Development of MEMS microchannel heat sinks for micro/nano spacecraft thermal control

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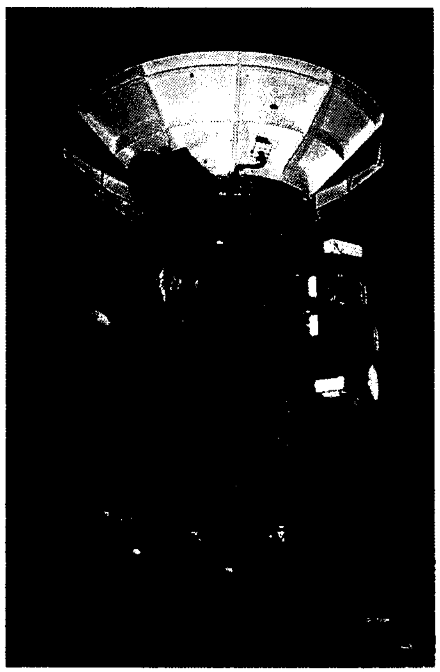
Background

• NASA is developing microspacecraft (10 to 100 kg) for future space science missions to reduce cost and increase functionality

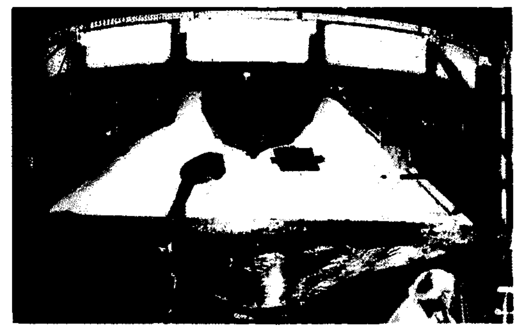
• NASA's New Millennium Program is developing technologies to reduce the mass of spacecraft in the next decade (from ~1000 to 100 kg) by miniaturization and/or integration of system components (MEMS, Multifunctional structures)

• Reduced spacecraft size increases thermal control complexity

~2500 kg
(before 1990)



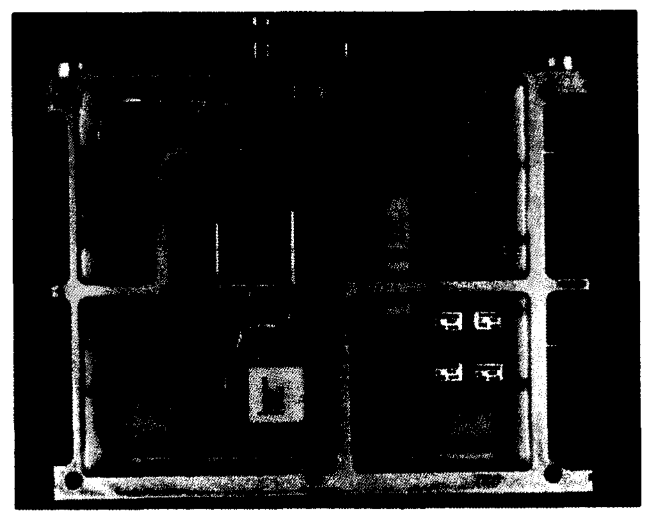
~1000 kg
(1996)



Small spacecraft
~100 kg
(2000 and later)

Microspacecraft Thermal Control Issues

- Power densities of miniaturized electronics, instrumentation, and avionics may exceed those in traditional spacecraft by an order of magnitude
- Reduction in spacecraft mass reduces the overall heat capacity of the system
- Mission objectives are likely to expose microspacecraft to extreme thermal environments
- Thermal control design must remove high heat fluxes, conserve energy, and maintain component temperature limits
- Current spacecraft thermal control is largely passive and uses additional mass to manage large power densities

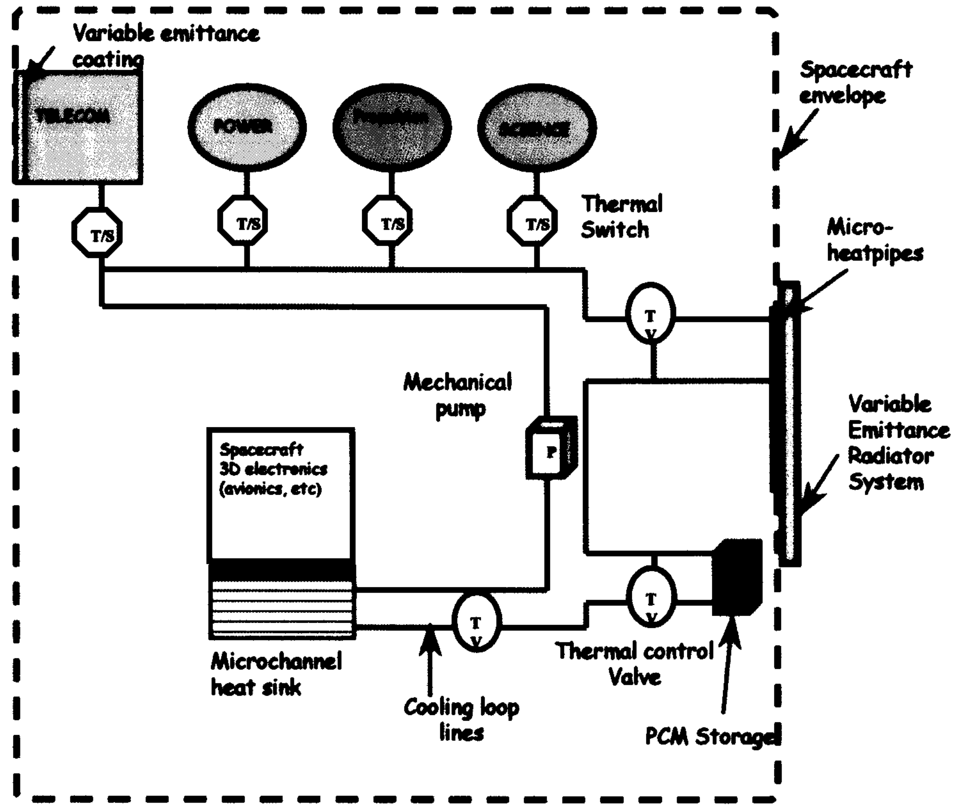


Motorola Small Deep Space Transponder

Microspacecraft Thermal Control Architecture

Concept

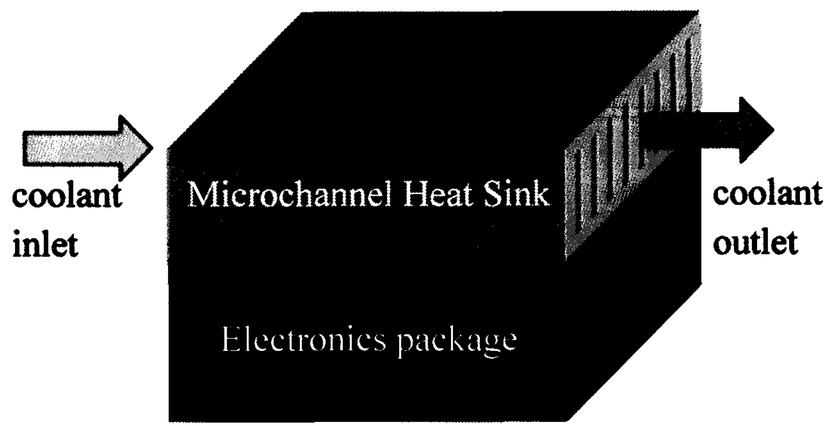
- JPL is investigating spacecraft thermal control based on a thermal energy management system (ITEMS) for future spacecraft
- Active thermal control with mechanically pumped liquid cooling system
- Potential to transport heat loads from high power density electronics over large distances
- Heat from electronics may be used to warm power, propulsion, and science subsystems
- Features robust and low mass alternatives to passive thermal control hardware



Integrated thermal energy management system architecture

Background

- High heat flux microchannel heat exchangers are well studied
- Microchannel geometry produces extremely efficient forced convection heat transfer.
- Compatible with microspacecraft thermal control architecture
- MEMS-based microchannel heat sink may be precision fabricated and integrated with electronic packages
- Compact size contributes little additional mass to the thermal control subsystem



Microchannel Heat Sink Concept

Objectives

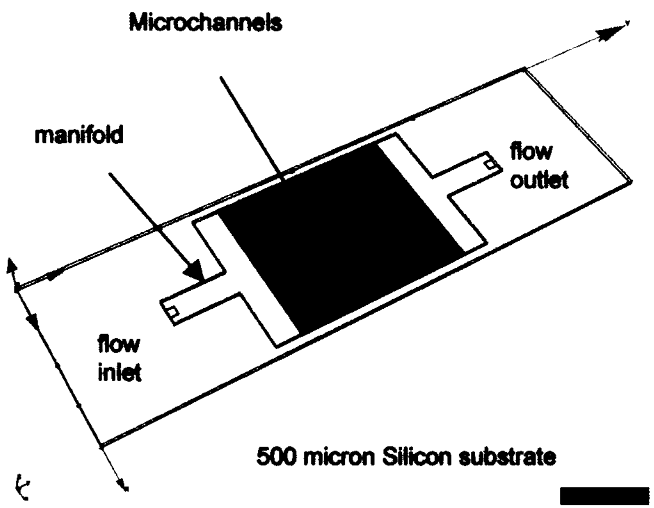
- Develop microchannel heat sinks compatible with microspacecraft thermal control requirements
- Build on existing research on modeling, design, and testing of microchannel heat sink devices (Tuckerman and Pease, Stanford University Microfluidics Laboratory) for single-phase liquids
- Account for spacecraft component reliability and integration concerns
- Develop a laboratory facility for testing and evaluating microchannel heat sink devices within context of microspacecraft thermal control architecture

Microchannel heat sink design requirements

- Thermal performance
  - 25 W/cm^2 heat flux removal
  - 80 °C max allowable component temperature
- Hydraulic performance
  - Space qualified centrifugal pumps have limited pressure head, 6 to 8 psid (40-50 kPa)
  - limit pressure drop to 2 psid (14 kPa) at max flow rate
- Single-phase cooling
  - extensive heritage of single-phase loop usage on aerospace applications
  - simplicity and flexibility of cooling loop design
  - increased pump reliability
- Channel footprint: 1 to 5 cm^2

Microchannel Heat Sink Design

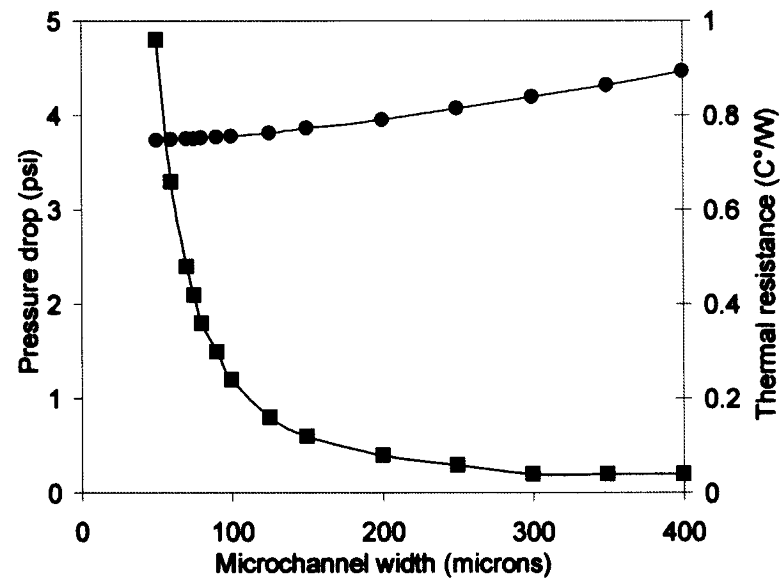
Stanford University Microfluidics Laboratory
MEMS-based parallel flow microchannel heat exchanger



- Channels etched in silicon wafer, capped with Pyrex glass
- Heater and temperature sensors on backside

Zhang, L., Banerjee, S.S., Koo, J., Laser, D.J., Asheghi, M., Goodson, K.E., Santiago, J.G., and Kenny, T.W., 2000, "A Micro Heat Exchanger with Integrated Heaters and Thermometers," *Proc. Solid State Sensor and Actuator Workshop*, pp. 275–280.

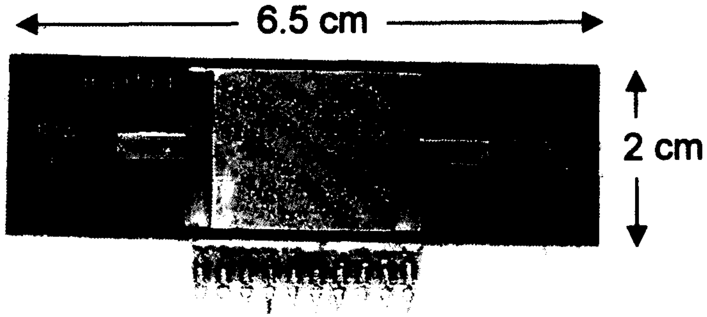
MICROHEX numerical model for microchannel geometry optimization (MIT)



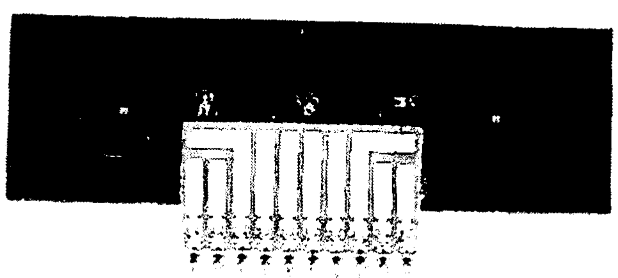
- Steady and uniform coolant flow (water)
- Channel width equal to fin width

Phillips, R. J., 1987, "Forced-Convection Liquid-Cooled Microchannel Heat Sinks", Master's thesis, Massachusetts Institute of Technology, Cambridge, MA.

Microchannel Heat Sink Design



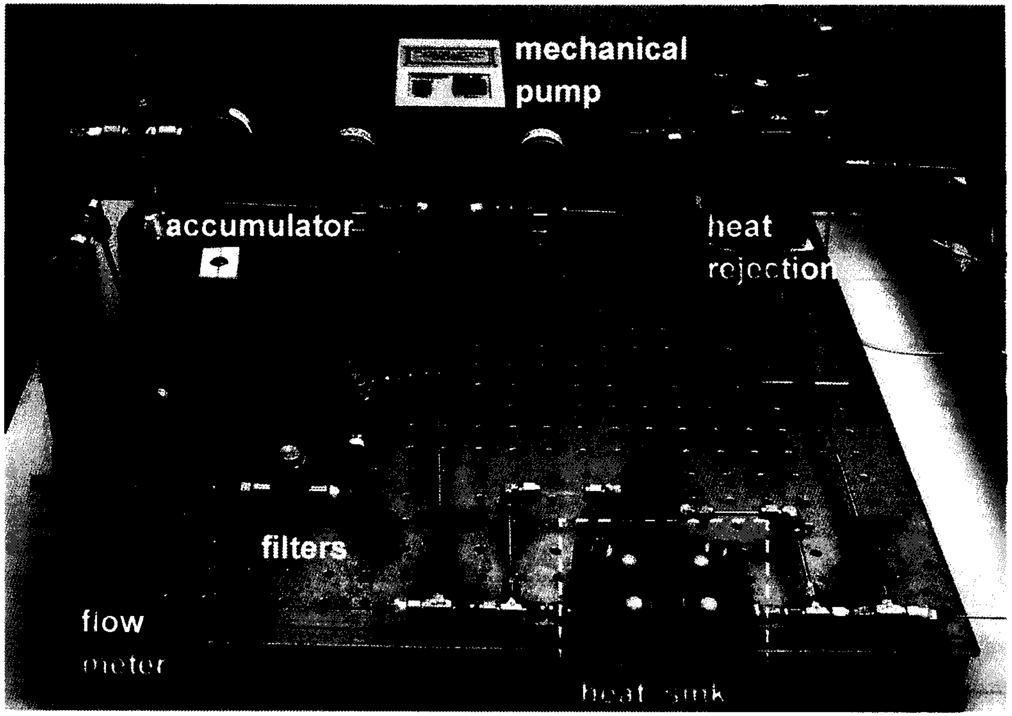
Top side (channels)

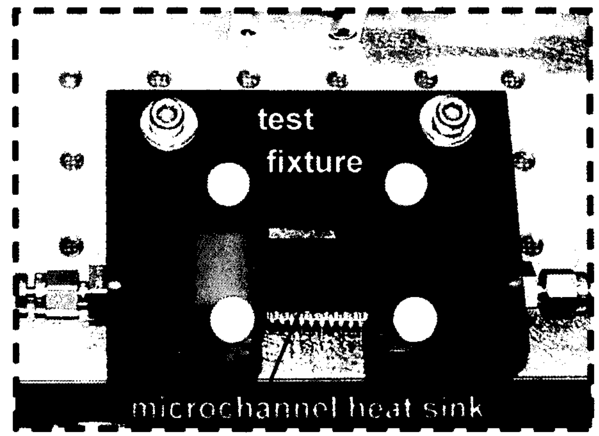


Back side (heater and temp sensors)

- Microchannels: 400 mm deep, 150 mm wide, 59 channels
- Channel footprint: 3.5 cm^2
- Serpentine Au-Pt-Ti heater deposited on backside
- Hy-Cal Engineering encapsulated platinum RTDs (1.5 mm^2) for temperature sensing
- Connections to surfboard with 25 micron gold wirebonds

Experimental Facility



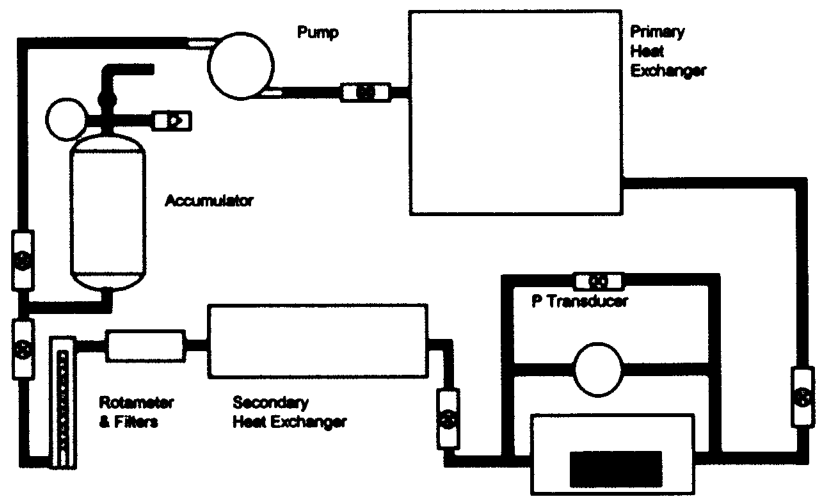


- Mechanically pumped cooling loop for heat sink testing
- Simulates spacecraft single-phase liquid heat rejection system
- Thermocouples monitor loop temperatures, pressure gauges and transducers monitor pressure drops

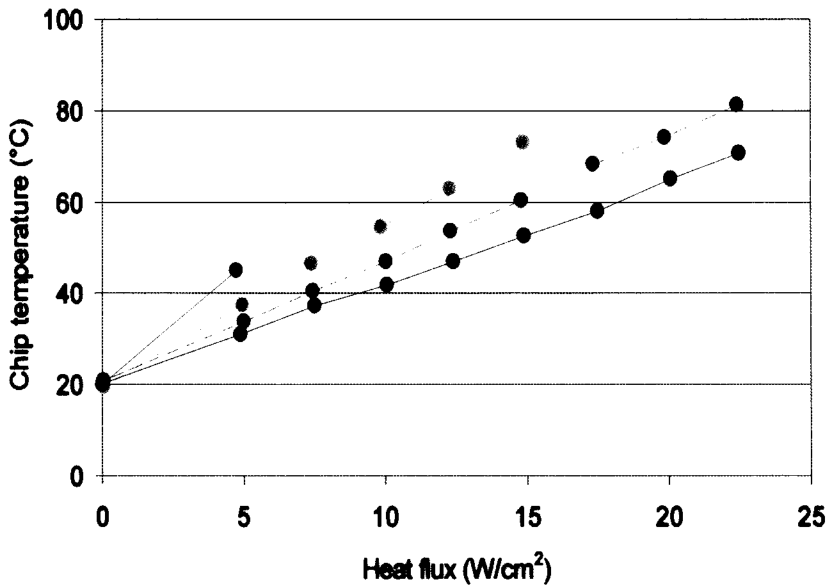
- Many possible working fluids
- System pressures up to 100 psi
- Suitable for long duration (lifetime) testing

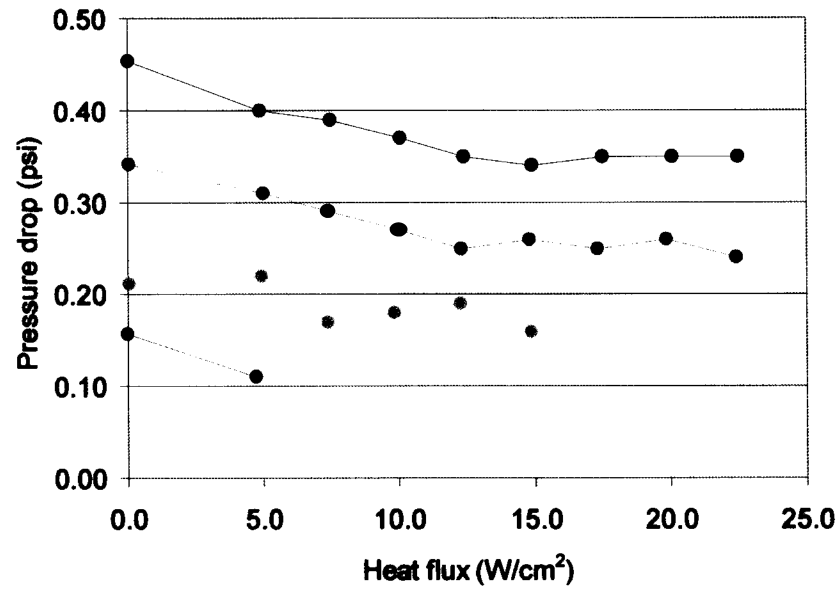
Experimental Method

- De-ionized water as working fluid
- System pressure of approximately 15 psig (200 kPa)
- Chiller and heat exchangers maintain inlet coolant temperature of 20 C
- Thermocouple probes measure inlet and outlet fluid temperatures
- Calibrated RTDs measure chip temperatures
- LabView DAQ records temperatures and controls power supply for chip heating
- Steady-state energy balance determines cooling rate of microchannel heat sink



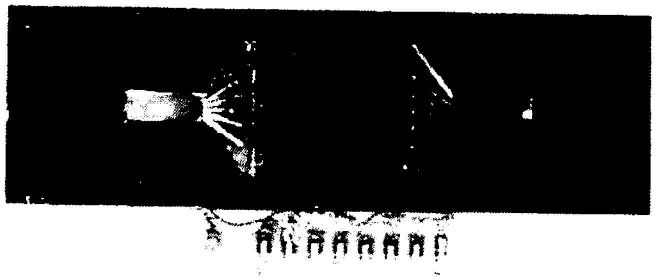
Steady-state device performance



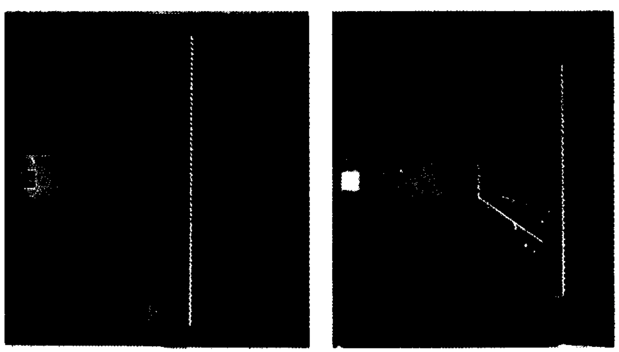


Experimental data: • 25, • 20, • 15, • 10 ml/min

Heat Sink Redesign



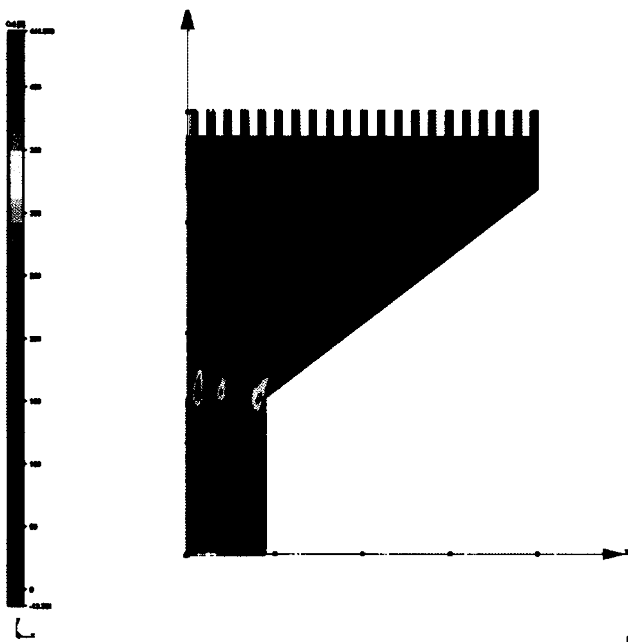
Top side (channels)



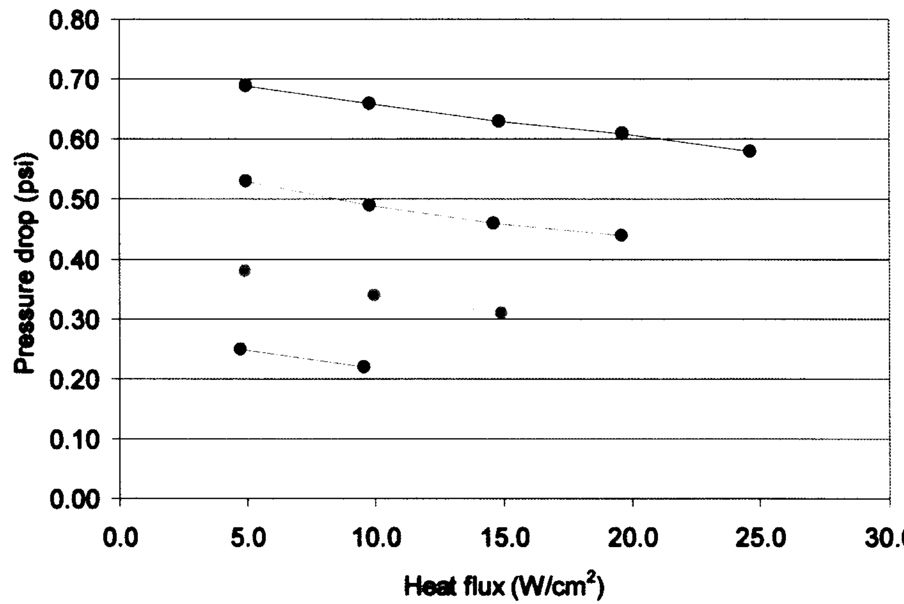
Manifold comparison

- Devices were redesigned to increase structural integrity while maintaining thermal and hydraulic performance
- Failure modes included de-bonding of the Pyrex glass and fracturing of the silicon wafer in the manifold
- Channel footprint was decreased to 2 cm^2
- Microchannel geometry: 325 μm deep, 125 μm wide, 42 channels
- Diffuser manifold was redesigned with CFdesign™ CFD/FEA code

Modeling and Experimental Data



Manifold CFD model:
Velocity magnitude contour plot



Steady-state device performance

Experimental data: • 25, • 20, • 15, • 10 ml/min

Summary

- A parallel microchannel heat exchanger design by the Stanford University Microfluidics Laboratory was adapted to meet thermal and hydraulic performance requirements for microspacecraft thermal control
- Microchannel heat sinks were fabricated at JPL and tested in a mechanically pumped fluid loop test assembly
- The first microcooler heat sink design was demonstrated to remove heat fluxes of up to 25 W/cm^2 with water as the cooling fluid
- Maximum device temperature of less than 80 °C and pressure drops of less than 0.5 psi were recorded for all test cases
- A redesign of the microchannel heat sink device improved structural integrity while maintaining acceptable thermal and hydraulic performance

Future Work

- Integrate microchannels in the simulated spacecraft mechanically pumped thermal control system
- Evaluate microchannel heat sink thermal performance with various working fluids
- Investigate alternate fabrication techniques and materials for microchannel geometry
- Evaluate the spacecraft thermal control capability of the integrated system for a few selected future deep space and earth orbiting missions

Acknowledgements

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