# Passive 2-Phase Liquid Techniques to Control Temperatures in Microelectronics and Power Systems

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## ABSTRACT

The presentation provides a brief overview of recently-published research describing techniques for using dielectric liquids in an evaporative mode to passively control temperatures in terrestrial power electronic, microelectronic, fuel cell and battery systems.

Experiments with immersion cooling of dual side soldered insulated gate bipolar transistor (IGBT) modules, for example, showed junction-to-fluid performance competitive with the best emerging pumped water technologies. Most Engineers dismiss the idea of immersion cooling for commodity electronics like servers in part because immersion systems have historically made use of costly hermetic pressure vessels and electrical connections. Ongoing research suggests that a new concept called "open bath immersion cooling" is far simpler and less expensive to implement than other pumped liquid cooling techniques. It simplifies server design and offers power densities as high as 4kW/liter while reducing operating costs and greenhouse gas emissions.

Passive 2-phase condensation heating has been used for decades in precision cleaning applications and to re-flow solder in various electronics manufacturing operations. Experiments show the utility of this technology for preheating and, during operation, cooling fuel cell stacks and lithium ion batteries. Data gathered with simulated bipolar plates showed the ability to passively remove the heat from a automotive traction scale polymer electrolyte fuel cell stack with 1°C temperature uniformity. Passive 2-phase technology provides a myriad of advantages relating to simplicity, cost, reliability, size, integration, efficiency and dielectric and fire protection.

## INTRODUCTION

Passive 2-phase cooling refers broadly to techniques that use a boiling liquid to remove heat from a surface and then transfer it without a pump by condensation to another surface. When that liquid is dielectric, electronics are often immersed in the liquid within a sealed container. Passive 2-phase immersion has been used for decades to cool transformers, computers and tens of thousands of gate-turn-off (GTO) thyristor-based traction inverters (Figure 1). This technology allows many and a variety of devices to be densely packaged in an arbitrary form factor within a protective, uniform temperature and ruggedized environment. It is arguably the most elegant way to capture all of the heat emitted by a spatially complex electronic assembly and it is often preferred over pumped liquid techniques for its simplicity, reliability and performance.

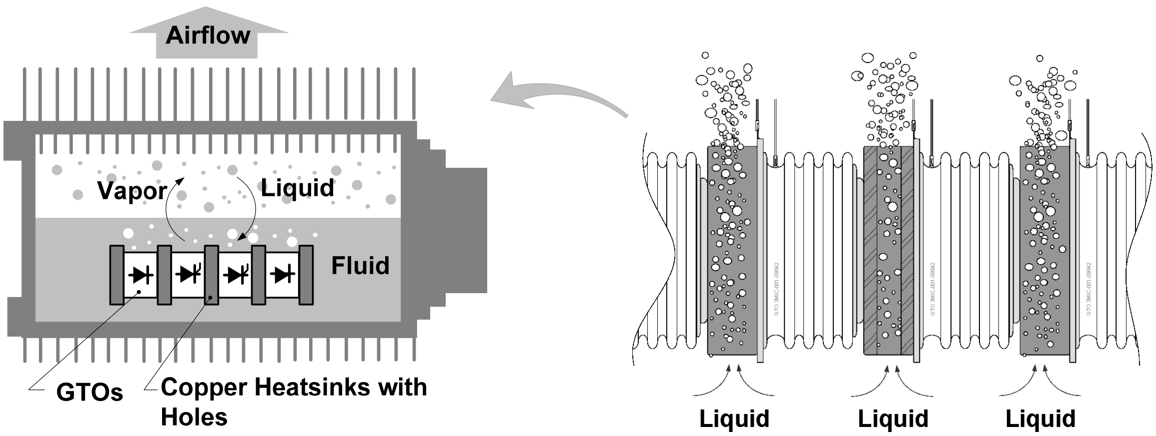


**Figure 1: Cross section of a 2-phase immersion-cooled GTO traction inverter**

Passive 2-phase condensation heating is commonly used in precision cleaning applications and to re-flow solder during manufacturing of printed circuit boards (Figure 2). In vapor phase soldering (VPS) systems, a printed circuit board with solder paste and devices pre applied is brought into a saturated vapor zone above a refluxing pool of an inert liquid with a boiling point above the eutectic point of the solder. Condensing vapor quickly heats the assembly to the boiling point of the liquid. VPS is often preferred over infrared and convective methods for its unique ability to quickly and efficiently heat irregular assemblies to uniform temperatures without overshoot.

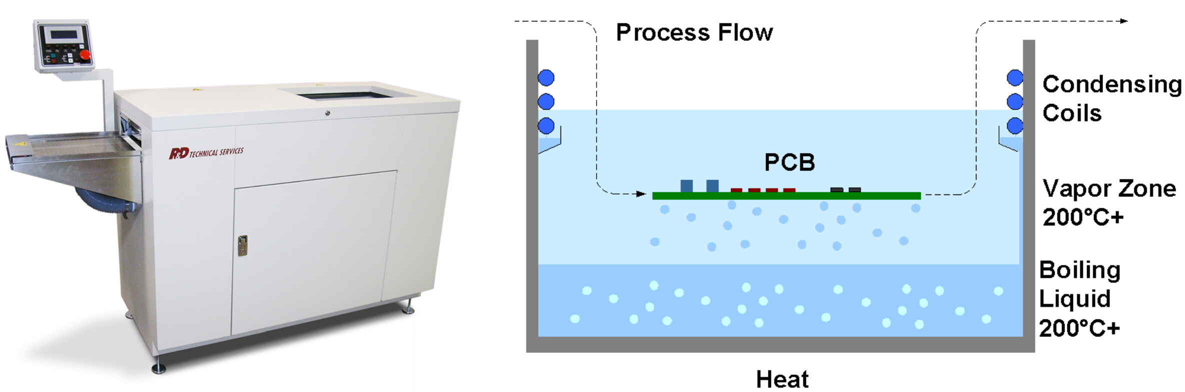


**Figure 2: VPS machine and process (photo courtesy of R&D Technical Services).**

## POWER ELECTRONICS

Passive 2-phase immersion is often used in large high voltage GTO-based traction inverters. However, recent research [1] has shown its utility for cooling high heat flux IGBT/MOSFET based power electronics, the common building blocks of smaller scale, lower voltage systems. Modules were built with dual-sided-solderable IGBTs soldered between copper heat spreaders that serve as collector and emitter leads (Figure 3). These modules were immerse d in a saturated pool of $C_3F_7OCH_3$, a hydrofluoroether working fluid at $T_f$=$T_b$. Modules built with die having an active area of $A_c$=0.144 cm$^2$ showed a junction-to-fluid temperature difference of $\Delta T_{jf}$=45°C at a heat flux of $Q''_c$ =1180 W/cm$^2$ and 55 Amp current. Modules built with $A_c$=1.46cm$^2$ die showed a junction-to-fluid temperature difference of $\Delta T_{jf}$=55°C at a heat flux of $Q''_c$=550 W/cm$^2$ and 305 Amp current. This performance level is competitive with the best emerging pumped water technologies and enables the thermal goals of the FreedomCAR project. Additional packaging studies [2] suggest thermal power densities as high as 4kW/liter are possible with as little as 50cc of fluid per kW.

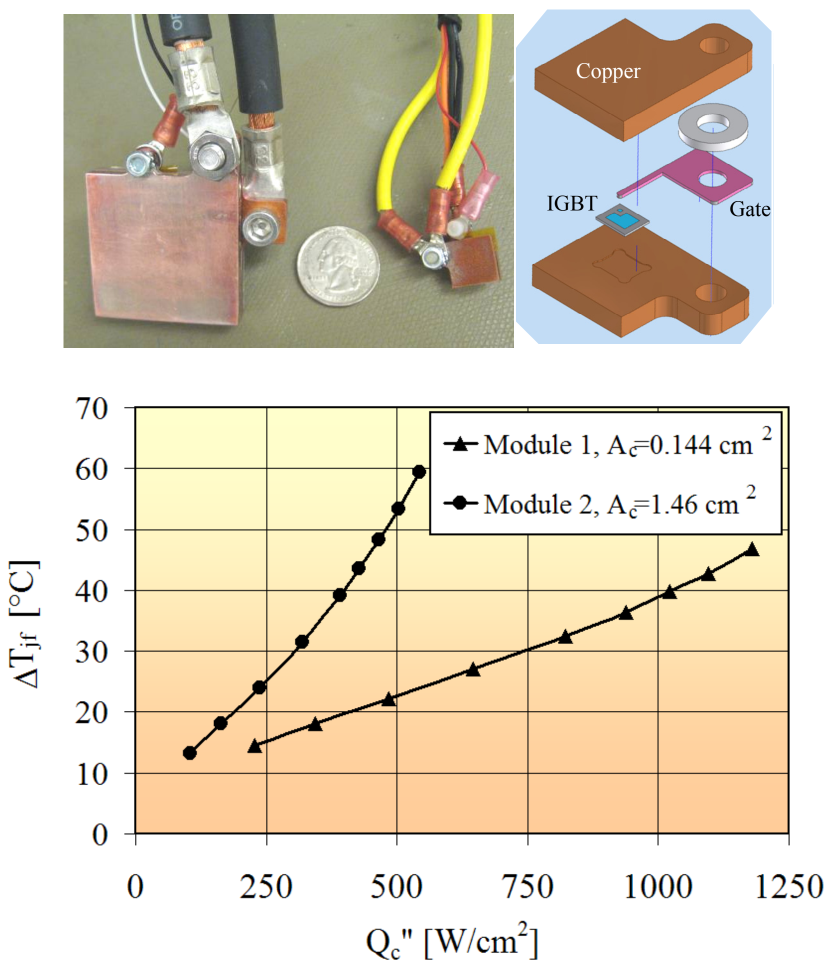


**Figure 3: Measured junction-to-fluid temperature differences for immersion-cooled IGBT modules.**

Immersion cooled GTO traction inverters have historically been nearly hermetic vessels, filled at the factory using elaborate evacuation, fluid degassing and leak checking procedures. For this reason, they are not field serviceable. The aforementioned research [1] demonstrated the viability of simple automatic in-situ degassing techniques that permit pour-in filling and field servicing.

## MICROELECTRONICS

The limitations of air cooling in the context of data centers are well known. Traditional *liquid* cooling technologies can dramatically increase efficiency, chassis and facility power density and the thermodynamic availability of the heat removed. However, these techniques are inherently costly and complex. Their use has been confined to mainframes and supercomputers, the cost barriers too high for the commodity datacom environment to bear.

Passive 2-phase immersion cooling can eliminate much of the cost and complexity of traditional liquid cooling approaches. However, as with power electronics, creating and maintaining a hermetic enclosure for commodity computational or communications hardware that must be field serviceable is challenging. It is for *these* reasons that most Engineers dismiss the idea of immersion cooling within a data center. However, immersion cooling *can* be applied without these complexities resulting in a system that is not only elegant but simpler, more dense, less expensive and at least as efficient as any other liquid cooling technique.

## OPEN BATH IMMERSION COOLING CONCEPT

In this concept [3], servers are immersed side-by-side in modular semi-open baths of a volatile dielectric fluid (Figure 4). The term "semi" denotes a bath that is closed when access is not needed much like a chest-type food freezer. Unlike the traction system mentioned earlier, these baths operate at atmospheric pressure and have no specialized hermetic connections for electrical inputs and outputs. Instead, electrical connections from a submerged backplane enter a conduit beneath the liquid level and exit the top of the tank. The only other opening is a vapor trap through which fluid emissions can be controlled with an on demand condenser. The fluid boils on heat generating components and the vapor rises to a condenser integrated into the tank and cooled by tower water or water used at some distance for comfort heating. If desired, the vapor can flow passively to an outdoor natural draft cooling tower to transfer its heat passively to outdoor air without water as an intermediate.

Among the advantages of this technique compared to more traditional liquid cooling schemes (Table 1), is the fact that <u>all</u> server- and most rack-level cooling hardware are eliminated along with considerations relating to their integration, reliability and power consumption. This not only simplifies server design and operation but eliminates e-waste. Experiments with a 17x20cm circuit board populated with twenty 200W ceramic CPU simulators enhanced on their integrated heat spreaders (IHS) with a boiling enhancement coating (BEC) showed power densities as high as 4kW per liter. Such density further reduces e-waste while increasing facility power density. The system scale thermal and energy efficiencies are very high (Figure 5) resulting in reduced greenhouse gas emissions[1] and operating costs versus traditional air and liquid cooling schemes (Figure 6).

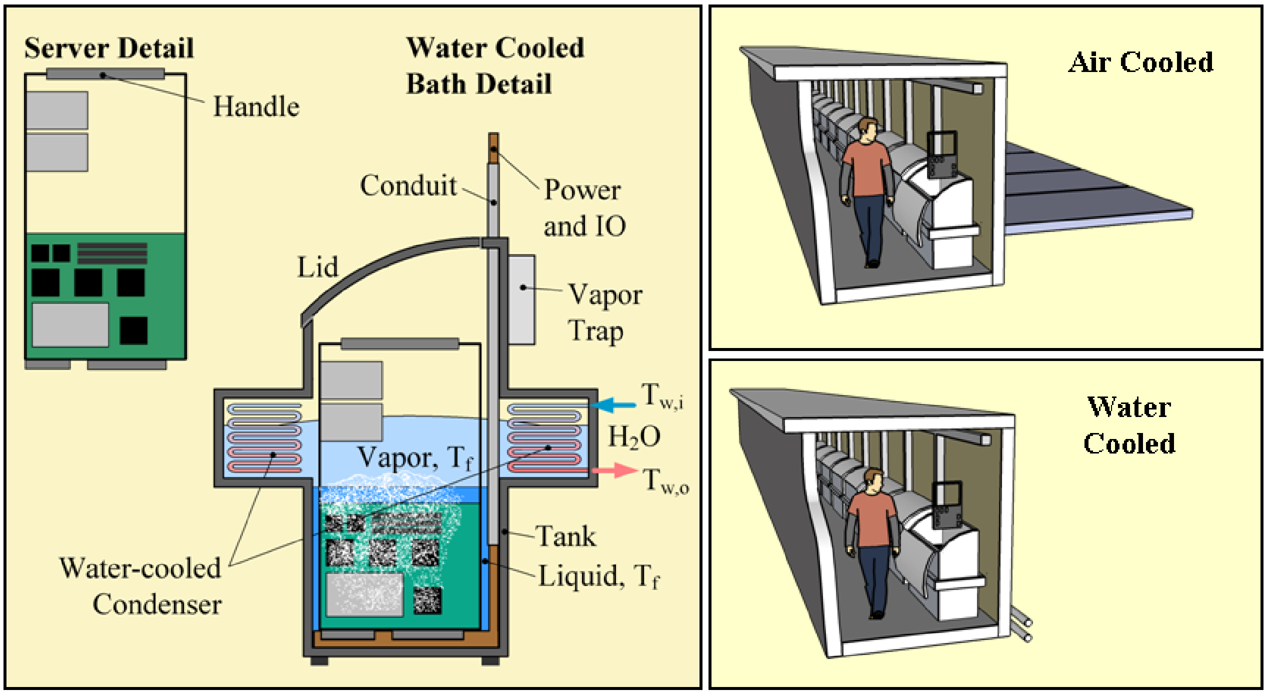


**Figure 4: Open bath immersion concept**

**TABLE 1: Advantages of open bath immersion cooling compared with other liquid and hybrid techniques**

| **Attribute** | See list |
|---|---|
| 1. No quick disconnects (QDs), clamshells, hermetic connectors. | a,c,d,(e) |
| 2. No pumps, fans, economizers, compressors | b,c,d,e,h |
| 3. No server/rack-level cold plates and plumbing | a,c,d |
| 4. Fluid losses at one point | a, e |
| 5. Intrinsic fire protection | h |
| 6 $\Delta T_{jf}$ is low, no fluid glide | g |
| 7. High power density (100x typical Air, 25x water) | h |
| **Advantage** | |
| a. Less risk due to leakage | f. Uniform device temperatures |
| b. Reduced power consumption | g. More efficient capture of heat |
| c. Uses less natural resources | h. Reduced facility construction cost |
| d. Reduced cost and complexity | |
| e. Reduced greenhouse gas emission | |

[1] Greenhouse gas emissions are generally quantified via Metirc Tons $CO_2$ Equivalent (MTCE)

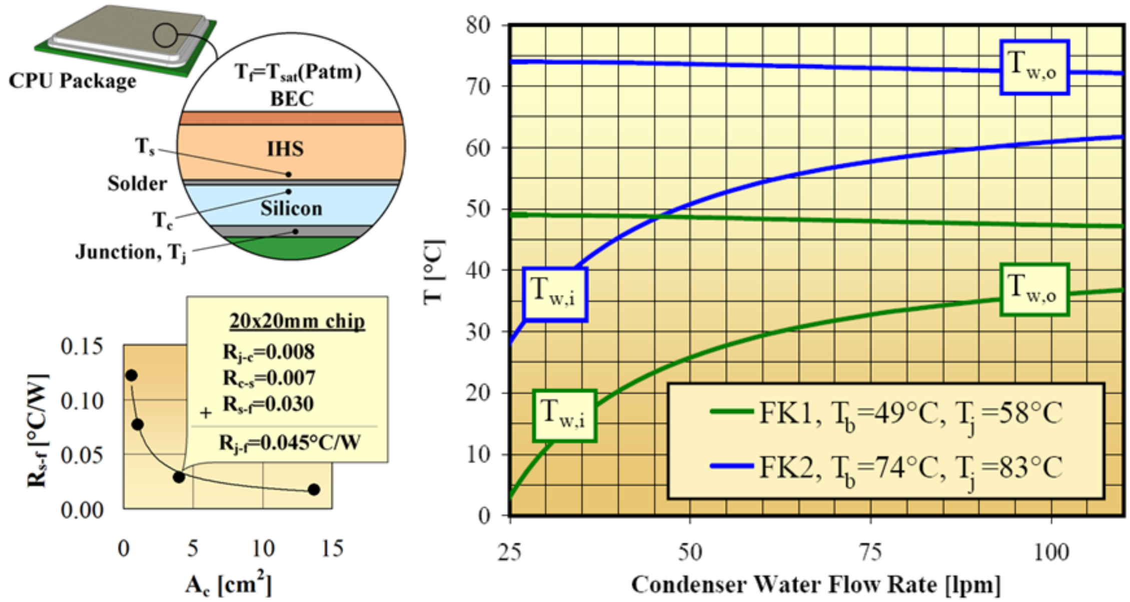


**Figure 5: Central processing unit (CPU)-to-fluid and fluid-to-water performance for 80 kW Bath comprised of 200W CPUs. FK1 and FK2 are two candidate fluids.**

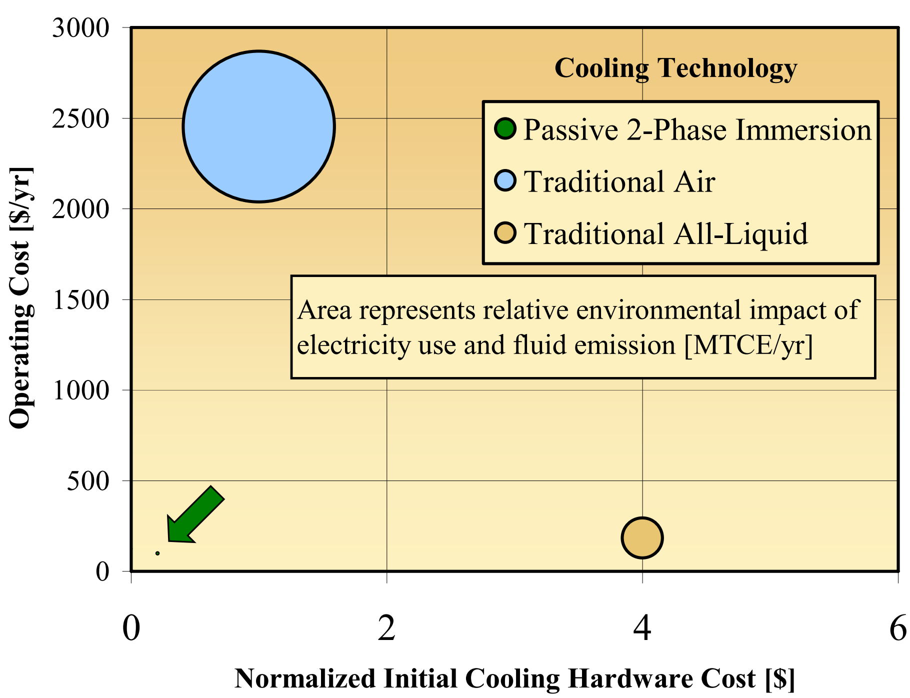


**Figure 6: Initial Hardware, Operating and Environmental Cost for 80 kW Bath or Rack (s). Does not include extra-rack and facility level costs.**

## FUEL CELLS

Though passive 2-phase techniques can be used in various types of fuel cells, they will be discussed here in the context of proton exchange membrane (PEM) fuel cells. In larger PEM cell applications, volumetric power densities are high enough that liquid cooling is required. Heat generated within the stacks is commonly removed by pumping a deionized aqueous or dielectric heat transfer fluid through passages within the bipolar plates. Warmed fluid is pumped through an air-cooled radiator that transfers the heat to ambient air. This single phase technique has disadvantages as shown in Table 2.

### SINGLE-PHASE DISADVANTAGES:

Because the stack, radiator and plumbing are filled with liquid, the weight and thermal mass of the system are increased. This increases the time and energy required to warm an idle stack to operating temperature. During operation, the coolant flow rate and pressure required to ensure sufficient temperature uniformity across the bipolar plates are substantial and active control of the cooling system is necessary if the stack is to operate properly. The required pump and control systems add cost and complexity while decreasing reliability. The pump discharge pressure makes the system more vulnerable to coolant leaks outside of the system and into the membrane electrode assemblies.

**Table 2: Advantages of passive 2-phase techniques to maintain PEM fuel cell temperatures.**

| Attribute | Single Phase | Passive 2-Phase |
|---|---|---|
| Simple | Active controls to regulate temperature.<br>Pump is required. | No active control.<br>No pump |
| Inexpensive | Pump and controls add cost. | Small fluid volume. No pump or controls. |
| Reliable, Low Maintenance | Mechanical systems prone to failure.<br>DI systems require maintenance.<br>Hydrocarbon fluids foul catalysts. | No moving parts.<br>No fluid maintenance.<br>Fluids non fouling.<br>Low pressure system. |
| Efficient | Pump power must be supplied.<br>Warm-up requires more energy/time. | Needs no power for operation.<br>Rapid warm-up w/o overshoot. |
| Lightweight, Compact | Pump and larger fluid charge add weight. | Fluid charge is very small<br>Bipolar plates thinner |
| Safe | Hydrocarbon type fluids combustible.<br>Aqueous fluids conduct electricity. | Working fluids non-flammable; some used for fire extinguishing |

Most hydrocarbon and aqueous fluids will foul the catalyst if they contact it. Deionized aqueous coolant systems require maintenance and monitoring to ensure the electrical resistivity of the coolant and prevent clogging of the coolant channels. Dielectric hydrocarbon coolants have low specific heat and thermal conductivity compared with aqueous coolants and low viscosity homologs exhibit increased volatility/flammability. Nonflammable halogenated fluids that might be used are expensive at the volumes required to fill a single phase system.

PASSIVE 2-PHASE ADVANTAGES:

A passive 2-phase system (Figure 7) using a nonflammable halogenated fluid with a boiling point near the operating temperature has distinct advantages (Table 2). First, it has no pump and fewer active controls. Electric pre heaters in the liquid inlet manifold boil the coolant causing its vapor to rise into the stack quickly warming it uniformly to operating temperature prior to operation. The stack will warm only to the fluid's saturation temperature without overshoot and its temperature uniformity is easily verified by monitoring one temperature. Because a low specific heat fluid resides only in the stack and because only the stack must be preheated, the amount of energy required to preheat is greatly reduced.

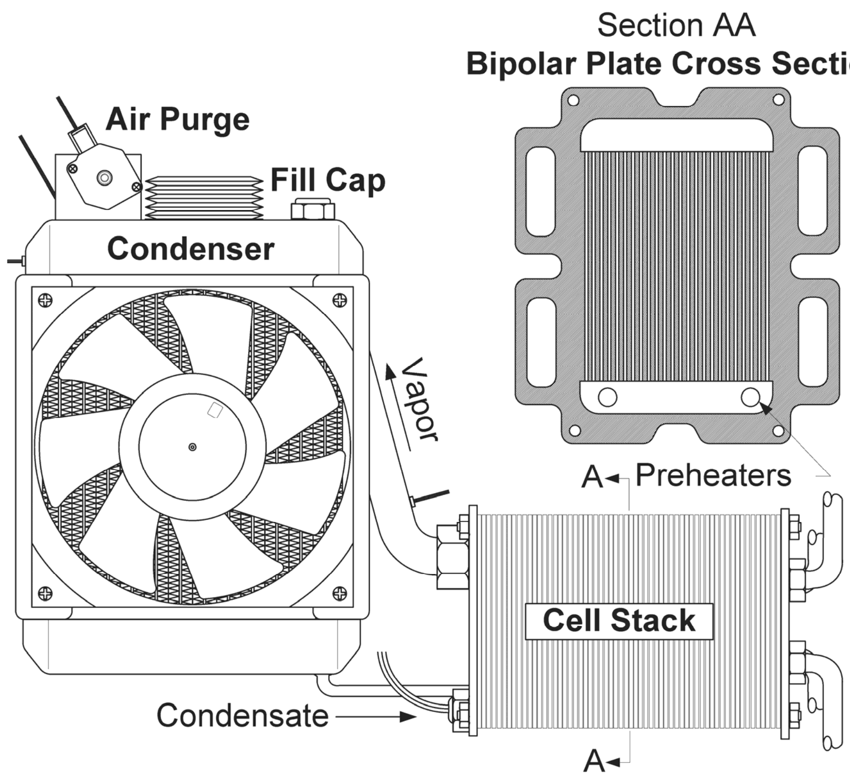


**Figure 7: Possible passive 2-phase PEM fuel cell system configuration.**

During operation, the temperatures across and between bipolar plates are very uniform. This temperature is dictated by thermodynamics and the system pressure and does not require active controls. A 2-phase system inherently produces an isothermal heat sink or source which operates at a temperature slightly below the membrane temperature. Such a sink has great potential for controlling the temperature and humidity of input gas streams.

Because the fluid resides only within the bipolar plates in passages that are considerably thinner (normal to the plane of the bipolar plate) and more narrow than those in single phase bipolar plates; the stack is smaller; the bipolar plate electrical resistance decreases; and the small resultant fluid fill makes more expensive, non fouling halogenated dielectric fluids quite feasible. Simple pour in filling of these fluids simplifies charging and systems can be automatically degassed as needed.

## EXPERIMENTS:

Figure 8 shows an experimental apparatus used to simulate a single PEMFC bipolar plate [4]. Parallel channels with thickness, t, of 100, 200 or 500 microns were formed with polymeric ribs between two heated aluminum plates. The heated/ribbed regions were W=100mm wide by H=75, 150 and 230mm high. The channels and the ribs separating them were s=w=1.6mm wide. The fluid used was perfluoropentane, an inert liquid that boils at atmospheric pressure at 29°C. The rising vapor was condensed by a water-cooled condenser; fell and returned at the bottom of the heated region. Temperature uniformity was calculated as the standard deviation of the 3 temperature measurements from thermocouples within the aluminum plates at the bottom, top and midpoint of the plate centerline.

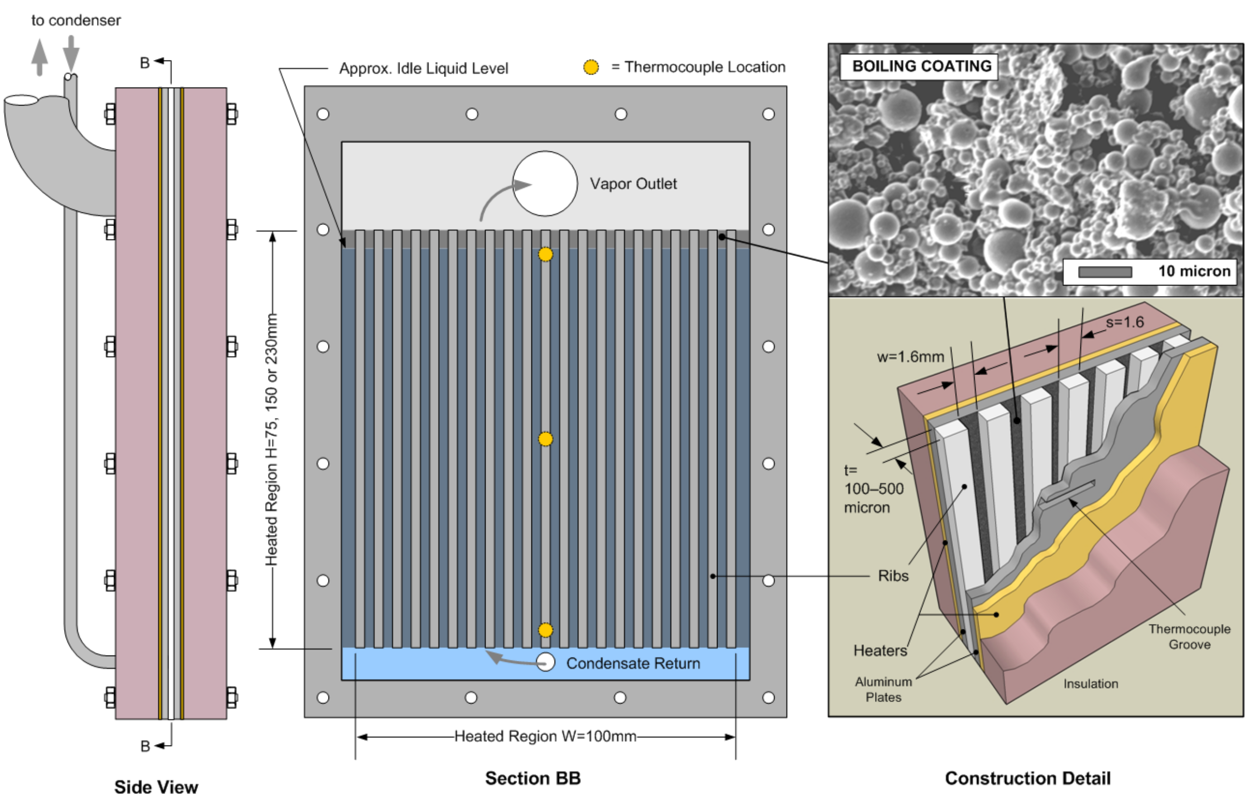


**Figure 8: Cross section of experimental apparatus for studying bipolar plate channel configurations.**

Various channel surface modifications were studied but one inexpensive porous coating performed best enabling the target temperature uniformity of 1°C at a heat flux of 0.5 $W/cm^2$ (per side) for the H=150mm case. For this height, the optimal channel thickness was near 200 micron and the bipolar plate required only 2cc of fluid to be filled while idle.

## LITHIUM ION (LI-ION) BATTERIES

Maintaining temperature in arrays of prismatic Li-ion cells is similar in many ways to maintaining fuel cell temperatures. Like fuel cells, Li-ion battery packs generate relatively low heat fluxes and must be warmed before operation. Typically this is accomplished with electric resistance heaters that transfer heat to conductive metal plates between cells. The speed of this technique is limited not only by the thermal diffusivity of the cells themselves but by thermal interfaces from cell to plate and plate to heater. This technique produces temperature gradients across and between the cells.

By filling the interstitial spaces between prismatic cells with a volatile dielectric coolant, both heating and cooling can be accomplished (Figure 9). Gaps between cells can be 250µm or smaller, maximizing cell density and decreasing the fluid requirement. During warm up, the fluid is boiled on heaters beneath the cells. The vapors rise heating the cells to operating temperature. Condensation heating ensures efficient and uniform temperature heat transfer without overshoot. When cells are operating, the fluid boils on the cell surfaces, again keeping surface temperatures uniform and transferring heat very efficiently to the housing or heat sink.

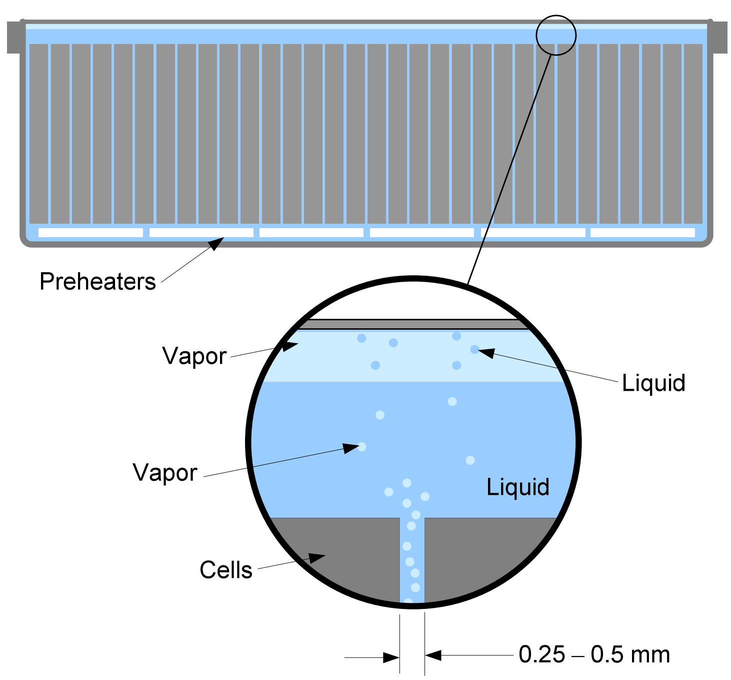


**Figure 9: Possible passive 2-phase scheme for preheating and cooling Li-ion prismatic cell stack.**

## WORKING FLUIDS

Fluids for the aforementioned applications should have suitable volatility and safety and dielectric properties. Immersion cooling applications historically used ozone-depleting chlorofluorocarbons (CFCs) and adapted to perfluorocarbons (PFCs) following the CFC phaseout. PFCs are known to have high global warming potentials (GWPs), a fact that has spawned the creation of new chemistries like hydrofluoroethers (HFEs) [5] and fluoroketones (FKs) [6]. The latter have among the lowest GWPs of man made compounds and are already widely used to replace Halon in fire protection applications. These fluids are available with a variety of boiling points suitable for different applications. Some are being field tested in immersion cooled GTO thyristor and computer systems today.

## CONCLUSIONS

Passive 2-phase immersion cooling with dielectric fluids is a proven technology that can be used to cool high heat flux IGBT/MOSFET devices with power densities up to 4kW/liter, requiring as little as 50cc fluid per kW. Open bath immersion cooling for datacom equipment is much simpler and less expensive than traditional liquid cooling techniques. It enables unprecedented power densities while reducing energy consumption and greenhouse gas emissions. When used to cool fuel cells or batteries, passive 2-phase techniques facilitate pre heating and in general offer many advantages when compared with pumped liquid technologies.

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**NOMENCLATURE**

| | |
|---|---|
| A | Area [$cm^2$] |
| H | heated region height [mm] |
| *Q* | power or heat [W] |
| *Q”* | heat flux [$W/cm^2$] |
| *R* | ideal gas constant = 8.314 J/mol-K or thermal resistance [°C/W], [°C-$cm^3$/W] |
| s | channel spacing [mm] |
| t | channel thickness [mm] |
| *T* | temperature [°C] or [K] |
| *V* | volume [$m^3$] |
| w | channel width [mm] |
| W | heated region width [cm] |

Subscripts

| | |
|---|---|
| *b* | boiling or boiling point |
| *c* | chip |
| *f* | fluid |
| *i* | initial or inlet |
| *j* | junction |
| *o* | final or outlet |
| s | sink |
| *w* | water |