

Dynamic Characteristics of Fluidized Bed Reactors

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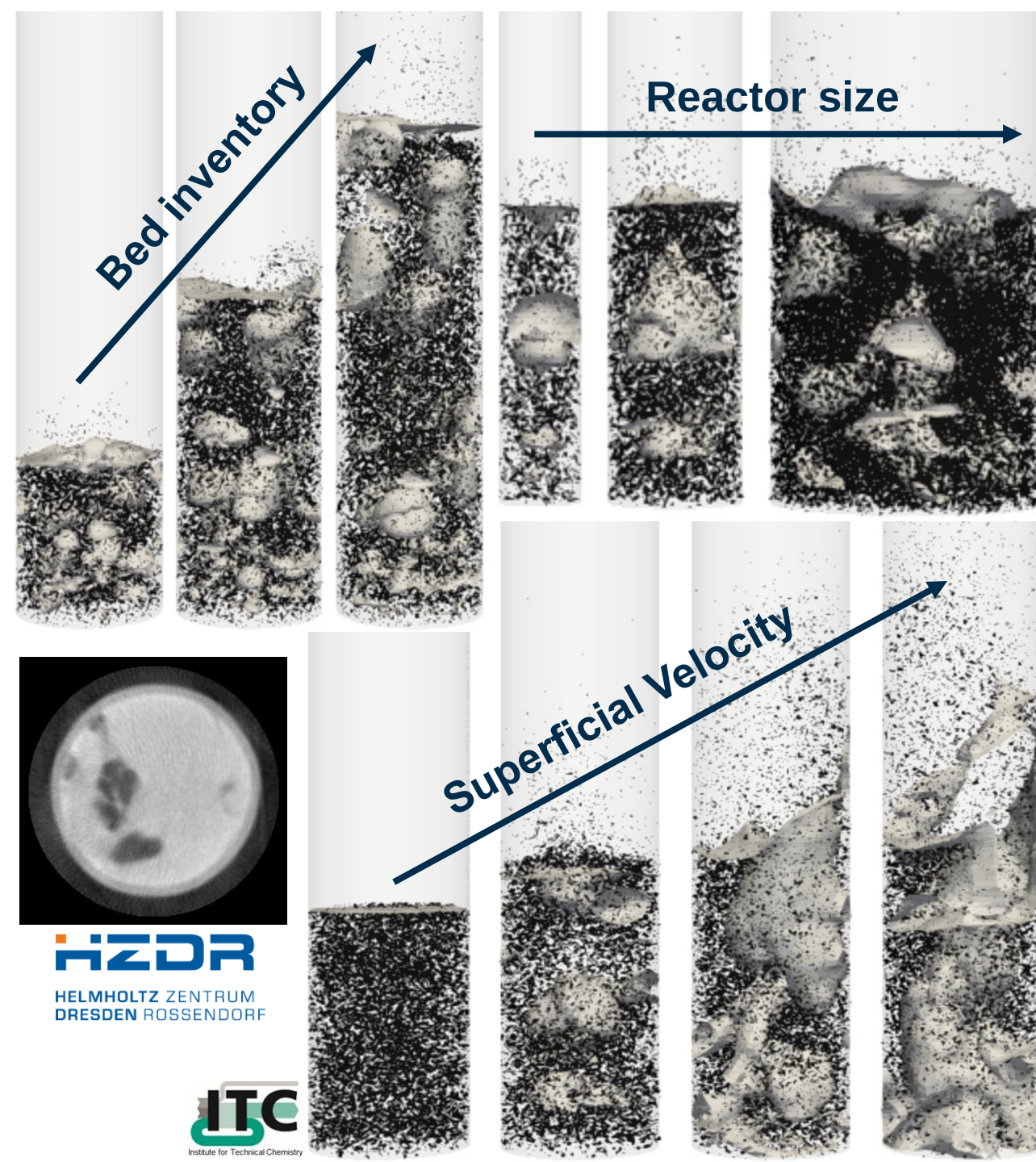
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JAHRESTREFFEN DER VDI / DECHEMA - FACHGRUPPEN

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Motivation

❑ **Plastic wastes**: ~ 400 Mt/year, ~10% recycled ^[1]

❑ Chemical recycling via **pyrolysis**

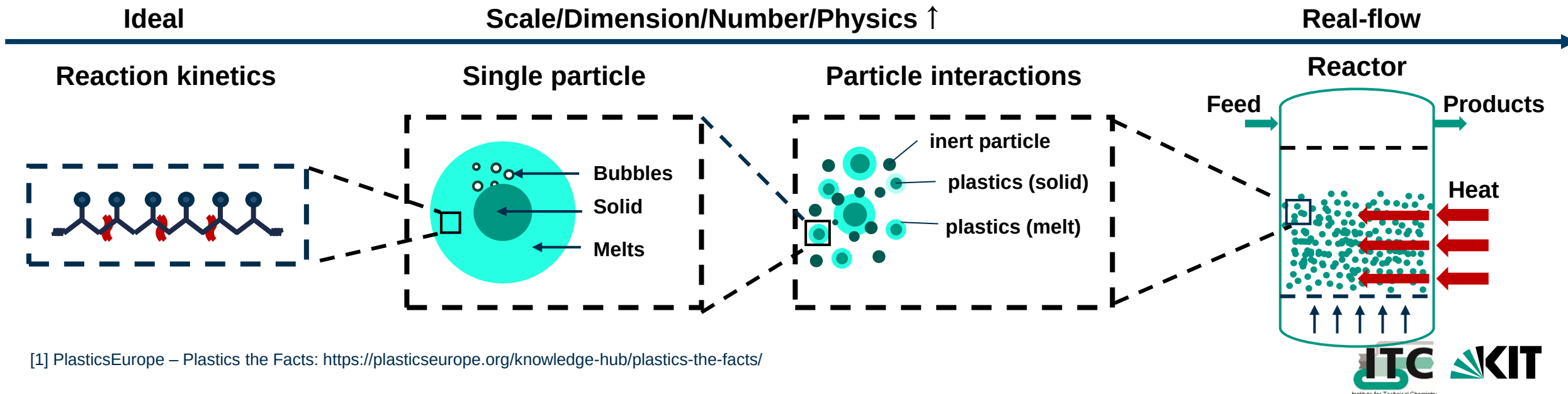
- Converting plastics into secondary raw materials
- Capable of mixed/contaminated plastics

❑ **Fluidized bed reactor** (FBR) as enabling technology

- Challenge: **scale-up**

❑ **Hydrodynamics** of FBRs

- Simulation of **cold-mode** FBRs
- **Dynamic** properties: bed kinetic energy, bubble surface area, bubble frequency
- Effects of **up-scaling**, superficial velocity and bed inventory



[1] PlasticsEurope – Plastics the Facts: <https://plasticseurope.org/knowledge-hub/plastics-the-facts/>

Operating Conditions

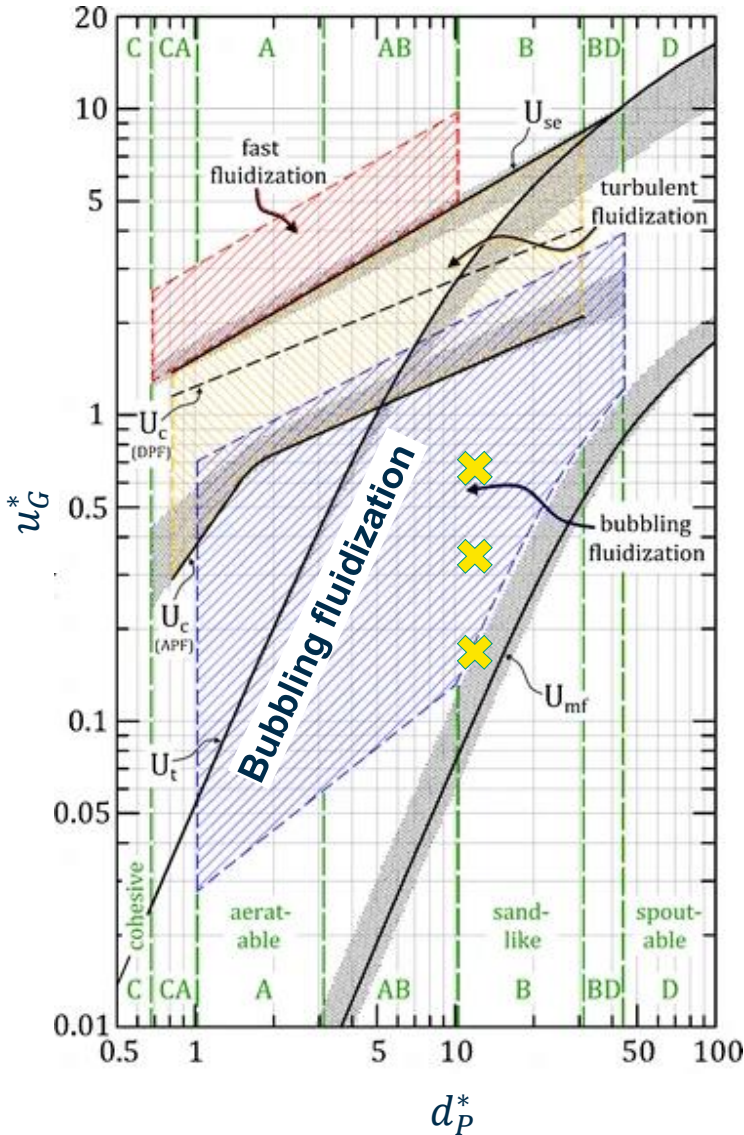
Variation of reactor diameter d_R

d_R [cm]	u_G/u_{mf} [-]	m_S [kg]
3	4	0.12
5	4	0.295
10	4	1.2
5	2	0.295
5	4	0.295
5	8	0.295
10	4	1.2
10	4	2.4
10	4	3.5

Variation of superficial velocity u_G

Variation of bed inventory m_S

Regime diagram for gas-solid fluidized bed



d_P	260 μm
ρ_P	2660 kg/m^3
ρ_G	1.20 kg/m^3
ν_G	1.51e-5 m/s^2
$d_P^* [-]$	12
$u_{mf} [\text{m/s}]$	0.058

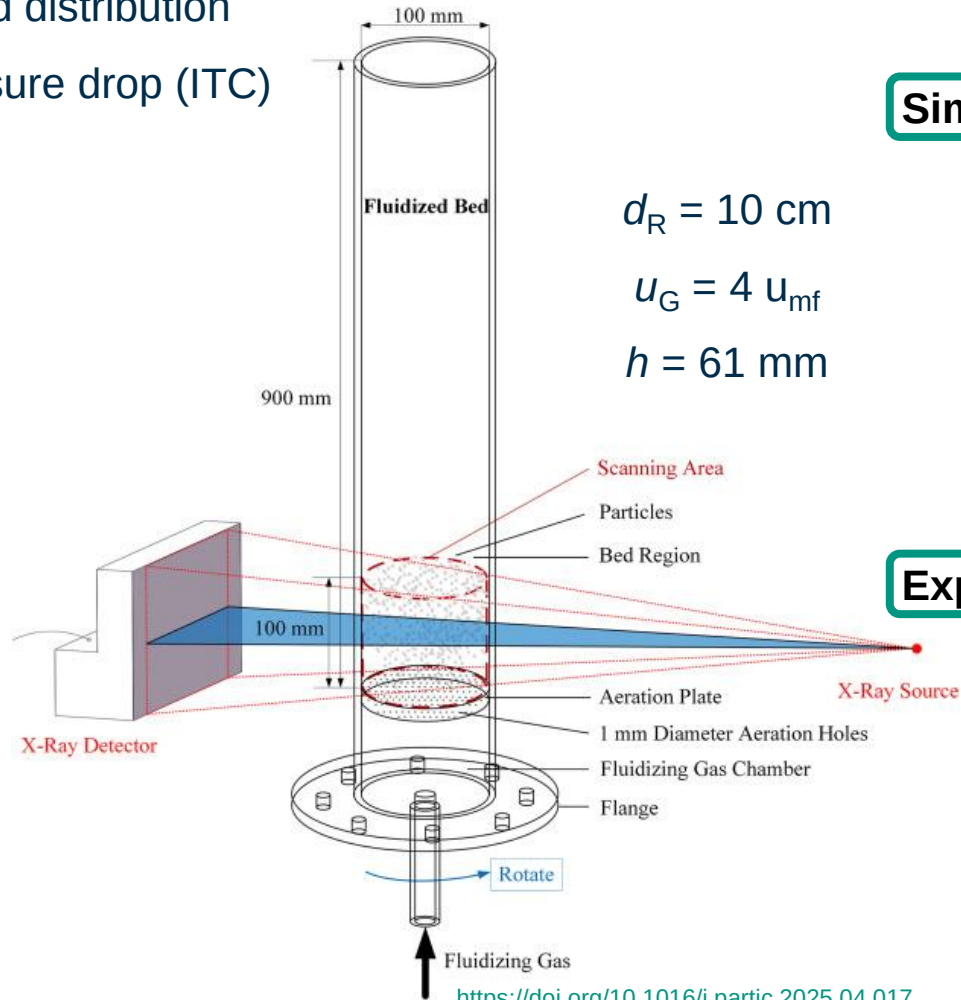
u_{mf} - Minimum fluidization velocity

$$u_G^* = u_G \sqrt[3]{\frac{\rho_g^2}{\mu_g(\rho_s - \rho_g)g}}$$

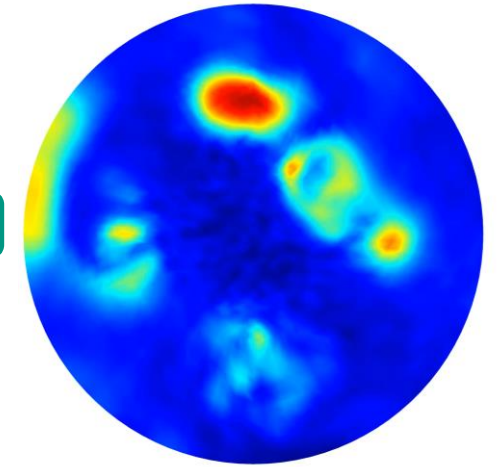
$$d_P^* = d_P \sqrt[3]{\frac{\rho_g(\rho_s - \rho_g)g}{\mu_g^2}}$$

Experimental Setup

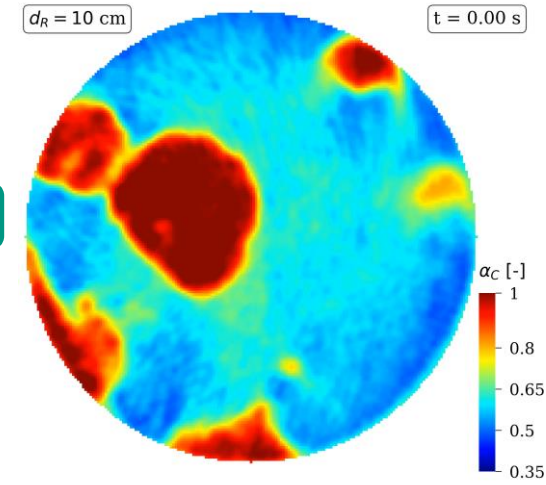
- ❑ Ultrafast X-ray CT, non-invasive (HZDR)
- Cross-sectional solid distribution
- ❑ Time-resolved pressure drop (ITC)



Sim.



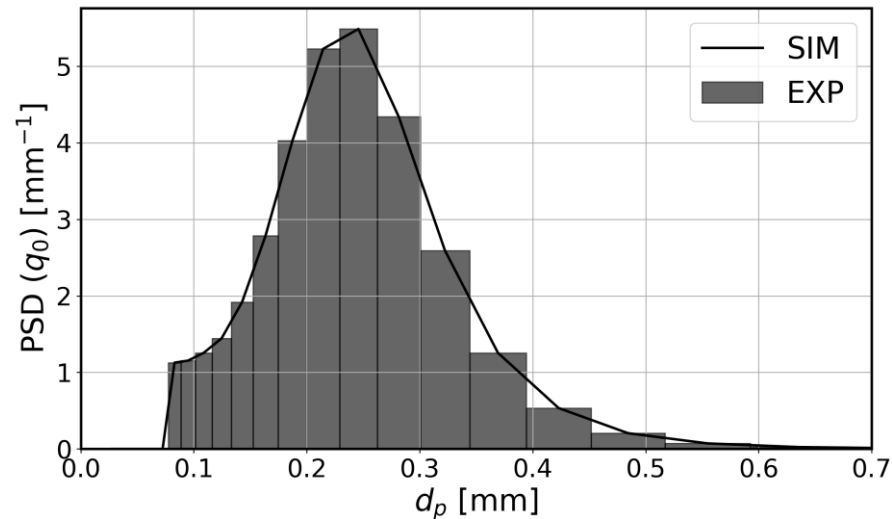
Exp.



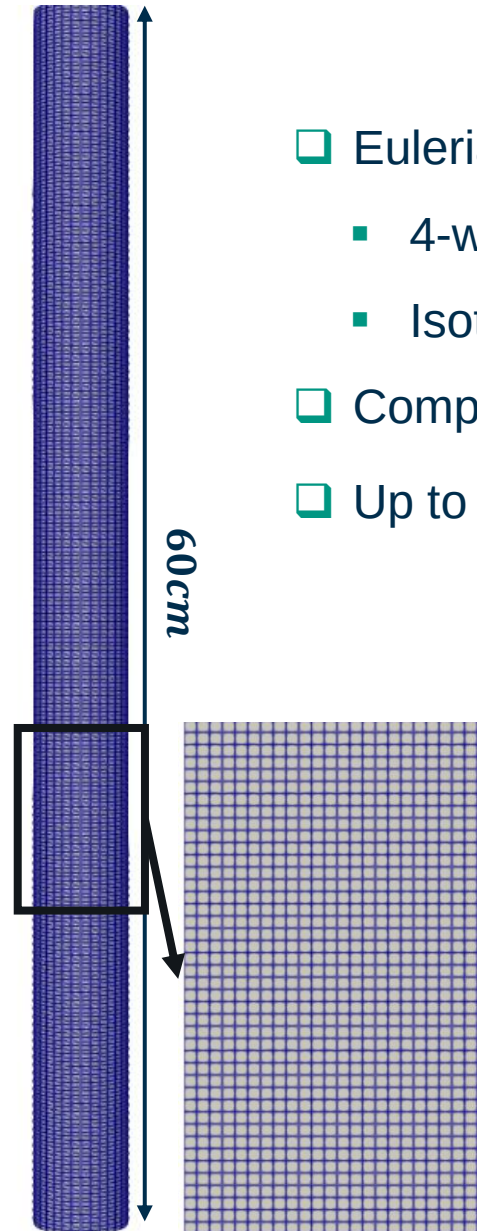
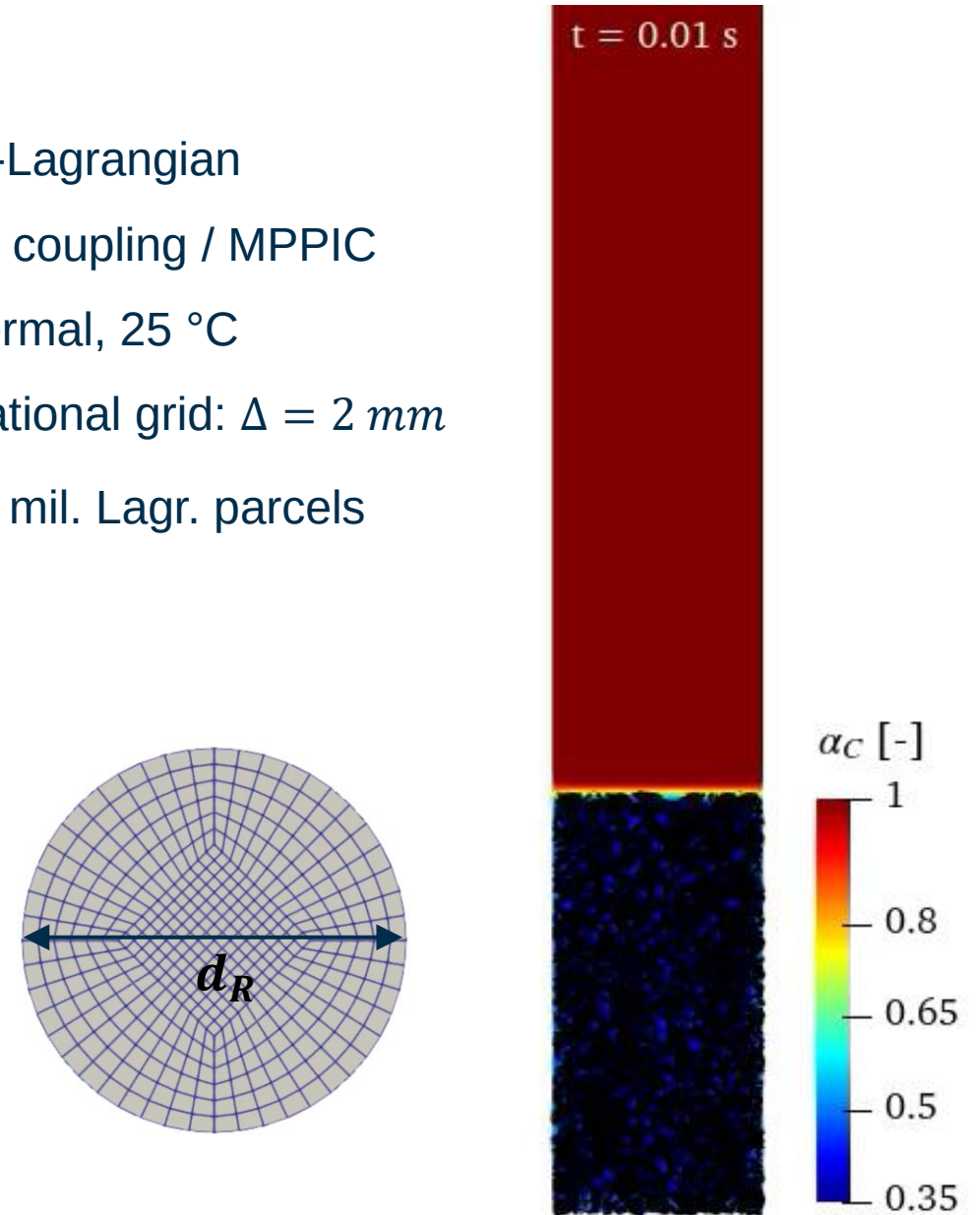
<https://doi.org/10.1016/j.partic.2025.04.017>

Simulation Setups

- ❑ Bed material: quartz sand
- ❑ Particle size distribution (PSD)
 - SMD: $d_p = 0.26$ mm
- ❑ Fluidizing agent: air, 20 °C

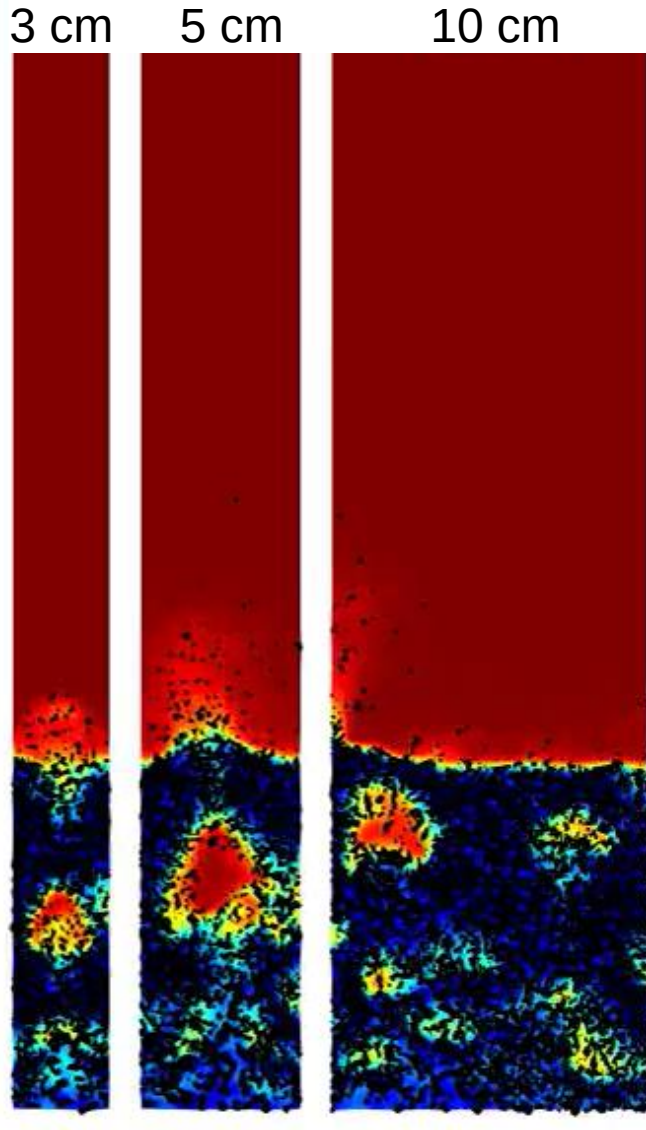


- ❑ Eulerian-Lagrangian
 - 4-way coupling / MPPIC
 - Isothermal, 25 °C
- ❑ Computational grid: $\Delta = 2$ mm
- ❑ Up to 35 mil. Lagr. parcels

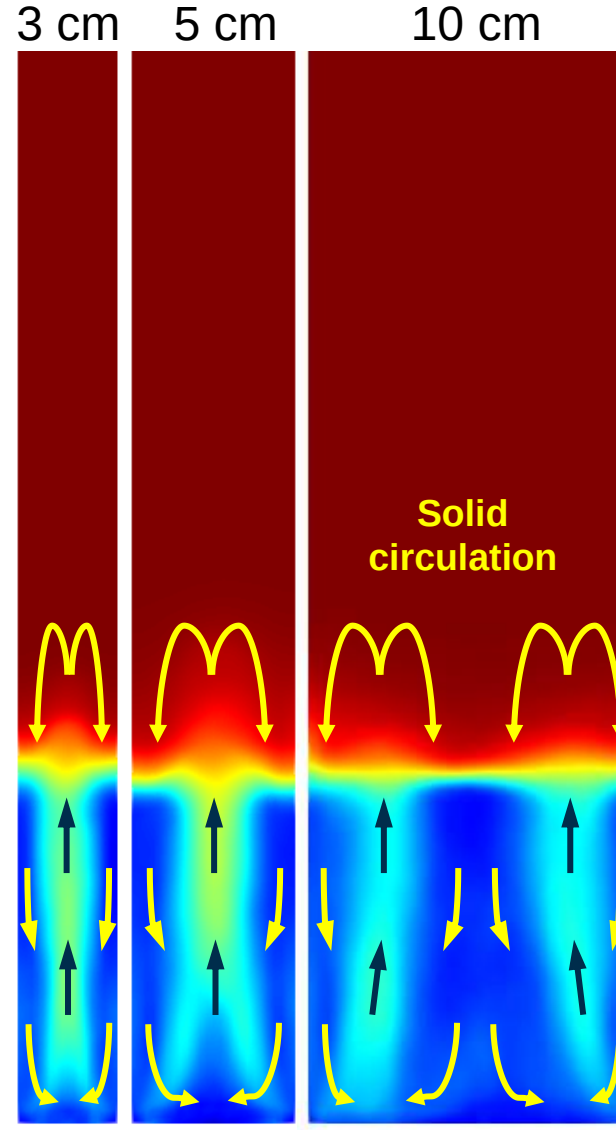


Up-Scaling

Instantaneous void fraction



Time-averaged void fraction



- ❑ Single- to multiple-array bubbling
- ❑ Increased bubble-to-wall distance

d_R [cm]	3	5	10
h_B [cm]	14.3	15.8	13.4
Δp_B [kPa]	1.43	1.45	1.40
$\Delta p_{B,Exp}$ [kPa]	1.61	1.49	1.52

Specific kinetic energy

$$k_S = \frac{1}{2} \sum_{i=1}^{N_p} m_{p,i} u_{p,i}^2 / m_S$$

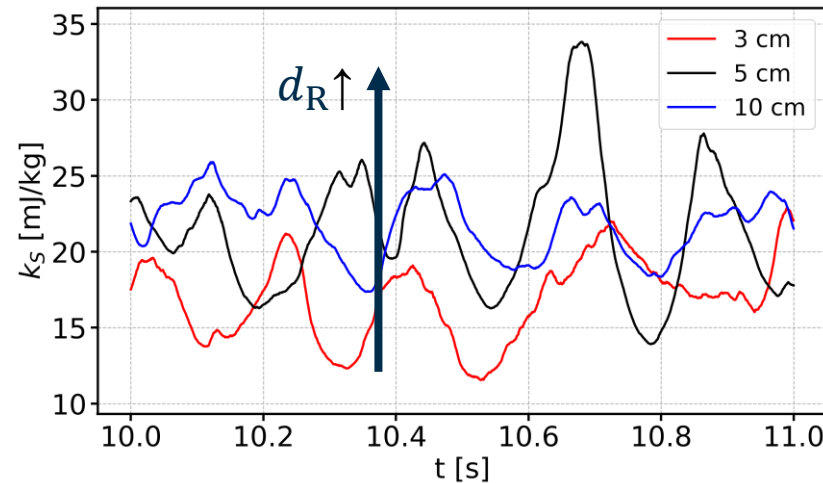
$$u_G = 4 u_{mf}$$

Up-Scaling

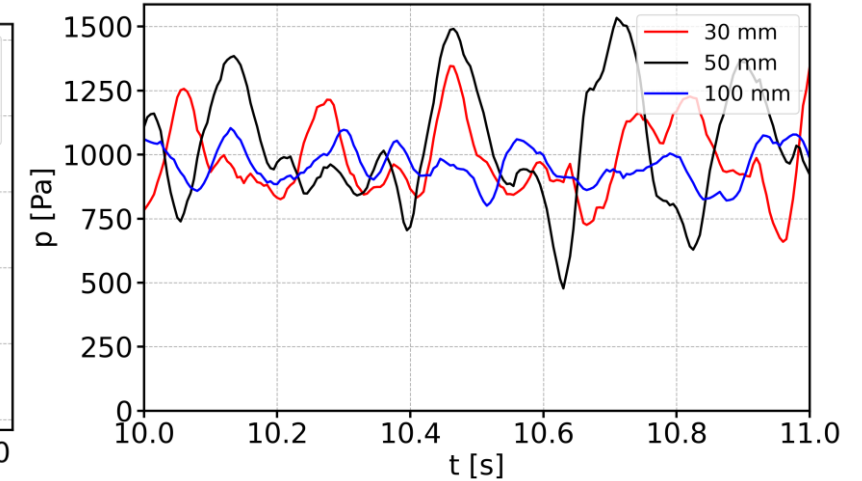
- ❑ Specific kinetic energy increases
- ❑ Amplitude decrease
- ❑ Similarity for bubble frequency calculated from local and global parameters

d_R [cm]	3	5	10
$\bar{k}_S$ [mJ/kg]	17.9	20.2	21.2
A_B/A_0 [-]	4.96	3.79	4.12
$f_{B,k}$ [Hz]	5.0	5.0	5.0
$f_{B,p}$ [Hz]	5.0	5.0	5.0
$f_{B,A}$ [Hz]	5.0	5.0	5.0

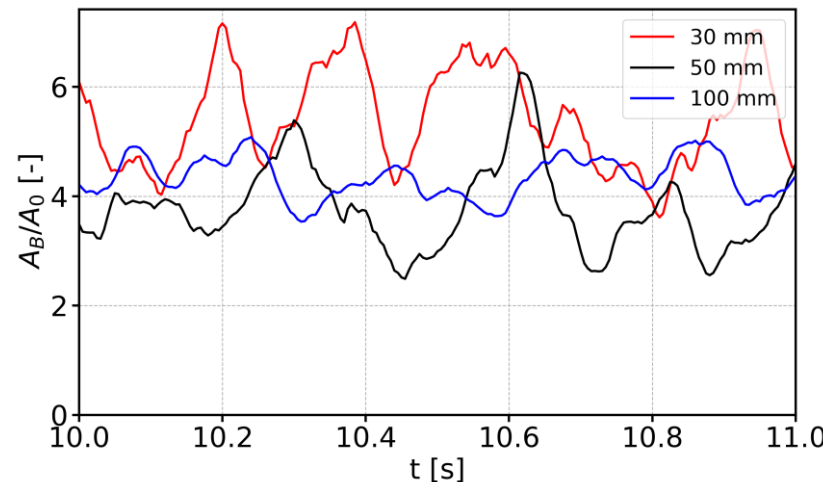
Specific kinetic energy



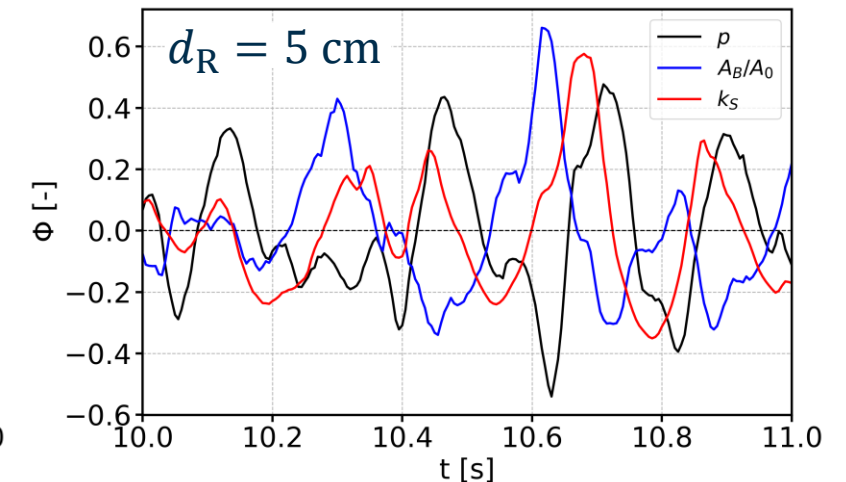
Local pressure at $h = 66$ mm



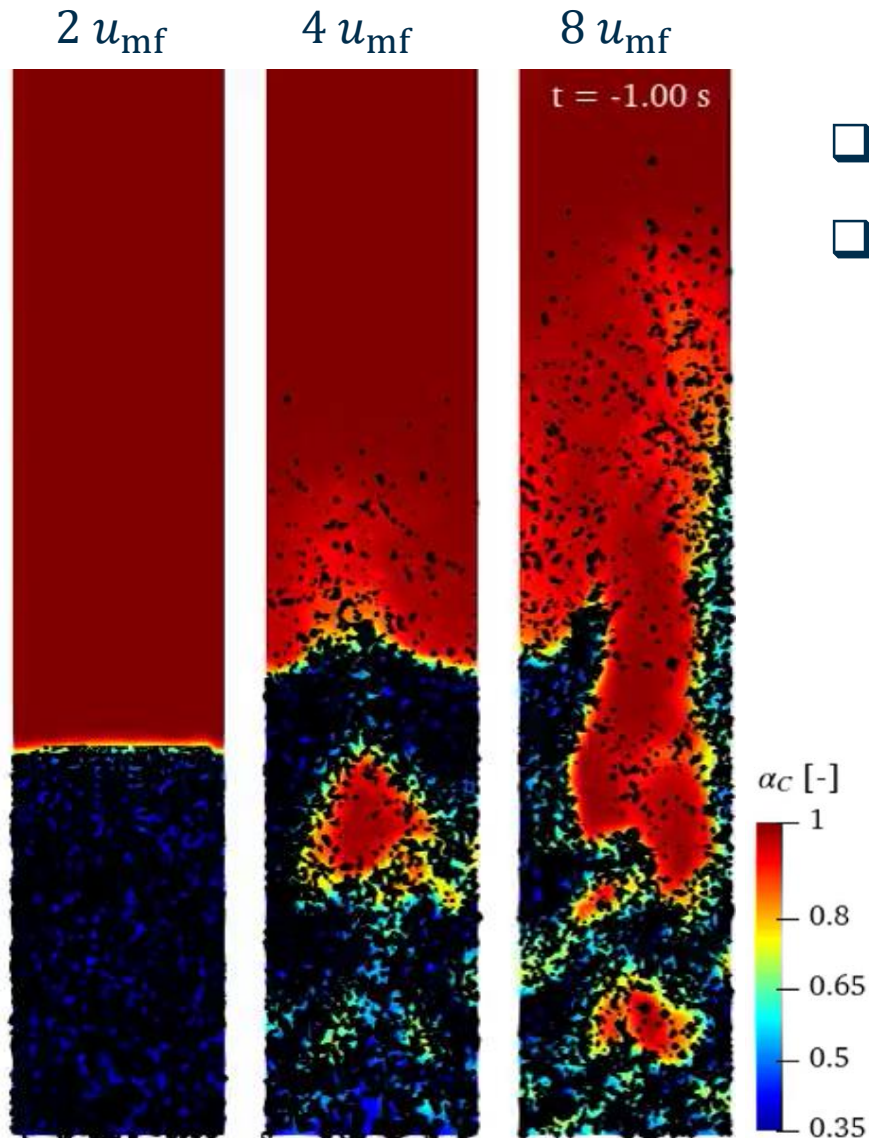
Bubble surface area



$k_S(t)$, $p(t)$, $A_B(t)$



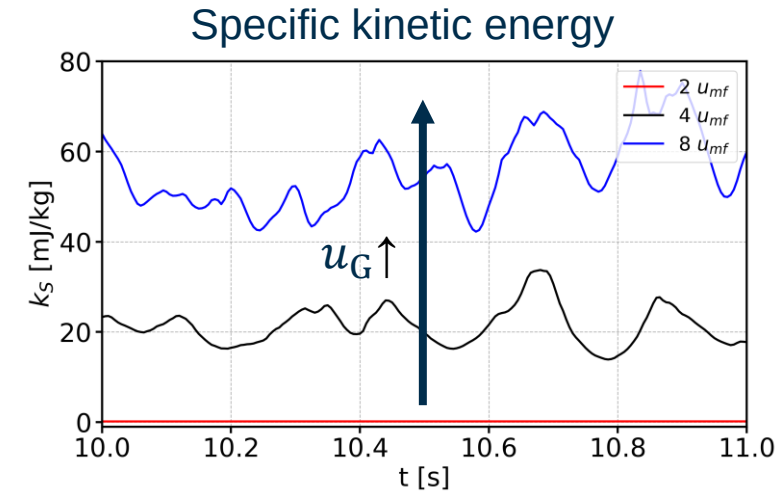
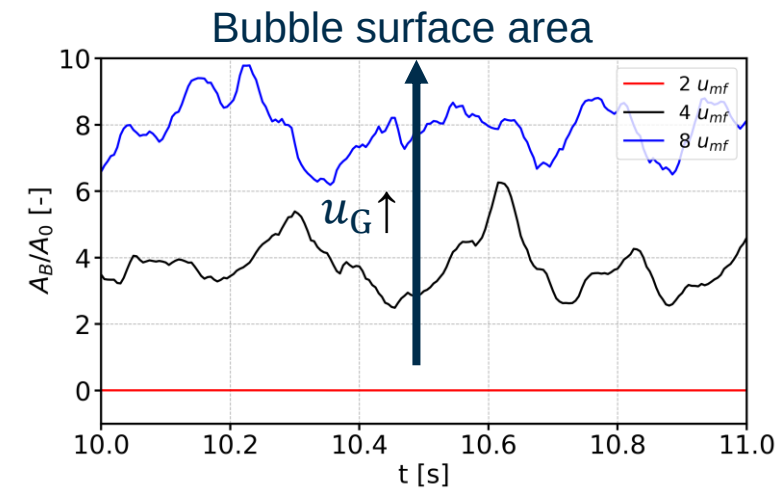
Increasing Superficial Velocity



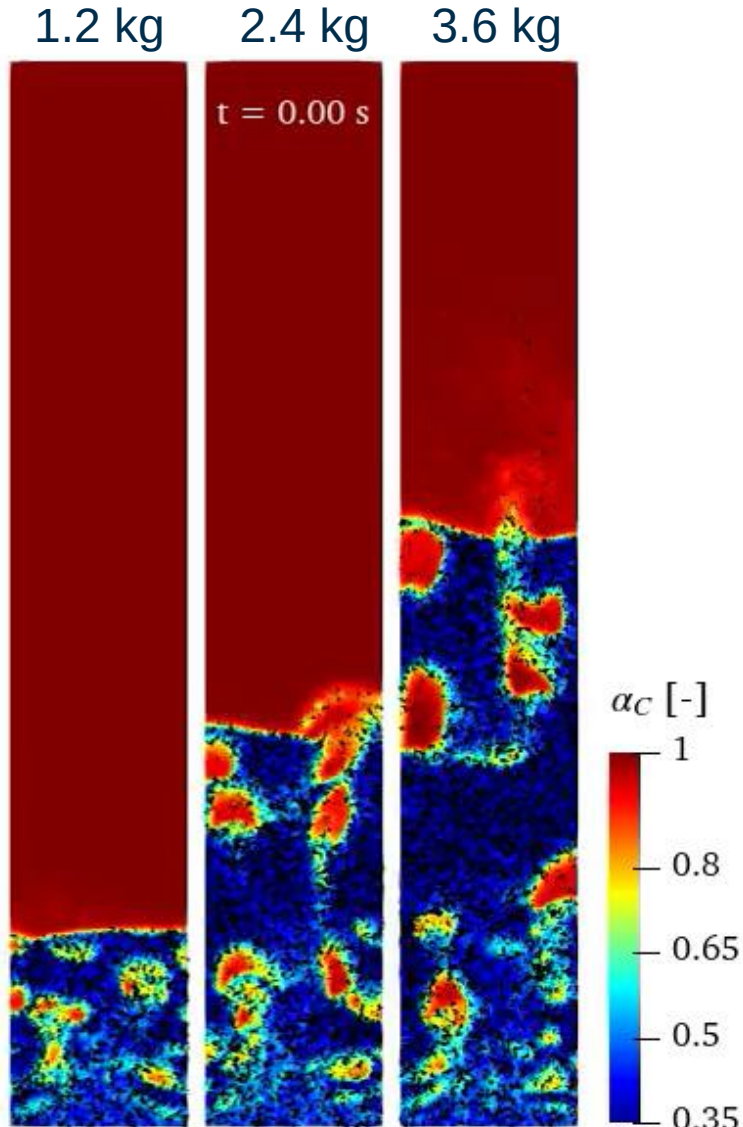
- ❑ No fluidization for $u_G = 2 u_{mf}$
- ❑ Increase of bed height, kinetic energy and bubble surface

u_G/u_{mf}	2	4	8
h_B [cm]	9.6	15.8	20.0
Δp_B [kPa]	1.17	1.45	1.42
$\Delta p_{B,Exp}$ [kPa]	1.47	1.49	1.48
$\bar{k}_S$ [mJ/kg]	0.2	20.2	56.5
A_B/A_0 [-]	0	3.79	7.9
$f_{B,k}$ [Hz]	-	5.0	7.0

$$d_R = 5 \text{ cm}, m_S = 295 \text{ g}$$



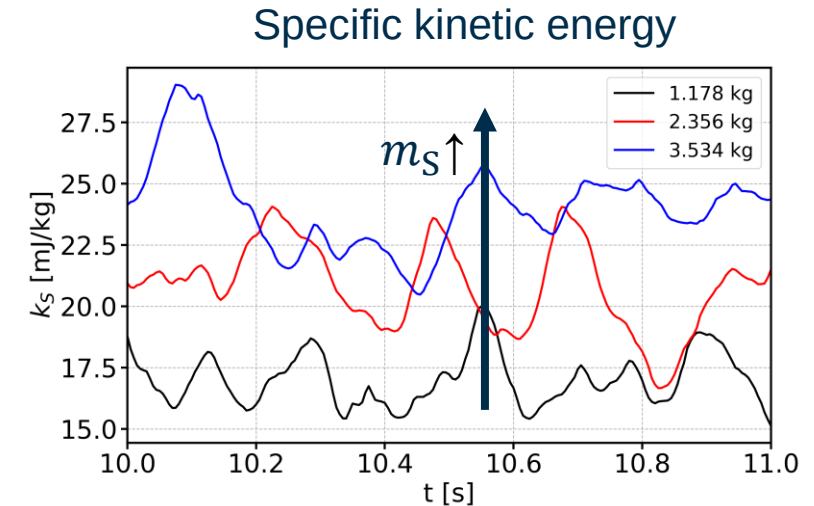
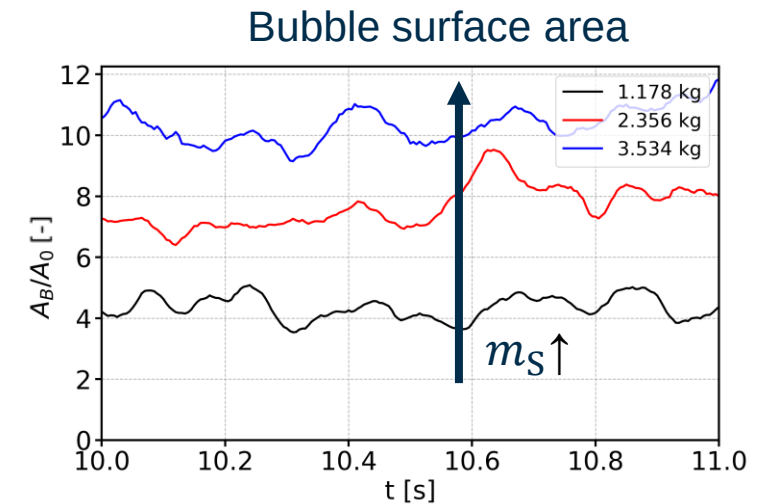
Increasing Bed Inventory



- ❑ Quasi-linear increase of bed height and pressure drop
- ❑ Specific kinetic energy increase
- ❑ Bubble surface area decreases

m_S	1.2 kg	2.4 kg	3.6 kg
$h_B [\text{cm}]$	13.3	26.7	38.8
$\Delta p_B [\text{kPa}]$	1.35	2.73	4.10
$\bar{k}_S [\text{mJ/kg}]$	16.9	21.2	22.3
$A_B/A_0 [-]$	4.3	7.6	10.3
$\bar{A}_B [\text{m}^2/\text{kg}^{-1}]$	0.028	0.025	0.022
$f_{B,k} [\text{Hz}]$	6.5	7.0	6.5

$$d_R = 10 \text{ cm}, u_G = 4 u_{mf}$$



Summary

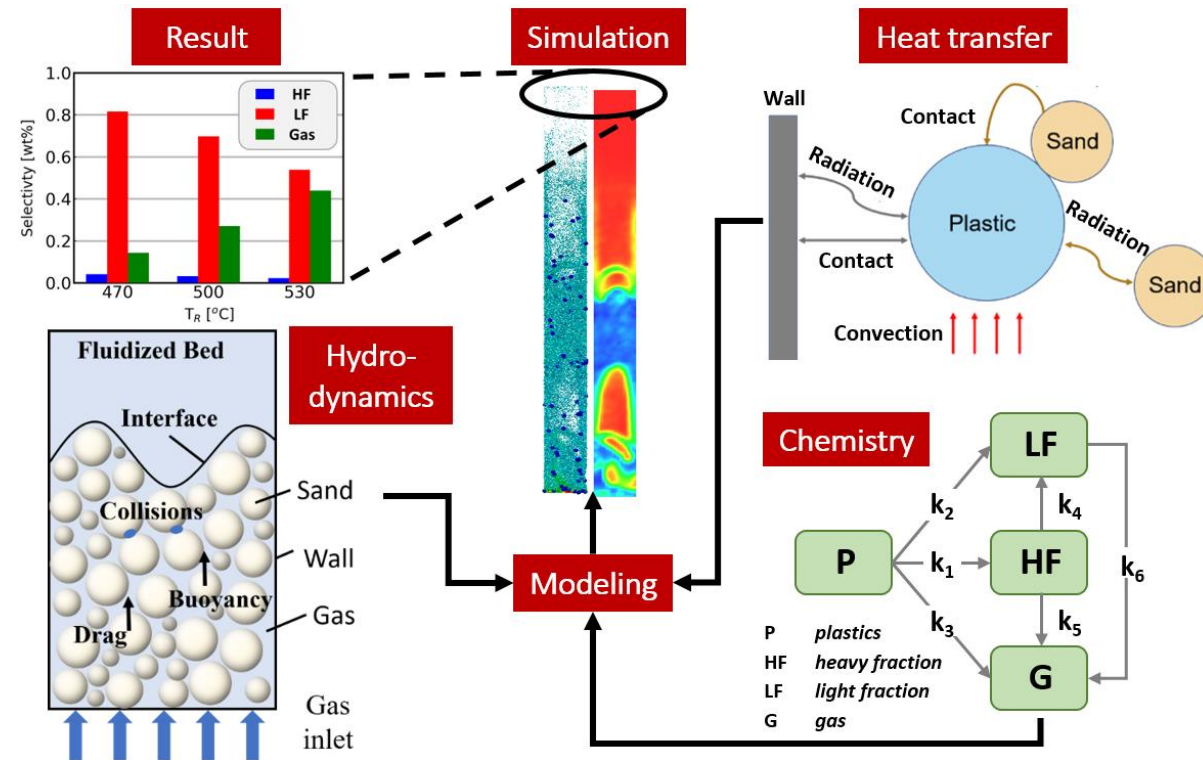
Dynamic characteristics of FBR

- Specific kinetic energy increases with reactor diameter, superficial velocity and bed inventory
- Bubble surface area increases with superficial velocity and decreases with bed inventory
- Bubble frequency increases with superficial velocity
- Consistency between integral and local properties

Thank you
for listening!

Outlook

- Further validation/up-scaling
- Mixing/heating/pyrolysis of plastics

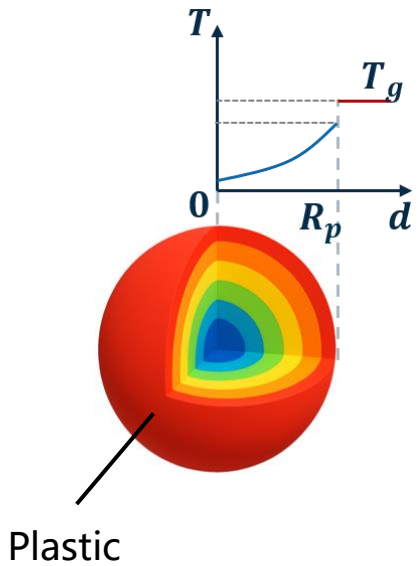




Modeling of Plastic Pyrolysis

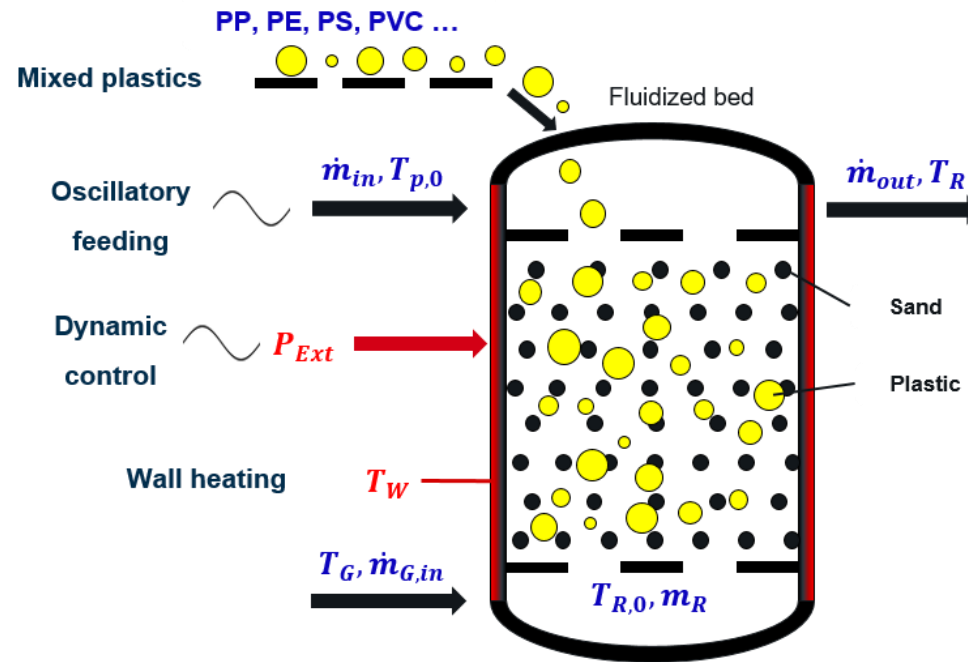
Single plastic particle

- Heat transfer vs. reaction
- Homogeneous (0D)
- Particle-resolved (1D)



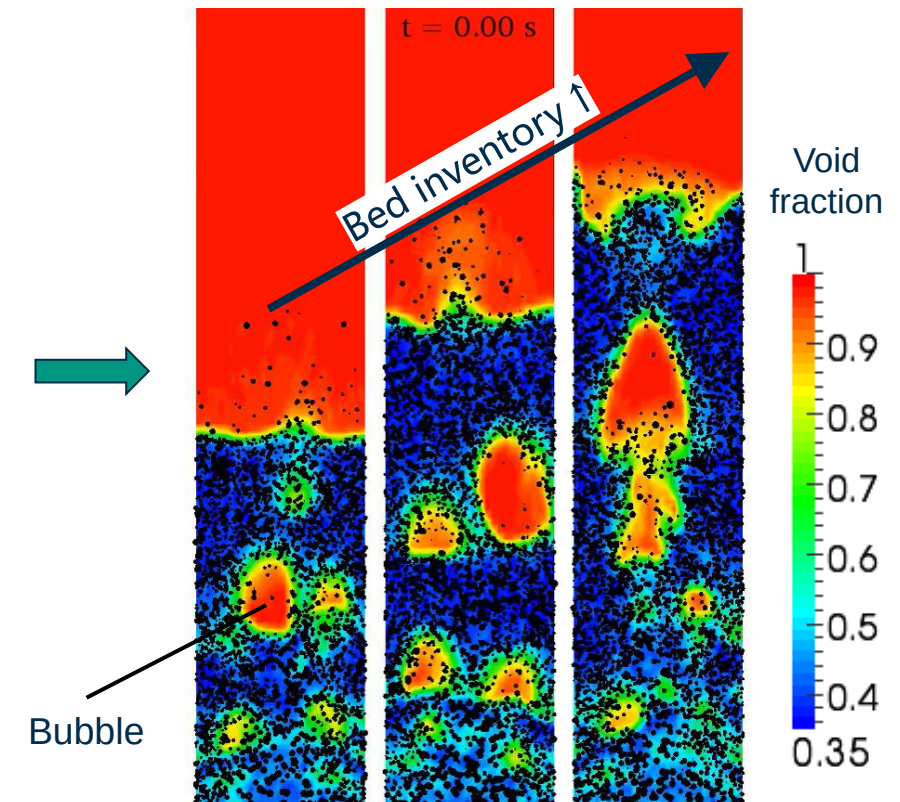
Stirred tank (reduced-order, 0D)

- Continuous feeding of mixed plastics
- Dynamic control of reactor temperature



Bubbling fluidized bed

- Spatially-resolved (CFD, 3D)
- Effect of hydrodynamics



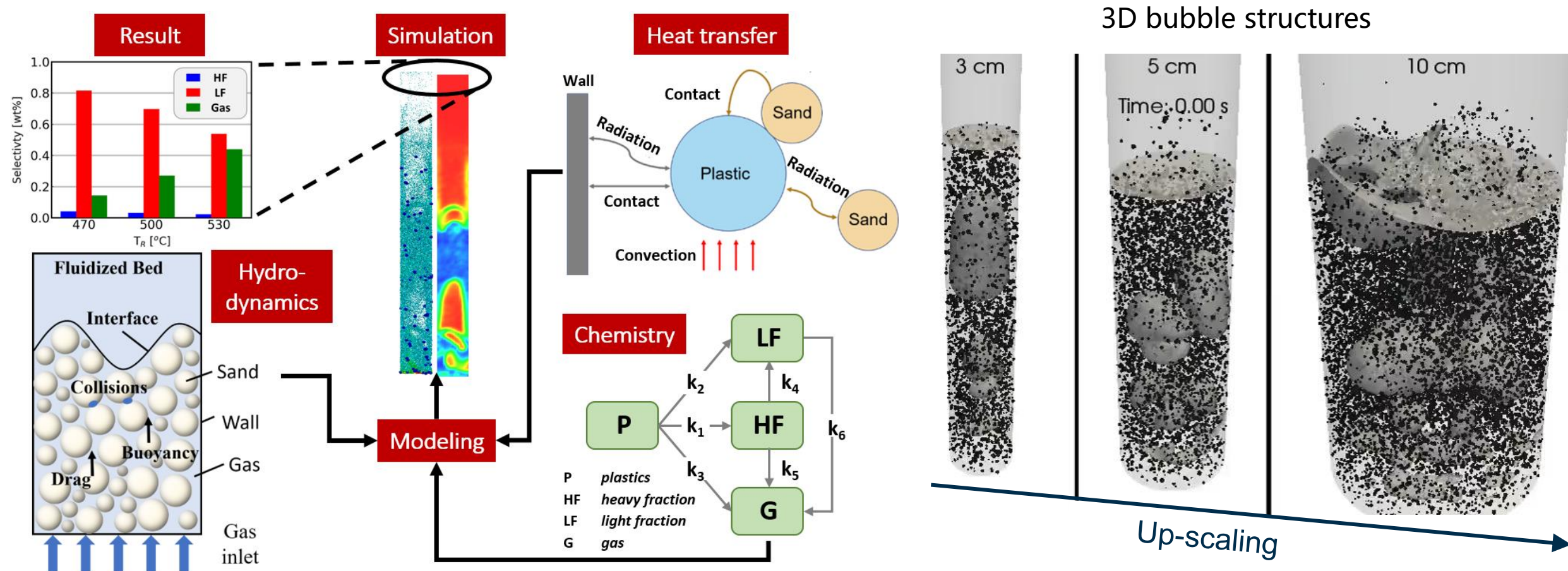
F. Zhang et al. Particle-resolved simulation of pyrolysis process of a single plastic particle. *Heat Mass Transf.* 61 (12), 2025.

F. Zhang et al. Assessment of Dynamic Characteristics of Fluidized Beds via Numerical Simulations. *Phys. Fluids* 36 (2), 023348, 2024.



CFD Simulation of Fluidized Bed Reactors (FBR)

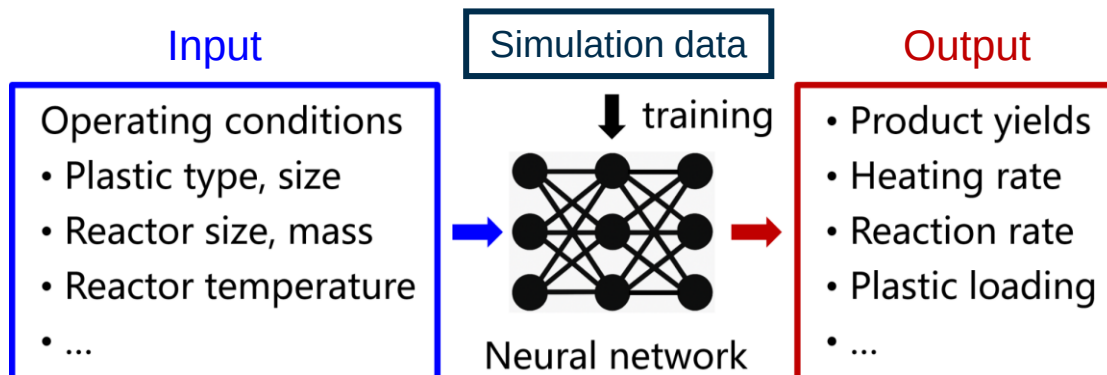
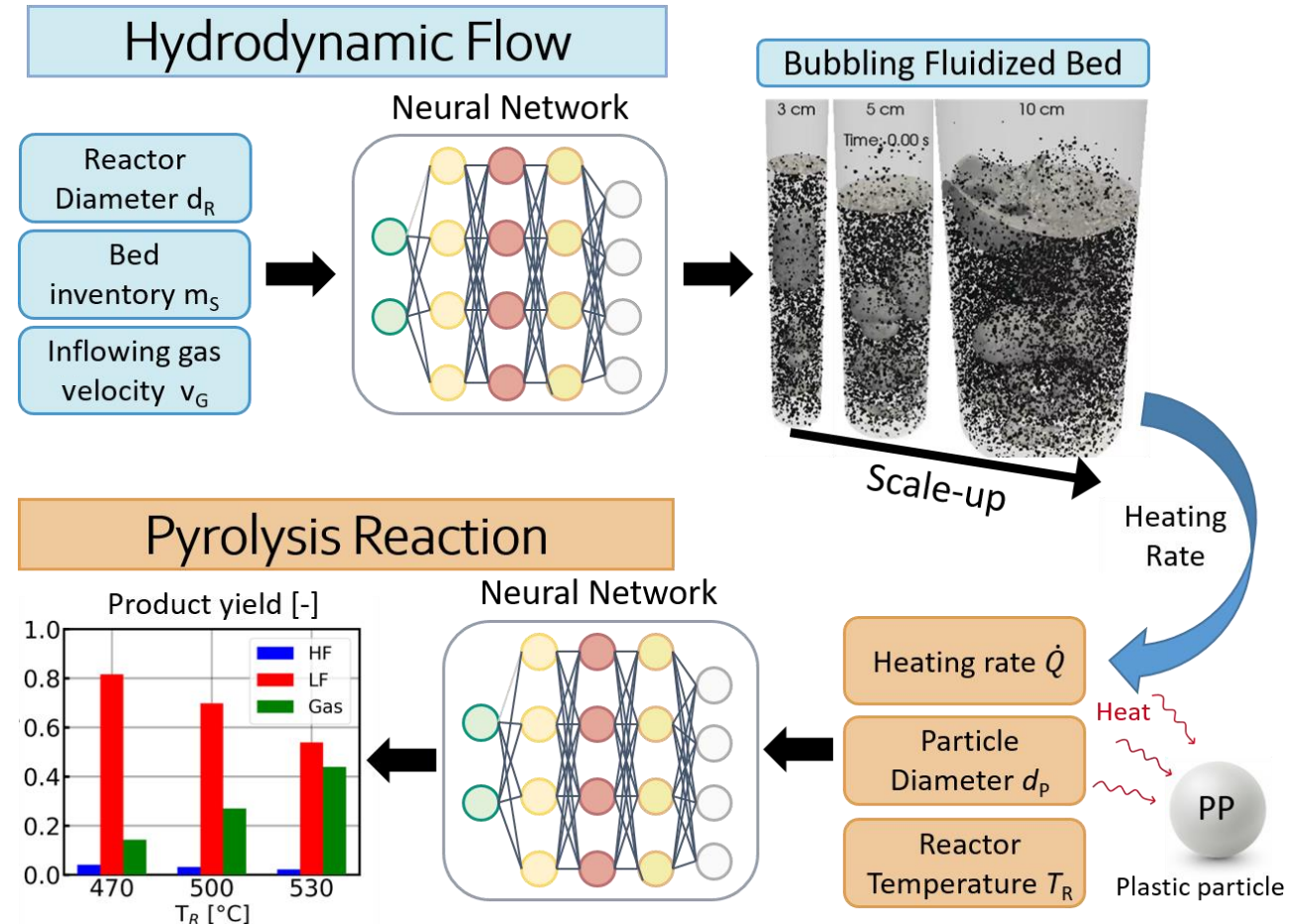
- Gas-solid reactive flows: hydrodynamics + heat transfer + **pyrolysis chemistry**
- Predicting operational performance and product yield → optimization of process parameters / scale-up



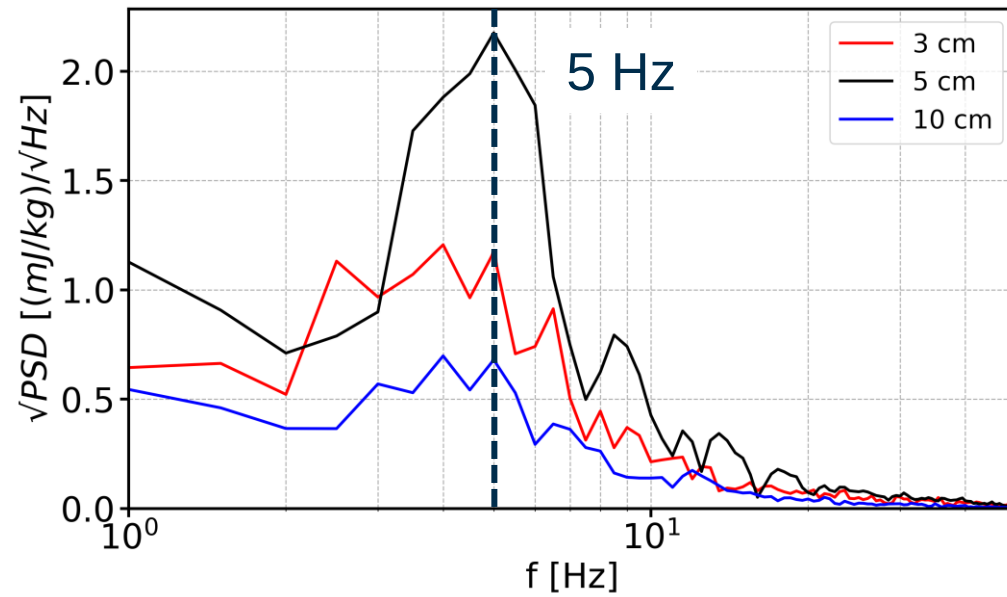


Data-Driven Pyrolysis Model

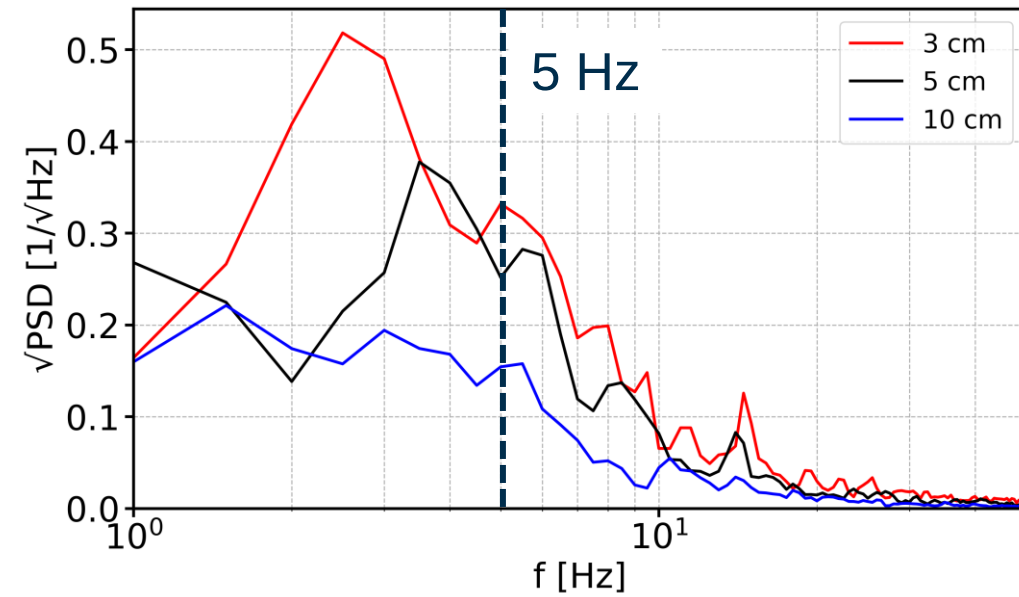
- Direct prediction from operating conditions with machine learning
 - Training on simulation data
 - Speed-up factor $\sim 20,000$
- Future/ongoing works
 - Thermo-physics: heat transfer, melting
 - Reaction kinetics for mixed plastics
 - Reduced-order/data-driven models



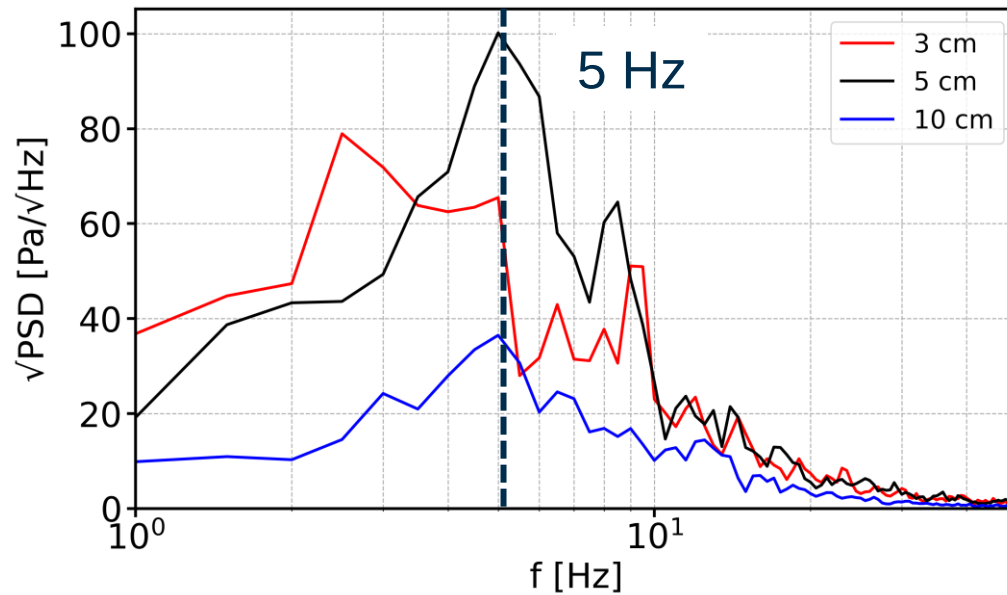
Specific kinetic energy



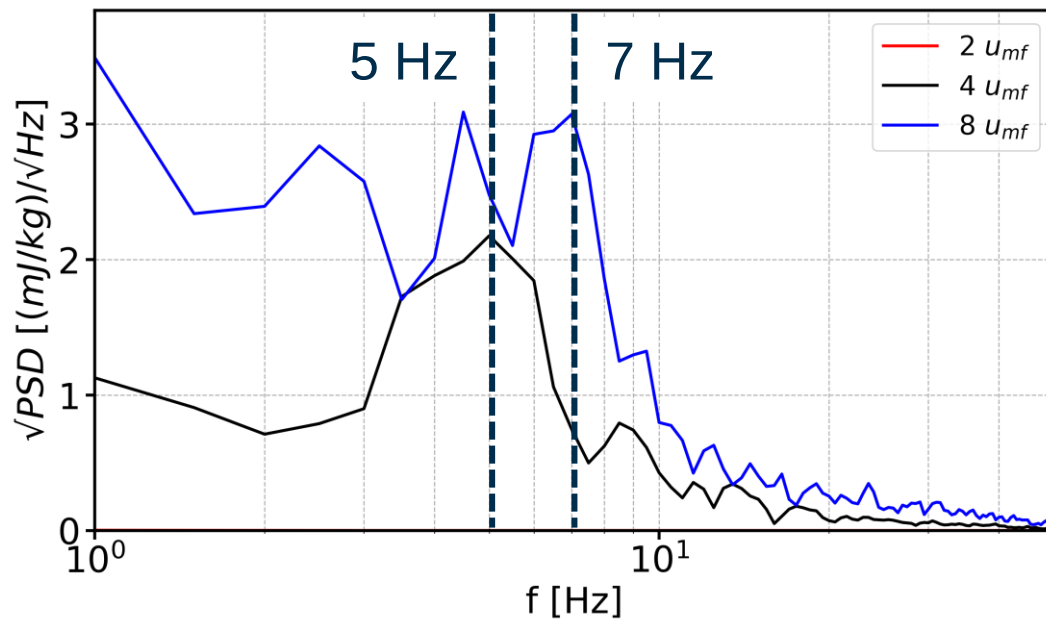
Bubble surface



Pressure



Specific kinetic energy



Specific kinetic energy

