Unified Modeling Suite for two-phase flow, convective boiling and condensation in macro- and micro-channels

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The present paper focuses on the unified modeling suite for annular flow that the authors have and continue to develop. First, the unified suite of methods is presented, illustrating in particular the most recent updates. Then, results for convective evaporation of refrigerants in non-circular multi-microchannel configurations for microelectronics cooling are presented and discussed. The annular flow suite includes models to predict the void fraction, the entrained liquid fraction, the wall shear stress and pressure gradient, and a turbulence model for momentum and heat transport inside the annular liquid film. The turbulence model, in particular, allows prediction of the local average liquid film thicknesses and the local heat transfer coefficients during convective evaporation and condensation. The benefit of a unified modeling suite is that all the included prediction methods are consistently formulated and are proven to work well together, and provide a platform for continued advancement based on the other models in the suite. Annular flow is of fundamental importance to the thermal design and simulation of micro-evaporators and micro-condensers for compact two-phase cooling systems of high heat flux components for the thermal management of computer chips, power electronics, laser diodes and high energy physics particle detectors. In micro-evaporators, annular flow is even more conspicuous than in macrochannels, since annular flow relegates bubbly and slug flows to only the first 3-10% of the vapor quality range. In convective condensation, annular flow is established almost immediately at the inlet of the channel and persists over most of the condensation process until the condensate floods the channel.

The purpose of the present paper is to present the unified modeling suite for annular flow that the authors have and continue to develop, focusing in particular on the prediction of the pressure drop and the heat transfer coefficient during convective evaporation in not only circular but most of all in non-circular multi-microchannels that are typical of microscale heat sinks. Presently, the unified annular flow modeling suite includes methods to predict the entrained liquid fraction, the void fraction, the walls shear stress, the frictional and total pressure gradients, and a turbulence model for momentum and heat transport inside the annular liquid film that allows *one method* for the prediction of the local average liquid film thickness and the local heat transfer coefficient during *both* convective evaporation and condensation ([1]-[8]). The practical advantage of a unified modeling suite is that all the included prediction methods are consistently formulated and are proven to work well together.

The heat transfer methods have been adapted to non-circular (rectangular and square) microchannels as well as the microchannels in a multi-port aluminum tube, without changing of the underlying equations but just stretching of the liquid film around the larger perimeter. Some examples of comparisons to the data are as follows:

Costa-Patry et al. ([9], [10]) for R245fa and R236fa flowing in 135 high aspect ratio silicon multi-microchannels is shown in Fig. 1. The channels were 85 μm-wide, 560 μm-high, aspect ratio of 6.56, hydraulic diameter of 136 μm, 12.7 mm-long, and separated by 47 μm-wide fins. Their heat transfer coefficients measured under non-uniform heat flux conditions are compared with the annular flow models predictions in Fig. 2, where both hot-spot and hot-row heat flux profiles have been tested.

Szczukiewicz et al. ([11],[12]) investigated two-phase flow evaporation of refrigerants R245fa, R236fa and R1234ze(E) flowing in 67 square cross section, silicon multi-microchannels, as shown in Fig. 3. The channels were 100x100 μm size, aspect ratio of 1.0, hydraulic diameter of 100 μm, 10.0 mm-long, and separated by 48 μm-wide fins. The agreement between measured data and predictions is quite satisfactory for R236fa and R245fa, while the R1234ze(E) data are somewhat underpredicted.

References

[1] Cioncolini, A., Thome, J.R., Lombardi, C., (2009a). Algebraic turbulence modeling in adiabatic gas-liquid annular two-phase flow. *Int. J. Multiphase Flow*, Vol. 35, pp. 580-596.

[2] Cioncolini, A., Thome, J.R., Lombardi, C., (2009b). Unified macro-to-microscale method to predict two-phase frictional pressure drops of annular flows. *Int. J. Multiphase Flow*, Vol. 35, pp. 1138-1148.

[3] Cioncolini, A., Thome, J.R., (2010). Prediction of the entrained liquid fraction in vertical annular gas-liquid two-phase flow. *Int. J. Multiphase Flow*, Vol. 36, pp. 293-302

[4] Cioncolini, A., Thome, J.R., (2011). Algebraic turbulence modeling in adiabatic and evaporating annular two-phase flow. *Int. J. Heat Fluid Flow*, Vol. 32, pp. 805-817.

[5] Cioncolini, A., Thome, J.R., (2012a). Entrained liquid fraction prediction in adiabatic and evaporating annular two-phase flow. *Nucl. Eng. Des.*, Vol. 243, pp. 200-213.

[6] Cioncolini, A., Thome, J.R., (2012b). Void fraction prediction in annular two-phase flow, *Int. J. Multiphase Flow*, 43, pp.72-84.

[7] Cioncolini, A., Thome, J.R., (2012c). Algebraic turbulence modeling in condensing annular two-phase flow: preliminary results, *ECI 8th International Conference on Boiling and Condensation Heat Transfer*, Lausanne, Switzerland, 3-7 June 2012.

[8] Cioncolini, A., Thome, J.R., (2013). Liquid film circumferential asymmetry prediction in horizontal annular two-phase flow, *Int. J.*

Multiphase Flow, 51, pp. 44-54.

[9] Costa-Patry, E., Olivier, J., Nichita, B., Michel, B., Thome, J.R., (2011a). Two-phase flow of refrigerants in 85μm-wide multi-microchannels, Part I: pressure drop. *Int. J. Heat Fluid Flow*, Vol. 32, pp. 451-463.

[10] Costa-Patry E., Olivier, J., Michel, B., Thome, J.R., (2011b). Two-phase flow of refrigerant in 85 μm-wide multi-microchannels: Part II: heat transfer with 35 local heaters. *Int. J. Heat Fluid Flow,* Vol. 32, pp. 464–476.

[11] Szczukiewicz, S., Borhani, N., Thome, J.R., (2012a). Two-phase flow boiling in a single layer of future high-performance 3D stacked computer chips. In *13th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems*.

[12] Szczukiewicz, S., Borhani, N., Thome, J.R., (2012b). Two-phase heat transfer and high-speed visualization of refrigerant flows in 100 x 100 μm^2 silicon multi-microchannels. In *ECI 8th International Conference on Boiling and Condensation Heat Transfer,* Lausanne, Switzerland, 3-7 June 2012.