Compact Heat Exchangers for Electronics Cooling

The use of liquid cooling in electronics is growing fast. Designers and end users are overcoming hydrophobia and embracing liquid cooling as a viable solution for high heat flux applications. Among other factors, an effective liquid cooling system depends on its heat exchanger's ability to remove heat. These heat exchangers come in different types, sizes and configurations, depending on the application.

Basic Equations

Figure 1 shows a typical, water-to-air, liquid cooled, closed loop system. Coolant liquid is pumped through a cold plate that is in contact with the IC component. The heat absorbed from the component is removed in the water-to-air heat exchanger and the cooled liquid continues its path through the loop.

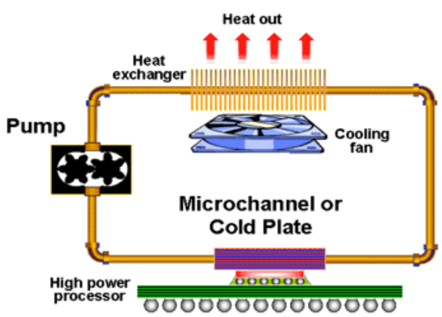

Figure 1. Water-to-Air Hybrid Electronics Cooling Loop [1].

The heat that is transferred from the water to the air can be calculated from Equation 1

$$q_L = \varepsilon . C_{\min}(T_{w2} - T_a) \qquad (1)$$

where T_{w2} and T_a are liquid and air temperatures entering the heat exchanger, C_{min} is the smaller of the air (C_a) or water (C_w) heat capacity rates that is the product of the mass flow rate and the specific heat at constant pressure.

The effectiveness of the heat exchanger, ε, is defined as the ratio of the actual to the thermodynamically maximum possible heat transfer in a heat exchanger. The surface temperature of the IC component where it contacts the cold plate is calculated from Equation 2.

$$T_{com} = q_L . R_{cp} + T_{w1} \qquad (2)$$

Where T_{w1} is the cold plate inlet water temperature and R_{cp} is the thermal resistance of the cold plate from the attachment of the IC component to the inlet of the cold plate, including the interfacial resistance between the component and cold plate.

The temperature rise of water resulting from component heat absorption can be estimated using Equation 3.

$$T_{w2} - T_{w1} = \frac{q_L}{C_w} \qquad (3)$$

In this equation, C_w is the heat capacity rate of the liquid that is the product of the mass flow rate and the specific heat of the liquid. Substituting and manipulating Equations 1-3 provides Equation 4, which relates the surface temperature of the IC component to the performance of the cold plate and heat exchanger.

$$T_{com} = q_L . (R_{cp} + (\frac{1}{\varepsilon . C_{\min}} - \frac{1}{C_w})) + T_a \qquad (4)$$

In the above equations, the subscripts w and a should be changed to the generic subscripts, c and h respectively, to indicate cold and hot fluid properties if the heat exchanger uses different fluid types.

Heat Exchanger Frontal Area

The surface areas of heat exchangers must be very large, especially on the side exposed to air. This is because the heat transfer coefficient in air cooling is much smaller than that of liquid cooling. Increasing the surface

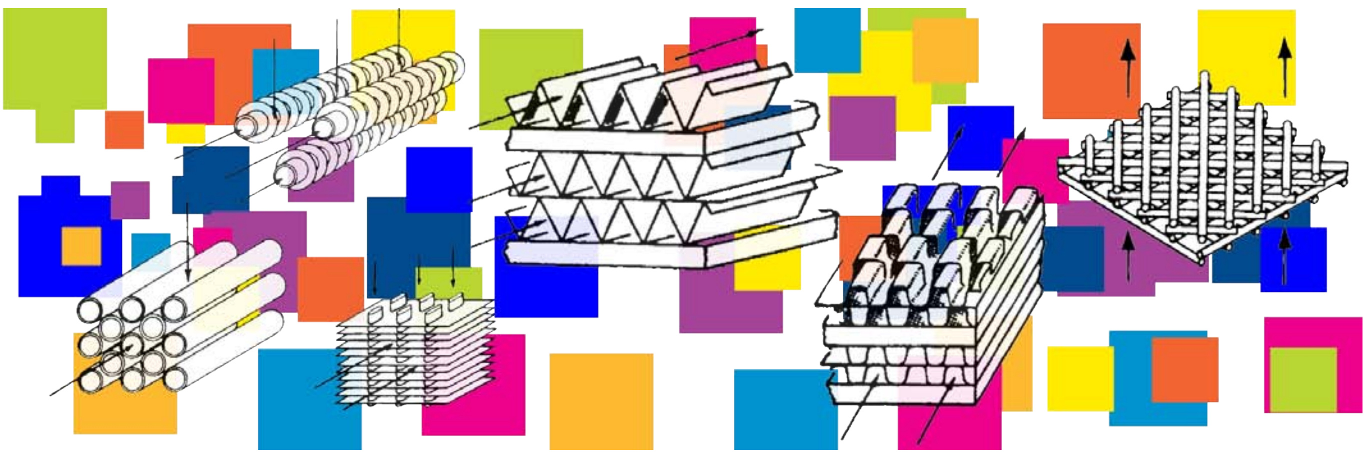

Figure 2. Heat Exchanger Fin Configurations Studied by Kays and London [2].

area on the air side will decrease thermal resistance and allow higher heat transfer between the air and liquid.

Even though large surface areas are needed for efficient heat removal, many cooling applications do not have the space for bulky heat exchanger units. This is particularly true with component and board level applications. It is important to use the available space in selecting the heat exchanger, and to enhance such parameters as the mass flow rate, the use of liquids with higher specific heat, or increasing the power of the cooling fans.

Heat Exchanger Fin Types

The air side of a heat exchanger is usually intensely finned to increase the thermal exchange between the air and the liquid. The fin types must be suitable for the specific applications. In their classic textbook, *Compact Heat Exchangers*, Kays and London investigated a number of fin configurations [2]. Among these configurations, straight fins, louvered fins, strip fins, wavy fins and pin fins are shown in Figure 2.

Marthinuss and Hall summarized the Kays and London air cooled heat exchanger test data and provided guidelines on how fin configurations are optimized by combining heat transfer, pressure drop, size, weight and costs [3].

In this study, the Colburn j-factor (J_H) and friction factor (f) correlations are used as heat transfer and pressure drop indices and are described in the following equations.

$$J_H = St\,\mathrm{Pr}^{2/3} \qquad (5)$$

$$f = \frac{t}{\frac{1}{2} r n^2} \qquad (6)$$

Where ρ and *v* are the density and kinematic viscosity of the fluid.

In Equation 5, St is Stanton Number, defined as:

$$St = \frac{\mathrm{Nu}}{\mathrm{Re\,Pr}} \qquad (7)$$

In Equations 5-7, Pr, t, v, NU, and Re are the Prandtl number, wall shear stress, fluid kinematic viscosity, Nusselt number and Reynolds number, respectively. Figure 3 shows the ratio of the Colburn j-factor and friction factor (J_H/f) versus the Reynolds number for the fin configurations shown in Figure 2.

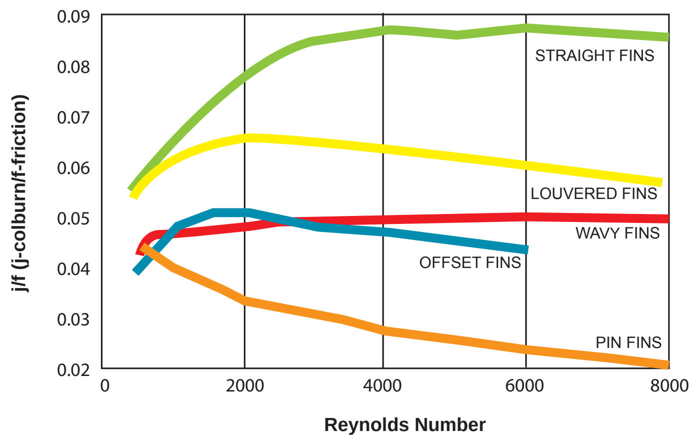

Figure 3. Heat Transfer/Pressure Drop for Different HEX Fin Configurations [2].

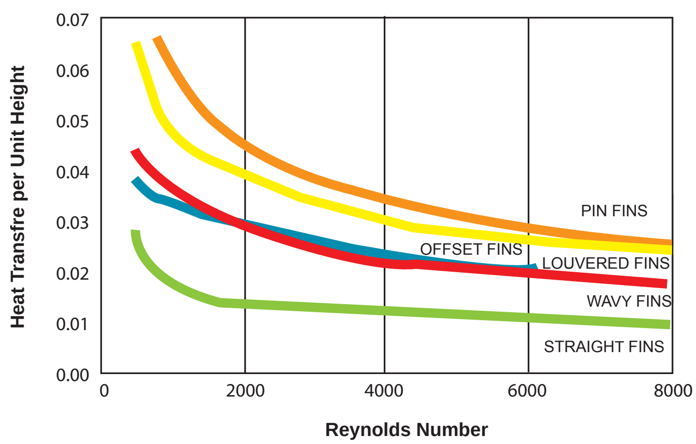

Figure 4. Heat Transfer per Unit Height for Different HEX Fin Configurations [2].

As is evident from Figure 3, when the critical design factor for a heat exchanger is the heat transfer per unit of pressure drop, the straight fin configuration is the most efficient, followed by louvered, wavy, offset and pin fin configurations.

Another important design factor in selecting heat exchangers is their size. For instance, many telecommunication chassis that are packed with electronics components do not have enough space for bulky cooling devices. In Figure 4, the ratio of heat transfer per unit height to the Reynolds number suggests that pin fins are most suitable configuration.

This is followed by louvered, offset, wavy and straight fin configurations.

Another important design factor, e.g. for optimizing heat exchangers used in avionics, is the weight. Here, Marthinuss and Hall ranked louvered fin configuration highest, followed by wavy, offset, pin and straight fin configurations [3].

Compact Heat Exchanger Liquid Coolant

Depending on the system and application, different types of fluids are used in compact heat exchangers. The advantage that a certain fluid brings to a specific application is owed mainly to its larger transport capacity of heat per fluid volume and to more effective heat spreading. To demonstrate this, consider thermal transport in an open system resulting from a change of enthalpy, as shown in Equation 8.

$$q = \dot{m} C_p (T_{out} - T_{in}) \qquad (8)$$

Where $\dot{m} = \rho VA$, (ρ is the fluid density, V is the velocity, and A is the cross sectional area), and C_p is the specific heat at constant pressure. If we consider the velocity and cross section as constants, the C_p and ρ will dictate the extent of heat transfer when different fluid is used. Table 1 shows the values of C_p and ρ, μ and k for ethylene glycol, water, and air at 300 °K.

Property	Ethylene Glycol	Water	Air
$C_p (kJ/kg\,^\circ C)$	2.42	1.07	0.001004
$\rho\ (kg/m^3)$	1100	996	1.17
$m (kg/m.s)$	0.0152	0.812×10^{-3}	1.858×10^{-5}
$k (W/m.K)$	0.252	0.617	0.026

Table 1. Thermodynamic Properties of Typical HEX Coolants.

Table 1 indicates that fluids with higher density and thermal capacity are capable of removing greater amounts of heat. In high heat flux applications, using such liquids dramatically increases the heat transfer. However, using liquids with superior thermal transport requires higher pumping power to push the liquid through the system. To

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decrease the power required to circulate the coolant, boiling heat transfer is employed in heat exchangers. In such devices, a refrigerant coolant vaporizes after it absorbs the heat from a hot source. Based on the complexity of the system, the hot coolant is pumped through a finned condenser section where the coolant is cooled and returned to liquid phase. Because the coolant changes its phase from liquid to gas and becomes less dense, the required pumping power to circulate the coolant is substantially less.

The use of phase change heat exchangers in electronics applications involves other items, including compressors, that not only increase the cost, but also bring up the issue of liability. This type of system should obviously be considered as the last resort if nothing else works, for the aforementioned reasons. However, as the need for sophisticated, two-phase heat exchangers increases, manufacturers will develop improved products that are more compact, reliable and less expensive than those currently available.

Compact heat exchangers are becoming an important part of electronics cooling solutions due to the steady increase in power of microelectronics. To use these devices to their fullest potential, it's important to understand their concept, benefits and limitations. To properly utilize a heat exchanger system, design factors such as pressure drop, heat transfer, size, weight and cost must first be prioritized. The simple rule is to choose a simple system that is proven to work before considering a more exotic system.

References:

1. Electronic Package Technology Development, Intel Technology Journal, Intel.com, Volume 09, Issue 04, November 2005.

2. Kays, W., London, A., Compact Heat Exchangers, Third Edition, McGraw-Hill, 1984.

3. Marthinuss J,, Hall G., Air Cooled Compact Heat Exchanger Design For Electronics Cooling, Electronics Cooling, February 2004.