Numerical Investigation of Gas Bubble Behavior for Pool Scrubbing in Nuclear Reactors using the Volume-of-Fluid Method

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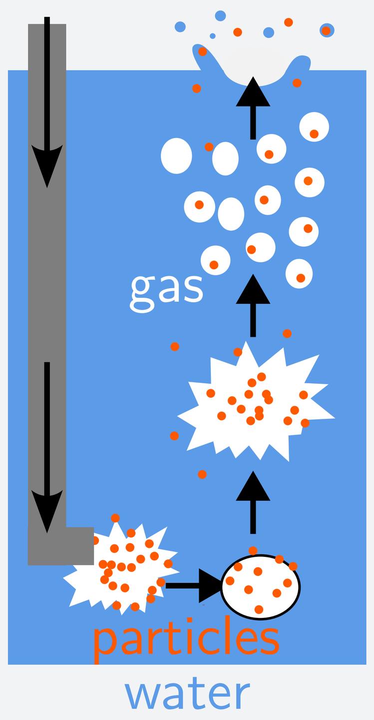
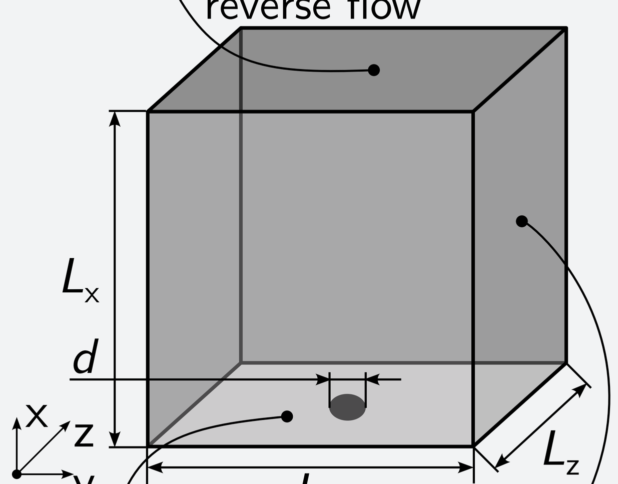
Industrial applications

- Gas injection in water important for
  - Oil and gas industry (Oil recovery techniques)
  - Chemical industry (Enhance mixing)
  - Cooling and heating systems (Improve efficiency)
- Pool Scrubbing Process (see figure on the right)
  - Severe accident treatment in nuclear reactors
  - Leakage of radioactive particles into air
  - Cleaning of contaminated air necessary
  - Injecting the air in a water pool to remove particles



Numerical methods

- 3D incompressible code PARIS (Aniszewski et al. 2021)
- 2^{nd} order discretization, Finite Volume method
  - Spatial: Central differences on staggered grid
  - Temporal: Predictor–corrector procedure
- Geometric Volume-of-Fluid method
  - Piecewise linear interface reconstruction
  - Directionally split advection
- Determination of surface tension force
  - Continuous Surface Force (CSF) model
  - Curvature calculation with height functions
- Pressure correction with projection method
- Static Smagorinsky turbulence model

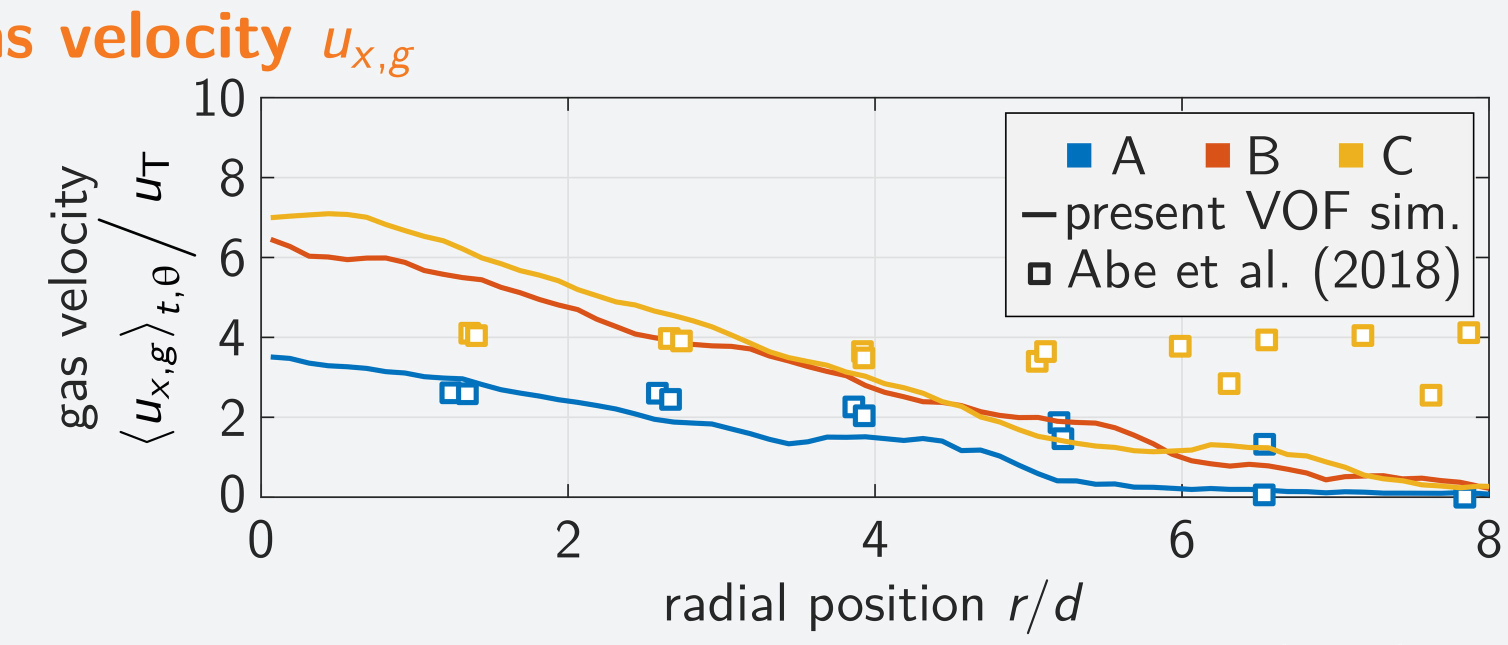


case	A	B	C
u_0 $\left[\frac{\text{m}}{\text{s}}\right]$	5	25	50
$\text{Re}_g = \frac{\rho_g u_0 d}{\mu_g}$	$1.9 \cdot 10^3$	$9.4 \cdot 10^3$	$1.9 \cdot 10^4$
$\text{Re}_l = \frac{\rho_l u_0 d}{\mu_l}$	$3.4 \cdot 10^4$	$1.7 \cdot 10^5$	$3.4 \cdot 10^5$
$\text{We}_g = \frac{\rho_g u_0^2 d}{\sigma}$	2.5	$6.3 \cdot 10^1$	$2.5 \cdot 10^2$
$\text{We}_l = \frac{\rho_l u_0^2 d}{\sigma}$	$2.1 \cdot 10^3$	$5.2 \cdot 10^4$	$2.1 \cdot 10^5$

- Injection of air in water
- $d = 6\,\text{mm}$
- Cubic cells $d/\Delta = 8$
- $L_x = L_y = L_z = 24d$
- Density ratio $\rho_l/\rho_g \approx 830$
- Viscosity ratio $\mu_l/\mu_g \approx 46$
- Eötvös number ≈ 4.9

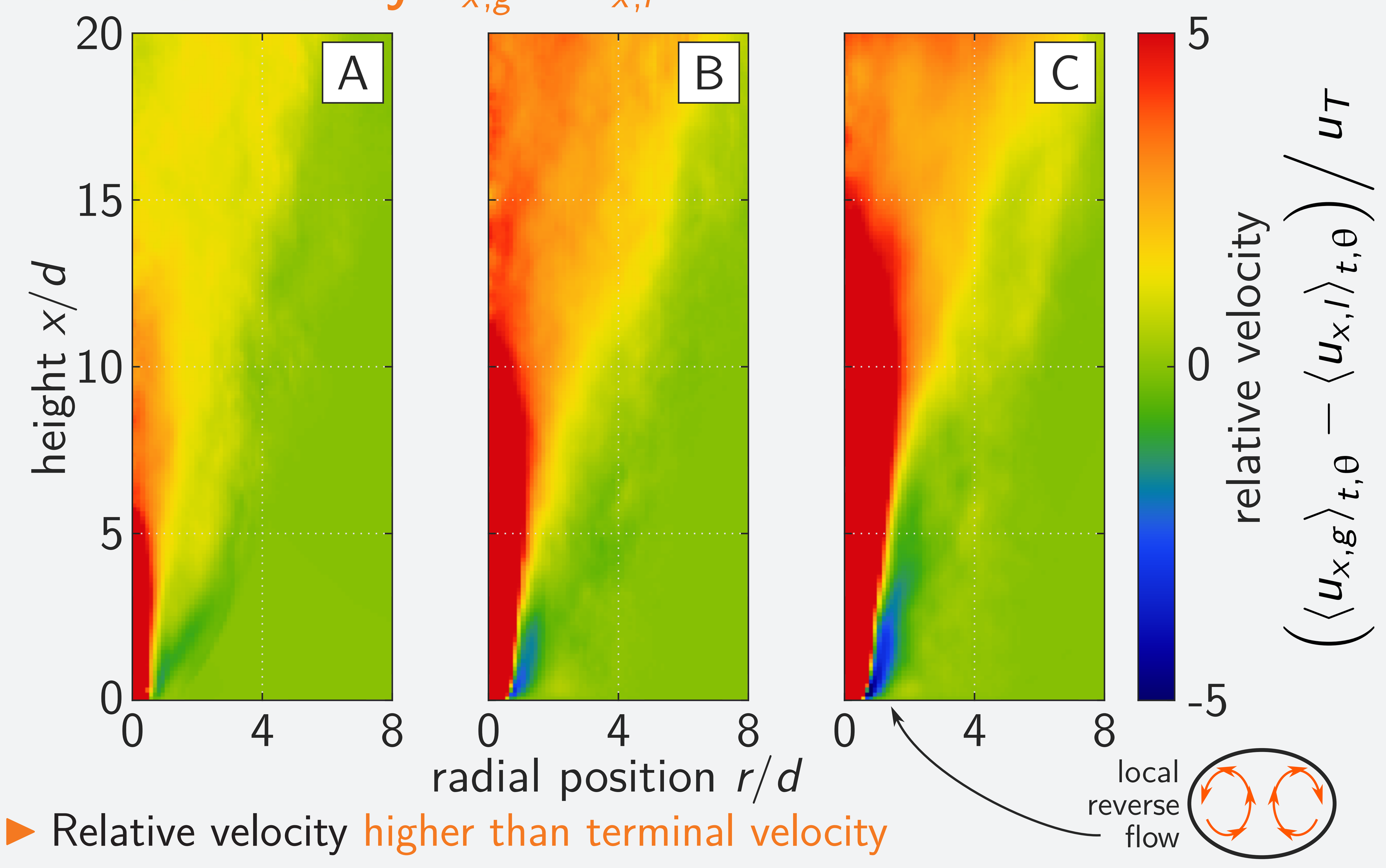
Statistical results

Gas velocity $u_{x,g}$



- Similar magnitude of gas velocity compared to Abe et al. (2018) at a height of $x/d = 16$ (no data available for case B)

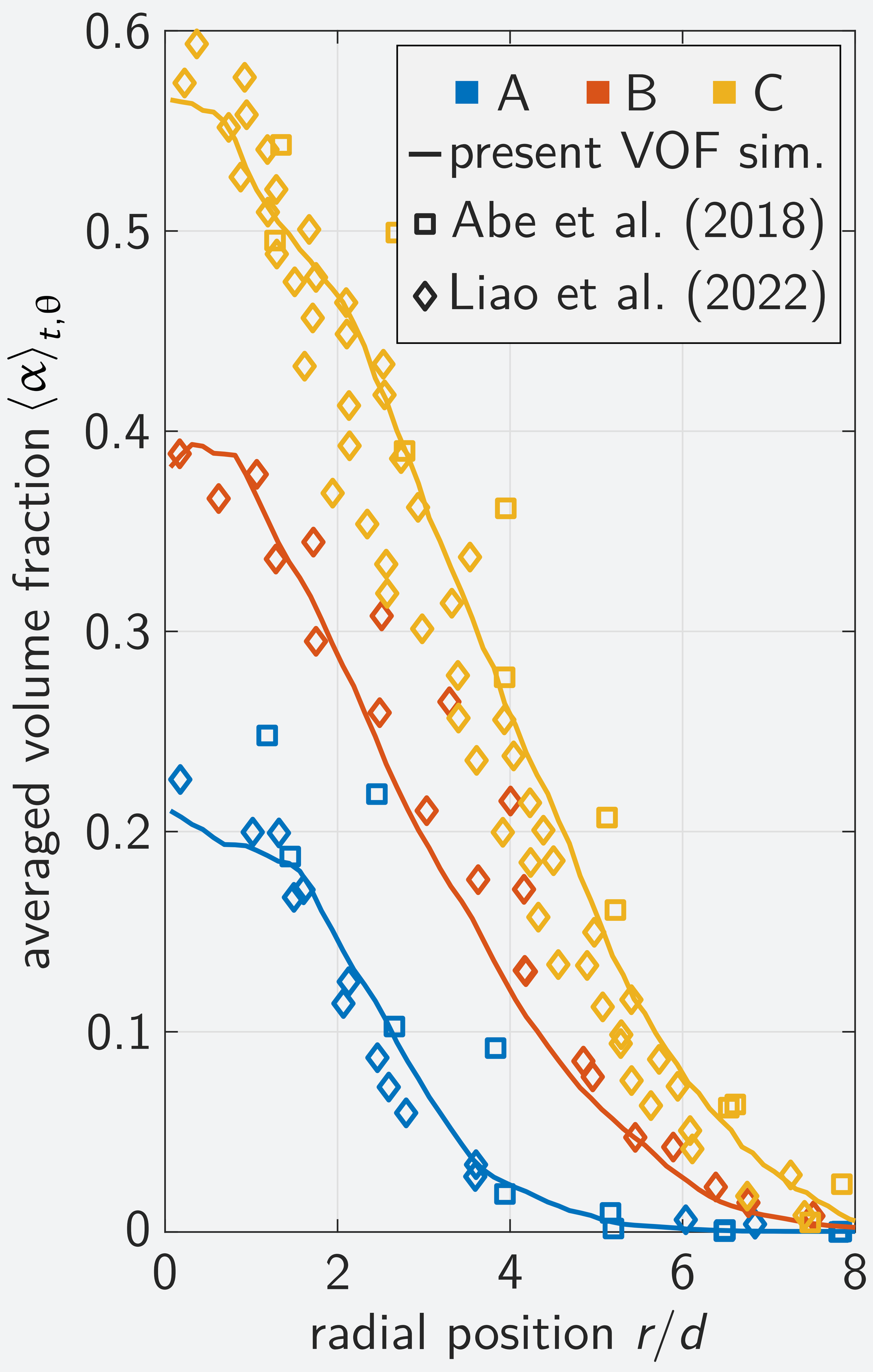
Relative velocity $u_{x,g} - u_{x,l}$



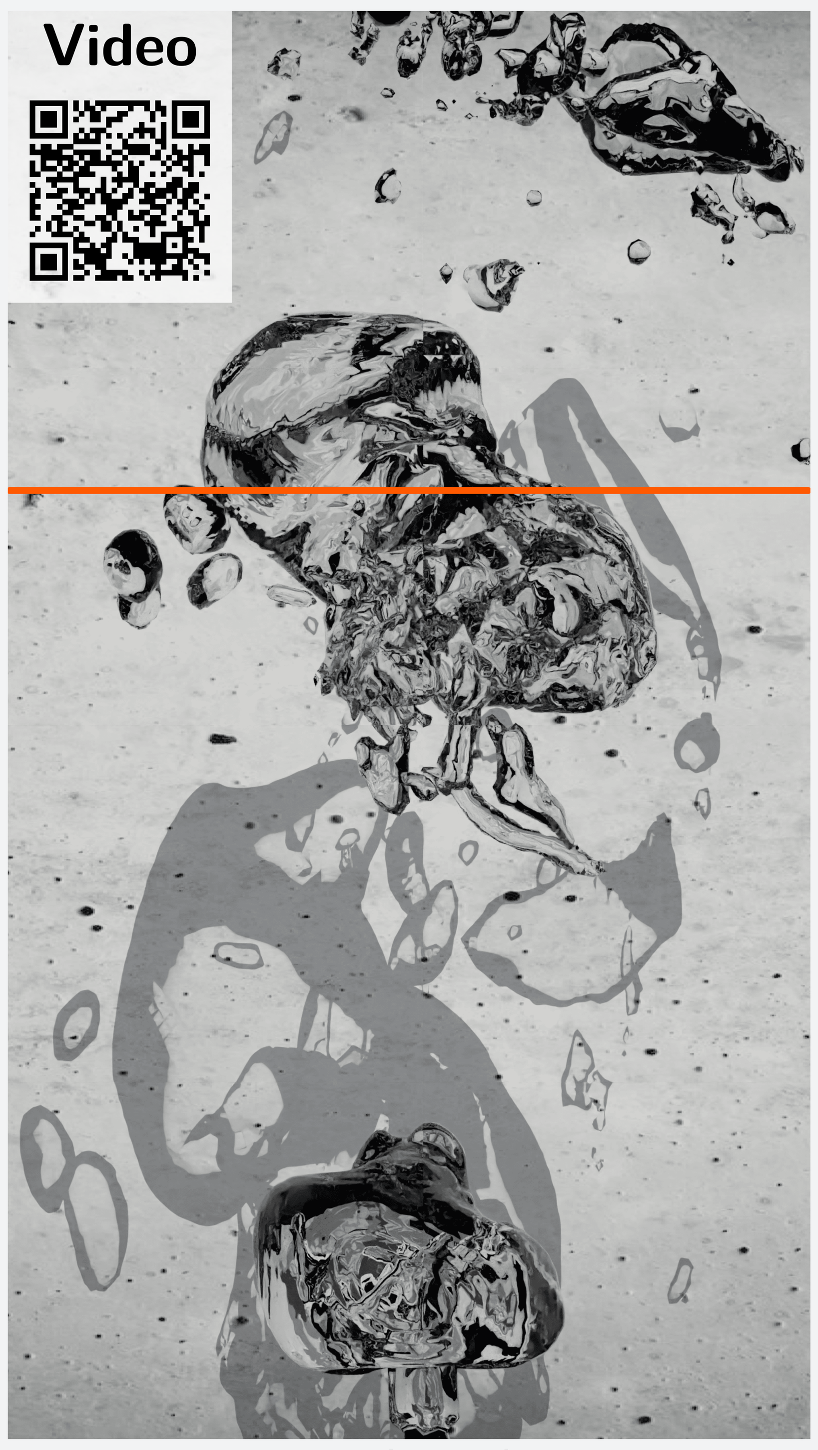
- Relative velocity higher than terminal velocity

Statistical results

Volume fraction α



Ray tracing visualization

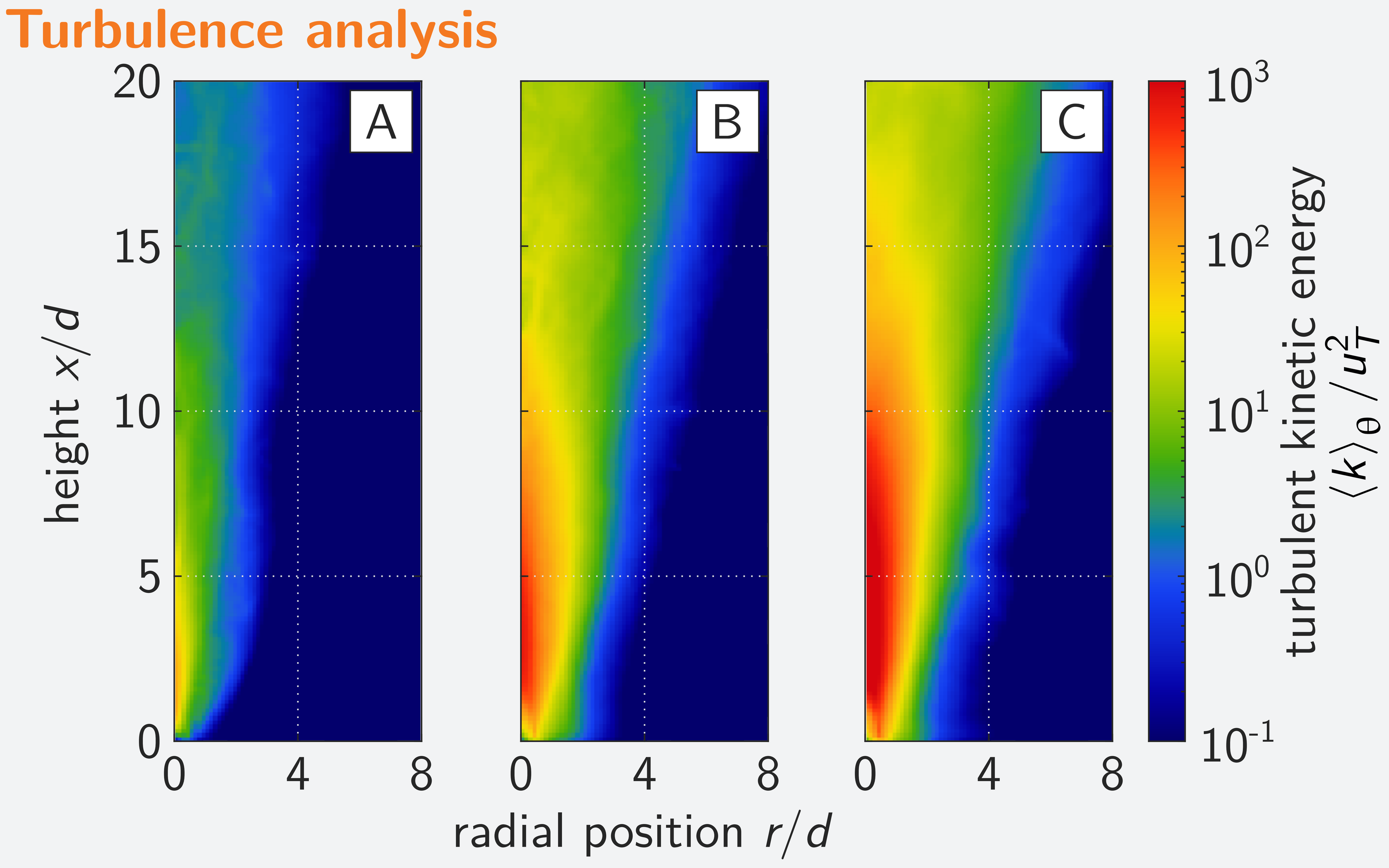


- Good agreement with literature values from Abe et al. (2018) and Liao et al. (2022) at a height of $x/d = 16$ (see orange line in ray tracing image)

Surface area of gas-liquid interface A

- Fluctuations $A' / \langle A\rangle_t$ for the different cases
- Standard deviation $\sigma_A = 20.2\,\%$, $\sigma_B = 22.2\,\%$, $\sigma_C = 23.1\,\%$
  - Potential indicator for increasing deposition rate at higher mass flow rates

Turbulence analysis



- Turbulent kinetic energy: $k = \frac{1}{2}\left\langle (u_x')^2 + (u_y')^2 + (u_z')^2 \right\rangle_t$
- Additionally calculated turbulence parameters: Dissipation rate ε, Kolmogorov length η and time scale τ_η, and Taylor length scale λ

Terminal velocity u_T

- Terminal velocity $u_T \approx 0.3\,\text{m/s}$ determined by peak of bubble size distribution ($d_b/d \approx 0.35$) and correlation equations

Conclusions and Outlook

- Method is capable of predicting flow and interface dynamics
- Valuable data base for developing efficient numerical models (e.g. Euler–Euler RANS)
- Identification of the influence of the domain size and boundary conditions
- Introduction of Lagrangian particles to predict decontamination factor

References

Abe, Y. et al. (2018). In: *Nucl. Eng. Des.* 337, pp. 96–107.

Aniszewski, W. et al. (2021). In: *Comput. Phys. Commun.* 263 (8), p. 107849.

Liao, Y., J. Li, and D. Lucas (2022). In: *Nucl. Eng. Des.* 390, p. 111713.