46th International Conference on Environmental Systems
10-14 July 2016, Vienna, Austria

ICES-2016-230

Micro-Channel Thermal Control System Development

Benjamin M. Slote[1], Renee Noble[2], Edward Salley[3], and Michael C. Kimble[4]
Reactive Innovations, LLC, Westford, MA 01886

Thermal control systems are a cross-cutting technology that applies to many NASA missions ranging from the International Space Station, to heavy lift launch vehicles, to satellites and small CubeSats. Of particular interest to all of these space vehicles is the acquisition of heat, especially from high heat flux electronic devices that can approach 1000 W/cm^2. Power electronics in these systems, as well as with many commercial systems, need improved heat removal technologies that can reject these high heat loads and maintain lower device temperatures in lightweight, compact, and cost-effective thermal management solutions. A new additive-based manufacturing approach for making micro-channel thermal management system has been developed by Reactive Innovations, LLC that departs from the traditional methods and introduces new performance features. Traditional methods are based upon subtractive methods removing material from a block to define the flow structure. Reactive's approach is an additive based technology where 3-dimensional flow networks are formed that contain varying sized channels and shapes, converging and diverging ducts, integrated venturi nozzles, manifolds, multi-channels, wicks, etc. that fully define the fluid flow regime. Feature sizes less than 1 micron upwards to 6000 microns along with varying sized shapes and 3-dimensional design characteristics have been produced using this method all fashioned into a single continuous flow network. The resulting thermal management systems are thus very lightweight. With this new manufacturing technology, compact and lightweight thermal management systems may be inexpensively produced ranging from single-phase to two-phase flow systems. Experimental performance data will be presented on these new thermal management devices and compared to commercial devices showing the merits of this new manufacturing technology and thermal management design.

I. Introduction

Electronic systems for aerospace, military, industrial, and consumer products have increasingly difficult thermal management requirements due to the electronic materials and designs. For instance, GaN power amplifiers are being used in more electronic systems that have power dissipation levels over 1000 W/cm^2. Similarly, systems including radio frequency power semiconductors for the commercial wireless telecom market, phased array radar systems, inverter modules for hybrid electric vehicles, and diode lasers used in surgical, nuclear detectors, and metalworking all have high heat flux removal requirements requiring new thermal management devices that are lightweight, compact, reliable, and cost effective to manufacture. Clearly, thermal control systems are a cross-cutting technology that applies to many NASA, DoD, industrial, and consumer applications.

Beyond thermal management devices that can remove high heat fluxes, an additional challenge is the development of additive-based manufacturing methods that can minimize the mass of these thermal management units by selectively placing material where it is required. Toward this need, Reactive Innovations, LLC has developed a new template-based additive manufacturing technology that enables us to produce thermal management devices that contain micron-size channels, orifices, diverging/converging ducts, venturi nozzles, porous wicks, and heat pipes with tailored properties. Reactive's additive-based manufacturing approach for making micron-sized flow channels departs from the traditional methods and introduces new performance features. Traditional methods are based upon subtractive methods removing material from a block to define the flow structure. Reactive's approach is an additive technology where 3-dimensional flow networks are formed with a dissolvable template that is subsequently encapsulated with copper or aluminum alloys. With this approach, material is placed precisely where it is needed to contain the single or two-phase heat transfer fluids and where this material is formed with specific geometric features to enhance thermal and fluid flow behavior.

---

[1] Research Engineer, bslote@reactive-innovations.com.
[2] Research Engineer, rnoble@reactive-innovations.com.
[3] Senior Research Scientist, esalley@reactive-innovations.com.
[4] President, mkimble@reactive-innovations.com.

II. Fabrication Approach

Present day micro-channel thermal management units are fabricated using precision engineering techniques that were originally developed for the semiconductor industry. Substrates including silicon, copper, carbon, and aluminum are used where precision cuts are made to form the micro-channels on the order of 50-500 microns wide. Chemical etching is also used with these substrates enabling batch processing and surface roughness control. These traditional fabrication methods remove materials from a block substrate to define uniformly flat walls and surfaces for the micro-channels. However, this fabrication approach is not amenable to creating 3-dimensional flow structures unless layers are laminated together. Additionally, the micro-channels have to be integrated into a housing or manifold structure adding additional mass, cost, and thermal resistance. This subtractive-based manufacturing process takes away material to define flow patterns, however, it leaves a substantial quantity of overhead material increasing mass and thermal resistance.

Reactive's new manufacturing method for producing micro-channel thermal management units enables the tailoring of channel sizes, geometries, and flow features for electronics cooling. The approach is essentially the reverse of that discussed above where we directly form and deposit a 3-dimensional structure that defines the fluid flow pathways as opposed to removing material from a block. The process starts off using a dissolvable template material to define the flow regime for the single or two-phase fluid. The template is fashioned into either single channels, multiple flow-channels, manifolded channels, channels with integrated venturi nozzles, channels with either a cylindrical, square, or triangular cross-section along with straight, converging or diverging flow features, channels with varying sized shapes as low as 1 microns and 3-dimensional flow characteristics all connected into a single continuous flow network. Figure 1 shows photographs of dissolvable templates that can be produced via extrusion or casting methods.

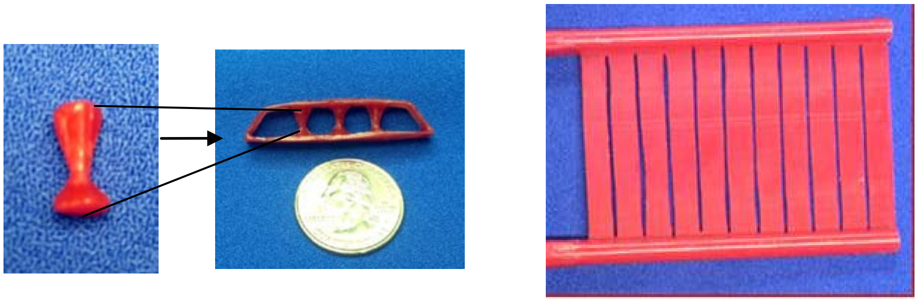

Figure 1. Dissolvable template structures for thermal management devices, a) venturi nozzle for a two-phase unit, b) micro-channel liquid-phase thermal management unit

Once a template structure is defined, that unit is encapsulated with a metal such as copper or aluminum where the thickness can be varied as necessary to withstand pressurized fluids or to impart thermal or structural performance features. To date, only copper and aluminum have been examined for this manufacturing method. Afterwards, the template material is dissolved producing hollow thermal management units that define the fluid flow pathways. This produces an intricate and continuous flow passage without seams or welds that defines the thermal management system. There is very little material overhead associated with the thermal management unit minimizing mass, volume, cost, and thermal resistance, all favorable metrics for aerospace and military thermal management needs.

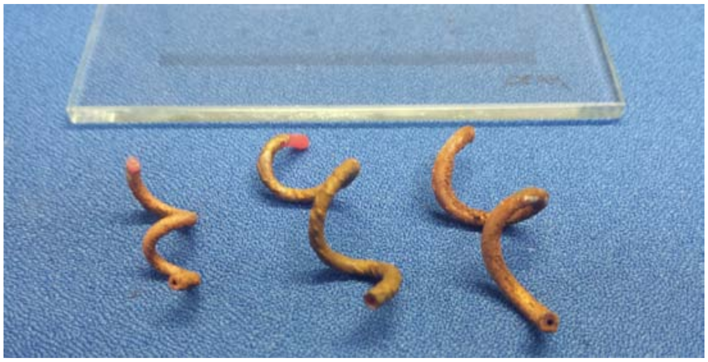

Figure 2. Spiraled cylindrical micro-channels

At the simplest level, templates can be extruded into straight cylindrical channels and even spiraled channels as shown in Figure 2. Such conformal spiral designs could be used for wrapping cooling loops around cylindrical batteries or capacitors in support of electric vehicle cooling for instance.

A cross-section of a cylindrical channel is shown in Figure 3 showing a 625 μm inner flow diameter and a 25 μm wall thickness. These channel dimensions are dependent on the template extrusion and metal encapsulation process where variations in the process conditions produce different sized channels. This is illustrated in Figure 4 for a 250 μm inner diameter and a thicker wall thickness of 88 μm. Good uniformity is shown with the wall thicknesses in these cross sections.

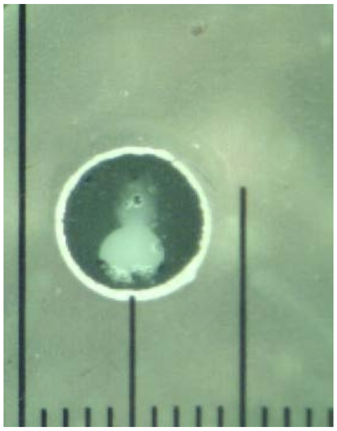

Figure 3. Cylindrical micro-channel with a 625 μm inner diameter and a 25 μm wall thickness (100 μm between gradation marks)

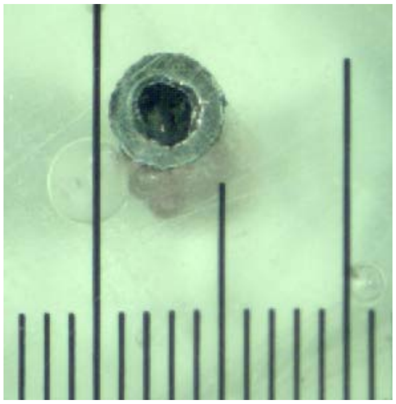

Figure 4. Cylindrical micro-channel with a 250 μm inner diameter and an 88 μm wall thickness (100 μm between gradation marks)

One of the true advantages of this template-based manufacturing process is the ability to exactly define the desired flow channel structure to optimize the heat transfer. For instance, placing a cylindrical cooling channel on a heated surface is a poor heat transfer design since the interfacial contact area between the heated surface and the channel is minimal. A better design is to have a flattened channel area that contacts the heated surface and where the channel design has low pressure drop. This is graphically illustrated in Figure 5 for the poor and optimal channel designs. Using the template-based manufacturing process, we produced a flattened micro-channel as shown in Figure 6 that optimizes the interfacial contact area between the heat source and the cooling channel. This semi-circle flow regime has a base width of 300 μm and a height of 212 μm with an 88 μm wall thickness (100 μm spacing between gradations).

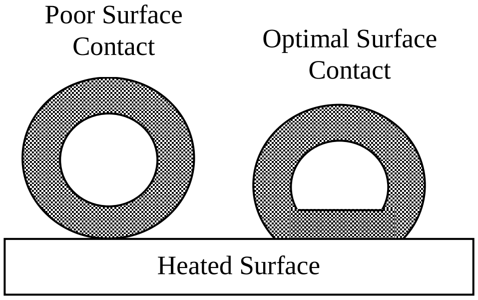

Figure 5. Schematic representations of poor and optimal surface contact between micro-channels and a heated surface

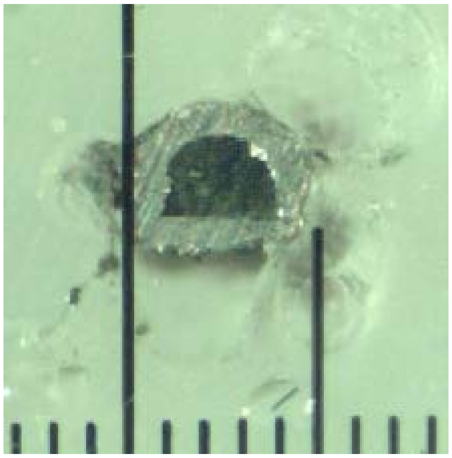

Figure 6. Semi-circular micro-channel structure with a 300 μm base by 212 μm high flow area

Reactive has used this template-based manufacturing process to produce a variety of micro-channel structures that could be used with power amplifier modules. Figure 7 shows a view of a 5 cm x 7.6 cm multi-array structure that has fluid flow manifolds located on opposing ends of 12 channel ribs. Of particular merit is that this liquid-cooled multi-channel unit only weighs 6 grams. The lightweight structure of these components is due to the additive manufacturing process that only places material where needed to hold moving fluids. Figure 8 shows a photograph of this multi-channel array where the fluid flow manifold has been opened up to view the internal flow channels. Smaller channel sizes may also be produced using this template-based manufacturing process as shown in Figure 9 for a 5 cm x 5 cm unit containing 34 micro-channels. Each channel has a fluid flow height of 127 μm and width of 838 μm as shown in Figure 10 where the manifold has been opened.

Figure 7. Liquid-cooled multi-channel array measuring 5 cm x 7.6 cm and weighing 6 grams

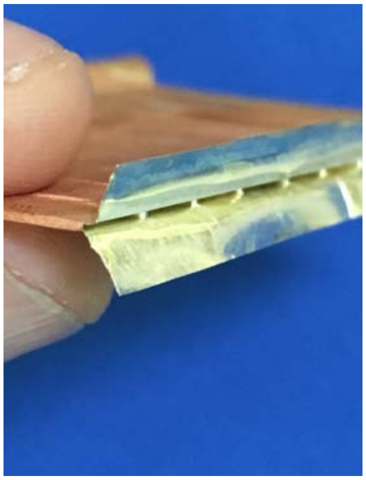

Figure 8. Internal view of a 12-channel array structure

Figure 9. Micro-channel array measuring 5 cm x 5 cm and weighing 1.8 g

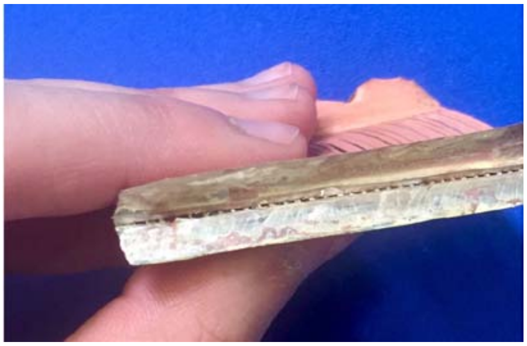

Figure 10. Micro-channel flow regions each measuring 127 μm by 838 μm

With this additive manufacturing technique, additional thermal management units can be produced including heat pipes, porous wicks incorporated into heat pipes, and loop heat pipe systems. Figure 11 shows a prototype of a heat pipe unit where all components were produced using the template manufacturing method to encapsulate the interior metallic wicks within an outer metallic housing.

Figure 11. Dissolvable template manufactured heat pipe prototype

Unlike conventional 3-D printers that process one unit at a time, this additive manufacturing process can produce many units at once keeping unit costs low. This inexpensive manufacturing process can produce a variety of thermal management designs that incorporate precision flow features in complex 3-dimensional shapes. Because all surfaces that define the fluid flow region are encapsulated with metal at the same time, there are no seams, welds, or seals giving leak-free, low-hydraulic resistance flow patterns for the coolant. The metal encapsulation process time can be varied to impart a desired thickness that affects thermal conductivity, operating pressure limits, and the final device mass. Figure 12 shows the relationship for copper based units where increasing the metal encapsulation time produces thicker wall units following a fairly linear trend. Burst pressure testing of these units were subsequently conducted until leaks occurred as shown in Figure 12. For devices with a wall thickness greater than 120 µm, they did not fail before reaching the maximum permissible test limit of 400 psi define by the burst pressure test apparatus.

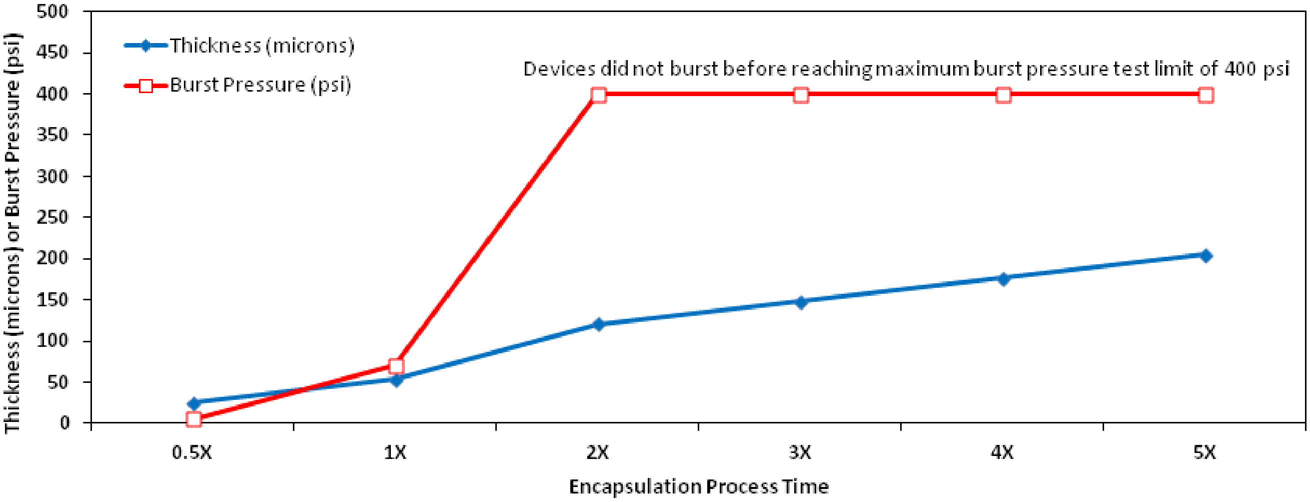

Figure 12. Relationship of copper encapsulation time, wall thickness, and burst pressure capability

III. Liquid-Cooled Thermal Management Units

To assess the heat transfer performance of these micro-channel thermal management units, an instrumented heater test platform was constructed to impose varying heat fluxes. On top of this heated platform, commercially available thermal management units as well as Reactive fabricated units were placed and assessed for their thermal performance. Commercial units included traditional fin structures using a fan and a liquid-cooled micro-channel structure made out of aluminum. Thermal performance testing of these devices was conducted using the same test platform and applied heat load to measure thermal responses. Analysis of the data includes the temperature response of the instrumented heater test platform over time, the thermal resistance, and the transient response capability of the thermal management unit.

A. Experimental Test Platform

The experimental heat transfer test platform is shown in Figure 13. This system has eight 300 watt heaters that traverse a 5 cm x 7.6 cm copper plate where each heater can be activated individually or collectively to simulate uniform heat loads, gradient heat loads, or hot-spot scenarios. The copper plate has 18 thermocouples installed into the underlying surface to enable surface temperature mapping. This thermal test bed enables us to assess heat fluxes upwards of 100 W/cm^2 for the various thermal management devices being produced. A National Instruments data acquisition system is used to measure the thermal and flow rate data.

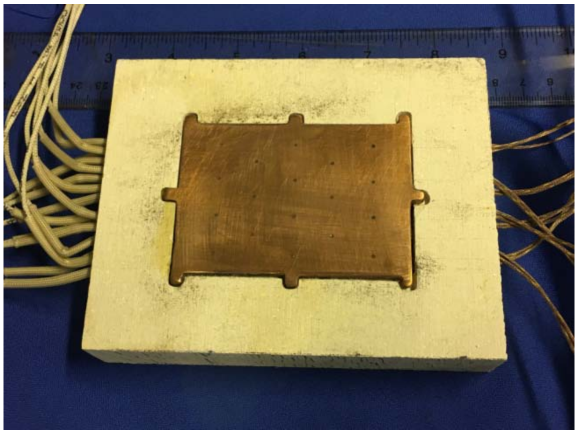

Figure 13. Instrumented thermal test platform

B. Baseline Fin/Fan Cooling

An initial fin and fan set up was used to obtain a thermal cooling performance baseline. Two aluminum fin structures with 2.5 cm high fins were placed over the thermal heater platform using thermal grease to ensure adequate surface connectivity as shown in Figure 14. An imposed heat load was applied with the fan initially turned off enabling the surface temperature of the heated copper plate to rise to an average temperature of 52 °C. Once equilibrated, the fan was turned on dropping the average surface temperature to 26 °C. This performance data is shown in Figure 15 showing the 26 °C temperature drop. The mass of the two fin structures is 217 g, not including the fan.

Figure 14. Photograph of baseline fin cooling

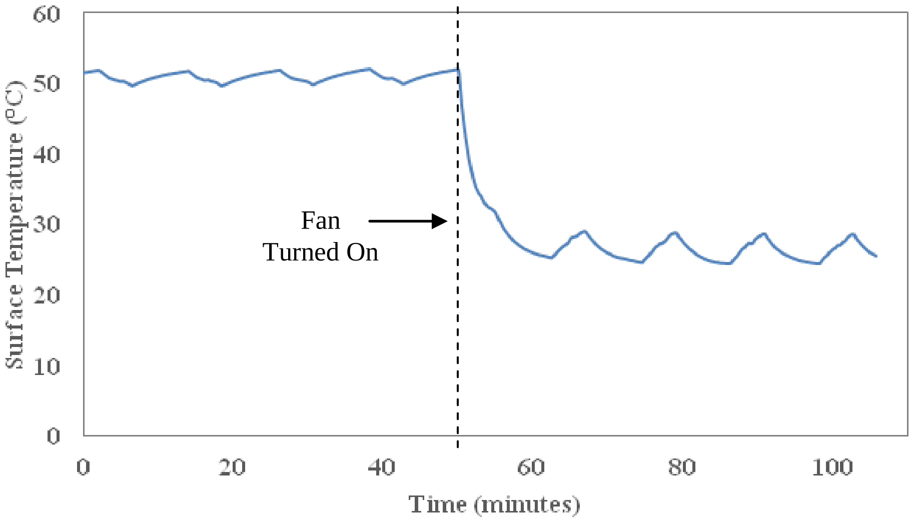

Figure 15. Thermal baseline performance of a fin and fan cooling approach

C. Commercial Liquid-Cooled Thermal Unit

A commercial liquid-cooled aluminum thermal management unit was assessed that has a 5 cm x 5 cm contact area weighing 181 grams without the clamping support unit. This unit was mounted to the heater block shown in Figure 16 and assessed using the same heat load as used previously with the fin and fan cooling system. Before any coolant was pumped through the thermal management unit, the system was allowed to equilibrate on the heater block rising to an average surface temperature of 65 °C. Some residual water in the unit along with ambient air temperature differences caused variations in the equilibrium temperature between the three experiments. Afterwards, a distilled water coolant was pumped through the commercial device at flow rates of 90, 130, and 240 ml/min keeping the inlet coolant temperature at 22 °C. The temperature distribution of the heated copper plate was recorded over time dropping from 65 °C to 23 °C as shown in Figure 17. Because of the size and high interfacial contact area of this commercial unit to the underlying heater block, it was readily able to conduct heat enabling free convection to cool it to 65 - 75 °C for the same imposed heat load that heated the fin structures to 55 °C. Flow rates higher than 90 ml/min gave similar thermal performance as shown in Figure 17 indicating that the unit is capable of handling higher heat loads than applied for this testing.

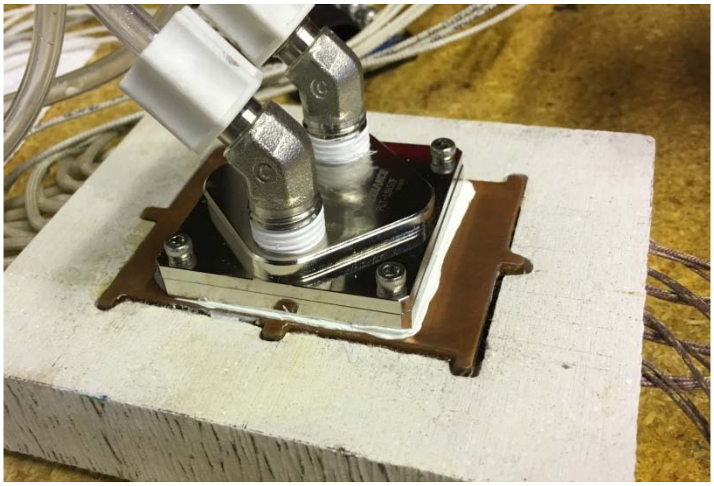

Figure 16. Set up of a commercial liquid-cooled thermal management unit on the heated platform

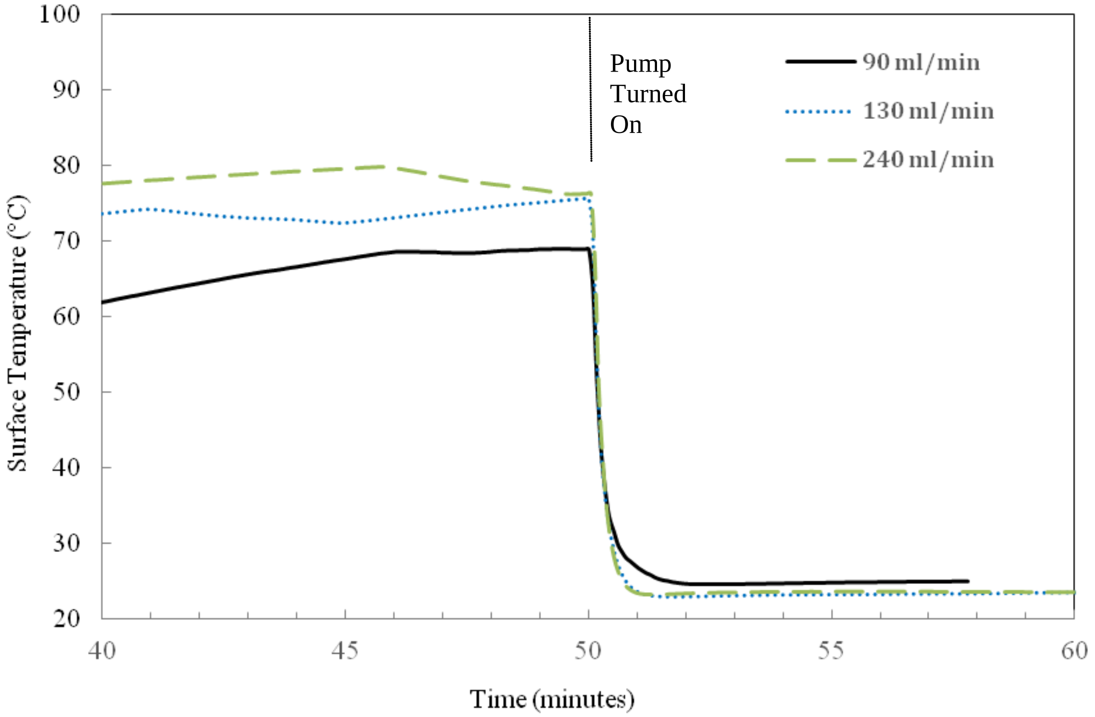

Figure 17. Thermal performance of a commercial 5 cm x 5 cm aluminum liquid-cooled micro-channel thermal management unit with a 22 °C inlet coolant temperature

D. Additive-Based Manufactured Micro-Channel Thermal Management Unit

Using the additive-template based manufacturing method discussed earlier, a liquid-cooled thermal management unit was fabricated to operate with the heater block as shown in Figure 18. This device has 12 channels each having outer measurements of 5800 μm wide by 1090 μm high. Manifolds measuring 5000 μm high and wide were incorporated on the opposing ends of the micro-channel device shown schematically in Figure 19. Produced using copper, this thermal management unit weighs 6 grams.

Figure 18. 12-Channel thermal management unit produced using the additive-based manufacturing process

Each micro-channel flow rib has a copper wall thickness of 20 μm giving a rectangular cross-sectional flow area of 5780 μm wide by 1052 μm high. Using these dimensions along with other pertinent design parameters for this thermal management unit, the corresponding Re numbers, friction factors, and calculated pressure drops for flow through a rectangular duct are sufficiently low for flowing water at varying rates through this device as summarized in Table 1.

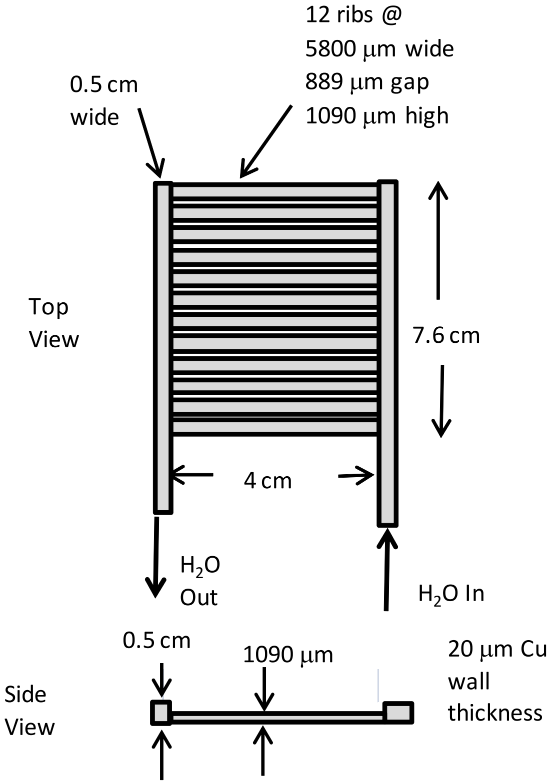

Figure 19. Dimensions of the 12-channel unit

Table 1. Reynolds Number, Friction Factors, and Pressure Drops in a 12-Channel Unit

Total Flow rate (ml/min)	Manifold				Per Individual Flow Channel				
	Velocity (cm/sec)	Re	f	Pressure Drop (psi)	Flow rate (ml/min)	Velocity (cm/sec)	Re	f	Pressure Drop (psi)
40.0	3.342	167.4	0.38	4.68E-04	3.33	0.91	16.1	3.97	5.45E-04
90.0	7.521	376.7	0.17	1.05E-03	7.50	2.05	36.3	1.76	1.23E-03
130.0	10.863	544.2	0.12	1.52E-03	10.83	2.96	52.4	1.22	1.77E-03
240.0	20.055	1004.6	0.06	2.81E-03	20.00	5.46	96.7	0.66	3.27E-03

An assessment of this 12-channel thermal management unit was assessed using the same heat load as with the fins and commercial device. This thermal management unit was placed upon the heated copper plate with the applied heat load without running cooling water through the unit. An average surface temperature of 100 °C for the copper plate was obtained at equilibrium at which point cooling water was pumped through the system at 30, 90, 100, 130, 190, and 240 ml/min with an inlet temperature of 22 °C. The corresponding drop in the average copper plate temperature was recorded over time giving the thermal performance shown in Figure 20. For flow rates greater than 100 ml/min, an average surface temperature of 28 °C was obtained with slightly higher surface temperatures for lower flow rates. Of particular note is the rapid thermal response evidenced by the change in the average surface temperature once the cooling water is applied, as well as the magnitude of the temperature drop Thermal limits of this copper based thermal management unit have only been assessed up to 100 °C to maintain a liquid state for the distilled water coolant.

IV. Comparison of Liquid-Cooled Thermal Management Units

A comparison of the commercial unit to that produced by this new manufacturing process is shown below in Figure 21 at water coolant rates of 90 and 130 ml/min. The initial temperature for each unit was monitored using the same heat load without active cooling applied to determine the relative degree of free convection and to establish a stable thermal profile before applying active cooling. As shown in Figure 21, the commercial unit has a higher free convection cooling capability due to the unit's size and higher surface contact area with the heater block. The gaps between the multi-channels in this particular design of Reactive's unit lower the surface area contact reducing its free convection capability. Applying active cooling to each unit by pumping water at the same pressure at 22 °C at either 90 or 130 ml/min, the underlying copper platform temperature dropped to the 23 to 28 °C range.

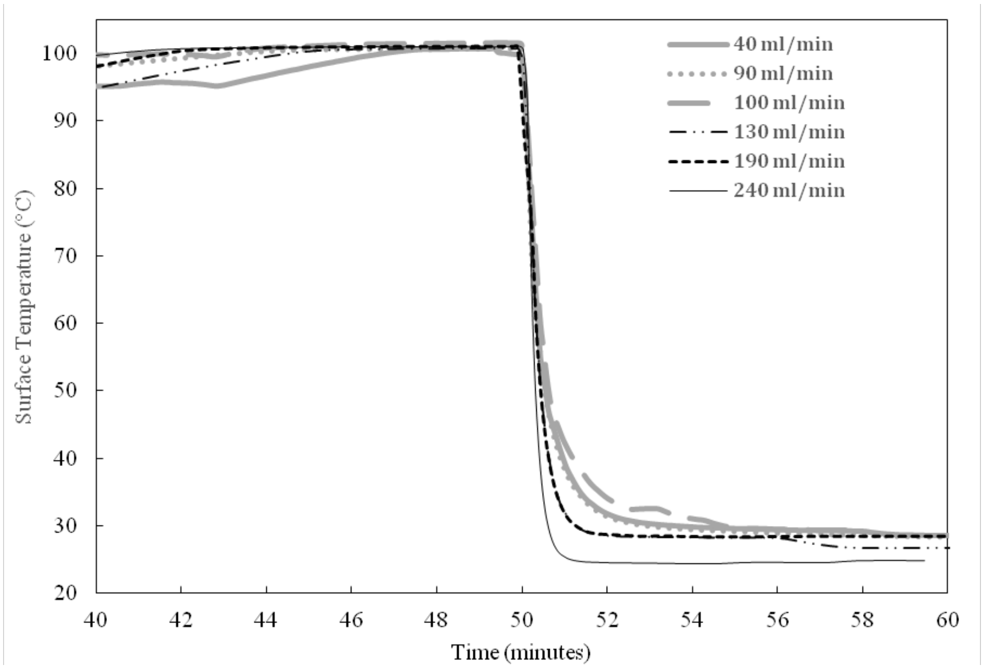

Figure 20. Thermal performance of a 12-channel unit at varying water flow rates

The thermal management response time was assessed by taking the derivative of the thermal responses from Figure 21 giving the time rate of change of the underlying copper platform as shown in Figure 22 for coolant flow rates of 90 and 130 ml/min, respectively. Both the commercial unit and the Reactive produced thermal management units have similar thermal response rates showing their capability of responding rapidly to thermal changes. However, when the mass and volume are considered in the analysis of these units, the lightweight and low volume design of the Reactive produced units show favorable performance metrics.

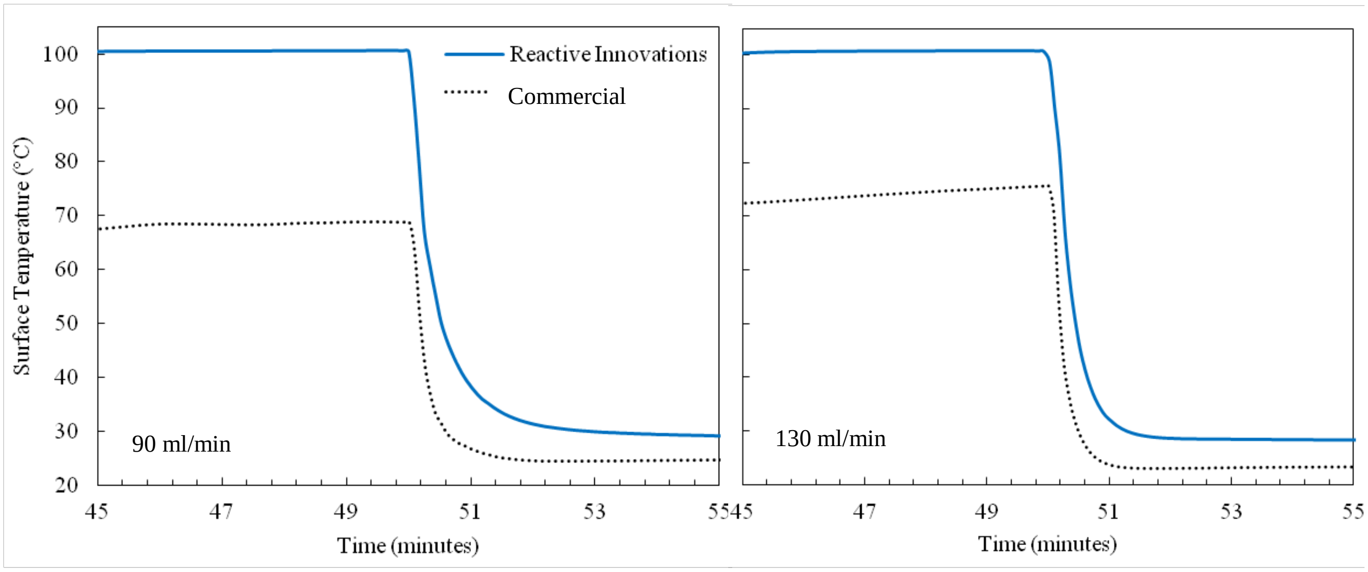

Figure 21. Thermal performance comparison of different thermal management units at coolant flow rates of 90 and 130 ml/min with an inlet temperature of 22 °C

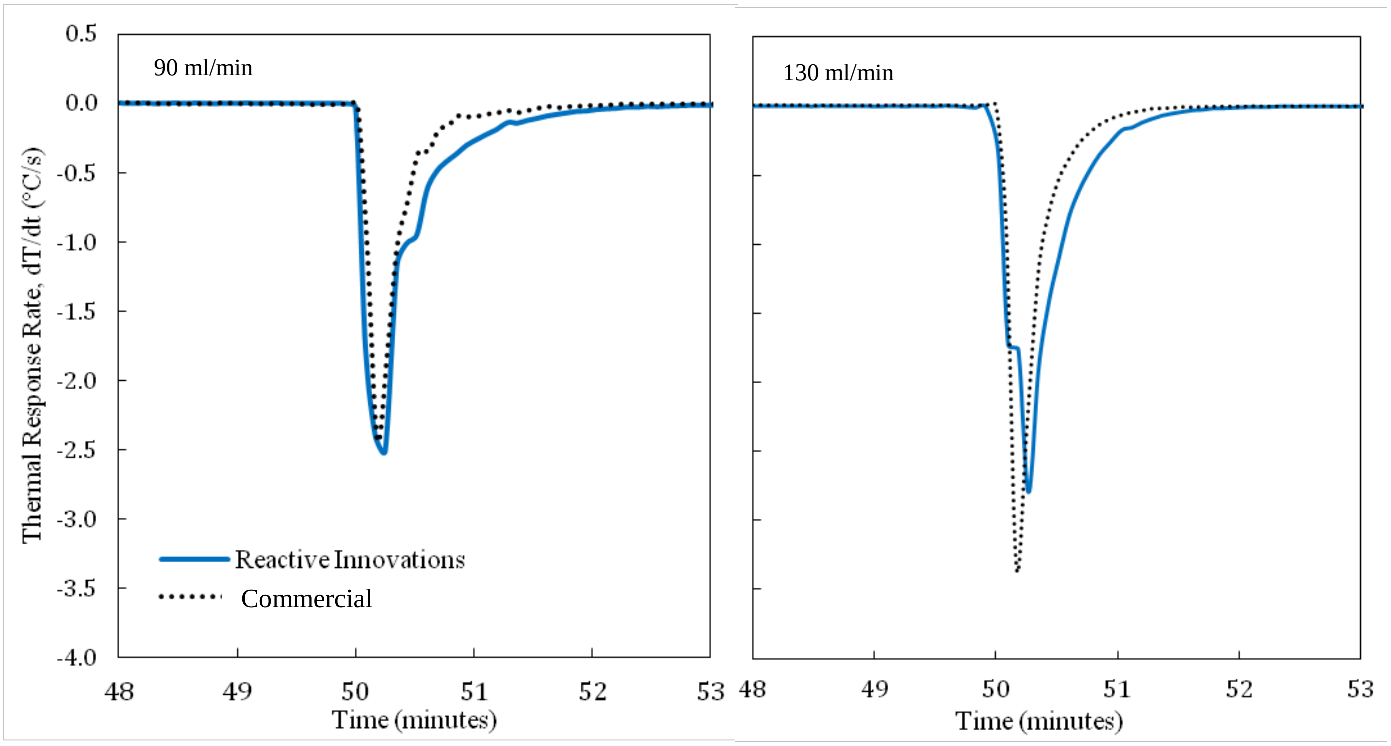

Figure 22. Thermal response rates of different thermal management units at coolant flow rates of 90 and 130 ml/min with an inlet temperature of 22 °C

A performance comparison of the three thermal management units are shown in Table 2 for the fin and fan unit, the commercial liquid-cooled micro-channel unit, and Reactive's 12-channel unit produced by the additive-based manufacturing process. All three of these units were placed on the heated copper base plate using thermal grease, however, no physical restraint was used causing some interfacial contact resistance. The average surface temperature and standard deviation of the heated copper plate was calculated based on measuring 12 thermocouples installed into the copper base plate. The coolant used for the liquid stream tests was water with an inlet temperature at 22 °C. In all cases, a steady 15.6 W was applied to the underlying copper plate. Additional information shown in Table 2 includes the time for the thermal management unit to reach a lower final temperature once active cooling was applied, the magnitude of this temperature change, and the final differential temperature between the average surface temperature and the coolant temperature averaged between the outlet and inlet water stream. Examining and measuring the active cooling temperature versus that obtained in the passive mode serves to help establish that the devices reached a stable temperature before being tested and to enable a transient performance assessment.

Performance metrics for these three thermal management units were assessed to obtain the thermal resistance, along with mass and volume-dependent metrics. Since one of the objectives with this new manufacturing method is to produce very lightweight thermal management units, it is relevant to consider how these thermal management devices perform with regard to mass, and volume. The fins had a mass of 217 grams and a volume of 152 cc, not including the fan or mounting hardware. With an ambient temperature of 22 °C, this device has a thermal resistance of 0.26 °C/W. The commercial liquid-cooled unit and Reactive's 12-channel unit had masses of 181 grams and 6 grams, respectively, where neither unit includes the mounting hardware, pump, flow lines, or fittings. The volume of these two units were 68 cc and 7.6 cc for the commercial and Reactive devices, respectively, including fittings. Table 3 shows the thermal resistance showing competitive metrics for the commercial unit in comparison to fins and to Reactive's 12-channel unit. For both the commercial unit and Reactive's 12-channel design, the thermal resistances decrease with an increase in the coolant flow rate. Furthermore, although thermal grease was used to mount all of these thermal management devices to the heated copper plate, no physical mounting hardware was used that would help reduce the interfacial contact resistance more in practice.

When mass and volume metrics are incorporated into the device performance, the lightweight and compact volume of Reactive's thermal management unit make it very competitive as summarized in Table 3. Given that any practical thermal management device must account for the mass and volume, the devices produced using Reactive's manufacturing technology show very competitive thermal behavior in a device that only weighs 6 grams and occupies a space of 7.6 cc. In comparison to the commercial liquid-cooled unit, the mass-adjusted thermal resistance of Reactive's unit is 14 times lower while the volume-adjusted thermal resistance is 4.4 times lower on average. This is due to the additive-based manufacturing technology that only places material where needed to contain the fluid flow and to contact the heated surface to be cooled. Continued advancements and optimization with this manufacturing technology and device design aim to minimize the channel flow sizes and reduce the interfacial contact resistance.

Table 2. Thermal Response Data for the Fin and Fan, Commercial Liquid-Cooled, and Reactive's Micro-Channel Thermal Management Units

	Before Active Cooling		After Active Cooling					
Cooling Device	**Avg. Temp (°C)**	**Std. Deviation (°C)**	**Avg. Temp (°C)**	**Std. Deviation (°C)**	**Time to Cool (min)**	**Temp. Change (°C)**	**Coolant Flow Rate (ml/min)**	**Surface-to-Coolant Temp. Differential (°C)**
Fins with Fan	52.0	0.41	26.0	0.55	10	26.6	-	4.0
Commercial Liquid-Cooled Unit	68.9	0.38	24.9	0.65	2.4	44.0	90	2.2
	75.7	0.33	24.1	0.54	1.2	52.5	130	1.7
	79.7	0.32	23.5	0.60	1.0	56.1	240	1.7
Reactive Innovations' 12-Channel Design	100.8	0.31	28.6	0.83	2.5	72.2	40	5.5
	100.7	0.32	28.0	0.83	2.5	72.7	90	5.9
	100.7	0.31	29.4	1.06	4.0	71.3	100	6.3
	100.8	0.31	27.4	0.60	1.8	73.4	130	3.6
	100.7	0.29	27.0	0.60	1.5	73.7	190	3.5
	101.0	0.32	24.8	0.62	1.3	76.2	240	3.1

Table 3. Thermal Resistance Performance Comparison of Three Thermal Management Devices

			Device Footprint			
Cooling Device	**Coolant Flow Rate (ml/min)**	**Thermal Resistance (°C/W)**	**Device Mass (g)**	**Mass-Thermal Resistance Value (g-°C/W)**	**Device Volume (cm^3)**	**Volume-Thermal Resistance Value (cm^3-°C/W)**
Fins with Fan	-	0.26	217	56	152	39.5
Commercial Liquid-Cooled Unit	90	0.14	181	25	68	9.5
	130	0.11	181	20	68	7.5
	240	0.11	181	20	68	7.5
Reactive Innovations' 12-Channel Design	40	0.35	6	2.1	7.6	2.7
	90	0.38	6	2.3	7.6	2.9
	100	0.40	6	2.4	7.6	3.0
	130	0.23	6	1.4	7.6	1.7
	190	0.22	6	1.3	7.6	1.7
	240	0.20	6	1.2	7.6	1.5

This thermal management technology has focused initially on developing a new manufacturing approach that can produce lightweight devices at relatively low costs. Having developed processes to produce copper wall thicknesses ranging from 20 to 200 μm, channel sizes as low as 127 μm, and simplistic multi-channel designs that show reasonable thermal performance in a compact and lightweight structures, the next steps being taken are to focus on improving the thermal management designs. This involves developing smaller channel sizes to increase heat transfer coefficients, improving mounting methods for securing the devices, optimizing conductive and convective pathways of the multi-channels, and extending the designs to two-phase systems. These will be presented in future work.

V. Conclusions

A new manufacturing method has been developed to produce lightweight thermal management units based on an additive production technique. The process uses dissolvable templates that define the fluid flow pathways for the thermal management device that are subsequently encapsulated with a metal over time followed by dissolving the template. This approach enables intricate flow features to be produced as small as 1 micron in size along with controllable wall thicknesses to hold fluid pressure and provide thermal conductive pathways. The manufacturing process culminates in very lightweight and compact thermal management systems that compare favorably to existing commercial devices. Extensions of the manufacturing technology may be used to produce comparable micro-channel chemical reactors and separators where enhanced mass-transfer and heat-transfer occur due to the small channel feature sizes

Acknowledgments

The authors wish to acknowledge the funding of this work through the Department of Energy SBIR program, Phase I and Phase II grant No. DE-SC0011232, entitled “Templated Micro-Channel Thermal Control System.”