

DESIGN PARAMETERS IN IMMERSION COOLING



Two phase Passive immersion cooling refers to a cooling system which uses a boiling liquid that changes phase to remove heat from one or more surfaces. The vapor is then moved to a condenser and falls back to the liquid bath passively. If electronics are to be cooled then the liquid needs to be dielectric and these electronic assemblies are often immersed in the liquid in a sealed container. Some examples are Gate-Turn-Off (GTO) Thyristors in high voltage traction systems, Insulated Gate Bipolar Transistors (IGBT's) as shown in Figure 1a-b.

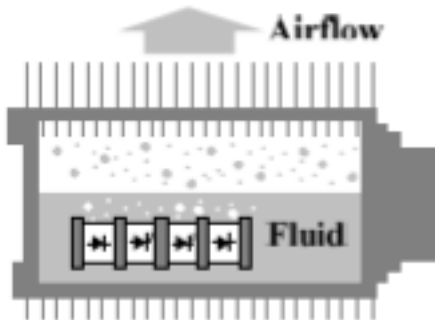
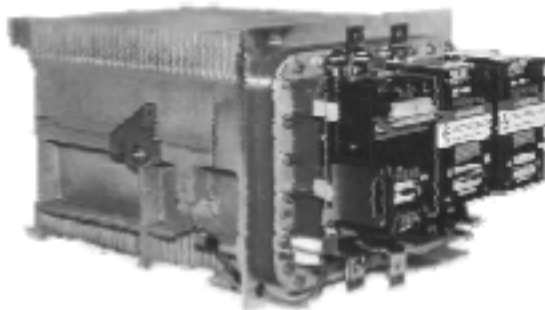


Figure 1a. Immersion Cooled GTO Traction Module [1]

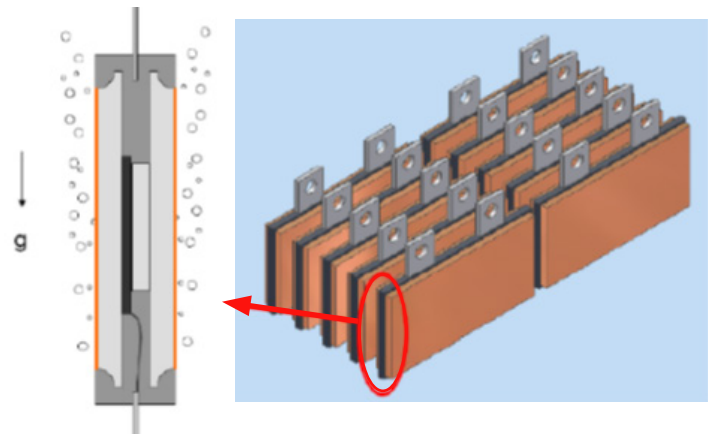


Figure 1b. Immersion Cooled IGBT Modules [2]

This technology is fairly promising and is particularly useful when the devices are densely packaged in arbitrary form factors. This cooling system is price competitive when compared to traditional liquid cooling systems since it does not require pumps, fans, cold plates, hoses, manifolds, couplings etc. However, traditionally, electronic and thermal engineers are averse to having live electronics come in direct contact with liquids and there a lot of non-thermal, subtle aspects which need to be given careful thought and consideration while incorporating such cooling techniques.

The different design and practical aspects that need to be evaluated can be listed as follows:

1. Fluid Chemistries
 - a. Physical Properties
 - b. Electrical Properties
2. Material compatibility
3. Effect of Air and water in the system
4. Thermal Decomposition

FLUID CHEMISTRIES

In the past ChloroFlouroCarbons (CFC) were used but their use has been limited due to its negative contribution to the ozone layer depletion. CFC made way for PerflouroCarbons (PFC) but due to its high global warming potentials, its usage is also on the decline. Currently their replacements will mostly include HydroFlouroEthers (HFE) and FluoroKetones (FK). The concern is that of hydrocarbon solvency. Mobile organic contaminants are likely to enter the immersion system, and in general these contaminants are hydrocarbon in nature and not very volatile. PFC and FK fluids are very poor solvents for hydrocarbons while HFE is slightly better. The Kauri-Butanol test is a measure of the hydrocarbon solvency and it is recommended that the engineer has the data for the KB value for the proposed fluid.

In general a PCB and the electronics on it are designed to operate in air with its own intrinsic di-electric properties. When the medium is changed to any of the fluids mentioned above, these properties need to be evaluated carefully. One possible scenario is where the movement of vapor bubbles causes transient discontinuities in the electrical properties of fluids. Additionally, the dielectric properties are frequency dependent. HFE fluids show significant reduction in dielectric constant at high frequency, Figure 2, indicating that this is not a good choice for high frequency applications. A careful consideration of the properties of the chosen working fluid should be given for the system under design. Table 1 shows the representative Fluid properties at 25°C.

Fluid Chemistry	PFC	FK	HFE	HFO
Example	C_6F_{14}	$C_6F_{12}O$	$C_6F_7H_3O$	$C_3F_4H_2$
T_b [°C]	56	49	34	-29
T_{crit} [°C]	178	169	165	95
k [W/m-K]	0.057	0.059	0.075	0.085
ρ_l [kg/m ₃]	1680	1610	1401	1094
H [kJ/kg]	88	88	142	145
P_r at 25°C [kPa]	30.9	40.4	64.6	677
P_r at 100°C [kPa]	350	441	706	supercrit
Resistivity [GOhm-cm]	1×10^6	1×10^4	0.1	NA
GWP	9300	1	370	4
KB	0	0	10	NA

Table 1. Representative Properties of Working Fluids Used in two Phase Immersion Cooling Systems [1]

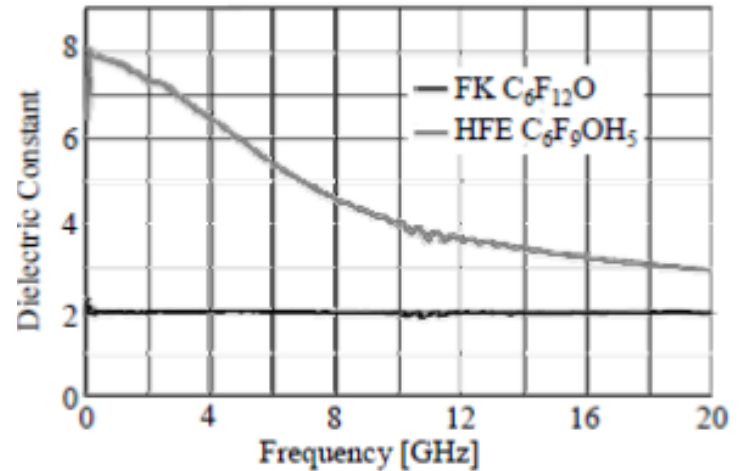


Figure 2. The Variation of Dielectric Constant with Frequency for a Representative FK and HFE Fluids [1]

MATERIAL COMPATIBILITY

Two processes that are inherent to two phase cooling, which potentially can affect the material compatibility and system health, are boiling and condensation. During boiling, some relatively non volatile substances, such as oils dissolved in the fluid are left behind by distillation. The resulting condensate (after the vapor condenses) has a high affinity to the same substance since it is free of it. If this condensate comes in direct contact with elastomers containing such dissolvable oils, it will either extract or solvate these oils. This can have unintended consequences of the immersion process. A Soxhlet extraction test is extremely useful to assess material compatibility in two phase applications. A typical set up to do the Soxhlet Extraction compatibility test of O-ring samples is shown in Figure 3. Detailed description of the test can be found in [1]

It is necessary to perform this test since the fluid soluble substances in one material can affect another material or the fluid itself. Furthermore the fluid soluble substances can adversely affect boiling performance by filling nucleation sites and increasing thermal resistance.

In general a few useful design tips suggested by [1] are:

1. Materials that contain extractable organics should not be used
2. Pre-treat materials to remove organics
3. Remove the organics in-situ by using activated carbon

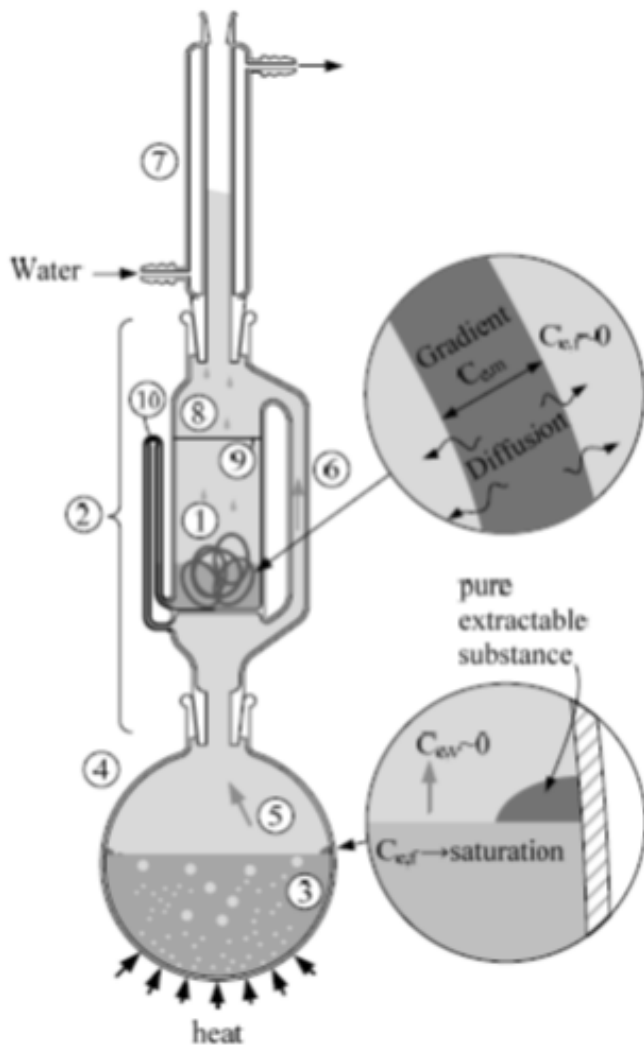


Figure 3. Schematic Diagram Showing the Glass Ware Set up for Soxhlet Extraction Compatibility test of O-ring Samples [1]

EFFECT OF AIR IN THE SYSTEM

Presence of Air in a sealed passive two phase system can cause the system to operate at higher than optimal temperature by impacting the condensation heat transfer. Even in systems that purge air automatically, this can be a source of fluid loss since some vapor is vented out along with the air. Corrosion due to the presence of oxygen in the air is also a potential area of concern.

Air can enter into the system either due to leaks and or due to the diffusion through elastomers/plastics. Since diffusion is driven by the difference in the partial pressure between the system and environment, air can enter the system even when the system pressure is above ambient. Figure 4 clearly shows how air diffuses into a pressurized container, in this case a balloon.

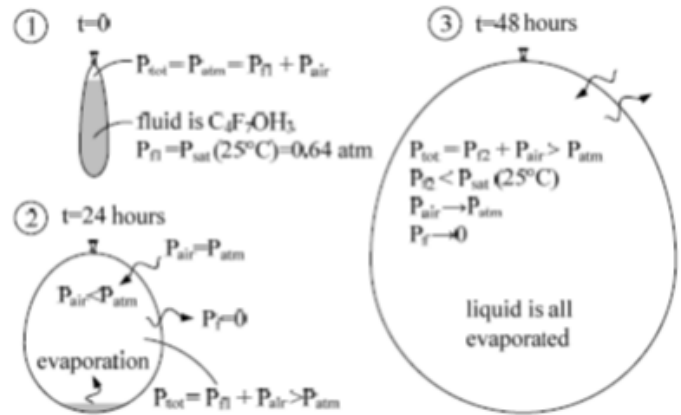


Figure 4. Experiment Demonstrating Air Diffusion into a Pressurized Container [1]

To prevent the entry of air or its effects on the system a few strategies have been tried and tested.

- Using volatile fluid (Boiling point $T_b < 20^\circ\text{C}$) so that system pressure remains above atmospheric at even the lowest expected ambient temperature. This might not be practical when the operating temperature approaches T_{critical} or if the pressure required becomes high.
- In larger systems like the GTO traction inverters, fluids with $T_{\text{boiling}} > 48^\circ\text{C}$ have been used but stringent leak checks such as helium leak checking methods are used to minimize air infiltration.
- Another practical approach to let the system breathe to ambient or use bellows as necessary to maintain the required pressure. This strategy has been successfully implemented in systems which run continually at nearly constant power such as datacom equipment.

EFFECT OF WATER IN THE SYSTEM

In general trace levels of water which can be dissolved in the fluid do not pose a big hazard to the system. However water in liquid form can solvate trace ionic contaminants present in the system and becomes corrosive. Liquid water does not react with PFC fluids but worsen the thermal decomposition of HFE fluids at temperatures $> 150^\circ\text{C}$. FK fluids react with water at room temperature. In both of these cases, water solvates some components and becomes corrosive. In general it is best to ensure the system is free from water at all times.

Water can enter the system at any time when the system temperature is below the ambient dew point and air enters the system. If the strategy used to mitigate the entry of air

is that of letting the system breathe air and the ambient dew point is lower than the system temperature, then this is not an issue.

However, water can still enter the system if the polymers contain significant amounts of water in them and or water diffuse through permeable materials. One way to remove the water from the system is in-situ water removal by using desiccants as is done in refrigeration systems. The point to note is to use the right amount of desiccant by anticipating the amount of water that could enter the system. Table 2 shows the desiccants that can be used with the different fluids.

Desiccant	Capacity at low H ₂ O levels	Capacity at 25°C, 50% humidity	Capacity at high temp	Fluid compatibility
silica gel	poor	high	poor	PFC, HFE, HFO
molecular sieve	excellent	high	excellent	PFC, HFE, HFO
CaSO ₄	good	low	good	PFC, HFE, HFO, FK

Table 2. Desiccants For Working Fluids in an Immersion Cooled System [1]

THERMAL DECOMPOSITION

In general, under normal operation fluid thermal decomposition is not likely with PFC and FK fluids since they are generally stable up to 300°C. HFE fluids tend to break down at around 200°C and it is not advisable to use these fluids for continuous duty above 150°C.

However, decomposition is possible in certain situations when there are high voltage arcs within the fluid and device failures leading to high, sustained temperatures, usually under a stable vapor film, which is also known as film boiling. While these failures are random phenomena, research is being conducted to assess the extent of decomposition under such circumstances. Pothapragada et al [3] have used the in situ removal of decomposition products like PerFluoroIsoButylene by pumping the fluid through basic (pH ~ 11) alumina granules. Currently, other suitable reagents for removing the decomposition products are being investigated.

In conclusion two phase immersion cooling can be a viable option to cool power electronics and high performance

computers. However it is very important to understand the non-thermal aspects that will play a significant role in the proper functioning of the system while implementing such a cooling system. Thermal engineers need to understand these factors apriori in addition to understanding the thermal performance capabilities of two phase immersion cooling techniques. It is essential to ensure material compatibility, mitigate the effects of air and water entry to the system, choose an appropriate working fluid and understand the potential risks of thermal decomposition of the chosen working fluid.

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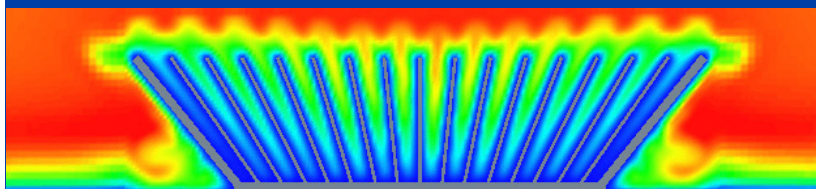
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