Convective condensation at small scales: Experimental and analytical advances

Srinivas GARIMELLA[1,*]

* Corresponding author: Tel.: ++1 404 894 7479; Fax: ++1 404 894 8496; Email: sgarimella@gatech.edu
1 Sustainable Thermal Systems Laboratory, Georgia Institute of Technology, Atlanta, USA

Interest in mini- and microscale geometries for the enhancement of heat transfer started in the early 1980s, with a focus on single-phase heat transfer enhancement. The small hydraulic diameters (D_h) led to high heat transfer coefficients (h), and also enabled high surface-to-volume ratios. These two features of smaller D_h led to the reduction of heat transfer resistance ($1/hA$), enabling high heat transfer rates in small packages. The electronics cooling industry, grappling with ever increasing heat dissipation from chips, provided the impetus for high flux geometries. Single-phase microscale heat transfer yielded to interest in boiling heat transfer due to the considerably higher h during phase change. This was important to remove the high heat dissipation rates from chips constrained to small spaces, and also because the chip-to-coolant resistance formed one of the dominant thermal resistances. Interest in condensation at the microscales lagged, however, because heat removal is often accomplished through rejection to ambient air, which presents the more significant thermal resistance.

In the early 1980s, with the dual emphases on reducing heat exchanger size due to smaller vehicles, and the phasing out of CFCs, automotive manufacturers started departing from round tube/flat fin geometries for condensers. The combination of multi-port microchannel extrusions in rectangular tubes and multilouver fins for the air-side led to the interest in condensation at the small scales. Because the multilouver fins provided higher air-side heat transfer h while also providing 10-20 times the surface area of the tubes, understanding the thermal resistance on the condensation side became more important. In several cases, condensers could benefit from the higher tube-side h possible with smaller D_h. The headered arrays of rectangular multiport tubes also offered the opportunity for the optimization of tube-side pass arrangements. Automobiles saw a relatively quick adoption of condensers with rectangular tubes with $400 < D_h < 700$ μm ports.

The understanding of condensation phenomena lagged behind the adoption of microchannel condensers. Initially, condensers were designed based on extrapolations of correlations for flow regime transition criteria, pressure drop, void fraction, and heat transfer for $8 < D_h < 25$ mm. These extrapolations were also across working fluids, because much of the literature on flow regimes in large D_h channels was based on air-water mixtures simulating condensing flows, and due to their typical origins in power plant applications, condensing steam. The significant differences in properties between air-water or steam on the one hand and condensing synthetic refrigerants on the other, in particular the vast differences in vapor-phase densities and surface tension, make such extrapolations ineffective in predicting condensation phenomena for these much different fluids. Also, the relative influence of gravity, shear, viscous forces and surface tension change significantly as D_h is reduced.

With the goal of achieving a comprehensive self-consistent modeling capability for condensation at small D_h for a wide range of fluids based on the underlying physics rather than purely empirical correlations, a small but growing research community, including the present author and coworkers, started systematically addressing these phenomena. The emphasis was on understanding the coupled flow morphology (i.e., flow regime and void fraction), and momentum, heat and mass transfer. Flow regimes were investigated in the late 1990s through visualization of the actual condensation process instead of surrogates through innovative test section designs that enabled visual access at the high saturation pressures characteristic of "real world" condensation. These experiments documented the decreasing influence of gravity and the dominance of surface tension effects at smaller D_h. Annular and intermittent flows were shown to dominate, while gravity dependent stratified/wavy flows were largely absent. Flow regime maps and transition criteria based on dimensionless parameters were introduced for a range of synthetic fluids with operating pressures all the way up to the critical pressure, in circular and noncircular geometries with D_h as small as 400 µm. These higher pressures are particularly important because almost all the refrigerants that replace the original high ozone depletion potential CFCs, and those that will replace the high GWP HFCs, require operation at much higher pressures for heat rejection. Flow visualization also revealed new insights into the void fraction, which is necessary for closure to models for determining pressure drops and *h*. Computational tools were developed using interface recognition and spline fitting techniques to identify phase distributions, which, along with models of interface boundaries, yielded void fractions.

Frictional pressure drop during convective condensation has been measured across small vapor quality changes. For annular flows, two-phase multipliers with the corresponding interfacial shear based on measurements at these small scales have yielded considerable success. For intermittent flows, mechanistic models that account for the pressure drops in the liquid slug, the interfacial shear at the liquid film-vapor bubble interface, and due to the transitions between the vapor bubble region and the liquid slug region fore and aft of the bubble have yielded excellent predictive capabilities. Measurement of condensing *h* poses unique challenges due to inability of direct heat duty measurements, as would be possible from electrical heat input in boiling experiments. The thermal amplification technique developed by the author, which addresses the coupled conflicting challenges of heat duty and thermal resistance measurement individually, has enabled accurate measurement of these heat transfer coefficients. Heat transfer models, with closure based on the underlying void fraction and pressure drop models, are yielding a unified, consistent picture of all relevant microchannel condensation phenomena.

Attention has now turned to condensation of multi-constituent zeotropic mixtures of fluids, e.g., ammonia-water and hydrocarbons. The zeotropic nature of these mixtures present new challenges due to the introduction of temperature and concentration gradients and coupled heat and mass transfer resistances in liquid and vapor phases. The author and his coworkers have investigated these coupled phenomena for several mixtures ranging from near-azeotropic to high zeotropic, and characterized the applicability of engineering approximations such as the Silver-Bell-Ghaly method, as well as the more rigorous non-equilibrium methods that explicitly address the relevant resistances in both phases. Research is also underway to address maldistribution in parallel channels typical of actual condensers.

Challenges remain. As D_h decreases, optical techniques to characterize flow phenomena reach their limits. At such small scales, *h* continues to rise, while due to the low mass flow rates, the heat duty that must be measured decreases drastically, making the measurement of *h* particularly challenging. Furthermore, with the increasing interest in binary fluid mixture condensation, it is important that novel nonintrusive techniques for measuring local surface and fluid temperatures be developed, so that the corresponding analytical models can be validated locally. The influence of surface tension over these ranges of mixtures, operating conditions, and geometries also requires more rigorous modeling than has been possible thus far. These challenges provide a roadmap for the investigation of convective condensation for a wide range of applications such as electronics cooling, air-conditioning and refrigeration systems, small-scale portable cooling and heating systems, and medical devices.