Towards a Euler-Euler multi-fluid solver for dense spray applications

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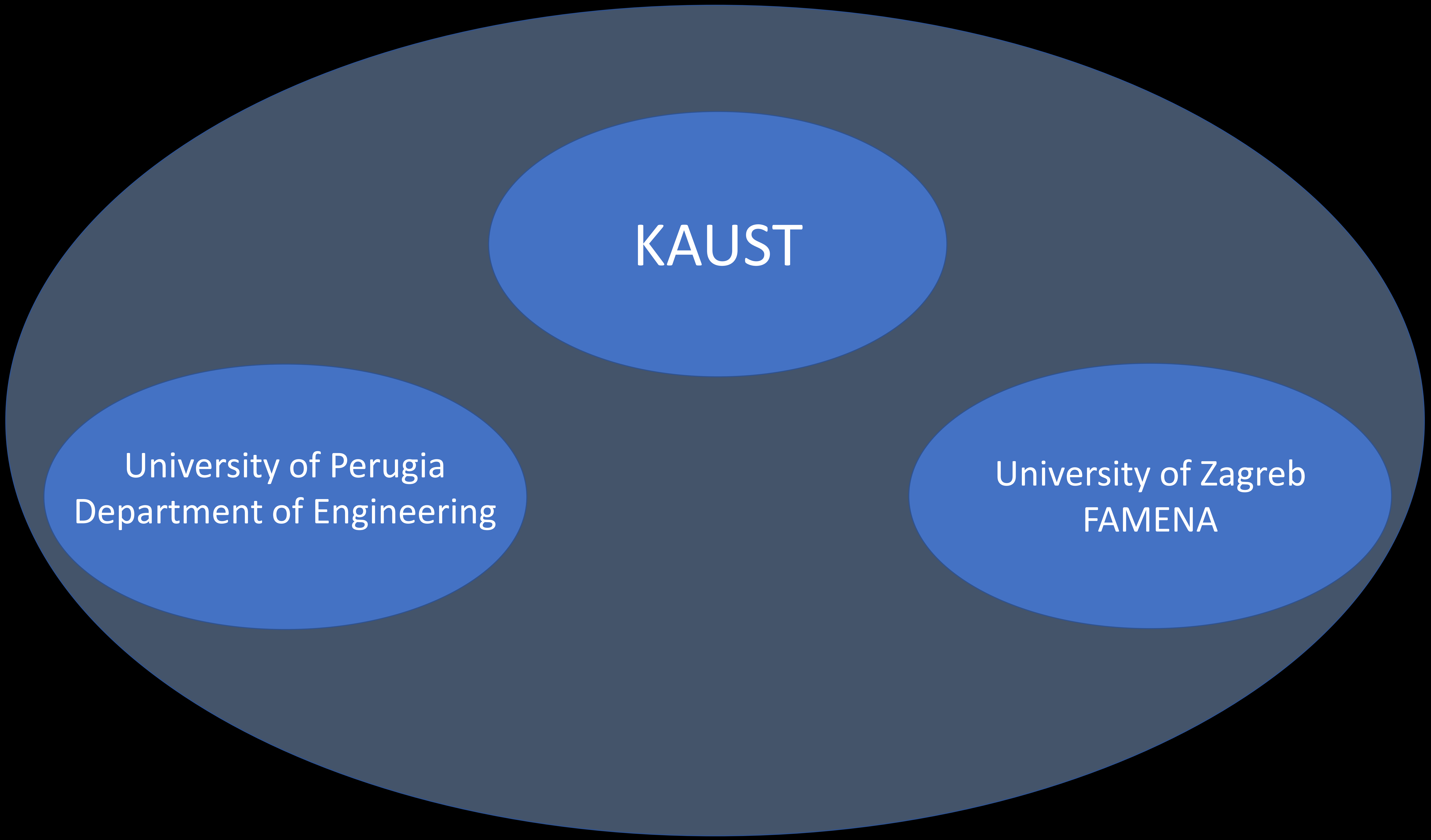
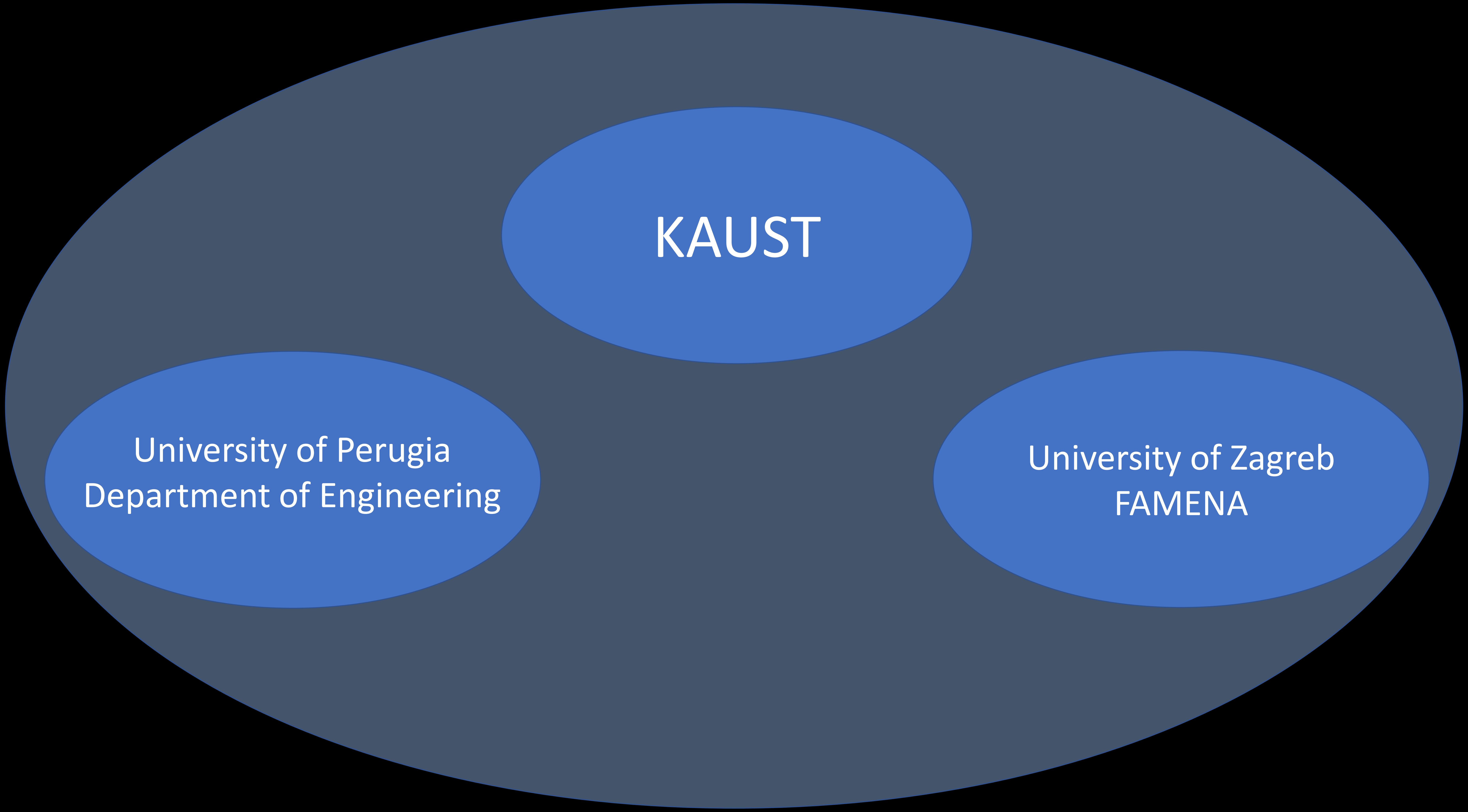
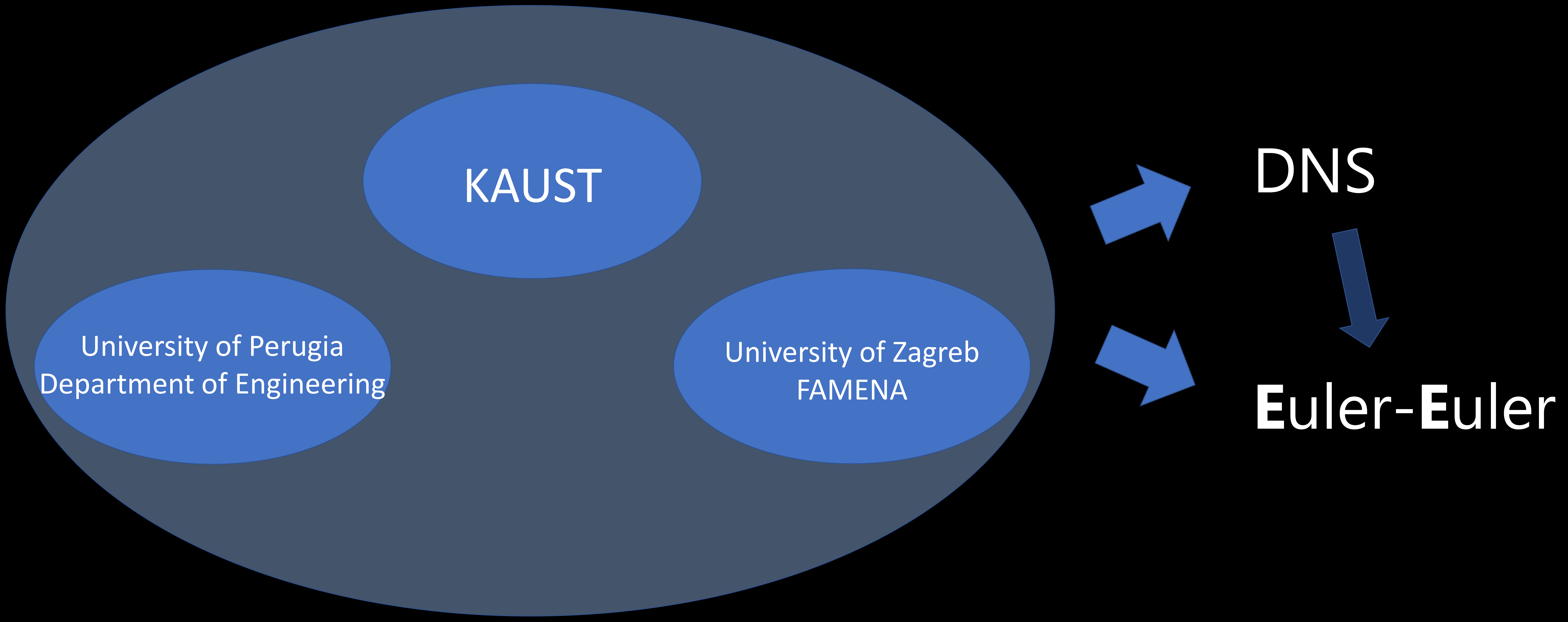
Predictive Modelling and Experimental Validation of Multi-component Dense Spray Dynamics





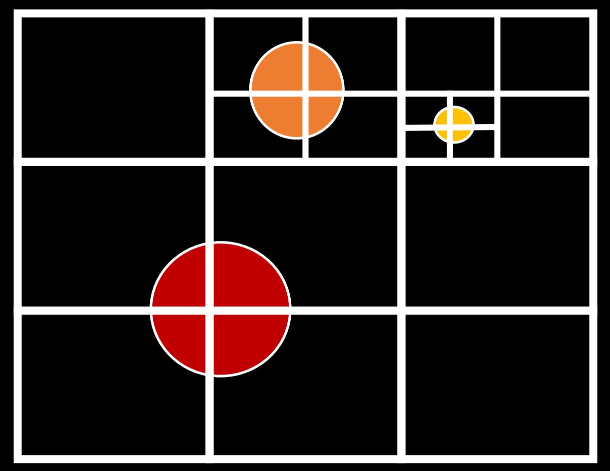
develop and establish high-fidelity modelling and experimental capabilities
to predict and characterize multi-component dense fuel sprays


KAUST
University of Perugia
Department of Engineering
University of Zagreb
FAMENA
DNS
Euler-Euler

Main parts of the presentation

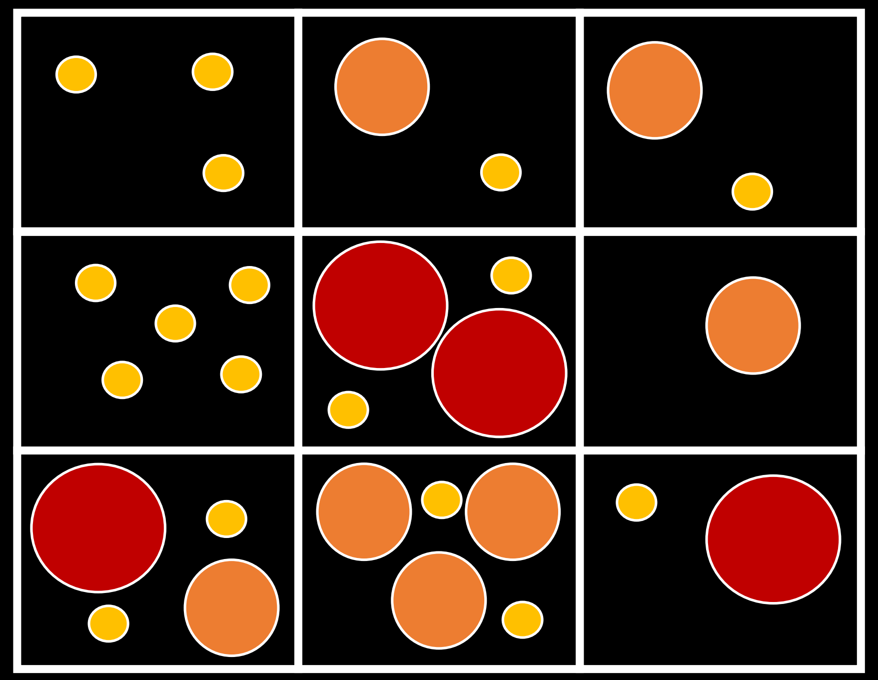
1. DNS solver
   - Solver description
   - Preliminary results
2. Euler-Euler solver
   - Solver description
   - Sub-model validation
   - Preliminary spray simulations

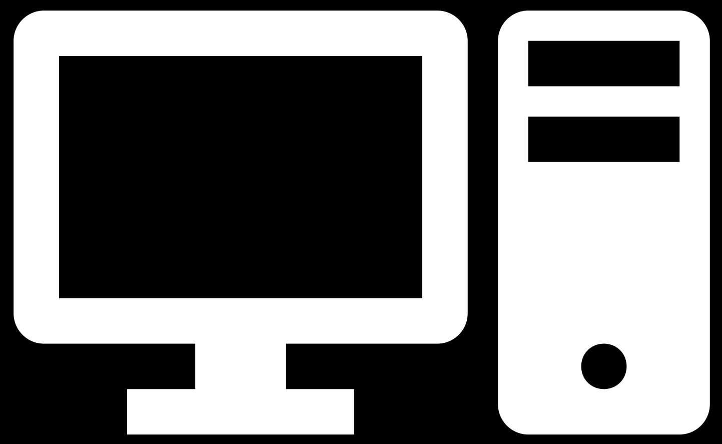
DNS



None

E-E



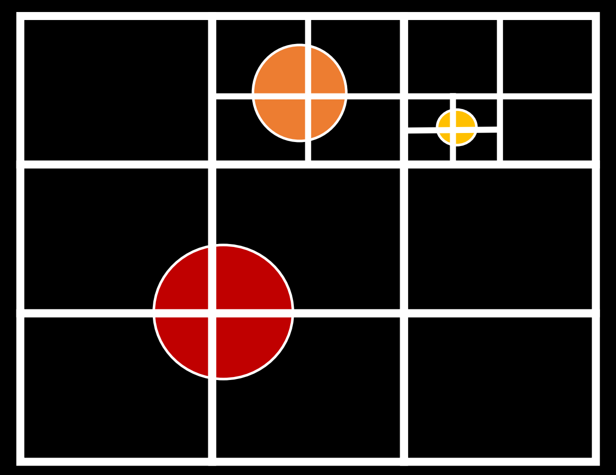


$$
\begin{aligned}
\overline{\mathbf{M}}_{\mathrm{d},i} = \; & \alpha_{\mathrm{d},i} C_{\mathrm{d},i} \frac{3}{4} \frac{\overline{\rho}_{\mathrm{c}}}{d_i} |\overline{\mathbf{U}}_{\mathrm{r},i}| \overline{\mathbf{U}}_{\mathrm{r},i} && \text{drag} \\
& + \alpha_{\mathrm{d},i} C_{\mathrm{l}} \overline{\rho}_{\mathrm{c}} \overline{\mathbf{U}}_{\mathrm{r},i} \times (\nabla \times \overline{\mathbf{U}}_{\mathrm{c}}) && \text{lift} \\
& + \alpha_{\mathrm{d},i} C_{\mathrm{vm}} \overline{\rho}_{\mathrm{c}} \left(\frac{D_{\mathrm{c}} \overline{\mathbf{U}}_{\mathrm{c}}}{Dt} - \frac{D_{\mathrm{d},i} \overline{\mathbf{U}}_{\mathrm{d},i}}{Dt} \right) && \text{virtual mass} \\
& - C_{\mathrm{d},i} \frac{3}{4} \frac{\overline{\rho}_{\mathrm{c}}}{d_i} \frac{\nu_{\mathrm{c}}^{\mathrm{t}}}{\sigma_\alpha} |\overline{\mathbf{U}}_{\mathrm{r},i}| \nabla \alpha_{\mathrm{d},i} && \text{turbulent drag}
\end{aligned}
$$

$$
C_{\mathrm{d},i} = C_{\mathrm{d0},i} \left(\exp(3.64\, \alpha_{\mathrm{d},i}) + \alpha_{\mathrm{d},i}^{0.864} \right)
$$

where

$$
C_{\mathrm{d0},i} = \exp\left(-51.8 + 13.2 \ln(\mathrm{Re}_i) - 0.824 \left(\ln(\mathrm{Re}_i) \right)^2 \right)
$$

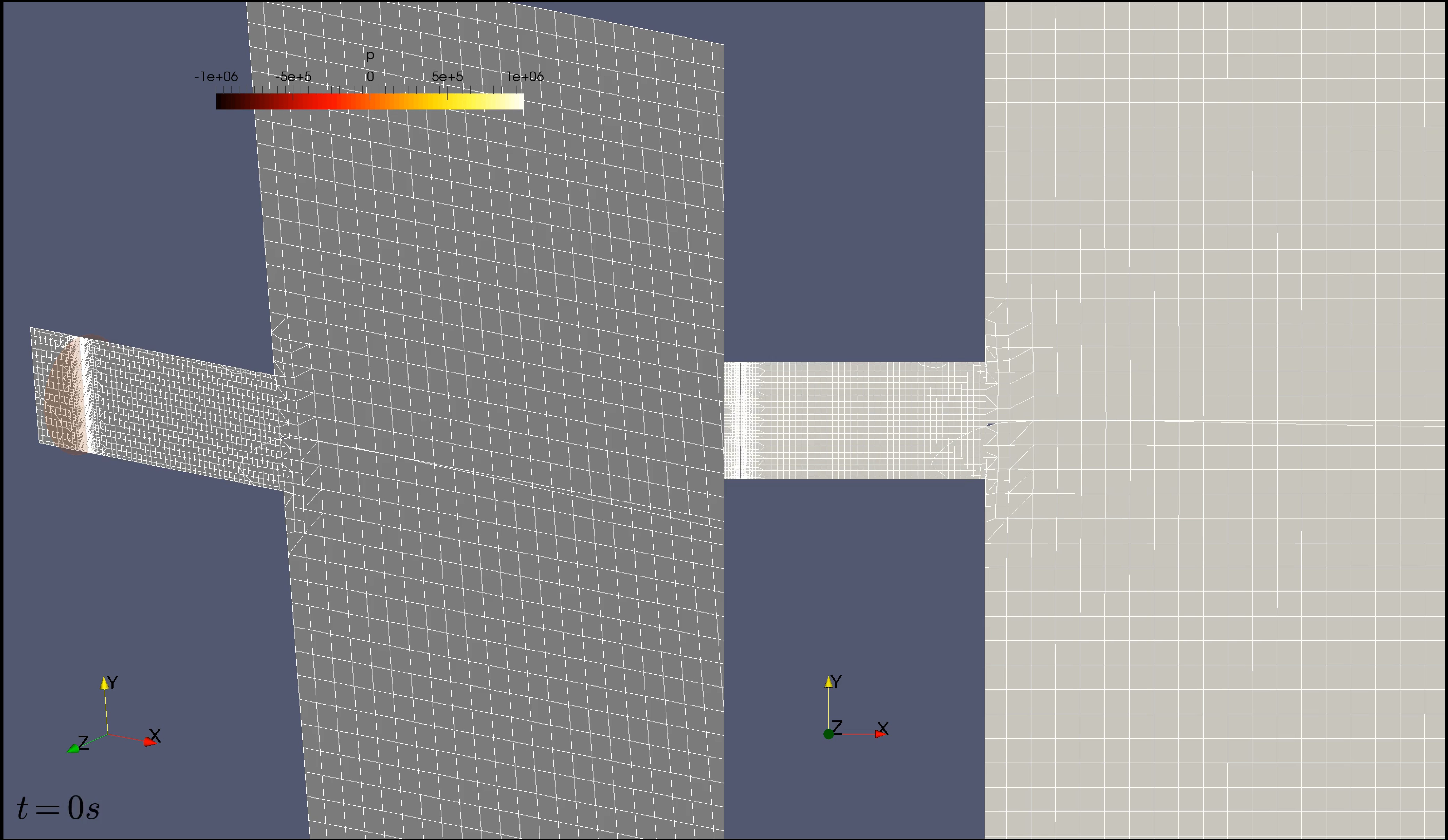


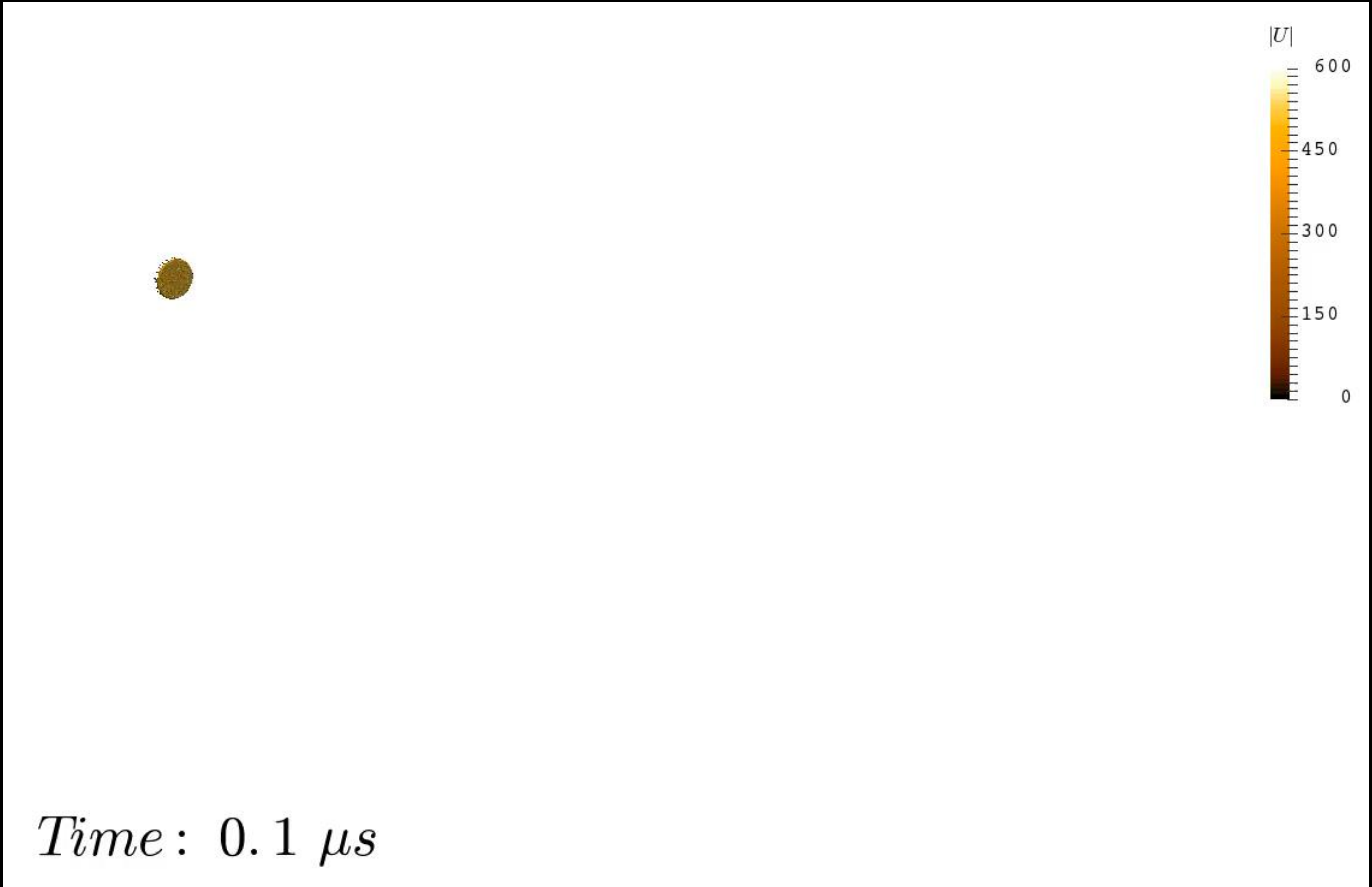
DNS

DNS solver

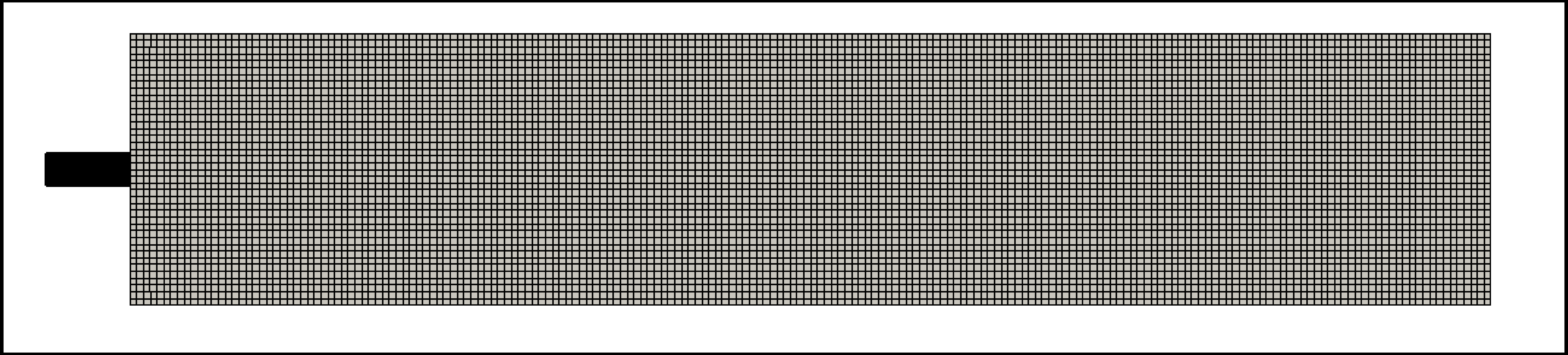
- Incompressible two-phase flow (fuel and air)
- Discontinuity at the interface due to the density jump and surface tension effects taken into account with the Ghost Fluid Method
- Geometric Volume-of-Fluid method used to represent and reconstruct the sharp interface
- Adaptive Grid Refinement with Dynamic Load Balancing

Perform AGR
if AGR performed and $N_{min}/N_{max} < \Delta$ **then**
  Perform DLB
end if
Solve pressure correction equation
while $i_{SIMPLE} < N_{SIMPLE}$ **do**
  Solve momentum equation
  while $i_{PISO} < N_{PISO}$ **do**
    Solve pressure equation
  end while
  Advect interface
  Assemble GFM discretisation data
end while

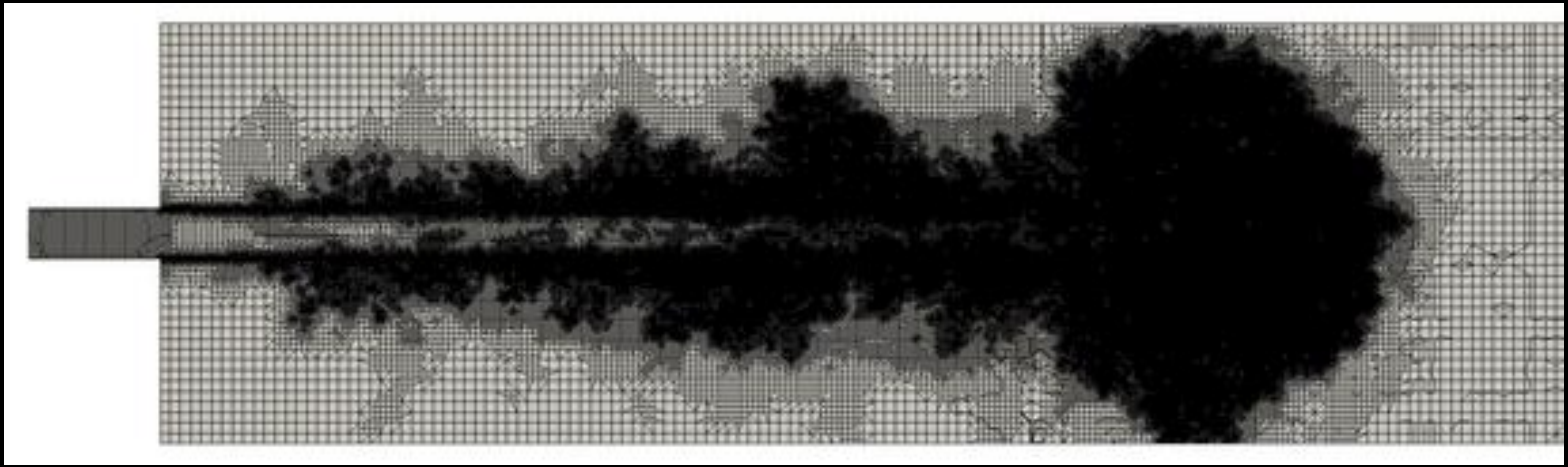

p
-1e+06
-5e+5
0
5e+5
1e+06
Y
Z
X
t = 0s
Y
Z
X

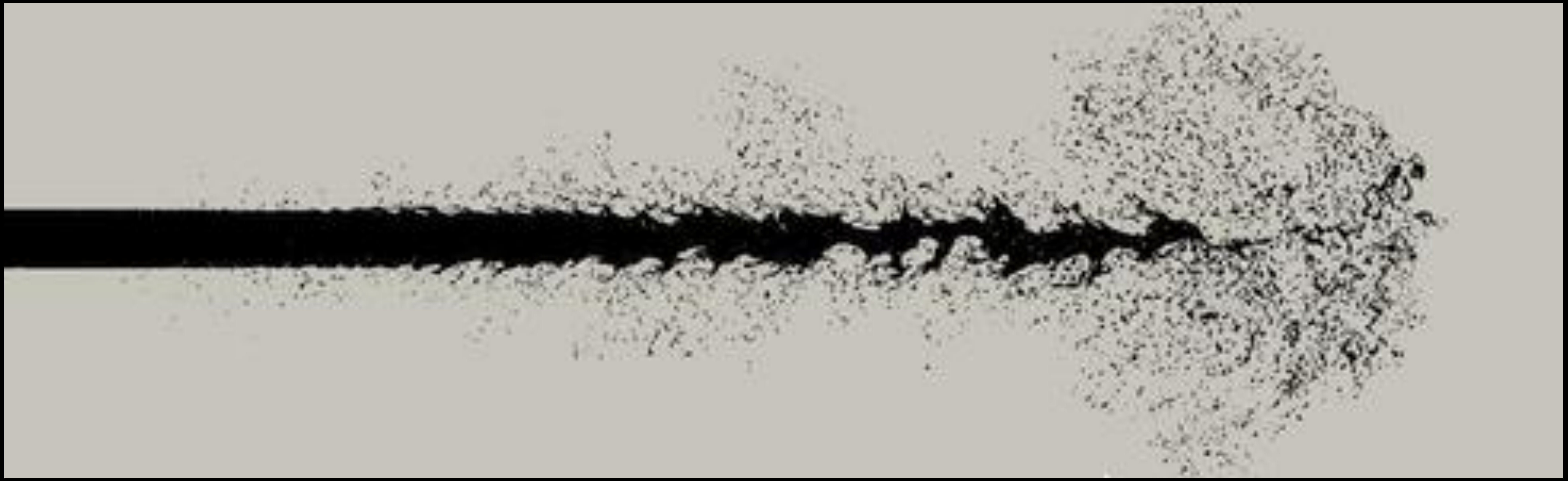

|U|
600
450
300
150
0
Time: 0.1 μs

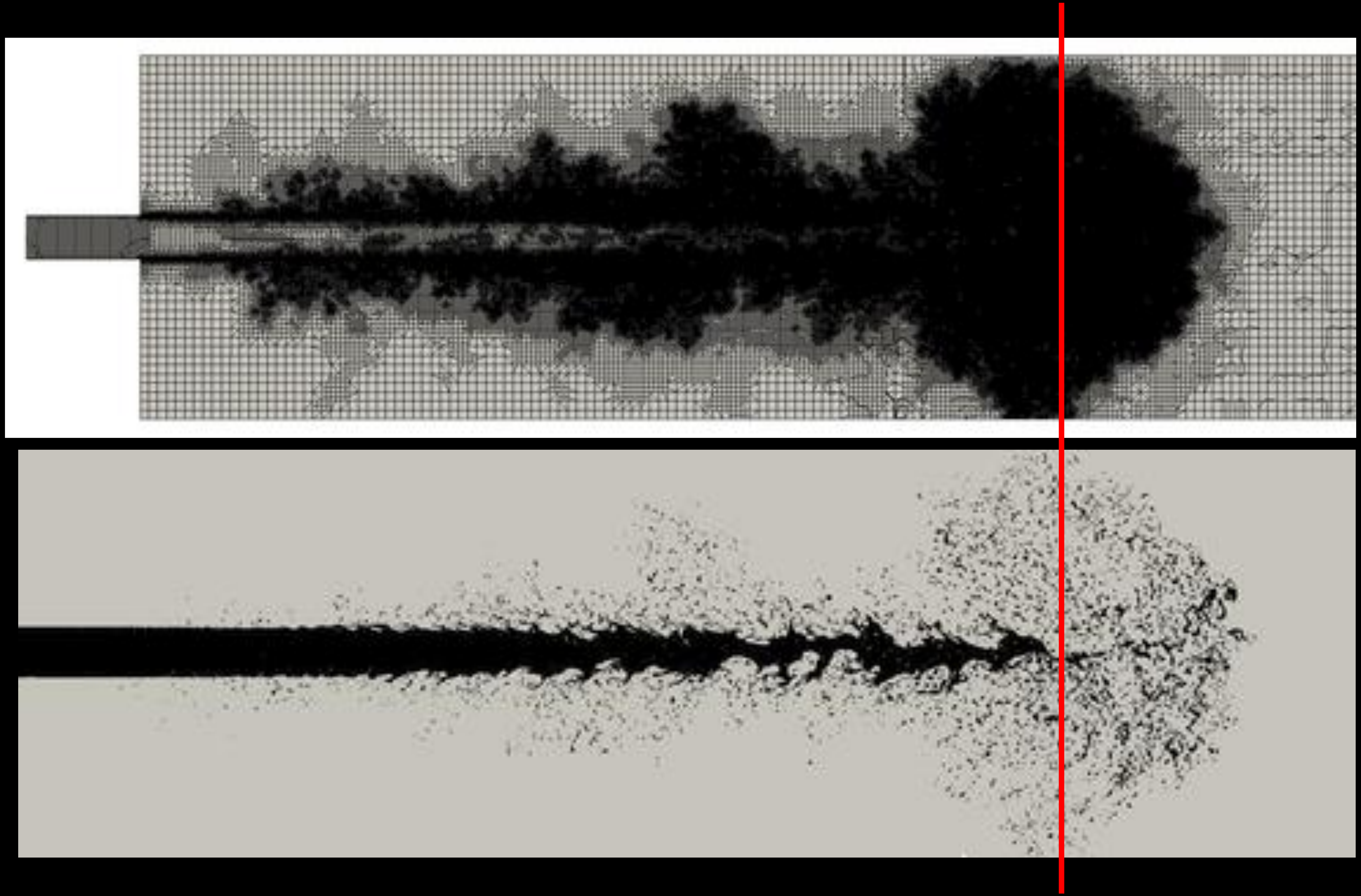
n-dodecane at 150MPa

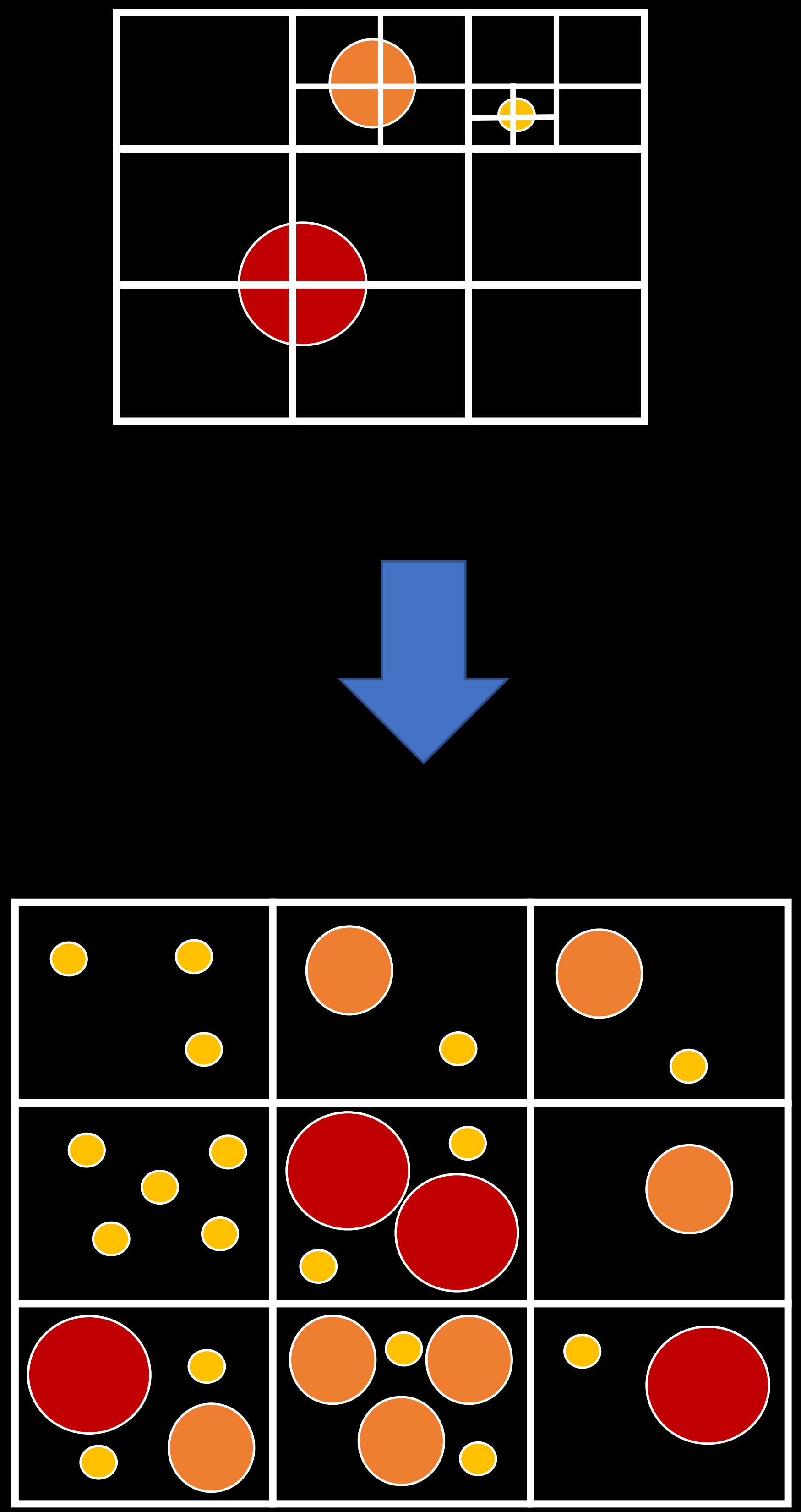


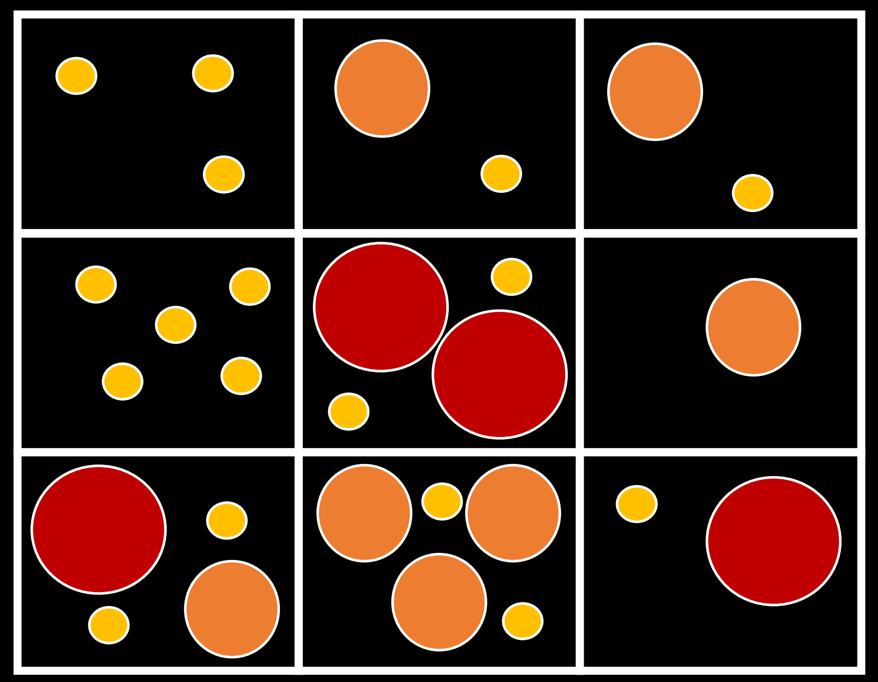
- Base cell size is 40 microns
- Four refinement levels are used, yielding 2.5 microns near the interface
- Grid is pre-refined near the interface and in the nozzle
- Started from 0.7M cells and ended up with 133M cells











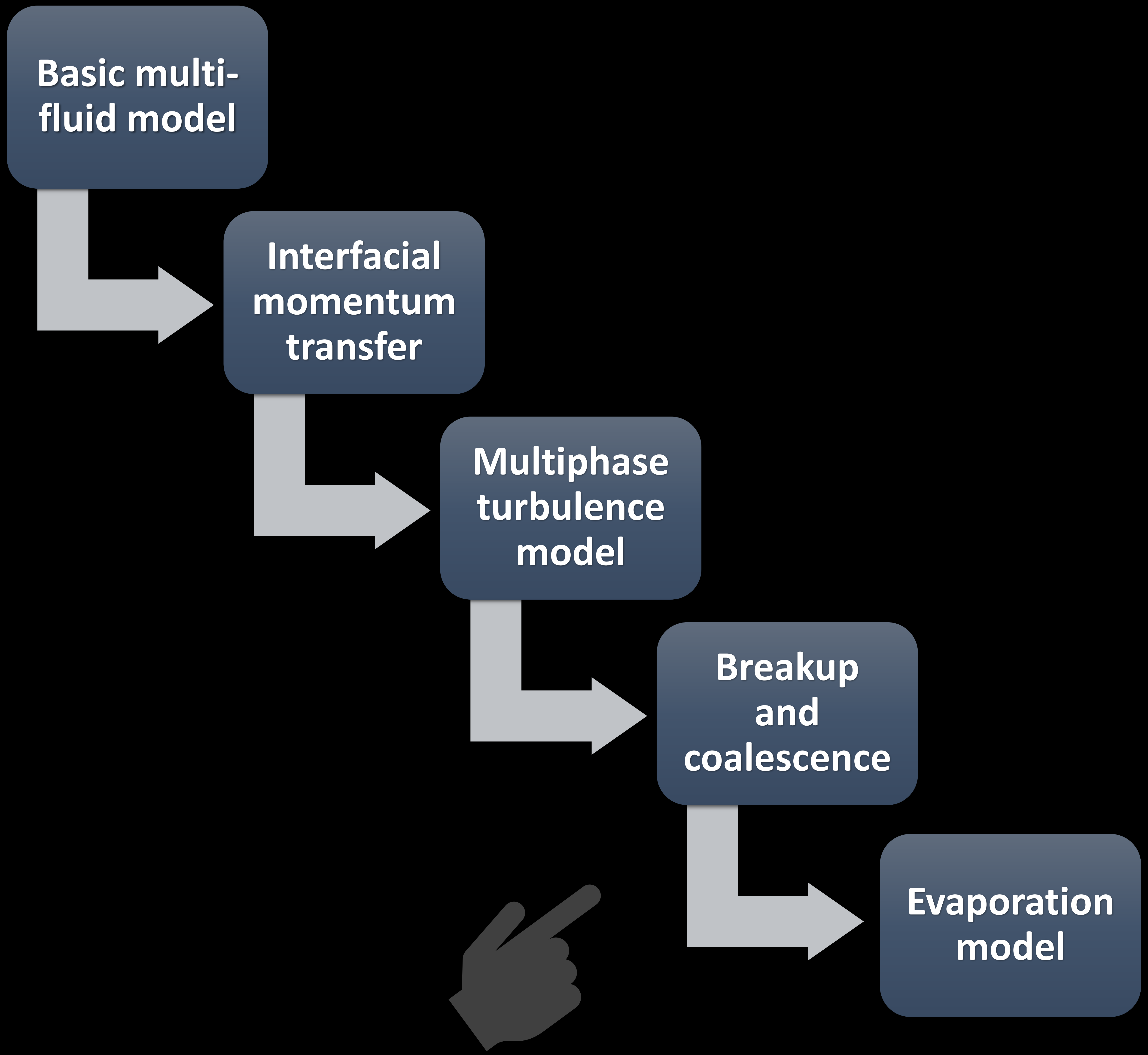
Euler-Euler

Euler-Euler solver

- Incompressible multi-fluid solver for polydisperse flows
  - multi-fluid – two-phase, but arbitrary number of droplet classes
  - method of classes in the Euler-Euler framework
  - polydisperse – droplets can vary in size
  - every class has a momentum and phase continuity equation
  - mixture pressure assumption – all phases/fluids share the same pressure equation

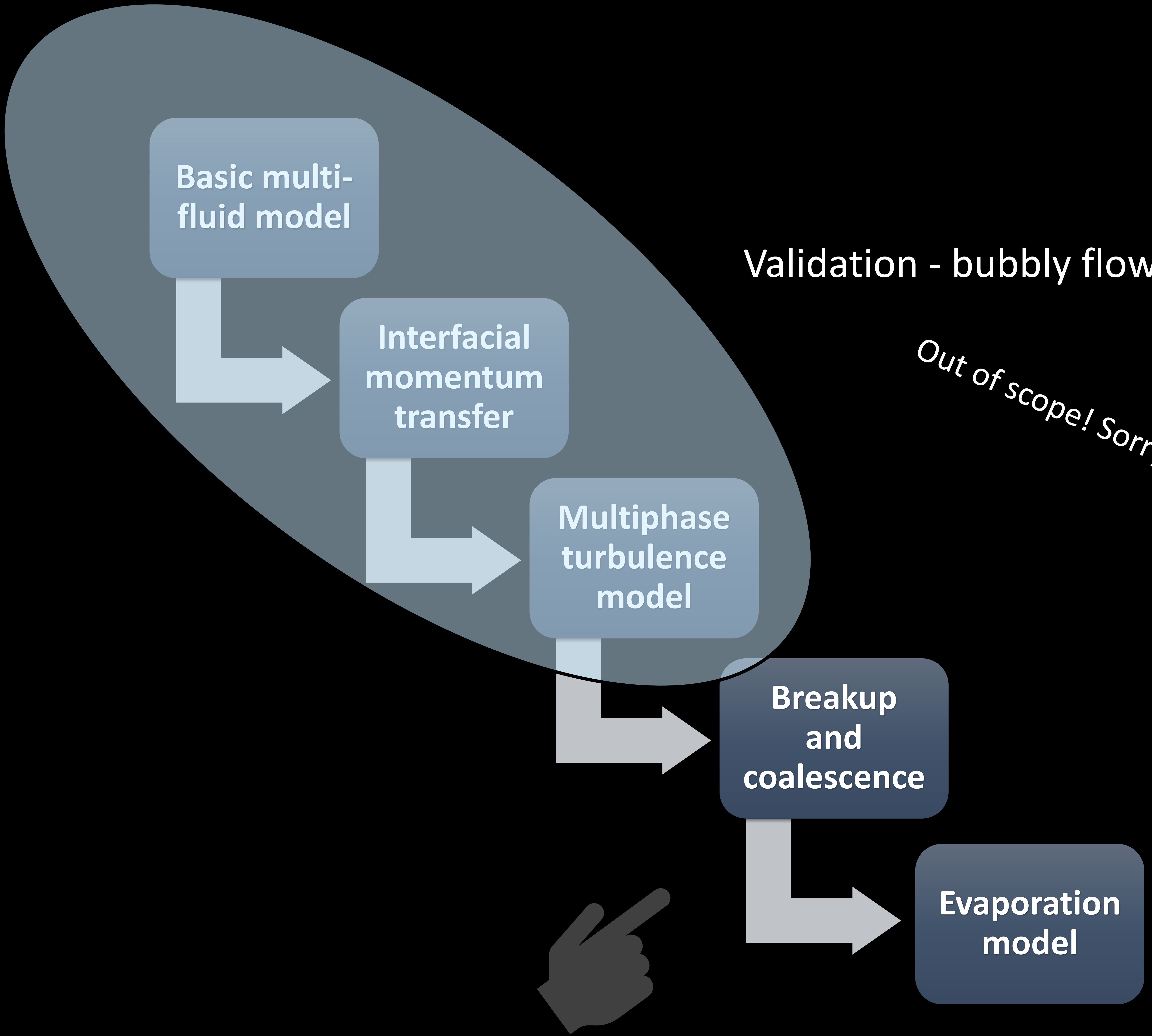
Euler-Euler solver

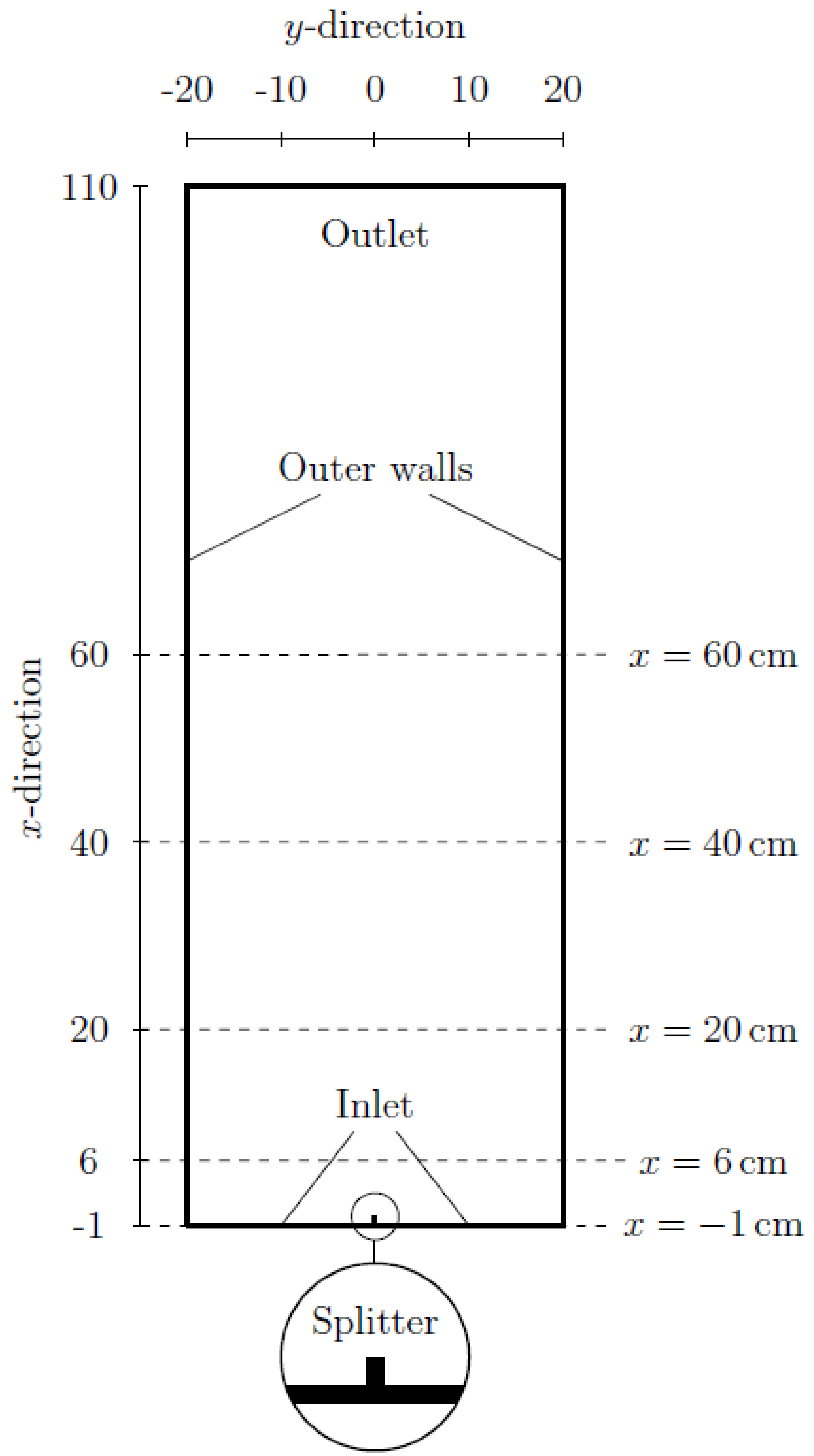
- Inter-facial momentum transfer
  - Drag, lift, virtual-mass, turbulent dispersion force (~~wall-lubrication~~)
- Mixture $k - \epsilon$ turbulence model (generalised for multi-fluid)
- Breakup and coalescence functionality


Basic multi-fluid model
Interfacial momentum transfer
Multiphase turbulence model
Breakup and coalescence
Evaporation model

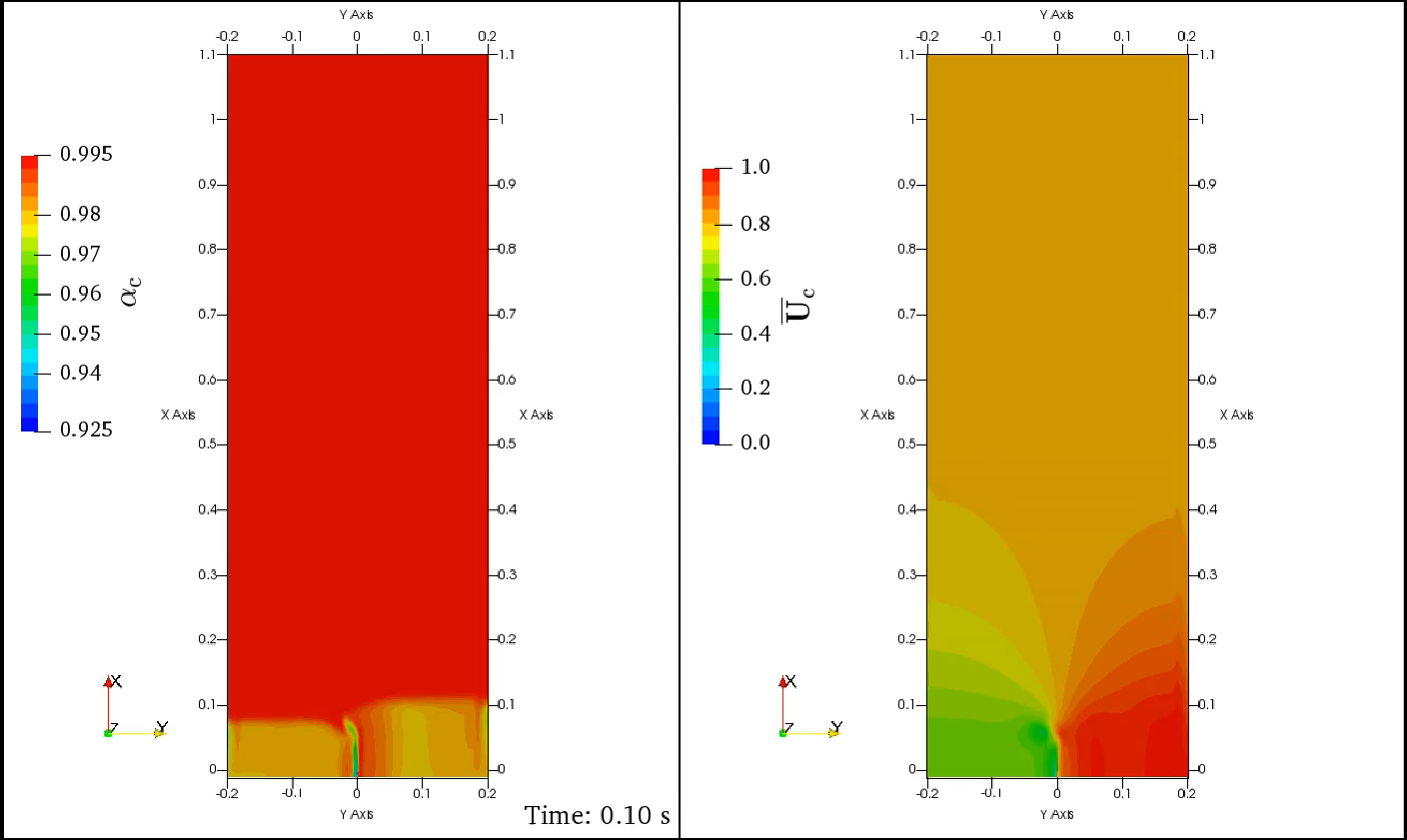
Validation - bubbly flow

Out of scope! Sorry!

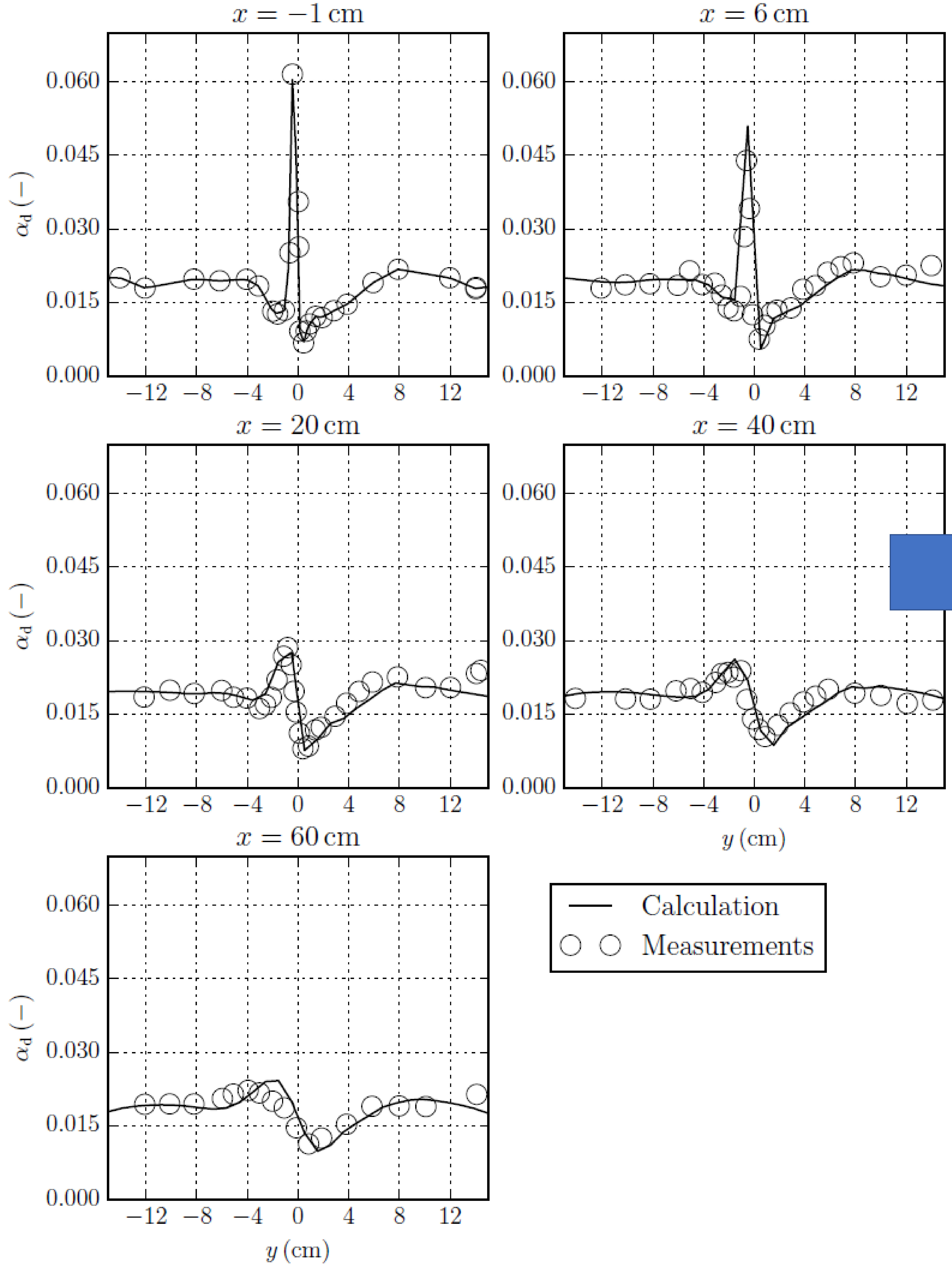


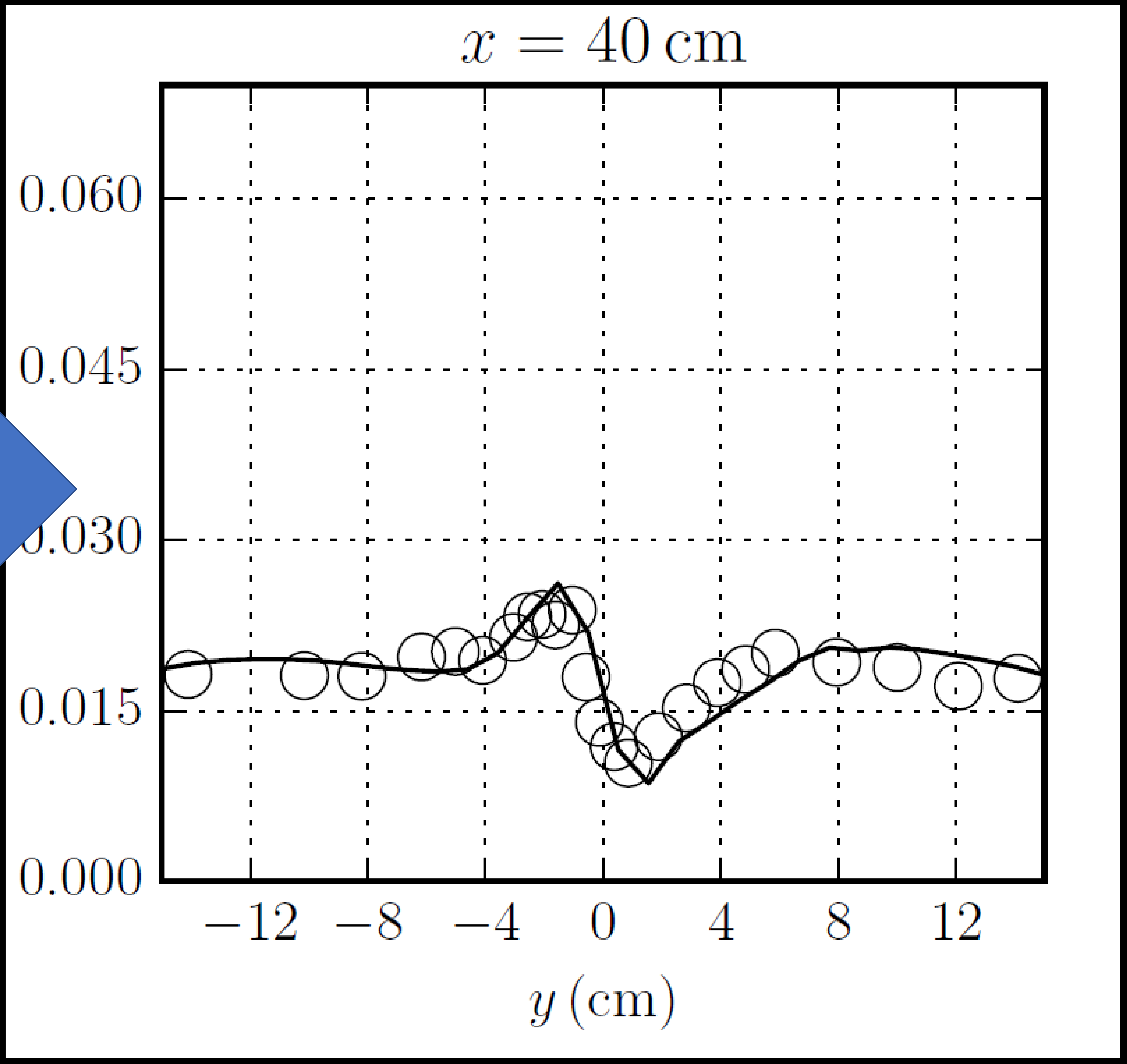


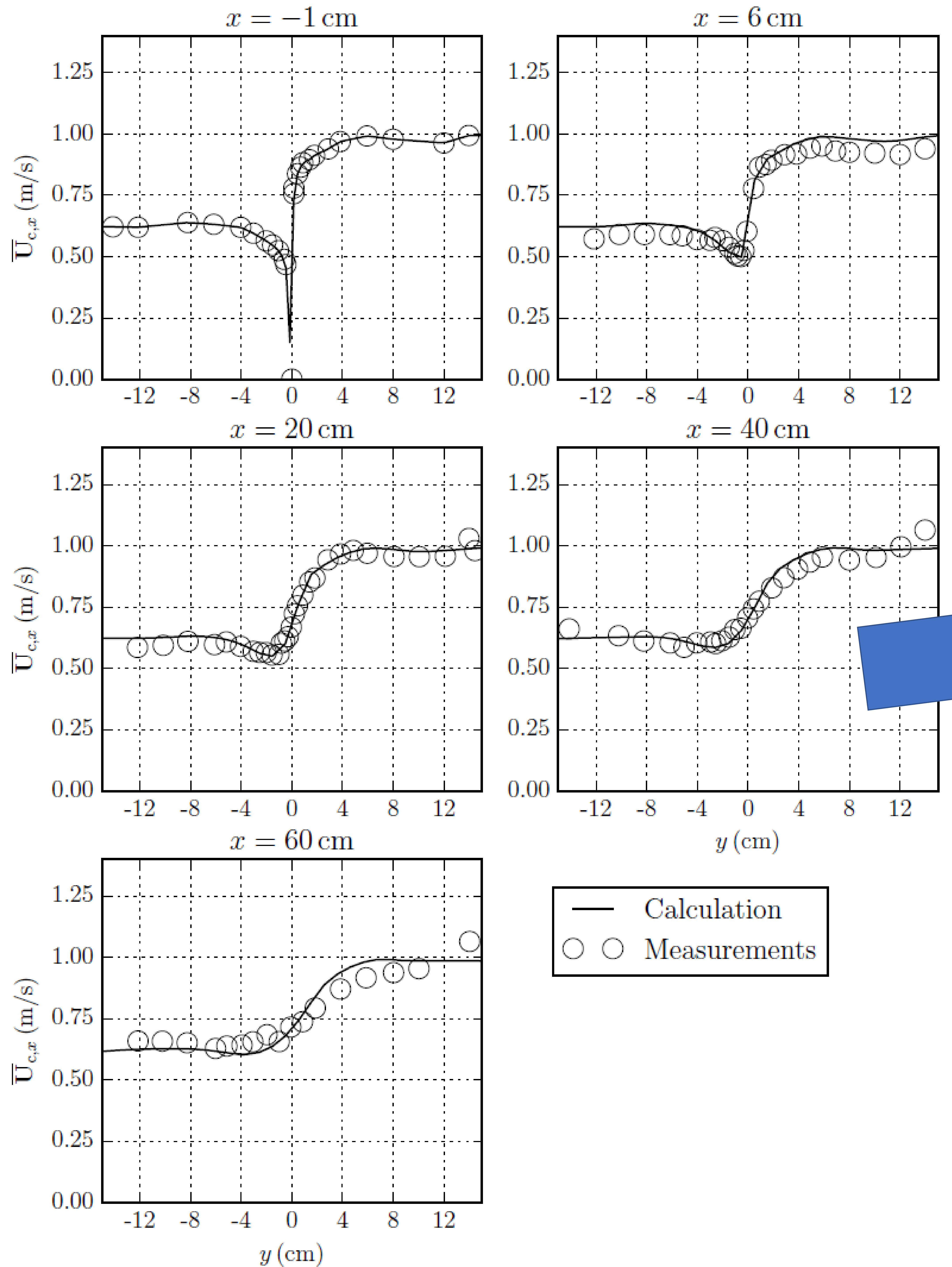
y-direction
-20
-10
0
10
20
110
Outlet
Outer walls
60
x = 60 cm
x-direction
40
x = 40 cm
20
x = 20 cm
Inlet
6
x = 6 cm
-1
x = −1 cm
Splitter

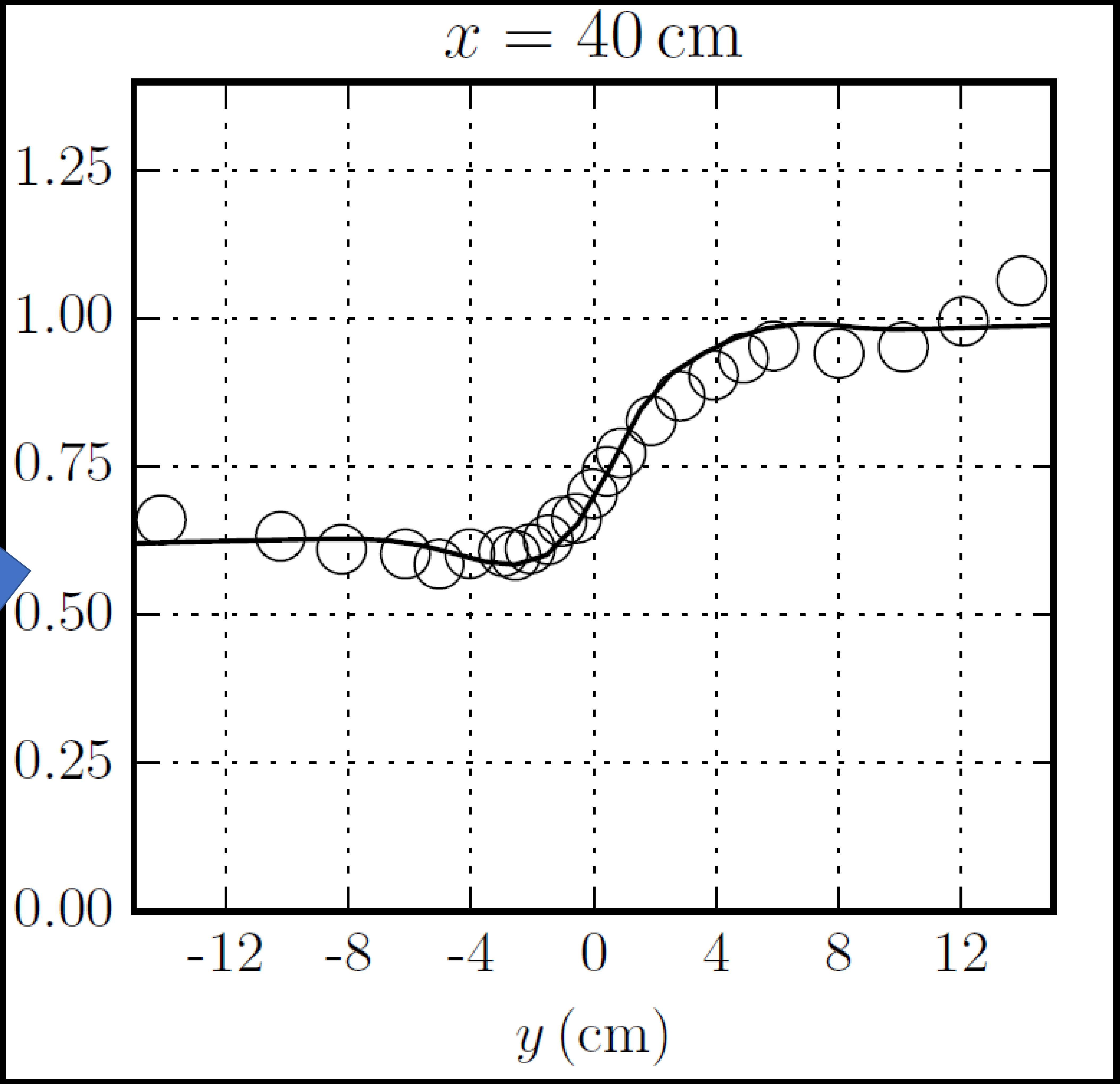


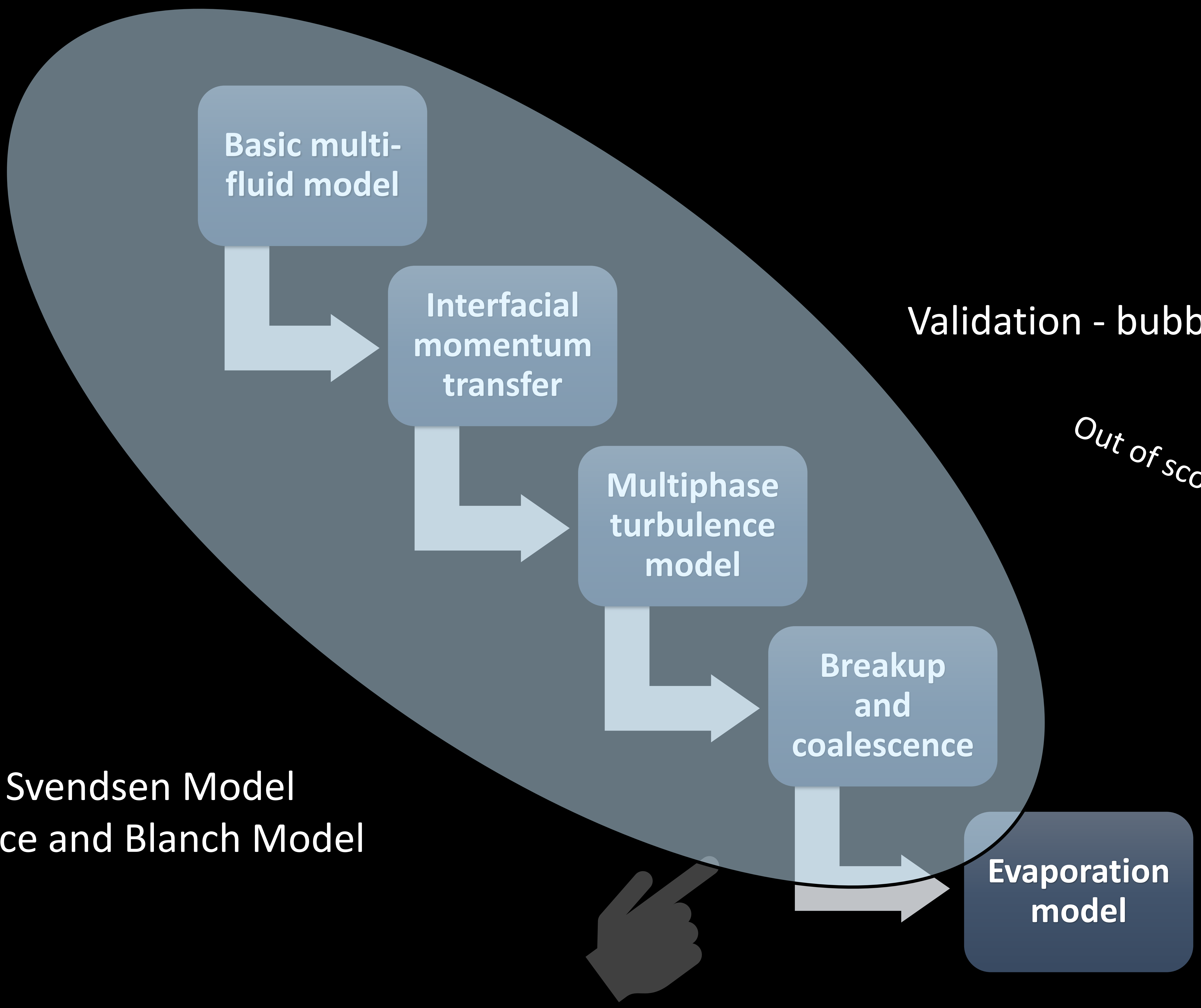
Y Axis
X Axis
0.995
0.98
0.97
0.96
0.95
0.94
0.925
αc
1.0
0.8
0.6
0.4
0.2
0.0
Uc
Time: 0.10 s


$x = -1$ cm
$x = 6$ cm
$x = 20$ cm
$x = 40$ cm
$x = 60$ cm
α_d (−)
0.000
0.015
0.030
0.045
0.060
−12 −8 −4 0 4 8 12
y (cm)
Calculation
Measurements


$x = 40$ cm
0.000
0.015
0.030
0.045
0.060
−12 −8 −4 0 4 8 12
y (cm)


x = −1 cm
x = 6 cm
x = 20 cm
x = 40 cm
x = 60 cm
U̅c,x (m/s)
y (cm)
Calculation
Measurements


x = 40 cm
y (cm)

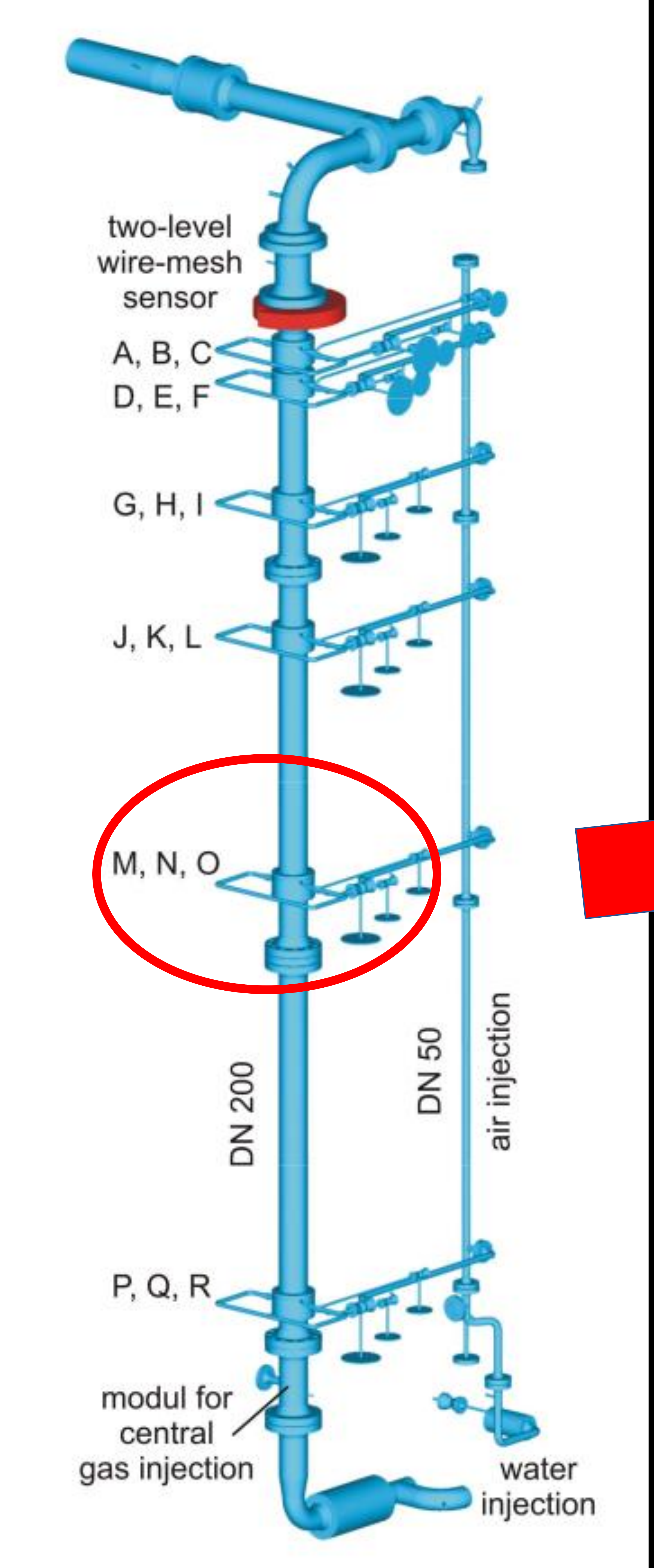


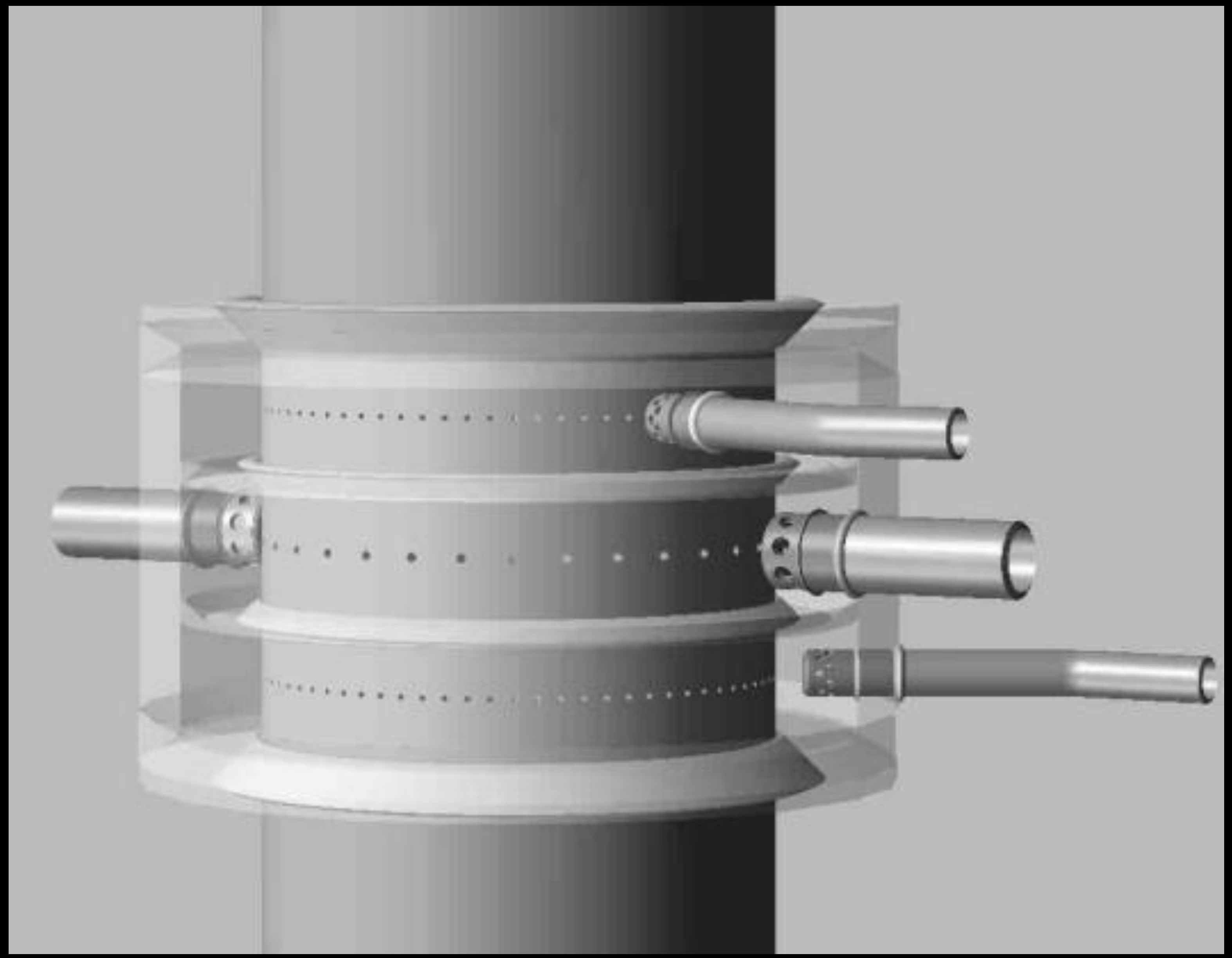
Validation - bubbly flow

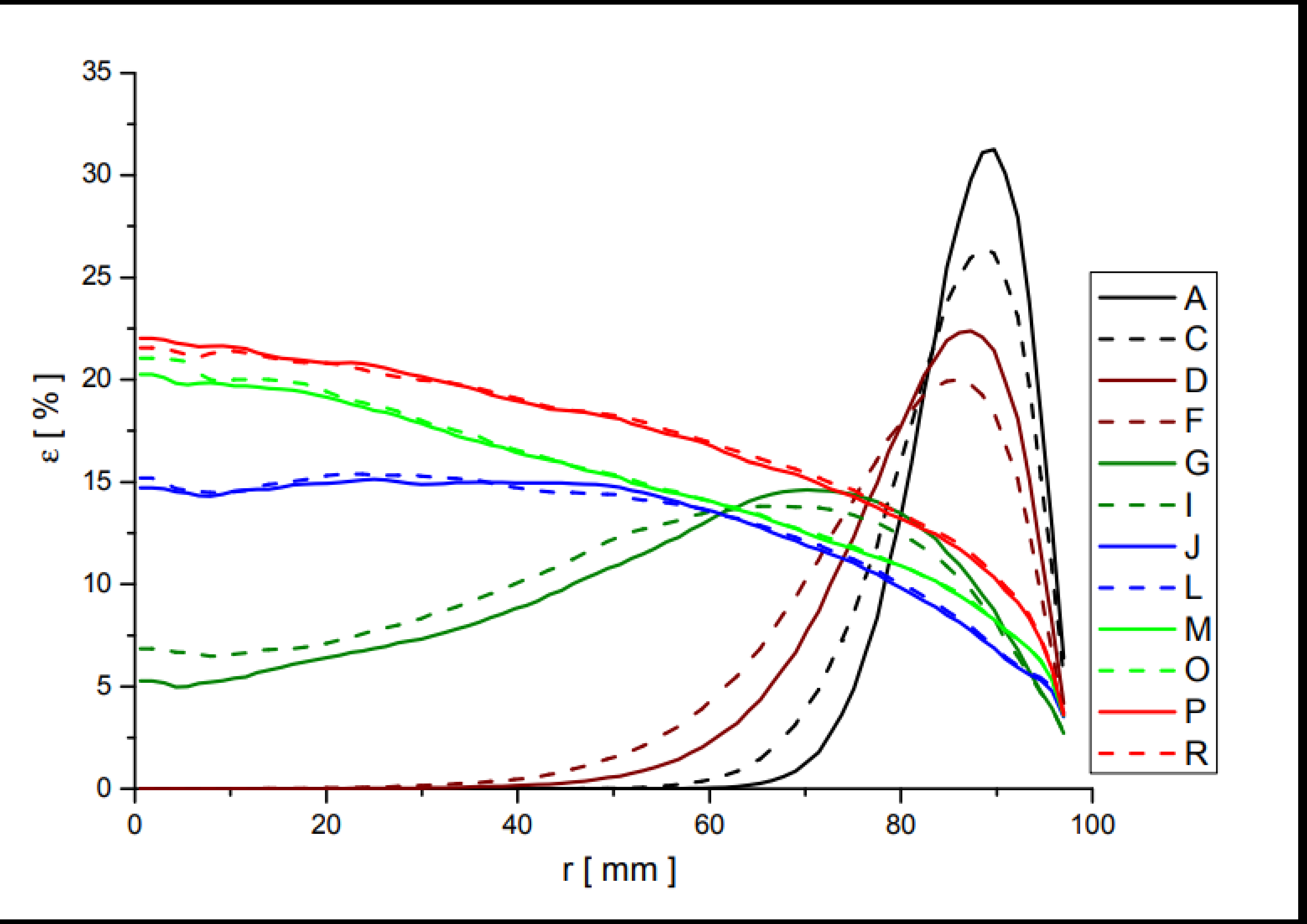
Out of scope! Sorry!

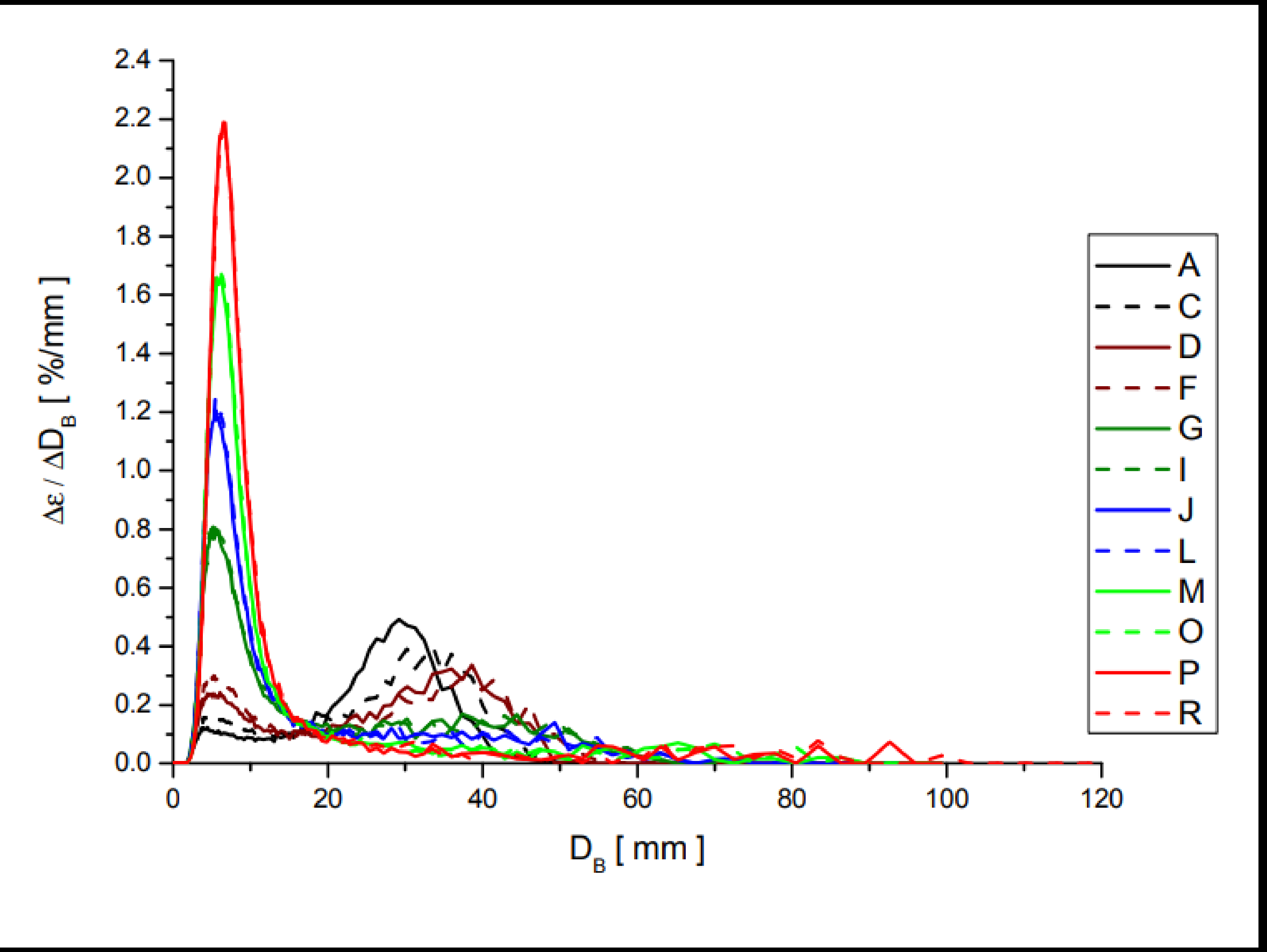
Breakup: Luo and Svendsen Model
Coalescence: Prince and Blanch Model

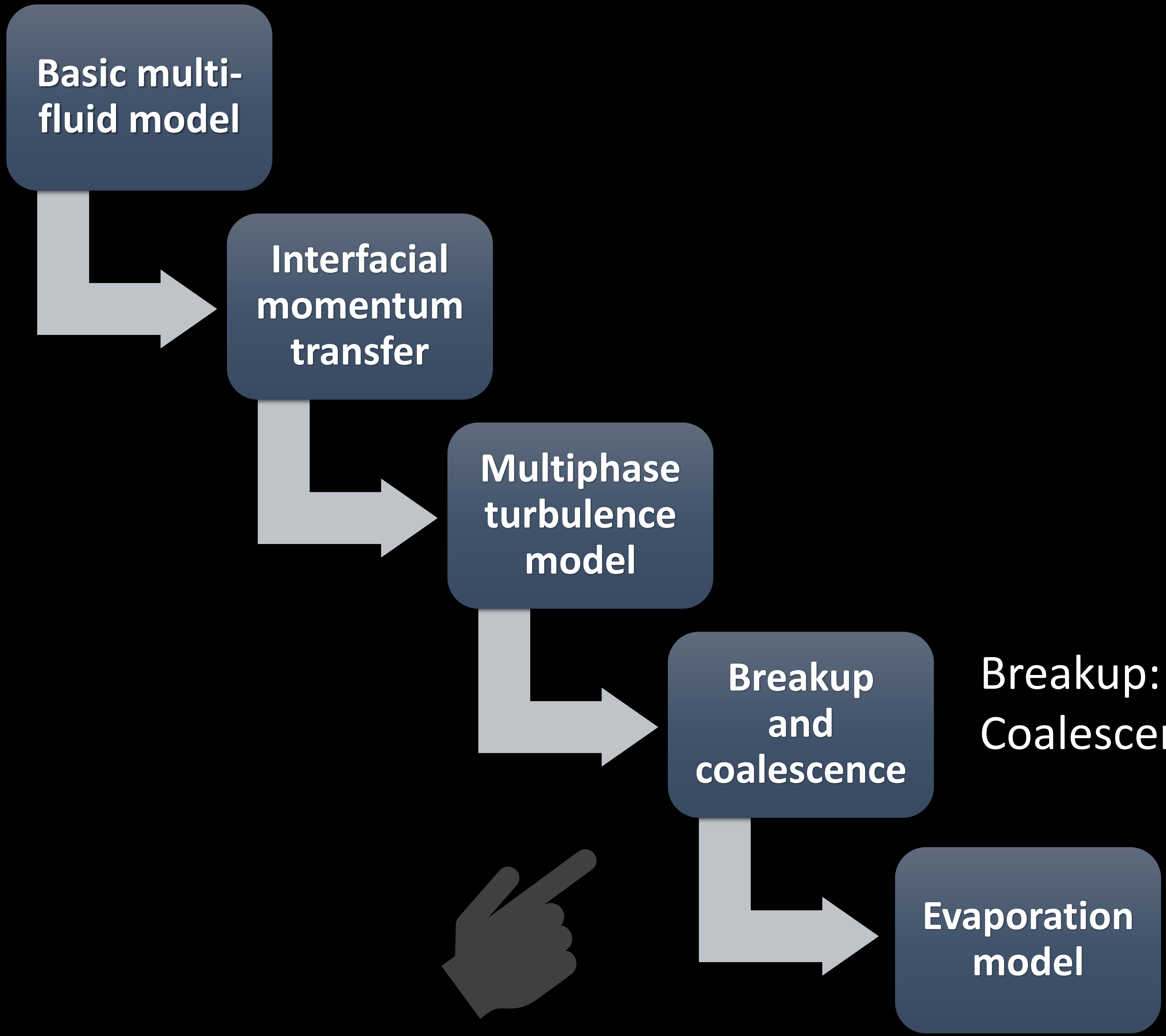
TOPFLOW (**T**ransient Tw**o** **P**hase **Flow** Test Facility.)



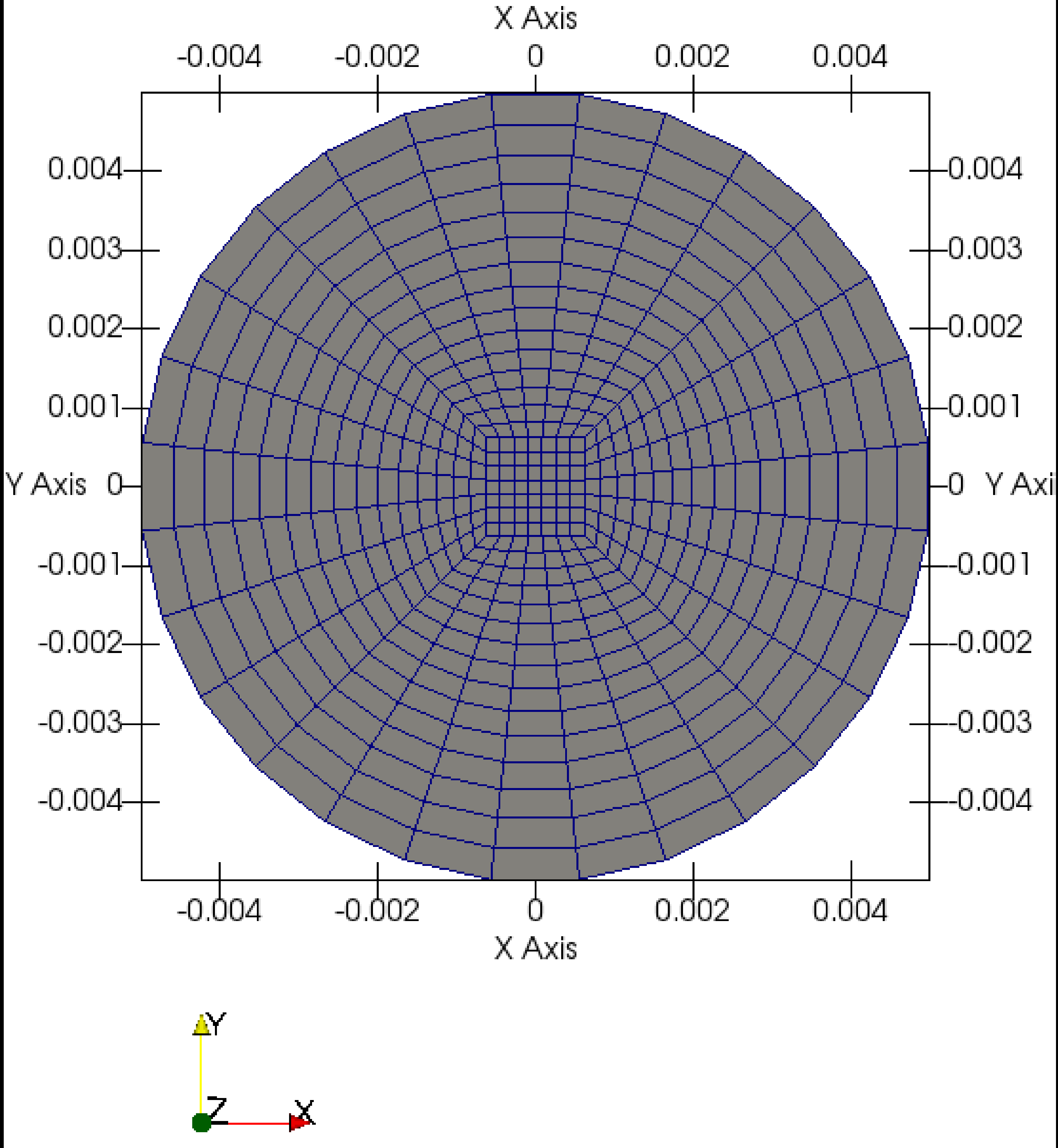


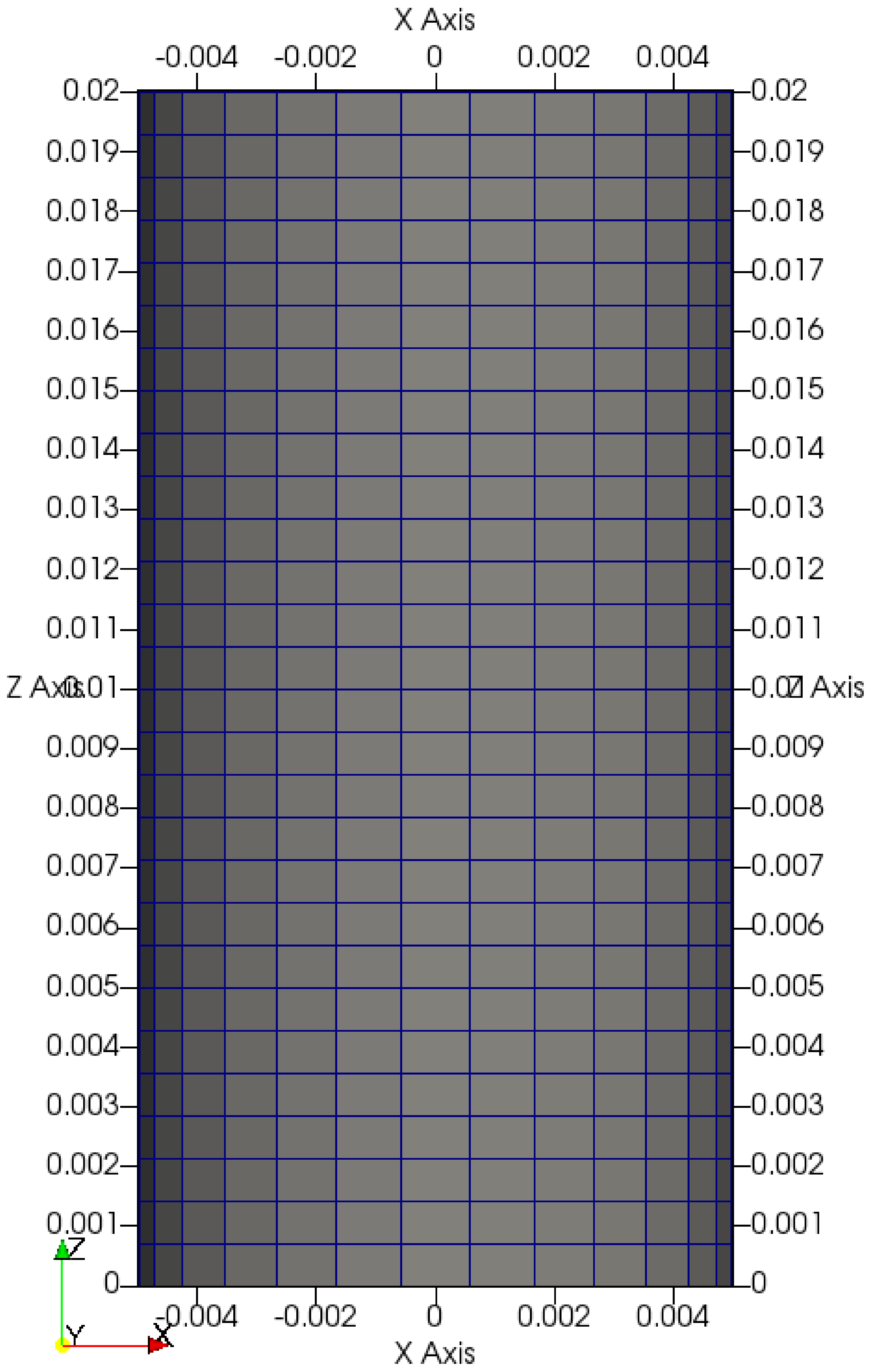

ε [%]
r [mm]
A
C
D
F
G
I
J
L
M
O
P
R

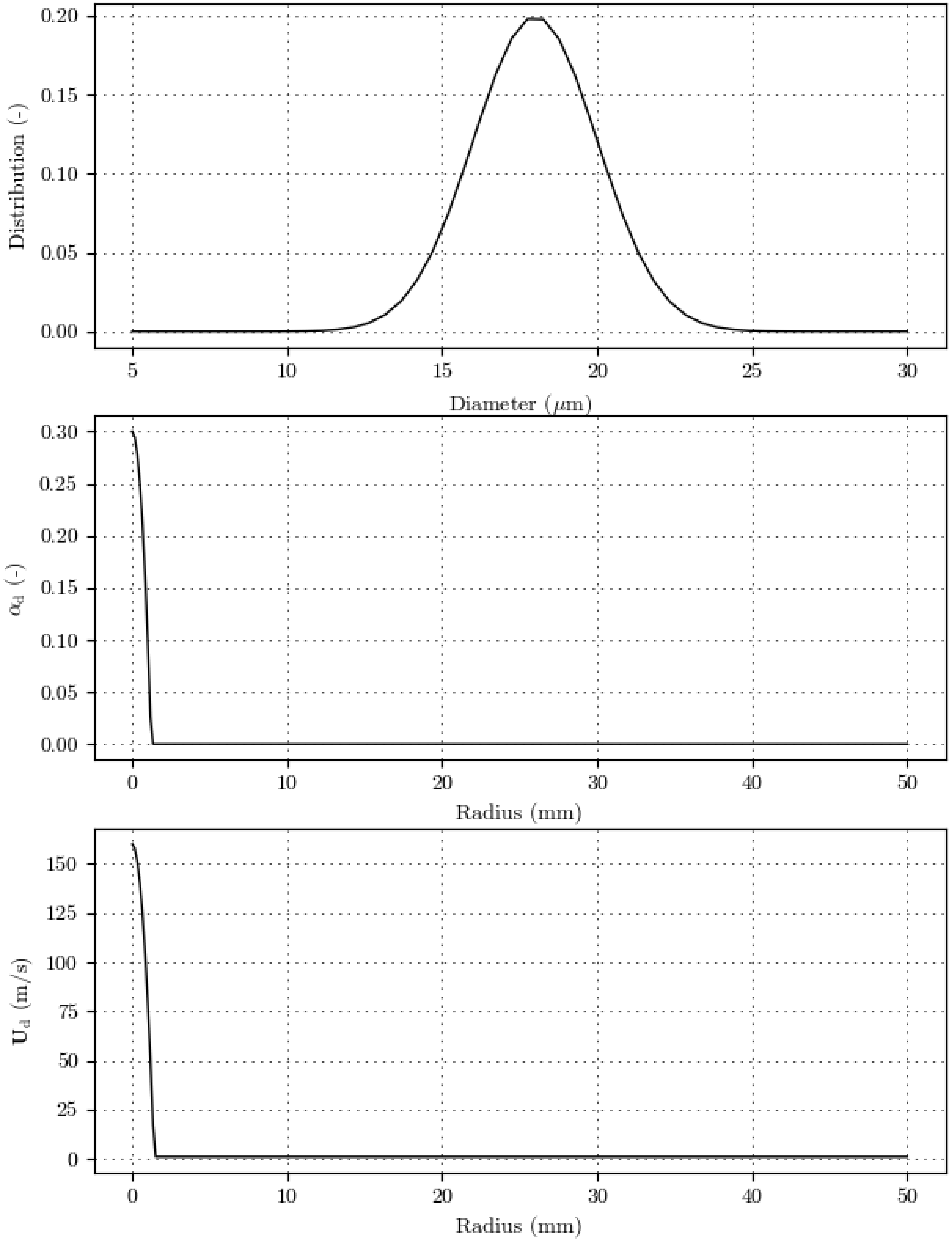

Δε / ΔD_B [%/mm]
D_B [mm]
A
C
D
F
G
I
J
L
M
O
P
R



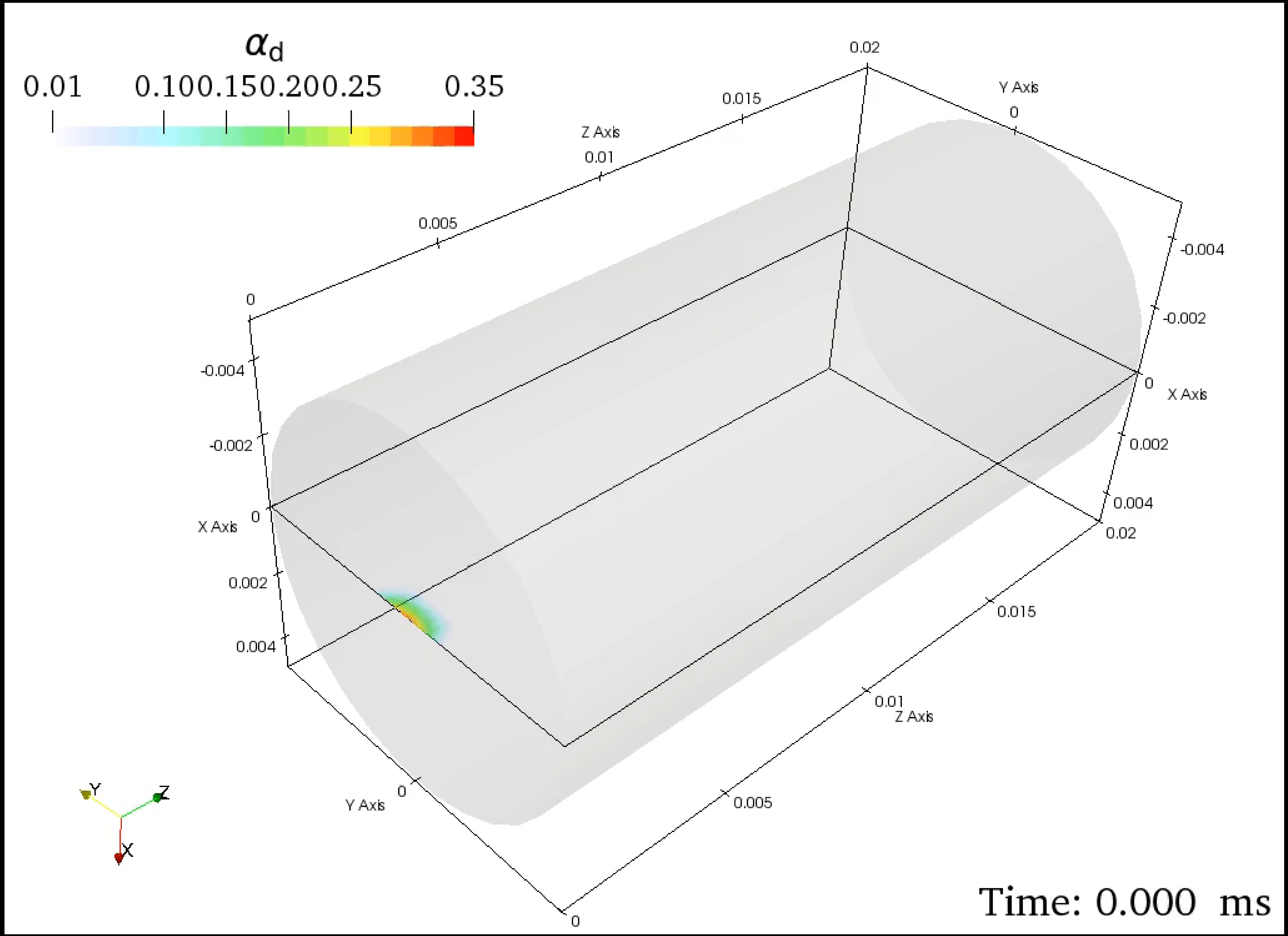
Breakup: ~~Luo and Svendsen Model~~
Coalescence: Coulaloglou and Tavlarides model

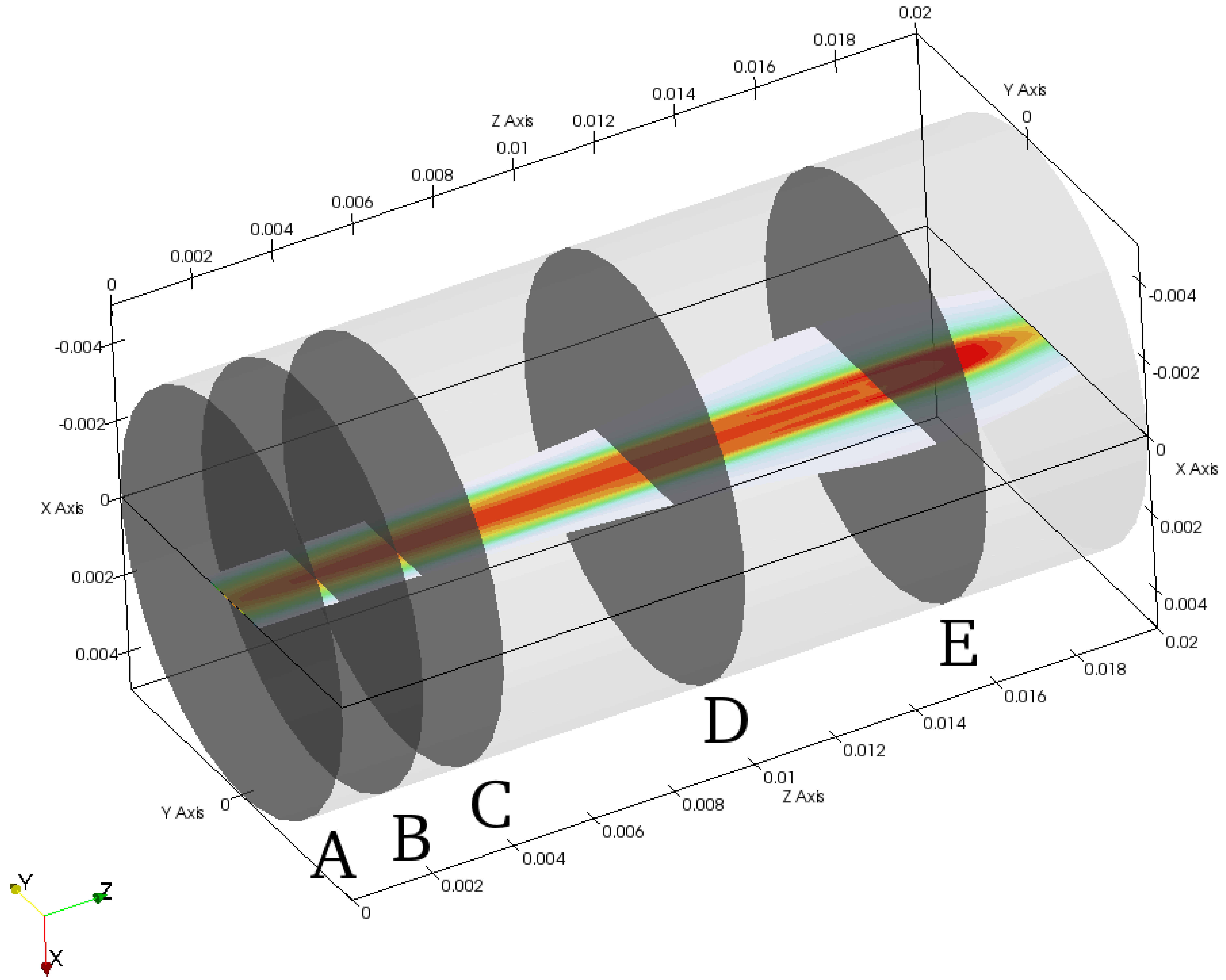

X Axis
-0.004
-0.002
0
0.002
0.004
Y Axis
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004
Y
Z
X

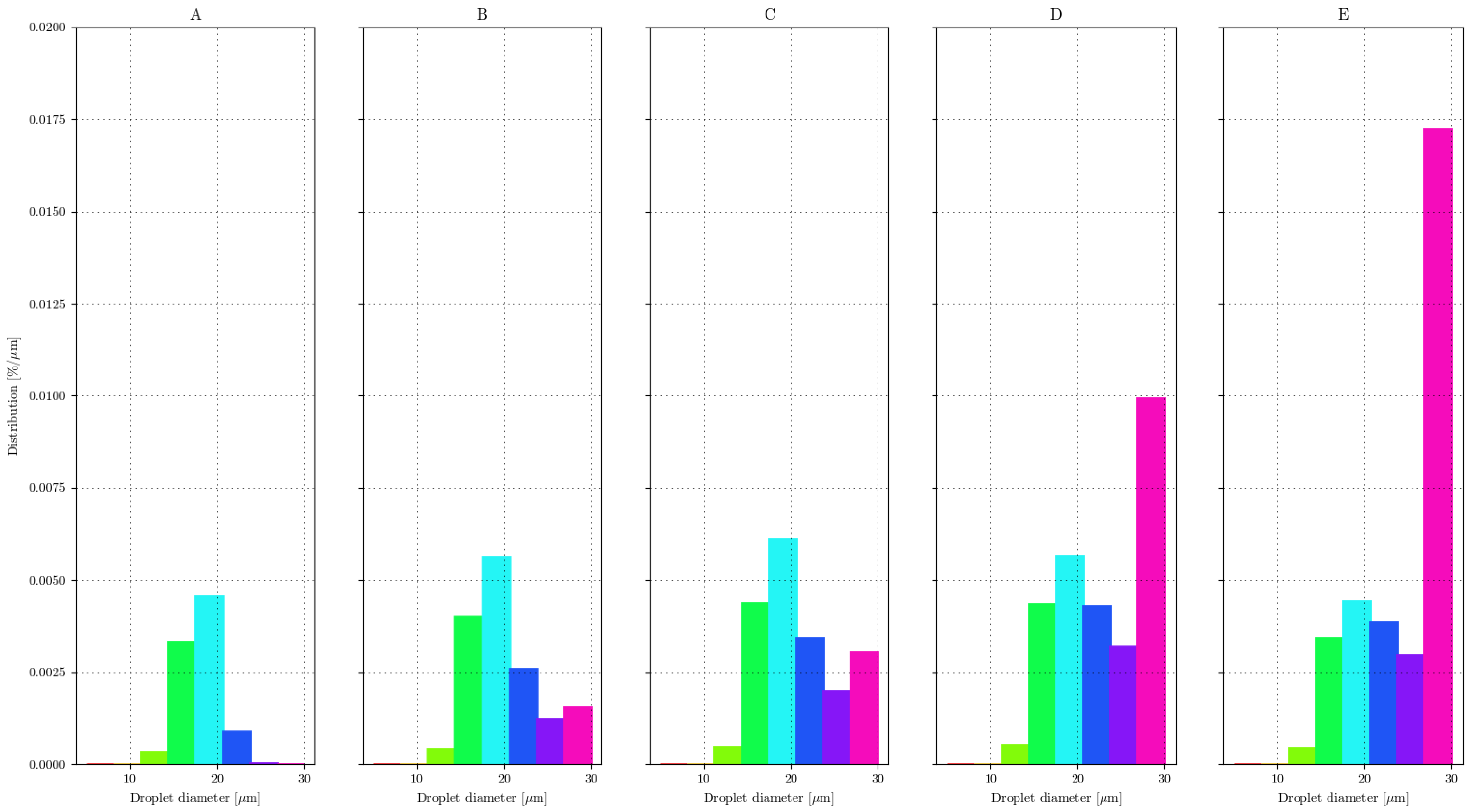

X Axis
-0.004
-0.002
0
0.002
0.004
Z Axis
0.02
0.019
0.018
0.017
0.016
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Z
Y
X

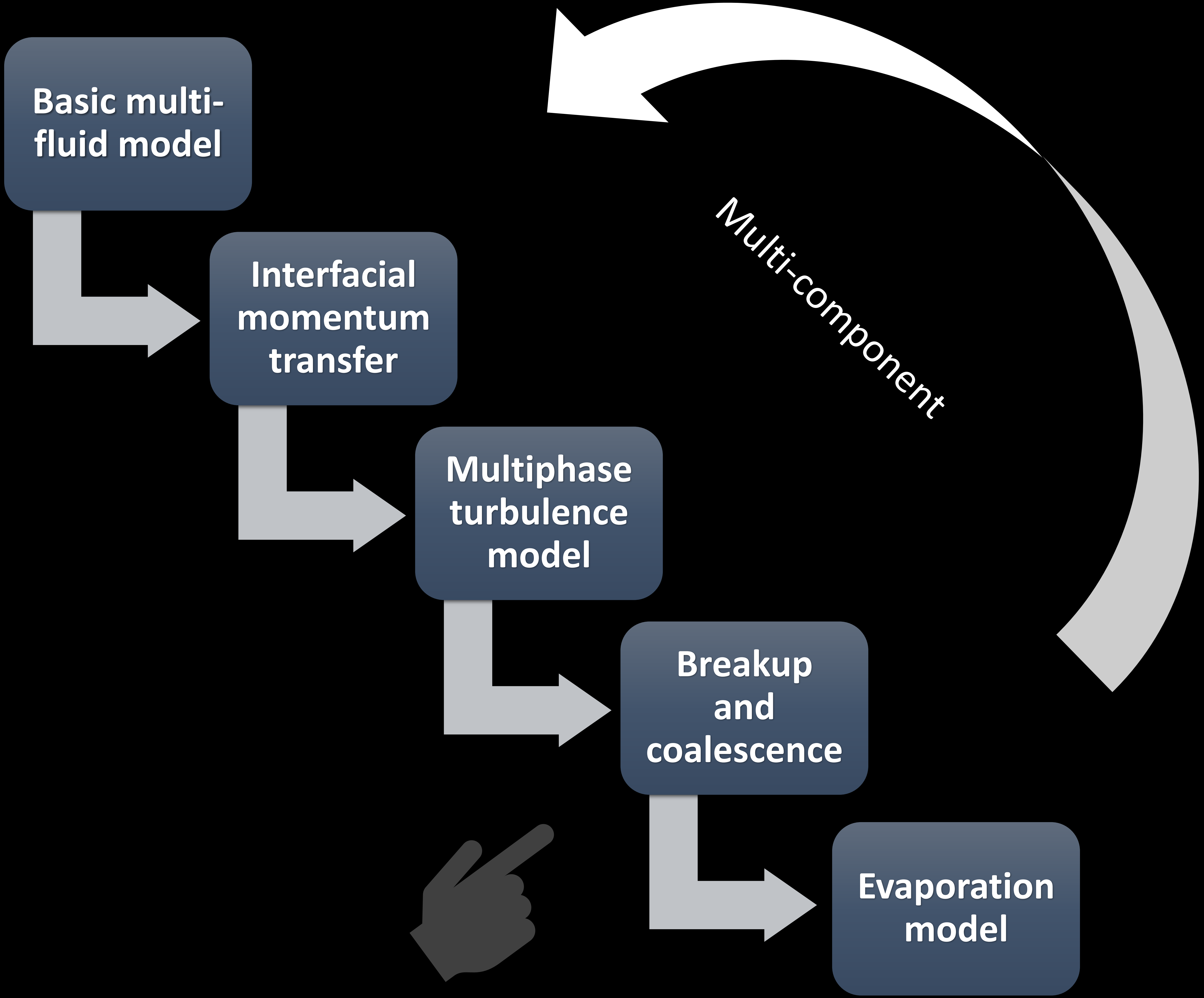


0.20
0.15
0.10
0.05
0.00
Distribution (-)
5
10
15
20
25
30
Diameter (μm)
0.30
0.25
0.20
0.15
0.10
0.05
0.00
α_d (-)
0
10
20
30
40
50
Radius (mm)
150
125
100
75
50
25
0
$\mathbf{U}_d$ (m/s)
0
10
20
30
40
50
Radius (mm)


α_d
0.01 0.100.150.200.25 0.35
Z Axis
Y Axis
X Axis
0.02
0.015
0.01
0.005
0
-0.004
-0.002
0.002
0.004
Y
Z
X
Time: 0.000 ms


Z Axis
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
Y Axis
X Axis
-0.004
-0.002
0.002
0.004
A
B
C
D
E
Y
Z
X


A
B
C
D
E
Distribution [%/μm]
0.0200
0.0175
0.0150
0.0125
0.0100
0.0075
0.0050
0.0025
0.0000
10
20
30
Droplet diameter [μm]


Basic multi-fluid model
Interfacial momentum transfer
Multiphase turbulence model
Breakup and coalescence
Evaporation model
Multi-component

Acknowledgements

- King Abdullah University of Science and Technology OSR-2017-CRG6-3409.03
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Questions?

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