Comprehensive Assessments of Boiling Models through Combinatorial Variations of Heat Flux Partitioning and Bubble Parameter Closures

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Contents

Introduction

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- Heat flux partitioning (HFP) models prevalent for modelling boiling flows in Eulerian-Eulerian CFD
- HFP models decompose total heat transfer
- Rely on closures for bubble dynamic parameters

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- Heat flux partitioning (HFP) models prevalent for modelling boiling flows in Eulerian-Eulerian CFD
- HFP models decompose total heat transfer
- Rely on closures for bubble dynamic parameters
    - A plethora of sub-models: Empirical, semi-empirical, and/or mechanistic
    - Limited predictive capability
        - Complex interdependency between bubble dynamics parameters
        - Overfitting of the model parameters on limited experimental data
        - Epistemological uncertainties: we do not fully understand the underlying physics

flow and operating conditions

fluid and surface thermophysical properties

single-phase heat transfer

departure frequency

departure diameter

nucleation site density

wait time

growth time

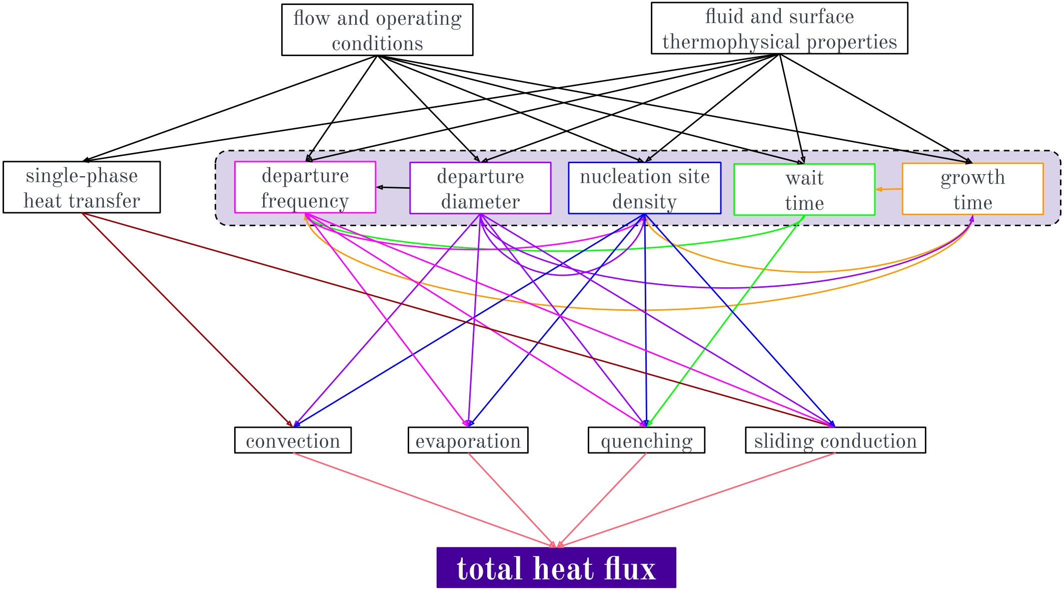
convection

evaporation

quenching

sliding conduction

total heat flux



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Eulerian-Eulerian CFD:

- Many closures: HFP and bubble parameter models; interfacial area transport modelling; bubble coalescence and break-up models; turbulence; ...
- Uncertainties in all the closures accumulate and obscure the uncertainties due to the HFP boiling models
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Zero-dimensional point-averaged simulations

- Model boiling at a point representative of the heater surface average conditions
- Heat fluxes modelled as explicit functions of wall superheat, flow conditions, characteristic length scale, fluid and surface thermophysical properties
- Cons: no spatio-temporal resolution such as CFD
- Pros: No need for iterative solutions; significantly fast runtimes ($\mathcal{O}(\text{ms})$); allows assessing boiling models' accuracy in isolation from other closures involved

XBOIL: MATLAB code

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- MATLAB code structured with modular functions
- Inputs: wall superheat and other operating parameters
- Outputs: bubble parameters and heat fluxes
- Allows easy selection between available models and additions of other sub-models
- Can sweep across all the different model combinations, along with graphical and tabular post-processing

Models implemented in XBOIL

Model type	Models implemented	Num. of models
Heat flux partitioning	RPI, MIT, Kim & Kim (based on RPI)	3
Bubble departure diameter	Bovard, Cole, Cole & Rohsenow, Colombo, Fritz, Golorin & Kolchugin, Kocamastafaogullari, MIT, Nam, Phan, Ruckenstein, Tolubisky & Kostanchuk, Van Stralen & Zijl	14
Bubble departure frequency	Brooks & Hibiki, Cole, MIT, Peebles & Garber, Sakashita & Ono, Stephan, Zuber	7
Nucleation site density	Hibiki & Ishii, MIT-modified Hibiki & Ishii, Lemmert & Chawla, Li, Wang & Dhir, Yang	6
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- Total number of possible configurations: 31,752
- Example computational cost: 19 ΔT_w points, with 12 Mac M4 Max Cores runs in 32.9 mins

Outline

Flow boiling experimental datasets

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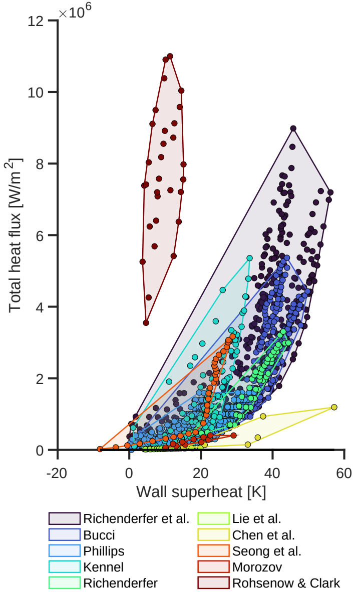
Table: Total of 112 boiling curves and 1,117 points.*

Dataset	p [bar]	u [m/s]	ΔT_{sub} [K]	n cases
Kennel (1949)	2–6	0.30–3.66	11.1–83.3	13
Rohsenow & Clark (1951)	103–138	3.05–9.14	69.5–109.0	5
Morozov (1969)	31–40.8	1.0	0	2
Chen et al. (1979)	1.01	0.20	40	1
Lie et al. (2006)	4.88	8.43–12.64	6, 13	5
Phillips (2014)	1.01–2.0	0.16–1.30	5–155	54
Richenderfer et al. (2018)	1.01–5.0	0.52–2.09	5–20	30
Lee et al. (2021)	1.0	1.0	76	1
Seong et al. (2022)	1.01	1.0	10	1

*All datasets use water as the working fluid except for Lie et al., which uses R-134a.

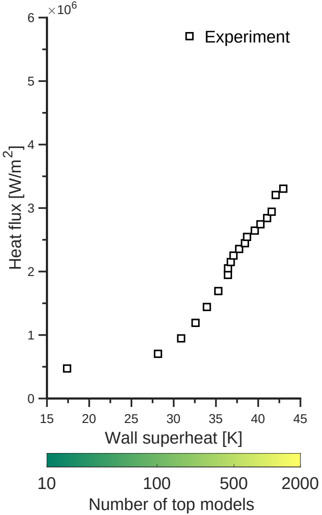
Table: Statistical summary of flow conditions

	Minimum	Maximum	Mean	Mode
Pressure [bar]	1.0	137.9	8.3	2.0
Velocity [m/s]	0.16	12.6	1.62	1.22
Subcooling [K]	0	109.0	17.9	10.0



Demonstrative boiling curve and selected sub-models

$p = 1$ bar, $u = 1$ m/s,
$\Delta T_{\text{sub}} = 10$ K



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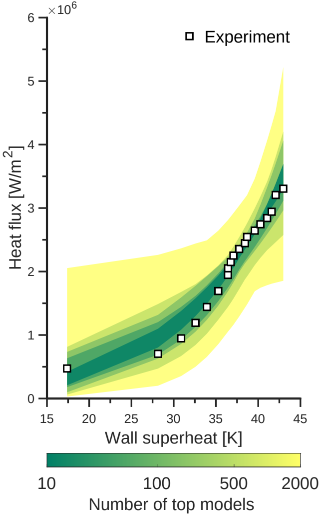

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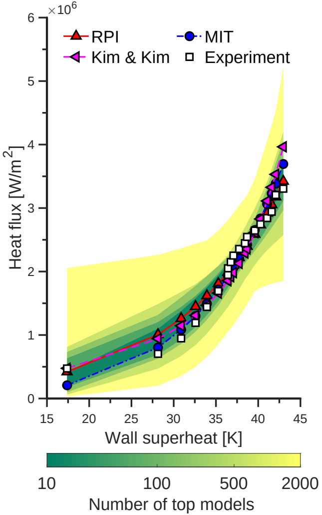

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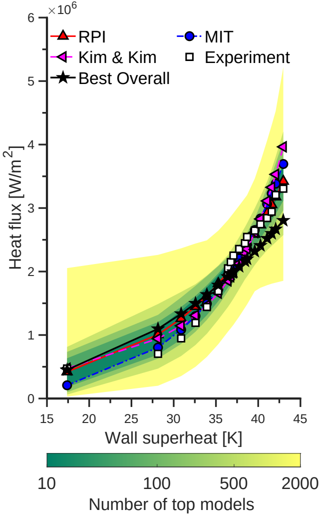

- <u>Best Case Models</u>: configuration with the lowest MSE for this boiling curve (best w/ each HFP shown as example)
- <u>Best Overall Model</u>: selection process
  - Rank top 100 models based on MSE
  - Pool these into a list of potential 'best overall' configurations
  - Test all pooled models across all tests cases
  - Select best overall-model as the one with the smallest aggregate MSE

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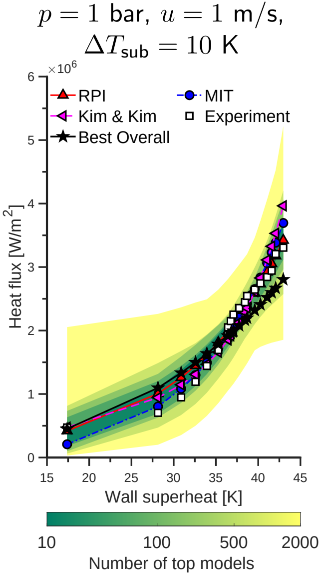

Model type	RPI	MIT	Kim & Kim	Best Overall
Heat flux partitioning	-	-	-	MIT
Departure diameter	Fritz	Phan	Ruckenstein	Van Stralen & Zijl
Departure frequency	Peebles & Garber	Peebles & Garber	Zuber	Stephan
Nucleation site density	Li et al.	Li et al.	Li et al.	Lemmert & Chawla
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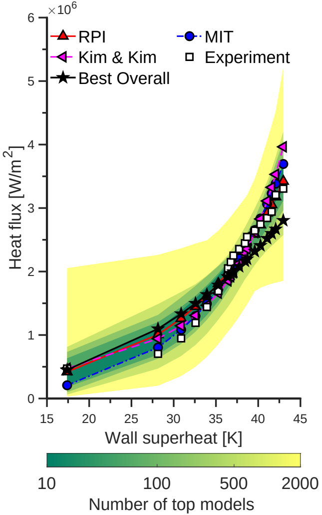

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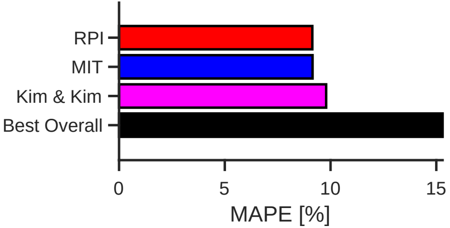

Comparison of bubble parameter predictions

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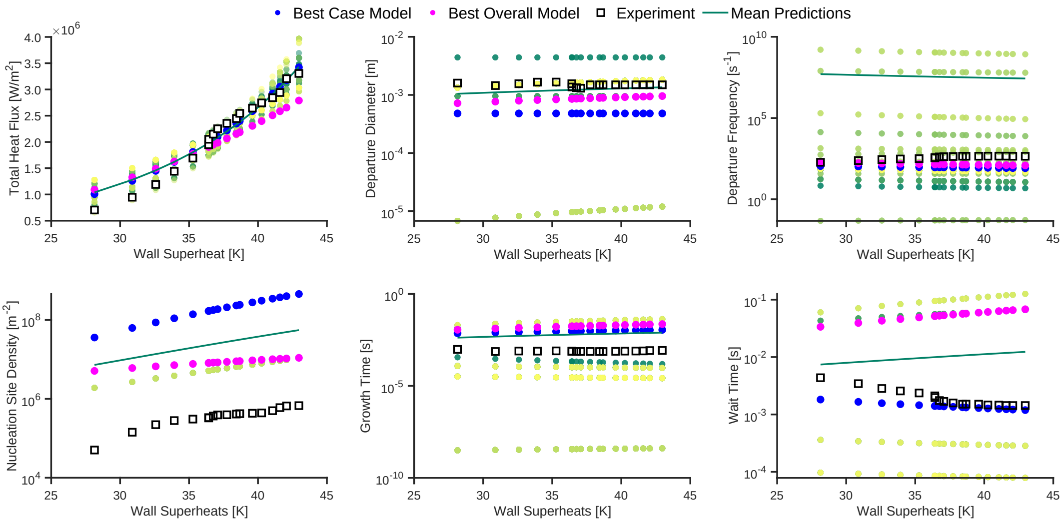
$$p = 1 \text{ bar}, \; u = 1 \text{ m/s}, \; \Delta T_{\mathsf{sub}} = 10 \text{ K}$$



Example boiling curves

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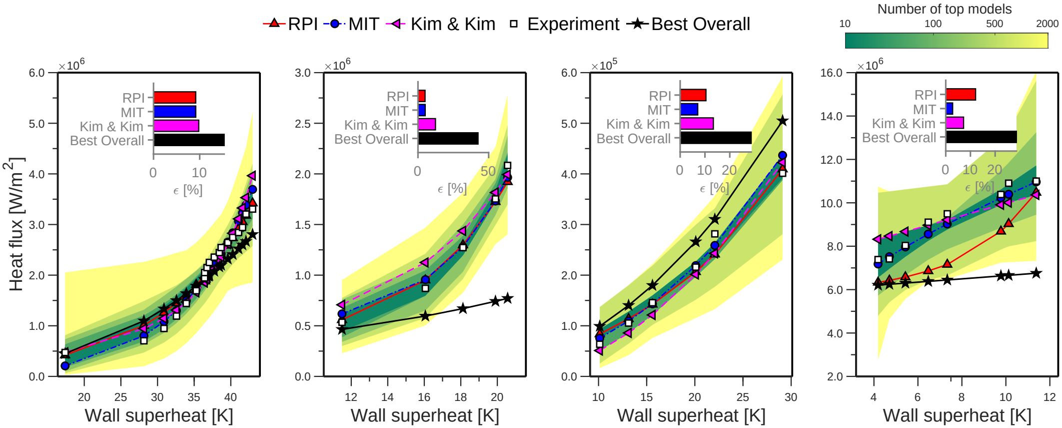

(a) p = 1 bar, ΔT_{sub} = 10 K, u = 1 m/s

(b) p = 6 bar, ΔT_{sub} = 28 K, u = 1 m/s

(c) p = 31 bar, ΔT_{sub} = 0 K, u = 1 m/s

(d) p = 138 bar, ΔT_{sub} = 80 K, u = 9 m/s

Performance of the best overall model across all the test cases

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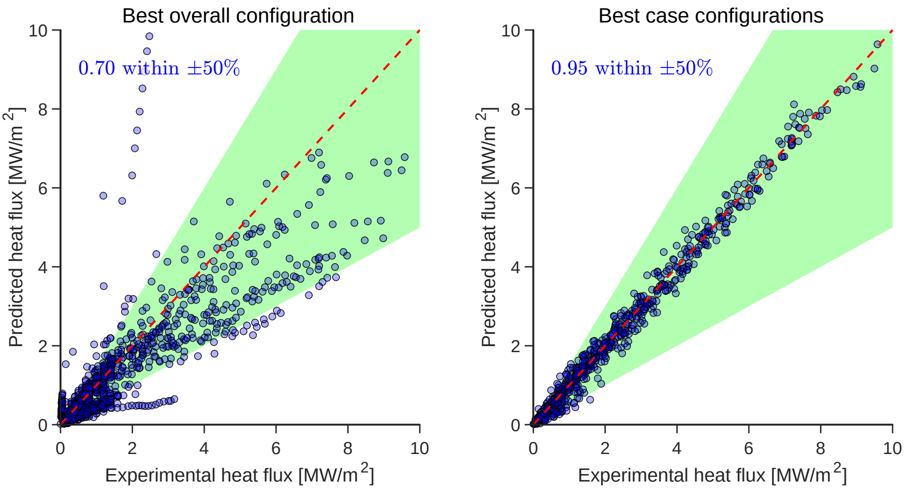

Sensitivity analysis of best overall configuration

- Perturb bubble parameters by $\pm 50\%$ of the predicted values: i) perturb the parameters one-at-a-time, ii) perturb all simultaneously.

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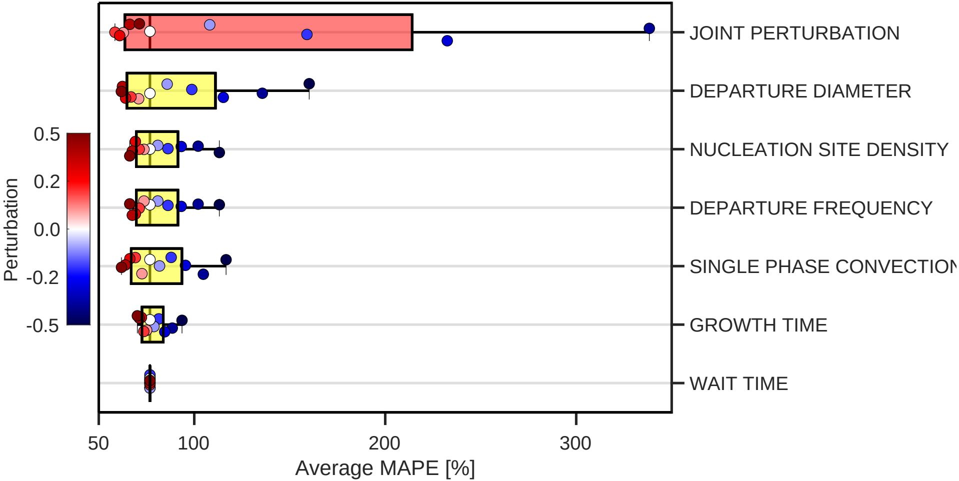

Assessing HFP models w/ experimental bubble parameters

- Use experimental values of bubble parameters in HFP models to predict heat flux.
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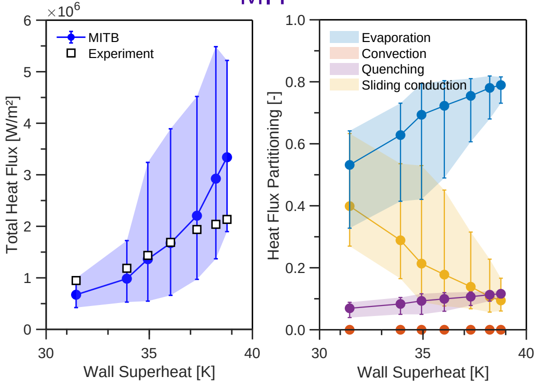

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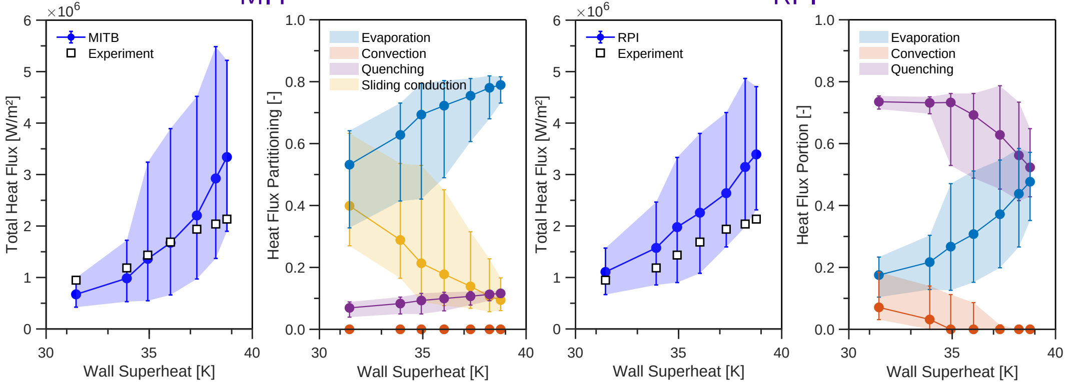

- Upper and lower limits computed by evaluating the HFP model with minimum and maximum values of experimental bubble parameters.

Conclusions and future work

- Models can reproduce experimental heat flux predictions, but need to use the right combination of sub-models.
  - Considerable discrepancy can exist between bubble parameter predictions and experimental measurements.
- No universal HFP model that provides consistently accurate results across various flow conditions.
- HFPs may produce similar heat flux predictions, but widely different breakdown of various components - lacking in physics.

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  - Integrating findings into multiphase CFD
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THANK YOU

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Example: MIT HFP model

total heat flux = single-phase + sliding conduction + evaporation + quenching

$$q'' = q''_c + q''_{sc} + q''_e + q''_q, \quad q''_e = q''_{ml} + q''_{in},$$

$$q''_c = \left(1 - S_{sl}\right) h_c \left(\Delta T_w + \Delta T_{\mathsf{sub}}\right),$$

$$q''_{sc} = \frac{k_l}{\sqrt{\pi\, \eta_l\, t^*}} S_{sl} \left(\Delta T_w + \Delta T_{\mathsf{sub}}\right),$$

$$q''_{ml} = \rho_l\, h_{lv}\, f\, \overline{N_b} \left\{ \delta_{ml}\, D^2_{ml}\, \frac{\pi}{12} \left[2 - \left(\left(\frac{D_{dry}}{D_{ml}}\right)^2 + \frac{D_{dry}}{D_{ml}}\right)\right] \right\}, q''_{in} = \frac{4}{3}\,\pi \left(\frac{D_{in}}{2}\right)^3 \rho_v\, h_{lv}\, f\, \overline{N_b},$$

$$q''_q = \rho_h c_{ph} \frac{2}{3} \pi \left(\frac{D_{\mathsf{inception}}}{2}\right)^2 f \overline{N}_b \Delta T_h.$$

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$$
\begin{aligned}
q'' &= q''_c + q''_{sc} + q''_e + q''_q, \quad q''_e = q''_{ml} + q''_{in}, \\
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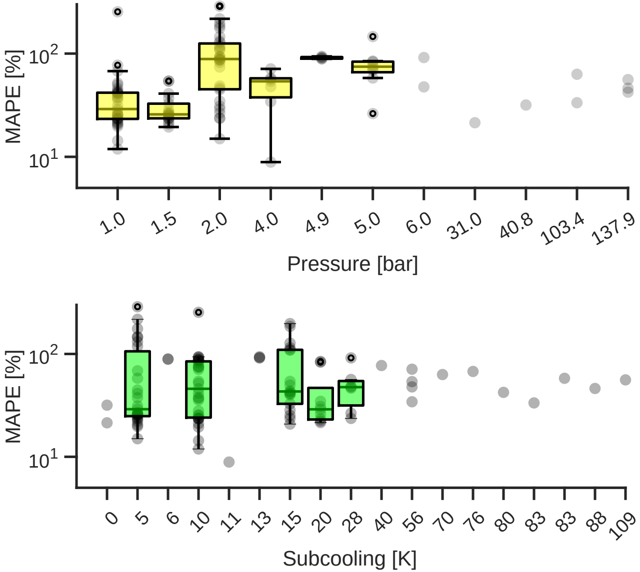
q''_{sc} &= \frac{k_l}{\sqrt{\pi\, \eta_l\, t^*}} S_{sl} \left(\Delta T_w + \Delta T_{\text{sub}}\right), \\
q''_{ml} &= \rho_l\, h_{lv}\, f\, \overline{N_b} \left\{ \delta_{ml}\, D^2_{ml}\, \frac{\pi}{12} \left[2 - \left(\left(\frac{D_{dry}}{D_{ml}}\right)^2 + \frac{D_{dry}}{D_{ml}}\right)\right] \right\}, q''_{in} = \frac{4}{3}\,\pi \left(\frac{D_{in}}{2}\right)^3 \rho_v\, h_{lv}\, f\, \overline{N_b}, \\
q''_q &= \rho_h c_{ph} \frac{2}{3} \pi \left(\frac{D_{\text{inception}}}{2}\right)^2 f \overline{N}_b \Delta T_h.
\end{aligned}
$$

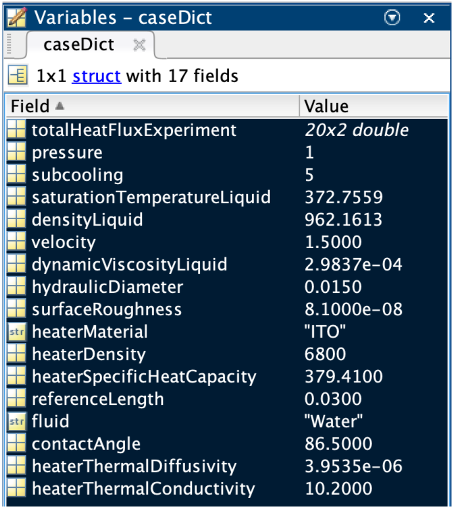
- flow conditions: ΔT_w, ΔT_{sub}
- fluid and surface thermophysical properties: k_l, η_l, ρ_l, ρ_v, h_{lv}, ρ_h, c_{ph}
- bubble parameters: D, f, $\overline{N_b}$, etc.

Flow condition effect w/ best overall model



Example code snippet

```matlab
% define the global parameters
getGlobalParams(struct( ...
    'caseDict', caseDict, ...
    'HFPModel', 'RPI', ...
    'departureDiameterModel', 'Stephan',
    'waitTimeModel', 'VanStralen', ...
    'growthTimeModel', 'VanStralen', ...
    'departureFrequencyModel', 'Cole', ...
    'nucleationSiteModel', 'LemmertChawla', ...
    'convectiveModel', 'Gnielinski'));
% define the wall superheats
wallSuperheats = linspace(1, 21, 30);
% calculate the total heat fluxes
for i = 1:length(wallSuperheats)
    wallSuperheatI = wallSuperheats(i);
    totalHeatFlux(i) = calcTotalHeatFlux(
        wallSuperheatI);
end
```


Variables – caseDict

caseDict

1x1 struct with 17 fields

Field	Value
totalHeatFluxExperiment	*20x2 double*
pressure	1
subcooling	5
saturationTemperatureLiquid	372.7559
densityLiquid	962.1613
velocity	1.5000
dynamicViscosityLiquid	2.9837e-04
hydraulicDiameter	0.0150
surfaceRoughness	8.1000e-08
heaterMaterial	"ITO"
heaterDensity	6800
heaterSpecificHeatCapacity	379.4100
referenceLength	0.0300
fluid	"Water"
contactAngle	86.5000
heaterThermalDiffusivity	3.9535e-06
heaterThermalConductivity	10.2000