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CFD simulations of boiling flows in nuclear reactor conditions

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Context and Objective

Prediction of flow boiling in nuclear reactor condition using multiphase CFD is very sensitive to the modeling of **Interfacial heat transfer, forces, and area** [1]. These parameters are **interdependent**.

Standard approach [2, 3]:

1. Build an Interfacial Area Equation or population balance model to determine **bubble diameter**
2. Validate model on **adiabatic flows** using force closure terms
3. **Add condensation and boiling** terms to simulate complete system

Our approach:

1. **Select heat transfer and force terms**
2. Enforce 3D **experimental diameter** measurements in the flow
3. Validate models on **reactor similarity** experiment
4. **Future work**: model bubble diameter in reactor conditions

Numerical Toolkit

TrioCFD open-source CFD code developed at CEA [4].
Euler-Euler approach [5]:

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \vec{u}_k) = \Gamma_k$$

$$\frac{\partial(\alpha_k \rho_k \vec{u}_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \vec{u}_k \otimes \vec{u}_k) = -\alpha_k \nabla P + \nabla \cdot [\alpha_k \mu_k \nabla \vec{u}_k - \alpha_k \rho_k \overline{u'_i u'_j}] + \vec{F}_{ki} + \alpha_k \rho_k \vec{g}$$

$$\frac{\partial(\alpha_k \rho_k e_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k e_k \vec{u}_k) = -P (\partial_t \alpha_k + \nabla \cdot (\alpha_k \vec{u}_k)) + \nabla \cdot [\alpha_k \lambda_k \nabla T_k - \alpha_k \rho_k \overline{u'_i e'_k}] + q_{ki} + q_{kw}$$

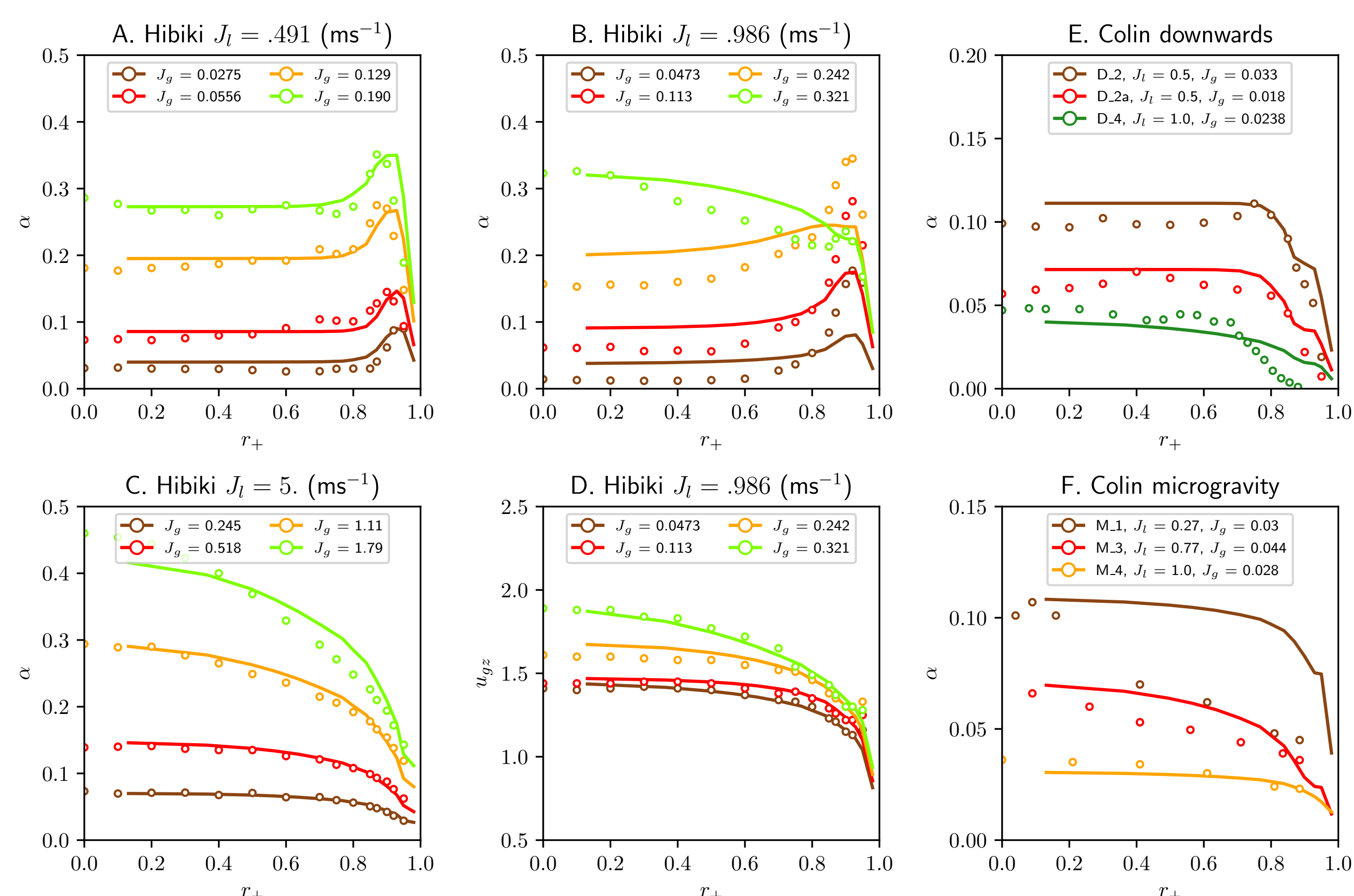
k- ω turbulence model [6]

Tomiyama drag force [7], **Burns turbulent dispersion** [8], **Sugrue lift force** [9], **Lubchenko wall lubrication** [10].

Zeitoun condensation [11], **Kurul-Podowski boiling** [12].

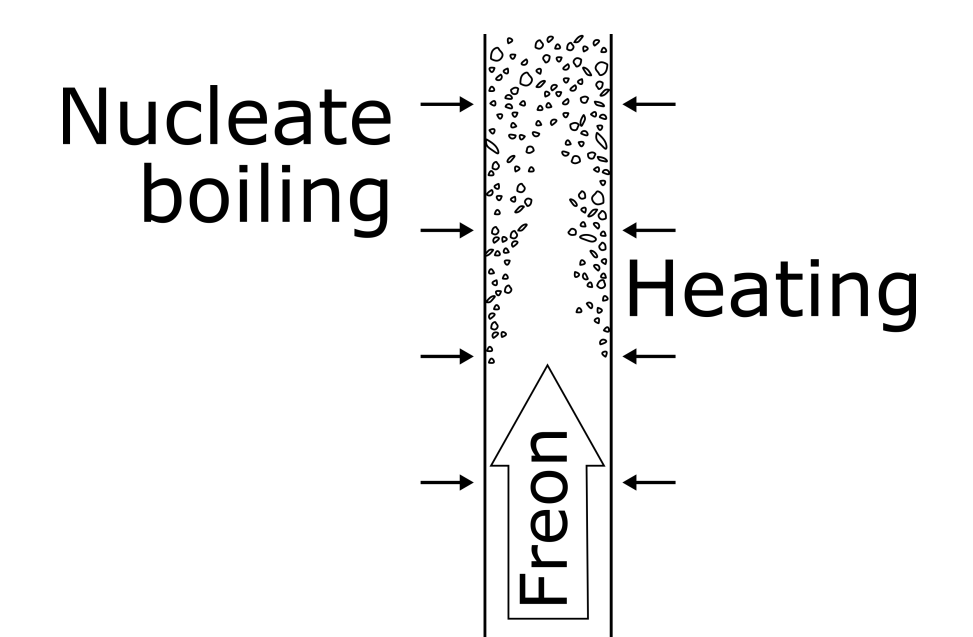
Air-water adiabatic validation

Upwards, downwards and micro-gravity flow experiments in pipes at atmospheric pressure [13, 14]. Steady-state radially-dependent experimental diameter is enforced in the simulations.



Debora: a reactor-similarity experiment

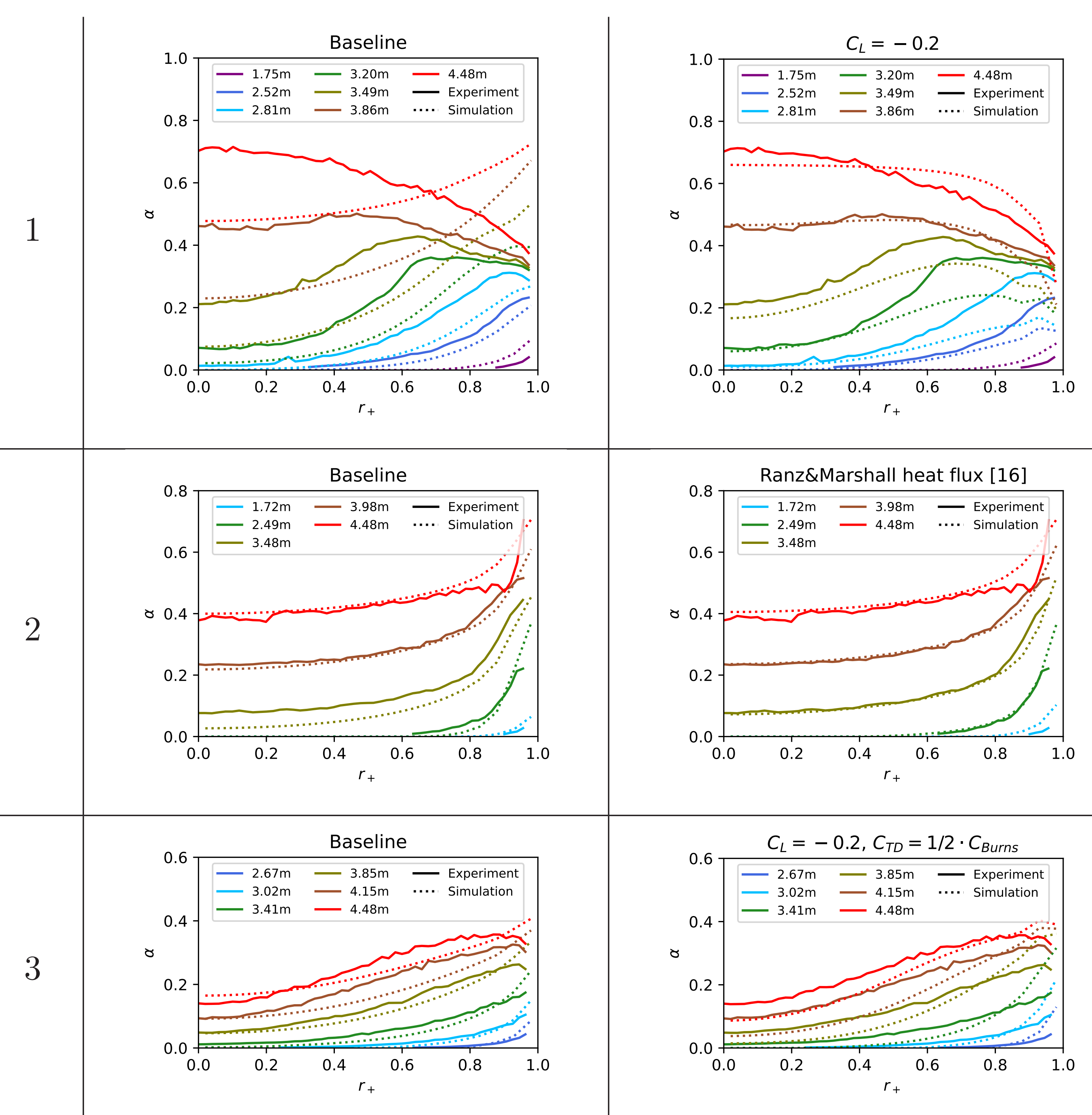
The Debora loop is a vertical heated Freon-12 pipe that fills **similarity criteria with nuclear reactor conditions** [15]. Density ratio, Weber number and Boiling number are respected.



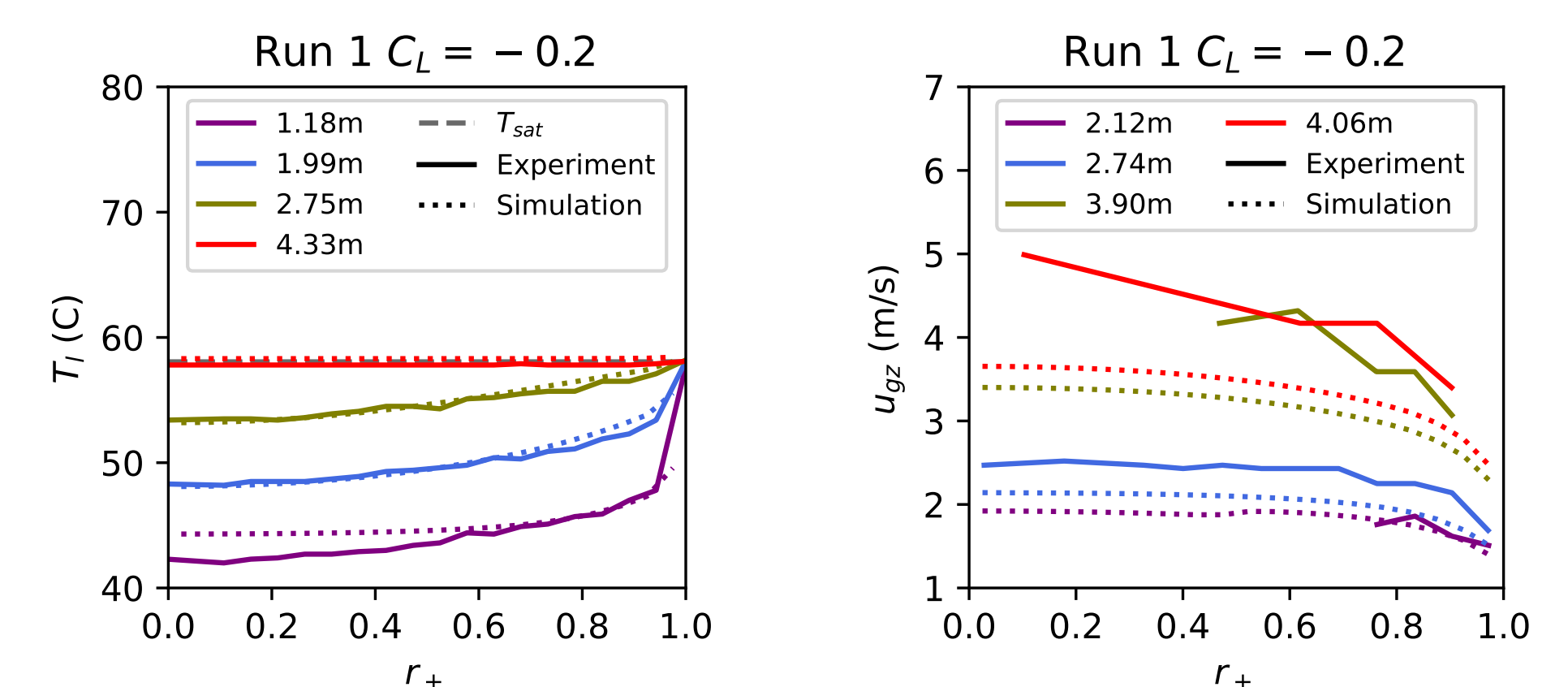
Liquid temperatures, void fractions, gas velocities and Sauter mean diameters are measured at different altitudes and radial positions.

Run number	1	2	3
Pressure similarity	Boiling Water Reactor	Pressurized Water Reactor	Pressurized Water Reactor
Liquid velocity	Maintenance ~2m/s	Maintenance ~1m/s	Normal operation ~3m/s

Boiling flow simulations



Temperature and gas velocity measures for run 1 with modified closures:



Conclusions and perspectives

- **Interfacial forces for isolated bubbles must be modified to simulate high void fraction, high pressure reactor flows**
- **Next step: build a unique set of closures for all runs**

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