Effectiveness of Linear Spray Cooling in Microgravity

ZeroG Team

University of Wisconsin – Madison

1500 Engineering Drive

Madison, WI 53706

Student Team Contact:

John Springmann

springmann@wisc.edu

(262) 488-8029

Faculty Advisor:

Timothy A. Shedd

shedd@engr.wisc.edu

(608) 265-2930

Introduction

Spray cooling is a method in which liquid droplets are sprayed directly onto a hot surface to cool it by the sensible heating and/or evaporation of the coolant [1, 2]. This method is one of the most efficient technologies for high heat flux cooling and heat transfer coefficients of 10,000 W/m^2K for refrigerants and 100,000 W/m^2K are common with water [2]. The continuing development of devices that generate high heat fluxes, like integrated circuits and laser diodes necessitates an efficient method of heat removal; spray cooling is an ideal solution. Electronic systems operating in space have many of the same thermal management requirements as earthbound systems but they must function in a significantly different environment. The utility of high heat flux components will only increase as the requirements and capabilities of orbiting systems grow [3, 4, 5].

Previous studies have not demonstrated that spray cooling functions independently of gravity, in fact most previous applications use gravity to assist drainage. Gravity was shown to have an effect on spray cooling systems that are dependent on orientation in a 1-G environment by Sone et al. and Yoshida et al. [6, 7]. Other researchers have used the drop research tower at NASA's Glenn Research Center to investigate residual fluid behavior in spray cooling and scientists have studied surface tension flow around spray nozzles onboard NASA's KC-135 reduced gravity aircraft [4, 8]. Rowden et al. have shown the effect of microgravity on spray cooling using computer modeling and suggest that the dominant factor in the heat transfer coefficient is the coolant's momentum [9].

We investigated linear spray cooling, a promising method which uses a linear configuration of conical spray nozzles. Regner and Shedd, researchers at the University of Wisconsin, recently demonstrated that spray cooling is independent of orientation with respect to gravity [1]. We hypothesized that spray cooling would function independent of gravity when using a linear spray array similar to what was used by Regner and Shedd. This hypothesis was proven onboard NASA's C-9 reduced gravity aircraft during the 18-25 second periods of microgravity. In between periods of microgravity, accelerations reaching approximately 1.7 Gs were experienced allowing an enhanced gravity test of linear spray cooling.

Experimental Setup

A dielectric fluorinert manufactured by 3M, FC-72, was chosen for its exceptional cooling efficiency. The test section is a polycarbonate box containing an Ohmite TGH series 1 Ω resistance heater and the spray array. The array is machined using conventional techniques and is described by Regner and Shedd [1]. The heat flux is controlled with an LHP 40-25 DC power supply.

The test section is contained within a closed fluid loop that is filled completely with the FC-72 at ambient pressure. The fluid is driven by a Micropump gear pump and controlled by a Reliance Electric 200SP AC drive. After passing through the test section, the liquid is air-cooled by a heat exchanger. Data was gathered by a flow meter, a differential pressure sensor across the test section, two pressure transducers, and four thermocouples dispersed throughout the loop. There are four additional thermocouples embedded in the heater, which has a surface area of 3.46 cm^2.

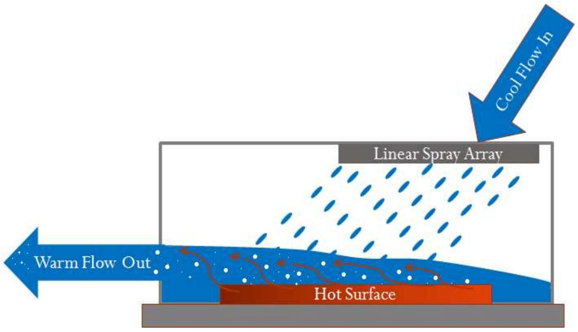

Figure 1. Spray box operation. Incoming liquid creates a turbulent mixture on the heated surface. This forces evaporated liquid off of the surface and allows cool liquid to contact the heater.

Procedures and Results

Spray cooling was started before beginning the parabolic reduced gravity maneuvers. A total of 32 parabolas were flown and the experiment ran continuously during both the low G (nominally 0 Gs) and high G (around 1.7 Gs) portions of the flight. The first ten parabolas were tested at a flow rate of 0.775 L/min and a heat flux of 50.29 W/cm^2. The heat flux and flow rate were increased to 52.02 W/cm^2 and 2.475 L/min, respectively, for the next three parabolas after which the heat flux was increased to 53.76 W/cm^2 for the remainder of the flight. The flow rate was raised to 3.860 L/min for the last twelve parabolas. Fairly conservative heat fluxes were used since the goal was to demonstrate independence of gravity, not peak system performance.

Data was analyzed by comparing the heat transfer coefficient to the level of gravity. The heat transfer coefficient, *h*, is defined as

$$h = \frac{q''}{T_s - T_{in}}$$

where q'' is the heat flux in W/cm^2, T_s is the surface temperature of the heater calculated by averaging the four thermocouples within the heater, and T_{in} is the fluid temperature at the inlet of the test section.

Figures 2-4 demonstrate the independence of the heat transfer coefficient and gravity. For each plot, the average heat transfer coefficient is constant over varying gravity. Greater flow rates saw an increase in the heat transfer coefficient and a decrease of its variation. We conclude that linear spray cooling performance increases with flow rate. The average heat transfer coefficients are 0.95, 1.22, and 1.40 W/cm^2C for the low, medium and high flow rates, respectively.

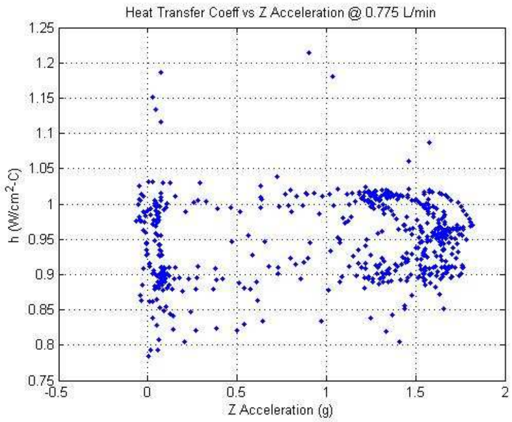

Figure 2. Spray cooling performance over the first 10 parabolas with a flow rate of 0.775 L/min and a heat flux of 50.29 W/cm^2.

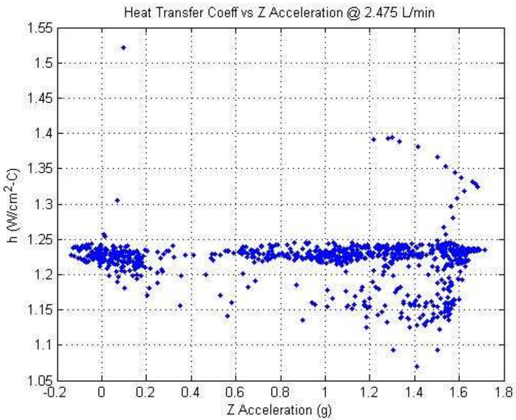

Figure 3. Spray cooling performance over parabolas 11-20 with a flow rate of 2.475 L/min and a heat flux of 52.02 W/cm^2 for 3 parabolas and 53.76 W/cm^2 for the remainder.

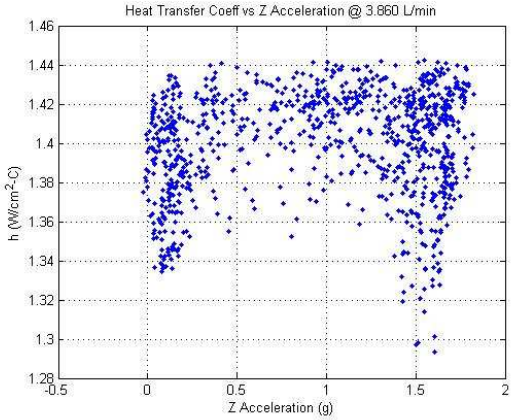

Figure 4. Spray cooling performance over parabolas 21-32 with a flow rate of 3.860 L/min and a heat flux of 53.76 W/cm^2.

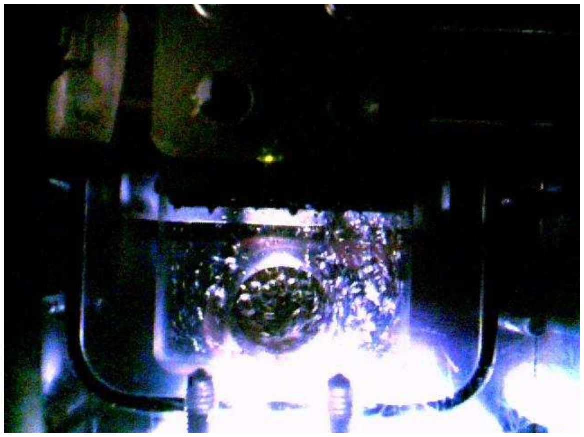

Figure 5. Flow off of heater, out of spray box. Notice the bubbles coming from right side of the heater only.

Flow Visualization

We imaged the coolant flow off of the heater during microgravity, as seen in figure 5. FC-72 is a nominally clear liquid and is illuminated by a strobe in the frame shown. The fraction of fluid that evaporates forms bubbles in the liquid flow and provides a secondary indicator of system performance. What should be noted is the predominance of bubbles on the right side of the image and lack thereof on the left side. This difference is evidence that one half of the heater failed during ground testing, reducing our effective area by 25%. Two of the thermocouples embedded in the heater consistently measured lower temperatures than the opposite two, supporting this explanation.

Correlation with Regner-Shedd Data

Heat transfer coefficients measured during the microgravity flight correlate nicely with previous data gathered by Regner and Shedd as seen in figure 6 [1]. Our data extends a model (figure 7) developed by Shedd to predict the heat transfer coefficient (*h*)

$$h_{model} = 0.0405 * \frac{k}{\nu} * P_r^{.5} * Q_{flux}^{.25}$$

as a function of spray rate (Q_{flux}) and the fluid's thermal conductivity, k, kinematic viscosity, v, and Prandtl number, P_r, for a linear spray array [2].

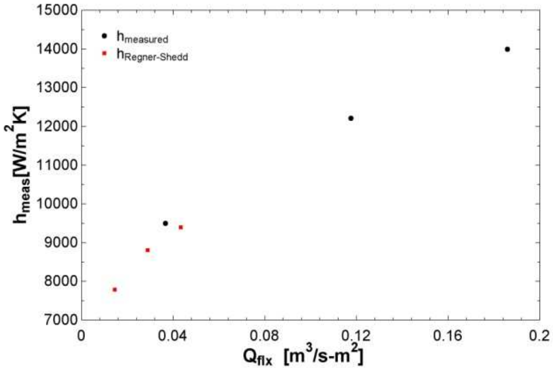

Figure 6. Similarity between microgravity measurements (black) and Regner-Shedd data (red)

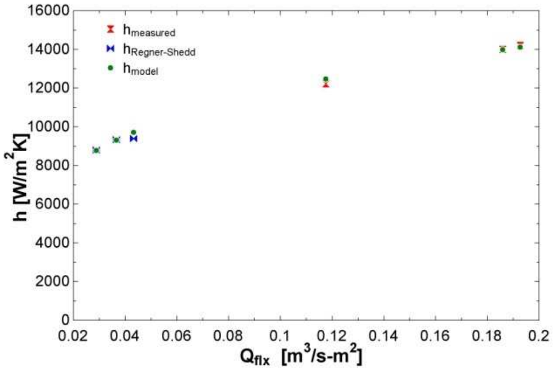

Figure 7. Agreement of microgravity measurements (red) and Regner-Shedd data (blue) with spray model [1].

Conclusion

We demonstrated that linear spray cooling is independent of gravity and is suitable for applications that experience variable gravity. Further, our results refine a model put forth by Regner and Shedd to predict the heat transfer coefficient of future linear spray arrays. We hope to further test the experiment this summer for publication in a peer-reviewed journal.

References

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