Effectiveness of Linear Spray Cooling in Microgravity

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Abstract. The continued development of computer processors, laser diodes, and other high heat flux devices (>100 W/cm^2) and their integration in space-bound and variable gravity systems necessitates advanced, compact, and gravity-independent thermal management systems. Spray cooling has shown great promise in addressing these concerns, especially through the use of multi-spray arrays. The dependence on gravity has been investigated for single spray systems but not for spray arrays. A linear spray array was tested in both microgravity (~0 g) and enhanced gravity (~1.8 g) environments aboard NASA's DC-9B reduced gravity laboratory. This study found the coolant flow rate to be the main determinant of the heat transfer coefficient while gravity was of little significance. The elimination of acceleration allowed the development of a simple relation between coolant flux and the heat transfer coefficient to aid the design of future ground and space-based thermal management systems.

Keywords: linear spray cooling, microgravity, high heat flux.
PACS: 81.70.Ha, 47.27.te.

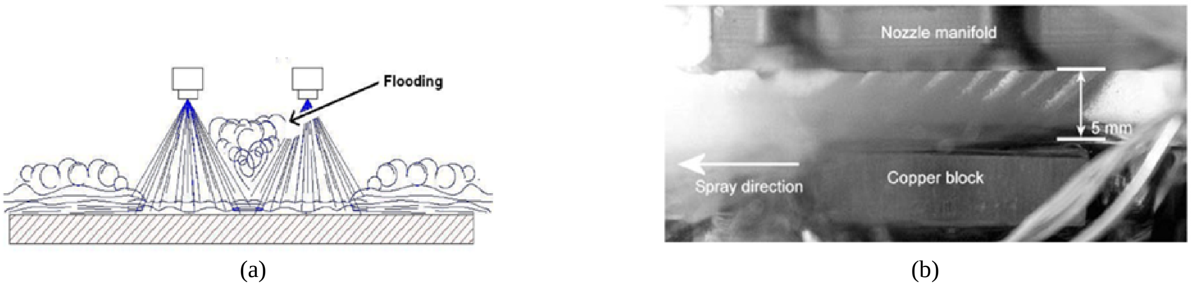
INTRODUCTION

The challenges to micro and variable-gravity high performance thermal management systems are numerous while there are few proven solutions. Single and two-phase cooling methods (like forced convection and heat pipes) work well in low heat flux conditions, but as integrated circuits, solid-state laser diodes, and many other components increase in capability they are also decreasing in physical size, requiring systems capable of removing heat fluxes spanning 100-1000 W/cm^2 (Baysinger, Yerkes, and Thomas, 2005; Shedd, 2007; Silk, Golligher, and Selvam, 2008). Flow boiling, jet impingement, and spray cooling methods have been considered. Flow boiling with water is limited to 100 W/cm^2 and the effect of low gravity is unknown (Ponnappan, Donovan, and Chow, 2002). Jet impingement methods are considered abrasive and cannot be used on delicate components (Baysinger, Yerkes, and Thomas, 2005).

Spray cooling is a promising technique that has shown high performance in laboratory experiments. Although the precise heat transfer mechanisms are not completely understood, spray cooling has been investigated in a microgravity environment. Yoshida, et al. (2001) looked at a single spray cone directed perpendicular to a heated surface and found that microgravity has a significant effect on the critical heat flux and Sone et al. (1996) determined a 14% variation in the critical heat flux as acceleration ranged from 0 to 1.5-2 Gs. Golliher, Zivich, and Yao (2005) found significant pooling on the heated surface due largely to surface tension when they studied a single spray in the 2.2 second drop tower at NASA Glenn Research Center. The applicability of single spray cooling systems are limited by the difficulty in covering a large area (>1 cm^2) and ensuring even spray density over the entire area (Shedd 2007).

Regner and Shedd investigated the effects of orientation of spray cooling. Instead of a single perpendicular spray, a linear array of sprays directed 45 degrees onto the heated surface was used (2007). It was found that while the performance of each orientation – such as spray in the direction of gravity or opposite that of gravity – varied at low heat fluxes, it became essentially the same for heat fluxes greater than 50 W/cm^2.

The authors chose a linear spray array based on previous work at the University of Wisconsin (Regner and Shedd, 2007; Shedd, 2007). In the design, multiple nozzles are spaced closely together in a regular pattern 5 mm from the heated surface. Past multi-nozzle spray arrays were directed perpendicular to the heated surface and suffered from significant fluid management issues, especially when system orientation and acceleration vary, as in Figure 1a (Pautsch and Shedd, 2005; Glassman, 2005; Silk, Golliher, and Selvam, 2007). Sprays angled at forty-five degrees from the vertical (figure 1b) avoid this limitation by directing fluid flow towards a defined exit, as shown by Regner and Shedd (2007).



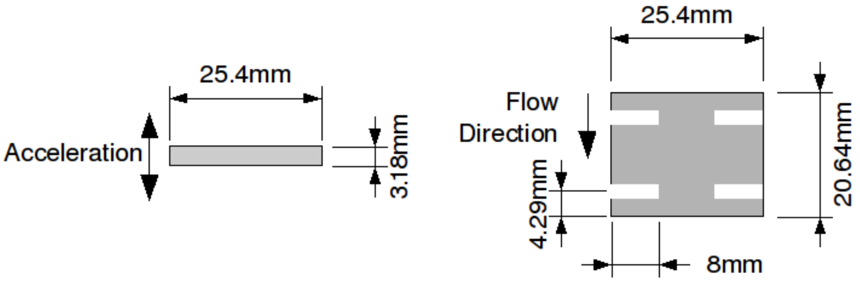
(a) (b)

FIGURE 1. (a) Liquid flooding occurs in sprays directed perpendicular to the heated surface, impairing the formation of sprays (Glassman, 2005). (b) Spray configuration as used by Shedd on which the present experiment is based (2007). A hot surface ('copper block') is cooled by sprays angled at 45° to prevent the formation of a vapor dome on the surface and direct fluid towards the drain.

METHODOLOGY

Microgravity Environment

Building on the work of Regner and Shedd, a linear spray impingement array was tested in microgravity onboard NASA's DC-9B Reduced Gravity Laboratory. A series of thirty microgravity (nominally 0 g) parabolas lasting 20-25s each were flown. Between the microgravity portions is an enhanced gravity period where up to 1.8 g was experienced. As seen in Figure 1, the experienced acceleration on the linear spray array and heater was perpendicular to the surface of the heater. The experiment was operated continuously during each of two flights, resulting in sixty total parabolas. The hour and a half flight demonstrated the capability of linear spray cooling systems on aircraft in a variable-gravity environment.



(a) (b)

FIGURE 2. (a) Edge view of the copper plate, where spraying occurred on the top surface. (b) Top view of the Ohmite TGHG current sense resistor with thermocouple locations shown.

3M Fluorinert FC-72 was chosen as the working fluid due to its high thermal conductivity, low electrical conductance, and common use in the literature (Silk, Golliher, and Selvam, 2008; Regner and Shedd, 2007; Baysinger, Yerkes, and Thomas, 2005; Yoshida, et al., 2001). An Ohmite TGHG 1 Ω precision current sense resistor simulated a computer processor with a 5.24 cm^2 surface area in the experiment. Four T-type thermocouples were embedded 6.35mm from the spray array edge and 8mm deep (Figure 2) which was driven by an LHP 40-25

DC power supply. A Micropump gear pump drove a closed loop which included a Lytron fin and tube heat exchanger, filter, and pressure-maintaining bladder. The system was operated at atmospheric pressure. Data were gathered by two pressure transducers, a differential pressure sensor across the spray box, a flow meter**,** four additional thermocouples, and a three-axis Freescale accelerometer, as in Figure 2. A National Instruments LabVIEW program sampled each sensor once every second and the pump and heater power supply settings were recorded. The two-phase flow exiting the heated section was recorded using a still camera and an LED strobe light. These images provide an alternate indicator of system performance and can be seen in Figure 5.

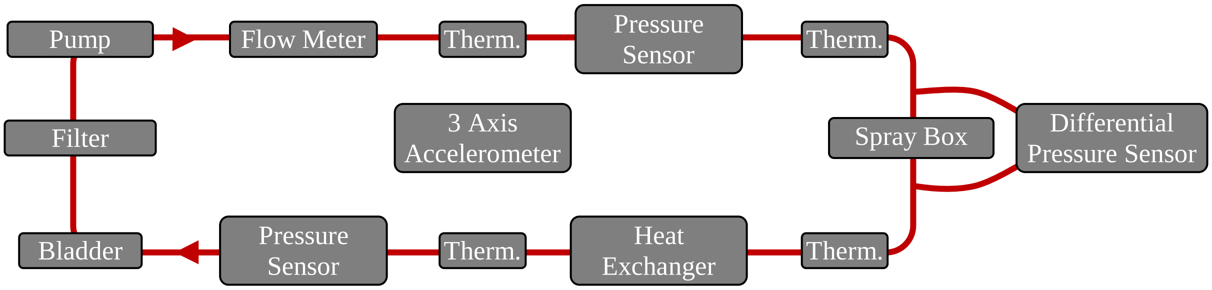


FIGURE 3. Closed loop schematic, flow directed clockwise.

ANALYSIS

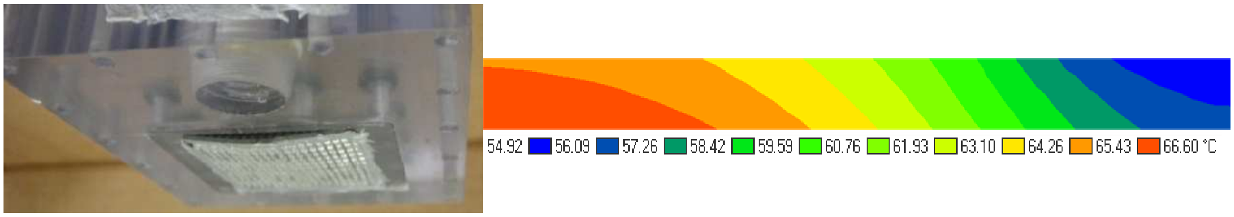
Of primary interest is the relation of the heat transfer coefficient and environment acceleration. For our purposes, the heat transfer coefficient, *h*, is defined as:

$$h = \frac{q"}{T_s - T_{in}} \qquad (1)$$

where $q"$ is the heat flux in W/cm^2 calculated from the power input to the heater, T_s is the average surface temperature of the heater from the four thermocouples within the heater, and T_{in} is the fluid temperature taken at the inlet of the spray box.

The initial ten parabolas were conducted at a flow rate of 0.775 L/min and a heat flux of 24.895 W/cm^2. They were then increased to 25.76 W/cm^2 and 2.475 L/min, respectively, for the next three parabolas. The remaining seventeen parabolas had a heat flux of 26.61 W/cm^2 while the flow rate was raised to 3.860 L/min for the last twelve parabolas. As the focus of the experiment is on the microgravity performance of the linear spray array, the system did not investigate behavior around critical heat flux.

Deviations from the Ideal

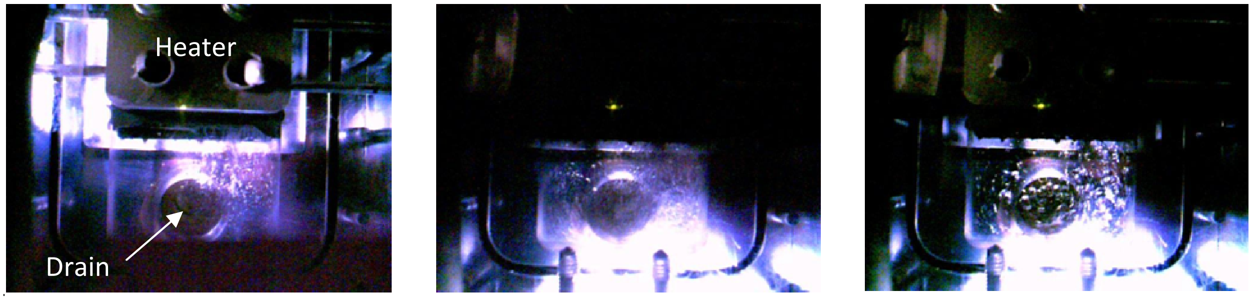


(a) (b)

FIGURE 4. (a) Rupture in spray array seal created a secondary flow path that bypassed the spray array and decreased spray formation on the left half of the spray array. (b) Heater cross-section perpendicular to flow direction; see Figure 2a for dimensions. The uneven heat distribution results from decreased spray creation on the left side of the heater.

Post-flight inspection of the spray box showed that the spray array seal ruptured along the edge nearest the drain, as seen in Figure 4a. This created a secondary flow path around the spray array and directly into the drain. In reference to Figure 4a, the rupture is located on the left side of the spray array and would have diminished sprays on the left side. This side saw greater temperatures than the correctly-performing right side. Knowing the heat flux in the heater, the temperature of each side (from the thermocouples embedded in the heater), and the outlet fluid temperature allowed the creation of a FEHT finite element heat transfer model, shown in Figure 4b. The effect of the greater coolant spray on the right is clear. Preflight ground testing saw the greatest flow rates and is likely when the seal ruptured. Considering the data, the measured average flow rate was higher than what was actually flowing through the array, forming sprays, and impacting the heater.

Bubbles created by the evaporation of coolant were imaged flowing off of the heater in Figure 5. As expected, the greater number of bubbles on the left side of each image results from the greater temperature on that side of the heater.



(a) (b) (c)

FIGURE 5. Visualization of the flow off of the heater for the (a) 0.775, (b) 2.475, and (c) 3.860 L/min flow rates. The underside of the heater is seen at the top of the picture and the spray box drain is the large circle in the middle lower half. Vapor generation is clearly shown by the bubbles flowing off the heater and swirling up and into the drain.

RESULTS

The heat transfer coefficient varied little with respect to environment acceleration, as seen in Figure 6. For each heat flux, flow rate was the primary determinant of performance. The average heat transfer coefficients are 0.47, 0.60, and 0.69 W/cm^2-K for the 0.775, 2.475, and 3.860 L/min flow rates, respectively.

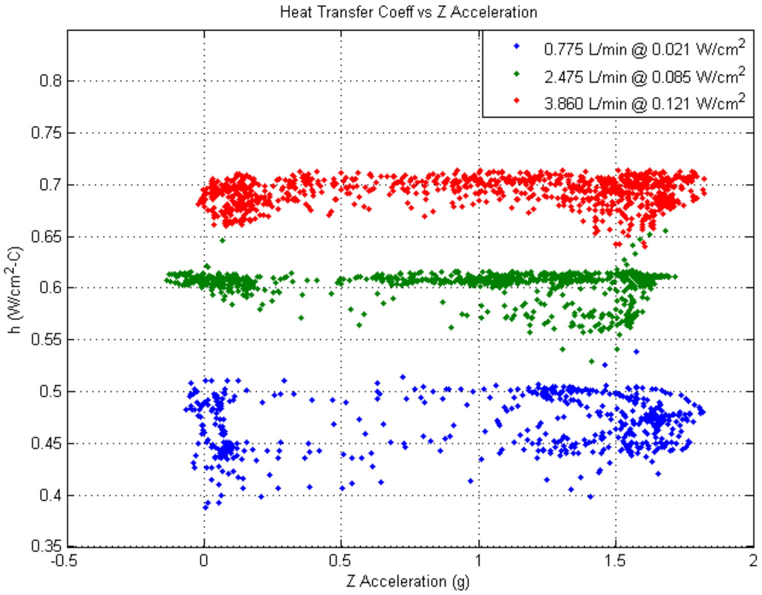


FIGURE 6. Microgravity heat transfer data; (bottom) The 0.775 L/min average heat transfer coefficient was 0.63 W/cm^2-C, (middle) the 2.475 L/min averaged 0.81 W/cm^2-C, and (top) 0.92 W/cm^2-C for the 3.860 L/min (center) flow rate.

Greater flow rates resulted in a general decrease in the heat transfer coefficient variation, and percent variation for the low, medium, and high flow rates is 27.8%, 19.2%, and 10.3%, respectively. Looking more closely at the relation between the heat transfer and system acceleration, Figure 7, the heat transfer coefficient tends slightly upward during microgravity and slowly lower during enhanced gravity. The transition between enhanced and low gravity also affects the heat transfer coefficient but the relation is not definitive. For now a certain variation in the heat transfer coefficient is to be expected for systems in variable acceleration, but this variation will be small compared to the average magnitude set by the flow rate, as seen in Figure 6.

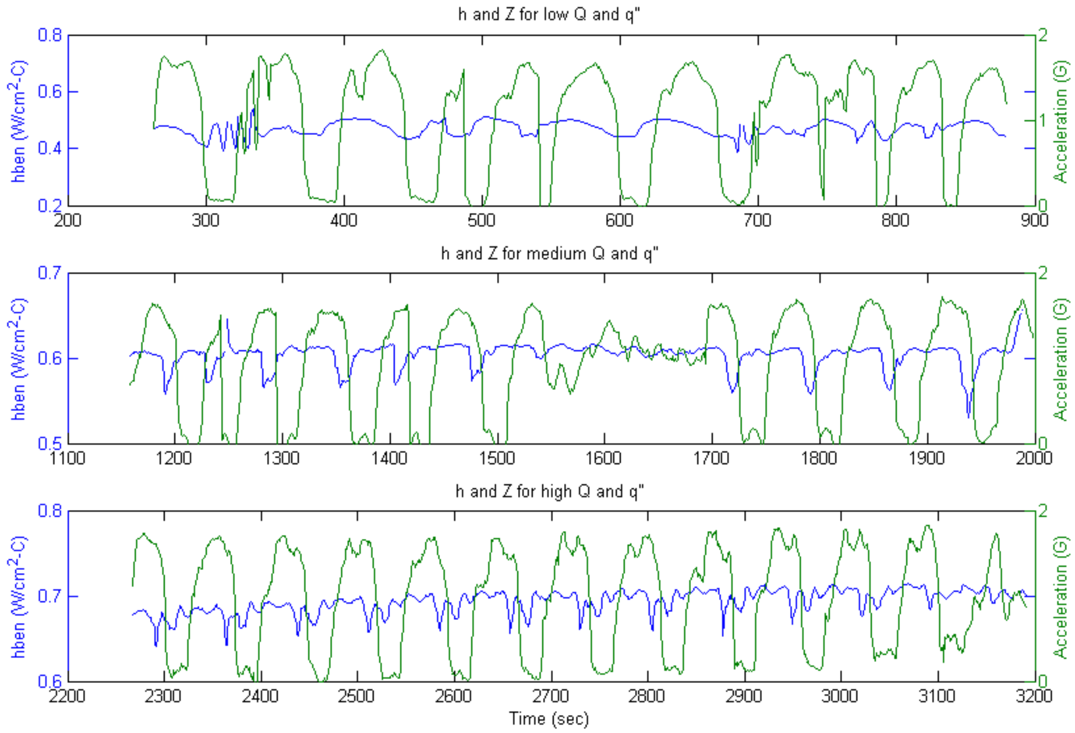


FIGURE 7. Heat transfer coefficient and system acceleration versus time. Low gravity causes a slow increase in the heat transfer coefficient while enhanced gravity leads to a decrease. The transition between low and high gravity has some influence though the exact relationship is not clear.

Correlation with Regner-Shedd Model

Measured heat transfer coefficients correlate with data from Regner and Shedd (2007) as shown in Figure 8. The current data fit a variation on a model presented in Shedd that predicts the heat transfer coefficient, h, as a function of spray droplet flux, Q_{flux}, and constants: the fluid's thermal conductivity, k, kinematic viscosity, v, Prandtl number, Pr, and an arbitrary constant, C, for a linear spray array (2007). Spray droplet flux is defined as the volumetric flow rate divided by the spray array area.

$$h_{model} = C\frac{k}{\nu} P_r{}^{a} Q_{flux}{}^{a} \tag{2}$$

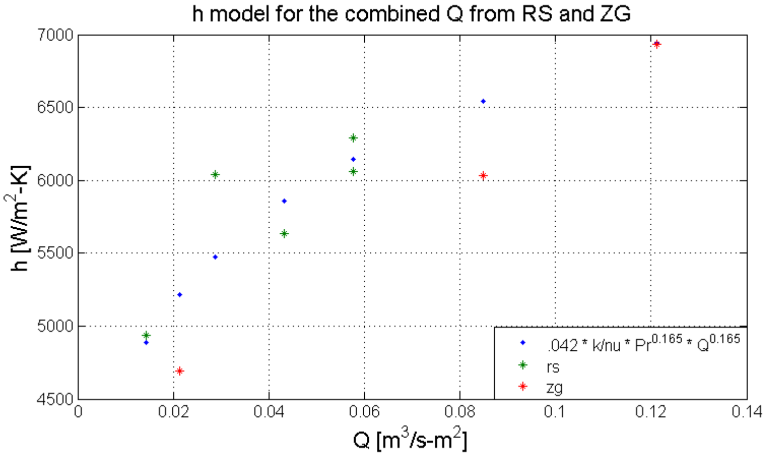


FIGURE 6. Microgravity data (*zg*) and Regner and Shedd (2007) data (*rs*) exhibit similar trends which can be explained by equation 2. Here, $C = 0.042$, $a = 0.165$.

CONCLUSION

The performance of a linear spray array is primarily controlled by the coolant flow rate but has some dependence on system acceleration. Due to non-constant system acceleration during the microgravity and enhanced gravity portions, the precise effect of acceleration on a linear spray array cannot be determined. Linear spray impingement cooling in constant-acceleration situations can be predicted and variable gravity performance can be expected to vary within a small amount. While in need of further research, linear spray array impingement cooling continues to show promise for a wide variety of low and variable gravity applications.

ACKNOWLEDGEMENTS

The authors are thankful to the University of Wisconsin Space, Science, and Engineering Center, the Wisconsin Space Grant Consortium, the University of Wisconsin – Madison Engineering Physics Department, the University of Wisconsin – Madison Mechanical Engineering Department, and NASA’s Reduced Gravity Student Flight Opportunities Program.

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