frac{1}{2}}}^{x_{j+\frac{1}{2}}}\mathbf{u}(x,t^{n})dx$$
$$+\frac{1}{\Delta x}\int_0^{\Delta t}F(\mathbf{u}(x_{j-\frac{1}{2}},t))dt - \frac{1}{\Delta x}\int_0^{\Delta t}F(\mathbf{u}(x_{j+\frac{1}{2}},t))dt$$

PhD thesis: E. Thorwirth, Robert Bosch GmbH and IAG Stuttgart, will be published 2008

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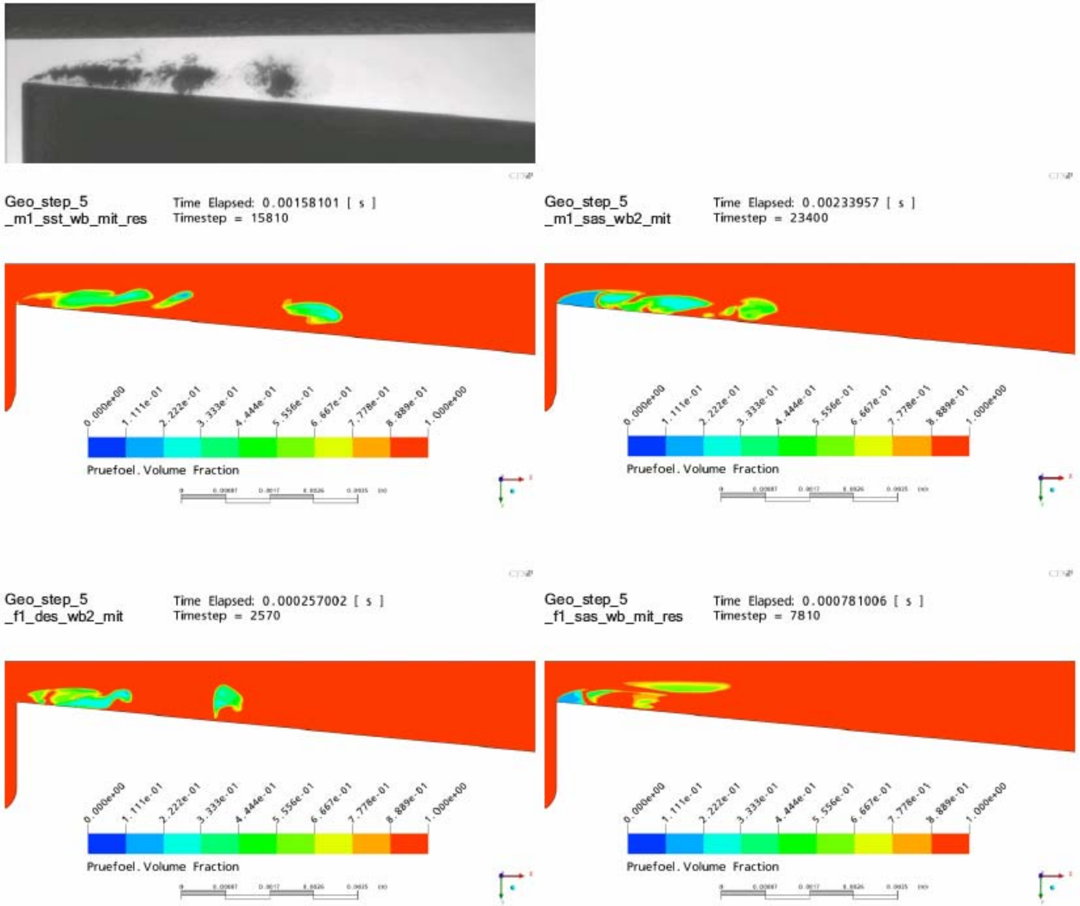
Simulation of cavitating flow

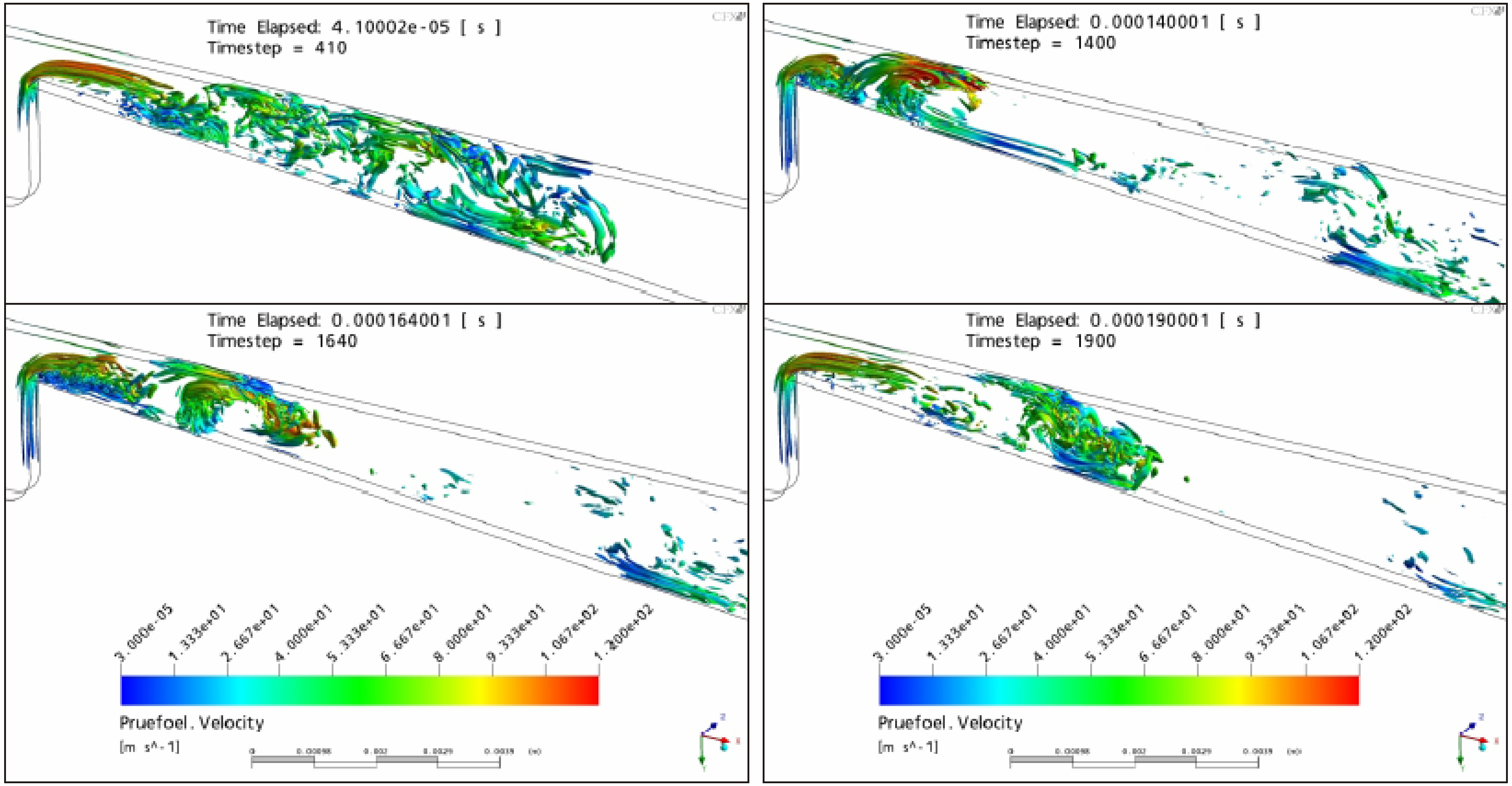


$$\Gamma = f(p, p_D, R_B)$$

In this case lin. Rayleigh-Plesset equation

3D commercial CFD Code CFX 11.0: Detached Eddy Simulation

Simulation of cavitating flow



Computed vortex structures generated on the step

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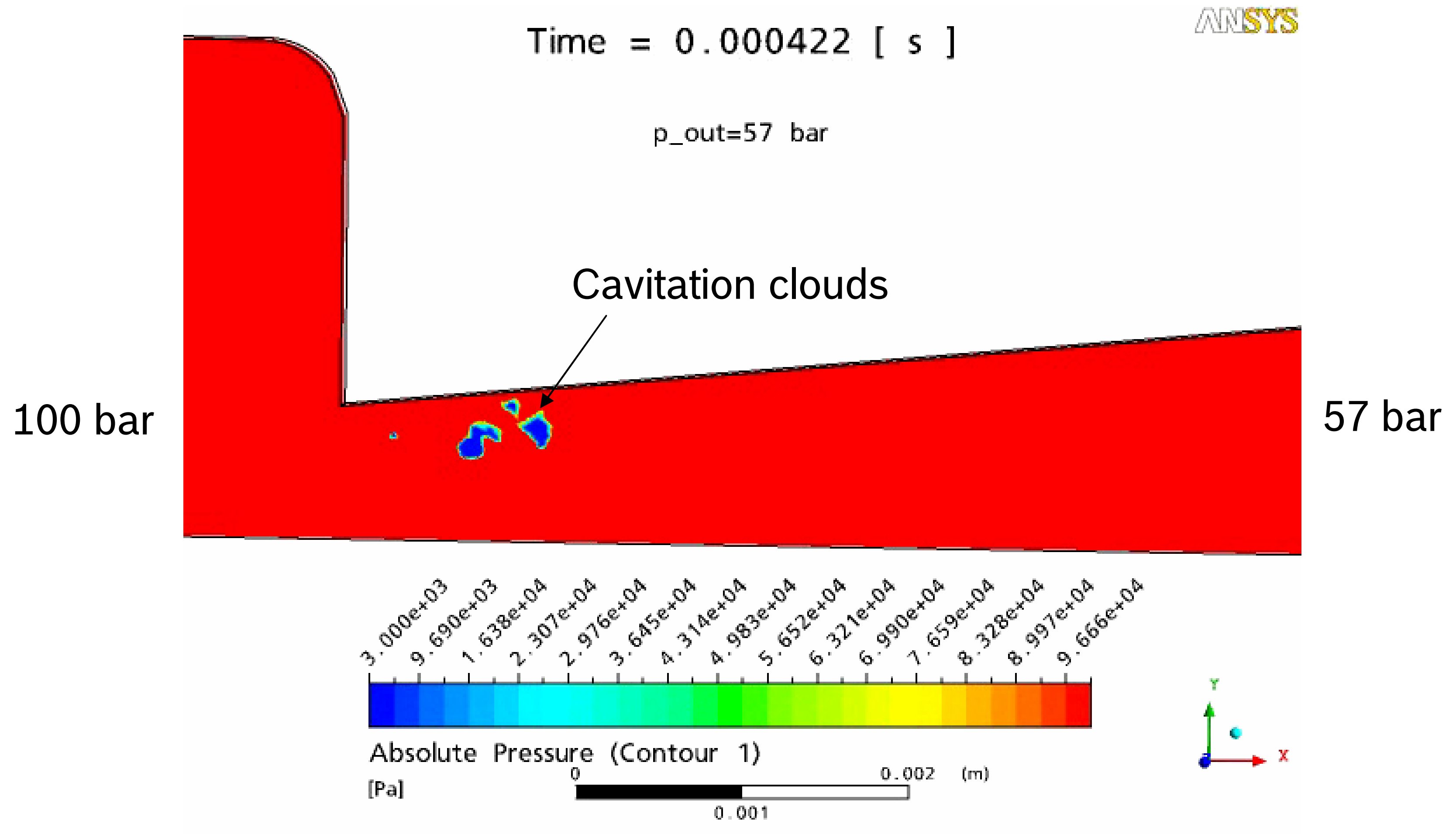
Summary cavitating flow

Wale-LES method



Summary cavitating flow

Summary

- Homogeneous two phase flow allows to describe cavitating flow
- Phase transition leads to multi-scale problems
- Cavitating flow leads to high transient flows
- For detailed simulation of cavitating flow are needed:
  - numerical schemes with high resolution in time and space
  - special boundary conditions to avoid reflection of pressure waves
  - a turbulence model which can handle phase transition as well as laminar-tubulent transition
- Cluster of computers

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