Simulation of Flashing and Steam Condensation in Subcooled Liquid using ANSYS CFX

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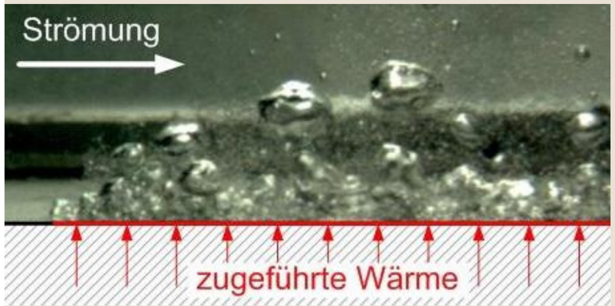
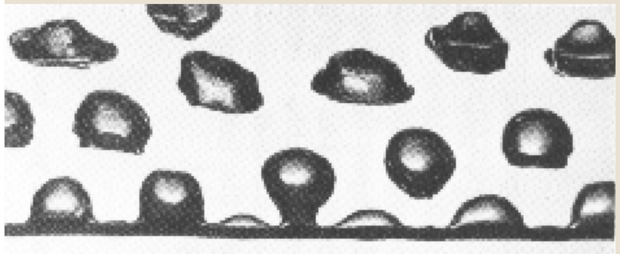
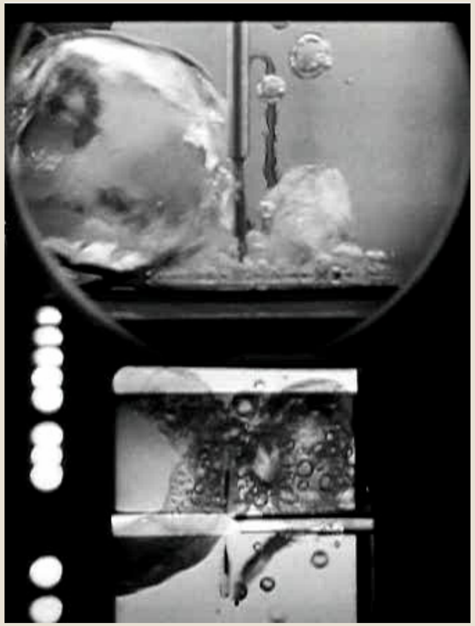
Introduction

Typical applications :

- NRS accident scenarios
  (e.g. SBLOCA, LBLOCA, PTS)
- Depressurization of superheated fluids (flashing)
- BWR fuel assemblies (boiling)







- Steam recondensation e.g. in containments
- Chemical reactor safety
- …

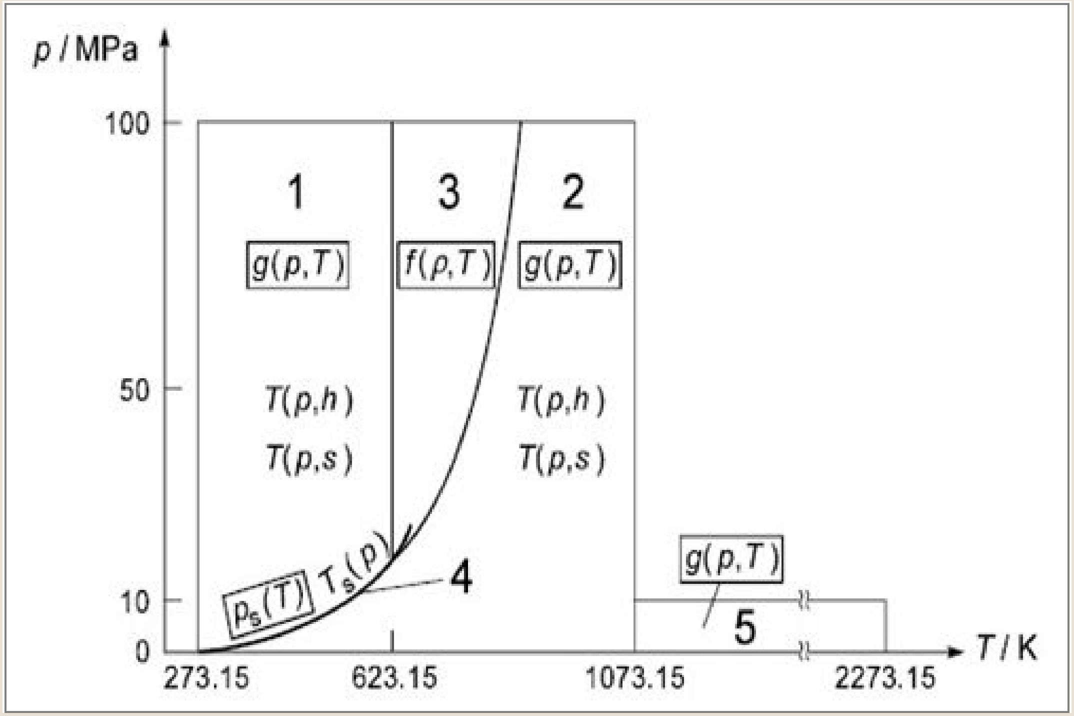
Material Properties: EOS

- Changes over wide range of (T,p)
  → fluid properties depend on thermodynamic state

- Equation of state (EOS) types in CFX:
  - Ideal gas law
  - Tabulated data; Real gas property (RGP) tables
  - Redlich-Kwong EOS
  - User defined equation of state (CCL, CEL)
- User defined materials and material properties
  → large degree of customizability

Material Properties:
IAPWS Properties of Water and Steam

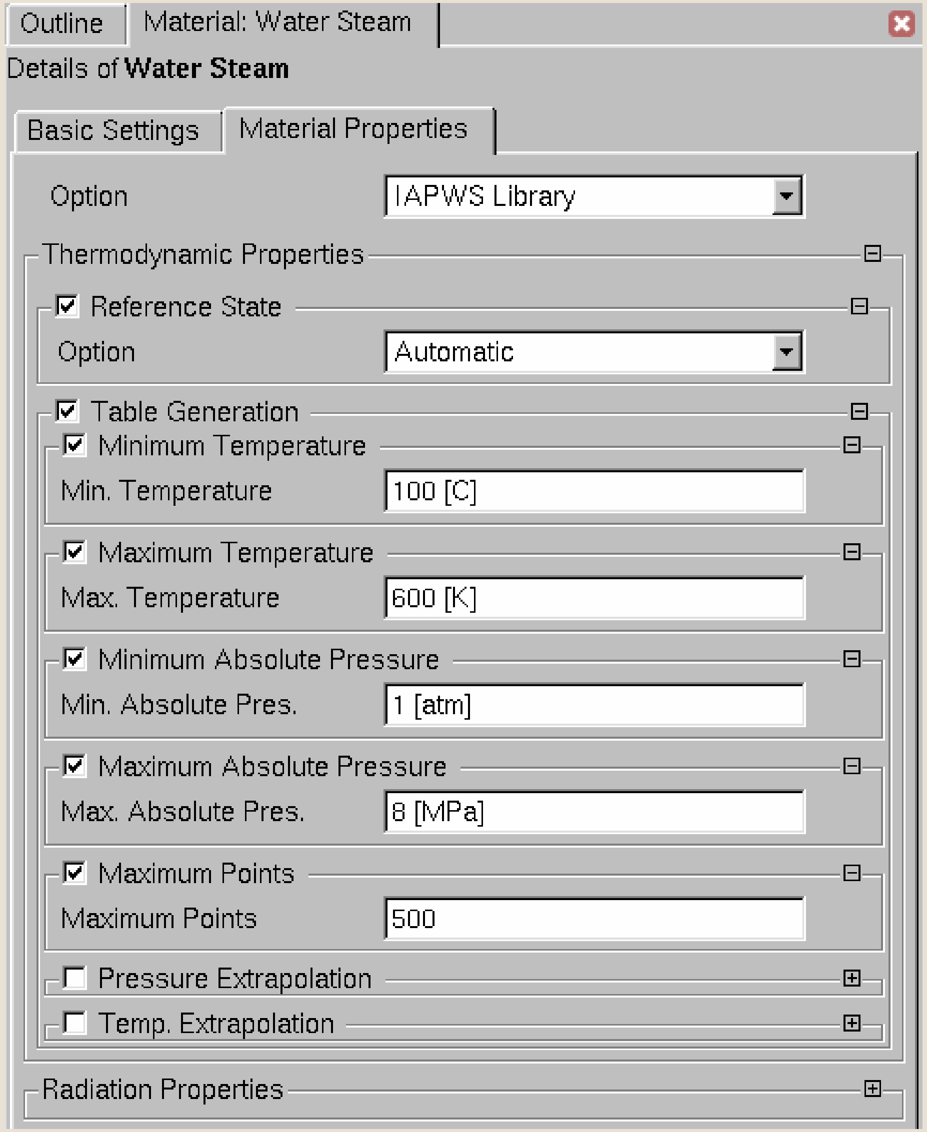
- **CFX-11.0:**
  IAPWS-IF97 equation-of-state implemented
  Reference: W. Wagner, A. Kruse:
  "The Industrial Standard IAPWS-IF97: Properties of Water and Steam", Springer, Berlin, 1998



1. **subcooled water**
2. **supercritical water/steam**
3. **superheated steam**
4. **saturation data**
5. **high temperature steam (currently not yet implemented in CFX)**

Material Properties:
IAPWS Properties of Water and Steam

- Water & steam selectable from IAPWS database
- specify (T,p) range
- CFX internal use of tabulated values for speed of computation
- Definition of "Homogeneous Binary Mixture Water & Steam"
  - phase pair related properties
  - 'container' for $T_{sat}=T_{sat}(p)$ and $\sigma=\sigma(T)$

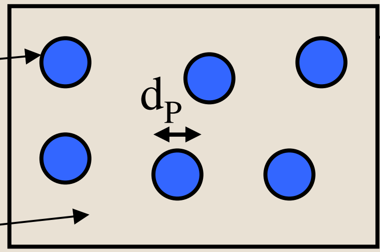


Thermal Phase Change Model – Bulk Condensation & Evaporation

- **Interfacial mass transfer =**
  Mass transfer rate per unit area × Interfacial area/unit volume

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

Swarm of rising vapor bubbles. Vapor inside is at saturation temperature



Volume V

Interfacial area

$N_p A_{p,lv}$

$$r_\alpha \equiv \frac{N_p V_p}{V}$$

Surrounding liquid at temperature T_l

Area density: $$A_{lv} = \frac{N_p A_{p,lv}}{V} \frac{V_p}{V_p} = r_\alpha \frac{A_{p,lv}}{V_p} = \frac{6 r_\alpha}{d_P}$$

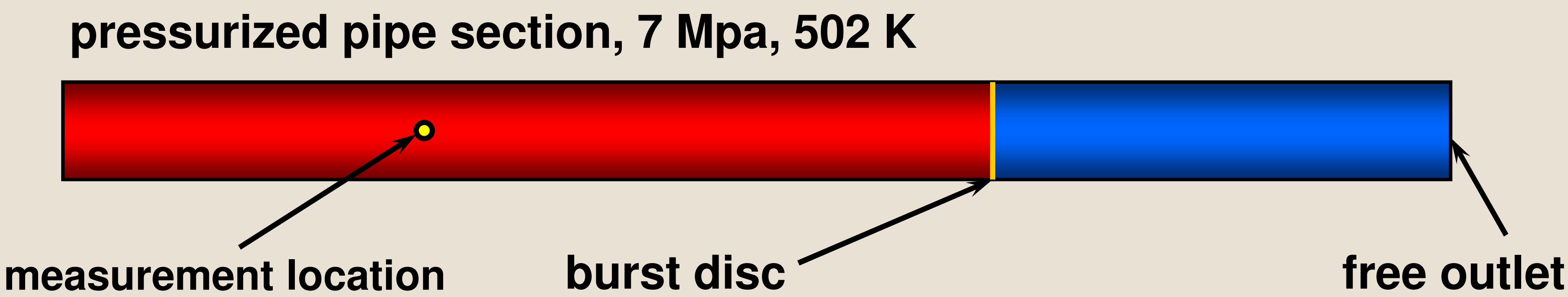
$$\text{Condensation/Evaporation rate} = \left[h_{lv} \left(T_l - T_s \right) / L \right] \cdot A_{lv} \qquad h_{lv} = \lambda_l Nu_{lv} / d_P$$

- **Heat transfer coefficient from e.g. Ranz-Marshall correlation**
  (further available: heat transfer coeff., Nusselt number, Hughmark correlation)

Validation: The Edwards Test

- **Edwards Test – well known test case in nuclear reactor thermohydraulics**
- **Used for validation of many 1-d/system & CFD codes, e.g. RELAP-5, ATHLET, SERAPHIM, etc.**
- **Experimental data available:**
  - Edwards A.R., O'Brien T.P.: "Studies of phenomena connected with the depressurization of water reactors", J. Br. Nucl. Energy Soc., Vol. 9, pp. 125-135 (1970).
  - Takata T., Yamaguchi A.: "Numerical approach to the safety evaluation of Sodium-water reaction", J. Nucl. Science & Technology, Vol. 40, No. 10, pp. 708-718 (2003).

Validation: The Edwards Test



- Pressurized pipe section (4.096m long) initially filled with water; 2m long pipe under atmospheric pressure

  $p = 7$ MPa
  $T_{Water} = 502$ K
  $L_{Pipe} = 4.096$ m
  $D_{Pipe} = 0.0732$ m

- Pressurized pipe closed with a burst disc, broken at t=0.0s
- Comparison of pressure & volume fraction over time at the measurement location at x=1.469 m from the left pipe wall

Edwards Test Flow Setup

Physical setup:

- 1d setup, 400 & 1000 grid cells (hexahedra)
- Pressurized pipe section:
  - filled with 99.9% water and 0.1% water steam
  - p=7 MPa, $T_{Water}=T_{Steam}$=502 K (saturation temperature)
- Pipe section under atmospheric pressure:
  - filled entirely with water steam
  - p=1 atm, T_{Steam}=373 K
- Eulerian two-phase flow simulation
  - assumed bubble diameter : d_{bubble}=1mm
- Laminar (no turbulence model)
- Two-resistance interfacial heat transfer model

  Water – Ranz-Marshall
  Water Steam – zero resistance
- Thermal Phase Change Model

Edwards Test Flow Setup (cont.)

Physical setup (cont.):

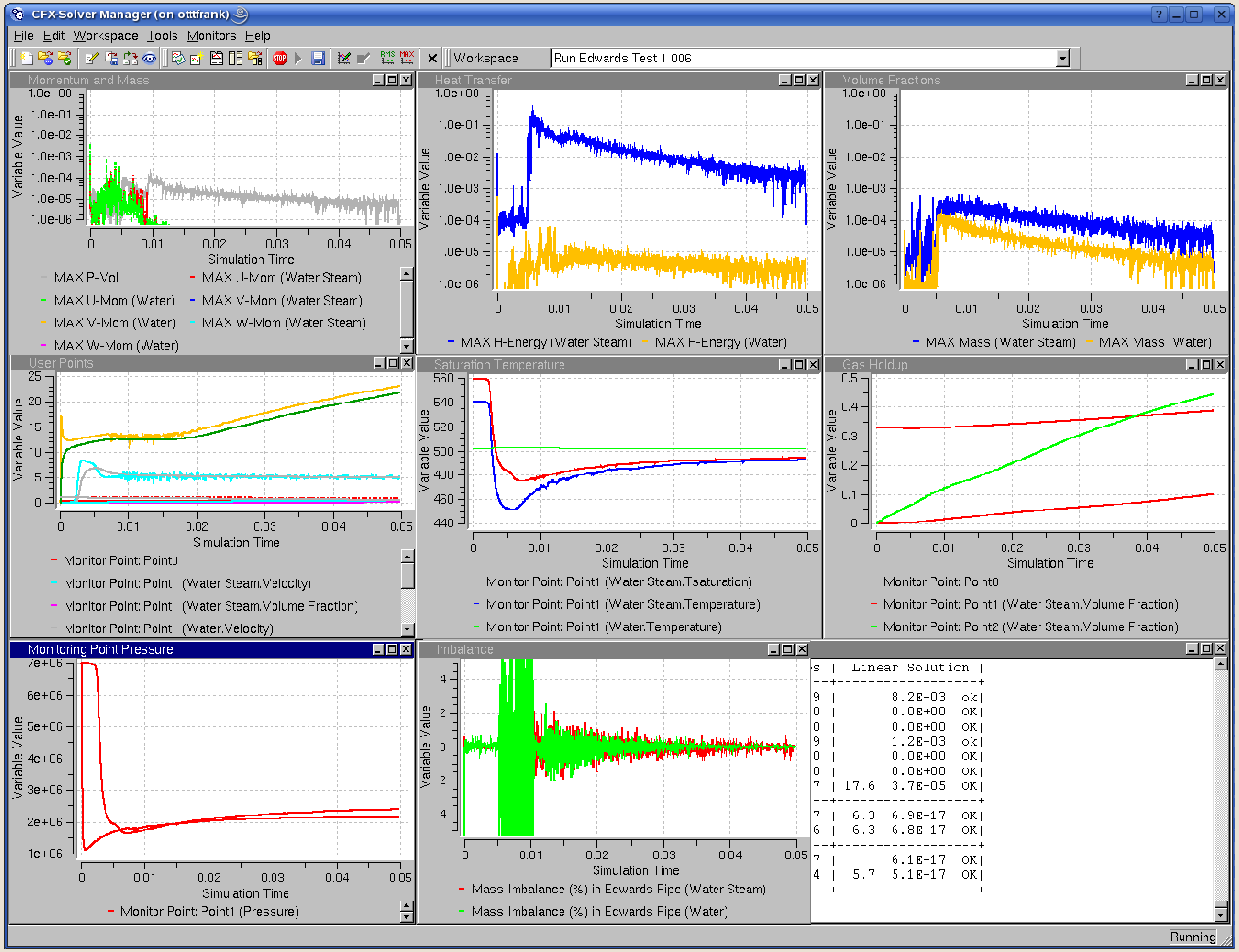
- Water & Water Steam properties

Case	Water	Water Steam
1) Redlich-Kwong EOS	incompressible, const. fluid properties	Redlich-Kwong EOS, high pressure cond. (1-30 MPa, 450-900 K)
2) IAPWS-IF97	compressible 0.1-8 MPa, 373-600 K	compressible, 0.1-8 MPa, 373-600 K

- Upwind advection scheme
- Transient simulation, 2nd order backward Euler time integration
- Adaptive time step control $\Delta t \in [1.0e^{-5}s, 1.0e^{-3}s]$, 15,…,35 coeff. loops
- Convergence criteria: Max. Residuals < 0.0001

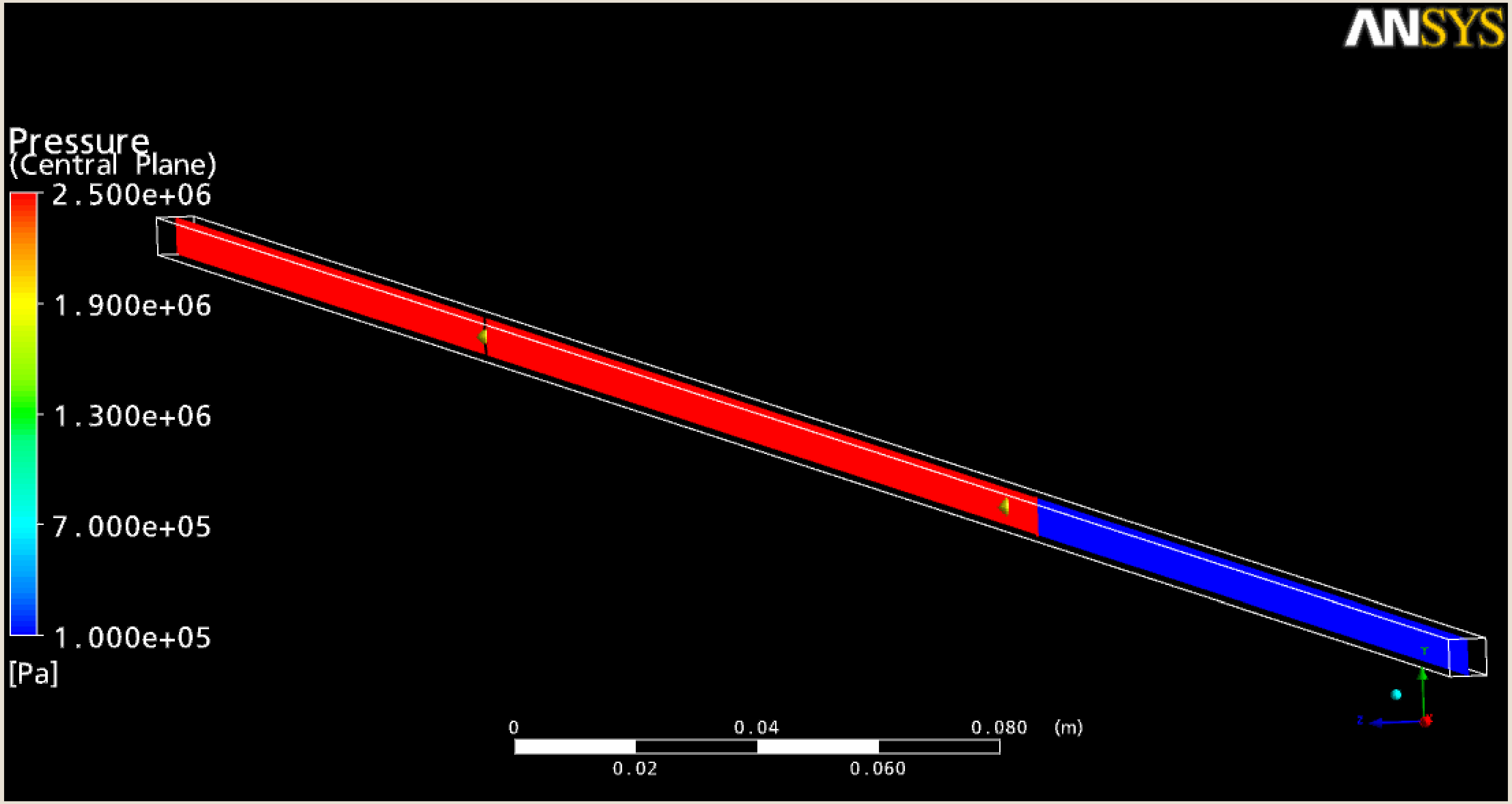
Edwards Test
CFX Convergence History

- Difficult convergence, due to sudden evaporation (flashing)
- Improved with 500 table entries in IAPWS-IF97 property tables



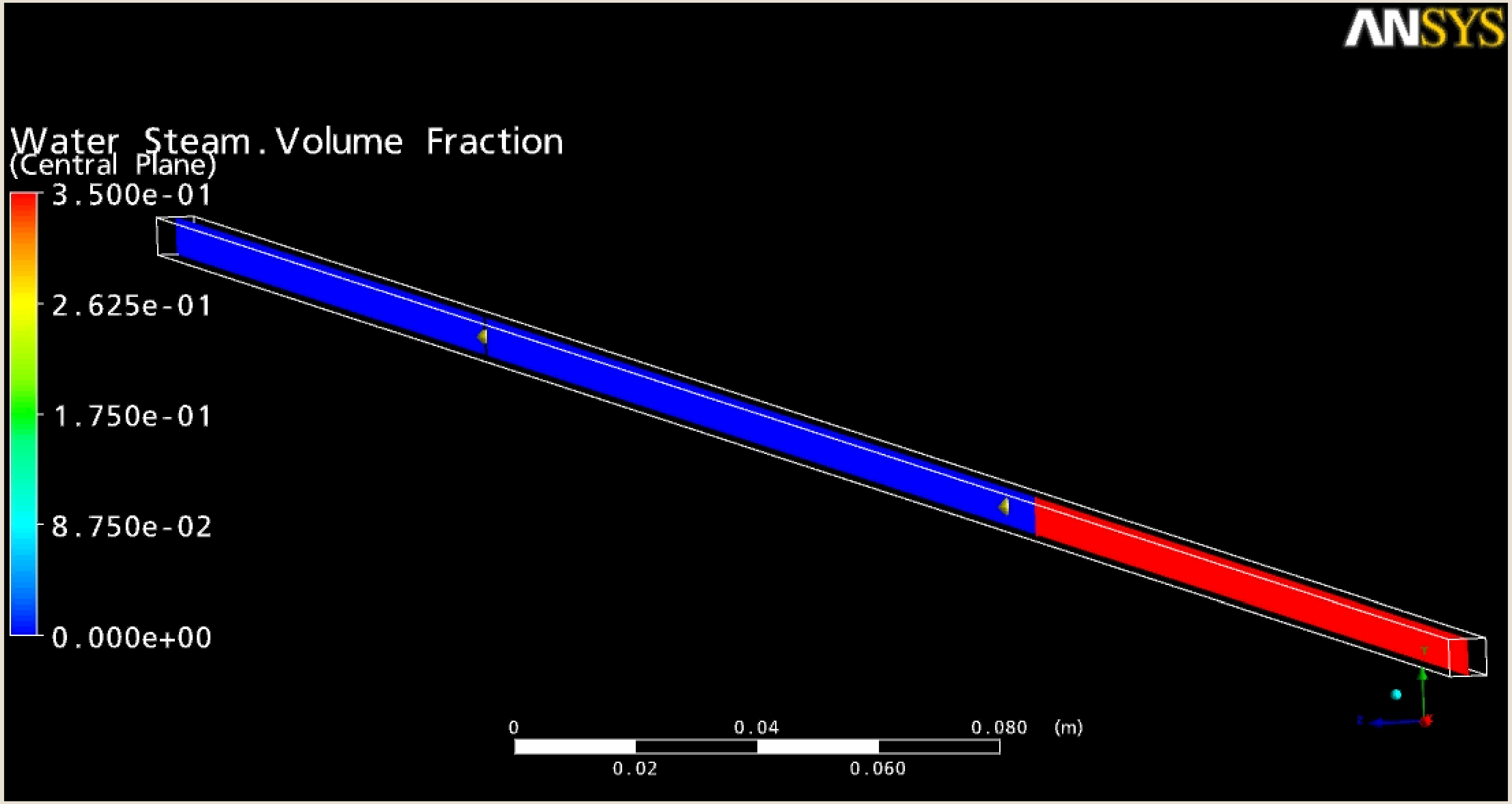
Edwards Test
Pressure Wave Propagation

- Pressure wave propagation in 1d geometry of Edwards pipe
- Further rise of pressure level due to evaporation



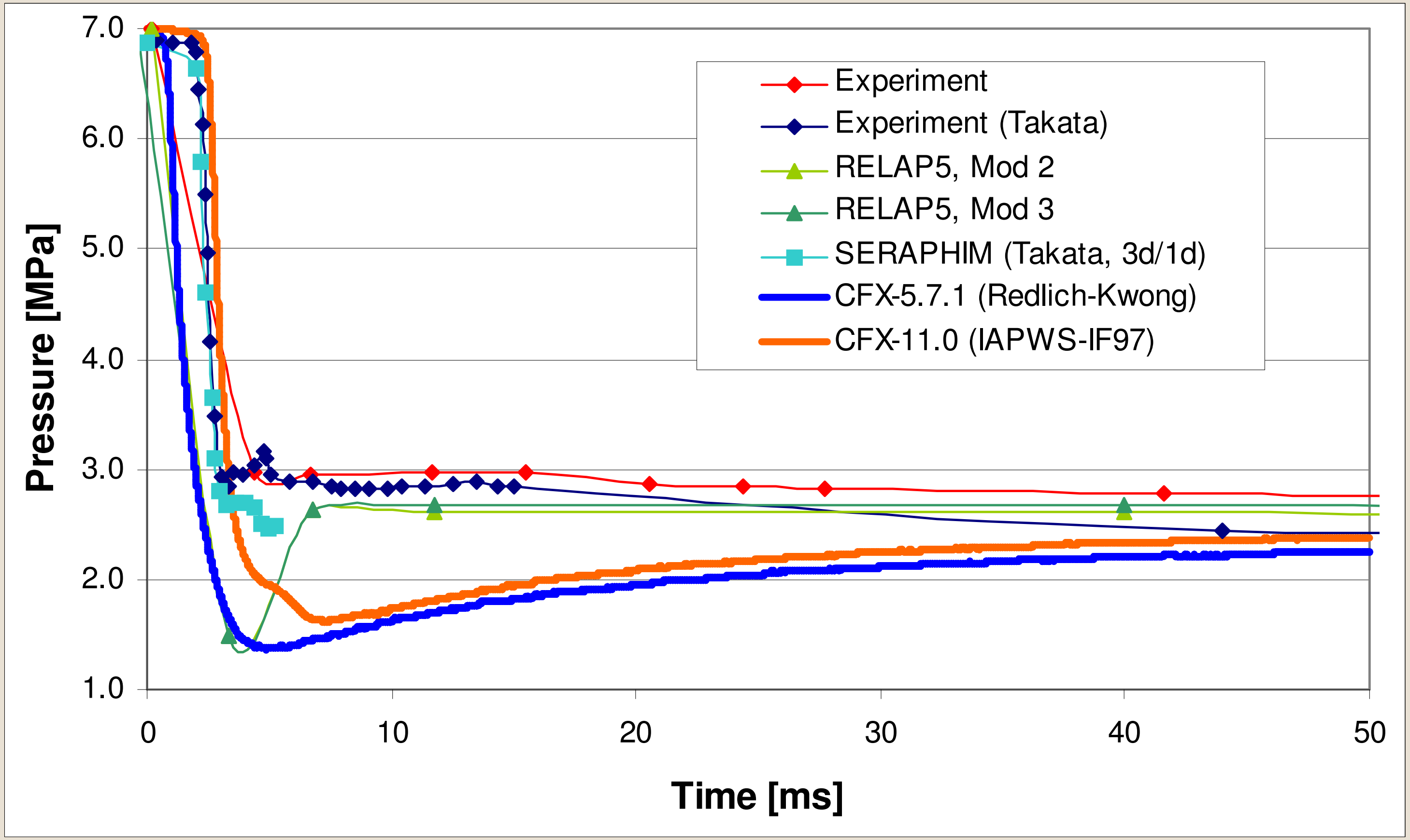
Edwards Test
Steam Volume Fraction Distribution

- Evaporation starts first at burst disc location
- Further evaporation after reflection of the pressure wave from left end of the Edwards pipe



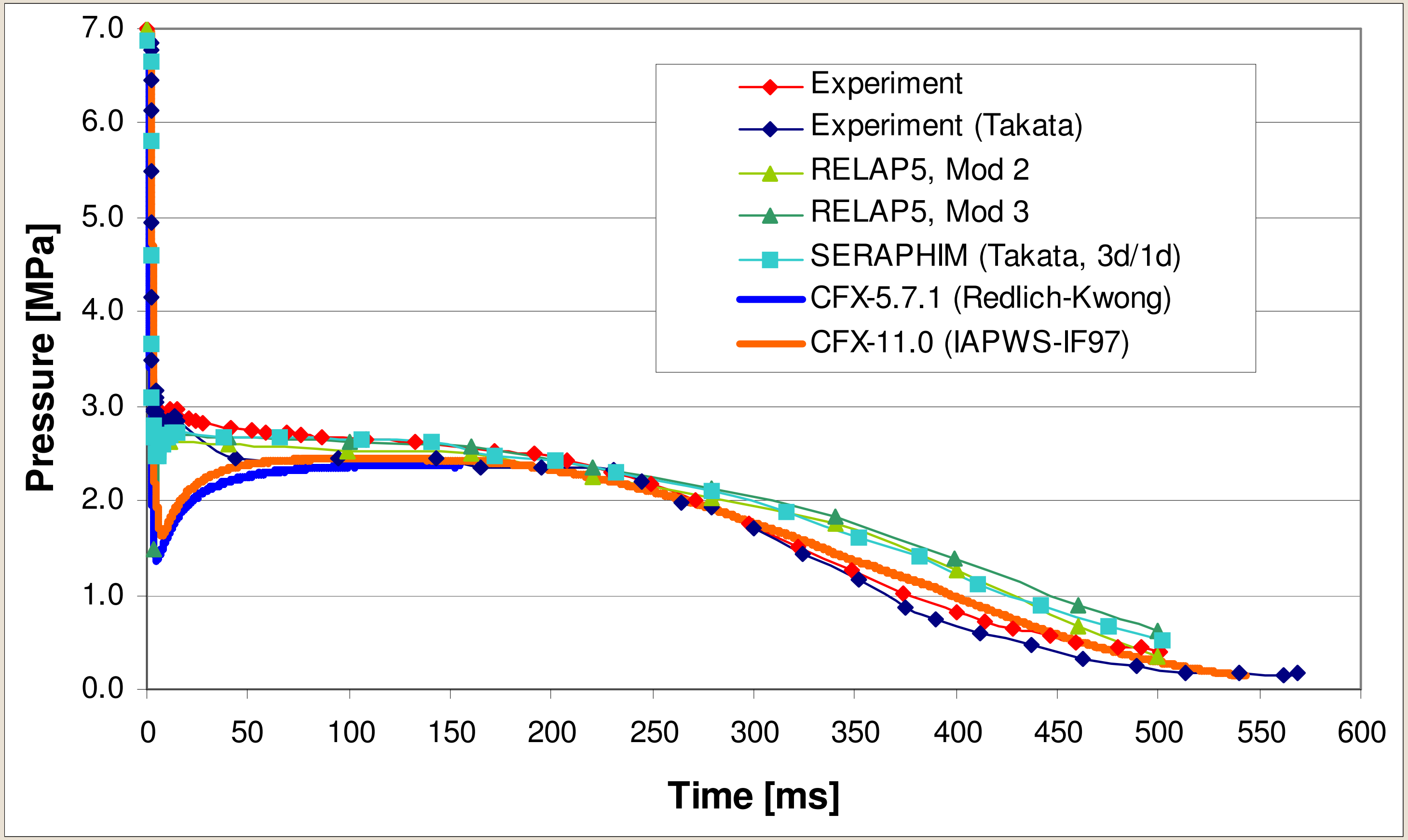
Edwards Test
Pressure at Measurement Location

- qualitatively good agreement for the difficult physics
- pressure wave propagation velocity in good agreement with Takata experiment; pressure drop slightly overpredicted



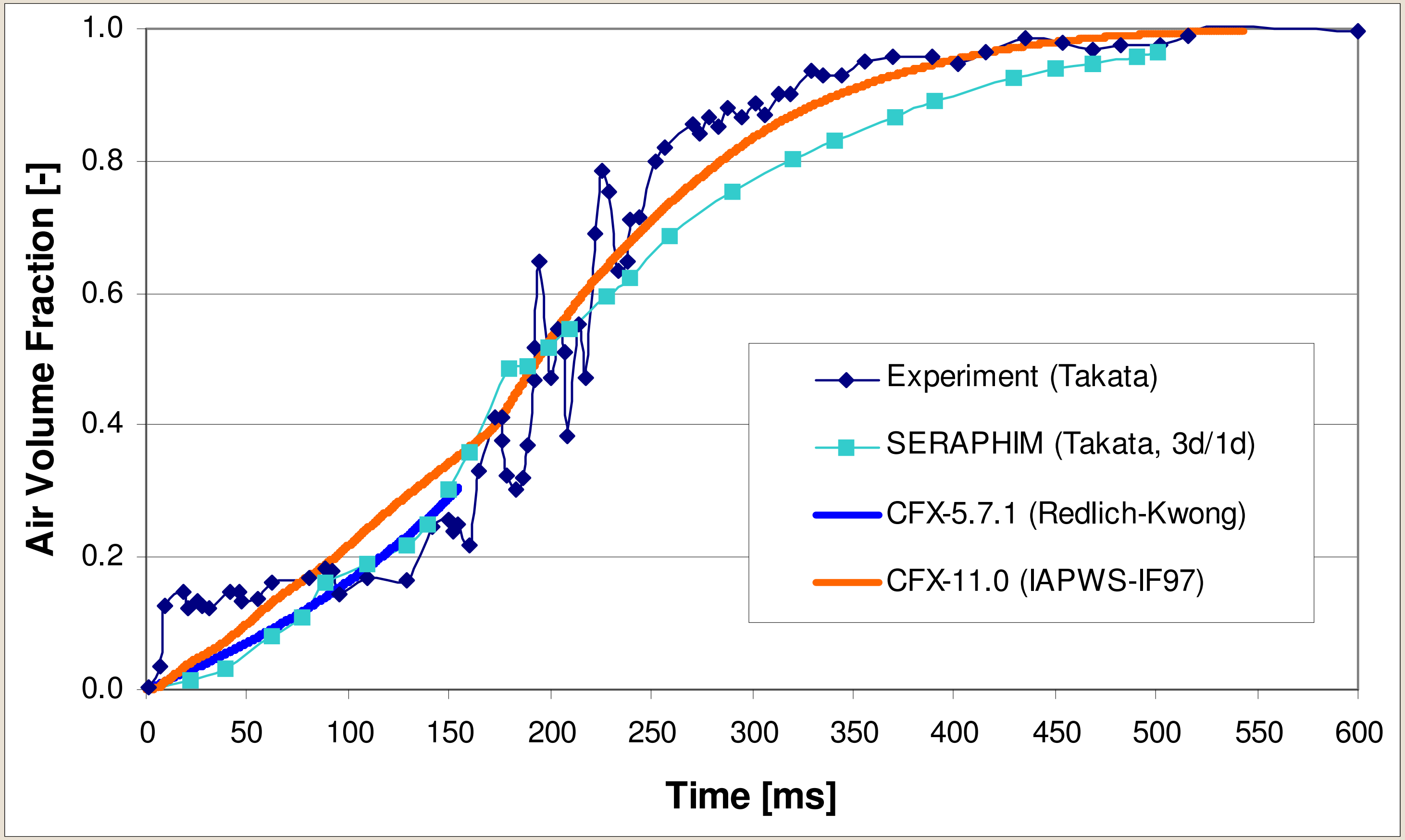
Edwards Test
Full Pressure Transient → T=550ms

- **pressure transient at measurement location x=1.469m**
- **good agreement to Takata experiment**



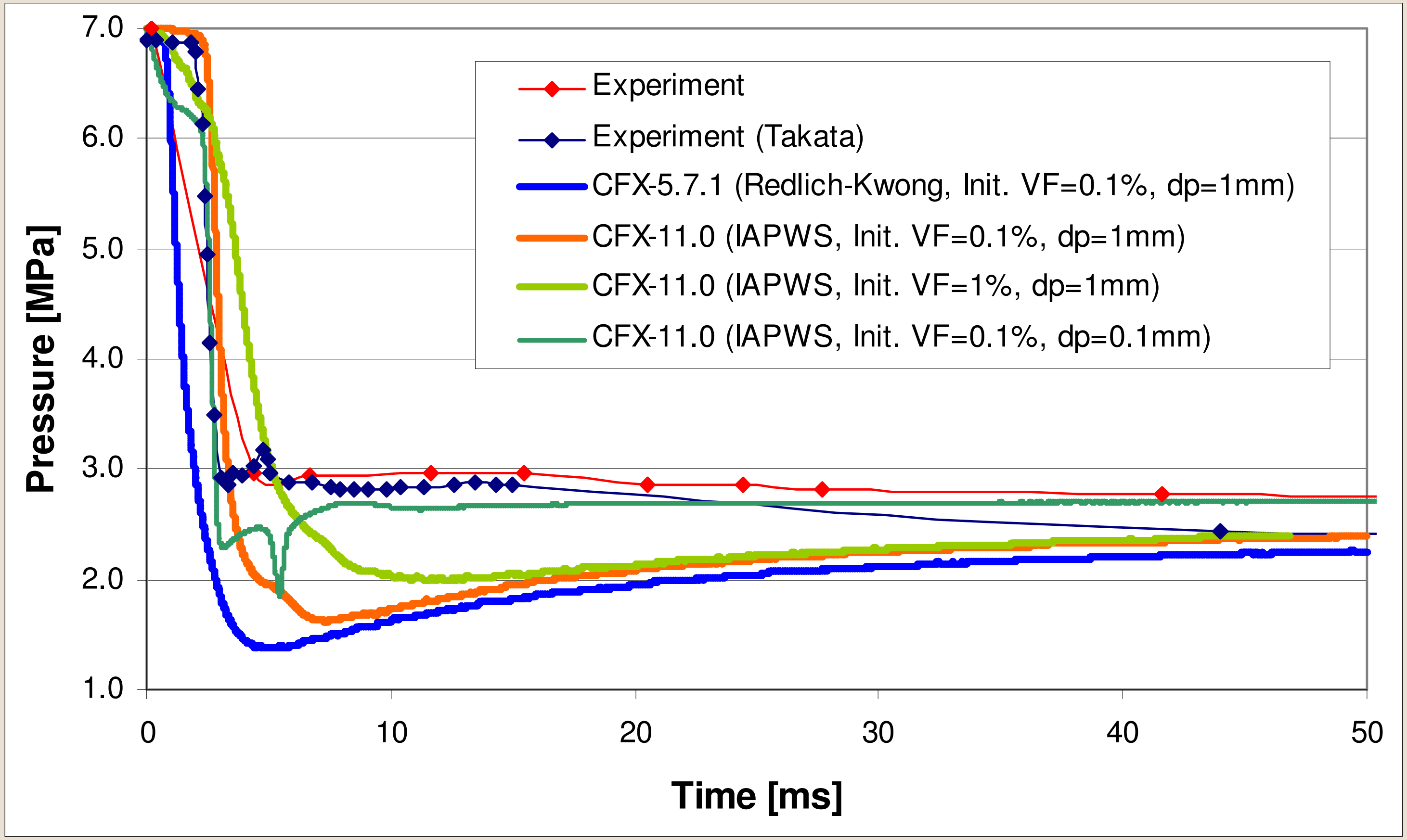
Edwards Test
Steam VF at Measurement Location

- **steam volume fraction transient at measurement location x=1.469m**
- **good agreement to Takata experiment**



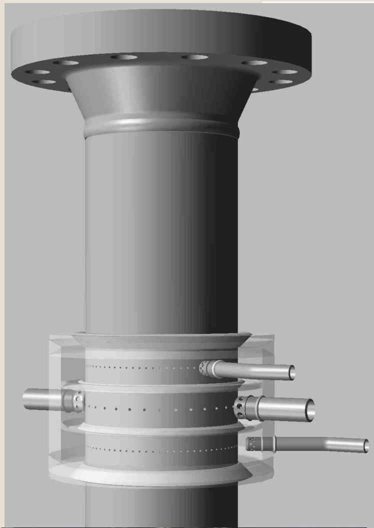
Edwards Test
Parameter Variation for Initialisation

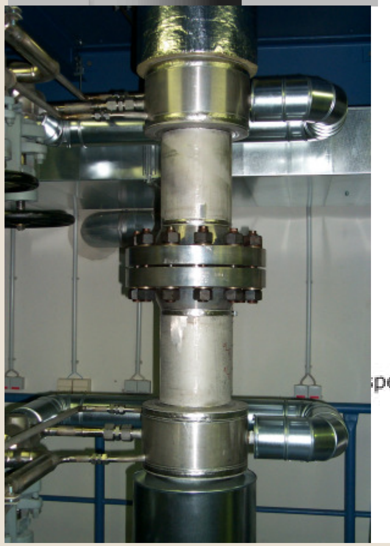
- Parameter variation wrt. initial value of vapor void fraction in pressurized pipe section and assumed bubble diameter
- Simulations performed for the first 50ms only

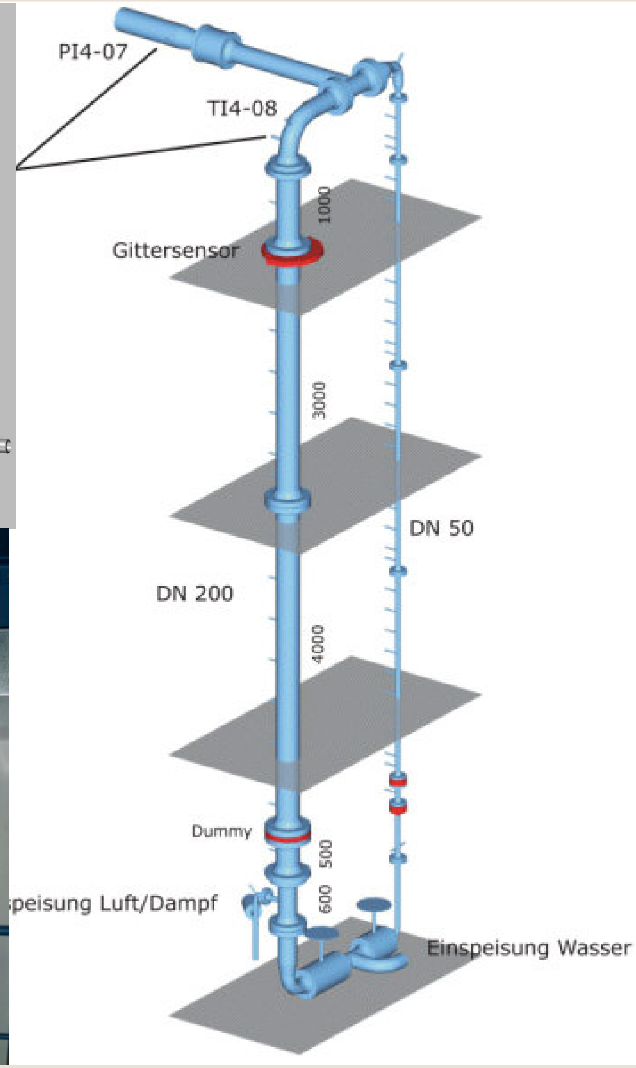


Steam Condensation in Subcooled Water Flow

- **TOPFLOW test facility @ FZD**
- **High pressure air-water and steam-water experiments P≤7MPa , T≤286°C**
- **Variable gas/steam injection through wall nozzles**
  → 2 different bubble sizes
  → variable height and superficial velocities
- **Measurement of gaseous phase VF, velocity and size distributions**
  → high-pressure wire-mesh sensors



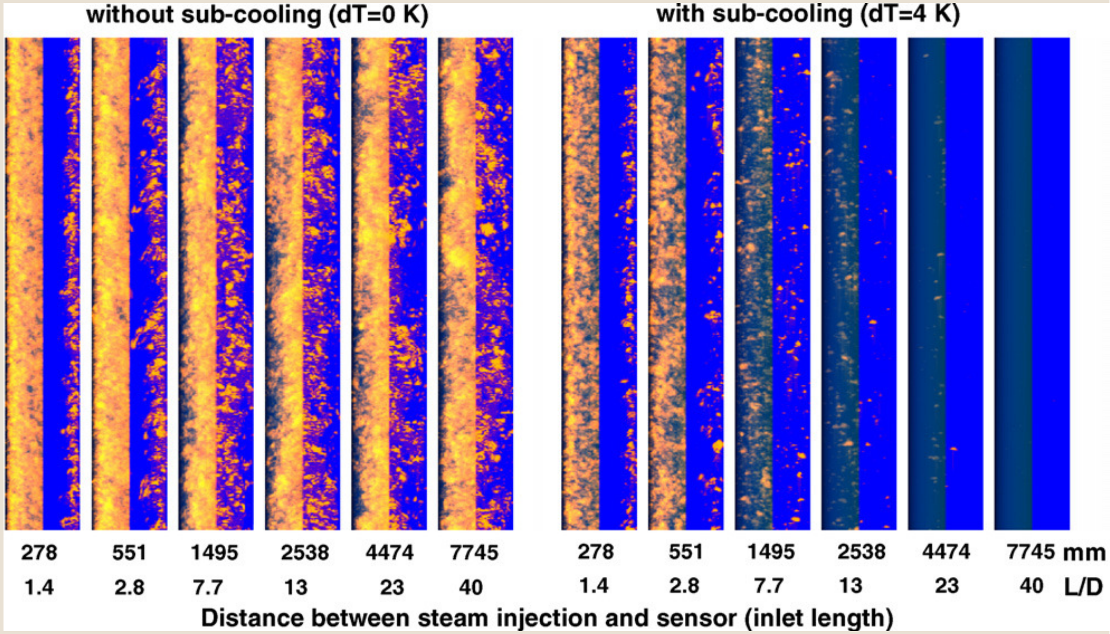




Steam Condensation in Subcooled Water Flow

- TOPFLOW experiment (FZD):
  - Superficial velocities: U_{Water}=1.0m/s, U_{Steam}=0.54m/s
  - Temperature: T_{Water}=210.5°C (483.6K)
    T_{Steam}=214.4°C (487.5K)
  - Pressure at wire-mesh sensor: p_{Sensor}=2.08 MPa
  - Liquid sub-cooling: ΔT=3.9K
  - L=7.8m, D=195.3mm

- Preliminary CFX test (setup derivation):
  - U_{Water}=1.0m/s, U_{Steam}=0.1m/s
  - L=3.8m, D=51.2mm



Lucas, D., Prasser, H.-M., Steam bubble condensation in sub-cooled water in case of co-current vertical pipe flow, Nuclear Eng. Design (2006), Article in press, doi:10.1016/j.nucengdes.2006.09.004

Re-Condensation Test Flow Setup

Physical setup:

- 3d setup, 60° pipe symmetry sector, 32.000 grid elem. (hexa's)
- Pipe initialization:
  - filled with 99.9% water and 0.1% water steam
  - p=2 MPa + hydrostatic pressure
  - $T_{Water}=T_{Steam}$=486.3K,…,485.4K (local saturation temperature=f(z))
- Water & Water steam from IAPWS-IF97 properties
- Eulerian two-phase flow simulation
  - assumed bubble diameter at inlet: $d_{P,Inlet}$=10mm

$$n'_P\Big|_{Inlet} = \left.\frac{r_p}{V_p}\right|_{Inlet} = \frac{6\, r_p\big|_{Inlet}}{\pi\, d_p^3\big|_{Inlet}}$$

  - further assumption: particle number density n_P'=const.

$$d_{P,local} = \sqrt[3]{\frac{6}{\pi}\,\frac{r_{P,local}}{n'_P\big|_{Inlet}}}$$

Re-Condensation Test Flow Setup (cont.)

Physical setup (cont.):

- SST turbulence model (cont. phase)
- 0-eq. disperse phase turbulence model + Sato bubble induced turbulence
- Interphase momentum transfer:
  - Grace drag
  - Tomiyama lift force
  - FAD turbulent dispersion force
  - Frank generalized wall lubrication force
- Two-resistance interfacial heat transfer model

  Water – Ranz-Marshall
  Water Steam – zero resistance
- Thermal Phase Change Model

Re-Condensation Test Flow Setup (cont.)

- Hi-Resolution advection scheme
- Transient simulation,
  2nd order backward Euler time integration
- Adaptive time step control
  - $\Delta t \in [5.0e^{-5}s, 5.0e^{-3}s]$
  - 10,…,30 coeff. loops (max. 70)
    → 3950 time steps for
    4.5s real time
- Convergence criteria:
  - Conservation target = 0.001
  - Max. Residuals < 0.0005
- Execution time:
  - approx. 168h on 6 CPU's

```
TIME STEPS:
  First Update Time = 0.0 [s]
  Initial Timestep = 0.001 [s]
  Option = Adaptive
  Timestep Update Frequency = 1
  TIMESTEP ADAPTION:
    Maximum Timestep = 0.005 [s]
    Minimum Timestep = 0.00005 [s]
    Option = Number of Coefficient Loops
    Target Maximum Coefficient Loops = 30
    Target Minimum Coefficient Loops = 10
    Timestep Decrease Factor = 0.75
    Timestep Increase Factor = 1.1
  END
END
```

Lift force, Wall Lubrication Force & Turbulent Dispersion

Lift force:

- due to asymmetric wake and deformed asymmetric bubble shape

$$\mathbf{F}_L = C_L r_G \rho_L (\mathbf{U}_L - \mathbf{U}_G) \times \nabla \times \mathbf{U}_L \qquad C_L = C_L(\mathrm{Re}_P, \mathrm{Re}_\nabla, \mathrm{Eo})$$

Wall lubrication force:

- surface tension prevents bubbles from approaching solid walls

$$\mathbf{F}_{WL} = -C_{wall} r_G \rho_L \left| \mathbf{U}_{rel} - (\mathbf{U}_{rel} \bullet \mathbf{n}_W) \mathbf{n}_W \right|^2 \mathbf{n}_W \qquad C_{wall} = C_W(\mathrm{Eo}, \mathrm{y/d_P})$$

Turbulent dispersion force:

- turbulent dispersion = action of turb. eddies via interphase drag

$$\mathbf{F}_{TD} = \frac{3}{4} \rho_L \frac{\overline{C_D}}{d_P} \frac{\nu_{tL}}{\sigma_{rL}} \left| U_L - U_G \right| \overline{r_G} \left(\frac{\nabla \overline{r_G}}{\overline{r_G}} - \frac{\nabla \overline{r_L}}{\overline{r_L}} \right)$$

FAD model by Burns et al. (ICMF'04)

Tomiyama's Lift Force Correlation – Eo Number Dependency on T_{sat}

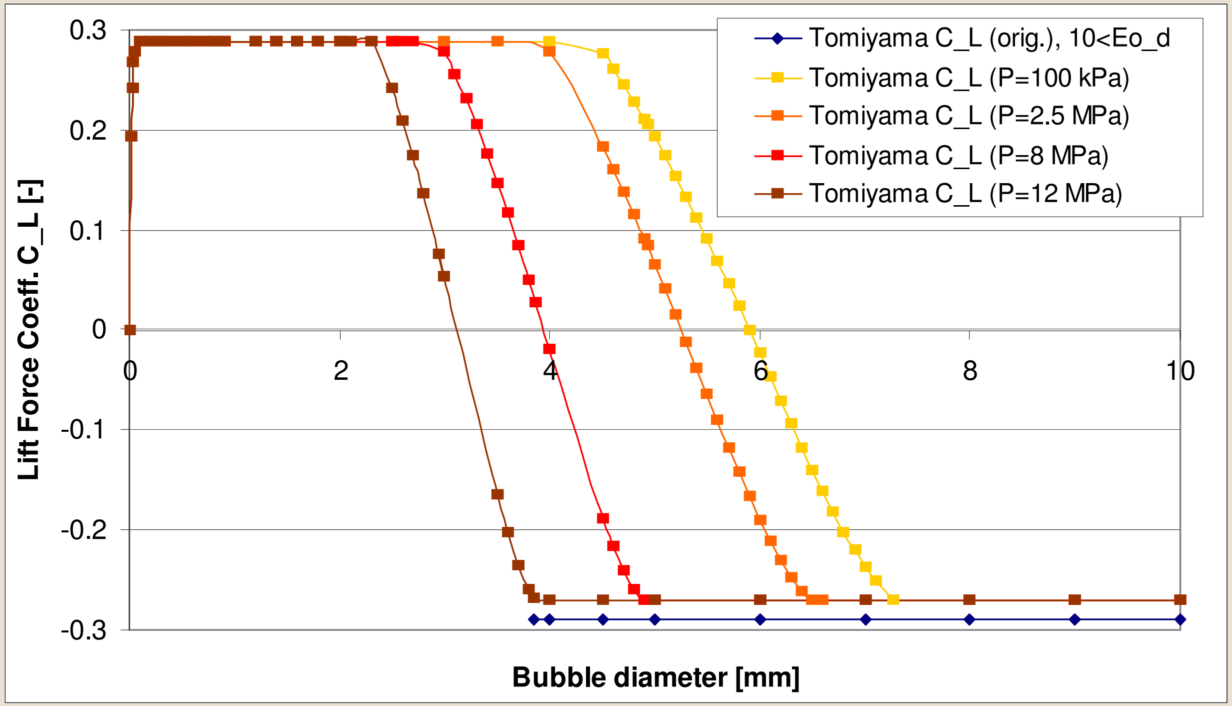
$$C_L = \begin{cases} \min\left[0.288\tanh(0.121\cdot \mathrm{Re}_P), f(Eo_d)\right] & Eo_d < 4 \\ f(Eo_d) = 0.00105 Eo_d^3 - 0.0159 Eo_d^2 - 0.0204 Eo_d + 0.474 & 4 \le Eo_d \le 10.0 \\ -0.27 & Eo_d > 10.0 \end{cases}$$

- **modified Eo_d number:**

$$Eo_d = \frac{g(\rho_L - \rho_G) d_H^2}{\sigma(T_{sat})}$$

- **horizontal bubble length scale:**

$$d_H = d_P (1 + 0.163 \cdot \mathrm{Eo}^{0.757})^{1/3}$$

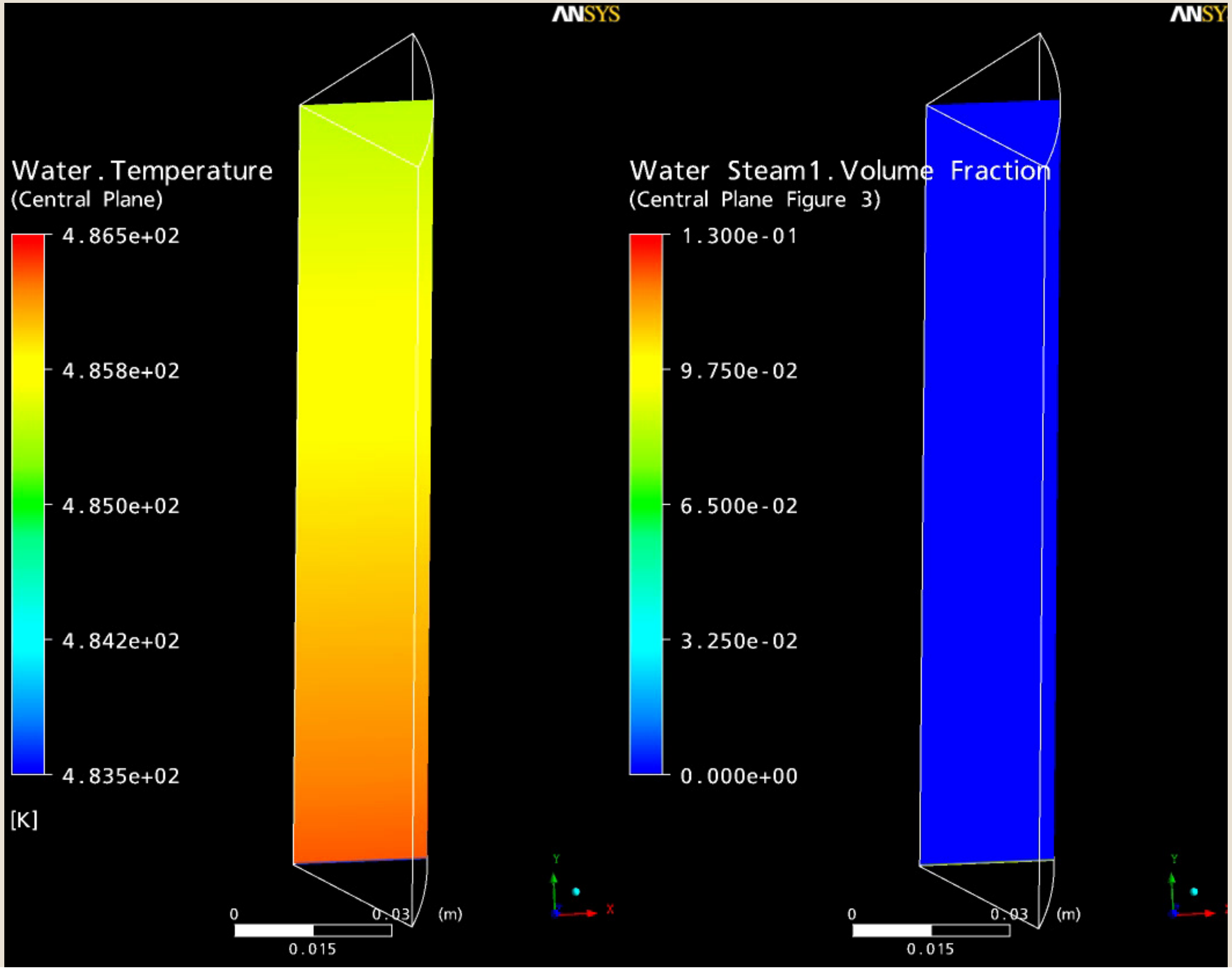


→ **sign change of lift force is dependent on system pressure/T_{sat}**

→ **Eo dependency for wall lubrication force as well**

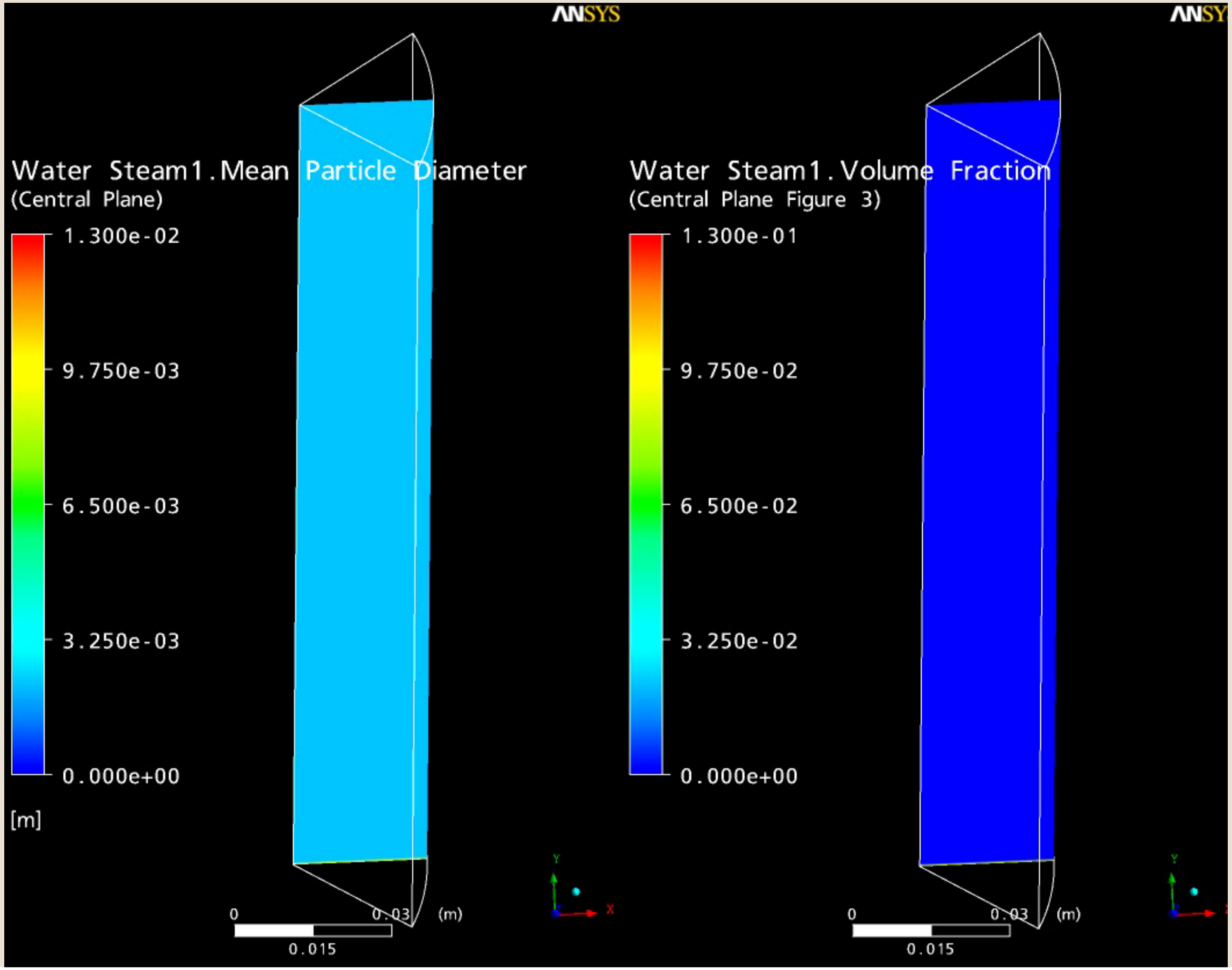
Steam Condensation in Subcooled Water Flow

- **preliminary result for condensation front propagation in 3.8m long pipe of 51.2mm diameter:**



Steam Condensation in Subcooled Water Flow

- **preliminary result for condensation front propagation in 3.8m long pipe of 51.2mm diameter:**



Summary & Outlook

- CFX-11.0 introduces IAPWS-IF97 industry standard water-steam properties
- Discussed two applications of CFX heat & mass transfer models:
  - Flashing, Edwards pipe
  - Re-condensation test @ TOPFLOW
- Good agreement of CFX results with Edwards test experimental data over wide range of water steam volume fraction $0.0 \le r_{Steam} \le 0.95$
- Developed preliminary CFX setup for re-condensation test in order to test IAPWS fluid properties & non-drag forces
- Current & future development:
  - bubble diameter distribution from inhomogeneous MUSIG model
  - model validation against TOPFLOW data

Thank You!