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Condensation at Small Scales: Measuring, Modeling, and Applications

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Abstract

Research on convective condensation has been accelerating over the past few decades, spurred by multiple drivers such as phase-out of a variety of synthetic refrigerants due to climate change concerns, the need for compact condensers and thermal management systems, and waste heat recovery systems. This leads to a very wide parameter space of hydraulic diameters (100 µm < Dh < 15 mm), operating pressures (100 kPa < P < 20 MPa), fluid properties, and mass fluxes (25 < G < 1000 kg m-2 s-1). These conditions necessitate an understanding of condensation across a wide range of thermodynamic and transport properties of pure fluids (R134a, CO2, ammonia, propane, pentane) as well as mixtures (refrigerant and hydrocarbon mixtures, ammonia-water.) Techniques for accurately measuring the high condensing heat transfer coefficients at small Dh will be presented. Flow regime maps and dimensionless transition criteria for a range of fluids with operating pressures up to the critical pressure will be discussed. Self-consistent models for condensation across this parameter space based on flow morphology and momentum, heat and mass transfer will be presented. Zeotropic mixtures present new challenges due to temperature and concentration gradients and coupled heat and mass transfer resistances in liquid and vapor phases. 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 will be discussed. Recent developments in applying AI/ML techniques to develop reduced-order models for this wide parameter space will be presented. Also, emerging techniques such as tunable acoustic enhancement of condensation will be briefly mentioned. The role of microscale phase change in enabling a variety of applications such as thermally driven heat pumps and carbon capture for decarbonization will be discussed.