Particle aggregation and breakage using `multiphaseEulerFoam`

A CFD-PBM approach

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Introduction

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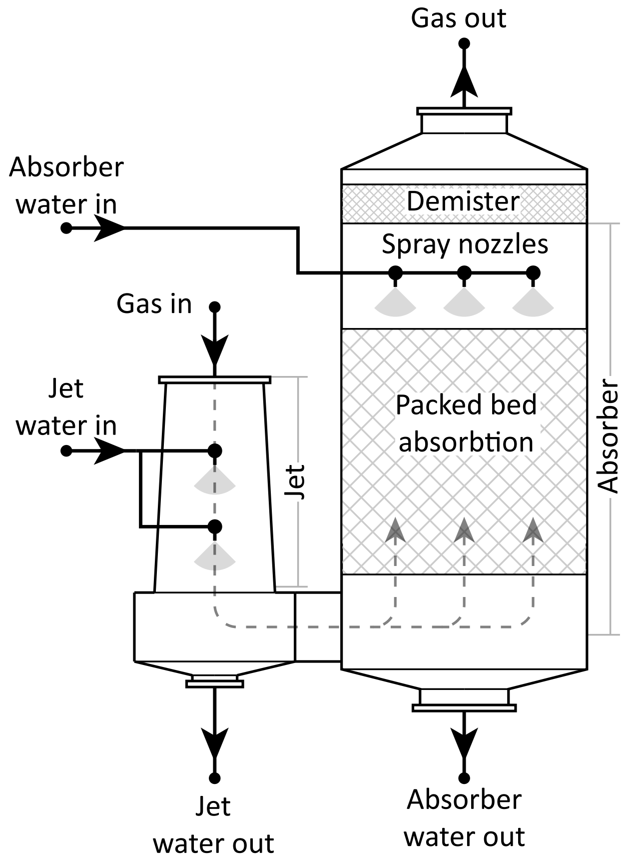
PhD Scope: Aggregation and breakage of micron-sized particles in turbulent flows for highly accelerated sedimentation onboard marine vessels

Background

Marine scrubbers clean the exhaust gas from the engine for SOx and ~40% of the particulate mass.
The particulate matter needs to be removed before discharged into the Oceans.



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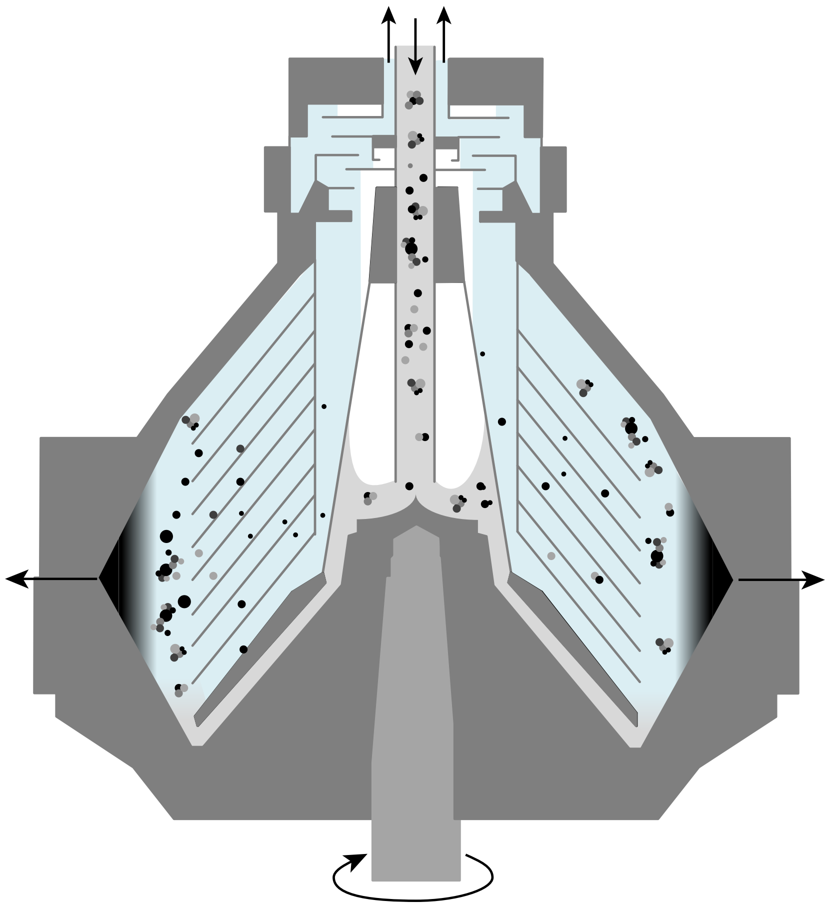
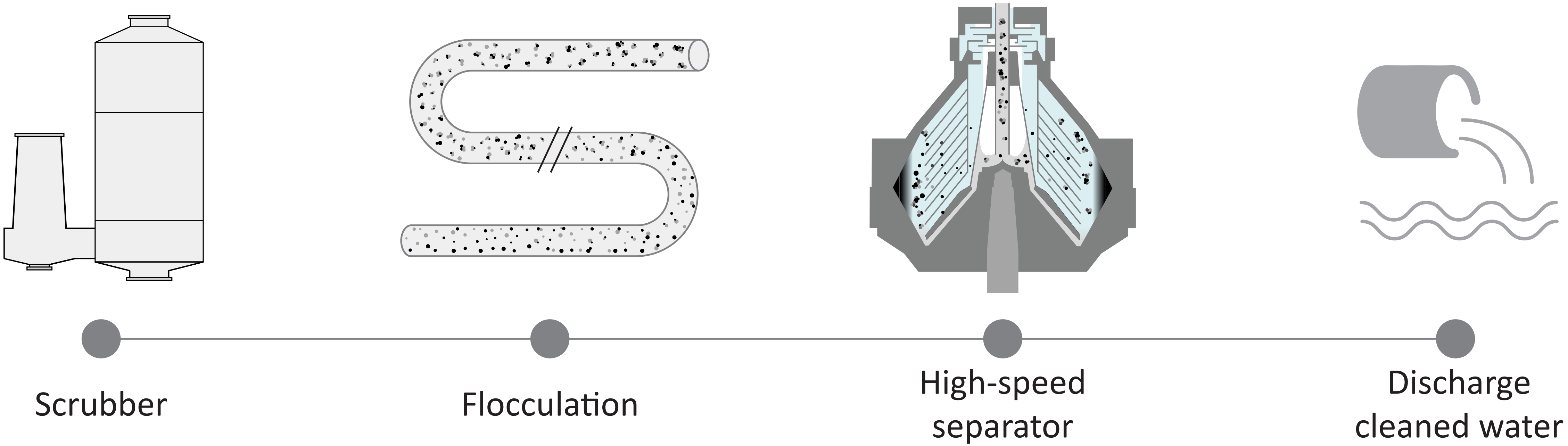
Motivation

High-speed separators are utilised for an accelerated sedimentation.
The particle size is the most important parameter for sedimentation.



Motivation

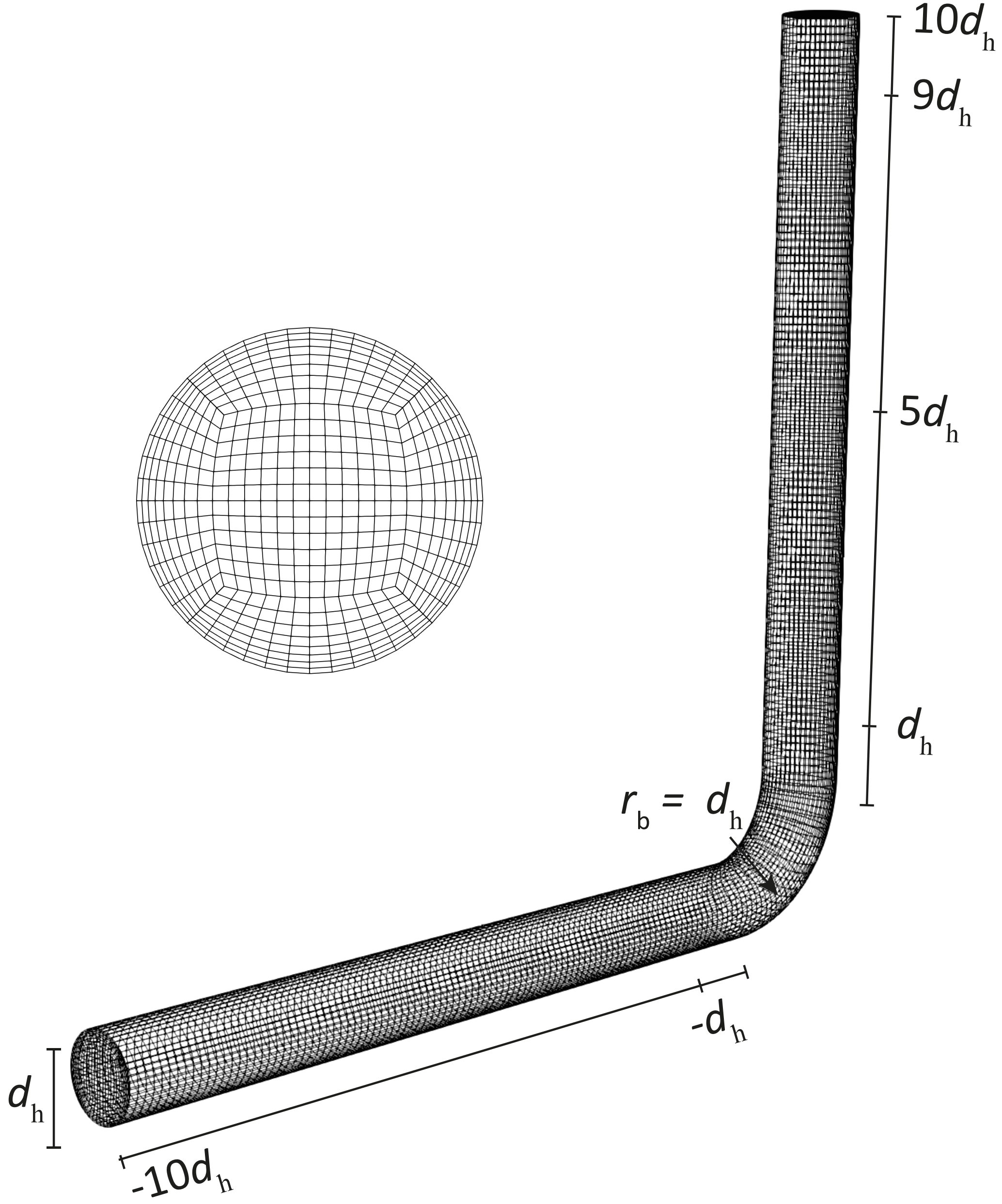
Micron-sized particles are agglomerated in a hydraulic flocculator before separation in the high-speed separator.



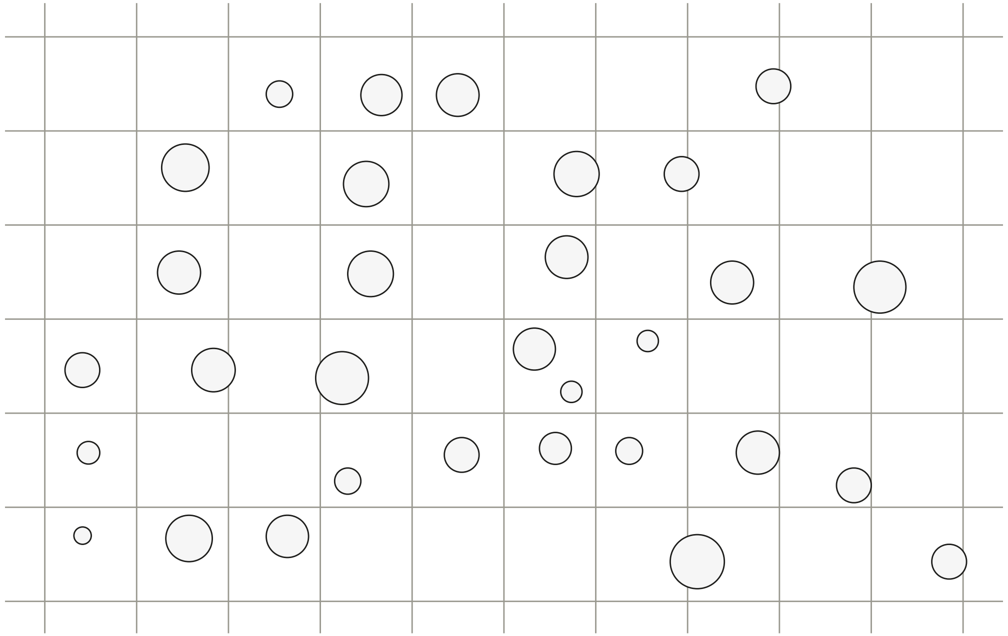
Computational domain

Designing a compact hydraulic flocculator and achieving the largest possible particle size distribution.

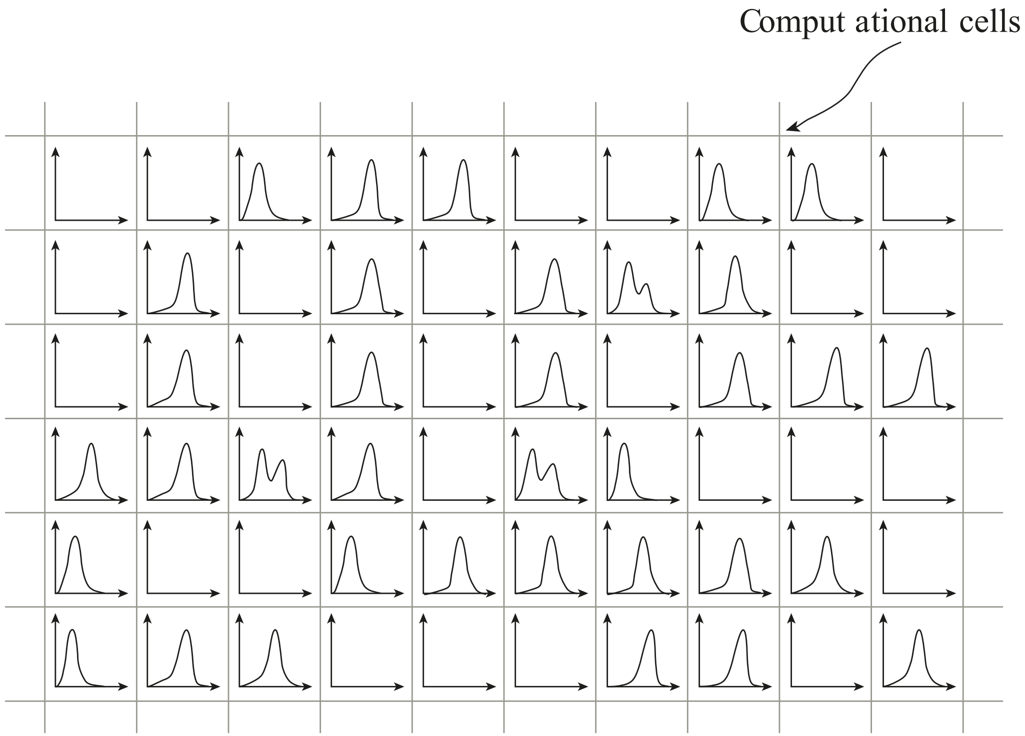
Analyse the particle size distribution through a 90° pipe bend.



Numerical method



Euler-Lagrangian



Euler-Euler

Governing equations

Euler-Euler approach using the population balance equations to track the particle size distribution

Mass- and momentum equations

$$\frac{\partial}{\partial t}\left(\alpha_\varphi \rho_\varphi\right) + \nabla \cdot \left(\alpha_\varphi \rho_\varphi \boldsymbol{u}_\varphi\right) = 0$$

$$\frac{\partial}{\partial t}\left(\alpha_\varphi \rho_\varphi \boldsymbol{u}_\varphi\right) + \nabla \cdot \left(\alpha_\varphi \rho_\varphi \boldsymbol{u}_\varphi \boldsymbol{u}_\varphi\right) - \nabla \tau_\varphi = -\alpha_\varphi \nabla p + \alpha_\varphi \rho_\varphi \boldsymbol{g} + \boldsymbol{M}_\varphi + \boldsymbol{S}_\varphi$$

where $\boldsymbol{M}_\varphi$ is the momentum exchange at the interfaces and $\boldsymbol{S}_\varphi$ is the source term.

Governing equations

Momentum exchange at the interfaces is the sum of external force

$$\boldsymbol{M}_{\varphi} = \sum_{\varphi=0,\varphi\neq\psi}^{N} \left(\underbrace{F_{D,\varphi,\psi}}_{\text{Wen-Yu drag}} + \underbrace{F_{L,\varphi,\psi}}_{\text{Saffman-Mei lift}} + \underbrace{F_{TD\varphi,\psi}}_{\text{Turbulent dispersion}} + \underbrace{F_{VM,\varphi,\psi}}_{\text{Virtual mass}} \right)$$

Saffman-Mei lift force published to `OpenFOAM-dev`

Population balance equation

The population balance equation,

$$\frac{\partial}{\partial t} n_v + \nabla \cdot (\boldsymbol{u}_\mathrm{p} n_v) = S_v \; ,$$

tracks the number density function. The PBE is solved by the class method which was implemented into `multiphaseEulerFoam` by Lehnigk et al. (2021).
Discontinuous changes due to aggregation and breakage are accounted for by the source term, S_v.

Aggregation kernel

The aggregation kernel for solid particles by Adachi et al. (1994) is implemented into `OpenFOAM-dev`.

$$a_{d,d'} = \frac{4}{3}\sqrt{\frac{3\pi}{10}}\sqrt{\frac{\varepsilon}{\nu}}\left(d + d'\right)^3$$

where d and d' are the diameters of two colliding particles.

Breakage kernel

The breakage kernel for solid particles by Kusters (1991) is implemented into `OpenFOAM-dev`.

$$b_{v'} = \sqrt{\frac{4}{15\pi}} \sqrt{\frac{\varepsilon}{\nu}} \exp\left(-\frac{\varepsilon_{\mathrm{cr}}}{\varepsilon}\right)$$

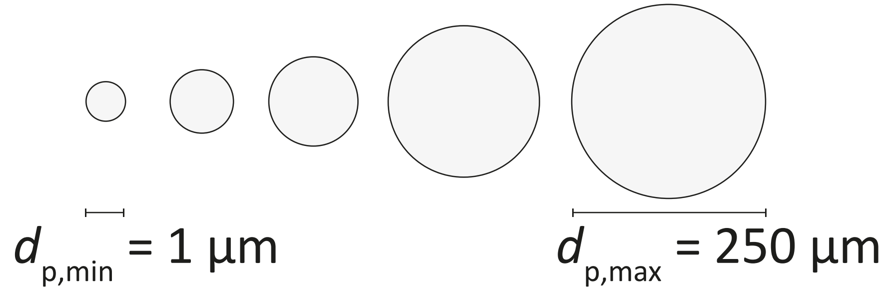
Herein the critical energy dissipation rate required to cause a break up is given by

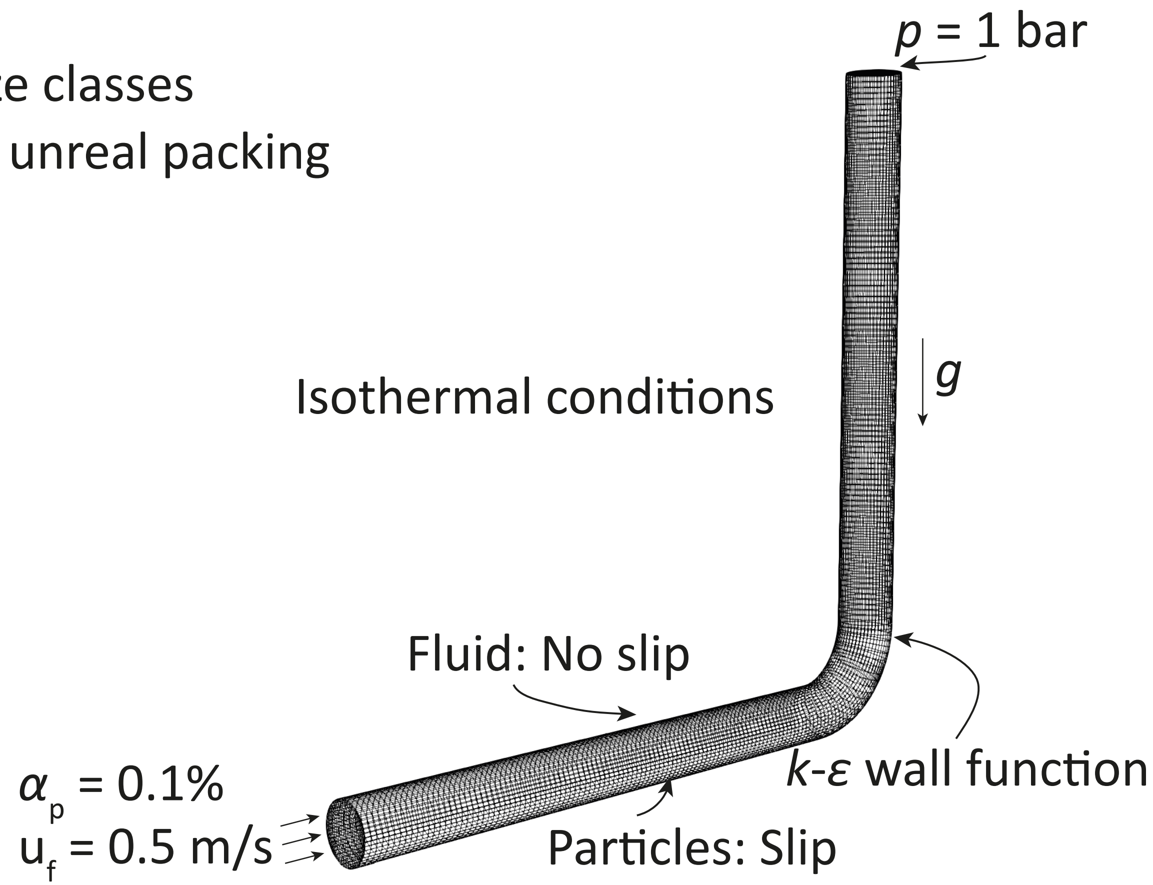
$$\varepsilon_{\mathrm{cr}} = \frac{B}{r_{\mathrm{c}}} \,,$$

where B is the particle strength parameter and r_{c} is the collision radius of a particle.

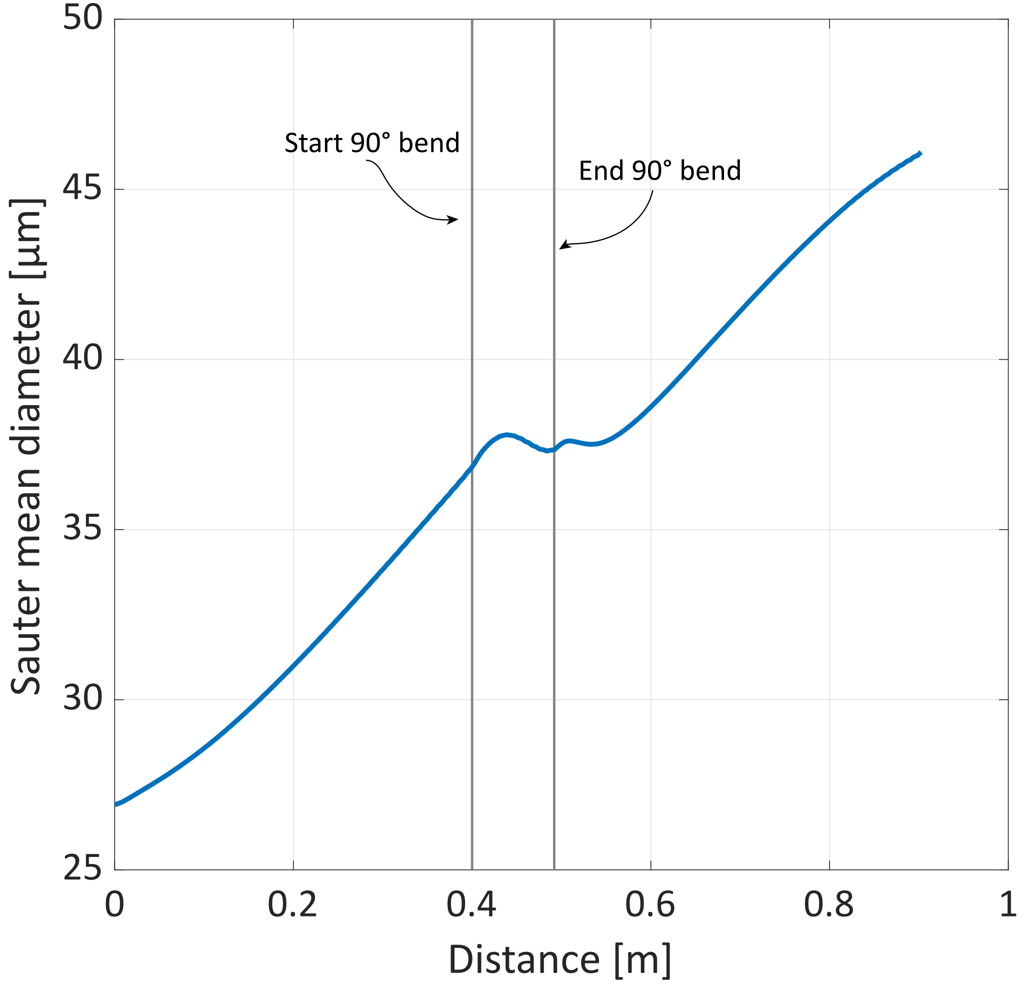
Simulation properties

- Logarithmic particle size range with 30 size classes
- Particle phase pressure model to prevent unreal packing
- Density ratio: ρ_p/ρ_f = 1.4

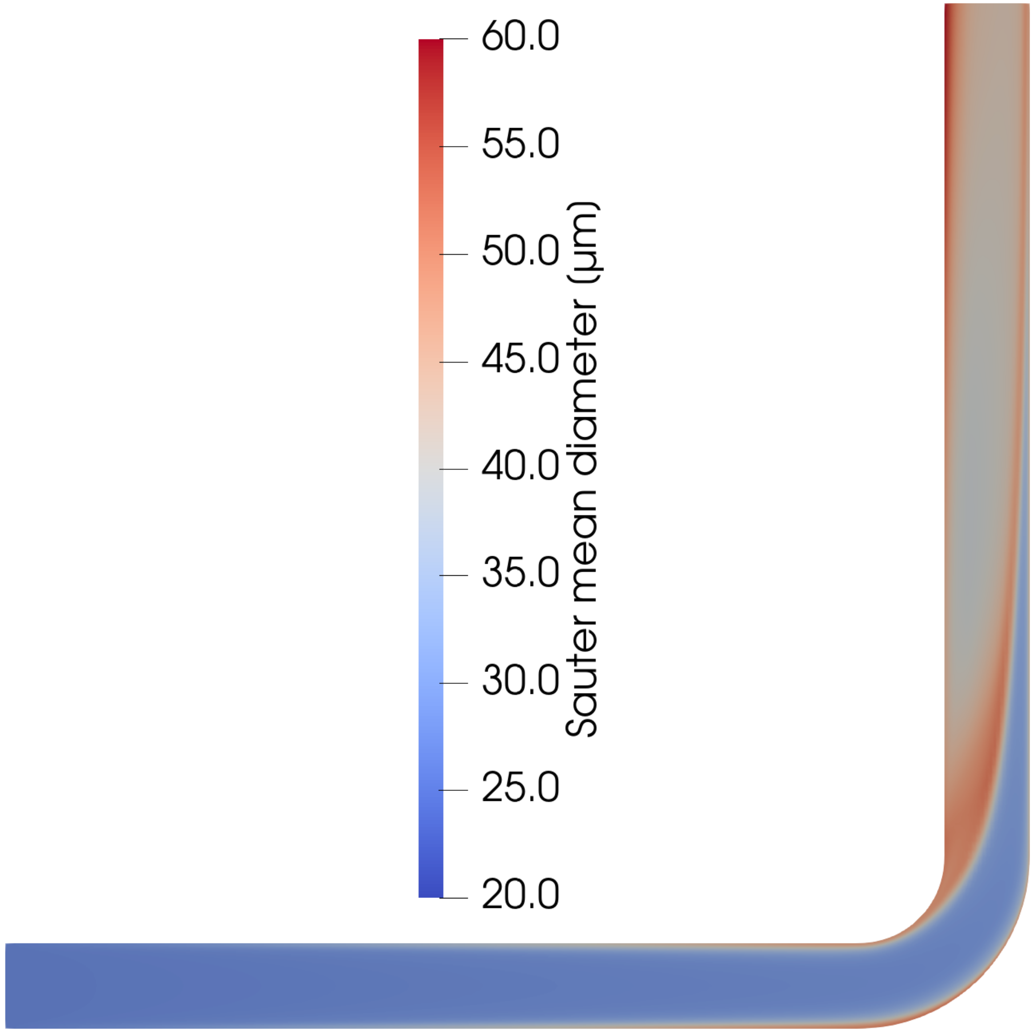




Results

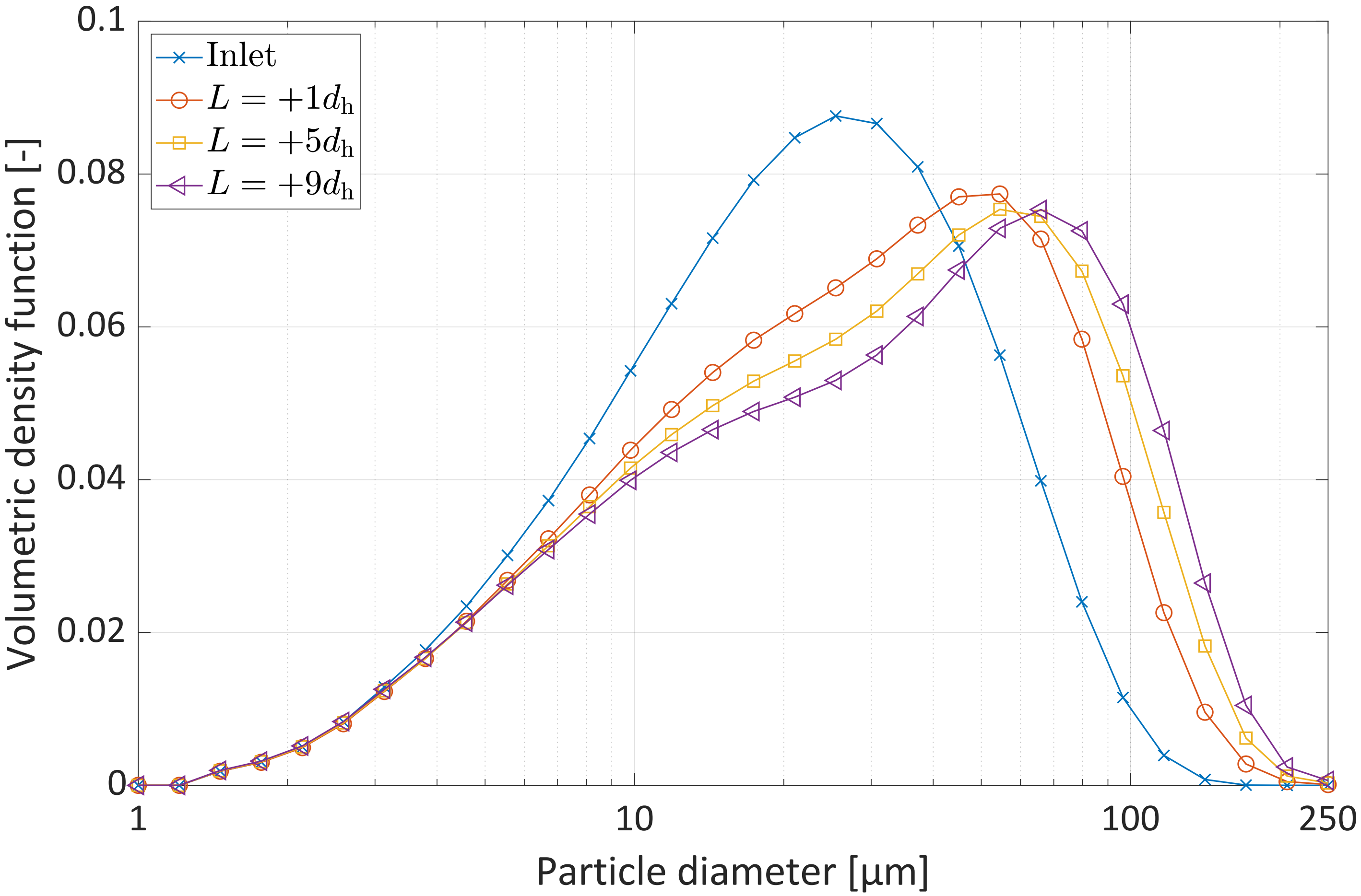


Start 90° bend
End 90° bend
Sauter mean diameter [µm]
Distance [m]
50
45
40
35
30
25
0
0.2
0.4
0.6
0.8
1



60.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
20.0
Sauter mean diameter (µm)

Particle size distribution



Development work

Closing remarks

The CFD-PBE framework allows to directly analyse the particle size distribution within the domain.

It is visible how the particles aggregate in the straight turbulent pipe and break up when subject to the sharp curvature of the bend.

On-going work is made to determine the best suited desing for marine installation for effective accelerated sedimentation.

Optimising the flocculation system allows for less pollutants discharged to the Oceans.

Source files

The presented 90° pipe bend is published to `OpenFOAM-dev` of OpenFOAM Foundation.

The tutorial is located under the `multiphaseEulerFoam` tutorials.

```
$FOAM_TUTORIALS/multiphase/multiphaseEulerFoam/RAS/pipeBend
```

The Saffman-Mei lift force model, the aggregation kernel and the breakage kernel are also published to `OpenFOAM-dev`.

Acknowledgements

A big thank you to Dr. Ronald Lehnigk and Dr. Fabian Schlegel from Helmholtz-Zentrum Dresden Rossendorf as well as Anders Schou Simonsen from Alfa Laval for their assistance in the development of this work.

Thank you for your attention.

If you have any question, feel free to ask or reach out.

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Presentation is available at GitHub.

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References

1. Adachi, Y., Cohen Stuart, M. A., & Fokkink, R. (1994). Kinetics of Turbulent Coagulation Studied by Means of End-over-End Rotation. Journal of Colloid and Interface Science, 165(2), 310–317. https://doi.org/10.1006/JCIS.1994.1234
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