Master's Thesis Engineering Technology

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Development and Validation of a CFD Multiphase Model for Micro-channels

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INTRODUCTION

The increasing global demand for flexible and low-carbon energy solutions has renewed interest in Small Modular Reactors (SMRs). A key component in these systems (and in many other high-efficiency technologies) is the Microchannel Heat Exchanger (MCHE).

Due to their small scale and high surface-area-to-volume ratio, MCHEs benefit significantly from two-phase flow phenomena, which enhance thermal performance through latent heat. However, these same phenomena introduce complex challenges in modeling such as strong surface tension effects, flow regime sensitivity, and interface-driven instabilities.

To address this, Computational Fluid Dynamics (CFD) has become a key tool. This work focuses on developing a CFD model for two-phase flow in microchannels using the Eulerian–Eulerian approach. The model aims to capture key thermo-hydraulic properties under varying operating conditions, serving as a predictive framework for MCHE design and optimization.

RESULTS

BASELINE MODEL: VERTICAL SMALL CHANNEL

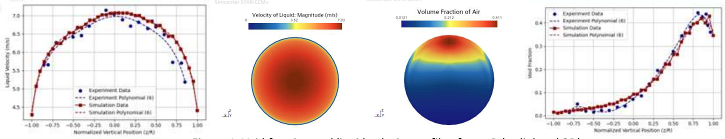

Figure 1: Void fraction and liquid velocity profile of case B (radial and 2D).

The model showed stable behavior across four different cases (A-B-C-D) and reproduced experimental void-fraction and liquid velocity profiles with average deviations of 4–11% as seen on Figure 1. The turbulent dispersion (C_{TD}) coefficient was found to be 0.80–0.85 and fell within literature ranges [1-3]. Minor deviations at low void fractions were attributed to reduced wall lubrication effects. A mesh sensitivity study confirmed the butterfly mesh performed best near walls. Overall, strong agreement with reference data and good mass conservation validate the model as a solid foundation for subsequent boiling simulations.

Figure 2: Effect of C_{TD} on baseline model (compressed view)

REFINED MODEL: HORIZONTAL MICROCHANNEL

To deal with the complex geometry of the Triplett experiment, a correction ratio (Ψ) was developed to adjust inlet values and match experimental averages, based on the velocity ratio (u_{dc}) [4]:

$$\Psi = \begin{cases} 1.2215 \cdot u_{dc}^{-0.813}, & \text{for } 0.05 < u_{dc} < 1 \\ \min\left[0.8, 0.5 + 0.432 \cdot \ln\left(\frac{u_{dc}}{0.5}\right)\right], & \text{for } 1 < u_{dc} < 1 \end{cases} \quad (1)$$

The correction factor performed well for high velocity ratios but underpredicted lower velocity ratios.

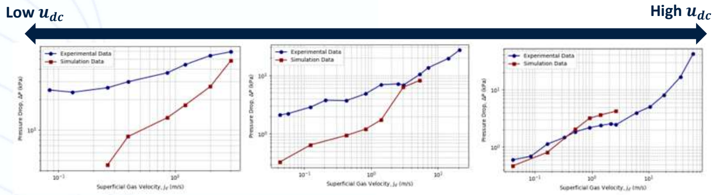

Figure 3: Pressure drop curves for case A (right), B (middle), C (left)

Using the void fraction correction method, pressure drop simulations were performed for three cases with distinct velocity ratios (A: $[u_{dc} > 1]$, B: $[u_{dc} \approx 1]$ and C: $[u_{dc} < 1]$). Simulations captured the trend and shape of experimental data well, but magnitude agreement varied as seen on Figure 3. Best results were seen in case A, cases B and C underpredicted pressure drop, primarily due to inaccurate void fraction initialization (predicted by Ψ) at low velocity ratios. This suggests that improving void initialization could significantly enhance model accuracy in transitional and liquid-dominant regimes.

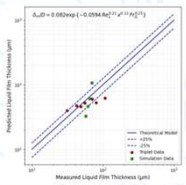

Figure 4: Liquid film calculations

Additionally, four flow regimes (bubbly, slug, wavy-annular, and annular) were qualitatively reproduced and compared to Triplett's experiments [4]. While bubbly flows were poorly captured, slug and annular flows showed more realistic structure. Annular flow was most accurately predicted, especially at higher gas velocities. Lastly, simulated liquid film thicknesses were compared against theoretical and experimental data [4,5]. Results generally aligned within ±25% of the theoretical curve. Moderate velocity conditions showed the best match, while extremes showed slight under- or overprediction. Overall, the model demonstrated good potential for capturing annular film dynamics in microchannels.

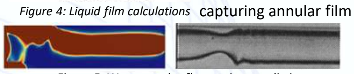

Figure 5: Wavy-annular flow regime prediction

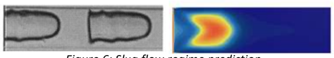

Figure 6: Slug flow regime prediction

MATERIALS & METHODS

A modular modeling strategy was adopted to develop the CFD framework in STAR-CCM+. The process began with an adiabatic two-phase interaction model (baseline and refined) and was subsequently extended to incorporate boiling and heat transfer effects. The Eulerian–Eulerian approach was used throughout, which requires modelling of the interfacial forces and boiling (dynamics). At each stage, the most suitable sub-models were selected based on a comprehensive literature review and iterative validation. The final model configuration ensures accurate prediction of interfacial forces and boiling dynamics across varying orientations, pressures, and geometries:

Table 1: Used sub-models for each modelling phase

Model	Drag Force	Lift Force	WL Force	TD Force	VM Force	Boiling	B- Dynamics
Baseline	Tomiyama	Sugrue	Antal	Lopez	Zuber	-	-
Refined	Tomiyama	Constant	Lubchenko	Burns	-	-	-
Boiling	Tomiyama	Constant	Lubchenko	Burns	-	All-Pressure	MITB

Regarding the other fundamental sub-models needed in the Eulerian–Eulerian approach (turbulence, bubble group sizing, and wall treatment), no extensive analysis was done in this study, as they were assumed to have a comparatively lower impact on the results. Nevertheless, standard and robust choices were made: the k–ε turbulence model, the S-Gamma approach for bubble groups, and a wall treatment targeting the log-law region.

Additionally, mesh sensitivity analyses and literature insights indicated that a directed butterfly meshing strategy yielded optimal results across all modeling stages.

BOILING MODEL: VERTICAL MICROCHANNEL

The boiling model accurately reproduced the pressure drop profile from Sumith et al., with an average error of 0.93% [6]. Simulations captured annular flow formation and liquid film dynamics. Deviations were linked to over/underprediction of film thickness, influenced by the excluded wall lubrication force (suggesting an improved model). The model also reproduced wall temperatures with <0.7% error. Overall, pressure and heat transfer trends were consistent with literature, validating the model under boiling conditions.

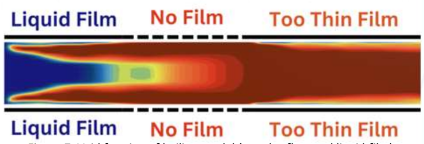

Figure 7: Void fraction of boiling model (annular flow and liquid film)

Additionally, wall superheat behavior was studied under varying heat and mass fluxes. Simulated wall temperatures showed good agreement with experiments. Key turning points (pink markers in Figure 9) marked transitions in boiling regimes: from nucleate boiling to annular flow, and from film evaporation to partial dry-out. While local heat transfer coefficients were overpredicted, superheat difference trends offered insight into film thinning and regime shifts. Future refinement of the model is needed for more accurate local effects.

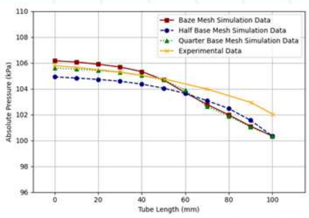

Figure 8: Mesh base size optimalization results

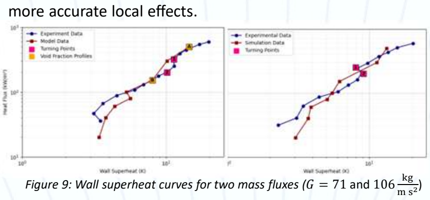

Figure 9: Wall superheat curves for two mass fluxes ($G = 71$ and $106 \frac{\text{kg}}{\text{m s}^2}$)

Lastly, a 0.1 mm base butterfly mesh gave the most consistent annular flow and film structure. Finer meshes (0.025–0.05 mm) introduced artifacts like inverted flow and dry walls. Pressure drop improved slightly at early regions with refinement, but deeper deviations were traced to physical modeling limits. A quadrilateral mesh failed to resolve annular patterns, required 4–5× more time, and produced inverted core flow. The butterfly mesh is thus recommended for reliable and efficient boiling flow simulations.

CONCLUSION

The adiabatic models show good agreement with literature in vertical small channels and horizontal microchannels using the chosen sub-models. Additionally for the Triplett geometry, a correction method for void fraction initialization was developed and validated. The model captures key fluid dynamics characteristics such as void fraction and velocity profiles, pressure drops (high u_{cd} ratios, flow regimes (annular) and liquid films. Mesh sensitivity studies confirmed the butterfly mesh as the most accurate and efficient for resolving near-wall structures and flow morphology.

The boiling model extended the adiabatic framework by incorporating phase-change effects, achieving excellent agreement with experimental pressure drops (≤ 0.93% error) and wall temperatures (≤ 0.7% error). It captured the development and dynamics of the annular liquid film. Wall superheat trends revealed key flow and heat transfer regime transitions, aligning with literature and confirming predictive capability. Mesh studies reinforced the butterfly mesh as optimal, with finer or structured alternatives introducing artifacts.

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References:
[1] Iskandrani and G. Kojasoy, "Local void fraction and velocity field descriptionin horizontal bubbly flow," *Nuclear Engineering and Design*, vol. 204, no. 1–3, pp.117–128, Feb. 2001.
[2] M.A. Lopez de Bertodano, Turbulent bubbly two-phase flow in a triangular duct, Ph.D. dissertation, Rensselaer Polytechnic Institute, 1992.
[3] K. Ekambara, R. Sanders, K. Nandakumar, and J. Masliyah, "Cfd simulation ofbubbly two-phase flow in horizontal pipes," *Chemical Engineering Journal*, vol. 144,no. 2, pp. 277–288, Oct. 2008.
[4] Triplett, S. Ghiaasiaan, S. Abdel-Khalik, and D. Sadowski, "Gas–liquid two-phase flow in microchannels part i: two-phase flow patterns," *International Journal of Multiphase Flow*, vol. 25, no. 3, pp. 377–394, Apr. 1999.
[5] E. Krepper, D. Lucas, and H.-M. Prasser, "On the modelling of bubbly flow in vertical pipes," *Nuclear Engineering and Design*, vol. 235, no. 5, pp. 597–611, Feb. 2005.
[6] B. Sumith, F. Kaminaga, and K. Matsumura, "Saturated flow boiling of water in a vertical small diameter tube," *Experimental Thermal and Fluid Science*, vol. 27, no. 7, pp. 789–801, Sep. 2003