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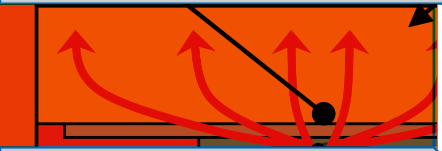

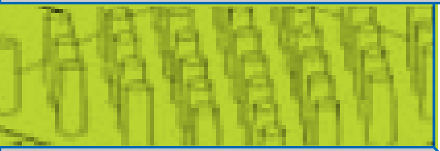

FUTURE COOLING

Thermal Management by Immersion Cooling

PROPERTY	FC-87	FC-72	FC-77	H_2O
Boiling Point @ 1 Atm (°C)	30	56	97	100
Density x 10^{-3} (kg/m^3)	1.63	1.68	1.78	0.1
Specific Heat x 10^{-3} (Ws/kgK)	1.09	1.09	1.17	4.18
Thermal Conductivity (W/mK)	0.05	0.05	0.06	0.63
Dynamic Viscosity x10^4 (kg/ms)	4.20	4.50	4.50	8.55
Heat of Vaporization x10_L^{-4} (Ws/kg)	8.79	8.79	8.37	243.8
Surface Tension x10^3 (N/m)	8.90	8.50	8.00	58.9
Thermal Coefficient of Expansion x 10^3 (K^{-1})	1.60	1.60	1.40	0.20
Dielectric Constant	1.71	1.72	1.75	78.0

Table 1. Thermal Properties of Fluorocarbon Fluids and Water [2].

The term ‘immersion cooling’ implies that a device is plunged entirely into a fluid. Following this course, traditional air cooling could be considered immersion cooling because an entire system is immersed in air, a gaseous fluid. However, immersion typically refers to a high power system that is immersed in some type of inert fluid, such as mineral oil or a 3M™ Fluorient™ Electronic Fluid, e.g. FC-77. Although water is the best fluid for heat transfer, there are many others on the market for use in electronics cooling by immersion or in cold plate applications [1]. To gain an appreciation for the thermal transport capabilities of different fluorinert fluids, it is instructive to compare their properties with water. Table 1 shows such a comparison.

The use of liquids is an attractive proposition for heat transfer. It provides three broad spectra and distinct benefits:

- High heat transport capability
- No need for a secondary medium between the heat source and the sink
- Effective heat spreading on a larger surface area

The residual benefits of having the heat source immersed in a coolant are also significant. For example, by immersing the electronics in a liquid bath, the thermal resistance between the heat source and the sink is eliminated, as shown in Figure 1.

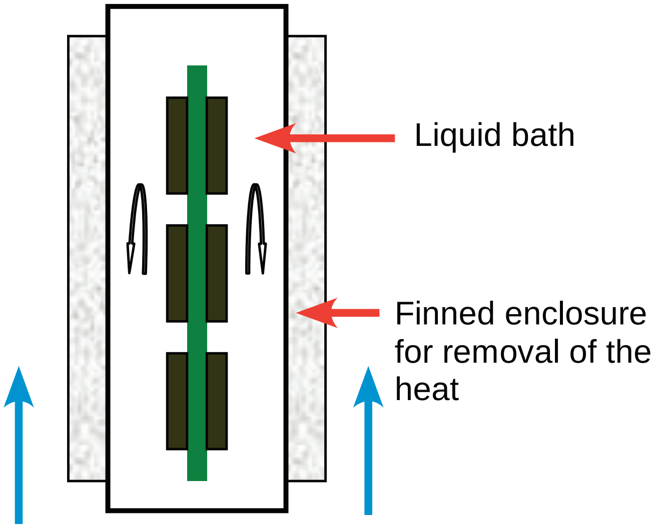

Figure 1. Immersion Cooling of Electronics in a Passive Mode, Providing a Direct Path Through the Liquid from the Source to the Sink.

Figure 1 shows a system where natural convection within an enclosure is used for cooling the devices on a double-sided PCB. If forced convection or boiling had been used, the thermal transport capability would have been significantly larger. Subsequently, higher heat dissipation from the electronics could have been achieved. Figure 2 demonstrates such a capability by comparing different heat transfer coefficients.

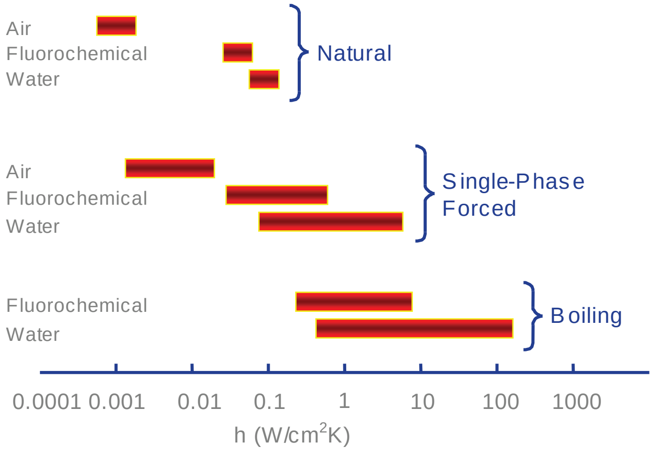

Figure 2. Heat Transfer Coefficients for Different Coolants and Cooling Configurations.

From Figure 2, it is quite evident that when fluorocarbons are used in the boiling mode or single phase, the heat transfer coefficient is substantially larger than from other cooling modes. The cooling capability is clearly demonstrated by Figures 3 and 4 [3]. Figure 3 shows the cooling capacity of 50 W/cm^2 in natural convection with moderate fluid temperature rise. If forced convection is used, the cooling capacity is increased appreciably at a lower temperature rise.

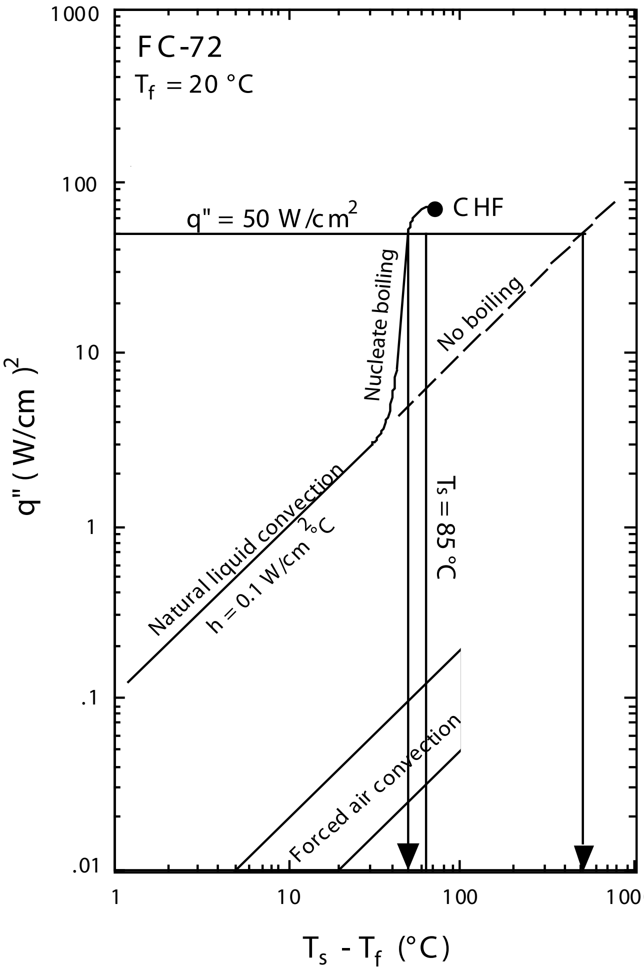

Figure 3. Comparison of Natural and Forced Convection in Fluorinert FC-72 [3].

In another example, Mudawar shows the thermal transport capacity of the same coolant, FC-72, in a boiling phase in different modes [3]. Jet impingement, mini-channel and low-speed cavity flow are compared not only with each other, but against conventional conduction cooled chassis.

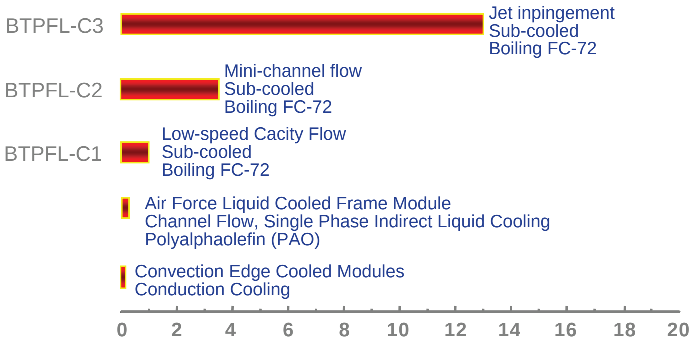

Figure 4. Comparison of Boiling FC-72 in Three Different Transport Modes vs Conventional Cooling [3].

Figure 4 describes thermal transport as a function of different heat transfer modes in an immersion configuration.

Figure 4 clearly shows that a fluid's flow delivery method can have a significant impact on its thermal transport capability, e.g., jet impingement, while allowing it to boil in a particular regime. When compared to conventional cooling, there is an order of magnitude change which corroborates the heat transfer coefficient data shown in Figure 2.

This fact suggests that the highest heat transfer can be achieved when the fluid boils. The boiling mode also provides another advantage: a constant component temperature that positively affects device reliability. However, there are no gains without penalties. Along with the packaging challenges to gain such high levels of cooling, thermal overshoots may occur when boiling begins. This is because, in these applications, the fluids tend to be low in surface tension and viscosity. This could create rapid dry out as a result of the liquid-to-vapor transition. Over the past decade, researchers have contributed many articles to the physics of boiling heat transfer and temperature overshoot. Such detail is not the scope of this article, but the reader should be aware of the potential challenges encountered by cooling with boiling heat transfer [4].

It is helplful to also note that both natural and forced convection can be rather effective for electronics cooling. Thermal transport capability may be best described by Figure 5, where the heat flux (W/cm^2) is presented as a function of "wall superheat" or the surface-to-liquid temperature difference for a typical fluorocarbon coolant [5].

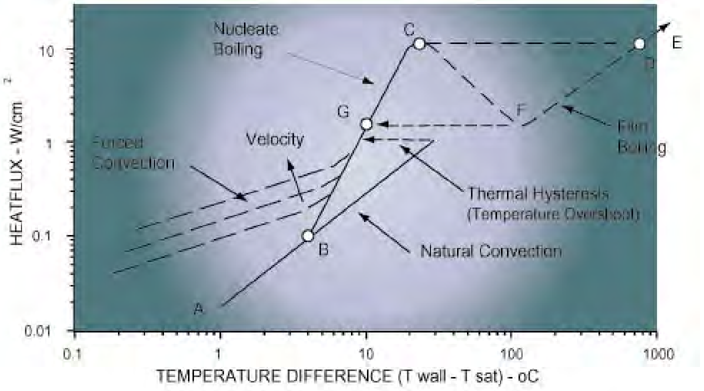

Figure 5. Heat Flux (W/Cm^2) as a Function of "Wall Superheat" or the Surface-To-Liquid Temperature Difference for a Typical Fluorocarbon Coolant [5].

Such a high heat transport capability is attractive for electronics cooling when dealing with high power devices or an aggregate of lower power devices concentrated in a small area. Perhaps the most famous immersion cooling application on the market is the Cray-1 computer. Introduced during the 1970s, its unique electronics packaging, dictated by the need for the highest communication speeds between different devices, required novel cooling to make the system operational.

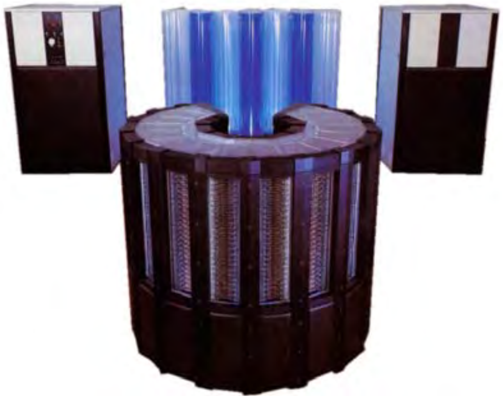

Figure 6. Cray Super Computer with Cooling Tower in the Background.

In this system all PCBs were installed horizontally and the entire system was immersed in coolant. Stacks of electronic module assemblies were cooled by a parallel forced flow of FC-77. Each module assembly consisted of 8 printed circuit boards on which were mounted arrays

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* Temperature range on these high performance systems greatly exceedes the standard range of -5 to 120 °C typically used.

of single chip carriers. A total flow rate of 4.5 l/s was used to cool 14 stacks, each containing 24 module assemblies. The power dissipated by a module assembly was reported to be 600 to 700 watts. Coolant was supplied to the electronics frame by two separate frames containing the required pumps and water-cooled heat exchangers to reject the total system heat load to customer-supplied chilled water [5, 6].

To get a scale of the cooling needed to make the Cray-1 operational, if air had been the coolant, the required volumetric flow rate would be on order of that created by a 747 jet engine. Obviously this would not only be physically impossible, it still may not have provided the necessary device temperatures to enable the desired communication frequency.

Another industry attempt in immersion cooling was made by IBM. The Liquid Encapsulated Module (LEM) developed at IBM in the 1970s was designed for package-level cooling with pool boiling [5]. Figure 7 shows two schematic drawings of a substrate with integrated circuit chips (100) mounted within a sealed package-cooling assembly containing a fluorocarbon coolant (FC-72). One design used an air-cooled heat sink to reduce package complexity, while the other integrated a water-cooled cold plate. In either case, internal boiling at the chip surfaces created high heat transfer coefficients (1700 - 5700 W/m^{2}K) to meet chip cooling requirements. Fins were placed internally to condense the vapor created as the result of the boiling and eliminate possible dry out. Either the air-cooled or water-cooled cold plate could be used to cool the package. As stated by Simons

> *using this approach, it was possible to cool 4 W chips (4.6 mm x 4.6 mm) and module powers up to 300 W. Direct liquid immersion cooling has been used within IBM for over 20 years as a means to cool high powered chips on multi-chip substrates during electrical testing prior to final module assembly [5].*

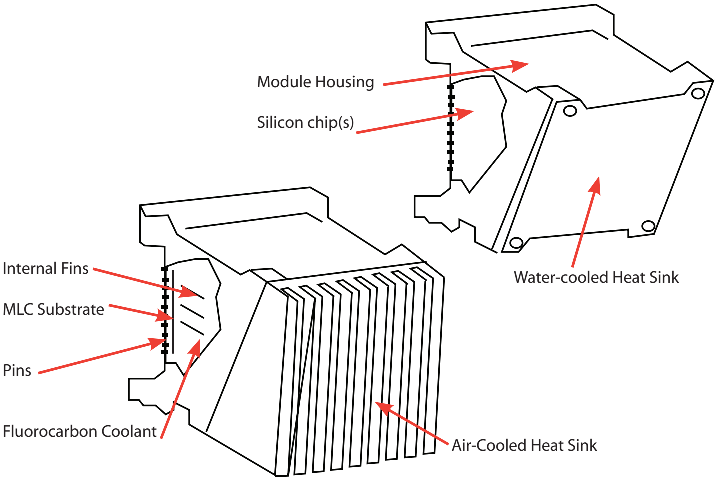

Figure 7. Air or Water-Cooled Liquid Encapsulated Module (LEM) Packages [5].

As mentioned at the start of this article, immersion cooling implies that the electronic device is immersed in some sort of inert fluid, whether mineral oil or fluorocarbon. As shown in Figures 6 and 7, the packaging required to make such cooling possible is a major departure from what is most commonly seen in the marketplace. Systems requiring such a level of cooling are typically far more complex and tend to have dedicated facilities for their maintenance and operation. Such a level of care with respect to the cooling system is rather obvious. Foremost, fluorocarbon fluids are rather expensive and should be used in a closed system. In summary, there are many issues about immersion cooling to be considered by the design engineer. These include:

- Pump cavitation prevention
- Vapor condensation
- Fouling – because fluorocarbons tend to pick up packaging materials from components and the boards, especially if boiling is involved
- Coolant compatibility with the seals and the plumbing system
- Surface cleanliness – surfaces that are in contact with the fluid should be properly cleaned
- Burnout management – some fluorocarbons at elevated temperature may produce hazardous gases

- Cost – operations and maintenance

It is clear from the above that cooling capacity is not the only point of consideration. Besides, the packaging of a system, its operation and maintenance also play significant roles in its successful deployment. If these issues can be addressed, as shown by some systems that are currently deployed, immersion cooling can be a very effective method for thermal management of high heat flux electronics.

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