Calculating the Loads for

Liquid Cooling Systems

This article presents basic equations for liquid cooling and provides numerical examples on how to calculate the loads in a typical liquid cooling system. When exploring the use of liquid cooling for thermal management, calculations are needed to predict its performance. While it is often assumed that a liquid coolant itself dissipates heat from a component to the ambient, this is not the case. A closed loop liquid cooling system requires a liquid-to-air heat exchanger. Because of its structure, several equations must be calculated to fully understand the performance and behavior of a liquid cooled system.

For this article we consider a liquid cooling system as a closed loop system with three major components: cold plate, heat exchanger and pump. The cold plate is typically made from aluminum or copper, and is attached to the device being cooled. The plate usually has internal fins which transfer heat to the coolant flowing through them. This fluid moves from the cold plate to a heat exchanger where its heat is transferred to the ambient air via forced convection. The final part of the cooling loop is the pump, which drives the fluid through the loop.

Equation 1, below, was derived to predict the final temperature of the device being cooled [1].

$$T_{mod} = q_L \square R_{cp} + T_{w1} \qquad (1)$$

Where:
T_{mod} = surface temperature of the device being cooled
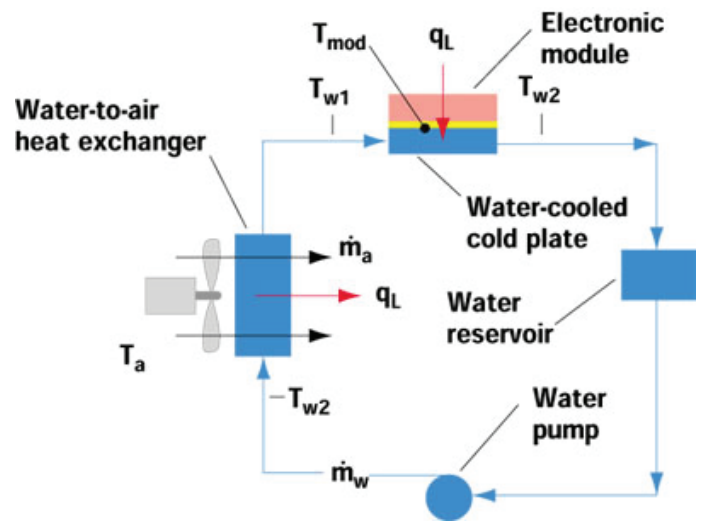q_L = power dissipated by the device

Figure 1. Closed Loop Liquid Cooling System [1] .

R_{cp} = thermal resistance of the cold plate and TIM
T_{w1} = water temperature entering the cold plate

In an open loop cooling system, the value of T_{w1} is known and controlled by the supply system. Calculating T_{w1} in a closed loop system is more involved. This is because the water temperature is both rising from the power transferred from the device and dropping while transferring heat to the ambient in the heat exchanger.

The temperature rise of the water due to the device power is given by,

$$T_{w2} - T_{w1} = \frac{q_L}{C_w} \qquad (2)$$

Where:

T_{w2} = temperature of the water exiting the cold plate and entering the heat exchanger

C_w = heat capacity rate of water

The heat capacity rate is found by multiplying the mass flow rate and the specific heat of water.

Once the liquid enters the heat exchanger it transfers heat into the air. The amount of heat tranfer, at steady state, is equal to the heat produced by the component.

$$q_L = \varepsilon \square C_{min}(T_{W2} - T_a) \qquad (3)$$

Where:

T_a = temperature of the air entering the heat exchanger

ε = effectivness of the heat exchanger

C_{min} = heat capacity rate of water (C_w) or air (C_a), whichever is smaller

Next, we solve Equations 2 and 3 for T_{w1}

$$T_{W1} = q_L \left(\frac{1}{\varepsilon \square C_{min}} - \frac{1}{C_W}\right) + T_a \qquad (4)$$

Finally, we combine Equations 1 and 4 to solve for T_{mod}

$$T_{mod} = q_L \square \left(R_{cp} + \left(\frac{1}{\varepsilon \square C_{min}} - \frac{1}{C_W}\right)\right) + T_a \qquad (5)$$

Several factors must be known to effectively use this equation as a design guide. First, we must determine the cold plate's thermal resistance. This can be obtained from a computational fluid dynamic (CFD) analysis of the cold plate using software such as CFDesign or Flotherm. It is also important to understand the manufacturing limits before starting the mechanical design. Typically a cold plate's design is driven by these limits, which control the minimum width of its internal channels and fins. A cold plate's thermal resistance is usually in the range of 0.05 to 0.25°C/W, depending on size and material.

Next, the performance of the heat exchanger must be specified. A heat exchanger's performance is the product of its efficiency (ε) and the total specific capacity rate flowing through it (C_{min}). The performance specifies, in units of W/°C, the amount of heat removed from the heat exchanger at a given difference between the water and air temperatures. A typical heat exchanger used for electronics cooling, with a 120mm fan, provides performance values of 11 to 20 W/°C [3].

As an example, consider the design of a liquid-cooled loop for cooling an Intel Xeon X5492 processor.

Where:

q_L= 150 W

$T_{mod, Max}$ = 63°C

T_a = 25°C

M_w = 0.032 L/s (0.5 gpm)

R_{cp} = unknown

Heat exchanger performance = 16.7 W/°C

Equation 5 is used to solve for the device temperature (T_{mod}) as a function of cold plate resistance. Figure 2 shows that to cool an X5492 processor in a 25°C environment a cold plate resistance of less than 0.18°C/W is required.

Device Temperature as a Function of Cold Plate Thermal resistance, 25°C Ambient
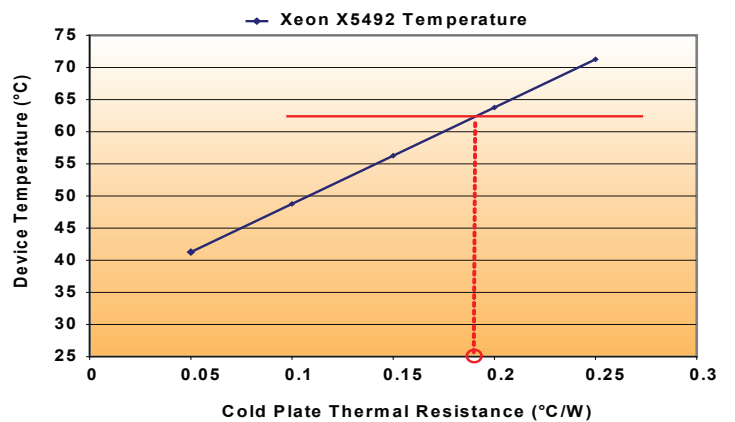

Figure 2. Device Temperature as a Function of Cold Plate Thermal Resistance.

The above example illustrates the basic steps needed to properly design a cooling liquid loop. It also shows the importance of characterizing all the components within a

system. The cold plate, heat exchanger, and pump must all be selected and designed as a group to ensure acceptable performance.

The heat exchanger is often the limiting factor in a compact system due to its relatively large size. Packaging and other mechanical concerns for the heat exchanger dictate that it should be considered first. The cold plate and pump are typically easier to optimize. For example, if a heat exchanger's size is limited, a copper micro fin cold plate and a high volume pump may be needed. If a sufficiently-sized heat exchanger is available, a lower cost cold plate and pump may be used with sufficient results.

In summary, liquid cooling loops are an important part of the electronics industry, and their use will continue into the future.

It is important to understand the impact on performance of all three major parts of liquid cooling loops (cold plate, heat exchanger and pump) to ensure an acceptable level of performance at the lowest cost. It is also critical to address the design of the heat exchanger as it can be the limiting factor in many systems.

References:

1. Simons, R., Estimating Temperatures in a Water-to-Air Hybrid Cooling System, Electronics Cooling, May 2002.
2. Iyengar, M. and Garimella, S., Thermal Optimization and Design for Manufacturability of Liquid-Air Hybrid Cooling Systems, Electronics Cooling, August 2008.
3. Whitenack, K., Demystifying Cold Plates, Electronic Products, May 2003.