Interfaces in single- and multi-constituent fluid condensation and sorption heat and mass transfer

Srinivas Garimella
Georgia Institute of Technology, Atlanta, GA 30032; sgarimella@gatech.edu

Phase-change heat and mass transfer plays an ever-increasing role in the transfer of large heat fluxes in a variety of applications, including refrigeration and air-conditioning, electronics cooling, waste heat recovery, chemical processes, and others. One of the key challenges in predicting heat and mass transfer in such applications is the understanding of the vapor-liquid interface, its movement, and transport between the liquid and vapor phases across the interface. Such interfaces can take vastly different characteristics depending on the geometries, fluid composition and properties, flow orientation, and the relevant governing forces such as gravity, inertia and surface tension. In particular, research on convective condensation spurred by the phase-out of synthetic refrigerants, and the need for compact condensers and thermal management systems has led to a wide parameter space of hydraulic diameters ($100 \mu m < D_h < 15 \text{ mm}$), operating pressures ($100 \text{kPa} < P < 20 \text{MPa}$), and mass fluxes ($25 < G < 1000 \text{ kg m}^{-2} \text{s}^{-1}$). These conditions necessitate an understanding of interfacial phenomena across a wide range of thermodynamic and transport properties of pure fluids (R134a, CO$_2$, 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 $D_h$ will be presented. Flow regime maps and dimensionless transition criteria for a range of fluids with operating pressures all the way up to the critical pressure will be discussed. Emerging self-consistent models for condensation across this parameter space based on flow morphology and momentum, heat and mass transfer will be presented. A new approach that models condensation in the annular regime for any arbitrary microchannel cross section will be highlighted. 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.

Interfacial transport in absorption and desorption processes is particularly challenging to address, due to the competing requirements of vapor-liquid equilibrium profiles, heat and mass transfer resistances in vapor and liquid phases, the large latent heat of vaporization, and the need to maintain counterflow of the two phases in small geometries. Examples of the measurement and modeling of convective absorption and falling film desorption in compact geometries that enable innovative heat pumps will be presented. In another application domain, fast heat and mass transfer kinetics in hollow microchannel fibers with internal coupling fluid flow and loaded externally with adsorbents is exploited to enable rapid temperature swing adsorption (RTSA) for CO$_2$ capture from power plants. A thermal wave heat recovery technique is developed to minimize external heat input for CO$_2$ capture in a representative 750 MW power plant. Such adsorbent-coated hollow fibers are also shown to yield several-fold plant footprint reductions in natural gas purification plants. Pressure swing adsorption (PSA) and temperature swing adsorption techniques employing microchannels yield up to 20-25 fold increase in the processing capacity at competitive gas purities and recoveries compared with conventional packed-bed designs. Further performance enhancement is achieved with working fluid gases and heat transfer fluids (HTFs) flowing through the same adsorbent-coated channel alternately, thereby eliminating complex header designs. Interaction of working fluid gases and liquid HTFs with the adsorbent in these common microchannels is predicted based on models and experiments on displacement phenomena in plug, annular and rivulet flow regimes in microchannels. A complete process model validated by mass spectrometry based experiments for heat and mass transfer in the individual stages of the purification cycle predicts a 100-fold increase in throughput and four times less volume compared with conventional designs.