

Reticulated Metal Foam Based Heat Exchangers

Introduction:

It is being realized that the thermal aspects of many advancing technologies may limit the performance, size and the cost of future products. Advanced discrete devices, hybrids, and modules of power, RF and digital devices are among such products. Derating performance by reducing current, switching speed (or using higher voltage, less efficient and more expensive devices) increasing size, weight, cost and efficiency are among such major issues facing power electronics designers. Heat spreading to reduce high heat fluxes, via increasing the size of the thermal base results in increased interconnect size and parasitics. The preferred approach is to transfer higher heat fluxes to the ambient by using a higher performance heat sink and by reducing or eliminating soft thermal interfaces.

Reticulated Metal Foams:

Reticulated Metal Foams (RMF), developed for structural application more than two decades ago are now becoming effective solutions to many thermal management problems (see Figure 1 for the physical structure of RMF) [1,2]. RMF are available, among others, in pure highly conductive metals such as Al and Cu. The metal foam based thermal technology is generic, flexible and scaleable. It is generic in terms of its compatibility with the cooling media, ranging from DI water, inert fluoro-carbons, and jet fuel, to air He or Ar. It is flexible in terms of its compatibility with various semiconductor devices and substrates such as Si, GaAs, and SiC, SiN, and many other ceramic metallic or composite materials. The metal foam based thermal technology is scaleable both in size and performance so that it can be applied to not only to discrete devices but also to Power Electronics Modules, Hybrid Multi Chip Modules (HMCM) integrated photonic and electronic devices, and also to double-sided Printed Wiring Boards (PWB) with constraining cores. In the as-fabricated state, the isotropic RMF consists of randomly oriented polygon shaped cells that can be approximated by dodecahedron (Figure 1) [3,4,5]

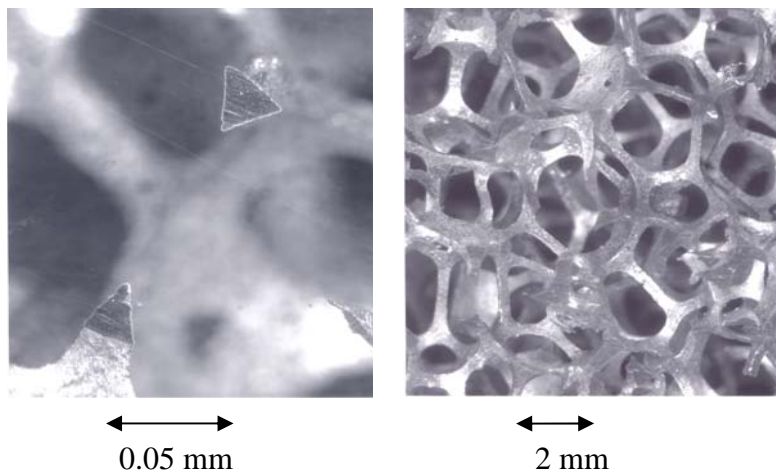


Figure 1. 30 pore per inch (ppi) metal foam consisting of nodes and ligaments forming a dodecahedron of 12 pentagon shaped facets.

Notice that the cross sections of the ligaments are triangular. The geometry of RMF does not allow boundary layers to grow, and introduce enhanced mixing through eddies and turbulence. These features result in higher local film coefficient.

Thermal Characteristics of metal foams:

The as-fabricated specific density (5% -10%) of RMF may be increased by successive compression and annealing steps. The compression increases the specific surface area, local convective heat transfer, effective thermal conductivity in the direction perpendicular to the plane of compression, and flow resistance of the RMF matrix. The amount and the direction of compression, as well as the initial pore size and relative density, are the variables that allow the properties of RMF to be tailored for a given application.

The high aspect ratio of axial to radial dimension of ligaments promotes linear and non-linear buckling, and the low yield stress of pure metal ligaments and thereby reducing the effective modulus of RMFs to a few kpsi. Furthermore, a RMF block may be sliced to smaller sized pieces before braze or solder attachment to the heated surfaces of low thermal expansion such as semi-conductors, ceramics, and Metal Matrix Composites so that the thermal stresses are further reduced. Since the CTE mismatch-related thermal stresses and deformations are limited, the reliability of the integral heat

exchanger and the thermal base (usually metalized ceramic plates carrying directly attached semiconductor devices) are not compromised as verified by hundreds of thermal cycles [6].

In summary, RMF based heat exchangers offer significant advantages over the alternative approaches to compact heat exchangers. Among those advantages, the most noteworthy ones are:

- a) Large specific surface area (as high as $400 \text{ in}^2/\text{in}^3$)
- b) Superior and scalable thermal performance
- c) Low weight, volume and cost per performance.
- d) Compatibility with a wide range of coolants
- e) High structural compliance and specific stiffness.
- f) High corrosion resistance

Thermal Performance limits of RMF based HXs:

The maximum thermal performance potential of RMF heat exchangers (HX) are shown below. The thermal performance surfaces are drawn for maximum attainable local film coefficients [7] of 0.01 and $1 \text{ (W/cm}^2 \text{ } ^\circ\text{C)}$ for forced convection with air and water, respectively. However, the maximum values of local film coefficients as measured with RMF HXs may be up to $4x$ higher than those reported in the literature. Therefore, the maximum effective film coefficients of $6 \text{ (W/in}^2 \text{ } ^\circ\text{C)}$ and $48 \text{ (W/in}^2 \text{ } ^\circ\text{C)}$ represent conservative values for air and water, respectively.

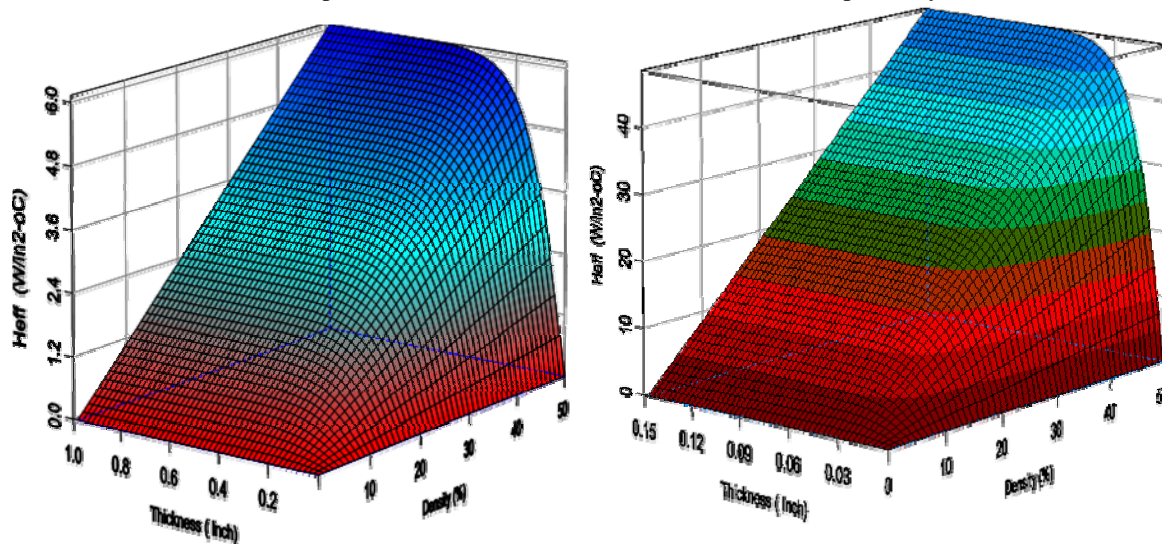


Figure 2. Thermal performance limits of 30 ppi RMF HXs with air (left) and water (right).

Thermal performance of air-cooled HXs: Pin and fin vs. RMF:

At this point it is important to know where do RMF HXs stand in comparison to pin or fin based HXs in order to know whether it is worth to include in the design options. Let's consider a few the high end commercially available HX options. We compared RMF based HX with HXs using (4) different extended surfaces shown in classic book of Compact Heat Exchangers of Kays&London [8] figure 3. Comparisons are based on the R_h , R_p , R_v and R_w ratios as defined in Table 1 below.

For all comparisons, the friction factor (f) and the Colburn factor (j) were taken from the test data reported in Kays& London for pin and fin HXs, and from similar tests conducted in the ERG and Northrop Grumman laboratories for the RMF based HXs [1]. Although the thickness of pin and fin profiles are different for each geometry, the thickness of RMF for all cases is $0.200''$.

1) The Plain Plate fin profile

Comparison of RMF with plain plate fin profile shows that the relative performance of RMF slowly increases with Reynolds number for the final compressed densities of RMF (ρ_f) 13.7% and 10% . The initial as-fabricated density (ρ_i) of RMF is 5% . The thermal performance approaches $3.5x$ and $2.5x$ of that of fin profile 46.45T at Re 1000 and above. The pressure drop approaches 100% and 40% of that of 46.45T for the same foam densities, respectively. The volume and the weight ratios are 60% and 40% at Re of 500 . Both of these ratios are slightly reduced at higher Reynolds numbers (Re) as shown in Figure 4 (a).

Table 1. Definition of terms

h_{eff}	Effective film coefficient * scaled for the base area of the HX.
h_l	Local film coefficient
A_{ht}	Total heat transfer area
A_b	Base area
η_f	Film efficiency
R_h	Ratio of the effective film coefficient of foam to fin.
R_p	Ratio of the pressure drop (psid) of foam to fin.
R_v	Ratio of the core volumes of the Al RMF based (HX) to fin based HX both dissipating (1) W. HXs use the same mass flow rate, and have the same temperature difference ($\Delta T=1$ °C) between the base and the coolant (air)
R_w	Ratio of the weights of the Al RMF based HX to fin based HX

$$* h_{eff} = h_l \cdot \eta_f \cdot \frac{A_{ht}}{A_b}$$

The physical dimensions of the pin and fin profiles are shown below in figure 3.

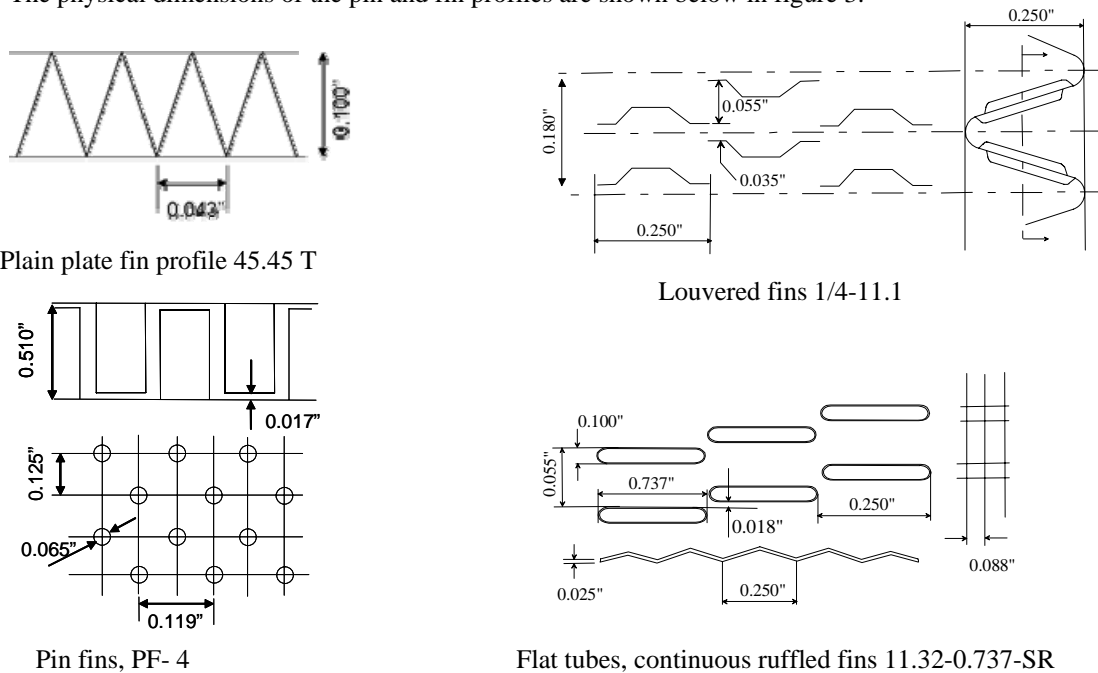


Figure 3 Pin-fin based extended surfaces for HX applications

2) The louvered fin profile

The louvered fin profile 1/4-11 comparisons used 20 pores per inch (ppi) and 30 ppi RMFs. The densities of RMFs are 5% and 10% for the 30 ppi and 20 ppi foams, respectively. The 20 ppi foam has somewhat lower thermal performance and lower flow resistance compare to 30 ppi RMF as shown in Figure 4 (b). The unit extended area densities are 6.9 (in²/in³-%) and 5.3 (in²/in³-%) for 30 ppi and 20ppi foams, respectively [1]. Therefore the surface densities of RMF used in this comparison are 34.5 (in²/in³) and 53(in²/in³) for the 30 ppi and 20ppi foams, respectively. The thermal performance ratios are 5.1x and 3.2x at Re=500 and they approach to 1.5x and 1x at Re=8000 for 20ppi and 30ppi foams, respectively. Relative thermal performance of Louvered fin profile increases with Re number and asymptotically approaches the values above. The flow resistance comparisons show that at Re=500 RMF HX design has 90% of the flow resistance of louvered fins, but this ratio steadily increases and reaches to 120% at Re=2000. R_p ratio reduced to 100% at higher Re numbers. The RMF HXs employed a single block and two parallel blocks of foams (Figure 4f) for 30ppi and 20ppi foams, respectively. This approach demonstrates the design flexibility of RMFs. The flow resistance of RMF HXs may be reduced using the flow partitioning technique to meet design requirements where a high performance and a low-pressure drop are needed. The volume and the weight ratios are 22% and 10% at Re=500, and they increase to 80% and 22% at Re=8000 for the 30 ppi foam. The same ratios are 18% and 23% at low Re number and 50% and 28% at high Re number for the 20 ppi foam based HXs

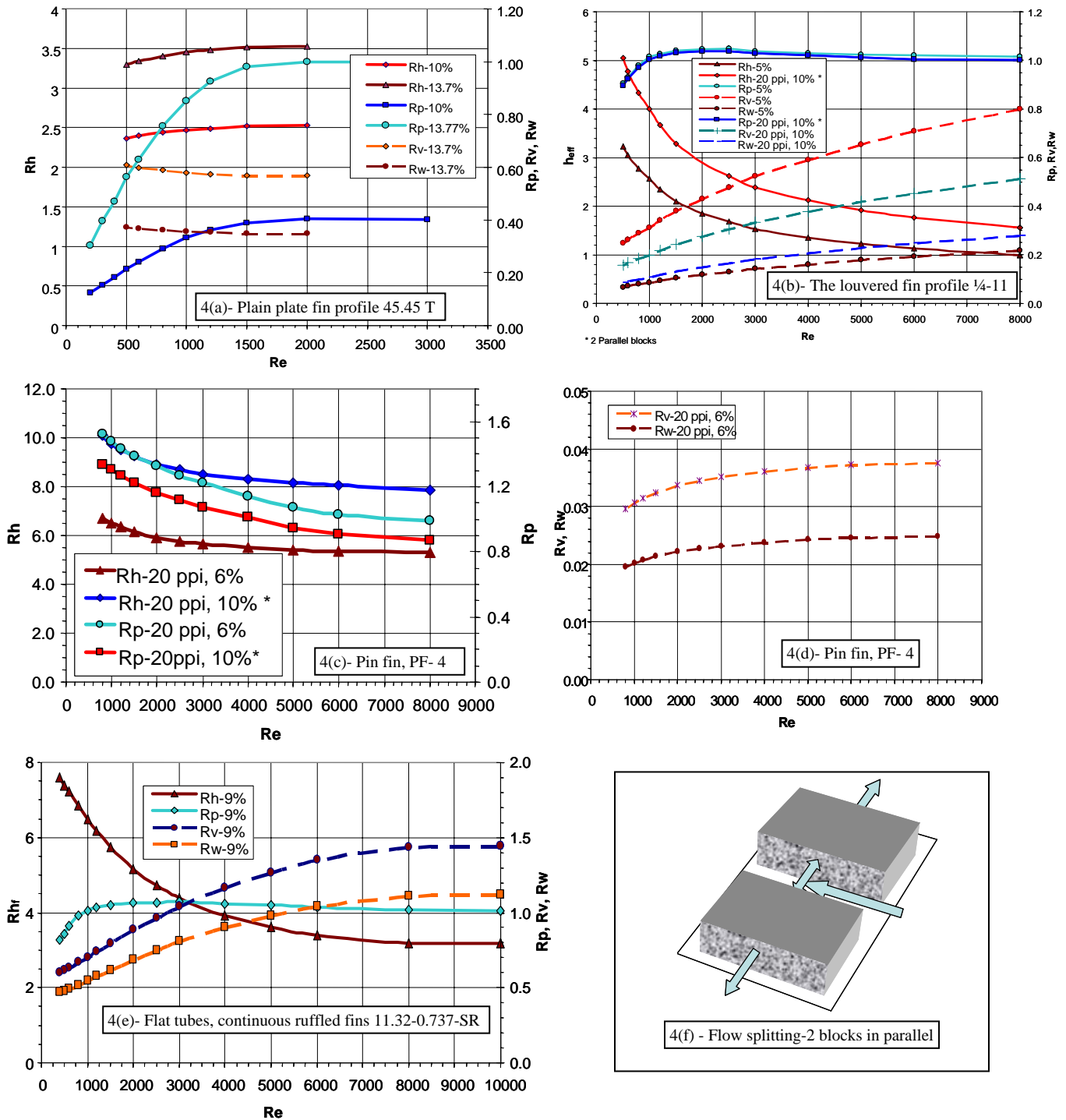


Figure 4. Comparisons of Pin-fin and RMF based HX

3) The pin fin profile

The pin fin vs. RMF based HX comparisons show that the foam based HXs have 10x and 6.5x the thermal performance of pin fins at $Re=1000$ as shown in Figure 4 (c). The relative performance of pin fin geometry steadily increase with Re numbers, and the Rh ratios become 8x and 5x at $Re=8000$ for the 10% and 6% dense 20 ppi foams, respectively. The flow resistance of RMF HXs is higher at low Reynolds numbers: 1.5x and 1.3x for 6% and 10% dense 20 ppi foams, respectively. The relative flow resistance of RMF reduces with Re numbers, and the Rp ratio reaches 100% and 70% (100% at $Re=4000$) at $Re=8000$. The 20 ppi 10% dense foam based HX utilizes (2) parallel blocks for flow portioning

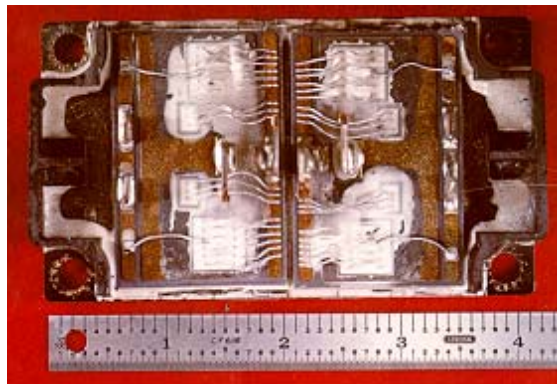
which reduces both the thermal performance and the flow resistance at any given value of Re number. The volume and weight ratios, however, are extremely low for both the 10% and 6% dense 20ppi foam based HXs as shown in Figure 4 (d).

4) The flat tube with continuous ruffled fin profile

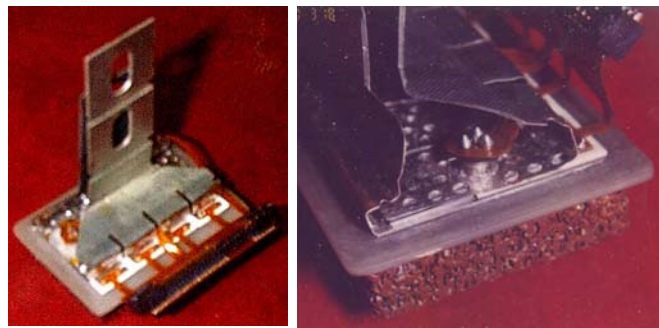
Performance comparisons for the flat tubes, continuous ruffled fins (11.32-0.737-SR) geometry are shown in Figure 4(e). The Rh ratio starts at 7.5x and reaches 3x at Re=10000 for the 20 ppi with 5% initial and 9% compressed density. The relative flow resistance starts at 80% for low Reynolds number of 200, follows the similar trend as in the louvered profile and reaches 100% at Re=8000. The R_v and R_w ratios are 60% and 50%, respectively, at Re=200 they steadily increase to 145% and 115% at Re=10000.

Applications of RMF based HXs:

Application of RMF based HX to commercial and military Power Modules such as Battery Power Conversion (BPC), Inverter-Converter-Control (ICC), etc. may offer significant Cost/Performance, volume and weight advantages. A BPC and 1/2 Bridge power modules with STD off-the-shelf external plain plate fin cold plate and with integral RMF based Cold Plate (CP) are shown in figures 5 and 6, respectively. RMF based cold plate also supports wireless interconnect technologies to further reduce parasitics.

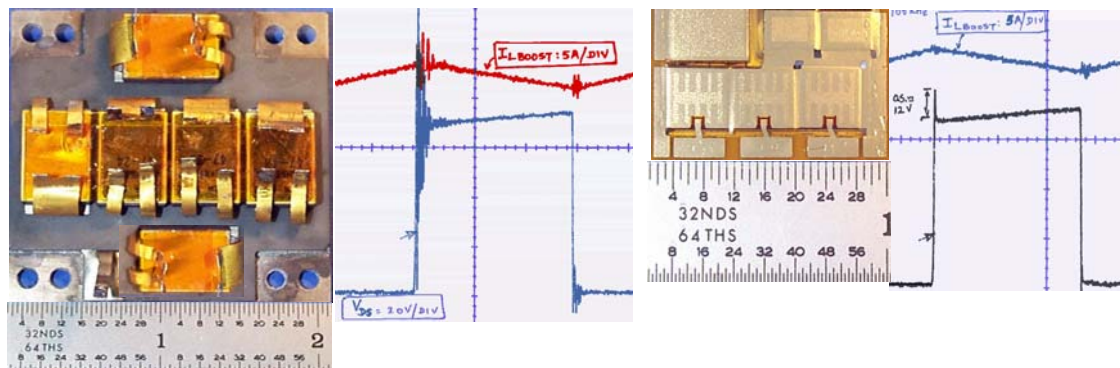


Commercial State of the Art 1/2 Bridge, 600V 200 Amp IGBT Power Module
 Packaging efficiency: 15%, Base area: 10.5 in²
 Weight: 4.5 lbs w/o CP, 12 lbs with CP
 Dissipation: 300 W



1/2 Bridge 1200V 400 Amp Power Module
 Packaging efficiency: 45%, Base area: 3.5 in²
 Weight: 1.2 lbs with CP
 Dissipation: 800 W (2.5 KW max)
 (Courtesy of SPCO)

Figure 5. 1/2 bridge Power modules using external CP (left) and integral RMF based CP (right)



Size: 2.00" * 2.00" * 0.300"
 Switch Voltage, Overshoot: ~ 70%

Size: 1" * 0.6" * 0.1"
 Switch Voltage, Overshoot: ~ 15

Figure 6. BPC modules designed to use an off the shelf external cooling technology (left) and one designed to use RMF based integral or external cooling technology (right-courtesy of GE Power and Controls Lab.). Volume reduction: 20X, Weight reduction: 16X, Performance: 5X, Power density: 7X. Note that the volume and the weight of the CPs are not included in the comparisons.

A counter flow 6 kW heat exchanger is shown in figure 6 below. A thin liquid section containing a dense 0.050" thick Al foam block (not shown in the photo) is sandwiched between (2) sections of airflow. Any number of single units may be stacked up to provide a scalable high performance low weight and low volume HX. Note that the T-shaped manifold blocks are for testing only, the field test ready design has significantly smaller manifold blocks.

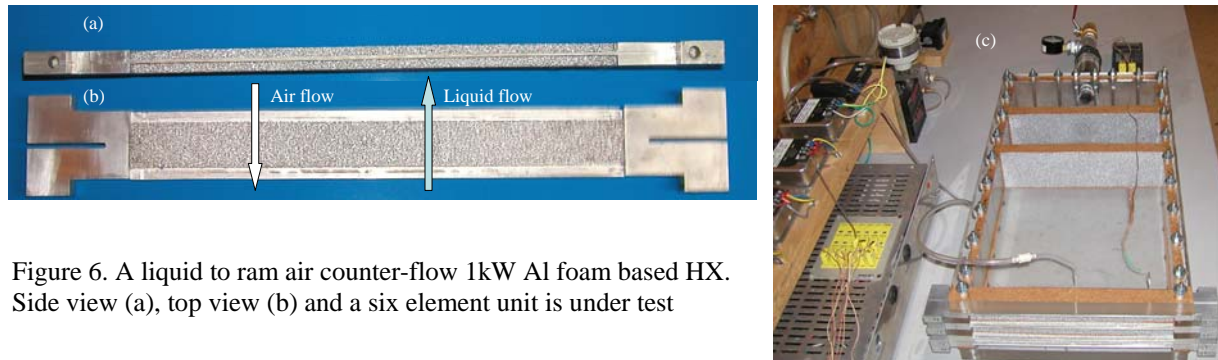


Figure 6. A liquid to ram air counter-flow 1kW Al foam based HX. Side view (a), top view (b) and a six element unit is under test

Summary:

The study illustrates that the advanced Integral RMF based HX technology offers significant performance, volume, weight advantages relative to the alternate approaches. The following list summarizes their key properties.

- Lower cost/performance
- Eliminates the need for derating devices
- Minimize parasitics
- Lowers switching and on losses
- Lowers T_j , provides higher reliability
- Air and liquid cool options
- Low flow resistance designs
- Power, RF and digital applications
- Discrete devices, hybrids and Modules
- Integral HX w/o soft interfaces
- Ideal for phase change HXs
- High surface density (SD)
- High corrosion resistance

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