# VERIFICATION AND VALIDATION OF NUMERICAL MODELS OF THE TRANSPORT OF INSULATION DEBRIS

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March 2011

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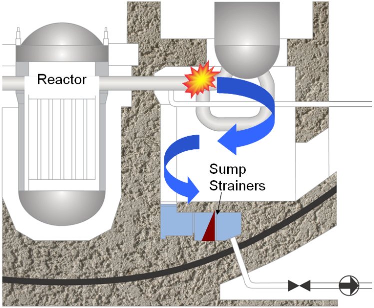
# Loss of Coolant Accidents in nuclear power plants

- The problem:
  - insulation material or other debris is released
  - debris transport to containment sump
  - fine debris can accumulate at and penetrate the strainers
  - large fibre debris is deposited in the sump
  - long-term exposure to boric acid may corrode metallic internals
  - solid corrosion products can accumulate in the filter cakes formed at the strainers
- The consequences:
  - pressure drop increases could compromise the long term operation of the ECCS
  - cavitation and loss or reduction of flow to the core
  - damage the strainers
  - fibres and corrosion products may accumulate in the reactor core




Thanks to TUEV Sued for use of the image.

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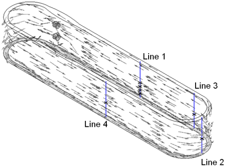
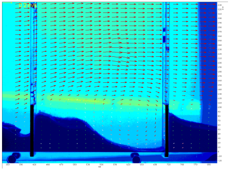
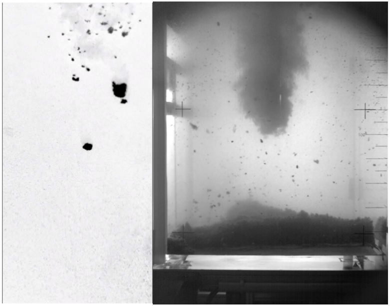
# Project overview

- Develop single effect experiments, empirical models and numerical simulations
- Generate fibre agglomerates
  - MD2 (PWR) and MDK (BWR)
  - steam jet (fragmentation rig)
  - high pressure water jet (Kärcher)
- Determine fibre transport characteristics
  - sedimentation in a vertical column
  - sedimentation and suspension in horizontal flows
  - transport driven by impinging jets
  - determine effect of fibre accumulation on strainers





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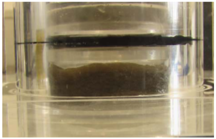
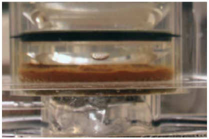
# Project overview

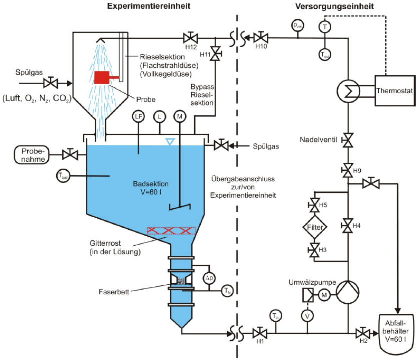
- Determine corrosion effects
  - conditions (temperature, dimensionalisation and flow rates)
  - media and materials (fibre cakes, boric acid, lithium hydroxide, hot-dip galvanized steel)

No corrosion



Corrosion



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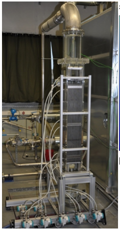
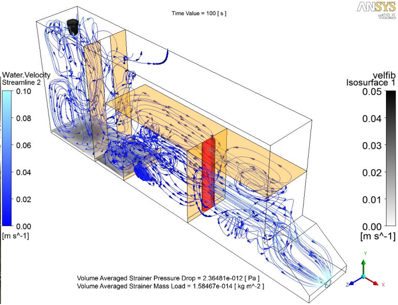
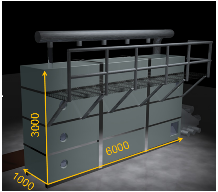
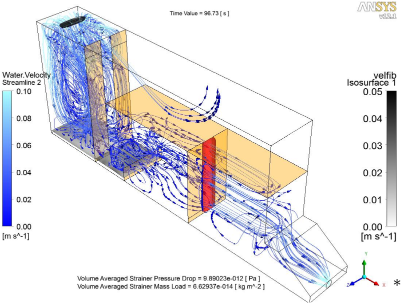
# Project overview

- Integral tests combine single effect experiments into
  - containment scale experiments
  - effect of sump internal structures
  - accumulation of fibres and corrosion particles in the fuel elements



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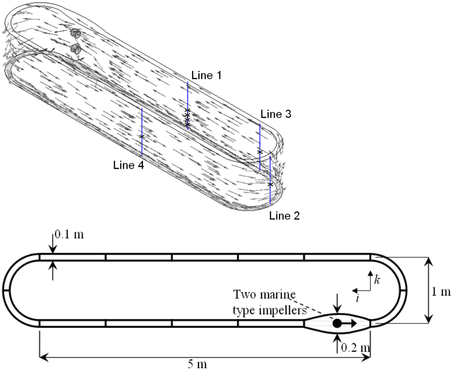
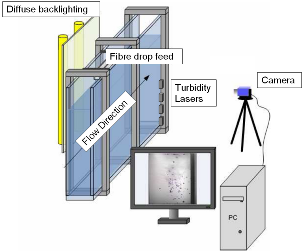
# Motivation

- Aim is determine the quantity of fibres/fibre agglomerates that reach the strainers
- Improve simulation methods used to model fibre agglomerate transport
- Determine fibre transport characteristics
  - sedimentation in horizontal flows
  - suspension in horizontal flows
- The developed model must be applicable to system codes of NPPs

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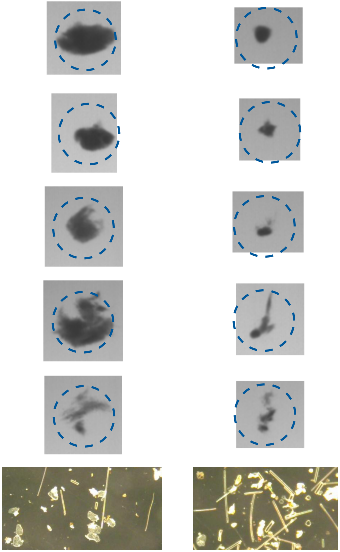
# Agglomerate fibres

- Particles can be classified by
  - sphericity
  - compactness
  - convexity
- Measured distribution of agglomerate velocities
- Estimated distribution of spherical diameter based on the measured cross-sectional areas of the agglomerates
- Spherical particles with an virtual density were specified to get observed settling velocities



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# Flow models

- Pseudo-continuous approach to model multiple dispersed agglomerate phases
  - Multi-fluid model(Eulerian multiphase model)
    i.e. momentum and mass equations for liquid and a mixture phase
  - Drift flux model (algebraic slip mixture)
    i.e. volume fraction equation with drift velocity
- Assume no agglomeration or fragmentation
- Mixture viscosity based on the correlation of Batchelor (1977) *J. Fluid Mech.* **83**:
  $\mu_r = 1 + 2.5 r_p + 7.6 r_p^2$
- Fixed particle diameter
- Base the density on the desired settling velocity
- Schiller-Naumann correlation for particle drag
- SST model for the transport of turbulence in the continuous phase
- Zero-equation model for the dispersed phase
- No-slip wall conditions for both phases
- For open channel flow, the top surface has a free-slip condition

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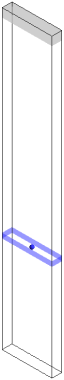
# Case study: Quiescent column sedimentation



- ~21.9 g of steam-blasted MDK or MD2
- Particle diameter (constant at 2.5 mm)
- 10 dispersed phases
  - 10 Algebraic slip mixture phases
  - combined DFM-MFM with 1 MFM phase + 10 DFM phases (9 + 1 constraint)
  - $U_{tp} = 10 - 114$ mm $s^{-1}$
  - $\rho_p = 1003 - 1200$ kg $m^{-3}$
- Numerical traces: point trace of mass or volume fraction
- Experimental traces: area fraction of fibre agglomerates
- Initialised with zero velocity field
- Convergence criterion was set at $1.2*10^{-3}$ for combined model
- Transient of 300 s with timesteps of
  EMM-ASM:
  `if(ddt<=0.1 [s], 0.001 [s], if(t=<100 [s], 0.005 [s], 0.01 [s]))`
  ASM:
  `if(ddt<=0.049 [s], 0.005 [s], if(t=<0.999 [s], 0.01[s],if(t=<1.999 [s], 0.05[s], 0.1 [s])))`

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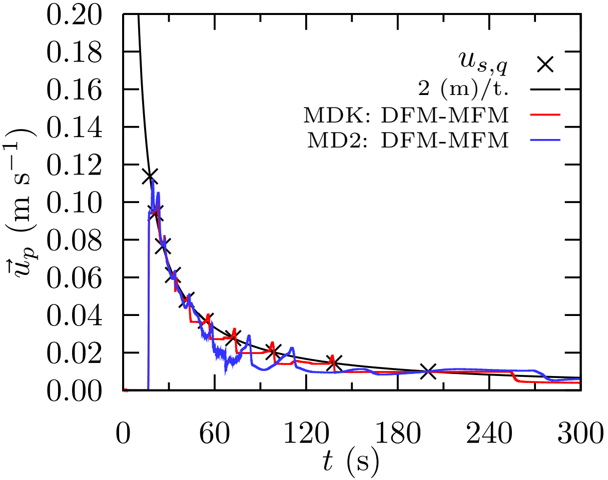
# Case study: Quiescent column sedimentation

Velocity traces




Note that dispersed phase with a velocity of 114 mm $s^{-1}$ was a constraint phase and in these case not directly modelled by the DFM approach

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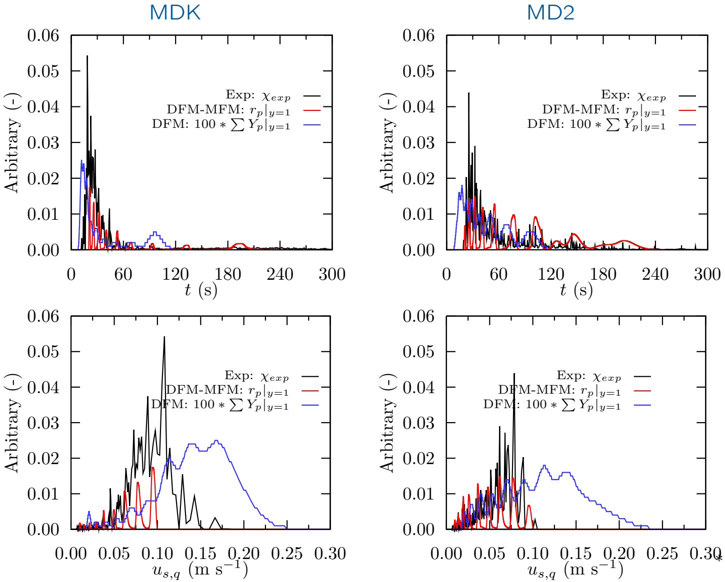
# Case study: Quiescent column sedimentation

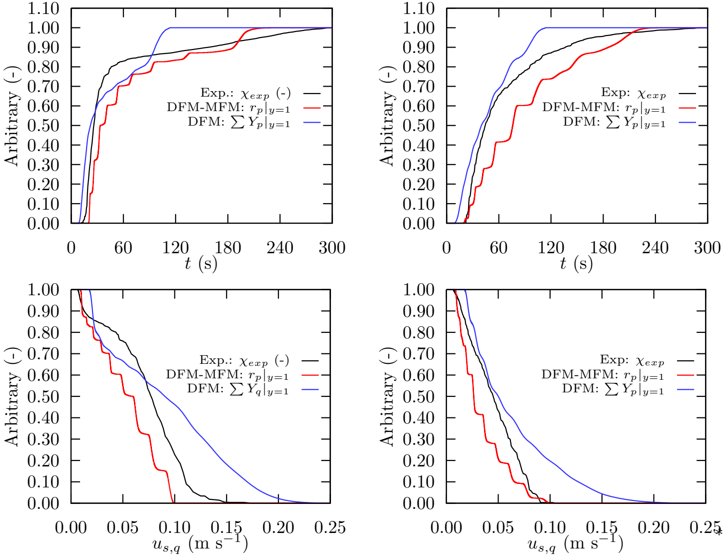
Area fraction and point value traces



# Case study: Quiescent column sedimentation

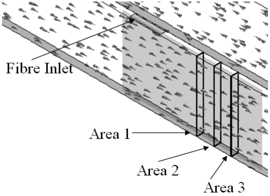
Normalised cumulative sum of the area fraction traces

MDK MD2



# Case Study: Sedimentation in a horizontal flow

- $\sim$ 21.9 g of MDK or MD2
- Mean velocity of 0.2 m $s^{-1}$ given by 1290 kg $m^{-2}$ $s^{-2}$ momentum sources at 0.305 and 0.68 m (Darcy-Weisbach equation)
- One MFM phase
  - $U_{tp} =$ 50 mm $s^{-1}$
  - $d_p = 5$ mm
  - $\rho_p = 1027$ kg $m^{-3}$
- Ten DFM phases (9 + 1 constraint) for both MDK and MD2
  - $U_{tp} = 10 - 114$ mm $s^{-1}$
  - $d_p = 2.5$ mm
  - $\rho_p = 1003 - 1200$ kg $m^{-3}$
- Transient of 10 s with `if(t<=0.5 [s], 0.0025 [s], 0.005 [s])`
- Initialised by interpolation of a transient solution of single-phase flow
- Convergence criterion was set at $2*10^{-4}$
- Inlet conditions estimated via Laws of Motion




MDK

MD2

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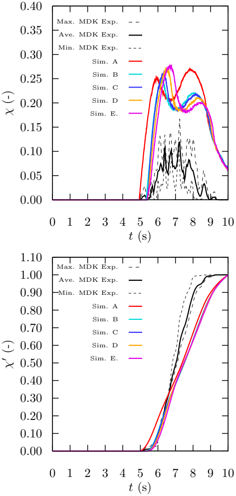
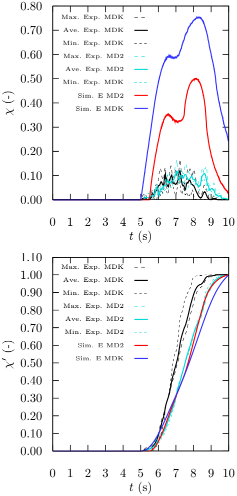
# Case Study: Sedimentation in a horizontal flow

Traces of the fraction of the volume integrals of the fibre volume fraction to the volumes

## Single dispersed phase




## Ten dispersed phases




| Case | Areas 1-3 Averaged Gradient |
| --- | --- |
| Sim. A | 0.277 ± 0.038 |
| Sim. B | 0.275 ± 0.028 |
| Sim. C | 0.276 ± 0.028 |
| Sim. D | 0.279 ± 0.026 |
| Sim. E | 0.282 ± 0.022 |
| Sim. E MDK | 0.261 ± 0.016 |
| Exp. MDK | 0.427 ± 0.017 |
| Sim. E MD2 | 0.326 ± 0.025 |
| Exp. MD2 | 0.326 ± 0.003 |

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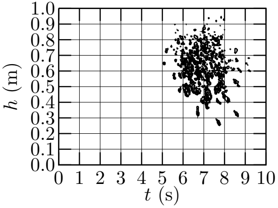
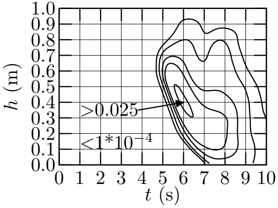
# Case Study: Sedimentation in a horizontal flow

Sequential profiles of the fraction at Area 3

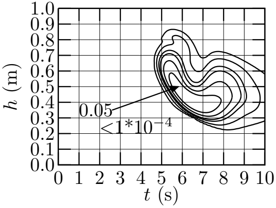
Exp. MDK



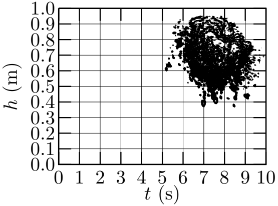

Sim. E MDK 10



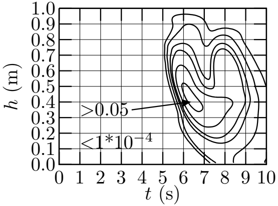

Sim. A 1



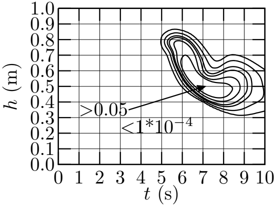

Exp. MD2




Sim. E MD2 10




Sim. E 1

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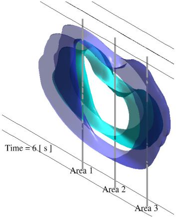
# Case Study: Sedimentation in a horizontal flow

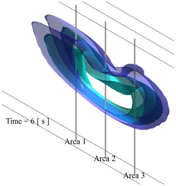
Isocontours at 1 and 0.1%

## MD2 Flow Image at 6 s

## Isocontours Sim. E MD2

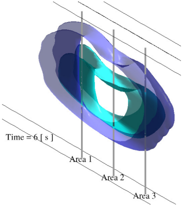



## Isocontours Sim. A

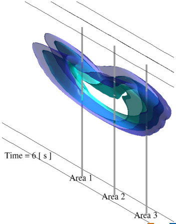



## MDK Flow Image at 6 s

## Isocontours Sim. E MDK




## Isocontours Sim. E

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# Conclusions

- Column Sedimentation:
  - Combined DFM-MFM approach verified by comparisons of fibre agglomerate velocity
  - Reasonable agreement with MD2 and MDK experiments for ten dispersed DFM phases
- Channel Sedimentation: Single and combined EMM-ASM models physically agree with experiments
  - single phase sedimentation agrees well with lower extent of the experimental studies
  - ten dispersed phase simulation agreement is better for the lighter phases, while it is weak for the lower extent
  - MD2 distributions are better matched to the experiments than MDK
  - all simulations show unphysical tails

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## Future Work

- Analyse recently performed channel suspension experiments
- Improve simulations of
  - channel sedimentation
  - channel suspension
  - simulate transport processes on the sump scale with internal structures
- Improvements include
  - alternative fibre agglomerate distributions
  - alternative turbulence models and/or boundary conditions
  - modifications to the underlying interfical forces

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## Acknowledgments


- Project partners:
  - + Institut für Prozeßtechnik, Prozeßautomatisierung und Meßtechnik Hochschule Zittau/Görlitz
    S. Alt, T. Gocht, W. Kästner, A. Kratzsch, S. Renger, A. Seeliger and F. Zacharias
  - + Institut für Sicherheitsforschung Helmholtz-Zentrum Dresden-Rossendorf
    A. Grahn, W. Hoffmann, E. Krepper, H. Kryk, and M. Wiezorek
- German Federal Ministry of Economy and Labor Contracts No. 1501270, 1501307, 1501360 and 1501363
- This project is not part of the oversight process and does not intend to deliver safety guidelines


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# Appendices

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# Case study: Quiescent column sedimentation

Determination of volume and mass fractions for MDK

| Agglomerate Phase | Terminal Velocity ($mm\ s^{-1}$) | Density ($kg\ m^{-3}$) | Dry Mass Fraction (-) | Mass Ratio* (-) | Dry Volume Fraction (-) |
|---|---|---|---|---|---|
| 1 | 10 | 1003.48 | 0.00020‡ | 0.047* | 0.030 |
| 2 | 14 | 1007.97 | 0.00009‡ | 0.021* | 0.008 |
| 3 | 20 | 1015.05 | 0.00009‡ | 0.021* | 0.005 |
| 4 | 28 | 1025.80 | 0.00012‡ | 0.028* | 0.004 |
| 5 | 37 | 1041.65 | 0.00026‡ | 0.063* | 0.006 |
| 6 | 48 | 1064.20 | 0.00035‡ | 0.084* | 0.005 |
| 7 | 61 | 1095.30 | 0.00082‡ | 0.197* | 0.008 |
| 8 | 77 | 1136.96 | 0.00098‡ | 0.237* | 0.007 |
| 9 | 94 | 1191.25 | 0.00094‡ | 0.228* | 0.005 |
| 10† | 114 | 1260.15 | 0.00030‡ | 0.072 | 0.001 |
| Sum | - | - | 0.00414 | 1.000 | 0.079+ |

‡ Initial conditions for mass fractions in the ASM case

* Initial conditions for mixture fractions in the EMM-ASM case

+ Volume fraction initial condition for the EMM-ASM case

† Constraint for the EMM-ASM case

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# Case study: Quiescent column sedimentation

Determination of volume and mass fractions for MD2

| Agglomerate Phase | Terminal Velocity (mm $s^{-1}$) | Density (kg $m^{-3}$) | Dry Mass Fraction (-) | Mass Ratio* (-) | Dry Volume Fraction (-) |
|---|---|---|---|---|---|
| 1 | 10 | 1003.48 | 0.00023‡ | 0.053* | 0.0346 |
| 2 | 14 | 1007.97 | 0.00032‡ | 0.074* | 0.0289 |
| 3 | 20 | 1015.05 | 0.00042‡ | 0.100* | 0.0235 |
| 4 | 28 | 1025.80 | 0.00041‡ | 0.096* | 0.0142 |
| 5 | 37 | 1041.65 | 0.00058‡ | 0.137* | 0.0131 |
| 6 | 48 | 1064.20 | 0.00057‡ | 0.133* | 0.0084 |
| 7 | 61 | 1095.30 | 0.00073‡ | 0.171* | 0.0074 |
| 8 | 77 | 1136.96 | 0.00065‡ | 0.153* | 0.0047 |
| 9 | 94 | 1191.25 | 0.00027‡ | 0.063* | 0.0014 |
| 10† | 114 | 1260.15 | 0.00009‡ | 0.020 | 0.0003 |
| Sum | - | - | 0.00426 | 1.000 | 0.1363+ |

‡ Initial conditions for mass fractions in the ASM case

* Initial conditions for mixture fractions in the EMM-ASM case

+ Volume fraction initial condition for the EMM-ASM case

† Constraint for the EMM-ASM case

*

# Case Study: Sedimentation in a horizontal flow

Determination of volume and mass fractions for MDK

| Agglomerate Phase | Terminal Velocity ($mm\ s^{-1}$) | Density ($kg\ m^{-3}$) | Dry Mass Fraction (-) | Mass Ratio* (-) | Dry Volume Fraction (-) |
|---|---|---|---|---|---|
| 1 | 10 | 1003.48 | 0.00098 | 0.047* | 0.150 |
| 2 | 14 | 1007.97 | 0.00044 | 0.021* | 0.040 |
| 3 | 20 | 1015.05 | 0.00044 | 0.021* | 0.024 |
| 4 | 28 | 1025.80 | 0.00059 | 0.028* | 0.020 |
| 5 | 37 | 1041.65 | 0.00131 | 0.063* | 0.029 |
| 6 | 48 | 1064.20 | 0.00174 | 0.084* | 0.026 |
| 7 | 61 | 1095.30 | 0.00407 | 0.197* | 0.041 |
| 8 | 77 | 1136.96 | 0.00490 | 0.237* | 0.035 |
| 9 | 94 | 1191.25 | 0.00469 | 0.228* | 0.024 |
| 10† | 114 | 1260.15 | 0.00149 | 0.072 | 0.006 |
| Sum | - | - | 0.02065 | 1.000 | 0.397‡ |

* Mass fraction conditions for mixture fractions

‡ Volume fraction condition

† Constraint for the EMM-ASM

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# Case Study: Sedimentation in a horizontal flow

Determination of volume and mass fractions for MD2

| Agglomerate Phase | Terminal Velocity ($mm\ s^{-1}$) | Density ($kg\ m^{-3}$) | Dry Mass Fraction (-) | Mass Ratio* (-) | Dry Volume Fraction (-) |
|---|---|---|---|---|---|
| 1 | 10 | 1003.48 | 0.00112 | 0.053* | 0.173 |
| 2 | 14 | 1007.97 | 0.00159 | 0.074* | 0.144 |
| 3 | 20 | 1015.05 | 0.00212 | 0.100* | 0.117 |
| 4 | 28 | 1025.80 | 0.00204 | 0.096* | 0.071 |
| 5 | 37 | 1041.65 | 0.00292 | 0.137* | 0.065 |
| 6 | 48 | 1064.20 | 0.00282 | 0.133* | 0.042 |
| 7 | 61 | 1095.30 | 0.00362 | 0.171* | 0.037 |
| 8 | 77 | 1136.96 | 0.00326 | 0.153* | 0.023 |
| 9 | 94 | 1191.25 | 0.00134 | 0.063* | 0.007 |
| 10† | 114 | 1260.15 | 0.00044 | 0.020 | 0.002 |
| Sum | - | - | 0.02127 | 1.000 | 0.682‡ |

* Mass fraction conditions for mixture fractions

‡ Volume fraction condition

† Constraint for the EMM-ASM

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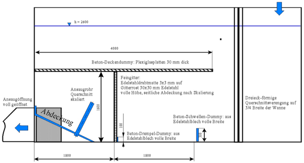
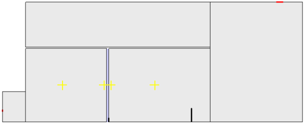
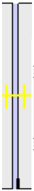
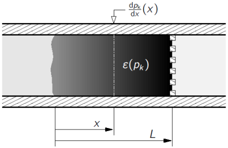
# Case Study: Sumps simulations

- Multifluid model with two dispersed phases
- Air bubbles and fibre agglomerates
  - Particle Size: $d_{pa} = 3$ mm & $d_{pf} = 5$ mm
  - Density: $\rho_{pa} = 1.185$ kg m$^{-3}$ & $\rho_{pf} = 1027$ kg m$^{-3}$
  - Liquid-fibre agglomerate mixture viscosity: $\mu_{rf} = 1 + 2.5 r_p + 7.6 r_p^2$
- Transient of 100 s with timesteps of 0.01 s
- Air flow rate of 44 m$^3$ h$^{-1}$
- Outlet flow is drawn at the same rate as the inlet
- Jet air volume fraction of 0.2
- Waterfall air volume fraction of 0.5
- Fibres injected between 5 and 35 s at a fraction of 0.2771
- Suction chamber outlet draws the liquid volume injected out
- SST turbulence model for the liquid phase
- Strainer model based on the Darcy-Ergun equation was applied to the large area sieve at 4.2 m (Grahn et al. (2010) *J. Eng. Gas Turb Power* **132**(8), 082902)





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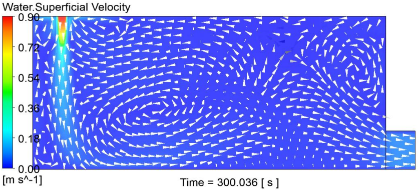
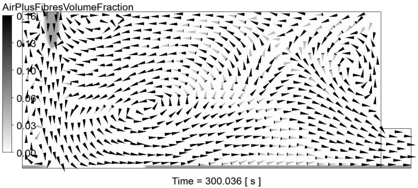
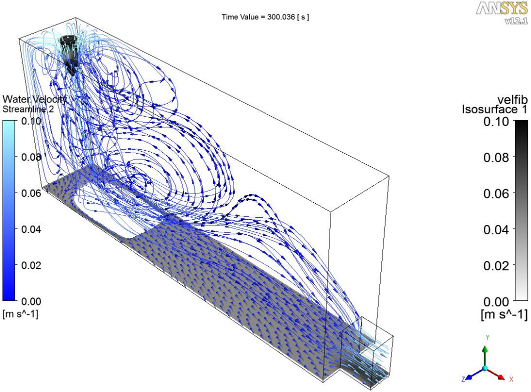
# Case Study: Sump with no internals

Jet inlet with no internal structures and no strainer.

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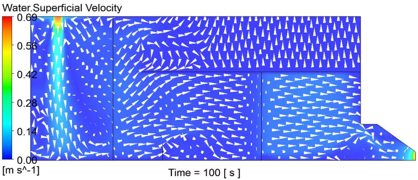
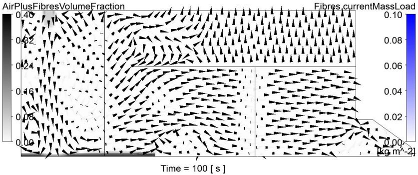
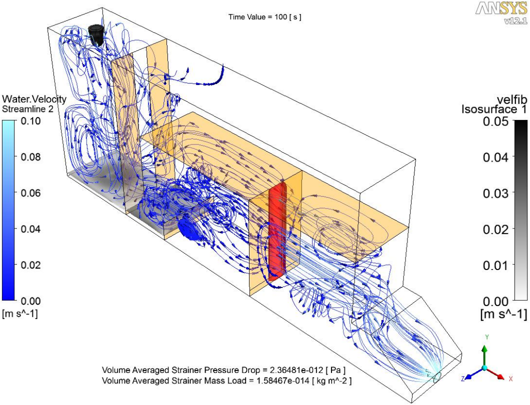
HZDR

# Case Study: Sumps with typical internal structures

Jet inlet with all internal structures.

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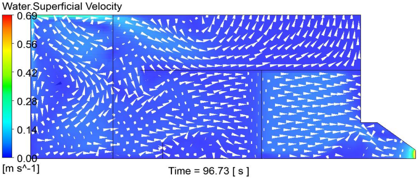
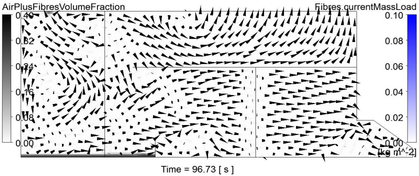
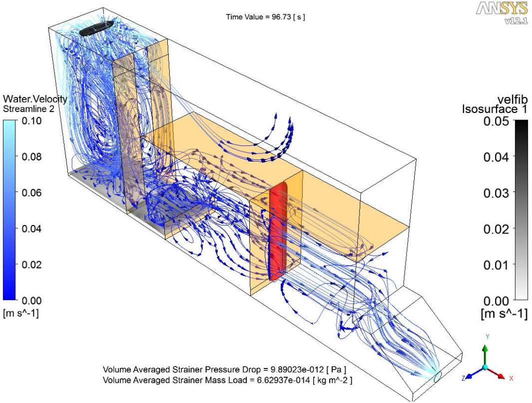
HZDR

# Case Study: Sumps with typical internal structures

Waterfall inlet with all internal structures.

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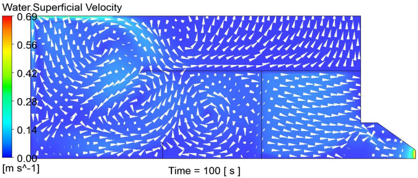
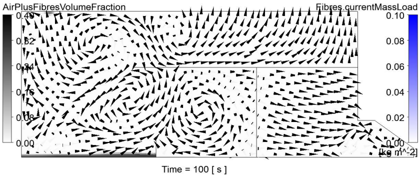
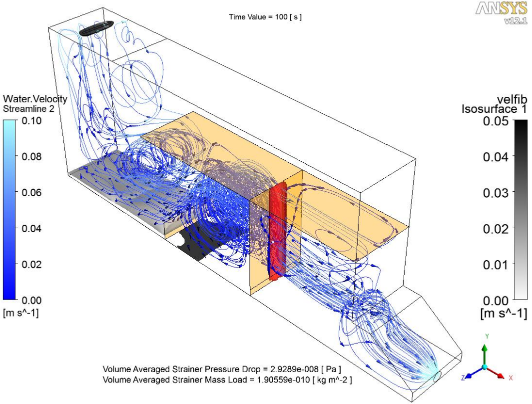
# Case Study: Sumps with typical internal structures

Waterfall inlet without the upstream baffles.

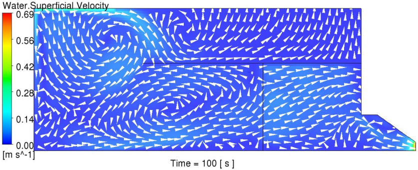


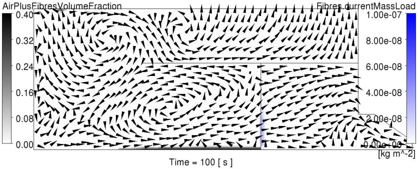



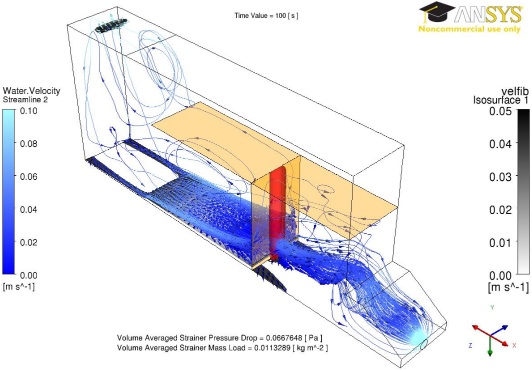



# Case Study: Sumps with typical internal structures

Waterfall inlet without the upstream baffles and weir.

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