18. Immersion Cooling

18.1 Passive Immersion Cooling

18.1.1 Introduction

This section presents an overview and guidelines far the packaging engineer and the subject of liquid immersion heal transfer of electronics. Power supplies, both law- and high-voltage, fall into this category, as do microcircuits having high heal density. The efficient heat transfer provided by nucleate and pool boiling has long been recognized as a superior cooling technique, but only recently base applications developed as a result of increased packaging flux densities.

Heat removal from electronic components has become a problem of significant interest due to the continuing reduction in feature size and increase in functional performance. A number of direct liquid immersion cooling techniques have recently been examined for removal of very high heat fluxes. For example, heat flux handling capabilities on the order of 200 W/cm^2 have been demonstrated with micro-channel heat sinks under flow boiling conditions. These high heat flux removal immersion cooling methods require an intimate contact between the coolant liquid and electronic components. Also, the use of forced convection, employed in many cases, increases design complexity and costs. These constraints are often unacceptable during product design and a strong need exists for the development of passive cooling techniques for removal of moderately high heat fluxes (up to 50 W/in^2).

Recent advances in material technology have resulted in several new materials with extremely high thermal conductivity. Fibers with unidirectional thermal conductivity of almost 1100W/m.K have been developed and used to produce composite materials in sheet form as potential substrate materials for electronic thermal management. In parallel to these advances in high thermal conductivity materials, efforts have been made to adapt several high performance thermal technologies to electronics cooling. An in-depth review of the saturated boiling process and the characteristic of common modes of boiling appear in foregoing sections.

18.1.2 Passive Immersion Module (PIM) Concept

Passive in that the module is a self-contained, sealed enclosure with no moving parts, where Electronic component(s) are immersed in the fluid contained within and the liquid acts as heat spreader to module cold plate, aided by vigorous boiling process.

The question now that why it is called "Passive immersion", and not "full immersion" or active immersion or whatever, Due to The passive cooler that doesn't use any pumps to move the fluid around, this system depend on free convection to work. Passive immersion cooling where there is physical walls separating the microelectronic chips and the surface of the substrate from the liquid coolant, Note that the electronics module to the customer can appear as an externally air-cooled “black box.” and no moving parts = increased reliability over pumped liquid systems.

The entire system components (except mechanical parts such as disk drives are submerged in specialized dielectric, non-corrosive, flouro-carbon based liquid. The liquid is cooled by a copper or aluminum cold plate. Heat is dissipated from the components directly into the liquid, and convection causes the heated liquid to move towards the colder liquid near the cold plate. Cooled liquid in turn flows down towards the components.

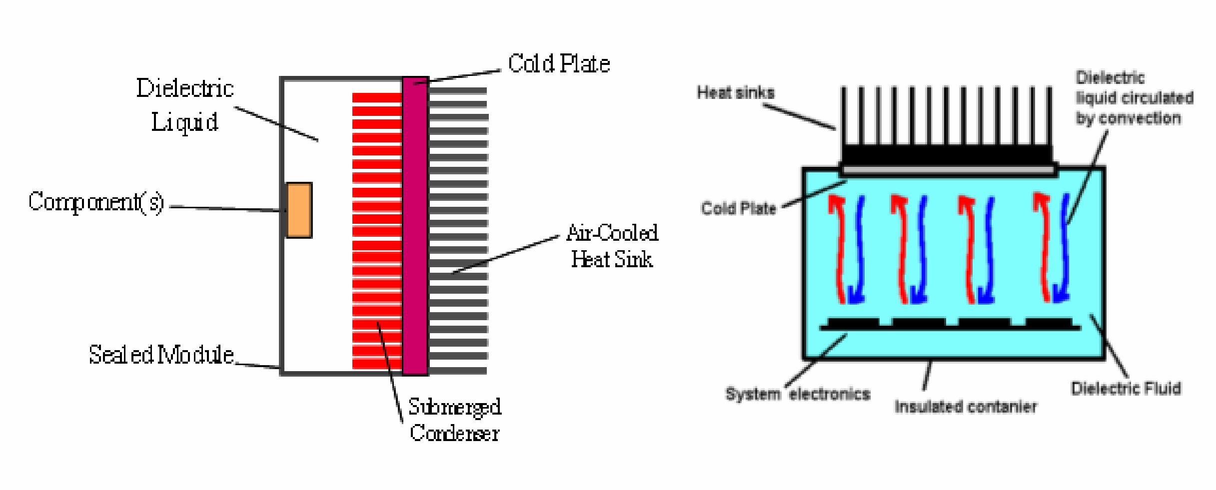

Figure 18.1 Passive immersion concepts

18.1.3 Types of Passive Immersion Cooling

Figure 18.2 illustrates the general types of liquid-filled packages; those basing vapor space above the components as in Figure 18.2a and b, and those that ate completely filled, as in Figure 18.2d and e. In same high voltage power supplies, as in Figure 18.2e, the space abuse the component is filled with a gas such as SF_6, which provide increased ace suppression at law temperature where the vapor dielectric properties are mush reduced. Packages that are completely fitted require an expansion device to account for volumetric changes of the fluid over temperature, whereas units with vapor space usually are designed to withstand both positive and negative pressure differentials caused by temperature and altitude changes in airborne applications. A completely filled unit in best foe heat transfer and voltage ace suppression, but it is heavy and requires a bellow: partially filled units on the other hand eliminate the need for bellows and may have poorer heat transfer and voltage suppression, especially when the components arc in the vapor space.

For all of the units depicted in Figure 18.2, the existence of some no condensable gas will degrade the thermal performance by impeding the heat transfer at the interfaces. It is good practice, therefore to pump the air from the package prior to filling and to degas the coolant since in many cases the liquid can absorb as much as 50 percent of its volume on gas at room temperature. Note that the condensers shown in Figure 18.2 are located either internal or external the package. In all eases the operating temperature of the liquid in related to the heat-sink or condenser temperature under steady-state conditions.

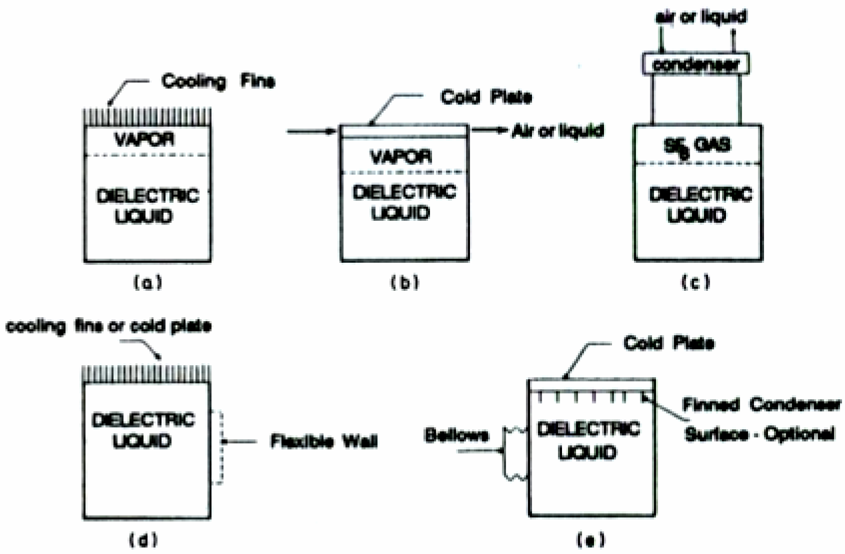

Figure 18.2 Types of liquid-filled enclosures. (a)Ambient cooled. (b) Forced convection cooled. (c) Forced convection cooled. (d) External condenser and (e) Filled enclosure

18.1.4 Passive Immersion Cooling Curve

The heat transfer process for immersion-canted components is explained by meant of Figure 18.3 (Liquid boiling curve), which illustrates the classical hailing curse with only alight modification. A heated microelectronics component immersed in liquid exhibits a superheat or temperature rise $\Delta T_{w\text{-}sat}$ from the wall to the liquid saturation temperature to a degree depending on the surface heat flux. At low flux levels, A to B, the heat transfer is by free convection with out phase change, and the natural convection film coefficient equations are applicable. Between B and C, an increase in flux level results in the formation of vapor bubbles and boiling occurs. Along this portion of the curve, higher heat flux rates produce activation of more nucleation sites with only small increase in temperature difference. The nucleate boiling regime from B to C in Figure 18.3 is characterized by a continuous stream of babbles, which travel from the component surface to the vapor interface in a partially filled enclosure or to the condenser surface in a filled unit. At C, the critical heat flux, or “burnout", is reached, and the component is completely blanketed with vapor. The babbles form so rapidly at the surface that a large increase in temperature results from C to D and beyond to the unstable region. Upon a reduction in heat flux rate, the operating point moves along to F and G and then along the nucleate boiling line to B.

Although the general shape of the curve in Figure 18.3 is common for the coolants used in immersion applications, the relative position of the curves are dependent on the coolant and the surface in contact. A surface treatment such as selective enchants and the depositions of alumina on silicon surface as well as the devotement of “dendridic” heat sinks are recent innovations introduced to increase the number of nucleation sites for improved heat transfer. Another phenomenon to be dealt with in boiling heat transfer is the hysteresis carve in Figure 18.3, identified as line BHI. This portion of the curve is less defined and shows a delay in nucleate boiling and an extension of the free-convection curve *AB.* Repeated test runs often result in lowering the incipience of boiling (paint H), as does surface treatment, and other means are used to promote nucleation at the surface.

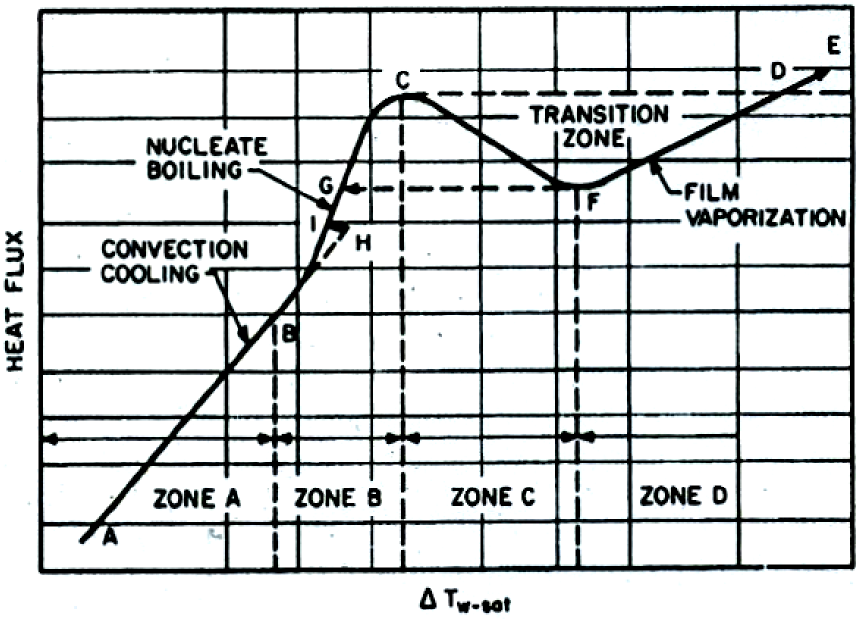

Figure 18.3 Liquid boiling curve

18.1.5 Advantage and Limitation

Advantages:

- Very wide operating temperature range
- Able to handle much larger heat loads than other methods
- Condensation on components is ruled out (they're submerged in a liquid)
- Absolutely silent

Disadvantages:

- Suitable dielectric fluid may be expensive
- Hardware upgrades are made difficult, since the module must be opened and drained to access the components.

Possible problems:

- If liquid on the component surfaces reaches boiling point (Many dielectric liquids have a low boiling point), gaseous bubbles could result, which although in theory would vastly increase heat transfer from the components due to the phase change, can lead to decreased efficiency if they accumulate on the surface of the cold plate. If it proves impossible to avoid bubbles then a means must be devised of condensing the bubbles back into liquid. One way of delaying the appearance of bubbles is to slightly increase pressure inside the module.
- It is possible that over time, the dielectric liquid will begin to lose its insulating properties, due to the introduction of impurities.

- If the liquid is to be super-cooled, then steps must be taken to prevent condensation on the outside of the module. The module must be well insulated to achieve this.

18.1.6 Design Guidelines

Free single-phase immersion cooling using a dielectric coolant such as Freon R-113, or a fluorocarbon such as FC-77, generally produces acceptable temperature rises for flux rates of under 5 W/cm^2 (32 W/in^2) higher flux rates results in nucleate boiling with mach smaller rates of temperature rise, that is, surface-to-liquid ΔT values, as the flux is increased compared in free-convection temperature rises.
The design of immersion cooling systems must include an examination of all of the internal heat

producing surfaces for maximum flux rates is order so maintain an adequate margin of safety with respect so the critical heal flux. Dielectric coolants suitable for immersion are typically those that exhibit large superheats of 10 to 30 ^{o}C; hence one mast sake account of this in designing liquid systems.

Fins used on component surfaces to enhance cooling efficiency as in pin grid array packages are best oriented in the horizontal or vertical planes for unrestricted heat transfer, as opposed to downward-facing surfaces, in which case bubble entrapment may lead to serious overheating, particularly in the case of high flux surfaces. Bubble escape is a necessary requirement in nucleate boiling in order to achieve free flow and liquid replacement near the boiling surface. The testing of enclosures using Plexiglas or glass windows can often reveal these trouble spots, which are correctable in the design phase. Surface treatment of cooled surfaces such as silicon to enhance nucleation can produce up to 50 percent increases in film coefficients us compared so smooth surfaces. Some common treatment methods include the following:

- Mechanical surface treatment. such us “vapor blasting’
- Etching techniques to roughen the surface
- Dendritic surface treatment to increase area-forming a brush of nickel powder with a magnet and plating the needles in place
- Laser treatment
- Machining microchannels or grooves into the surface

18.2 Active Immersion liquid cooling for High Power Density Microelectronics

18.2.1 Introduction

Since the development of the first electronic computers in the 1940s, the development of faster and denser circuit technologies and packages has been accompanied by increasing heat fluxes at the chip and package levels. Over the years, significant advances have been made in the application of air cooling techniques to manage increased heat fluxes. Although air cooling continues to be the most widely used method for cooling electronic packages, it has long been recognized that significantly higher heat fluxes can be accommodated through the use of liquid cooling as in active immersion liquid cooling. Applications of active immersion liquid cooling for microelectronics may be categorized as either indirect or direct.

Indirect liquid cooling is one in which the liquid does not contact the microelectronic chips, nor the substrate upon which the chips are mounted. In such cases a good thermal conduction path is provided from the microelectronic heat sources to a liquid cooled cold-plate attached to the module surface, as shown in Figure 18.4. Since there is no contact with the electronics, water can be used as the liquid coolant, taking advantage of its superior thermophysical properties.

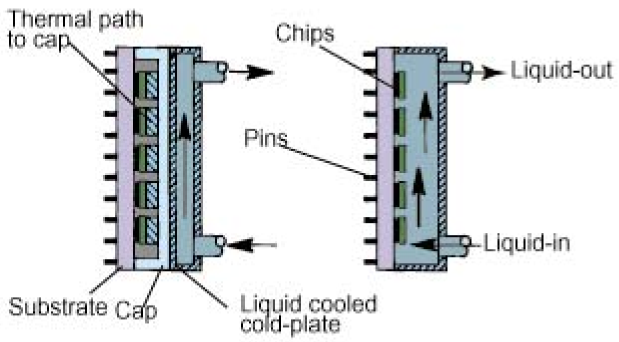

Figure 18.4 Example of indirect and direct liquid immersion cooling for a multi-chip module package

Direct liquid cooling, the focus of this article, may also be termed direct liquid immersion cooling, since there are no physical walls separating the microelectronic chips and the surface of the substrate from the liquid coolant. This form of cooling offers the opportunity to remove heat directly from the chip(s) with no intervening thermal conduction resistance, other than that between the device heat sources and the chip surfaces in contact with the liquid. Interest in direct liquid immersion as a method for cooling integrated circuit chips may be traced back as early as the 1960s.

Direct liquid immersion cooling offers a high heat transfer coefficient which reduces the temperature rise of the chip surface above the liquid coolant temperature. As shown in Figure 18.5, the relative magnitude of a heat transfer coefficient is affected by both the coolant and the mode of convective heat transfer (i.e. natural convection, forced convection, or boiling). Water is the most effective coolant and the boiling mode offers the highest heat transfer coefficient. Direct liquid immersion cooling also offers greater uniformity of chip temperatures than is provided by air cooling.

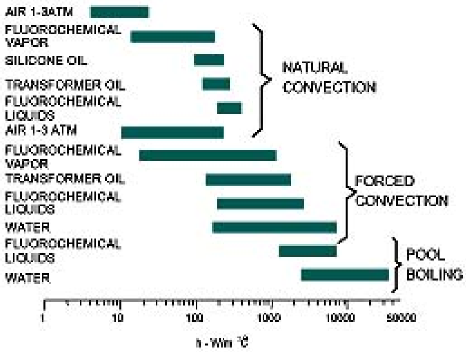

Figure 18.5 Relative magnitude of heat transfer coefficients for various coolants and modes of convection

18.2.2 Coolant Considerations

The selection of a liquid for direct immersion cooling cannot be made on the basis of heat transfer characteristics alone. Chemical compatibility of the coolant with the chips and other packaging materials exposed to the liquid must be a primary consideration.

There may be several coolants which can provide adequate cooling, but only a few will be chemically compatible. Water is an example of a liquid which has very desirable heat transfer characteristics, but which is generally unsuitable for direct immersion cooling on account of its chemical characteristics. Fluorocarbon liquids (e.g. FC-72, FC-86, FC-77, etc.) are generally considered to be the most suitable liquids for direct immersion cooling, in spite of their poorer thermo-physical properties.

As shown in Table 18.1, the thermal conductivity, specific heat, and heat of vaporization of fluorocarbon coolants are lower than water. These coolants are clear, colorless per-fluorinated liquids with a relatively high density and low viscosity. They also exhibit a high dielectric strength and a high volume resistivity. The boiling points for the commercially available "Fluorinert" liquids manufactured by the 3M Company, range from 30 to 253 °C.

Table18. 1 Comparison of thermophysical properties of fluorocarbon coolants and water

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)	1.633	1.680	1.780	0.997
Specific Heat x 10^{-3} (w-s/kg-K)	1.088	1.088	1.172	4.179
Thermal Conductivity (w/m-K)	0.0551	0.0545	0.057	0.613
Dynamic Viscosity x10^4 (kg/m-s)	4.20	4.50	4.50	8.55
Heat of Vaporization x10_L^{-4} (w-s/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

These liquids should not be confused with the "Freon" coolants which are chlorofluorocarbons (CFCs). Although some of the "Freons" (e.g. R-113) exhibit similar cooling characteristics, concern over their environmental effect on the ozone layer preclude their use.

18.2.3 Other Considerations

Although this discussion has concentrated on the merits of immersion cooling, coolant selection, and possible modes of heat transfer; several other considerations should be kept in mind when considering direct liquid immersion for cooling electronics**.**

- Since fluorocarbon liquids are expensive they should only be considered for use in closed systems. Whether the application is in a self-contained module like the LEM (Liquid Encapsulated Module package) or a forced flow scheme, care must be taken to ensure that the seal materials chosen are compatible with the liquid. Information or guidance in this regard may sometimes be obtained from the manufacturer of the coolant. If boiling is to take place, then the design must incorporate a means to condense the resulting vapors.
- A finned surface may be designed for this purpose as in the LEM example, or a remote finned condenser surface cooled by air or water might be used. In flow systems, care must be taken in selecting a pump.
- The relatively high vapor pressure of the low boiling point fluorocarbons generally requires that a higher suction head be provided to prevent cavitation in the pump. Whether using a self-contained boiling module or a circulating flow system, care should be taken to make sure all internal surfaces in contact with the coolant are clean. This will ensure that manufacturing process residues or unclean surfaces do not introduce a contaminant into the liquid which could be carried to the heated chip surfaces and interfere with the boiling process.
- In forced circulating liquid systems, it may be desirable to add a particulate and a chemical filter to ensure the long-term purity of the coolant. By selecting the appropriate liquid coolant and the mode of heat transfer, and by giving appropriate attention to these other considerations; direct liquid immersion cooling can be used successfully to provide an effective solution for cooling high heat flux chips and packages.

18.2.4 Application (Examples)

In spite of prolonged interest in direct immersion liquid cooling as a means to cool high heat flux micro-electronics, there have been only a limited number of applications. As with indirect liquid cooling, these applications have been almost exclusively in the large mainframe and supercomputer arena. This is not surprising, since this has been the microelectronics technology sector with the highest packaging densities and concentration of heat.

The Liquid Encapsulated Module (LEM) developed at IBM in the 1970s provides an example of a package utilizing pool boiling. As shown in Figure 18.6, a substrate with integrated circuit chips (100) was mounted within a sealed module-cooling assembly containing a fluorocarbon coolant (FC-72). Boiling at the exposed chip surfaces provided high heat transfer coefficients (1700 to 5700 w/m^2-K) to meet chip cooling requirements. Internal fins provided a means to condense the vapors and remove heat from the liquid. Either an air-cooled or water cooled cold-plate could be used to cool the module. 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.

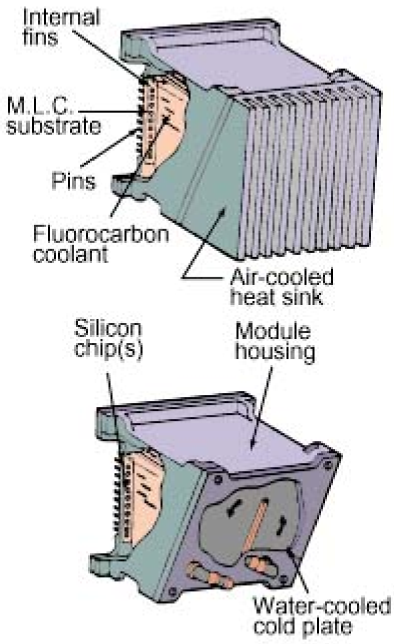

Figure 18.6 Air or water-cooled Liquid Encapsulated Module (LEM) packages

An example of a large scale forced convection fluorocarbon cooling system is provided by the CRAY-2 supercomputer. As shown schematically in Figure 18.7, stacks of electronic module assemblies were cooled by a forced flow of FC-77 in parallel across each module assembly. Each module assembly consisted of 8 printed circuit boards on which were mounted arrays of single chip carriers. A total flow rate of 70 gpm was used to cool 14 stacks containing 24 module assemblies each. 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.

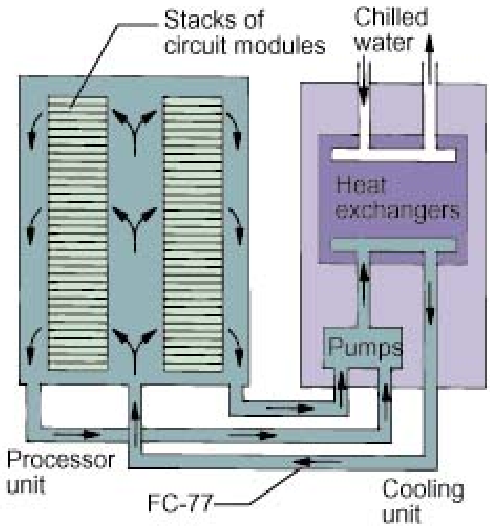

Figure 18.7 CRAY-2 liquid immersion cooling system