Many critical applications today, in electronics, optics and aerospace fields, among others, demand advanced thermal management solutions for the acquisition of high heat loads they generate in order to operate reliably and efficiently. Current competing technologies for this challenging task include several single and two-phase cooling options. When these cooling schemes are compared based on the high heat flux removal (100-1000 W/cm²) and isothermal operation (within several ºC across the cooled device) aspects, as well as system mass, volume and power consumption, spray cooling appears to be the best choice.

The current study focused on high heat flux spray cooling with ammonia on enhanced surfaces. Compared to some other commonly used coolants, ammonia possesses important advantages such as low saturation temperature, and high heat absorbing capability. Moreover, enhanced surfaces offer potential to greatly improve heat transfer performance. The main objectives of the study were to investigate the effect of surface enhancement on spray cooling performance, and contribute to the current understanding of spray cooling heat transfer mechanisms.

These objectives were pursued through a two stage experimental study. While the first stage investigated enhanced surfaces for the highest heat transfer coefficient at heat fluxes of up to 500 W/cm², the second stage investigated the optimized enhanced surfaces for critical heat flux (CHF). Surface modification techniques were utilized to obtain micro scale indentations and protrusions, macro (mm) scale pyramids, triangular grooves, straight fins and pin fins. A third group, multi-scale structured surfaces, combined macro and micro scale structures.

Experimental results indicated that micro and macro structured surfaces can provide heat transfer coefficients of up to 534,000 and 426,000 W/m²ºC at 500 W/cm², respectively. Multi-scale structured surfaces offered even a better performance, with heat transfer coefficients of up to 772,000 W/m²ºC at 500 W/cm², corresponding to a 161% increase over the reference smooth surface. In CHF tests, the optimized multi-scale structured surface helped increase maximum heat flux limit by 18%, to 910 W/cm² at nominal liquid flow rate. During the additional CHF testing at higher flow rates, most heaters experienced failures before reaching CHF at heat fluxes above 950 W/cm². However, the effect of flow rate was still characterized, suggesting that enhanced surfaces can achieve CHF values of up to ≈1,100 W/cm² with ≈67% spray cooling efficiency.

The results also helped shed some light on the current understanding of the spray cooling heat transfer mechanisms. Data clearly proved that in addition to fairly well established mechanisms of forced convection in the single phase regime, and free surface evaporation and boiling through secondary nucleation in the two phase regime, enhanced surfaces can substantially improve boiling through surface nucleation, which can also be supported by the concept of three phase contact lines, the regions where solid, liquid and vapor phases meet. Furthermore, enhanced surfaces are capable of retaining more liquid compared to a smooth surface, and efficiently spread the liquid film via capillary force within the structures. This unique advantage delays the occurrence of dry patches at high heat fluxes, and leads to higher CHF.

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