The demands for increasingly smaller, more capable, and higher power density technologies in microelectronics, energy, or aerospace systems have heightened the need for new methods to manage and characterize extreme heat fluxes (EHF). Microscale liquid cooling techniques are viewed as a promising solution for removing heat from high heat flux (HHF) systems. However, there have been challenges in physical understanding and predicting local thermal transport at the interface of micro and nanoscale structures/devices due to ballistic effects and complex coupling of mass, momentum, and energy transport at the solidâ€“liquidâ€“vapor interfaces over multiple time and length scales. Moreover, itâ€™s challenging to experimentally validate new HHF models due to lack of high resolution techniques and measurements.

This dissertation presents the use of a high spatiotemporal and temperature resolution measurement technique, called Time-domain Thermoreflectance (TDTR). TDTR is used to characterize the local heat transfer coefficient (HTC) of a water-cooled rectangular microchannel in a combined hot-spot heating and sub-cooled channel flow configuration. Studies focused on room temperature, syringe-pumped single-phase and two-phase water flow in a ≈480 μm hydraulic diameter microchannel, where the TDTR pump heating laser induces local heat fluxes of ≈0.5â€“2.5 kW/cm² in the center of the microchannel on the surface of a 60â€“80 nm metal or alloy thin film transducer with hot-spot diameters of ≈7â€“10 μm.

In the single-phase part, a differential measurement approach is developed by applying anisotropic version of the TDTR to predict local HTC using the measured voltage ratio parameter, and then fitting data to a thermal model for layered materials and interfaces. Itâ€™s shown that thermal effusivity distribution of the water coolant over the hot-spot is correlated to the local HTC, where both the stagnant fluid (i.e., conduction and natural convection) and flowing fluid (i.e., forced convection) contributions are decoupled from each other. Measurements of the local enhancement in the HTC over the hot-spot are in good agreement with established Nusselt number correlations. For example, flow cooling results using a Ti metal wall support a maximum HTC enhancement via forced convection of ≈1060±190 kW/m²∙K, where the well-established Nusselt number correlations predict ≈900±150 kW/m²∙K.

In the two-phase part, pump-probe beams are first used to construct the local pool and flow boiling curves at different heat fluxes and hot spot temperatures as a function of HTC enhancement. At a same heat flux level, itâ€™s observed that fluid flow enhances HTC by shifting heat transfer mechanism (or flow regime) from film boiling to nucleate boiling. Based on observations, itâ€™s hypothesized that beyond an EHF flow may reduce the bubble size and increase evaporation at the liquid-vapor interface on three-phase contact line but itâ€™s unable to rewet and cool down the dry spot at the center due to the EHF.

In the last part of two-phase experiments, transient measurements are performed at a specific heat flux to obtain thermal temporal fluctuations and HTC of a single bubble boiling and nucleation during its ebullition cycle. The total laser power is chosen to be between the minimum required to start subcooled nucleation and CHF of the pool boiling. This range is critical since within 10% change in heating flux, flow can have dramatic effect on HTC. Whenever the flow gets closer to the dry spot and passes through it (receding or advancing) HTC increases suddenly. This means that for very hot surface (or regions of wall dry-out), continuous and small bubbles on the order of thermal diffusion time and dry spot length scales respectively could be a reliable high heat flux cooling solution. This could be achieved by controlling the bubble size and frequency through geometry, surface structure and properties, and fluid's thermos-fluid properties.

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The public is welcome to attend.