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Two phase Modeling of Turbulent Flow in a Nozzle with Gas Pockets and Bubbles

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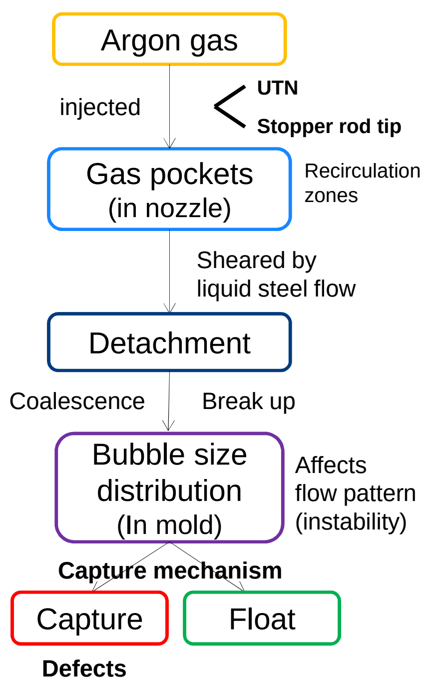
Motivation



- **Multiphase flow** comes into the picture when argon gas is injected through **UTN** or **stopper rod tip**.
- **Bubble size distribution** is important:
  - **Flow pattern** is affected by bubbles.
  - Small bubbles could be **captured** on solidified shell.
- Computational model is a valuable tool to understand the phenomenon.

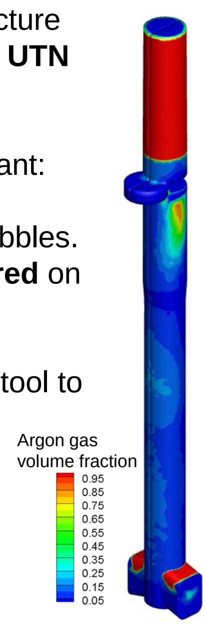


Fig 1. Gas volume fraction distribution in slide-gate system

Overall classification of Two phase flow : Continuum

Quasi – multi phase methods

Algebraic-Slip mixture model (Thomas et al,1994)

Treat bubbles as species that is diffused into continuous phase

C × 1 + NS × 1 + SD × 1

Mixture model (Fluent manual)

Track secondary phase through VF equation and use weighted averages for material & fluid properties (=mixture property)

C × 1 + NS × 1 + VF × 1

Multi-fluid methods

Eulerian-Eulerian model (Fluent manual)

Treat both fluids as continuous phase

C × 2 + NS × 2

Population balance model

- Homogeneous MUSIG (Lo, 1996)

Coalescence and breakup between bubbles are considered by solving Boltzmann equations

C' × (number of bubble sizes + 1) + NS × 2

- Inhomogeneous MUSIG (Krepper, 2007)

Allow to have different velocity fields between bubbles

C' × {(number of bubble sizes + 1) × number of velocity groups)} + NS × (number of velocity groups+1)

Interface capture / tracking methods

Interface capture

Mesh surface is attached to interface (move together with fluid)

- Moving grid method (Liu et al, 2014)
  - Moving a single grid line to match interface (Muzaferija & Peric, 1997)
  - Moving other grids for good mesh quality (Fluent manual)
- SPINE method (FIDAP manual)

Interface tracking

- Marker and cell (MAC) (Harlow et al, 1965)

Add massless particles as markers on secondary fluid and track them

C × 1 + NS × 1 + P × number of markers

- Surface marker (Chen, 1991)

Add massless particles as markers on interface and track them

C × 1 + NS × 1 + P × number of markers

- Volume of Fluid (Hirt & Nichols, 1981)

An Interface is defined as boundary of volume fraction between 0 and 1

C × 1 + NS × 1 + VF × 1

- Level set method (Osher & Sethian, 1988)

Define interface as interface function and track it through transport equation C × 1 + NS × 1 + I × 1

C: continuity
NS: Navier-Stokes
N: Newton's equation of motion
C': modified continuity equation
SD: Species diffusion equation
VF: volume fraction transport equation
I : interface transport equation
P : particle trajectory equation

Overall classification of Two phase flow: Discrete

Particle based methods

Discrete phase model (DPM) (Hoomans et al, 1996)

Treat liquid as continuum, but bubbles as particles and track all by Newton's equation of motion

C × 1 + NS × 1 + (N+P) × (number of bubbles and/or inclusions)

Smooth particle hydrodynamics (SPH) (Lucy,1977)

Hybrid model between continuum model and discrete model : solve continuum PDEs for both phases using discrete particles by substituting the spatial derivatives to interpolation functions of neighbor particles.

{C×1 + NS×1 + E×1 + (P+N) ×1} × (number fluid particles)× 2(phase)

Lattice-Boltzmann method (LBM) (Shan & Chen, 1993)

Solve Boltzmann equations for fluid particle distribution functions of each phase.

B× 2(phase)

Dissipative Particle Dynamics (DPD) (Groot and Warren, 1997)

Track each fluid particles (a particle = a group of molecules) using Newton's equation of motion.
(A coarse-grained version Molecular Dynamics)

{(P+N) ×1 × number of particles} × 2(phase)

Scale	Method	Liquid	Gas
Macro-scale	DPM	continuum (grid-based)	particle (no grid)
	SPH	particle (no grid)	particle (no grid)
Meso-scale	LBM	particle (grid-based)	particle (grid-based)
	DPD	particle (no grid)	particle (no grid)
Molecule-scale	MD	particle (no grid)	particle (no grid)

Molecular Dynamics (MD) (Alder and Wainwright, 1959)

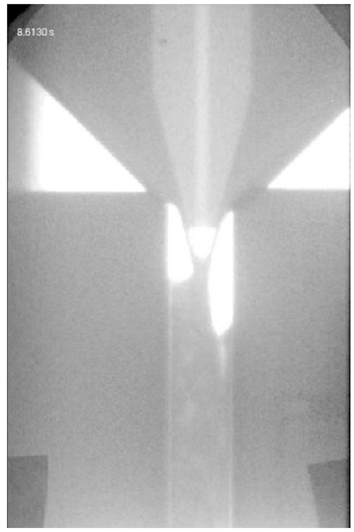
Track all molecules of each fluid using Newton's equation of motion

{(P+N) ×1 × number of particles} × 2(phase)

C: continuity
NS: Navier-Stokes
E : equation of state
N: Newton's equation of motion
B: Boltzmann equation
NS': discrete version NS equation
C': discrete version continuity
I : interface transport equation
P : particle trajectory equation

Objectives

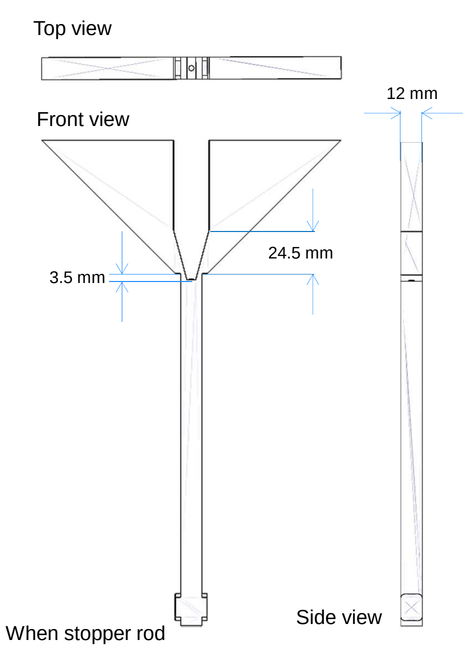
- Test **several multiphase models** by benchmarking **Dresden experiment** (Timmel et al., 2014).
  - 1D pressure energy model (analytical model)
  - Single phase model
  - Eulerian Eulerian model
  - VOF model
- Compare the numerical results with experiment data.
  - Pressure distribution in nozzle
  - Gas pocket shape
- Check pros and cons of each method.



Video from Dresden

Geometry of Dresden experiment

- Geometry (Timmel et al., 2014)



When stopper rod position = 9.5 mm

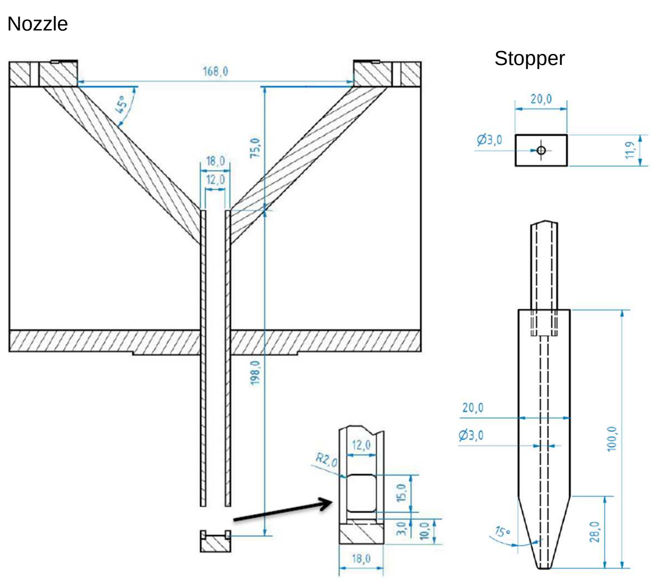


Fig 2. Blueprint of Dresden experiment geometry

Operating condition

Operating condition	Values
Operating temperature T_{op}	room temperature 293 K
Stopper rod position	9.5 mm
Tundish level	70 mm
Galinstan flow rate Q_l	115 cm^3/s
Argon gas flow rate Q_{gas}	1.7 cm^3/s
Submergence depth h_{sub}	92 mm
Wall roughness	Smooth wall (acrylic)
Gas volume fraction α	1.4 %

Material property	Values
Galinstan density ρ_l	6440 kg/s (~92% of liquid steel)
Galinstan viscosity μ_l	0.0024 Pas (~40% of liquid steel)
Galinstan surface tension	0.718 N/m (~58% of liquid steel)
Contact angle	120 deg (non-wetting) (~80% of liquid steel)
Argon gas density ρ_g	1.6228 kg/s
Argon gas viscosity μ_g	2.125× 10^{-5} Pas

Ref.: Geratherm Medical AG manual(2002)
Karcher et al. (2003)

Gas volume fraction calculation (Thomas et al., 1994)

$$H_f = \frac{P_{atm}}{P_{port}} \times \frac{T_{op}}{T_\infty}$$

P_{atm}: atmosphere pressure (101325 Pa)
T_∞: room temperature (293 K)
P_{port} : pressure at port ($= \rho_l\, g h_{sub}$)

$$\alpha = \frac{Q_{gas} H_f}{Q_{gas} + Q_l} \cong 1.4\%$$

1. 1D pressure energy model: Pressure distribution

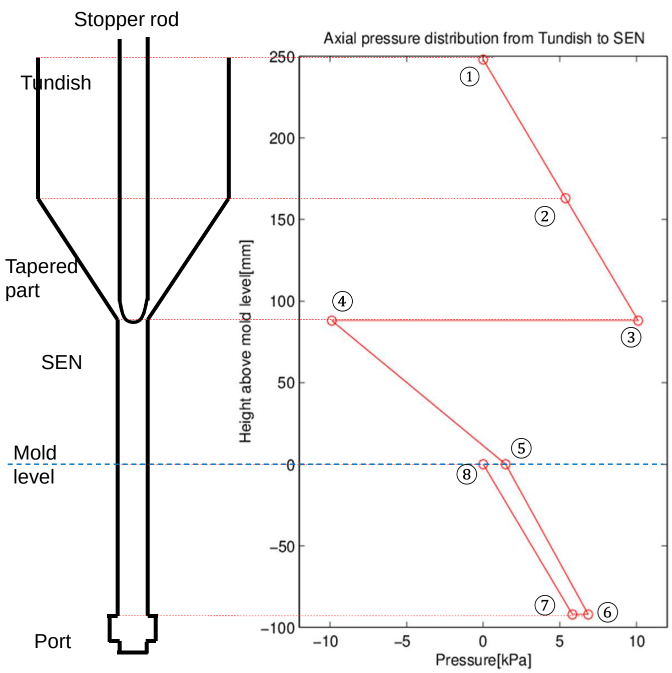


Fig 3. Axial pressure distribution in stopper rod system

① $P_1 = 0$
② $P_2 = P_1 + \rho_l g z_{12}$
③ $P_3 = P_2 + \rho_l g z_{23}$
④ $P_4 = P_3 - \rho_l e_{L_{stopper}} - \frac{1}{2}\rho_l {V_{gap}}^2$
⑤ $P_5 = P_4 - \frac{1}{2}\rho_l {V_{SEN}}^2 f \frac{z_{45}}{D_{SEN}} + \frac{1}{2}\rho_l {V_{gap}}^2 - \frac{1}{2}\rho_l {V_{SEN}}^2$
⑥ $P_6 = P_5 - \frac{1}{2}\rho_l {V_{SEN}}^2 f \frac{z_{56}}{D_{SEN}}$
⑦ $P_7 = P_6 - \rho_l e_{L_{elbow}}$
⑧ $P_8 = P_7 - \rho_l g z_{87}$

P_x : gage pressure at the point x
ρ_l : Galinstan density
A_{SEN} : cross-section area of SEN
V_{SEN} : velocity in SEN
V_{gap} : velocity in stopper rod gap
$z_{ab} = z_a - z_b$
f : friction factor (=0.027)
g : gravity acceleration
D_{SEN} : SEN diameter

Q_l : liquid flow rate
ρe_{Lelbow} : pressure loss by elbow
C_1 : minor loss constant = 0.5
C_2 : stopper rod constant = 0.624
H_{SRO} : stopper rod position

$$V_{SEN} = \frac{Q_l}{A_{SEN}} \qquad V_{gap} = 2V_{SEN}$$
(from geometry)

$$\rho e_{L_{elbow}} = C_1 \frac{1}{2}\rho {V_{SEN}}^2$$
(White, 2011)

$$\rho e_{L_{stopper}} = \{0.5\left(\frac{A_{SEN}}{C_2 H_{SRO}^2}\right)^2 + \left(\frac{A_{SEN}}{C_2 H_{SRO}^2} - 1\right)^2\}\frac{1}{2}\rho {V_{SEN}}^2$$
(Liu et al., 2014)

2. Single phase flow: Numerical setup

- Boundary conditions

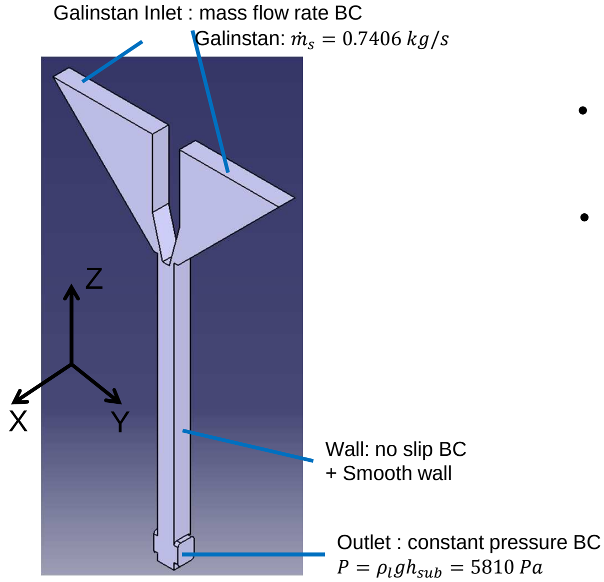


Fig 4. Boundary conditions of single phase flow simulation

- Turbulence model:
  - Standard $k-\varepsilon$ model
  - The law of the wall for boundary layers
- Mesh:
  - 60,000 cells (cell size: ~2mm)
- Numerical scheme:
  - Second order Upwind
  - Steady state simulation

2. Single phase flow: Numerical simulation result

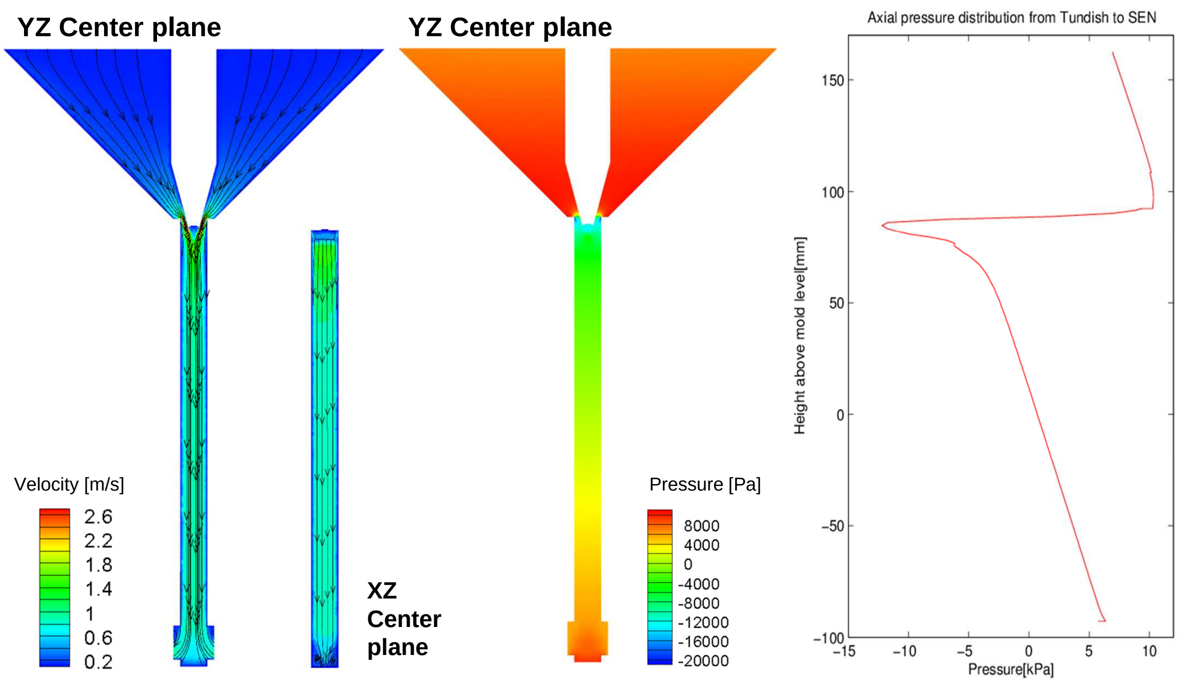


Fig 5. Velocity, pressure field and axial pressure distribution of single phase flow model result

2. Single phase flow: Comments

- Three recirculation zones are shown near SEN inlet :
    - Stopper tip, both side walls of SEN inlet.
    - Location matches to gas pocket positions in Dresden experiment.
- Recirculation zone at port is small due to short port length (3mm).
- As expected in 1D pressure energy model, sudden pressure drop happens at SEN inlet by stopper rod.
    - Minimum pressure happens at SEN inlet wall
        - Easiest place for gas accumulation.

3. Eulerian Eulerian model: Numerical setup

- Boundary conditions

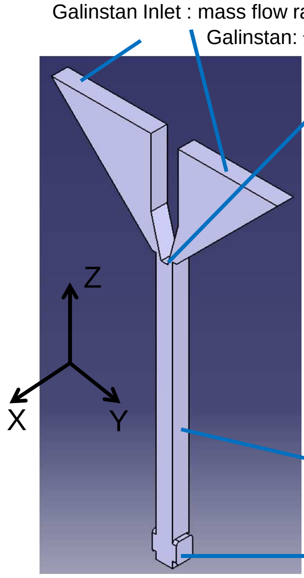


Fig 6. Boundary conditions of Eulerian Eulerian model simulation

- Two phase model:
    - Eulerian Eulerian model is used.
    - Bubble size : $d_{bubble} = 3\ mm$
    - Drag force : Schiller-Naumann model
- Turbulence model:
    - Standard $k - \varepsilon$ model for both phase
    - The law of the wall for boundary layers
- Mesh:
    - 60,000 cells (cell size: ~2mm)
- Numerical scheme:
    - Transient simulation (URANS)
    - Second order Upwind

3. Eulerian Eulerian model: Numerical simulation result

YZ Center plane

YZ Center plane

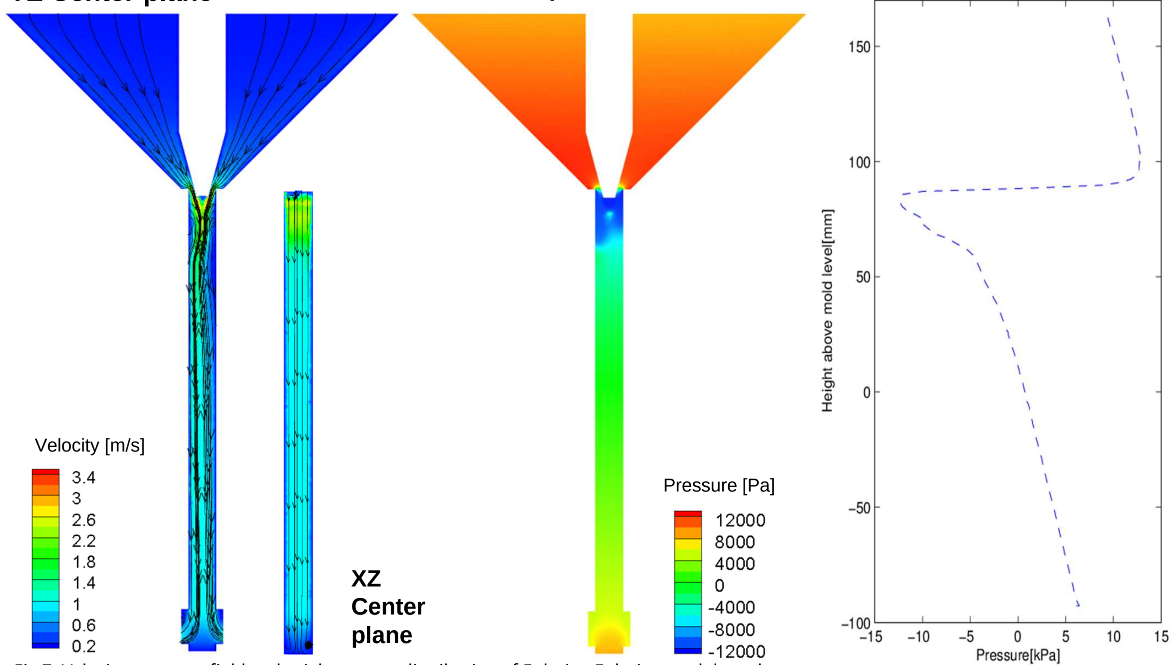


Fig 7. Velocity, pressure field and axial pressure distribution of Eulerian Eulerian model result

3. Eulerian Eulerian model: Numerical simulation result

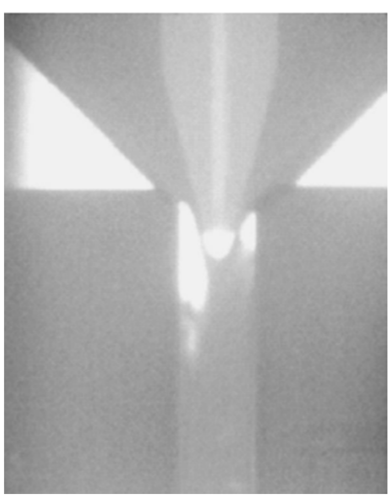
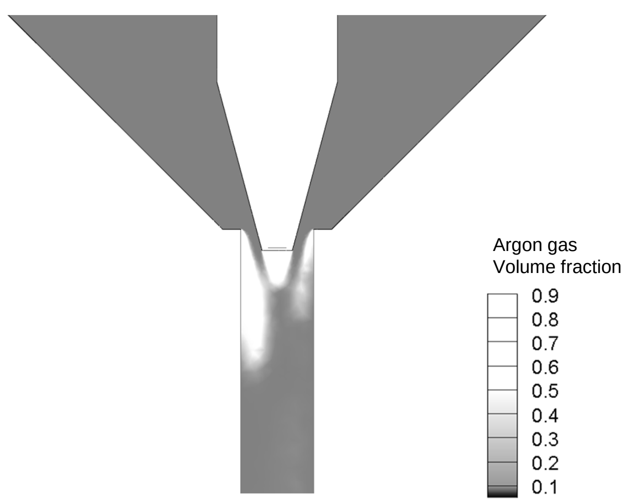


Figure from Timmel et al. (2014) Fig 4(a)



Projection view (from front) of volume fraction in Eulerian Eulerian model

Fig 8. Comparison of gas volume fraction from experiment (left) and Eulerian Eulerian model (right)

3. Eulerian Eulerian model: Comments

- Eulerian Eulerian two phase model with $k - \varepsilon$ turbulence model is able to capture three gas pockets (stopper tip, both SEN inlet side walls).
- Gas pocket size is determined by recirculation zone size and gas flow rate.
  - Deeper stopper rod position increases recirculation zones (more separation) → bigger gas pocket at stopper tip, thicker and shorter gas pockets at side walls (Timmel et al, 2014)
- Faster than VOF : efficient method if bubble size information is not necessary.
- Cannot resolve small bubble interface : no help to understand bubble size distribution.

Pressure distribution comparison

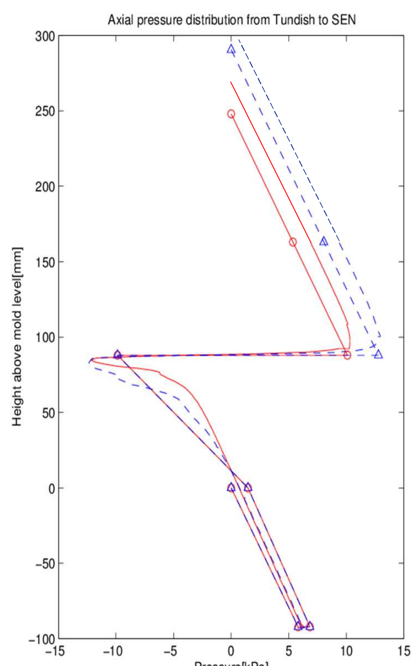
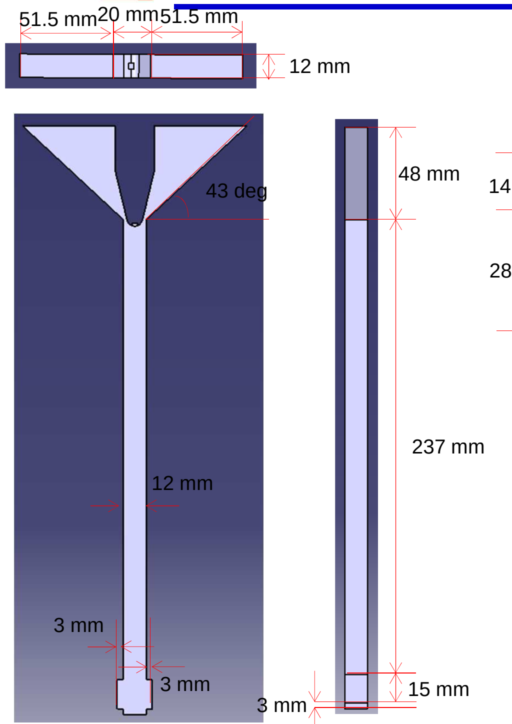


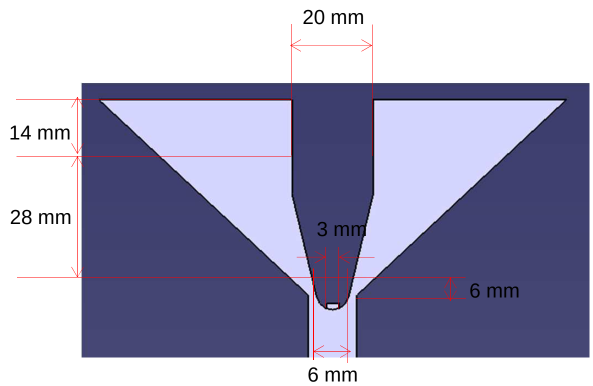
Fig 9. Comparison of axial pressure distribution from 1D analytical model, single phase model and Eulerian Eulerian model

Single phase numerical model
Single phase analytical model ($C_2 = 0.624$)
Two phase Eulerian Eulerian model
Two phase analytical model ($C_2 = 0.552$)

- Two phase flow requires higher tundish level.
- Analytical model results roughly match to single phase and Eulerian Eulerian model.

4. VOF model Computational domain





Geometry is slightly different to the Eulerian-Eulerian model case:
this geometry is estimated from picture on the paper (Timmel et al., 2014) before getting answer from Dresden.
(Especially, **57mm deeper submergence depth**)

4. VOF model: Numerical setup

- Boundary conditions

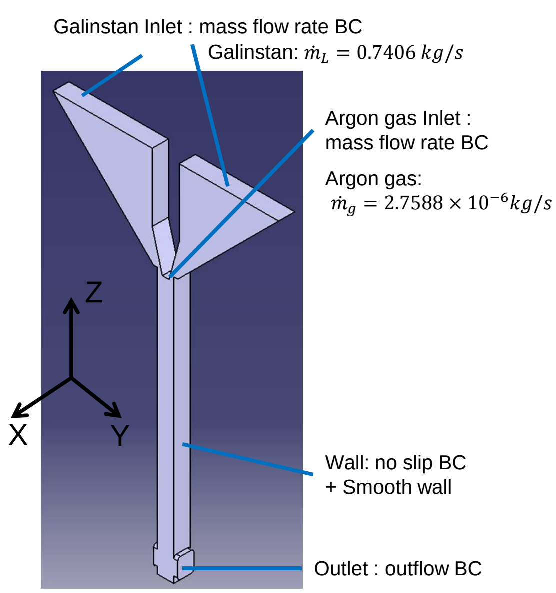


Fig 10. Boundary conditions of VOF model simulation

- Two phase model:
  - VOF model is used.
  - Surface tension is included. (continuous surface force model)
  - Explicit + Geometric reconstruction scheme
- Turbulence model:
  - Filtered URANS (SAS model) is used.
- Mesh:
  - 1 million cells (cell size: ~1mm)
  - Mesh refinement near SEN inlet
- Transient simulation
  - Time step : 10^{-5} second

4. VOF model: Numerical simulation result

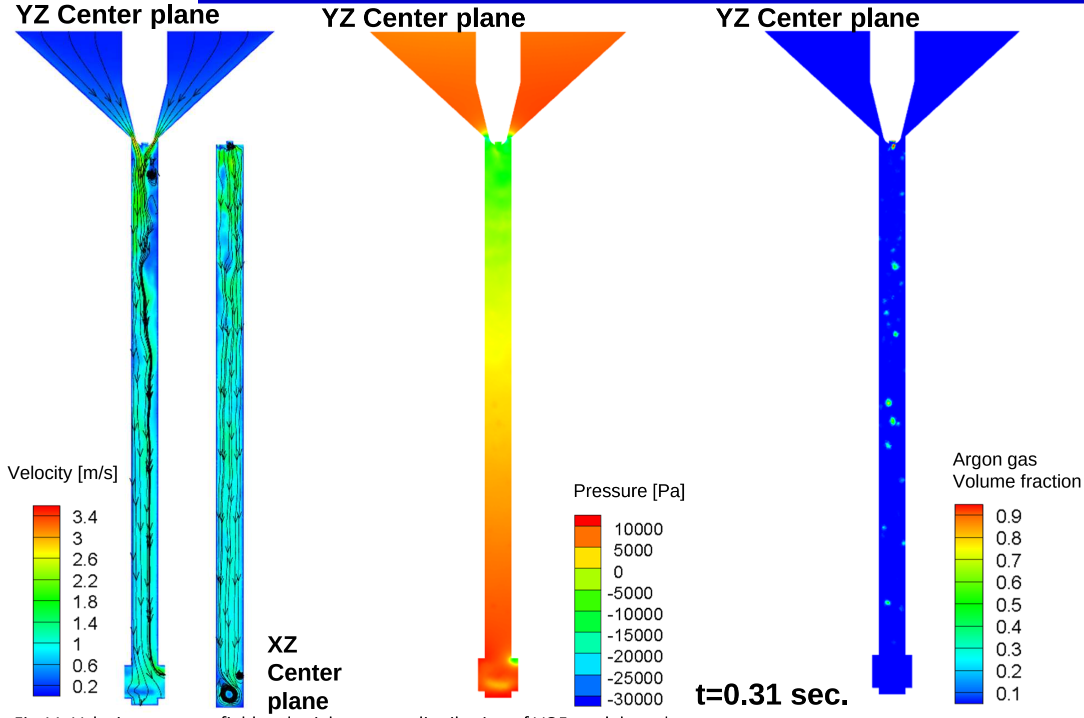
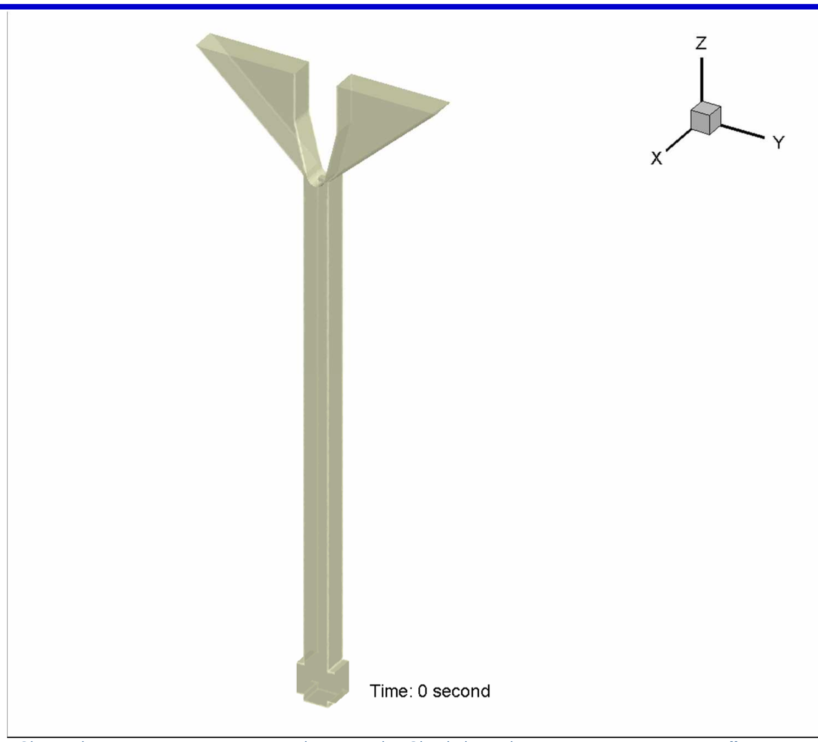
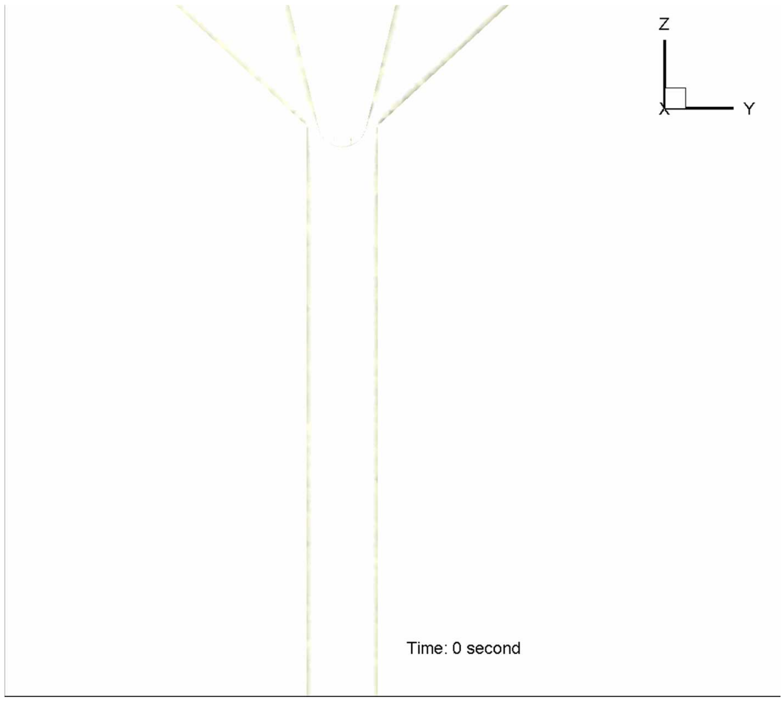


Fig 11. Velocity, pressure field and axial pressure distribution of VOF model result

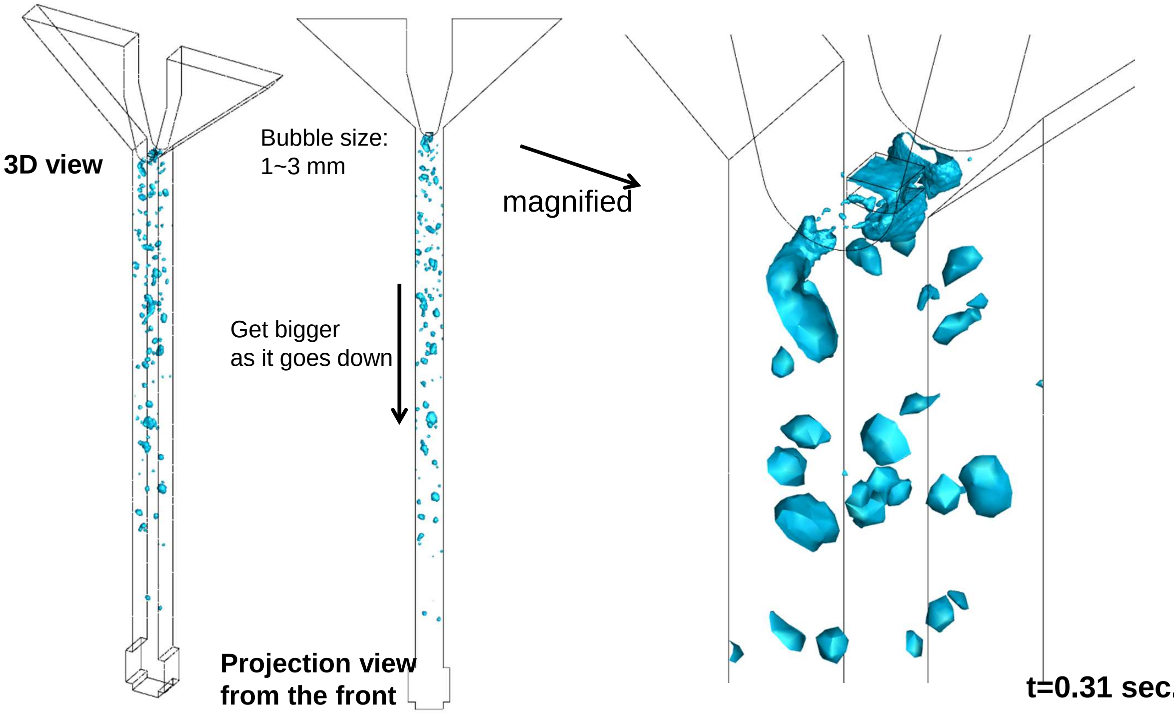
4. VOF model: Numerical simulation result



4. VOF model: Numerical simulation result



4. VOF model: Numerical simulation result



4. VOF model: Comments

- VOF two phase model with filtered URANS turbulence model is able to **capture bubble interfaces** in turbulence. (with explicit + geometric reconstruction scheme)

- It shows detachment of small bubbles from gas pocket at stopper tip.

- Requires **finer mesh** (smaller than bubbles) to resolve exact interface shape, and **small time step** to keep Courant number ~1.
  (current mesh is **not enough** to clearly capture the small bubbles)

- **More calculation time** is required to observe gas pockets at SEN inlet side walls.

  - Gas is filled from stopper tip (in thickness direction), and then expand to width direction → gas captured in recirculation zones at SEN side walls

- Outflow BC is used since constant pressure BC causes instability when bubbles cross the BC.

Conclusions

- **Pressure distribution** of Single phase and Eulerian Eulerian model **match** to1D pressure energy model result.

- **Eulerian Eulerian** model **captures three gas pockets**, but not small bubbles.

- **VOF** model is promising method to **figure out bubble size distribution**.

  - Able to **capture bubble detachment** from gas pockets.
    (explicit + geometric reconstruction schemes are used for clear interface)

  - High computational cost is required due to fine mesh (smaller than bubbles) & small time step (to keep Courant number ~1).

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