Optimization of Microchannel

Heat Exchangers

It's no secret that power densities in electronics have continued to rise, and researchers have been forced to explore new thermal management technologies to keep those electronics from overheating. The thermal management challenge becomes even more complicated by the trend towards miniaturization and the prevalence of mobile electronics. Microchannel heat exchangers hold much promise as a solution to these problems, and they continue to be the subject of much research, including ways to optimize them.

There is no strict definition regarding what constitutes a microchannel heat exchanger, but it is generally accepted that channel hydraulic dimensions of less than 1 mm are called mini- or microchannels [ ]. Often, fin thicknesses and channel widths are on the order of a few hundred microns. As with conventional air cooled heat sinks, microchannel heat exchangers must be optimized with respect to their fin geometry, and this often becomes a balancing act between thermal resistance and pressure drop.

On the one hand, because microchannel heat exchangers have such small features, they can pack a lot of surface area into a small volume. This generally translates to increased heat transfer ability; but traditional heat exchangers can also be replaced by microchannel heat exchangers that are smaller and lighter. In one example, Hawkins-Reynolds et al [2] were able to maintain performance while reducing mass by 25% and core volume by 60%. A comparison can be seen in Figure 1, where the larger heat exchanger is about 300mm in length.

On the other hand, the smaller the features become, the more the pressure drop across them tends to increase, requiring greater pumping power for the cooling fluid. The microchannel heat exchanger shown in Figure 1, for example, has a cold side pressure drop 75% higher than the previous design.

To optimize a microchannel heat exchanger that might be used in a mobile application with high power density, Park et al. [3] began by defining the pump characteristics that would be expected in that type of application. Three compact pumps were tested, and Pump B was selected because of its compact size and performance. The pump parameters are shown in Table 1 and Figure 2 below.

Figure 1. Traditional and Microchannel Heat Exchangers [2]

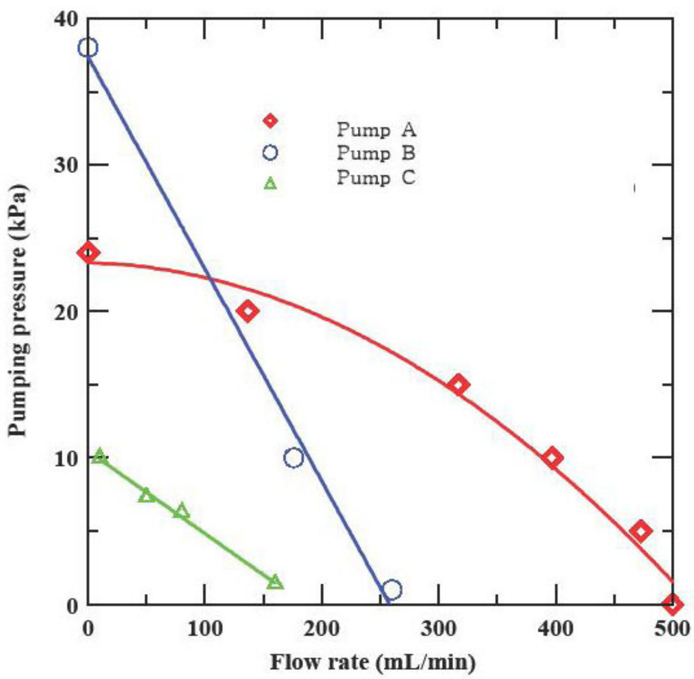

Figure 2. Comparison of Pump Characteristics [3]

	Flow rate	Pressure	Size
Pump A	High	Medium	38×40×30
Pump B	Medium	High	32×35×8
Pump C	Low	Low	40×40×7

Table 1. Pump Comparison for Microchannel Heat Exchanger [3]

Park et al [3] used the parameters of Pump 2 in an analytical analysis to determine optimum microchannel fin geometry, and then corroborated that analysis with experimental testing. The researchers chose to take a two step approach to their analysis. First, they held all geometry fixed and varied only the channel width. When an ideal channel width was calculated, then it was kept constant as fin thickness was optimized.

The geometry of a microchannel heat exchanger is shown in Figure 3 above and, based on suitability for mobile devices, external dimensions were fixed at L x W = 10 x 10 mm, channel depth D_d = 300 μm, and base plate thickness t = 200 μm. The overall thermal resistance of the heat exchanger was defined as the heat flow in (q) divided by the temperature difference between the base plate (T_h) and the inlet fluid temperature (T_i).

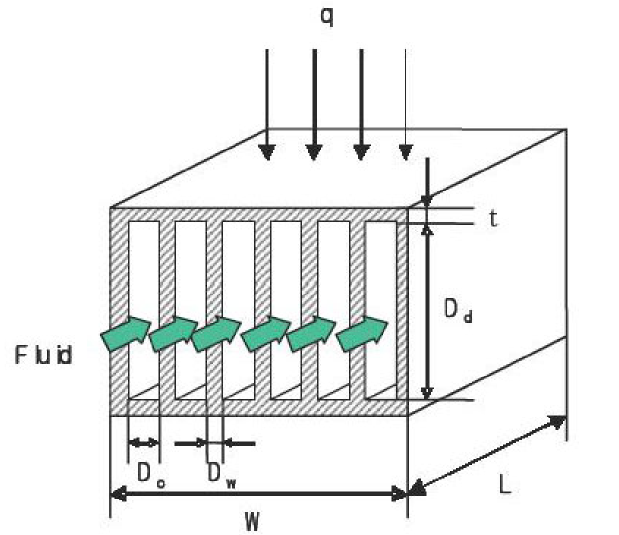

Figure 3. Geometry of a Microchannel Heat Exchanger [3]

Analytically, this overall resistance can be broken down into three components: spreading resistance in the heat exchanger, convective resistance from the heat exchanger to the coolant, and capacitive resistance of the coolant flow. These are summarized by Equations 1-4 below where,

t = base thickness (m)
L = length (m)
W = Width (m)
K_s = thermal conductivity (W/m.K)
n = number of fins
h = heat transfer coefficient (W/m^2.K)
Q = flow rate (m^3/s)
ρ_f = density (Kg/m^3)
C_{pf} = specific heat (J/Kg.K)
D_w = fin thickness (m)
D_c = channel width (m)
D_d = channel height (m)
β = fin efficiency
The coolant used was DI water.

$$R_{total} = R_{cond} + R_{conv} + R_{cap} \quad (1)$$

$$R_{cond} = \frac{t}{k_s LW} \quad (2)$$

$$R_{conv} = \frac{1}{2nhL(D_d + D_c)\,\beta} \quad (3)$$

$$R_{cap} = \frac{1}{Q\rho_f C_{pf}} \quad (4)$$

The equations were solved using the pump flow parameters using equations for both developing flow and fully developed flow, and then were plotted against the experimental results. For the experimental testing, microchannel heat exchangers were fabricated by using an etching process on silicon wafers 500 µm thick. In the first testing step, channel width was varied from 65 µm to 315 µm, and it was found that a channel width of approximately 100 µm yielded the best performance. Next, channel width was fixed at 100µm, and the fin thickness was varied from 8 µm to 41 µm. Optimum performance was seen with a fin thickness around 20 µm.

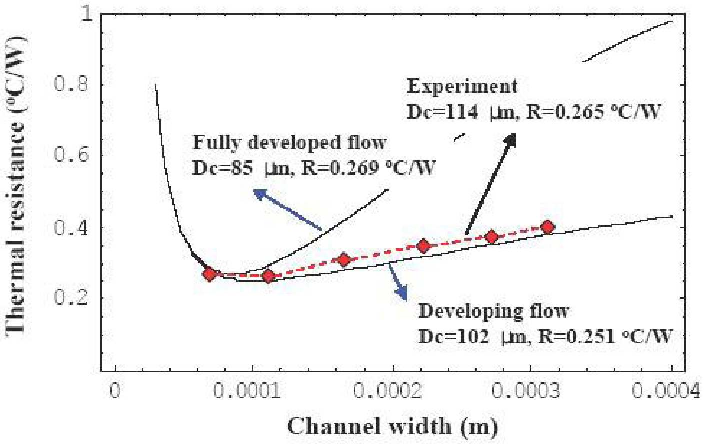

Figure 4. Microchannel Heat Exchanger Performance vs. Channel Width [3]

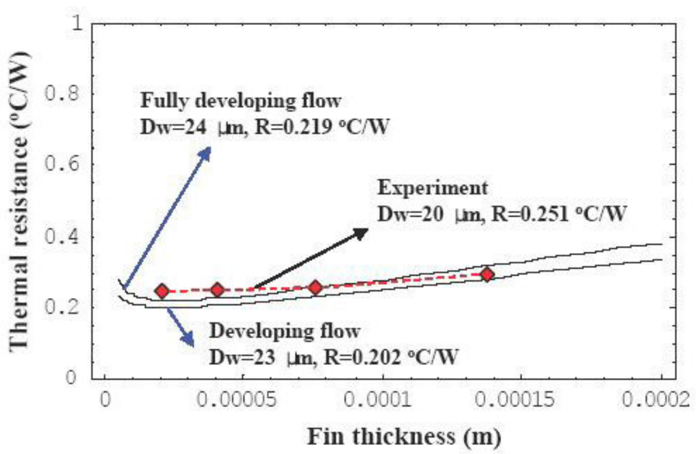

Figure 5. Microchannel Heat Exchanger Performance vs. Fin Thickness [3]

The plots comparing the analytical and experimental results are shown in Figure 4 and Figure 5 below. It can be seen that the experimental results agreed quite closely with the analytical model for developing flow. In general, the theoretical results were slightly better than the experimental, and this was thought to be due to less than ideal flow distribution in the experimental heat exchangers.

This analysis was simplified by the assumed operating parameters of a mobile device, so that the researchers were able to limit the number of variables. Khan et al [4] took a different approach in which the goal was to optimize the microchannel heat exchanger by minimizing entropy generation. They developed a set of equations describing the entropy generation depending on varying heat exchanger geometry and flow properties. The heat exchanger model itself was similar to that of Park et al. [3], where one side of the heat exchanger was heated, and water was used as the cooling fluid. The equations were solved using numerical methods, and several interesting results were developed.

In Figure 6 below, the entropy generation is plotted as a function of the channel aspect ratio in microchannel heat exchangers with three different Knudsen numbers. In general terms, the larger Knudsen numbers represent heat exchanger geometries with larger features, although all parameters are still in the realm of microchannels. It can be seen here that entropy generation is less for larger Knudsen numbers, because there is less hydraulic resistance for the coolant. The aspect ratio that gives the best overall efficiency appears to be around 0.16. It should be noted that this does not denote the maximum absolute performance, but the minimization of entropy should give a good idea of the most efficient system in terms of pumping efficiency and thermal resistance combined.

Using the entropy generation analysis, Khan et al. also illustrate the effects of the heat exchanger material on entropy generation. Many manufacturing techniques for microchannels involve etching in silicon, as opposed to traditional heat exchanger materials such as aluminum or copper. Figure 7 shows that the thermal conductivity of the heat exchanger material is not so critical, above 150 W/m-K or so. The thermal conductivity of silicon happens to be around 150 W/m-K.

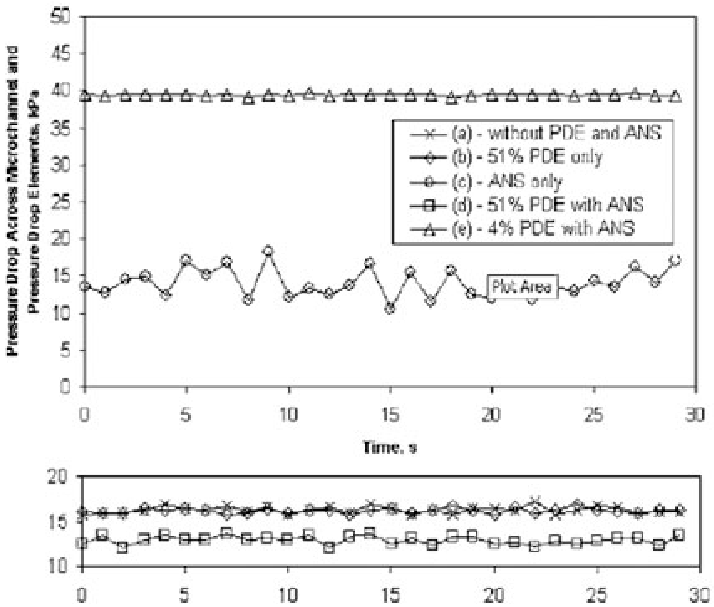

Figure 6. Entropy Generation as a Function of Channel Aspect Ratio [4]

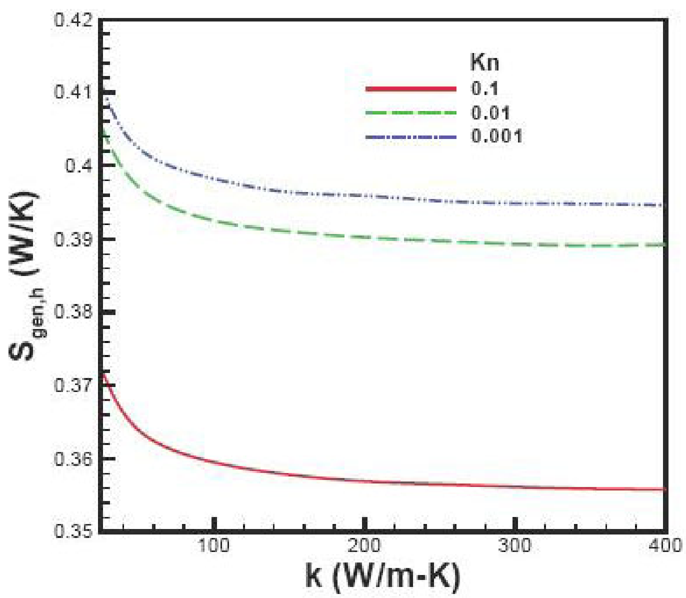

Figure 7. Entropy Generation as a Function of Heat Exchanger Material [4]

These two plots are only an example of the parameters that were analyzed using the entropy minimization method. But microchannel heat exchangers are also subject to some other factors that neither author mentions, such as clogging. Because of the small size of microchannels, they are subject to fouling from small particles that might not have as much effect on other heat exchangers. If care is not taken to ensure a clean coolant loop, thermal performance could suffer. To some degree, fouling is a concern for all heat exchangers, though, so it just needs to be taken into consideration when evaluating microchannels.

In addition, these two vastly different optimization methods are of many other techniques. As with any problem, the method chosen to find the answer depends on the factors that are most critical, whether they are price, size, efficiency, performance, or anything else.

References:

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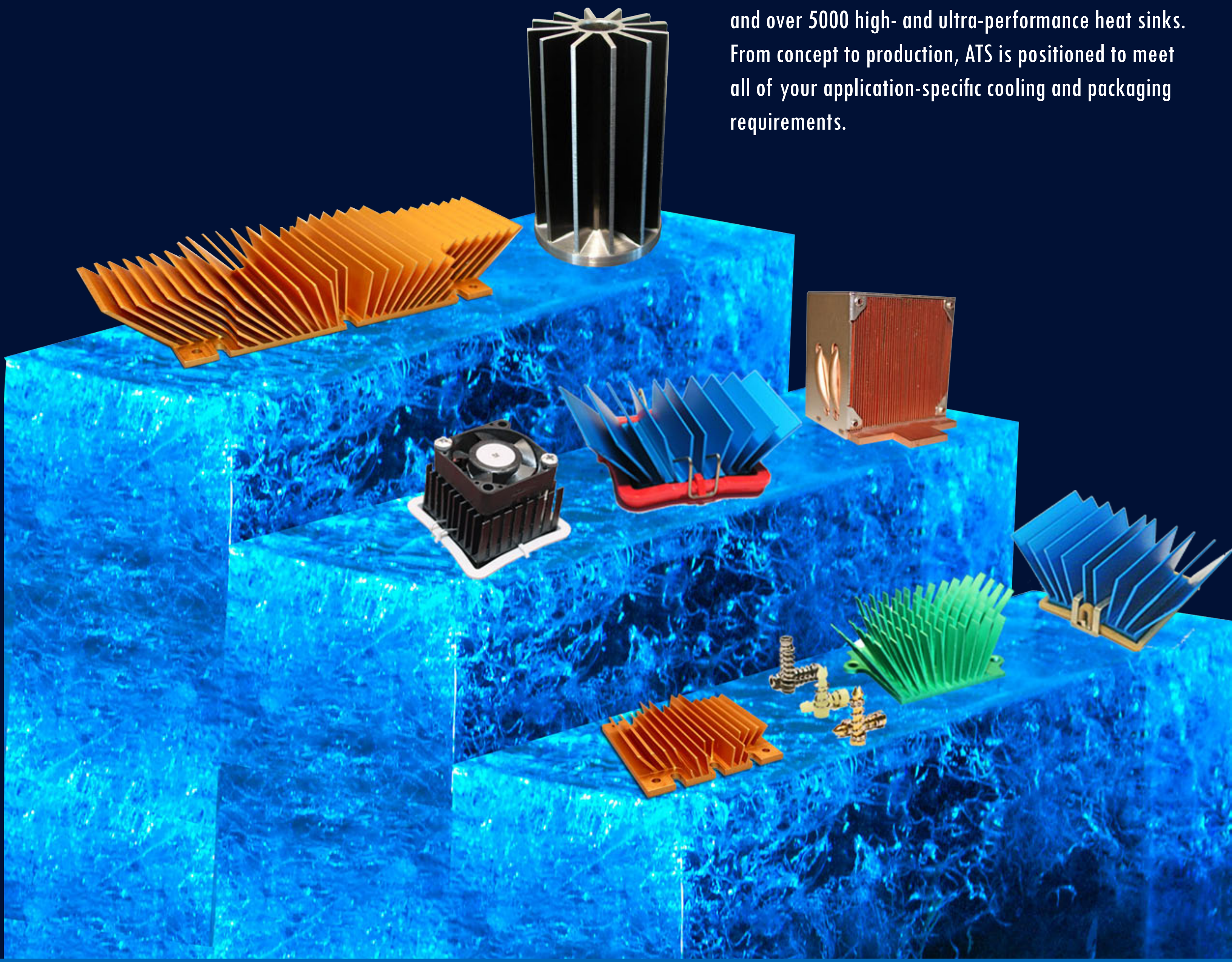

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