POLITECNICO DI TORINO

Master's Degree in MECHANICAL ENGINEERING

Master's Degree Thesis

Critical overview and feasibility study of two-phase immersion cooling systems for power electronics

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Dedication

Dedico questa tesi di laurea magistrale, che corrisponde alla fine di un percorso altamente stimolante e formativo, ai miei genitori che hanno sempre creduto in me, supportandomi ed essendo stati sempre presenti.

A mio padre che mi ha insegnato cosa voglia dire il lavoro, sin da piccolo, e grazie al quale ho iniziato ad approcciarmi al mondo della meccanica, capendo che ingegneria meccanica sarebbe stata la mia direzione sia universitaria ma anche di una futura carriera professionale; a mia mamma che mi ha sempre supportato con comprensione e La ringrazio per avermi insegnato a non arrendermi mai nella vita, ma a riprovarci sempre e a puntare al meglio di volta in volta.

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Raffaele

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Abstract

The ever more decreasing size of power electronics is going to obtain devices always more compact and with a direct correlated consequence of higher heat fluxes obtained.

After a first introduction to power electronics devices (classification, applications, market size,...) are analyzed the related heat losses causes and the failure types with the aim to start the study of thermal aspects.

Indeed to stabilize the temperature below a maximum threshold of safety up to now were used different air and liquid cooling systems (indirect single and two-phase) that are in this work reviewed from the historical ones applied to electronics devices up to those used in our decade.

A detailed classification of the cooling techniques for power electronics is showed with a particular attention to heat fluxes (W/cm^2) that each one is able to cool and, at the end of chapter 3, are graphically compared in an histogram.

All this previous work is done to compare and to have a focused vision on the two-phase immersion cooling in comparison to the traditional ones solutions.

Indeed from now on, starting from a theoretical study of boiling phenomena (why a liquid boil, curve of "pool boiling", variation of CHF at different pressures, Rohsenow correlation, CHF varying the surface inclination,...) and condensation process, are reviewed the historical applications of two-phase cooling for electronics till nowadays; are in detail reported and compared both Papers/Scientific articles and Patents regarding prototypes of entire systems to cool power electronics immersed in two-phase fluids (semi-open bath or sealed and pressurized tanks) with emphasis on the parameters and configurations able to increase heat flux or to simply improve some characteristic of reliability, material compatibility, compactness, etc...

Is done a critical overview on the kinds of fluids mostly used to cool power electronic, from the the traditional ones to the ones subject of researches in our years. The comparison is done mainly between the non-dielectric traditional fluids (Water, Ethylene glycol,...) and the new Low-Global-Warming dielectric fluids, so the ones with low environmental impact and a non-electrically conductive nature used with success in direct immersion cooling of power electronics.

To conclude this thesis work is also done a review of surface types for pool boiling, tabulating the maximum CHF reached for traditional and most innovative couplings enhanced surfaces-fluids.

So, in general, the main aim of this thesis is, at first, to have a complete vision of why and where the two-phase immersion cooling of power electronics is convenient to be used and a following clear classification and detailed vision of the different parts/components for the entire cooling system (plus related possible thermal im-

provements) with the goal to have a full knowledge updated to the latest technologies useful like a starting point in hypothetical future researches.

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Chapter 1

Introduction to Power Electronics

The society in the last decades has been moving more and more toward an electricity-based word with a consequent increase in global energy needs [71].Recent studies declare that the growing in population number, enhancements in global industrialization and quality life will increase the energy consumption by 28% between 2015 and 2040 [143].

However the most influential contributions that can reduce carbon emissions (the first cause of global warming [151]) are: the improve of energy efficiencies in the production and in the demand side [44].Reliable sources (wind, solar, sea-waves,...) are already available solutions for the green energy production [108] and even regarding the future trend of utilization of clean energy a series of devices are been intensively improved in the last decade (electric vehicles, electric motor drivers, energy storage,...).So, power electronics have a fundamental role to have a more efficient energy generation, transmission and distribution [72] at every level of electrical power systems.

The U.S. Advanced Research Projects Agency-Energy (ARPA-E) predicts up to 80% of electrical energy in the U.S. is estimated to pass through power electronics by the year 2030, so an increase of more than 160% from 2005 [25].For this reason the use of power electronics for the conversion and transmission of electricity is becoming a really important task that needs to be improved constantly following the requirements of even compact, reliable and more efficient devices. Nowadays, some applications of power electronics to better understand the really big fields of applications are: renewable energy systems [61], lighting [142], electric mobility [193], and others sustainable applications...

1.1 Power electronic converters classifications

Power electronic converters, designed from power and control circuits, where the first generates the voltage and current harmonics and the second minimize or amplify these, are characterized by power electronic switches components such as diodes, thyristors and transistors like MOSFETs or IGBTS and others components like inductors and capacitors.

In general the power electronic converters are classified into six categories, namely, AC–DC, DC–AC, DC–DC, AC–AC, Diode Rectifier and Static Switches [77] [198].

In general, the choice of which depend on the applications and wanting to do some examples to start understanding better these devices: AC-DC is used in household appliances or before the battery box in electric vehicle to convert grid AC voltage to DC voltage , DC-AC in the connections between renewable sources with lines and in motor drives, DC-DC in energy storage devices to get regulated DC voltage for different loads or to increase the energy delivered by solar photo-voltaic/wind turbines and AC-AC converters useful where is needed to modify the voltage or frequency of AC sources.Anyway in the following sub-chapters, are explained the working details and others applications for these really important devices.

A graphic summary comparisons of electronic converters with some application at different ranges of Power Capacity and Operation Frequency is showed in Fig 1.1.

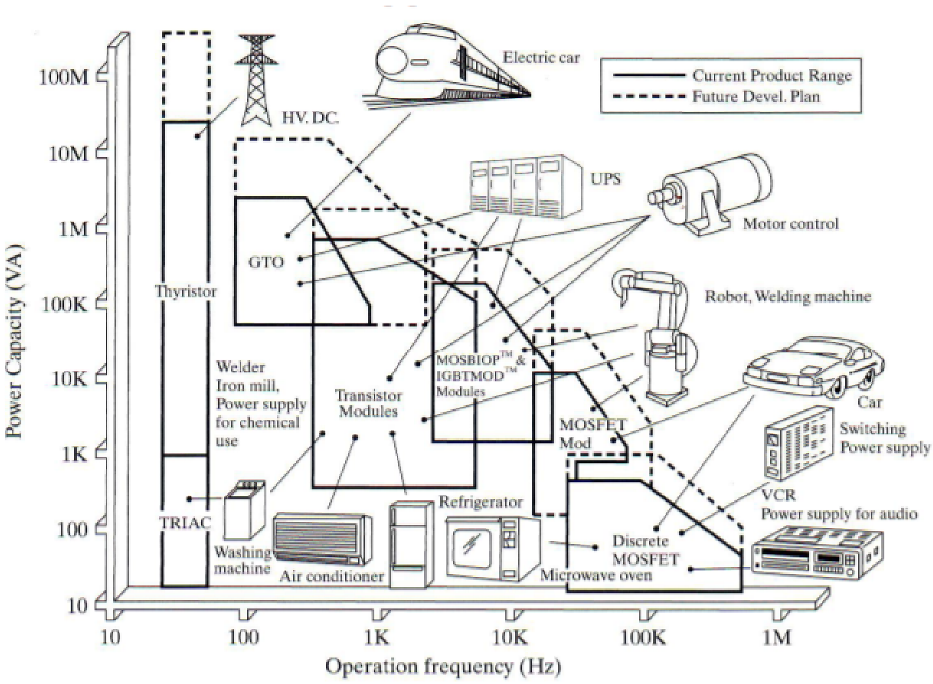


Figure 1.1: Working range of Power Electronic Devices [154]

1.1.1 AC–DC converters

AC–DC converters of electric power, or "controlled rectifiers" like they are usually called, are able varying the firing angle (so the angle at which is applied the pulse to turn on and make the silicon rectifiers to conduct) of thyristors to control the DC output voltage from an AC input voltage (single or three phase), see Fig 1.3a.

They can work in low-, medium- or high-power ranges and are used in adjustable-speed drives (ASDs) for controlling the induction motor, switch-mode power supplies (SMPSs), uninterrupted power supplies (UPSs), and utility interface like solar PV, battery energy storage systems (BESSs), in process technology like electroplating, welding units, etc.,battery charging for electric vehicles, and a lot of commercial domestic devices (television, computers, battery chargers, etc...) [170].

An AC–DC power converter can be studied as a three-port network where the instantaneous power at AC port is composed by an averaged DC power and an AC ripple power, see 1.2.

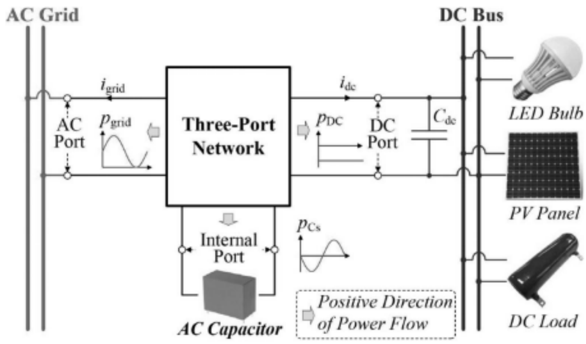


Figure 1.2: Three-port network AC-DC [187]

The averaged DC power is balanced by the DC power from the DC port, while the AC ripple power is buffered by an internal power storage device connected to the internal port of the power converter.An AC capacitor Cs is used as the internal storage of the power converter [187].

1.1.2 DC–AC converters

DC–AC converters even called "inverters" from a DC input current deliver an AC output with a specified magnitude, phase and frequency, see Fig 1.3b; however a typical inverter uses four switches or thyristors where the alternating switching of these provides an alternating current through the load.

They can work in medium- and high-power applications (>5 kW), such as speed control in motors, high-voltage DC transmission (HVDC), on-grid RE sources, and numerous other industrial operations.

In general there are two categories of inverters: the voltage source inverters (VSIs) [145] and current source inverters (CSIs), in base of the types of load and source [191].

1.1.3 DC–DC converters

DC–DC converters, even called "DC Chopper", from a fixed DC voltage make a DC voltage higher or lower and vice versa, changing even the polarity sometimes, see Fig 1.3c. In fact, for example, they can regulate the motor speed thanks to the control of the output voltage and load deviation. These converters have high efficiency and fast dynamic response.

There are two categories of DC–DC converters: non-isolated DC–DC converters and isolated DC–DC converters [172].The firsts have a magnetic storage feature that makes them heavy with low efficiency and low power density, the seconds works at high frequency and can reduce noise production and electromagnetic interference (EMI) [58].

1.1.4 AC–AC converters

AC–AC converters, see Fig 1.3d,are even called "Voltage regulator/controller" and from an AC voltage load fixed are able to obtain an AC output voltage at different amplitudes, phases and frequencies thanks to the use of TRIAC (vary firing angle).

Many applications can be covered by these type of converter like for example uninterrupted power supplies, high power AC to AC transmission, adjustable speed drives, renewable energy conversion systems and aircraft converter systems.

1.1.5 Diode Rectifier

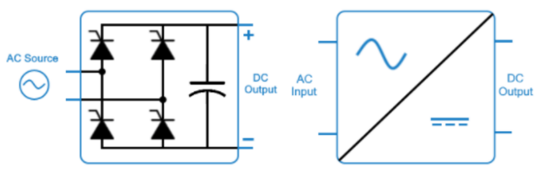
A Diode Rectifier from an AC voltage (single or three phase) is able to obtain a fixed and smoother DC voltage. See Fig 1.3e.

1.1.6 Static Switches

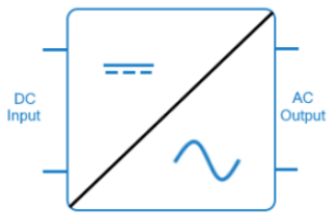
Static Switches are power devices that can operate as static switches or contactors and they can be AC static switches or DC static switches.

They connect the load with the source and provide an abrupt switching between the sources.

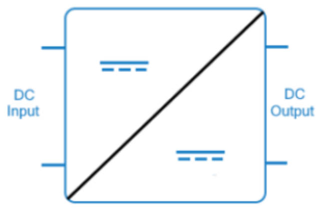
A static switches inside an UPS (Uninterruptible Power Supply) can be see in Fig 1.3f.



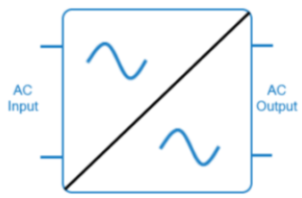
(a) AC-DC



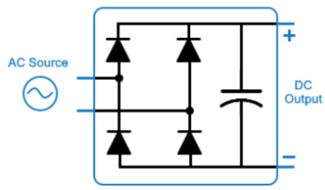
(b) DC-AC



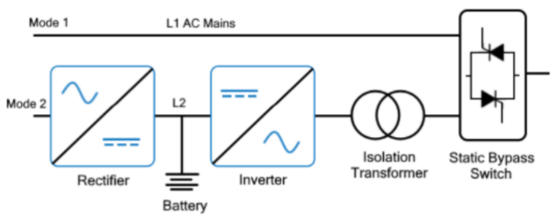
(c) DC-DC



(d) AC-AC



(e) Diode rectifier



(f) Static switches

Figure 1.3: Power electronic converters [1]

1.2 IGBTs

To satisfy the requirements of low cost, high reliability, compact design and high efficiency, the IGBTs (Insulated-gate bipolar transistors) are today the dominant power semiconductor devices principally used as electronic switch.

IGBTs power modules work in broad spectrum of current and voltage level and so, are used in electric and hybrid vehicles, wind turbines, photo-voltaic applications, UPS, home applications, etc... [135] as can be seen in Fig 1.4.

Silicon and SiC IGBTs are generally used nowadays, in particular the SiC (commercially availables since 2001) are the more advanced one solutions for higher frequencies and voltage of application (from 600 V to tens of kilovolts). The low voltage applications (<600 V) of IGBTs are project to be characterized within 2023 by the GaN devices that are of superior performance in all the fields, compared to Si ones, except the one of thermal conductivity because it is created by different substrates like silicon, silicon carbide, sapphire that obviously being different materials, have different coefficient of thermal expansion and so collateral problem of stress, high defect density,...The GaN semiconductor, usually is held by a lateral architecture that makes the thermal problems higher, so to conclude, up to now SiC devices have a technological maturity higher and is going to be adopted and implemented even more.

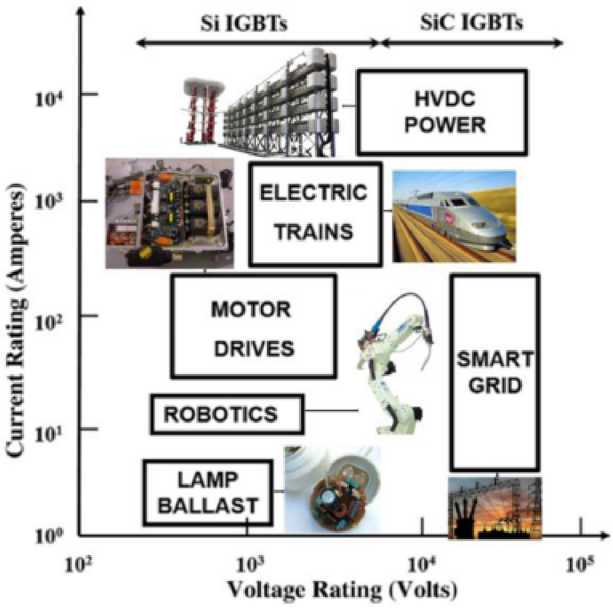


Figure 1.4: IGBTs application spectrum [11]

Invented in 1982 [12] with the first properly working and commercial devices introduced in 1988 [19] reached a market size of 5.40 billion USD in 2020 with a growth of 8.0% just in that year.The expected growth is from 5.85 billion USD in 2021 to 11.24 billion USD in 2028 with an annual growth rate of 9.8% in this range period according to the analysis of Fortune Business Insights [2].

Today IGBTs have the same switching velocity of the best MOSFET (the first was realized in 1959), with a resistance to overload very high in comparison, justifying why is expected that it will be the dominant one device in even more fields of application.

Anyway, the Asia Pacific region is expected to rich the highest market share of IGBTs; we can even observe this trend in Fig 1.5.

A trend of the last years market size of IGBTs just in solar energy applications is shown in Fig 1.6 and regarding the global market share for applications in 2020 see Fig 1.7.

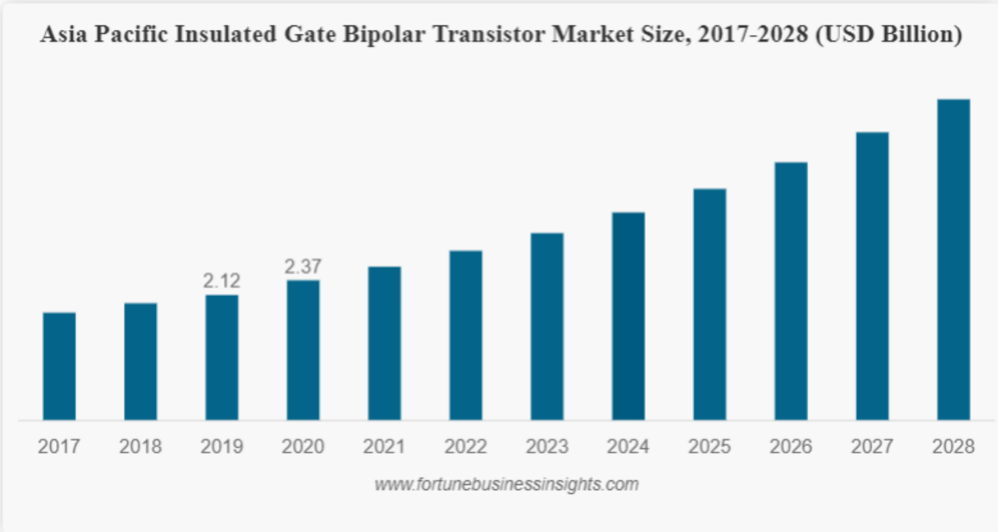


Figure 1.5: Trend of IGBTs Market in Asia Pacific [2]

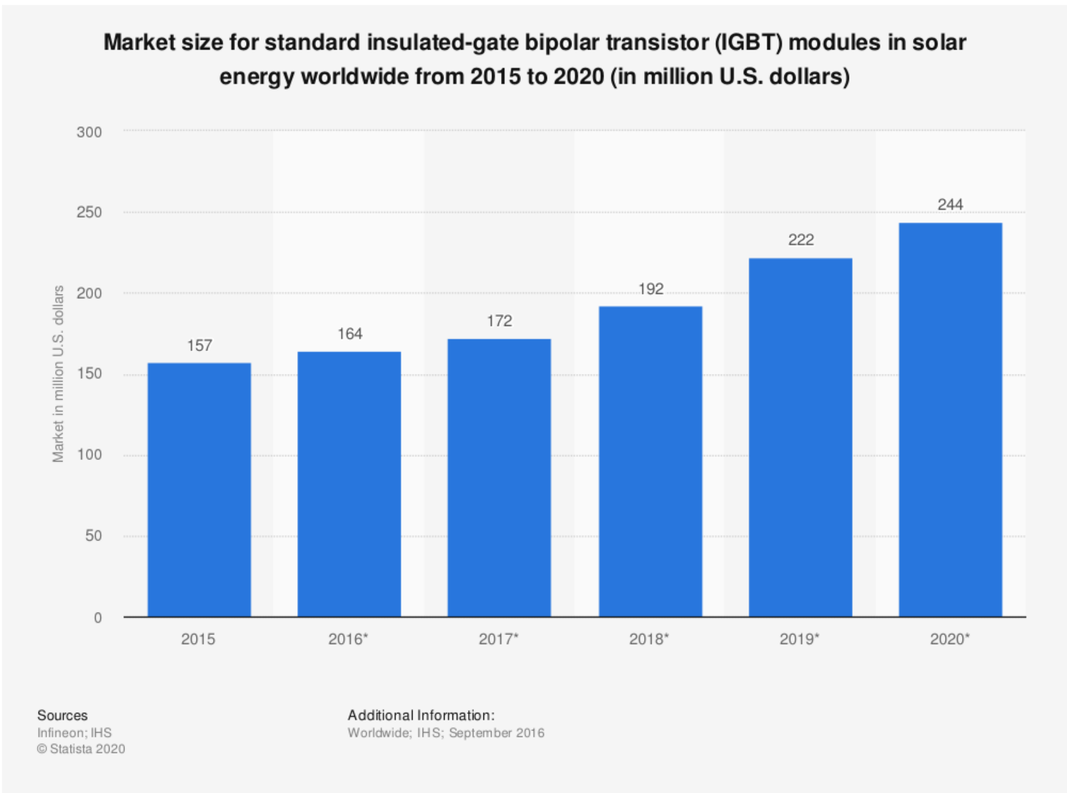


Figure 1.6: Market size for standard insulated-gate bipolar transistor (IGBT) modules in solar energy worldwide from 2015 to 2020 [3]

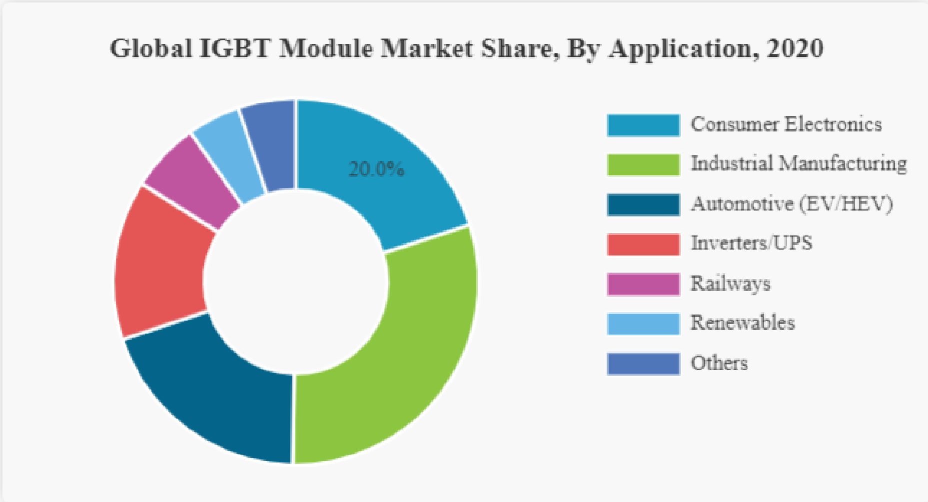


Figure 1.7: IGBTs Market Share for application in 2020 [2]

1.2.1 IGBTs in Electrified Vehicles

The U.S. Department of Energy (DOE) updates the goals to get for 2025 for boost the integration of the electrified vehicles (EVs) in the market, with specific target for power electronics like a reduction of 18% for theirs costs and around 87% of volume reduction, so in practice higher power density goals in respect to 2020 technologies [184].

Today the EVs work principally with AC permanent magnet (PM) or AC induction machine (IM) as electric machines (EMs) [155], and so a traction inverter (DC-AC) is needed for deliver a variable frequency alternating current from a direct current of the battery pack; another need is even a converter used as a rectifier (AC-DC) when the machine works as a generator and so must be delivered direct current to the battery as is schematized in Fig 1.8.

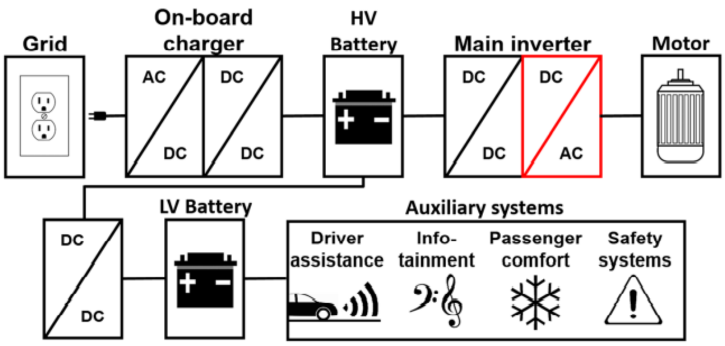


Figure 1.8: General vision of power converters in electric vehicles [25]

The inverters mostly used nowadays due high efficiency and low cost are the three phase voltage source inverters (VSI) based on IGBTs where apart from the DC-AC conversion can be usually available a previous DC-DC converter to step up the battery voltage and supply the DC-AC inverter with controlled DC voltage.

IGBTs provided with a blocking voltage of 650-1200V can quietly handle the actual battery pack voltages that ranges of 200-400V for EVs.

Up to now the range of traction inverters is between 30–60 kW in hybrid electric vehicles with a waste heat of around 4,5KW (for the inverter of 60KW) in high efficiency devices, but it will be between 100–500 kW in the future with a significant related heat wast.

Talking about the heat flux coming from IGBTs for EVs that needs so to be dissipated thought an optimal solution, we are in a range of 100–150 W/cm^2 (for Si inverter systems) that are going to increase up to 500 W/cm^2 (for future SiC inverter systems) due to downsizing of the chip itself and the increasing in current density [9] [195].

1.2.2 IGBTs in Solar Panels

The Compound Annual Growth Rate (CAGR) of solar panels installations in Europe was of 34% between 2010 and 2020 [59] and is predict to double by 2025.

Even for solar inverters, IGBTs are the most efficient and more adequate solution today.

In this specific application for solar devices usually are used to obtain an AC single-phase or triple-phase sinusoidal voltage output load to be delivered to the transfer lines (frequency and voltage depend on the market application) from a DC voltage generated by the solar panel [38] [178].

Usually, before the DC-AC inverter there is a DC-DC booster converter to obtain a specified DC voltage and an AC-AC switchboard to reduce the high frequency harmonics for obtaining a pure AC power ready for load consumption [46], see Fig 1.9.

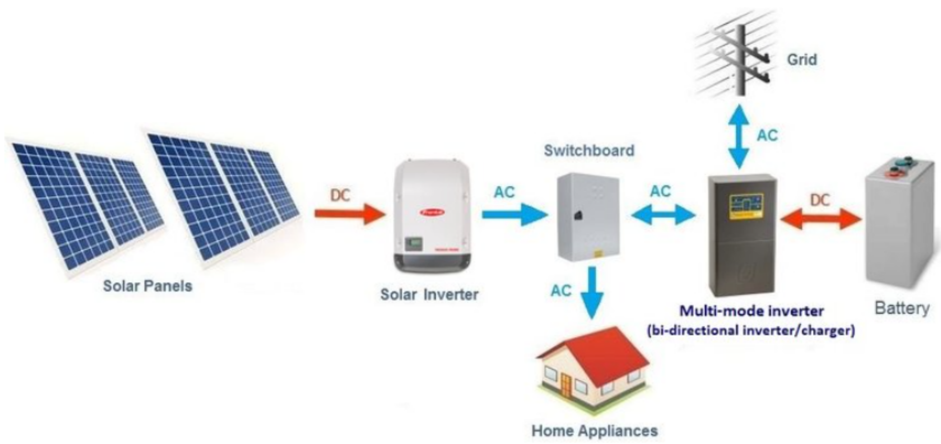


Figure 1.9: General vision of power converters in solar panels [176]

Anyway, the inverters of solar panels can be divided in two categories: the string inverters and the central inverters. As reported in February 2022 by the Fraunhofer Institute for Solar Energy Systems [59], 1500 V is the maximum DC voltage and a power for single module of 600W maximum, string inverters (the ones used in residential and small applications) cover the 64% of the market share with a peak power reached up to 150KWp; instead the central inverters (applied to large and utility-scale systems) cover the 34% of the market share with a peak power above 80KWp.

Just a little production (around 5% of the inverter market) are DC/DC converters.

Chapter 2

Thermal aspects of power electronics

While for microprocessor chips the heat flux needed to be removed is more than 100 W/cm^2 with the goal of maintaining the device below 85 °C, for power semiconductors heat fluxes in hot spots could be even greater than 1 KW/cm^2 with a maximum temperature allowed of 175°C (SiC IGBTS for example)[133].

Considering that the main parameters that influences these devices are temperature, efficiency, dimension, reliability and cost, is implicit that increasing its density, will increase consequently the total heat dissipated in the next future, so are needed even more sophisticated, compact and efficient cooling systems [153], where even the intensified heat load aspects and related thermal problems needs to be considered and adequate.

2.1 Heat losses causes

IGBTs are affected by two kinds of thermal losses in semiconductor chips: conduction losses and switching losses.The first type depends on the conducted current and happens during the on-state working component; the second depends on the current, duty cycle, switching voltage and switching frequency and happens during on/off states because the current and the voltage are present for a short time across the semiconductors and this cause an high power dissipation for a very short time [107].

IGBT's chips can generate heat losses up to several hundred watts in nominal operations and when they are linked in parallel in one package, can dissipate at maximum around 10KW of power.

2.1.1 Failure types

Today the IGBTs are packaged in the wire-bonding module [128] [99] and the most common failures are solders and wires break, delamination of bonded surfaces, heel cracks, ceramic substrate fracture, etc...

The main causes of these failures come by thermal heat that lead high thermal-mechanical stresses and, in particular going on with the working cycles, a little changing in the component due to heat can be exponential more dangerous proceeding in time [148] [153].

Anyway, between the chip and the heat-sink a junction temperature of 125°C is the maximum one to stay in safe condition for Silicon based IGBTs and 175 °C for SiC IGBTs [70], but usually this temperature is specified by the manufacturer and cannot be exceeded.

For the future, new packaging technologies may solve or decrease these structural and thermal problems.

Beyond maximum temperature we need to keep attention even to temperature oscillations of the base plate ('Thermal cycling') and temperature oscillation of the silicon chip ('Power Cycling').

1 The thermal cycling acts in soldering joint between the ceramic insulator and the base plate because the expansion coefficients of the copper and the solder material are different by a factor of more than 2 in comparison to the ceramic material, so this cause stress to soldering joint that consequently induced an increase in thermal resistance, larger temperature oscillations and so a premature fail.

2 The power cycling regards the fact that the expansion coefficients of bond wires (Al usual) and the chip (Silicon) differ by a factor of 6, so if temperature oscillates, the bond wires start to lift off with a consequence of an increase in voltage drop that is always more, cycle after cycle, and so even higher losses going forward in time [107].

So in conclusion, for the system reliability, maintaining the IGBT surface temperature and all its component at a temperature that is enough constant is a really important goal [21].

Chapter 3

Analysis of the cooling solutions for power electronics

As explained in the previous chapter, power electronic suffers of thermal problems effects and these can cause malfunction and eventually failure of the component and as a consequence its reliability is dependent on it (higher temperature of semiconductors means the worse reliability and durability) [111].

So, for bypass these problems, adequate cooling solutions and thermal management of power electronic systems are needed.

This chapter will show, after an initial theory part to understood the ways of heat transfer and the thermal factor to keep attention on for having a comparison view of the thermal aspects of various systems, a view of historical cooling solutions for power electronics and an overview of the cooling methods with the range of the respective heat fluxes to help the choose of the adequate cooling solution for the specific flux of a specific power electronic device.

At the and of the chapter even a comparison rating of the costs of these systems.

3.1 Basis of heat transfer and thermal aspects to consider in cooling systems

Usually the manufacturer of power electronic devices publishes even the thermal aspects, for having from the customer side the evaluation and comparison using some thermal factors so is important to spend few pages on the basis of the thermodynamic.

As reported in many books, like "Heat transfer" of Bonacina, Cavallini, Mattarolo [24] and "Termodinamica" of Calì, Gregorio [29], heat is the form of energy that manifest itself in the passage in one body when there is a difference of temperature.

First principle of thermodynamic is the equivalence of different forms of energies, instead the second determine the way of natural transfer of heat (from one system warmer to one colder).

Exists three ways of heat transfer which can happen simultaneously or with the predominance of one to others. They are conduction, convection and irradiation.

- Conduction: it is heat transfer inside solid, liquid or gaseous bodies due to the kinetic energy release from molecules in hotter zone to the closest in colder spaces (plus the electronic component part due electrons in metals).

The quantity of heat that pass a section A in terms of flux q [W] can be written as in Eq.3.1:

$$q = \frac{\lambda A}{l}(t_1 - t_2) \tag{3.1}$$

Where, A and l are respectively the area and the length of material "passed trough" the heat, (t_1 - t_2) the difference of temperature in the two sides of the body and λ the thermal conductivity.

This last one parameter, is the one that represents the quantity of heat transmitted for unity of time, unity of transversal surface, unity of length of the material layer and for unitary difference of temperature (λ [W/m°C]). Its value is characteristic of each homogeneous material solid/liquid/gas (highest value for silver and copper) and depends on the temperature (in general for pure metals it decreases a bit increasing the temperature; for liquids depends on the types, for example water increases its thermal conductivity increasing the temperature; for gasses increase increasing the temperature) and on the pressure (increasing the pressure will increase the thermal conductivity in gasses and liquids in particular).Of interest in some engineering classification can be even the ratio λ/l that is the thermal specific resistance.

- Convection: it is a heat transport between one surface and the fluid that touches it.Is necessary for having convection that the fluid moves relatively to surface, if this not happen there is just conduction between the systems in contact.This time the equation is 3.2:

$$q = \alpha_c A(t_1 - t_2) \tag{3.2}$$

Where A is the area of touched section, (t_1 - t_2) the temperature difference between the surface and the nearest fluid and α_c [W/m^2 °C] the coefficient of thermal convection.

α_c depends not only from the fluid properties (conductivity, specific heat), but principally from outflow conditions (natural convection, forced convection, boiling, condensation) and the related velocity with direction.

To have just a relationship in order of magnitude regarding the heat transfer coefficients of the fluids, as we can see the Fig 3.1, can be notice that water forced convection has values higher than two of magnitude in comparison to the air natural convection, but is just with water pool boiling (and after we will mention even the forced water boiling) that values of heat transfer coefficient up to four order of magnitude in comparison to the basic one solutions can be reached.

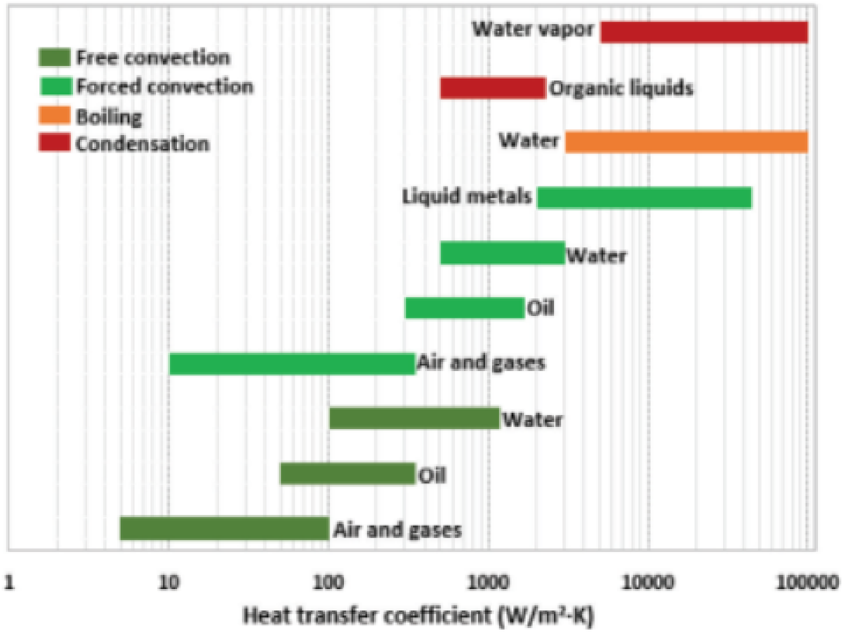


Figure 3.1: Heat transfer coefficient comparison chart [140]

- Irradiation: it happens with the propagation of electromagnet waves (like light) and is present in the vacuum or in transparent substances.

  Usually the irradiation factor can be considered in parallel to the convection one in the superficial heat transfer coefficient α, especially in presence of natural convection with gas at low temperatures.

3.2 Historical evolution of cooling solutions for electronics

The first relevant paper regarding the cooing solution of power electronics goes back to 1942 and was for vacuum tubes (the precursors of transistors, used as signal amplifier or current rectifier in radios, televisions, firsts digital computers, etc...), (water and forced-air cooling) [138]. Here Prof. Mouromtseff started saying that for the design of electronic tubes there are more mechanical, metallurgical, and heat engineering problems than those of pure electronic character, confirming so the still actual challenges of thermal aspects.

Before this, are not avails many articles regarding practical cooling solution for electronics, but just principally mathematical and experimental studies regarding theoretical thermal aspects.

We can mention Cockcroft that in 1925 studied the temperature distribution in a transformer or other laminated core of rectangular cross section [41], Mouromtseff and Kozanowski that in 1935 studied four types of 11,3 KW water-cooled vacuum tubes, see Fig 3.2 [139], in 1942 Elenbaas analyzes the heat dissipation of parallel plates by free convection for electrical systems [52] and this study was the precursor of the future researches of finned arrays.

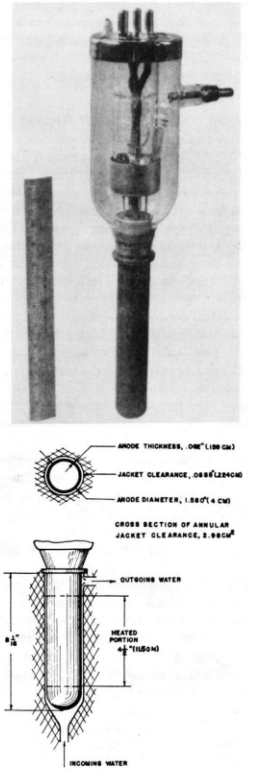


Figure 3.2: Water cooled vacuum tube [17]

In general after 1930 air-cooled vacuum tubes became of higher interest in comparison to the water-cooled one for eliminate the electrically insulated water circuit and the danger of freeze-up as seen in Fig 3.3 [17].

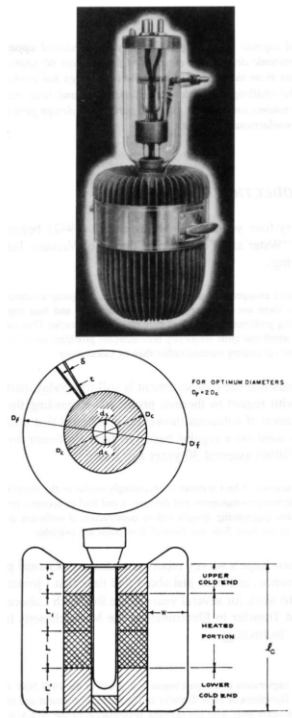


Figure 3.3: Air cooled vacuum tube [17]

After 1950s, so the period of the invention of the transistor, hundreds of researches and practical applications of heat transfer in electrical and electronic devices was conducted.

Moreover to guarantee a reliable and efficient package, the air or water cold plate represented a well known system to design properly heat exchanges for electronics. In 1950's even solutions and nucleation studies with two-phase dielectric fluids starts to be considered for having a compactness and higher performance of the high density cooling systems [92][159], see Fig 3.4.

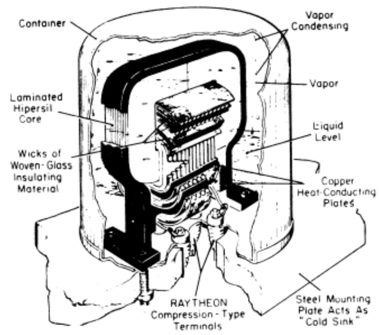


Figure 3.4: Cooling system for transformers using two-phase fluorocarbon liquid [92]

The 1960's were signed by an increase of the number of electronic components and the born of high-field electromagnets so the cooling techniques evolved in a more sophisticated and organized solutions, but was in 1970's with the introduction of printed circuits, for supercomputer applications, that the number of electronic components per chip increases of 3 order of magnitude from the early 60's.Thanks to improvements in cooling solutions 0,1-10W per chip can be reached and thanks to the compactness multi-chip modules becomes commonness [16].Even numerical analyses and finite elements techniques were introduced to design the systems and miniaturization made experimental data acquisition even more sophisticated like for example for the temperature distribution acquisition.

80's years was characterizes by researches on direct-immersion liquid (even if there was reluctance to place electronic components immersed in the liquids) and indirect cooling with micro-channels heat exchanges development [181].

From that period a continuous improvement in efficiency and reliability are continuing until nowadays with the evolution of the basis solutions analyzed previously for managing even higher density heat fluxes.

3.3 Overview on the classification of the cooling techniques for power electronics

A good thermal planning helps not only to have an efficient system, but even to save money in particular in big plants, so the main goals are higher power dissipation and smaller module size.

So a classification of the main cooling techniques is listed below with the aim of explain the main features and choose the optimal cooling solution for the proper thermal management of the system.

In literature a first block subdivision of the different solutions is the type of heat transfer method: Conduction, Natural convection, Forced convection.This first classification is effective to have a primary subdivision but we will go more deeply in a second sub-classification regarding the coolant agent used with always a particular attention on the dissipated heats transfer.

3.3.1 Solid-State Cooling Technologies

Before being exchanged with the fluid, the heat from the generation side passes trough the surfaces in contact with it, and this happen in all the types of devices. These surfaces are characterized by conduction diffusion heat transport an so a thermal conductivity of the solid conductors in a range of 0.5–1700 W/m·K in base of the material. An overview of the classical elements to the most innovative one are listed below.

- Heat Sinks, Thermal Interface Materials (TIM), and Conduction Plates: From the heat source part to the material parts around, heat is moved via convection and the following parts are used, for different applications in the system, but aimed at the same scope of dissipate and transfer heat in an optimal way.

  Regarding the heat sinks, so the cheaper passive conduction solutions that give the possibility to increase the contact area between the hot side and the cooling fluid, the most common strategies to increase its heat transfer are increasing the surface area or choosing one material with higher thermal conductivity (common ones are made of copper (386 W/m·K) or aluminum (200 W/m·K)) and with a proper shape in base of the type of fluid flow available. Anyway, can be dissipated in standard solutions some W/cm^2.

  TIMs, so the material used to fill the air gap and so increase the heat transfer between two different solid materials (heat sink with chip or package), are widely studied to get the best thermal characteristics [122]. Pastes made of polymeric liquid, aluminium, silicone or graphene as the last frontier [8] are the most used nowadays.

  When is needed an higher dissipation and high performance, advanced heat spreaders called conduction plates are used.The main goals of research in these components is to find the most conductive and light material like for example the pyrolytic graphite that at room temperature shows a thermal conductivity of 1,700 W/m·K and an heat flux up to 50 W/cm^2 [147].

- Magnetic Cooling: As can be observed in Fig 3.5 magnetic cooling utilizes the principle of demagnetisation of magneto-caloric materials (gadolinium, dysprosium,etc) to decrease the temperature and obtain really low temperatures. Commonly applications of these devices are used where there are volume and weight limitations and is needed no noise generation [27].

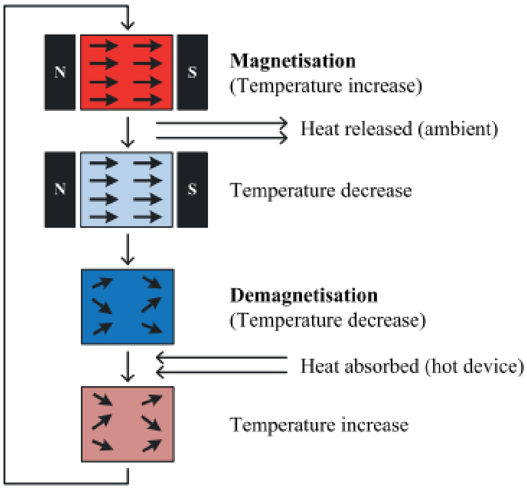


Figure 3.5: Magnetic cooling scheme [111]

- Thermoelectric Cooling: With principal advantages of accurate and rapid temperature control, less weight and volume, the working principle of thermoelectric cooling is the DC current flow that creates heat transfer and so cooling or heating in the two sides of the device, see Fig 3.6. The maximum cooling heat fluxes of few W/cm^2 (around 10 W/cm^2), high cost and low efficiency so its application is really limited to few specific applications.

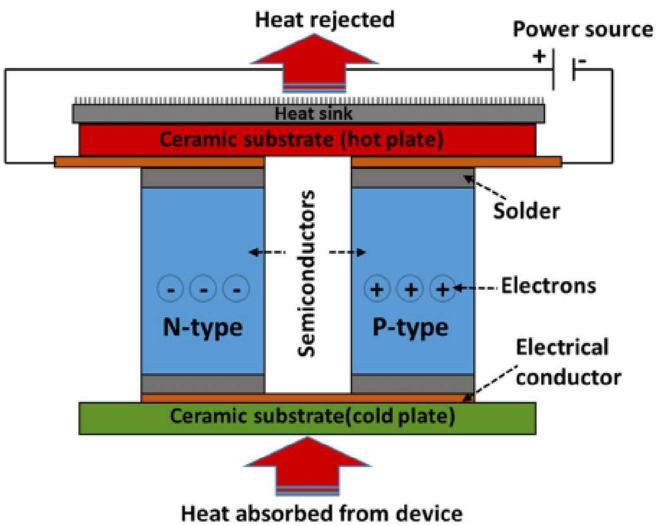


Figure 3.6: Thermoelectric cooling scheme [141]

3.3.2 Air Cooling Technologies

Air cooling is in comparison to others the simplest and reliable solution at low cost. Usually coupled with an high thermal conductive bulk material (aluminium, copper, etc...) and fin arrays, is to be considered that as well as the velocity of the fluid is a really important parameter even and the contact surface area is fundamental and important to be designed well for the device where it will be applied.

Following are classified the convective and forced alternatives.

- Air Cooling (Natural Air Convection): The natural air cooling is used just when few watts are needed to be dissipated (heat flux less than one W/cm^2) [18]. It is a really simple solution in fact just air convection is used and the moving reason of heat flux is the difference of temperature between the hot surface and the environment that produces a difference of density of the fluid (air). Usually are used extruded surfaces or fin arrays in aluminium or copper to increase the contact surface with air.

- Fans: Air cooling with the forced convection induced by fans has usually heat dissipated in of about 1 W/cm^2 for 60°C of temperature difference and heat transfer coefficient in the range 25–250 W/m^2·K, but advanced solution with particular channels can shows a maximum of about 50 W/cm^2. The limit of these systems is the low power density that can be reached [158] and a medium noise level.

- Piezoelectric Devices: To be adopted when heat power consumption is in the order of tens of W with an heat flux of a W/cm^2 maximum, substantially piezoelectric devices are generators of air flow, so convection effects. In practice a vibrating diaphragm creates an air flow impacting the hot surface.This system despite the low heat dissipated has good characteristic for the noise, reliability and performance [60].

- Synthetic Jet Impingement: With thermal parameters similar to piezoelectric devices, synthetic jet impingement are small devices that creates a turbulent air flow for dissipate heat better [129].

- Electrohydrodynamics (EHD): EHD, able to dissipate at maximum 40 W/cm^2, with piezoelectric devices are the ones with the lowest volume. Used principally in laptops and LEDs cooling applications [82][166], the working principle in general is a creation of neutral ions that accelerated by a voltage drop hit the hot side to cool, see Fig 3.7. The benefits are: no vibration, low power consumption and the possibility to be scaled to large applications.The principal bad effect is the degradation of the electrodes (anode and cathode).

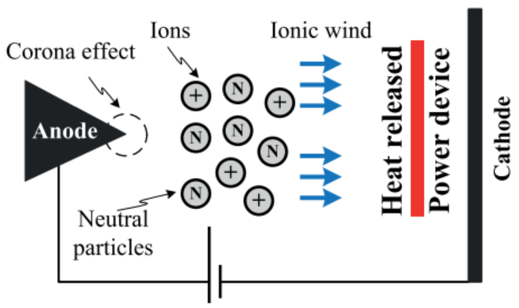


Figure 3.7: EHD cooling [111]

- Thermoacoustic: Just some W of heat dissipation, an heat flux less than one W/cm^2 and a really low efficiency this system utilizes the physical principle of thermoacustic effect so the sound is able to move heat, see Fig 3.8. A resonator produces sound waves and so a pressure change in practice [126].

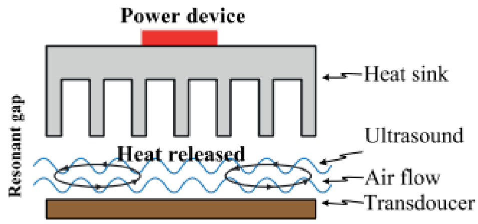


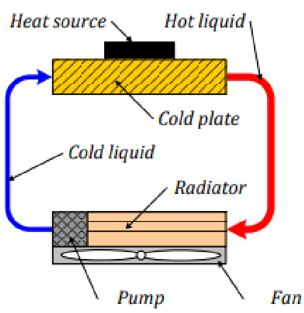
Figure 3.8: Thermoacoustic cooling [111]

3.3.3 Liquid Cooling Technologies

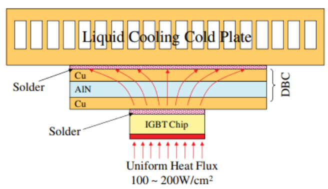
Even if starting talk of liquid cooling can unconsciously bring the attention to the collateral possible problems like corrosion, leakage, flammability, electrical conductivity and many others in comparison to the air one, it remains one of the best solution in electronic power cooling for the reason of higher thermal conductivity offered by liquid (water one for example is 0.58W/m·K in comparison than air one that is 0.024W/m·K at 20°, so quite 20 times more) and higher specific heat capacity (water one for example is 4184 J/kg·K in comparison than air one that is 993 J/kg·K at 20°, so 4.23 times more) the higher density of the system that can be reached [136](IGBT module for direct liquid cooling realizes a 30% reduction in thermal resistance and allow a 40% reduction in size compared to the conventional air configuration [76]).

The usual classification of liquid cooling solutions is in base of how the liquid enters in touch with the device to cool down so if direct cooling or indirect one and starting from this first subdivision are analyzed after the sub categories included [111], but in general was analysed that direct cooling devices are able to reduce thermal resistance up to 30% if compared to the indirect liquid cooling type [153].

- Cold Plates: Involved in electronics cooling since 1960's when was used in spacecraft for NASA Apollo missions, shows an heat fluxes of about some hundreds of W/cm^2 and high efficiencies. Cold plates cooling method like the one in Fig 3.9b uses the high heat transfer of the liquid (in comparison to the air), but this liquid needs to be recirculate by a pump and cooled by an heat exchange with air in the other side as seen in Fig3.9a [23].



(a) Cold plate system



(b) Schematic for IGBT package integrated with liquid-cooling cold plate[186]

Figure 3.9: Cold plates cooling [23]

- Microchannel: To increase the heat flux until 790 W/cm^2 and even efficiency, microchannel (channels of heat sink at maximum of several hundred of micromethers) is one of the most common solution for cooling power electronic. The main benefits are in general the high cooling in comparison to liquid flow in plates thanks to the reduction in thermal resistance increasing the number of micro-channels [10], higher surface area/volume ratio, so more compactness and minimal use of coolants and a creation of laminar flow decreasing the channel diameter (heat transfer coefficient inversely proportional to hydraulic diameter [112]), but the mayor problems to be considered here are the pressure drop that is inversely proportional to the hydraulic diameter of channels as the pioneers of these microchannel systems Tuckerman and Pease in 1981 mentioned (system tested with heat flux dissipated of 790 W/cm^2, a temperature increase of 71°C and a pressure drop of 207 kPa) [181] (so high request of pumping power to compensate this problem) and the clogging due the micromiter dimension of the channels (so a proper filtration of the liquid is necessary).

  Regarding the type of liquid, water is the favorite one due to the excellent heat capacity and thermal conductivity, but is needed a particular attention in high-voltage applications for avoid discharge events and even in particular cold applications because the freezing point of electronic devices is -40° that is much lower than the freezing point of water. Alternatives liquids are refrigerants, nanofluids or 50/50 propylene glycol and water mixture [190] but they increased not only the thermal resistance but also pressure losses (compared to just water at the same flow rate) due to the more high viscosity.

  Brunschwiler et al. in 2008 studied an high-performance chip stacks cooled with de-ionized water in microchannels reaching a maximum heat flux removal of 537 W/cm^2 at 60Kpa of pressure drop [28].

  The latest trend in microchannel cooling systems are 3D printed one with geometries generated by numerical optimization to get the best compromise for pressure drop and temperature uniformity [74].

- Electrowetting: An electric field to the fluid changes its surface tension and so pushes the fluid into the channels or into the porosity of the material more easily as seen in Fig 3.10.

  Around 50 W/cm^2 maximum can be dissipated with this kind of system.

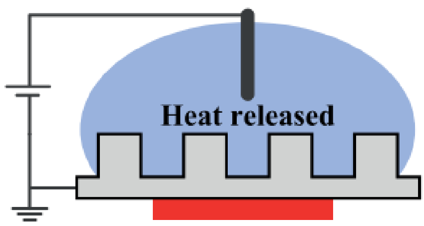


Figure 3.10: Electrowetting cooling [111]

- Immersion (forced flow): Now in comparison to the previous solutions the fluid enters in contact with the electronic devices submerging it, so must be dielectric at first. Can dissipate hundreds of Watts with an heat flux up to 1000 W/cm2 in some particular forced convection [111].

- Jet Impingement: Here a grid of holes creates many and really fast impinging jets that hits in different sides the device to cool down so in practice can rich really low thermal resistances [78].

  The jet velocity, impact angle, type of nozzle, type of fluid, distance from jet to surface to cool are relevant parameters to consider for design this type of cooling system.

  Natarajan and Bezama demonstrated that a single-phase water submerged jet can reach a heat transfer coefficient as high as 52 000 W/m^2·K [144].

  In the study of Bhunia and Chen [20] is showed that heat dissipation in a jet cooling of an inverter module for hybrid vehicle is 1.8 times higher than liquid forced convection cooling in most of the pin fin cold plate.

  The highest heat flux removal thanks to a jet impingement system was reached by Silverman et al. in 2006 [169] and was of 2000 W/cm^2.Here was utilized a metallic alloy of gallium and indium as working fluid (melting point of 15,7 °C). So, this is an exception with a particular fluid, in general jet cooling can give the possibility to achieve heat flux removal around 1000W/cm^2 [51].

  Anyway this solution demonstrated to be one of the preferable in particular for hot spot removal and in comparison to microchannels for a reduction in pressure drop at the same heat flex removed [86][85].

3.3.4 Two-Phase Cooling Technologies

The lasts frontier of power electronic cooling is the two-phase one.With the basic improvements of better space utilization, so more compact system thanks to the enhanced heat removal rates and improved temperature uniformity (non constant temperature distribution causes material stress with the potential risk of failure), another fundamental improvement is the possibility of better managing the waste heat removal for higher overall system performance [153].These benefits are to be conducted principally to the coolant latent heat of vaporization that now is introduced and so to the surplus of heat removed thanks to the changing phase of the liquid, so in practice for dissipate the same heat of single phase is needed lower flow-rates.In our ages there is a big limit of simulations for two-phase flows and pressure prediction in particular for microchannels that is an open topic of research even today.

- Heat Pipes: Thermal conductivity ranging from 50 to 200 kW/m·K and heat flux in a range of 10-300 W/cm2 can be obtained. The principle of working (Thermosiphon heat pipe) starts from the thermal load from chip applied to the evaporator that makes it evaporate and creates a pressure drop.This pressure forces plus capillary forces or gravity (the most determinant in thermosiphon heat pipe) pushes the vapor to the condenser and the cycle re-begun. More long is the pype more effective is the system. The contraindication of these systems are the pressure losses due to the capillary pipes and entrainment losses due to liquid and vapor interactions, in particular for short pipes reduces the heat transfer [79].

- Microchannel: The single-phase microchannels suffers of the phenomena of hot spots that can be passed or reduced using two-phase solutions that, as said before, decrease the temperature differences in the system enhancing temperature uniformity distribution, as showed in one study of 2008, the temperature gradients along the flow path is of 0.7 ◦C/mm for a heat flux of 255 W/cm^2 [6], so three times lower than comparable single-phase cooling.

  Lee and Mudawar in 2006 implemented a microchannel two-phase evaporator device using R134a fluid, with a surface dissipating a uniform heat flux of 100 W/cm2 maintaining device temperatures below 55°C (total evaporator heat load of 640 W) and capable of providing a heat transfer coefficient up to 50000 W/m^2·K [113]; Krishnamurthy and Peles in 2009 studied the flow boiling of HFE 7000 in a microchannel structure reaching 110 W/cm^2 [100].

  Hirshfeld et al. thanks to microchannels was able to dissipate untill 1436 W/cm^2 but with a really high pressure drop of 325 Kpa, a flow rate of 4.2 l/min and a calculated heat transfer coefficient of 67 000 W/m^2·K [75], and this is the highest heat flux in literature of microchannels.

- Spray: The phenomena of just single-phase liquid spry cooling can be implemented with the ability of the phase change of the fluid (see Fig3.11 to have an higher heat removal thanks to the latent heat of vaporization reached the cooled heat flux up to 1200W/cm^2 like in the work of Pais et al. where de-ionized water is used with a jet receiving surface rough.

  The spry can be created in two ways: pressure spry (thought the liquid that traverse the nozzle is applied an high pressure) or atomized spry (the liquid is breaks into droplets thanks to an air flow at high pressure).

  The principal advantages of this method are a major surface/volume ratio in correlation with an uniform temperature distribution in the hot surface but suffers of high pressure needed (310 KPa) for the droplet breakup [79].

  Fabbri et al. experimentally studied enhanced surfaces (with cubic/pyramids fins) during spray cooling of two-phase PF-5060, with an achievement of heat transfer coefficient of 24000 W/m^2·K.

  Anyway this solution for cooling power electronic is still in a high research phase because is nowadays not really clear and precise for the predictability and repeatability of fluidic and thermal behaviour, for the reasons of difficult experimentally and of simulations to test and predict the spays (many physical and geometrical parameters are to be considered).

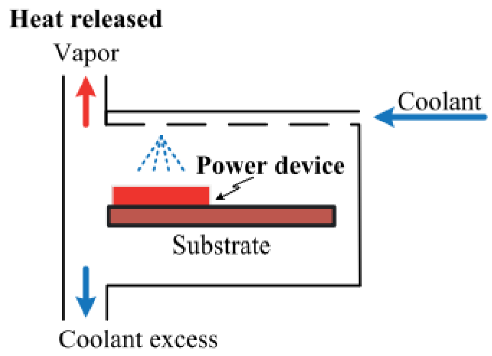


Figure 3.11: Two-phase spry cooling scheme [111]

- Immersion (Pool boiling): Regarding the immersion cooling of power electronic devices in two-phase liquids we will analyze it more deeply theoretically and with real solutions in the following chapter as the main subject of analysis of this study. Anyway to have a comparison view, can be reached for this solution around 600 W/cm^2 of heat flux cooled but, as can be seen after, this parameter in boiling is highly influenced by the temperature difference between fluid and heated wall, by the surface structure and the type of two-phase fluid.

3.4 General comparison view

To have a general comparison view of heat fluxes that can be dissipated by the different technologies can be seen the Fig.3.12.Here the maximum heat fluxes reached are taken by the most valid and recent articles or recommended state-of-art regarding cooling solutions for power electronic, articles already cited in the previous section.

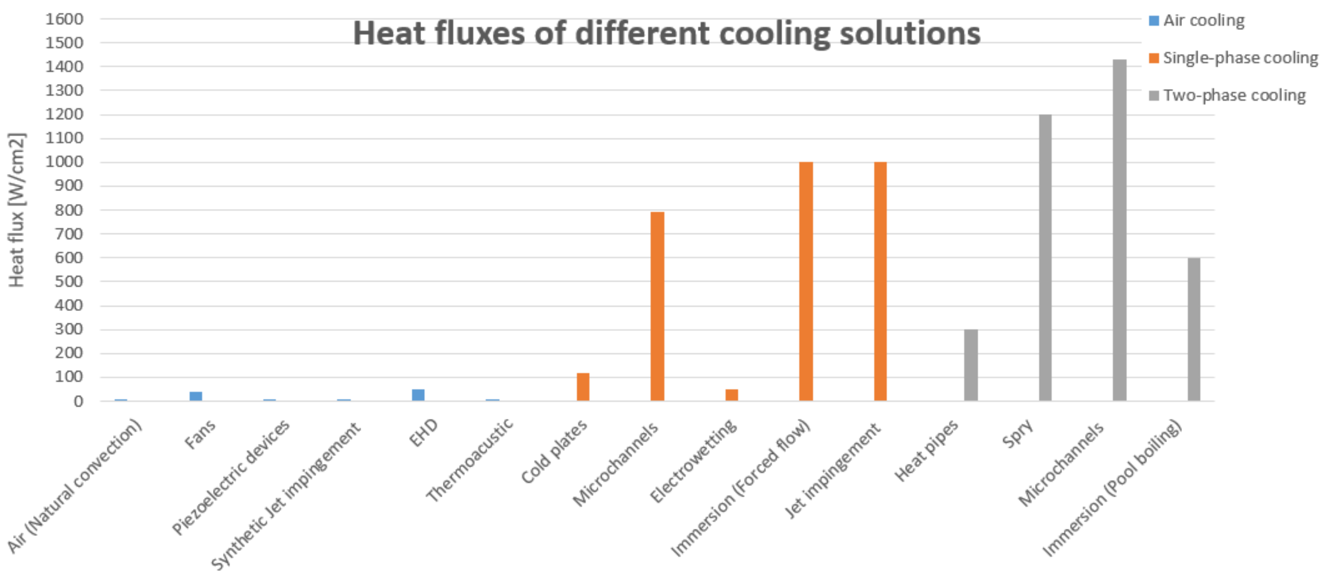


Figure 3.12: General comparison view of dissipated heat fluxes for different cooling solutions

Despite microchannels and jet cooling are able to remove high heat fluxes, there are several disadvantages in these systems like the propensity to clogging and fouling (in particular with water can be more prone to microbial or fungal growth and so corrosion), an extra risk of leaks due high pressures and of not less importance additional yearly power consumption for pumps and re-circulation pressurized lines.

So is clear that even if some solution has an heat flux reached higher in comparison to others, the parameter needed for the choice is not just this one. Indeed, particular attention must be putted even on efficiencies, reliability, hot spot removal, costs, packaging density, flexibility, easy access and replacements,... [51].

Applications must be considered for having an optimal efficiency of the entire system.Like, for making an example, two-phase immersion cooling can be an intelligent solution in EVs thanks to the optimization of using the already existing radiator as heat releases from the fluid, so eliminating complexity and increasing the integration into existing commercial systems.

A global comparison of relative costs for these cooling solution was done. These costs ratings are not compared on the basis of the plant consumption, but on the basis of the cooling device itself.To be more specific could be done even a study of power consumption in an year because could happen that solutions with initial costs high can be more convenient as savings power/money over years.

Anyway the higher cost of production for the cooling devices are noted for mirochannels devices due to the production of the microstructure of channels and the necessity to guarantee high sealing to resist at the high pressure of fluid.

After microchannels, in the same order of magnitude for price, there are cold plates, jet impingement, spry cooling and immersion pool boiling system.

All the others system, in particular the ones using air as coolant, are the cheapest one for the first investment, also because are a mature technology, but in therm of long therm power consumption, they are one of the most expensive.

Chapter 4

Cooling modules of power electronic converters in automotive applications

Starting saying that the performance (low thermal resistance, high power density,...) is an important parameter in power electronic packaging in general, if we analyze the application to automotive field this is not the only one goal, infact even cost and reliability are not of less significance. In this chapter a comparison of the cooling solutions for IGBTs applied to existing hybrid and fully electric vehicles are studied.

4.1 Standard power electronics cooling packaging for automotive traction inverter

The basic one cooling package, like the one in fig 4.1 can be described starting from the semiconductor element that is the part where heat is generated.It is connected at the top with wires and at the bottom with a die-attach of aluminium (the most common in high power devices), tin or silver because this die-attach needs to bond the substrate and must have both the properties of electrical and thermal conduction.

This die-attach links under a metallic part (usually copper or aluminium) with a following substrate and a metallic part again. The metallic part upside is just an electrical ground for the semiconductor; the metallic part below instead needs to provide a stress release for the substrate, connection and an additional heat spreader of the baseplate.To attach the metal with the ceramic material is used a metal matrix composites (MMCs) made from a base of copper or aluminium with additives like SiC, molybdenum,tungsten, carbon nanotubes.

The substrate, so the layer mentioned before that is between the two metallic parts, is the first element that needs to be electrically insulate but maintaining an higher thermal conductivity.The ceramics are the ideal material like alumina (Al2O3)(low cost for the production maturity and low thermal conductivity of 24 W/m·K), beryllia oxide (BeO)(really high cost but the best thermal conductivity of 270W/m·K), aluminium nitride (AlN)(high cost but high thermal conductivity of 150–180 W/m·K), Si3N4 (for higher power application for its really low dielectric strength or for extreme temperature swing environments).

Under the ceramic substrate there is again the metallic part as explained before and now there is the TIM (for the higher mechanical compliance) or a solder for linking the substrate with the heat sink to decrease the contact resistance [25]. Heat sink or channels are used to get in touch with the coolant liquid that usually is water/ethylen glicol mixture.

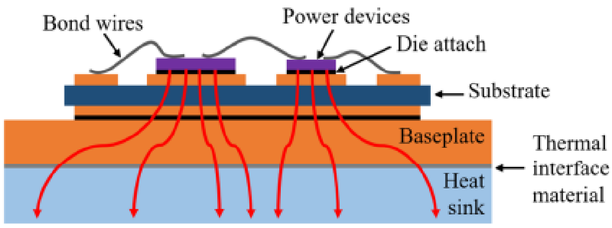
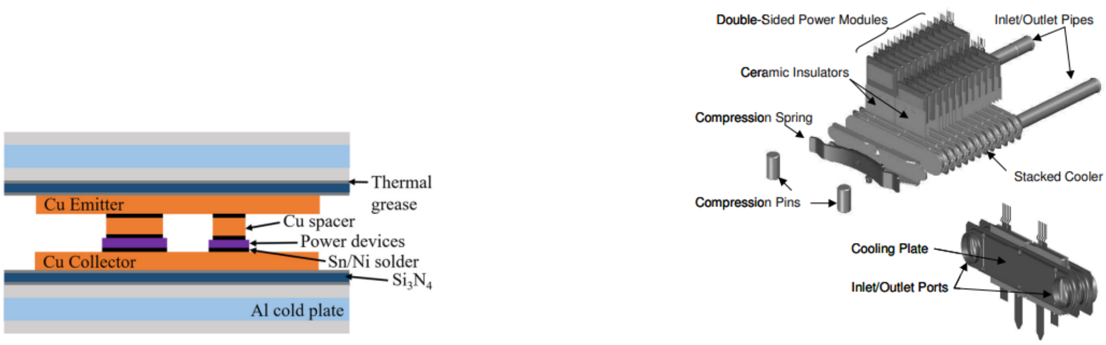


Figure 4.1: Standard power electronics cooling module [25]

4.2 Lasts developments in automotive power electronics cooling packaging

Reporting some example of these modules to have an overview of the evaluations in the years for the design side and improved characteristics we can start from the scheme of Toyota Prius 2004, the first hybrid system of Toyota (it employs a PCU with a boost converter and two inverters, each one of the two motor/generator) [164].This is still really close to the standard devices described in the previous section; a first improvement can be seen in 2008 Lexus LS 600h, Fig 4.2a,where the same PCU of before was able to rich higher output power in the same space, so higher power density (almost five times grater than the 2004 device) and adding a second cooling side a decreased thermal resistance of 38% adding a second upper cooling plate [119]. In a global view of the full packaging of the 24 pairs of silicon chips, as shown in Fig 4.2b, was utilized a paralleling of 13 cold plates with the modules between each others and water as a refrigerant fluid.



(a) Cold plate system (b) Exploded View of Power Stack

Figure 4.2: Lexus LS 2008 power electronics cooling module [25]

Toyota Prius 2010 to decrease thermal resistance applied the principle of making the heating part as close as possible to the cooling side (3,8mm instead of 9,0mm in the one of Toyota Prius 2004) plus an elimination of TIM (the part with the highest thermal resistance) and base plate, see Fig 4.3,.Another relevant upgrade was the use of channel cooling and a series of rectangular holes in the Al part with the purpose of stress release (stress caused by the link of the Al side with the ceramic one).

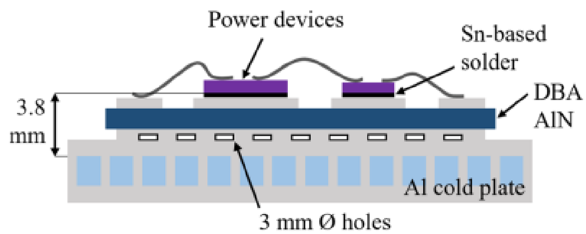


Figure 4.3: Toyota Prius 2010 power electronics cooling module [25]

Honda accord 2014 utilized copper near the device for having an higher heat diffusion in this side, so the part more critical and further down the cold plate is done of aluminium, see Fig 4.4.

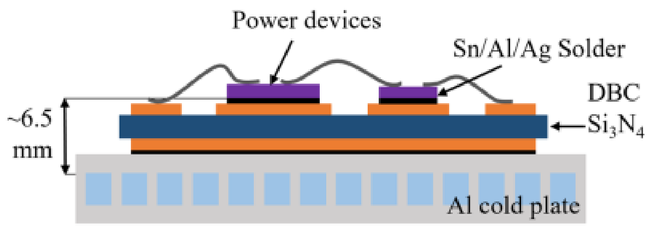


Figure 4.4: Honda accord 2014 power electronics cooling module [25]

Tesla Model S 2015 power module, as shown in Fig 4.5,with an external cast aluminium, has 6 parallel IGBTs per switch for a total of 36 IGBTs.Coolant is split into three for cool three heat sinks with internal fin geometry.

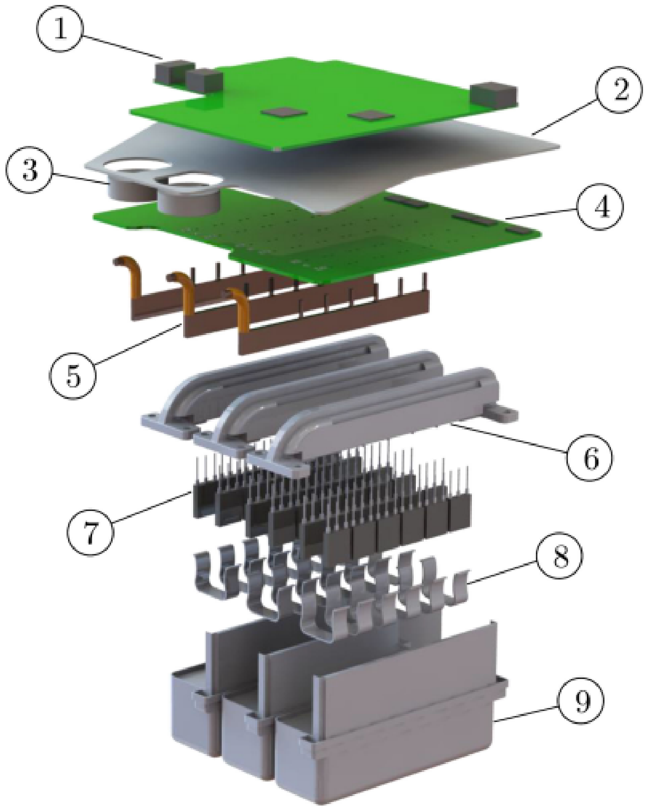


Figure 4.5: Tesla Model S 2015 power electronics cooling module: 1) Control board. 2) Aluminium shield. 3) Phase current sensor ferrite ring. 4) Gate driver board. 5) Phase busbars. 6) Heat sinks. 7) TO-247 package IGBTs. 8) IGBT clips. 9) DC-link capacitors [155]

Chevrolet Volt 2016 (General Motors) created an entire package of copper (for the part near the IGBTs and the cold plates both) in a double side channel cooling in a serpentine path,see Fig 4.6, to cool the motor inverter of 87KW and the generator inverter of 48KW.

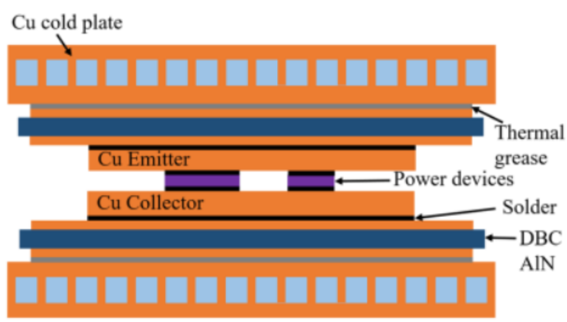


Figure 4.6: Chevrolet Volt 2016 power electronics cooling module [25]

Toyota Prius 2016 was the fourth generation of Prius.Here the improvement in this component was that the power module was of type of seven “power card” format made of resin molded an integral heat exchanger, open a vision for the possibility of scalability of these invertes thanks to paralleling [155], see Fig 4.7.

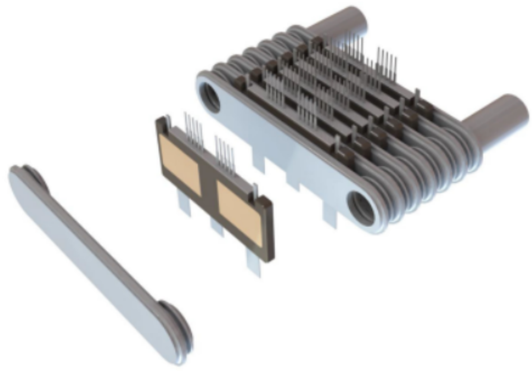


Figure 4.7: Toyota Prius 2016 power electronics cooling module [155]

4.3 Future trend in automotive power electronics cooling packaging

Even in this case passive two-phase immersion cooling may be a future trend in power electronic converters for automotive application but will require a proof of long-term reliability, factor that is not easy to get due to the even high temperatures of operation.

These temperatures that can be reached (175°C for SiC devices for example) means that in a generic working moment, the coolant loop can have an higher inlet temperature, like 105°C usually, and so all the packaging components must resist and reliable working at least at this temperature till a maximum of 175°C or even more in the future...So, the already existing solutions can be upgrade in particular in die attach materials and thermal interfaces materials but even the packaging design will need to be review for the high value of heat flux that will be needed to evacuate.

Anyway one valid publication regarding an HEV application of immersion cooling was published by Campbell and Tolbert [30](this system will be analyzed in chapter 6).

Chapter 5

Two-phase immersion cooling

5.1 First introduction of two-phase immersion systems

Heat transfer related with immersion cooling includes natural convection, forced convection and boiling. The nucleated boiling is performed when the heated surface passes, of a certain value, the two-phase liquid saturation temperature, so is present a latent heat exchange in comparison to the single-phase cooling one and in addition the bubbles flow upward create a mixing of the fluid without the use of pumps or other devices.

Another advantage is the ability to cool directly entire surfaces so can be reach a temperature uniformity minimizing the hot spot problems (always present in particular for structure really dense of electronics).

Thanks to these, the heat transfer coefficient can be an order of magnitude higher than the equivalent single-phase forced convection.

Coming back to the general view of these systems, the condensation of the vaporized liquid happens inside the tank thanks to the contact with an external cooled coil or heat sink (forced air cooling in these devices) and the cycle repeats continuously.

The tank is usually degassed (non condensable gasses mixed into fluid decrease the thermal performances), so should be perfectly sealed in theory but in the reality is quite impossible to have a perfect seal, so for this reason will anyway take inside some level of air tolerated, verified in production with helium mass spectroscometry.

5.2 Physical and thermal basis of boiling phenomena

As explained in thermodynamic texts regarding heat transfer phenomena, like "Heat transfer" of Bonacina, Cavallini, Mattarolo [24], is known that heating a liquid in a tank, in some conditions, will happen the boiling phenomena so, the phase changing liquid-vapour. Boiling starts just when the superficial temperature of the liquid is higher then the saturation temperature of the liquid.

If the liquid is not moved by others external phenomena, except the one of the boiling itself, we are talking of "pool boiling". The boiling phenomena are really complex, with different heat transfer regimes and are not yet well understood; all the happenings are not related and developed experimentally and computationally in an exhaustive way up to now.

Anyway, to understood the pool boiling phases, can be used a two axis diagram, like the ones of Fig 5.1 that represents the heat flux in function of the temperature difference between the wall and the saturation temperature.This graph is referred to saturated water in quite, at atmospheric pressure and flat copper surface.

Starting from the left one region, so the region where the heated surface has a temperature a bit higher than the saturation temperature, happens just natural convection phenomena because the liquid heats up and moves upward until the surface where it evaporates.

Continuing to heat up the superficial temperature, in the nucleate boiling region, bubbles start to born and grow (is from here on that there is a large amount of heat transferred to the fluid with a small thermal gradient due to the latent heat of vaporization). The nucleation starts in the heated surface not randomly, but in the points where there are microscopic cavities (even a theoretical flat surface has statistically a certain quantity of cavities/little pits/...). Raising the surface temperature bubbles increase in diameter and frequency, increase the nucleation points and they reach the surface of the liquid where they tend to join together forming columns of vapor.In the case of water at atmospheric pressure this region is between 10-30°C of surplus in degree to the 100°C of the saturated temperature of water.

However, at a certain point, after the point C in figure (critical heat flux of around 100-150 W/cm^2 at a temperature difference of 30°C for water with the previous hypothesis), the relative velocities between the "cold" descendent liquid that take the place of the evaporated one and the bubbles that go upward are so high that the liquid is not able to fill continuously the surface causing a creation of an unstable/intermittent steam layer that covers the heated surface and consequently a gradual decreasing of the heat flux released.

But continuing to heat the wall, this "problem" will vanish passing to the film boiling zone, starting point D in Fig.5.1, where starts a stable creation of steam layer in the surface that detaches with continuity the bubbles, so heat transfer is conducted now through the vapor film instead of through the liquid film. The heat transfer increases again reaching the same level of the critical heat flux and even surpass this (the thermal radiation phenomena become the principal mechanism to heat transfer), but now the surface temperature should be more high than the fusion temperature of the general materials used as heat transfer, so in practice this point is quite never the goal, but the CHF point yes because is here that happens the maximum heat flux that can be practically reached.

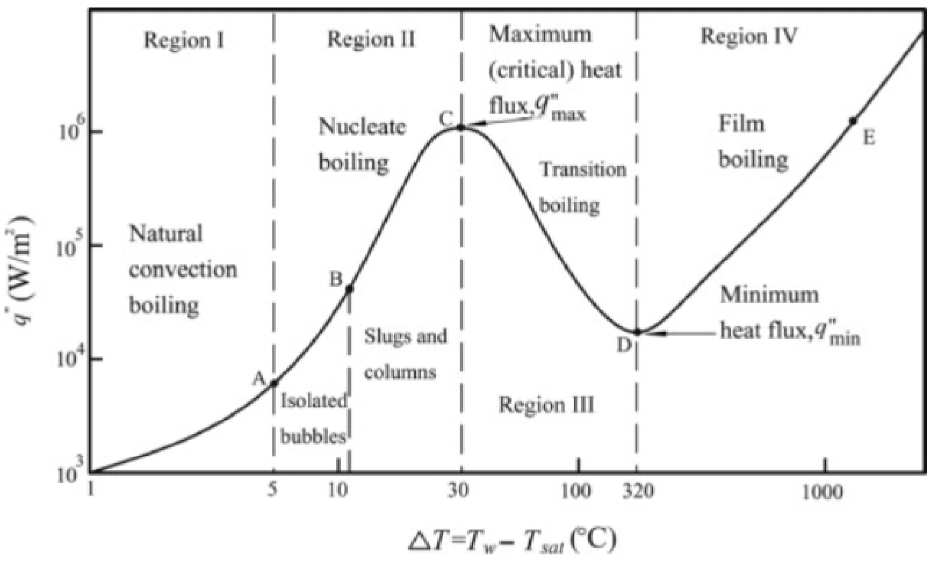


Figure 5.1: "Pool boiling" curve of water [55]

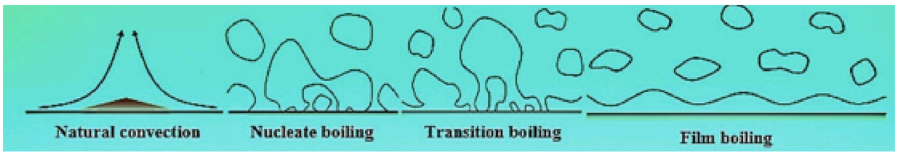


Figure 5.2: Drawings of boiling phases in the different regions [117]

These phenomena described above are referred to saturated liquid; in case of subcooled liquid happens the same things but, for example in the case of nucleate boiling, more is the subcooling of the liquid more the bubbles will condense into the liquid itself.

So, the heat fluxes that can be reached are related to many factors, and depend on the single regime of boiling analyzed.

The most used and complete formulation relate to nucleate boiling regime (the one of mayor engineering interest for the best fit with experimental counter-evidence [45]) is the Rohsenow correlation, see eq. 5.3 [123].

$$q = \mu_f h_{fg} \left[\frac{g\left(\rho_f - \rho_g\right)}{g\sigma} \right]^{1/2} \left(\frac{c_{pf}\left(T_w - T_{\text{sat}}\right)}{h_{fg} \text{Pr}_f C_{sf}} \right)^3$$

Figure 5.3: Rohsenow correlation [123]

Rosenow shows that the main influencing parameters of the heat flux q $[W/m^2]$ are:

- μ_f: dynamic viscosity of the fluid [kg/m·s]
- $h_f g$: enthalpy of vaporization [J/kg]

- g: gravitational acceleration [m/s^2]

- ρ_f: density of the fluid [kg/m^3]

- ρ_g: density of gas [kg/m^3]

- σ: surface tension at interface liquid/vapour [N/m]

- c_{pf}: specific heat of liquid [J/kg·K]

- Tw-Tsat: difference in temperature between surface and saturation temperature [°C]

- Pr_f: Prandtl number of liquid

- C_{sf}: surface fluid factor tabulated depending on the coupling between surface material and liquid type

Now is clear that heat flux in these two-phase pool boiling systems (in nucleation zone) is influenced principally by the difference in temperature between the surface and the saturation temperature (q α ΔT^3), by the type of liquid used (to mainly influence is the specific heat of liquid) and by the surface material and conformity.

Regarding the macroscopic geometric form, experimentally, are not shown particular conditioning to the nucleation boiling of quite fluids (even if some structure with porous matrices in recent years are showing interesting goals), instead are interesting the increase of heat flux related to the use of roughened surfaces (heat flux at a determined super-heat temperature higher up to 3-4 times in comparison to plain surfaces thanks to the higher number of nucleation sites, so small bubbles at faster rate), but this subject is more deepened in the last chapter.

Regarding dissolved gasses or tensioactive substances, they can decrease the maximum heat flux indeed additives at high molecular weight, ultrasounds or electrostatic fields can increment its.

5.2.1 Critical heat fluxes (CHF) varying the pressure

In 1945 Cichelli and Bonilla [40] experimentally shows that CHF increases gradually increasing the pressure in a first range until reaches the maximum value (1/3-1/4 of critical pressure) and a following decreasing trend till the critical pressure (CHF approaches zero in this point), like seen in the Fig.5.4, an experimentally plot, by Sutopo in 2008, for different fluids and geometric heaters under saturated conduction.

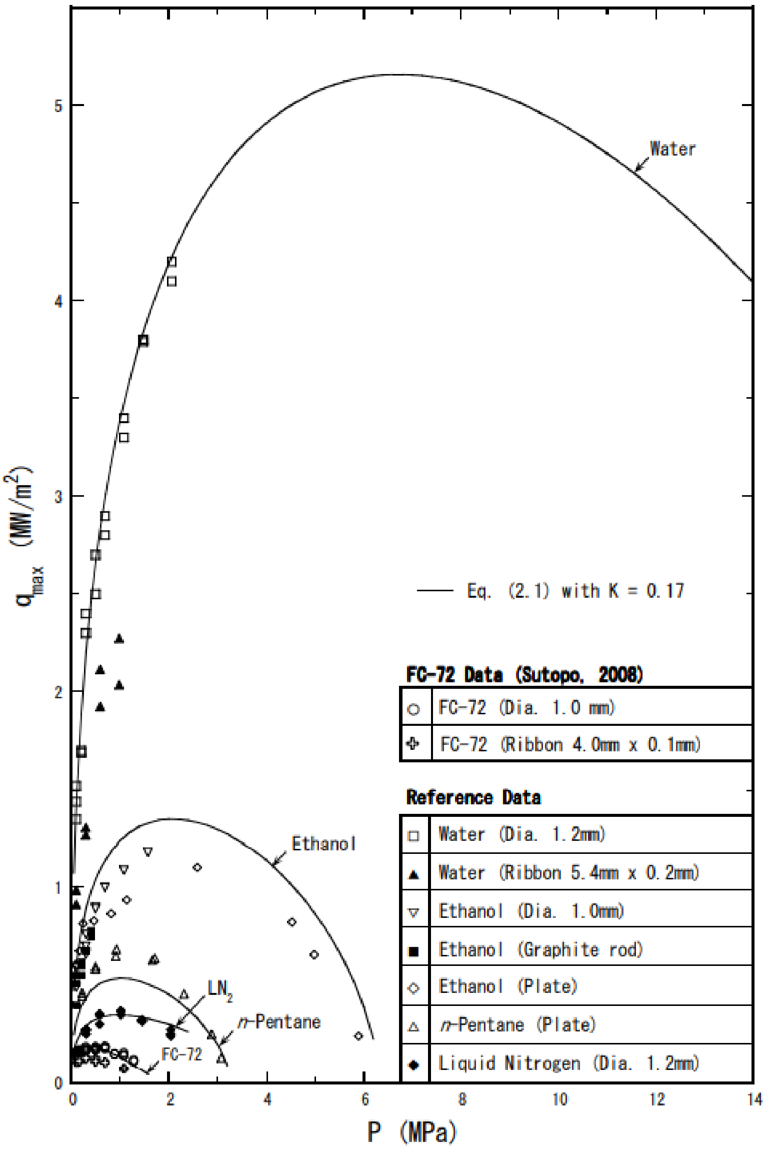


Figure 5.4: CHF at different pressures of various fluids and geometric heaters [57]

Indeed nowadays there are not enough scientific articles and experimental validations of the physics involved to have a clear and exhaustive understanding of the phenomena of high pressure pool boiling process.

Theoretically is confirmed that the thermophysical properties of fluids change varying the pressure (increasing the pressure decreases the latent heat of vaporization and the specific volume).

Smreeti Dahariya and Amy R. Betz in 2019 have deepened this subject seeing the thermophysical characteristics of a plain polished copper surface heated and immersed in saturated water at different pressures [45]. They demonstrated experimentally and with the most valid mathematical correlations that:

1 The pressure reduces the size of nucleating bubbles significantly, approximately 46% of reduction is observed in the bubble size from the atmospheric condition to 62.05 Bar (so size of departing bubbles inversely proportional to pressure);

2 Increasing the pressure is showed a slightly increase of the detachment fre-

quency;

3 As a direct consequence of points 1 and 2:

-the increase of CHF and heat fluxes for the different degrees of superheat increasing the pressure (significant improvement in particular over 25 W/cm^2), plus a lower degree of superheat increasing the pressure, see Fig.5.5;

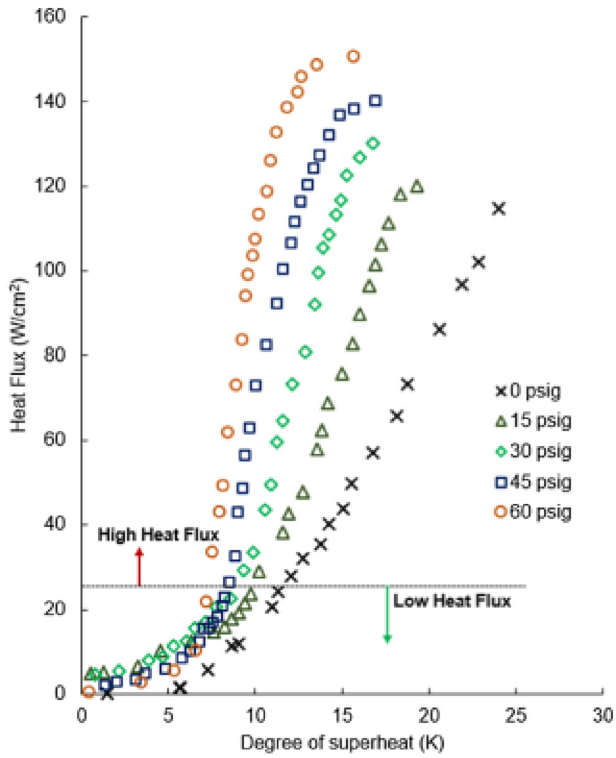


Figure 5.5: Pool boiling curve at different pressures for water on smoother copper surface [45]

-the increase of heat transfer coefficient for the different heat fluxes increasing the pressure (at 100 W/cm^2, 50%, 75%, 125%, and 175% of enhancement was measured against 0 psig for 15 psig, 30 psig, 45 psig and 60 psig respectively), see Fig.5.6.

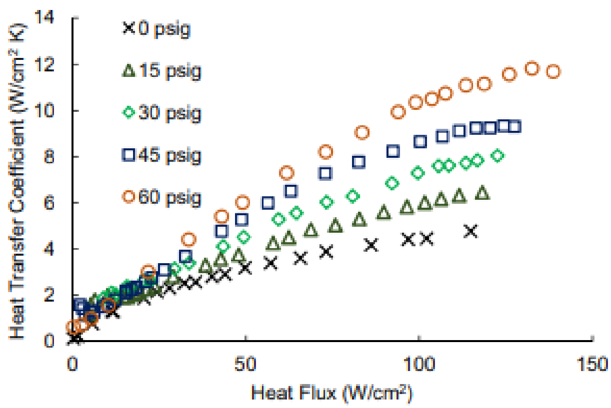
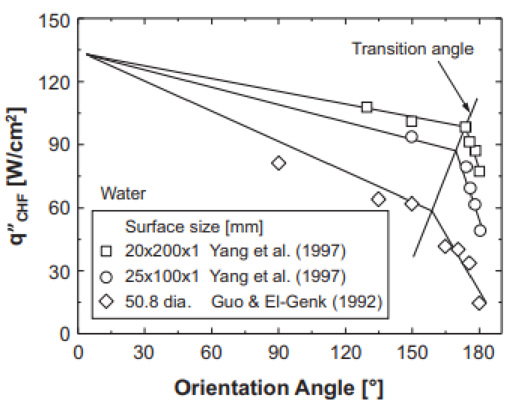


Figure 5.6: Heat transfer coefficient at different pressures in pool boiling [45]

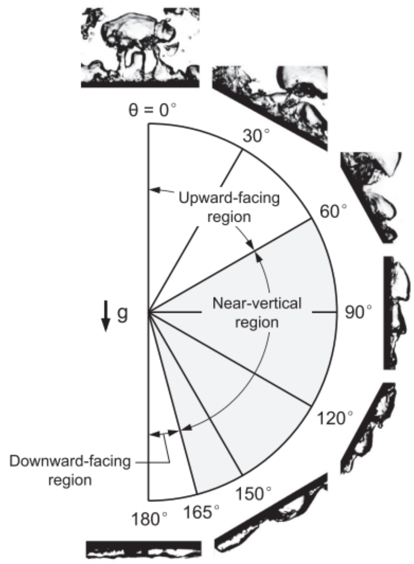
5.2.2 Critical heat fluxes (CHF) varying the surface inclination

Yang et al. and Guo El-Genk demonstrated and correlated the influence of orientation angle of the heated surface on the CHF in a pool boiling regime (for water).

As can be seen in Fig.5.7a, apart the fact that surface size has a strong effect on CHF for vertical and downward-facing orientations and the transition angle increases increasing the surface area, the graph shows that pool boiling CHF slightly decreases as surface orientation angle increases from 0° (Upward-facing) to 90° (Vertical) and more fast decreases as orientation angle continue to increase up to 165°-180° (Downward-facing) (the transition angle). At this angle, that depends on the surface size, occurs a really drastic reduction of CHF caused by an evident vapor stratification and difficulty of bubbles discharge [62](see Fig.5.7b).



(a) Effect of orientation angles in the CHF



(b) Photographic view of boiling at different orientation angles

Figure 5.7: What happen changing the orientation angle [118]

Is needed to specify that even if the best (regarding CHF) inclination angle of surfaces is the upward-facing, in real systems and plants with many heaters, must be considered even the factors of global compactness and of the influence of one heater to others so, is generally used (in particular for multi-board immersion cooling systems) the vertical position.

5.3 Physical and thermal basis of condensation phenomena

A saturated vapour condenses if in contact with a surface with a lower temperature.

Condensation can happens in surfaces that are wetted by a film of condensate (the most common) or non-wetted when there is dropwise flow [160].

Apart from the liquid and vapour intrinsic physical characteristics, the heat transfer depends on the fact that condensate from the higher part of the surface flows downstream, the flux can be fast moving or quiescent for vapour and condensate on the cold surface.

So, for the reason that the factors influencing the heat transfer are many, and complex, condensation is quite difficult to model accurately so usually are taken some ideal assumptions.

Nusselt model (1916) is the most complete analytical formulation to determine heat transfer coefficient even if applies some assumptions (neglect inertia/acceleration, convection in the film, surface shear stress and doesn't consider neither the effects of changing the condensate properties at variables wall temperatures) and is applied on a vertical plate and horizontal tube with radius much higher than the film thickness, as shown in Fig.5.8.

The vapour considered is saturated, surfaces analysed are isotherm, flow governed just by gravity and viscous forces and with the main assumption that heat transfer through the condensate is pure conduction.

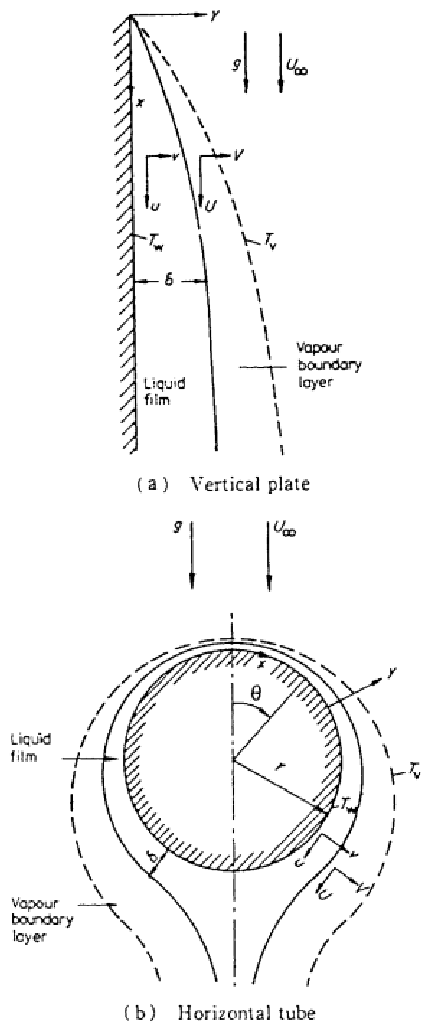


Figure 5.8: Condensation on a vertical plate and horizontal tube [160]

Following these assumptions, can be obtained for the case of vertical plate condenser, the mediate heat transfer coefficient on the surface:

$$\alpha = 0.943 \left[\frac{\rho \Delta \rho g h_{lg} \lambda^3}{\mu L \Delta T} \right]^{1/4} \tag{5.1}$$

Where:

- ρ= liquid density
- $\Delta\rho$= Vapour density - Condensate density
- g= acceleration of gravity
- h_{lg}= latent heat of vaporization
- μ= liquid viscosity
- λ= liquid thermal conductivity
- ΔT= Tvapour-Tsurface
- L= plane height
- d= external tube diameter

The Nusselt equation derived from the eq. 5.1 (for the vertical plate) is:

$$Nu = 0.943 \left[\frac{\rho \Delta \rho g h_{lg} L^3}{\mu \lambda \Delta T} \right]^{1/4} \tag{5.2}$$

The equations of before are the same for inclined planes, with angle γ from the vertical, just substitute to the gravity acceleration g the vertical component $gcos\gamma$.

Is to specify that, if the wall is too high, the flux could became turbulent instead of laminar and so these equations are not still valid.

The Nusselt's theory gives α values lower than the experimental ones of about 20%, but being approximated in defect, they will give oversized apparatus (working condition satisfied).

For horizontal tubes (with radius much higher than the film thickness) and the same assumptions mentioned before, can be written the mediate heat transfer coefficient of the circumference (is needed a mediation because in the lower part of the tube section there will be an higher thickness of the condensate film ans so lower fluid flow, as seen in fig. 5.8):

$$\alpha = 0.725 \left[\frac{\rho \Delta \rho g h_{lg} \lambda^3}{\mu d \Delta T} \right]^{1/4} \tag{5.3}$$

- d= external tube diameter

And from eq. 5.3 the related Nusselt equation (horizontal tube):

$$Nu = 0.725 \left[\frac{\rho \Delta \rho g h_{lg} d^3}{\mu \lambda \Delta T} \right]^{1/4} \tag{5.4}$$

Is important to itemize that these equations are experimentally validated with highest precision for pure vapor (only one molecular constituent) [180].

Up to now the formulations are referred to film condensation, but if impurities are present in the surface of the condenser (plate or tube), happens the formation of fluid drops instead of uniform condensate. Here, thanks to the absence of the thermal resistance from the fluid film, are achieved heat transfer coefficients from 4 to 8 times higher of the film condensation.

This kind of condensation is of difficult predictability and is quite hard to stabilize these thermal parameters in a real plant application (for safeness is suggested to design as film condensation) [24].

5.4 History of two-phase immersion cooling with practical applications

This chapter has the aim to give an historical view of two-phase immersion cooling applications for high performance electronics justifying the reason of the application of this cooling strategy to power electronic converters nowadays and as a future dominant trend in high dense packages.

Firsts application for cooling of transformers

Liquid immersion systems starts to be utilized since 1940's to cool high-voltage transformers, but the really first mention of a technique able to cool with a evaporative refrigerant was of Greene and was applied to radio transformers cooling (this information is written just in others old articles as citation, but the patent is not avails). This system utilized the phenomena of the direct evaporation of refrigerant, but to condense this fluid external compressor and condensing coil was used causing high problems of leakage, non-accessibility and degradation of electronic components mainly due the pressure effect.

Applications for cooling the memory arrays of supercomputers

The first useful and the real father of this technology was the patent regarding the immersion cooling in low temperature boiling dielectric fluid of S.Oktay working for IBM (New York) in 1968's [149], see Fig 5.9, with the target of cool the memory arrays of 'computers' (ferrite-core). It was mainly a preliminary study of feasibility for cooing electronic parts in two-phase fluids pool without compressors (so no completely sealed structures for helping maintenance) or indirect heat exchange. This patent is really revolutionary in particular for the fact that the nucleate vapors from the boiling liquid (fluorocarbon) is condensed at the interface of another/s upper superimposed liquids less dense but with higher boiling point kept at predetermine temperature with a simple external system that used to cool the condenser liquid (water or a silicate ester).

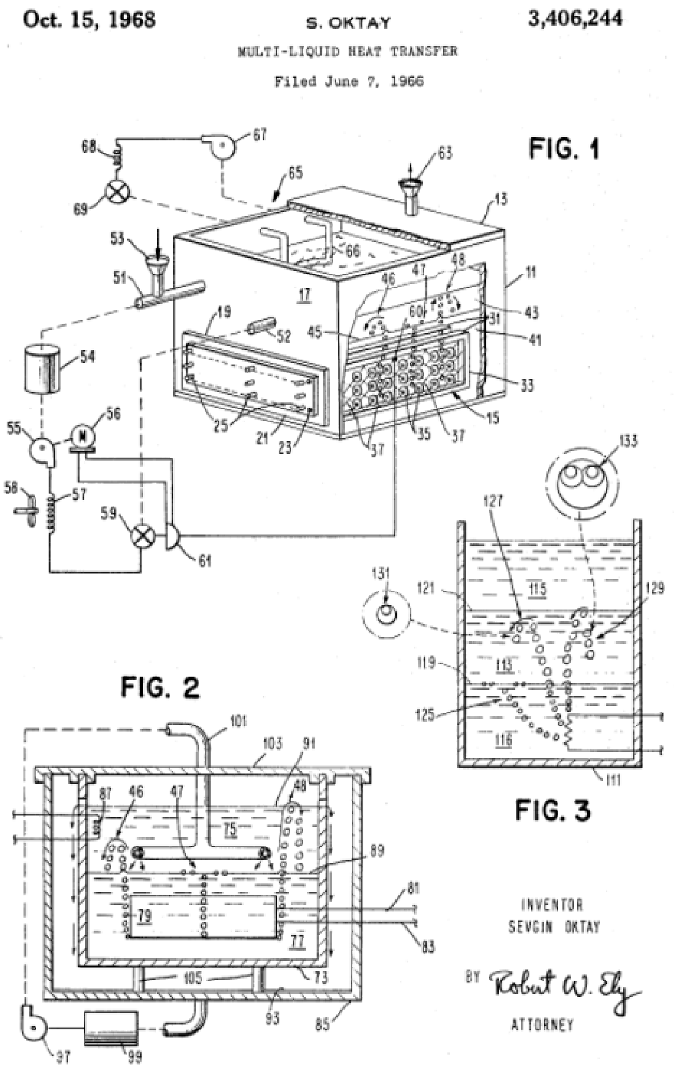


Figure 5.9: Section and exploded views of the entire system, S.Oktay's patent [149]

Just 2 years later, in 1970 was published by Richard C.Chu and John H.Seely (working for the same company of S.Oktay) a patent [39] of a system able to cool electronic components separately (easy connection and disconnection), thanks to the contact with low-boiling temperature fluid (fluorocarbon liquids) that evaporate for each module independently (cooling of each module without interrupt the work of the rest of the system) and accumulates in a common sealed and low-pressure vessel due to condensation with following gravitational flow to the bottom that happen touching a heat exchange cooled wall, see Fig 5.10.

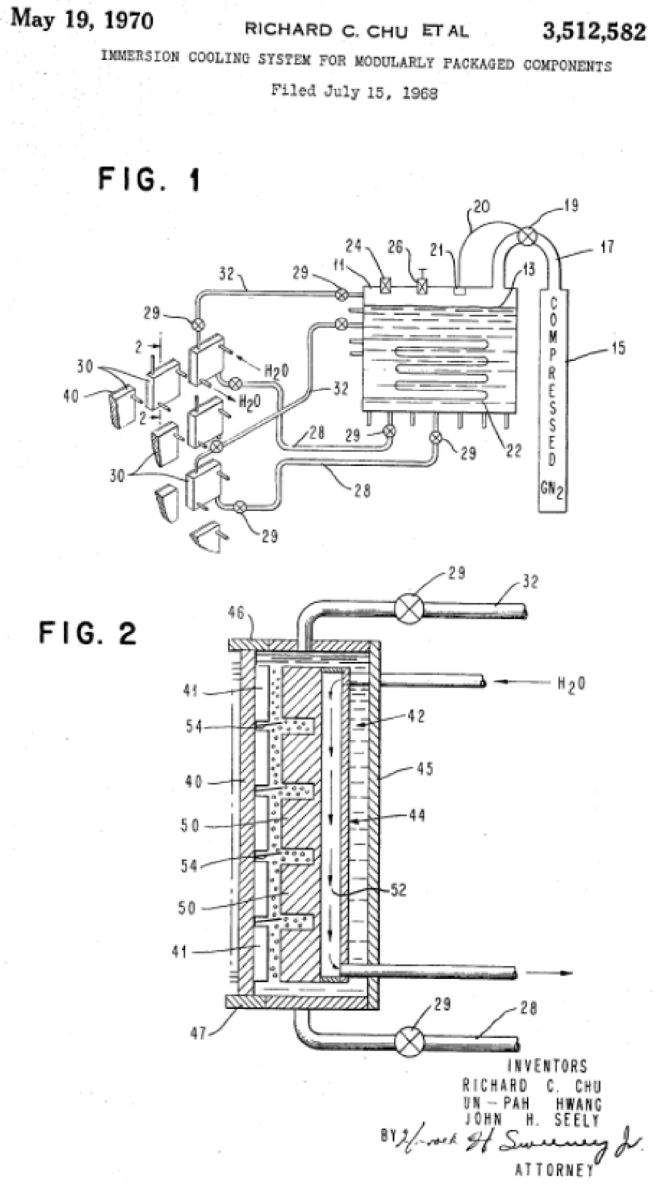


Figure 5.10: Section and exploded views of the entire system,Richard C.Chu's and John H.Seely's patent [39]

With the evolution of supercomputers, and so a power density for these devices of 1,4 MW/m^3 in the 80's, was needed an even more believable cooling strategies but the immersed ones, able to rich that goal regarding the high density cooling, was not so able to guarantee an adequate trust from investors even for the problem of provide an efficient packaging for the mechanical and electrical assembly and the difficulty on create an accessible and easy modular system.

In 1986, to give a solution to the above mentioned problems, Seymour R.Cray Jr. patented the first high density electronic assembly for supercomputer integrated circuits immersed for cooling in refrigerant (fluorinet of 3M company) [167], see Fig

5.11. These memories, with an easy access from operators, were arranged in adjacent radial stacks with a space between each others to make possible the passage of the coolant which submerged the entire system.

This revolutionary compactness of electronics allowed to create the faster supercomputer on the planet in that years, the Cray-2 (acquired chiefly from the US Department of Defense, the US Department of Energy and from NASA), see Fig 5.12.

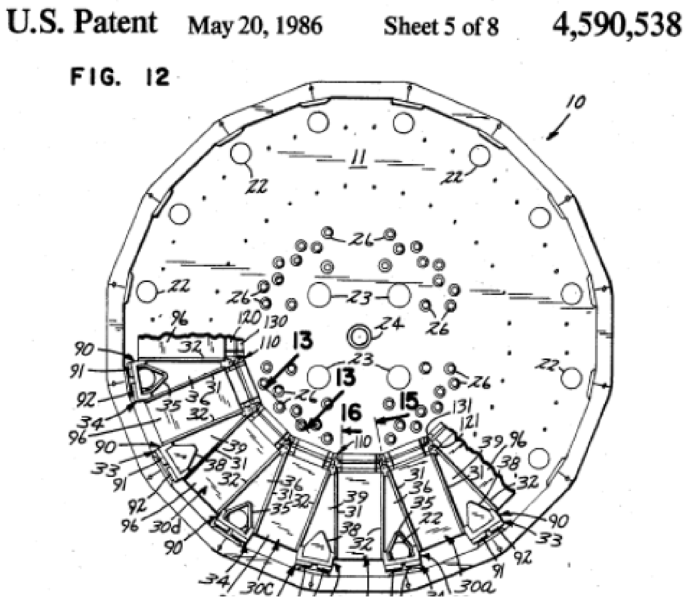


Figure 5.11: Section of the tank, Seymour R.Cray Jr's patent [167]

Figure 5.12: Supercomputer Cray-2 [175]

Anyway, in the lasts decades of last century complementary metal-oxide semiconductors (CMOS) starts to be utilized for integrated circuits. This technology was a big improvement in particular for the fact that utilises an extremely low current flow.

Low current means implicitly lower consumption and so lower heat dissipation, so for this reason the research on immersion cooling of supercomputer proceeded slowly until the actual decade where starts to be needed, in particular with the rapidly growth of Data Center, that elaborating every year an incredible increasing number of data, required more than before decades an achieving of high heat dissipation due to extreme packaging and so really high density electronic.

Current application and future trend for cooling high density power Data Center

Regarding one of the main field of application of two-phase immersion cooling in our decades we have the Data Center principally.In fact, the cooling systems of these devices spend around 38% of the energy consumption of the machine and in a worldwide view the energy consumption of data centers is the 1,3% of the global one and 2% of the US electricity usage [150]. With a quantity of data that are exponential even more year after year and so the implicitly necessity of storage and transmission of these, the structure of data centers was needed to become more efficient also in the cooling side, in particular in 2009, Green Revolution Cooling restarted the trend of open bath immersion cooling for HPC (High Performance Computing) and in 2010 was born the first commercial immersion cooled data center in the world by the Midas Green Technologies.

From 2016 with the increasing trend of crypto-mining the needed of immersed solutions starts to be even more important pushing the researches and the born of a big quantity of start up in this field.

In 2018, Open Compute Project (an organization that publishes online the technical and most common practice regarding data center design of the major companies in this field, like ARM, Meta, IBM, Wiwynn, Intel, Nokia, Google, Microsoft,...), started a new project called Rack and Power/Advanced Cooling Solutions showing the really importance of sharing knowledge for a global improvement of efficiency for cooling solutions both for IT growth and always more green solutions.

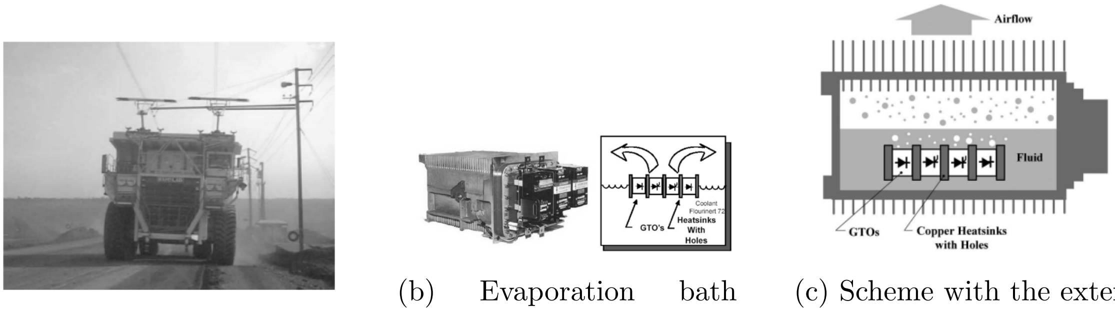
In 2019 OCP published in San Jose the first standards for industries in the immersion cooled solutions for data center and just in 2020 Telecommunications Industry Association mentioned for the first time immersion cooling as a feasible solution, opening an era for the big cloud companies that declared the starting to exchange the previous technologies with immersion cooling.

Two-Phase Immersion Cooling of Power Electronics in large Traction Systems

The immersion two-phase cooling on large traction systems start to be utilized since 1980s for cooling the gate turn-off (GTO) thyristors. These systems were applied for example in the France's Train a Grande Vitesse (TGV), high-speed train system [179] and large electrical machines used in mines like excavators and haul trucks, see Fig 5.13a, where here the GTOs or IGBTs played the role of AC inverter drives for ensure the correct supply of current to the motor and other auxiliaries like air conditioning, lighting, etc... [26].

One module, for making an example, is composed by a parallel of GTOs each one associated on both sides with an evaporator to increase the heat transfer area; this stack is completely immersed in Fluorinet 72 inside another bigger cylindrical tank which is finned to increase the heat transfer surface area between itself and the forced air from outside. This system in general was designed for operation on 2600 V lines, is compact and sealed for dirty environments with a power density for the AC drive cabinet approximately of 1 MW/m^3, see Fig 5.13b.

The use of such technologies was chooses principally to have a greater cooling capacity and a cost convenience thanks to the fact that pumps and others auxiliary components were not longer needed in these systems, plus a non indifferent advantage in particular in polluted environments, of completely sealed working components and liquids in respect to external surroundings.



(a) Haul truck operating with trolley lines

(b) Evaporation bath power module used in large ac trucks

(c) Scheme with the external forced air for condensation

Figure 5.13: Truck two-phase immersion cooling bath for GTOs [26]

5.5 Main parameters in the tanks that influence thermal performances

Since these first applications in traction systems of two-phase cooling systems for converters, was needed an even more refined investigation on the main parameters influencing the thermal performances, like the study of GEC-ALSTHOM (the french company producer of TGV) [179] which declared that the main source of problems in the thermal behaviour of the system is the effect of non-condensable gas (mainly air) inside the fluid when the tank is filled and even by the absorbed one due to the not perfect sealing.

Seeing the temperature distribution inside the tank while increasing the quantity of air into the fluid, was seen that the one at the bottom that is lower normally (here a small layer of quiescent fluid doesn't move causing to fins and wall surface in contact with fluid to be enough thermally useless) is going to be even more low due to fluid stratification; the temperature at the top (in the zone of condensation) is going to be even lower regarding the others in the tank due to the continuous accumulation of the gas here; all the others temperature in the system are going to increase increasing the quantity of air into fluid. So even a small amount of non-condensable gas in the coolant can have a bad effect on thermal behaviour (in particular decrease the condensation heat transfer coefficient).

A second parameter for relevance that is determinant in thermal efficiency is the external air flow rate and after the components stack position (so all the others geometrical components inside the tanks that are used as a flow deviator or used for others kinetic scope).

Regarding the level of liquid inside the system, of course it must be experimentally tested for getting the best quantity to put inside the tank, but it is less significant regarding thermal improvements (the only important thing is that its level must be high enough from the stuck position to guarantee an optimal mixing and convection heat transfer, like the inclined plate in fig 5.14).

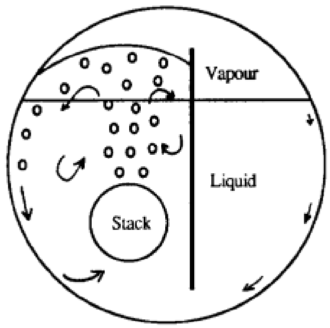


Figure 5.14: Schematic representation of the tank section [179]

After this macroscopic view, of course are to be properly studied in design the parameters influencing thermally boiling and condensation, but these aspects were seen at the beginning of this chapter.

Chapter 6

Patents and prototypes of two-phase immersion cooling for power electronics (IGBTs)

In this chapter are analyzed and compared the most relevant scientific articles and patents related to two-phase immersion cooling systems for power electronics.

In the first sub-chapter (studies from scientific articles) are analyzed systems using different types of fluids, different sizes of power converters, analyzed the criticism and possible improvements, etc...; the main focus was anyway oriented to investigate the practical solutions used to reach the maximum heat flux.

In the second sub-chapter (studies from patents) are showed ideas of system improvements and innovative ways of design for these immersion cooling devices, without paying attention to the thermal and materials aspects (as the patents in general are done).

6.1 Papers and scientific articles

1. The first paper analysed was published in the 8th European Thermal Sciences Conference (EUROTHERM 2021) by Jollyn, Nonneman and Paepe [177].

   This experimental study was done to cool the power module of the inverter in drivetrain applications (Infineon HybridPACK type FS400R07A1E3, so six-pack with IGBTs and diodes working at 650 V and 400 A, the one in Fig.6.1). Usually, at maximum load, this system generates heat fluxes up to 30 W/cm^2 (so anyway not high fluxes).

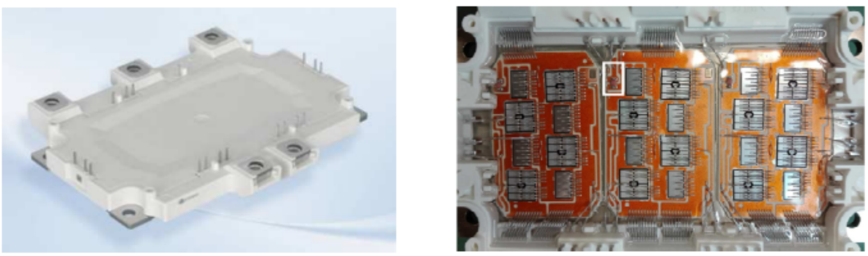


Figure 6.1: Infineon power module case(left) and its interior (right)[177]

The base plate of the power module is cooled with direct immersion in Novec 649 (boiling point at 49°C at atmospheric pressure and even if its thermal characteristic are low regarding the fluxes exchanged, it shows an extremely Low-Global-Warming factor, high dielectric strength, non-flammability and non-toxicity).

This refrigerant is putted in a sealed stainless steel reservoir, that was degassed before, and covers the power module bolted at the bottom.

Moreover at the top there is a copper coil, with a pumped circulation of water-glycol, for condensing the vapour, see Fig. 6.2.

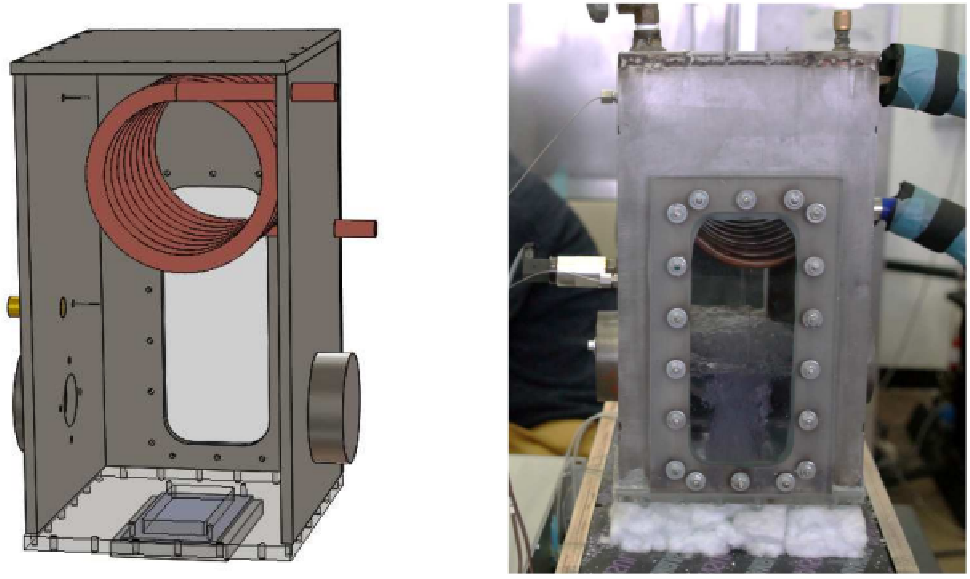


Figure 6.2: Reservoir: CAD drawing (left) and picture of experimental set up (right) [177]

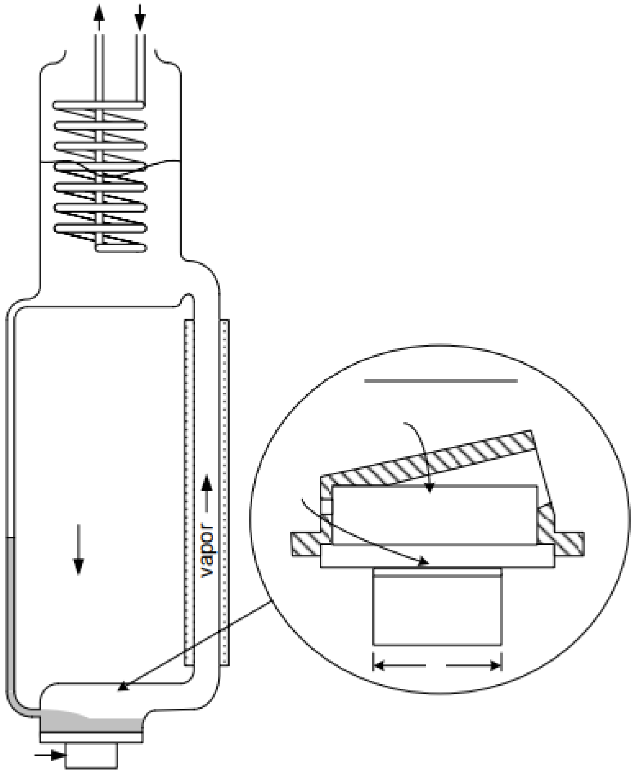
The highest heat flux reached was at CHF point and was of 14.6 W/cm^2 so quite the half the one needed to cool the maximum power of this power module.

The solution to increase this extremely low heat flux dissipated could be or another coupling refrigerant-surface conformity or a more high gradient of temperature between the power module surface and the two-phase fluid.

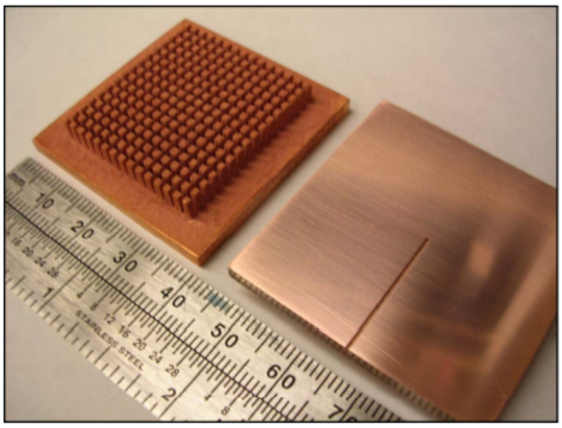
2. Phillip E.Tuma from 3M company experimentally tested a passive two-phase thermosyphon system (light, compact and chip) with a micro porous coating (done by sintering, brazing and flamme or plasma spraying) on the immersed sink for enhance heat flux in a pool boiling of segregated hydrofluoroether C3F7OCH3 (boiling point at 34°C) at atmospheric pressure [183].

   Up to 230W from power electronic device was successfully cooled (at this power was measured the best sink-fluid resistance) and a liquid condenser was putted at the top. The vapour line is separated by the returning line of condensed liquid (section of 3mm) to avoid interference as seen in Fig. 6.3a.

   The heat flux reached was of 255 W/cm^2 with a resistivity of 0.15°C·cm^2/W and 400 W/cm^2 with 0.20°C·cm^2/W, in the copper finned surface with the previous mentioned micro porous coating and segregated hydrofluoroether C3F7OCH3 fluid (Fig.6.3b).



(a) Test system

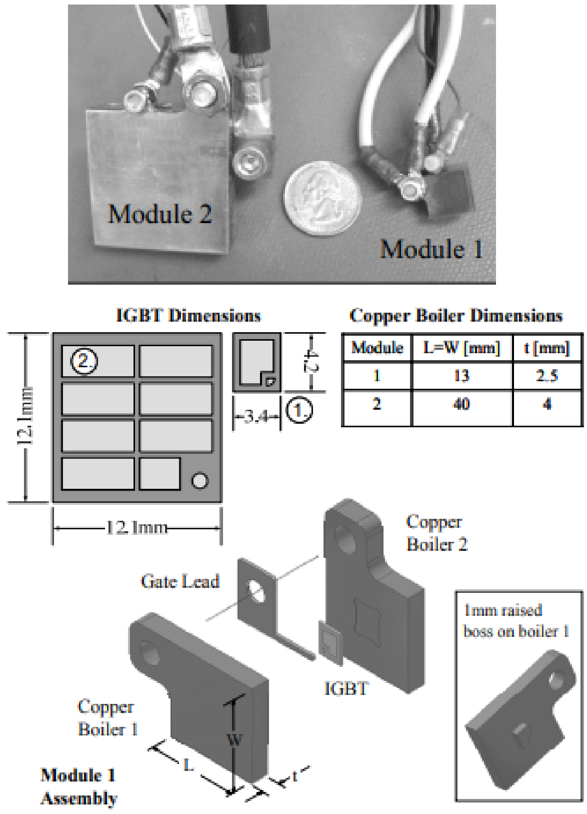


(b) Flat and finned copper surfaces with micro porous coating

Figure 6.3: Boiler thermosyphon system utilizing Segregated Hydrofluoroether Working Fluids [183]

3. Following the consideration achieved in the previous article, the same author thought that, a way to increase the heat flux to be dissipated could be even utilizing both the sides of the die packaging the surfaces with two copper plates [15].

   So dual-side-solderable IGBTs were assembled like seen in Fig. 6.4.



Module	L=W [mm]	t [mm]
1	13	2.5
2	40	4

Figure 6.4: IGBT, module assembly and copper boiler dimensions [15]

These modules were immersed in saturated pool of C3F7OCH3 (the same dielectric fluid of the previous paper).

Experimentally was measured a peak heat flux of 1180 W/cm^2 with a resistance of 0.040°C·cm^2/W in a die surface of 0.144 cm^2 and 550 W/cm^2 with a resistance of 0.11°C·cm^2/W in a die surface of 1.46 cm^2.

Was even tested a complete immersion system (with two of the 1,44cm^2 IGBT modules coupled) in an acrylic enclosure and at the top an added air-cooled condenser, see Fig.6.5.

110cc of fluid in this system was able to dissipate efficiently up to 800W.

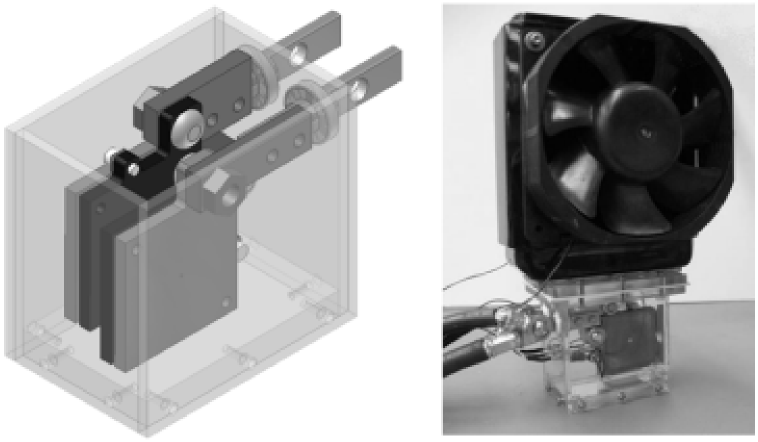


Figure 6.5: Tested system with upper air condenser [15]

4. Now a really important paper studied is the one of Campbell and Tolbert published by IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS in 2007 [30].

   They presented a two-phase cooling method using the bath of R134a refrigerant (at 21°C) for dissipate the heat of one IGBT (International Rectifier IRGBC20UD2 with 1KHz of frequency for on/off cyle, 480V of voltage applied and gate voltage of 13V); the glass vessel is closed with aluminum top and bottom flanges (pressure inside 590 kPa) and a condensing tube is putted at the top, see Fig.6.6.

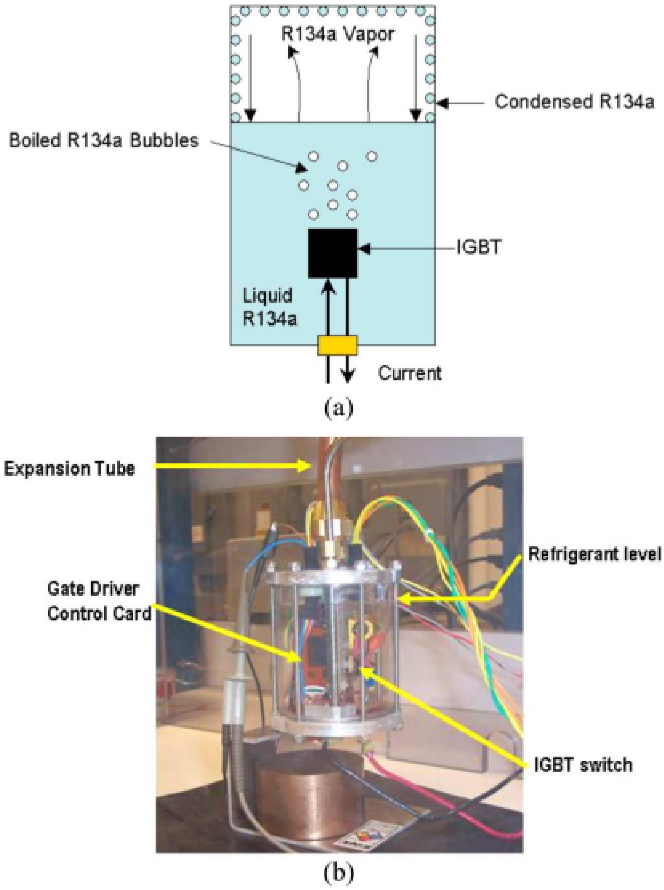


Figure 6.6: Experimental set up.(a) Schematic drawing.(b) Experimental tank picture [30]

R134a (boiling point at 26.3 °C) was used for the low vapour/liquid volume ratio so the volume to contain vapour is lower at a certain pressure (with a benefit that in closed vessels the working pressures can be engineering affordable and even more safe system).

This immersion cooled experiment was conducted in parallel with the same IGBT air cooled, confirming the effective dielectric characteristic of this fluid (voltage and current waveforms are identical in the two cases and no particular switching discrepancy among them), the no deterioration of electric parts (850 days of immersion and tests) and heat flux reached for this IGBT in R134a was of 114 W/cm^2.

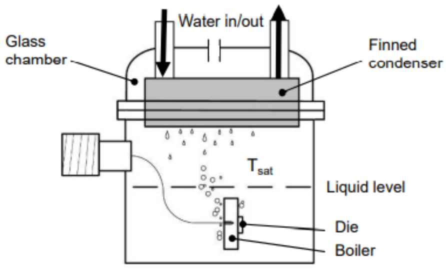
In secondary tests, the same vessel with the same IGBT was putted in operation with an automotive air-condition system of 9320W (compressor, condenser and a control system) used usually to cool the cabinet. This system was more than able to cool just one IGBT.

This coupling was even tested after with a goal of a practical application on cooling a 30KW traction inverter (six-IGBTs) of HEVs (about 1200W of heat loss estimated).The value reached here experimentally was of cooling up to 605W but just for a laboratory impossibility to reach the target of heating resistors, but based on extrapolation this system is able to dissipate even

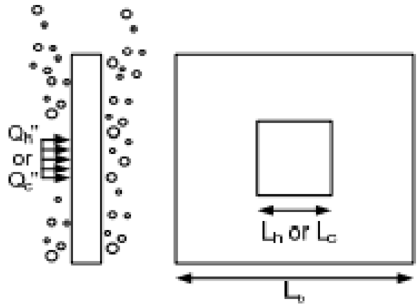
1200W from IGBTs maintaining its temperature below 110°C (125°C is usually the maximum one allowed for Si IGBTs).

5. In 2008 was published in the ASME Summer Heat Transfer Conference the work of Barnes and Tuma from 3M Company [14] regarding an immersion cooling in saturated C3F7OCH3 liquid (boiling point at 34°C) of an IGBT die (International Rectifier IRGC75B60KB) at atmospheric pressure and with an upper water cooled condensation system like is represented in Fig. 6.7a.

   This die is soldered (SnPb solder) to a copper heat spreader with micro porous metallic boiling enhancement coating, see Fig. 6.7b.



(a) IGBT immersion cooling experimental setup



(b) Immersion cooled boiler

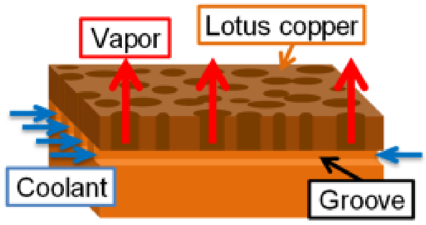
Figure 6.7: Immersion cooling of IGBT in segregated hydrofluoroether liquid [14]

   Boiler temperature measurements showed a peak boiler-to-fluid heat transfer coefficient of 14W/cm^2·K at a die level heat flux of 255 W/cm^2 but the maximum heat flux reached was of 400 W/cm^2 (13W/cm^2·K) with a junction-to-fluid thermal resistivity of 0.20°C/(W/cm^2) and a junction-to-fluid temperature differential of 80°C at this heat flux.

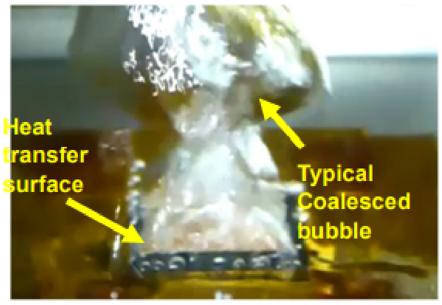
6. In 2020 the Journal of Thermal Science and Technology in Japan published a study regarding a possible solution to cool the future heat flux expected for the SiC based inverter in EV (around 500W/cm^2) with two-phase free-power immersion cooling (so cooling system more compact and light thanks to no need of pump) [195].

   At first was discussed an ideal stacking structure around the SiC power element by quantitatively estimating the thermal resistances and the temperature jumps under high heat flux conditions of 300-500 W/cm^2.

   After a power-free two-phase immersion cooling technology was proposed to create the ideal stacking calculated before. So now, the author with Lotus Thermal Solution Co., applied the Lotus-type of porous copper having a unidirectional pore structure jointed onto a grooved heat transfer surface (this geometric structure makes possible to the fluid to supplied naturally the grove by the strong discharge of the vapor and as important aspect liquid supply is divided by vapor creation, "breathing effect", so higher CHF can be reached), see Fig 6.8.



(a) Lotus copper on a grooved heat transfer surface



(b) Photo of experimental surface

Figure 6.8: Enhanced surface for increasing heat transfer [195]

The experimental system was composed,like in Fig.6.9, of a 1cm^2 copper lotus grooved heat transfer heated by four heaters to simulate the heat from power electronics. This is immersed in a container of glass (air degassed) at atmospheric pressure with distilled-water that is in a condition of saturated pool boiling (100°C) for the tests. There is even an upper water condenser.

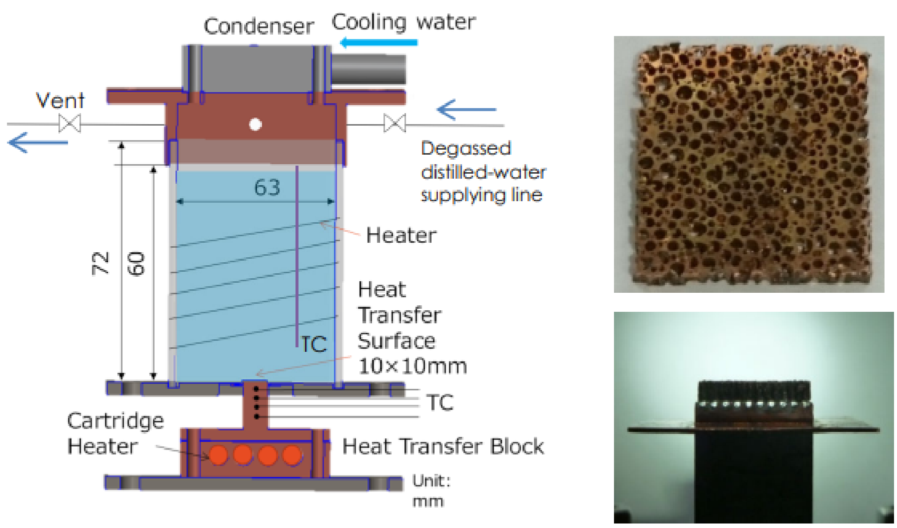


Figure 6.9: Experimental set up [195]

Experimental tests with groves of different section shows that groves of 0,5 mm are the ones to dissipate till 461 W/cm^2 with a wall super heat of 60K. CHF can be increased up to 534 W/cm^2 (value 3.71 times higher than that of the smooth surface) but the maximum wall superheat will increase to up 111 K.

7. Up to now were always explained systems with an interface of specific conformity and material between the electronic part and the pool of water or electronic converters directly immersed in dielectric fluids. Now with this article, published in the International Journal of Heat and Mass Transfer in 2020 [22], can be shown an alternative solution of immersing the electronics directly in de-ionized water to take all the thermodynamic benefits of this fluid with

a coat of the device with 1-25 μm Parylene C (it is deposited with an ultra uniform thickness on the electronics through a chemical vapor deposition that enables gas penetration into nanoscale trenches and crevices) to make the entire circuit electrically insulated (effectiveness of no current leakage up to 200Volts).

Gallium Nitride (GaN) transistors was used as source of heat and cooled heat fluxes up to 562 W/cm^2 are reached in water pool and up to 452 W/cm^2 in water-ethylene/glycol mixture (50%-50%); to be considered that in parallel tests with the same board immersed in dielectric fluids reached at maximum 111 W/cm^2.

A 2 kW power DC-DC converter operating at 97.2% of efficiency (56W of heat loss) was tested utilizing this system and confirmed the success of this research, see Fig 6.10.

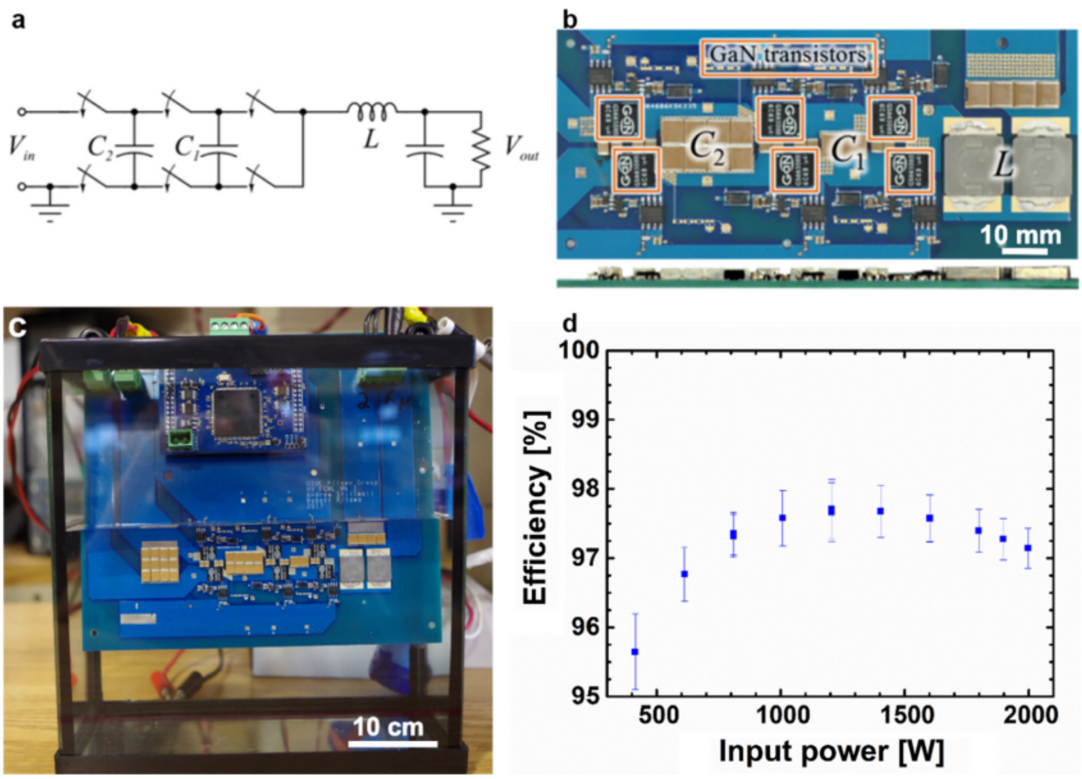


Figure 6.10: (a)Scheme of 4-level Flying Capacitor Multilevel Converter.(b)Photo of tested FCML.(c)Photo of the coated converter immersed in a pool of de-ionized water.(d) Efficiency as a function of converter input power [22]

In this research is not studied a pressure control of the tank or a condensation system, but certainly this article is the clear demonstration that direct immersion cooling in de-ionized water of high-power electronic can be achieved thanks to electrical insulating coatings and gives basis for the future research that is still an open case of study in this field; industrially is needed an higher reliability to become feasible.

6.2 Patents

1. Starting from one simple system patented in 2013, is analyzed at first the one of Campbell, Richard C.Chu, Milnes P.DAVID, etc. [115].

   They patented a system to cool power electronic devices by immersion with a particular use of two immiscible dielectric fluids, see Fig.6.11: the bottom one is in direct contact with the heater device and boils; the upper one is the condensing fluid and has a lower specific gravity and a higher thermal conductivity than the fluid below plus a propensity to facilitate the condensing of vaporized boiling fluid.

   An upper structure touches the condensing region (the one that touches the condensing fluid) and for a smaller part the sub-cooling region (the one that touches the boiling fluid). To externally cool the condenser can be used or a air fan cooled fins (Fig. 6.11) or for higher fluxes to be cooled even water cooled heat exchange, like in Fig. 6.12.

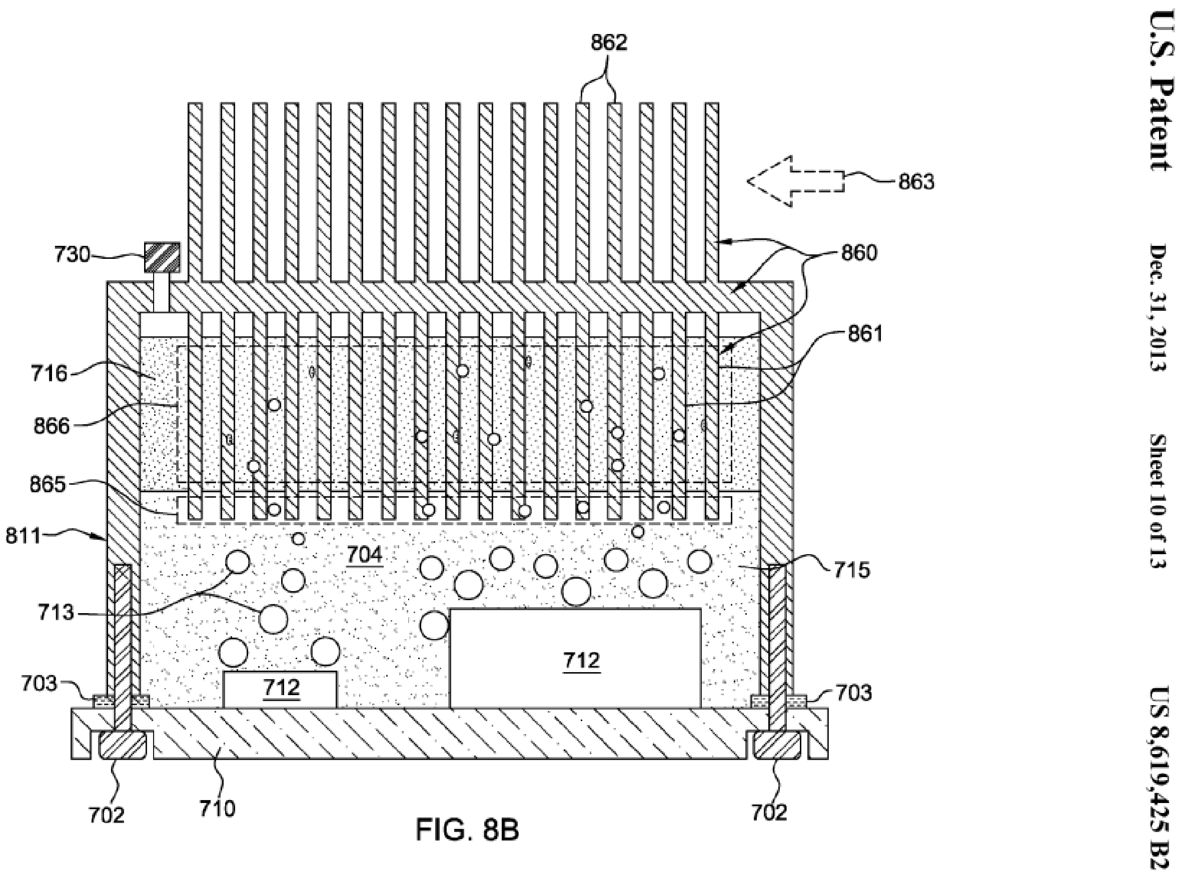


Figure 6.11: System drawing, air-cooled condenser [115]

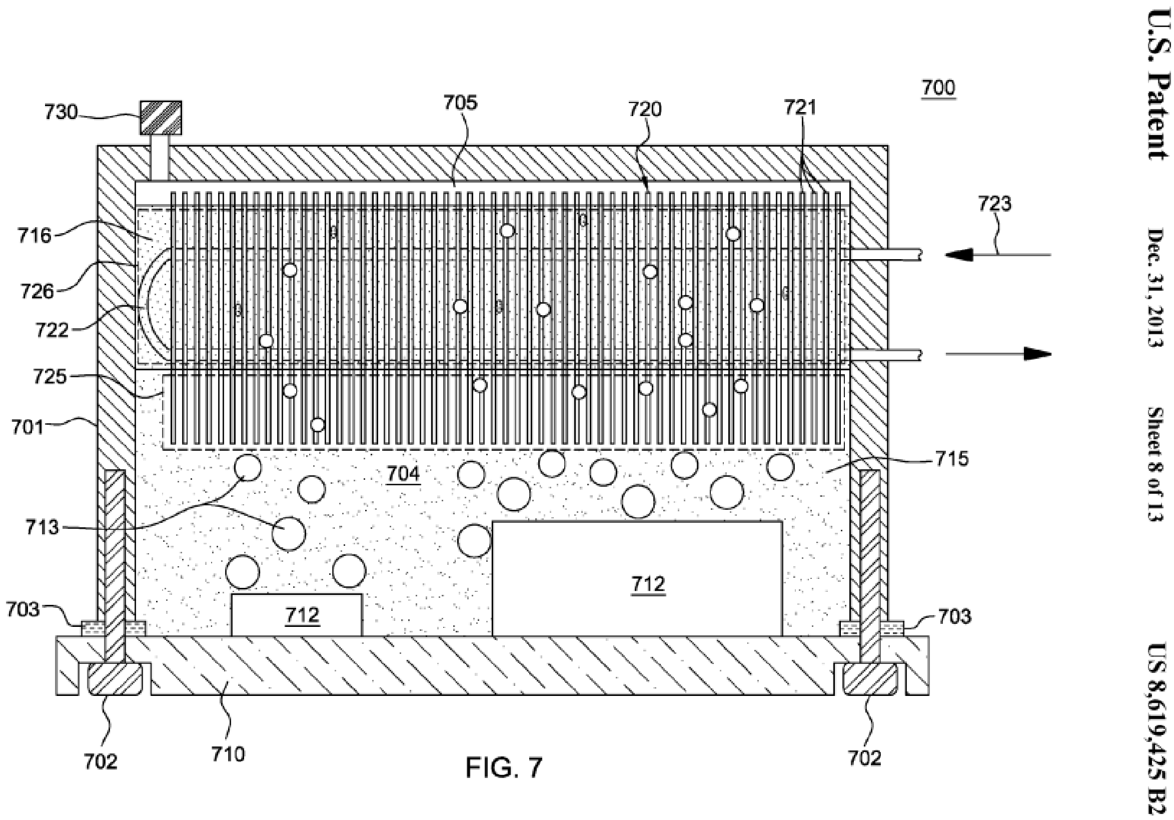
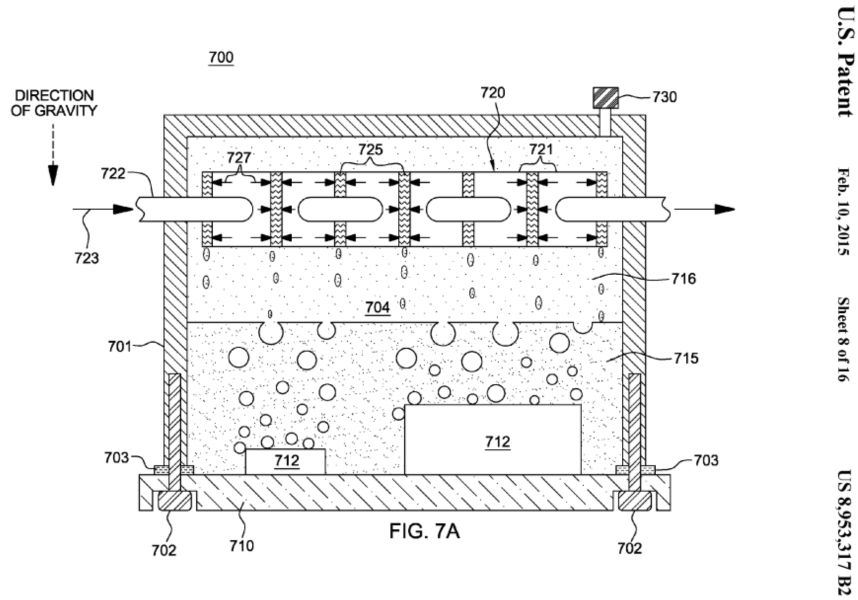
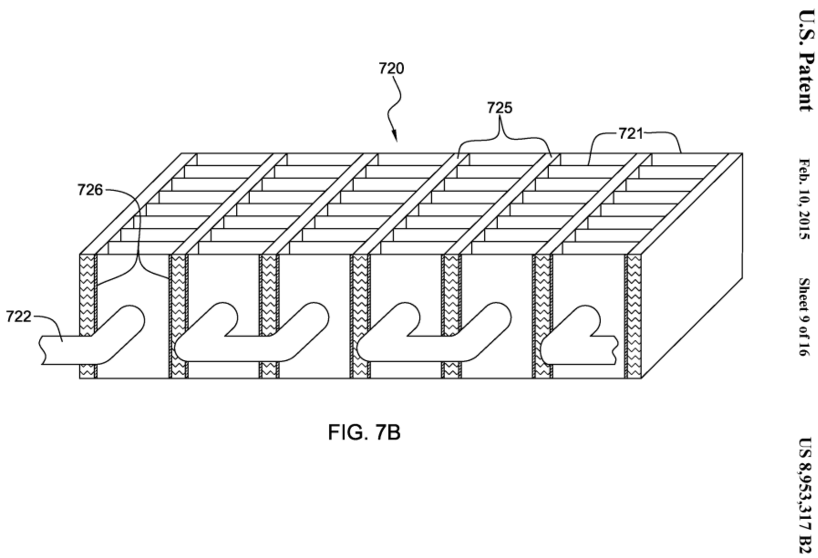


Figure 6.12: System drawing, water-cooled condenser [115]

2. Just two years later, the same authors of the previous work, enhanced the already crated systems, Fig.6.13a, using a vapor-condenser made with a parallel of tube-type liquid cooled conductive fins and wicking components between these to facilitate the drawing (and so increase the heat transfer) of the condensed fluid from the surface of the fins, like can be seen in Fig.6.13b [116]. These wicking strips can be made of porous metal (like porous silver, porous copper, porous aluminum, sintered copper,...), porous glass or porous ceramics.



(a) System drawing.



(b) Condenser drawing.

Figure 6.13: Two-phase immersion cooling of power electronics with a particular condenser [116]

3. Browne, Gunturi,etc from General Electric Company, patented in 2015 a method and system to cool the heat from power semiconductor devices in harsh environments like in deep sea [174]. The electronic is press-packed in a cylindrical bodies spaced by heat sinks and immerses in a dielectric fluid pool-cooling pressure vessel; an externally cooled plate condense the vapour. Are added even a plurality of radially inwardly extending stiffening ribs to

increase the surface area of heat transfer, see Fig.6.14, so heat is dissipated mainly by the boiling phenomena and condensation and secondly via convection/conduction thanks to these ribs.

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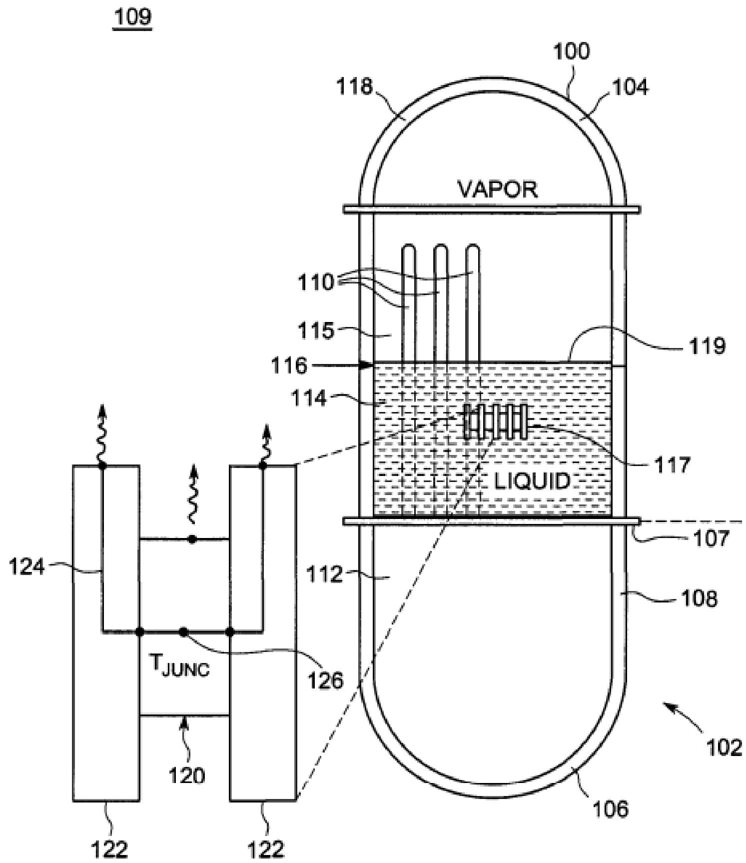


FIG. 1

Figure 6.14: System drawing [174]

4. In 2017 the inventors Campbell, Shepard and Katsumata published an European Patent for cooling power converters or motor controller [90].

   In traditional immersion cooling systems, the tank with the dielectric fluid inside is rigid to resist to the change of pressure as a consequence of heating. In this patent was proposed a particular sealed housing but with a variable volume in base of the pressure status inside to reduce the rate of pressure change over time, see Fig.6.15.

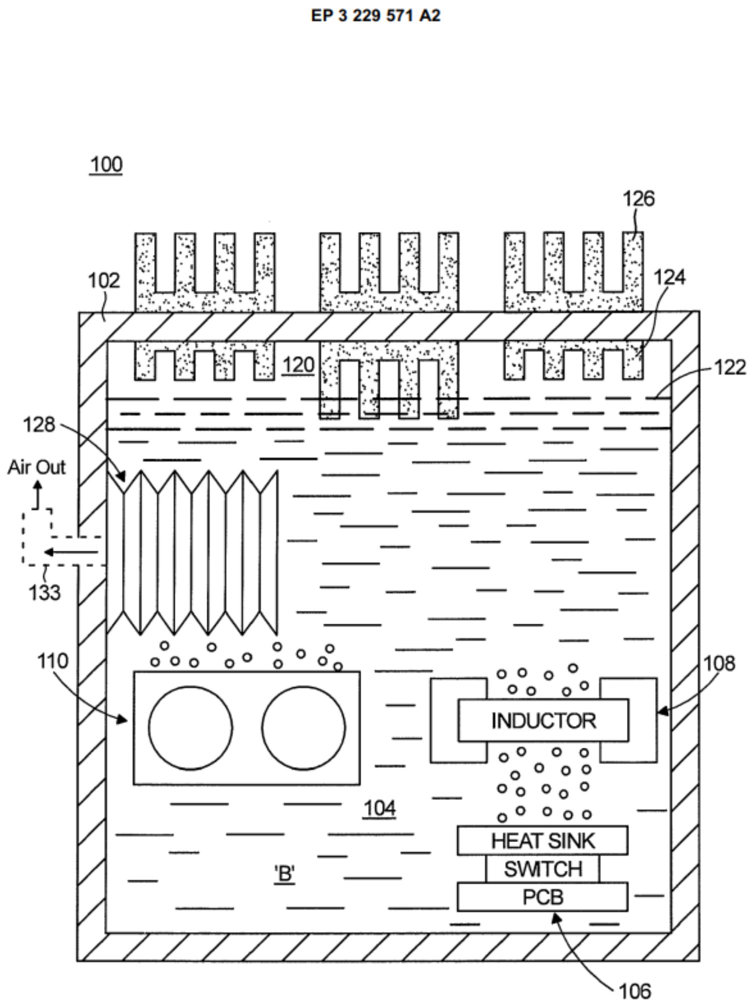


Figure 6.15: Sealed immersion cooling system with a solution to reduce the rate of pressure changing inside [90]

As can be seen in the previous drawing, the changing in pressure inside the chamber is allowed thanks an elastic bellows that can be metallic (aluminium, steel, ...). This bellows is moved by a constant spring sized adequately to the specific pressure range expected.

5. Usually pool boiling immersion cooling is considered a non adequate solution for application where can happen change of the orientation for the electronic device. Even as explained in the previous chapter the orientation doesn't influence a lot the heat fluxes dissipated by boiling is small inclination, it can be a factor really determinant if there is an often change and for really high inclination can determine a drastically reduction in dissipation.

   In 2016 was published by some inventors from Toyota Motor Engineering and Manufacturing North America, Inc. a patent regarding a system to maintain the upward orientation for pool boiling cooling of electronic devices, as seen in Fig. 6.16b [48].

   The stabilizing unit is a gyroscope that here is drown, Fig.6.4, as passive one (moved just due to external forces like gravity force) or can be even active (powered by one or more motors, magnetic devices,...). This gyroscope with the electronic device inside is completely immersed in a dielectric two-phase liquid in a tank similar to the ones described already before, completely sealed, and with a traditional air condenser.

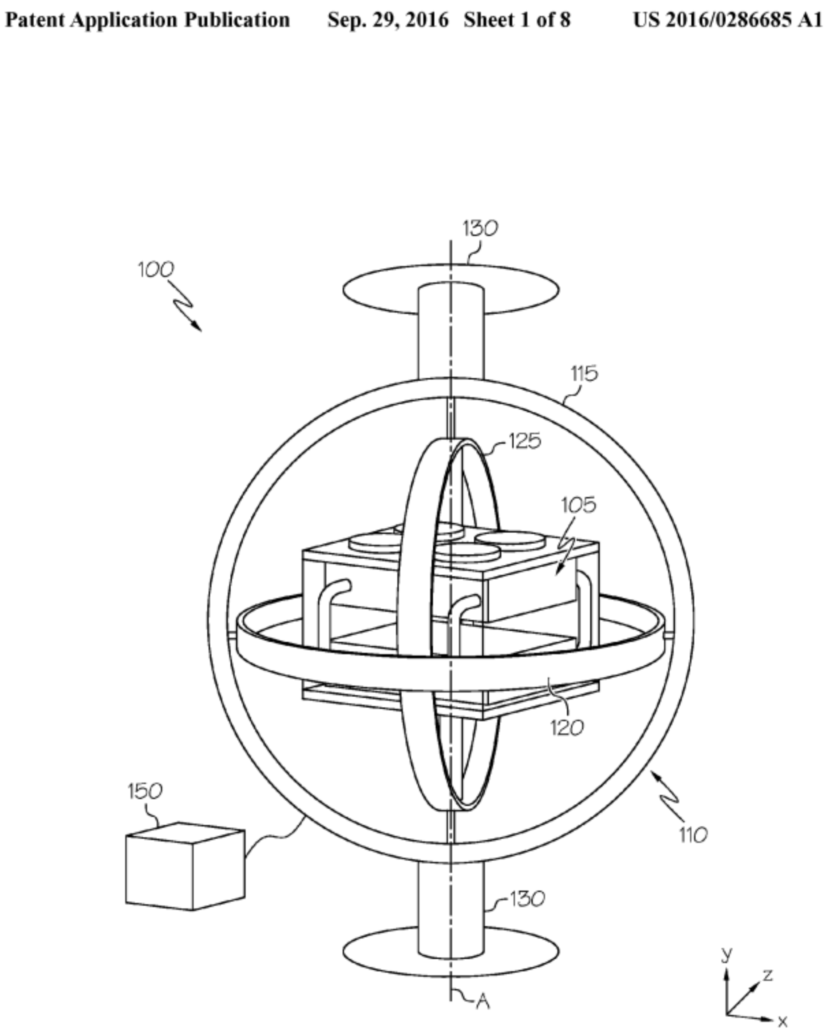
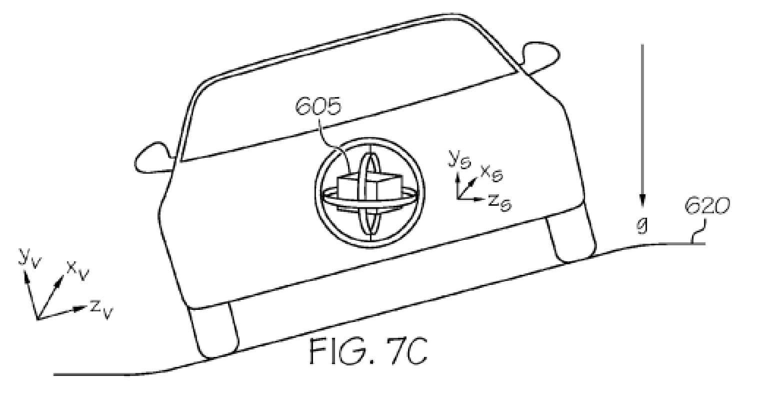


FIG. 1

(a) Stabilizer drawing



(b) Example of stabilizer in a practical application

Figure 6.16: Stabilizing unit to maintain the pool boiling cooling upward in a plurality of orientation [48]

6. In the same year and by the same group of Toyota Motor Engineering and Manufacturing North America, Inc. was published a patent for extending the maximum heat flux cooled by two-phase immersion with a method of chamber parameters control [47].

   The inlet of the fluid arrives to a chamber with a surface that, heating by power electronics, will generate the boiling cooling. Externally is present a pump device (may be one or more components of a condensing cycle) and a a temperature conditioning unit (with in input the outlet of the pump).

   The innovation is the control system, in fact the temperature conditioning sent a fluid into the chamber at a variable temperature in base of the signals received by the pressure sensor inside the chamber and the temperature sensor of the device, see Fig. 6.17.

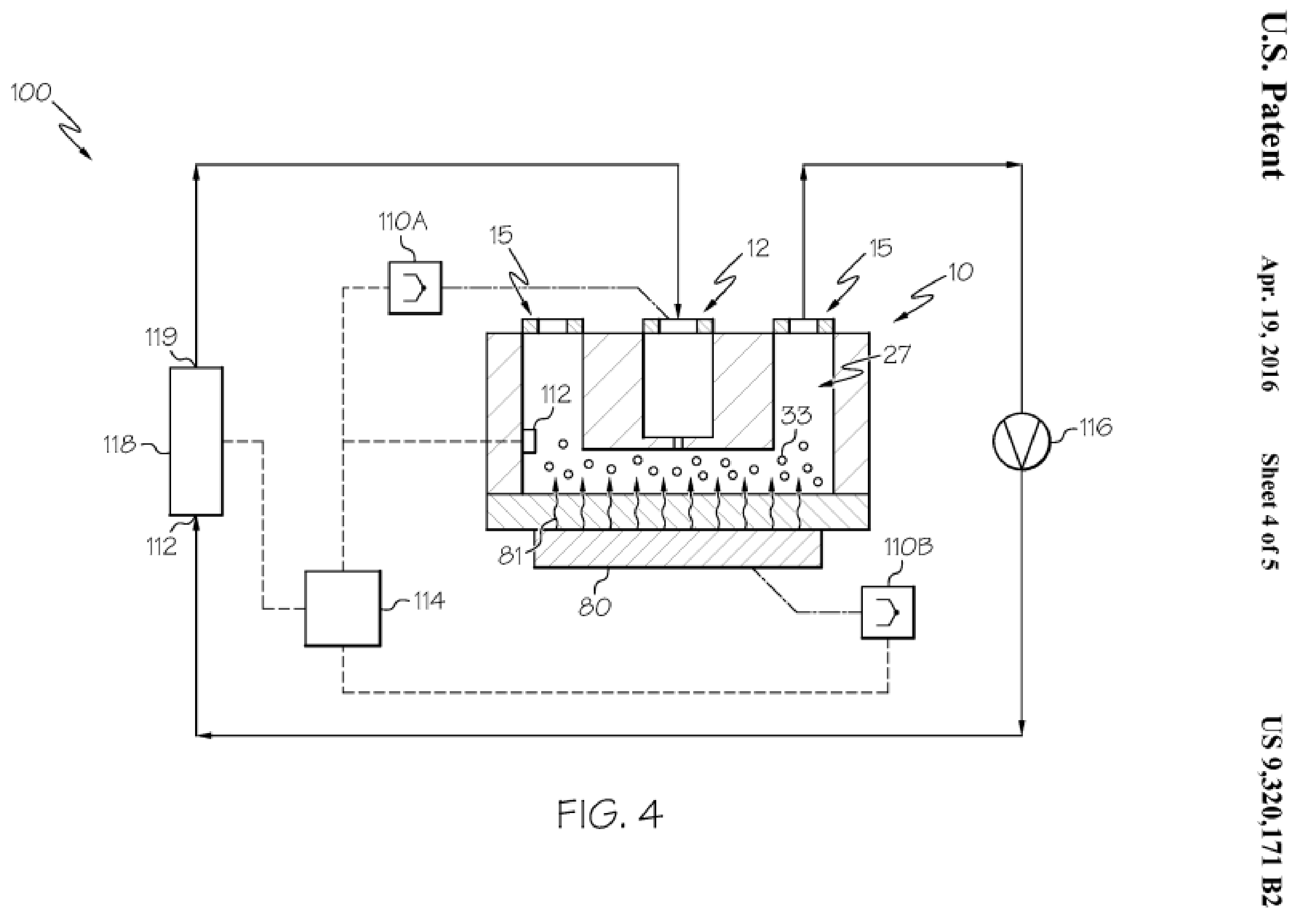


Figure 6.17: Scheme of the entire plant [47]

Chapter 7

Fluids used for cooling power electronics

Even if the literature shows that microchannel forced conduction and systems with two-phase fluids are the best ones in heat flux removing, must be notice that they are limited even for the maximum heat transfer coefficients that the conventional fluids show. To accommodate a heat flux of 100 W/cm^2 at a temperature difference of 50 K requires an effective heat transfer coefficient (including a possible area enlarging factor) of 20,000 W/m^2·K [112]. So, for passing the limitations of these fluids, start to be studied and utilized fluids with higher thermal performances and nowadays even with lower environmental impact for reaching the goal of sustainability planned by nations.

Maintaining the focus of this research on two-phase immersion cooling of power electronics, we will resume the new emerging dielectric (and non) fluids with related thermal and environmental characteristic (ozone depletion potential-ODP and global warming potential-GWP), compared to the traditional ones.

Keep attention to the fact that even if some fluid can shows better thermal characteristic, the parameter to consider are more wide and is really important to consider these in base of the specific cooling application. Indeed as a general rule ideal coolant should be as much possible inexpensive, non-toxic, non-flammable and obviously is better that should be with high thermal conductivity, low viscosity, etc...

Of course even factors like chemical compatibility between fluid and electronic is to be considered at first [163].

7.1 Non-dielectric fluids

Non-dielectric fluids show in general higher thermal characteristics in comparison to dielectric fluids, but due their conductive nature can't be utilized for direct cooling as long us are used particular electrical insulate coatings for the electronic board.

Even the viscosity is lower in comparison to dielectric fluids due to their commonly aqueous nature.

The most common non-dielectric fluid is water [W] (the highest heat transfer coefficient in either condensation or boiling, compatible with Cu/SS, if deionized decreases its corrosion effects and electrical conductivity), see Tab.7.1.

	Water (W)	Ethylene glycol (EG)
Boiling point at 1 atm (°C)	100	198
Freezing point (°C)	0	-12.9
Thermal conductivity (W/m K)	0.613	0.26
Specific heat (KJ/Kg K)	4.18	2.84
Viscosity (mPa s)	0.89	19.83
Density (Kg/m^3)	1000	1109
Dielectric strenght, gap KV,(mm)	65-70	37
Heat of vaporization (KJ/Kg)	2256	800
Global warming potential (GWP)	/	4
Ozone depletion potential (ODP)	/	0
Flammability	No	Yes

Table 7.1: Water and ethylene glycol characteristics

Others are ethylene glycol [EG] (high thermal properties, low freezing point at -12,9°C, high boiling point at 197°C, compatibility with Cu/Al/SS, no odor; is classified toxic), see Fig. 7.1, or a mixture at different percentage of these [W/EG] in base of which characteristic we need in predominance for our cooling system (the thermal advantages of water or the low FP/high BP of ethylene glycol); propylene glycol [PG] (in comparison to EG it has higher cost and viscosity, the same corrosion action and the advantage of non-toxicity), W/methanol, W/ethanol, NaCl solution potassium formate [KFO] solution, and liquid metals (like Ga-In-Sn that shows high thermal properties).

7.2 Dielectric fluids

Regarding the non conductive and inert fluids that are used as coolant of electronic devices (but anyway in needed to study also the compatibility with the material and the toxicity not only the dielectric characteristics), they can be subdivided in general in 4 main categories [141]:

- Aromatics based liquids: they are the cheapest and with the best thermal performances but they are classified as toxic and some of these have a non-neutral odor (keep attention for safety and quality of working environment for operators). Some examples: diethyl benzene (DEB), toluene, benzenes, xylene, etc...

- Silicone based liquids: commonly called silicon oils are widely used as coolant for their optimal characteristic that, being a synthetic polymeric compound, changing the chain length changes consequently the viscosity and the freezing point, so controlled properties. They show no-odor and non-toxicity (guarantee safe working ambient).

- Aliphatics based liquids: used for direct cooling of electronics they include aliphatic hydrocarbons of paraffinic and iso-paraffinic type (including mineral oils). No-odor and non toxic.

- Fluorocarbons based fluids: generally used as fluids for immersion cooling of electronics with the goal of inertness, stability, non-flammability and high dielectric properties. These fluids are compatible with all the kinds of materials and so provides an high corrosion resistance and long therm reliability.

The negative aspects of these fluids in comparison to non-dielectric ones are the fact that: are expensive, show low thermal properties (thermal conductivity and heat capacity) and the possibility of leak (due to low surface tension).

Appertain to this category fluorinert fluids (FC-40, FC-43, FC-72, FC-770, FC-3284, etc...), hydrofluorocarbons (HFC), hydrofluoroethers (HFE) and fluoroketones (FK).

The 3M company is nowadays a leader company in dielectric fluids studies and marketing; 3M Fluorinert and, more recently, for the environmental attention the 3M Novec fluids are the categories of fluids mostly used in single and two-phase immersion cooling for electronic devices. The specific characteristics of each type of dielectric fluid are reported in Tab.7.2 for the Fluorinert ones and Tab.7.3 for the Novec ones. In general the two groups show characteristics that depend on the single type of fluid; the biggest differences are regarding the environmental impact and toxicity of these fluids: the Novec ones show the lowest global warming potential (GWP)[1] and quite zero ozone depletion potential (ODP)[2] and are non-toxic (safe for operators during installation/maintenance and adequate for semi-open baths) indeed fluorinert series has even quite zero ODP but higher GWP and is even a bit more toxic (must be keep attention to the safety of operators).

[1]Cooling liquids starts to be strongly regulated since Montreal Protocol in 1987 and in particular from Kyoto Protocol in 1997 refrigerant with high environmental impact were banned directly. The regulations became even more stringent years after years with a really alert attention after the Paris Agreement in 2015 [88].

GWP= greenhouse gases warm the earth by absorbing energy and decreasing the rate at which the energy escapes the atmosphere. In base of the type of gas is evaluated their specific residence time in atmosphere. GWP is a measure of how much energy the emission of 1 ton of a generic gas will be absorbed over a given period of time (100 years usually), related to the emissions of 1 ton of carbon dioxide (CO2) in the same temporal slot. CO2 has a GWP of 1 and is the reference gas. So higher GWP means higher heating of Heart in comparison to CO2 impact. Regarding the range of dangerous, the slots can be grossly: $<$300 low impact; 300-1000 medium impact; $>$1000 high impact [54].

[2]ODP= it is the measure of how much danger to the ozone layer can be caused by a chemical substance; its value is taken with a reference of the impact of the same quantity in mass of trichlorofluoromethane (CFC-11) that has the ODP of reference equal to 1. Even for this parameter, higher are the values, higher is the environmental impact [67].

	FC-40	FC-43	FC-72	FC-770	FC-3284
Boiling point at 1 atm (°C)	155	174	56	95	50
Freezing point (°C)	-57	-50	-90	-127	-73
Thermal conductivity (W/m K)	0.065	0.065	0.057	0.063	0.062
Specific heat (KJ/Kg K)	1.1	1.1	1.1	1.038	1.1
Viscosity (mPa s)	1.8	2.5	0.38	0.79	0.42
Density (Kg/m^3)	1850	1860	1680	1763	1710
Dielectric strenght, gap KV,(mm)	46	42	>40	>40	43
Heat of vaporization (KJ/Kg)	68	70	88	86	105
Global warming potential (GWP)	>5000	>5000	>5000	>5000	>5000
Ozone depletion potential (ODP)	0	0	0	0	0
Flammability	No	No	No	No	No

Table 7.2: 3M Fluorinert dielectric fluids [4]

	Novec 7000	Novec 7100	Novec 7200	Novec 7300	Novec 7500	Novec 649
Boiling point at 1 atm (°C)	34	61	76	98	128	49
Freezing point (°C)	-122	-135	-138	-38	-100	-108
Thermal conductivity (W/m K)	0.075	0.069	0.068	0.063	0.065	0.059
Specific heat (KJ/Kg K)	1.3	1.183	1.22	1.14	1.128	1.103
Viscosity (mPa s)	0.32	0.38	0.41	0.71	0.77	0.40
Density (Kg/m^3)	1400	1510	1420	1660	1614	1600
Dielectric strength, gap KV,(mm)	40	40	40	40	40	>40
Heat of vaporization (KJ/Kg)	142	112	119	102	89	88
Global warming potential (GWP)	420	297	59	210	100	1
Ozone depletion potential (ODP)	0	0	0	0	0	0
Flammability	No	No	No	No	No	No

Table 7.3: 3M Novec dielectric fluids [5]

7.3 Nanofluids

To reach the request of increasing the heat flux cooled from even more dense power electronics, particular mixture starts to be created, like nanofluid refrigerant where micro-sized (1-100nm) metals, oxides, carbides, carbon nanotubes particles are dispersed in traditional dielectric and non-dielectric liquids.

Must be keep attention to the use of these fluids for electronic cooling because the nano-particles could deposit or damage the component in base of the kind of flows.

The presence of added particles enhances the thermal conductivity of the base liquid and increasing their percentage concentration, like can be seen in Fig.7.1, is showed that for different types of material particles and base fluids there is a relative enhancement in thermal conductivity in comparison to simple base fluid.

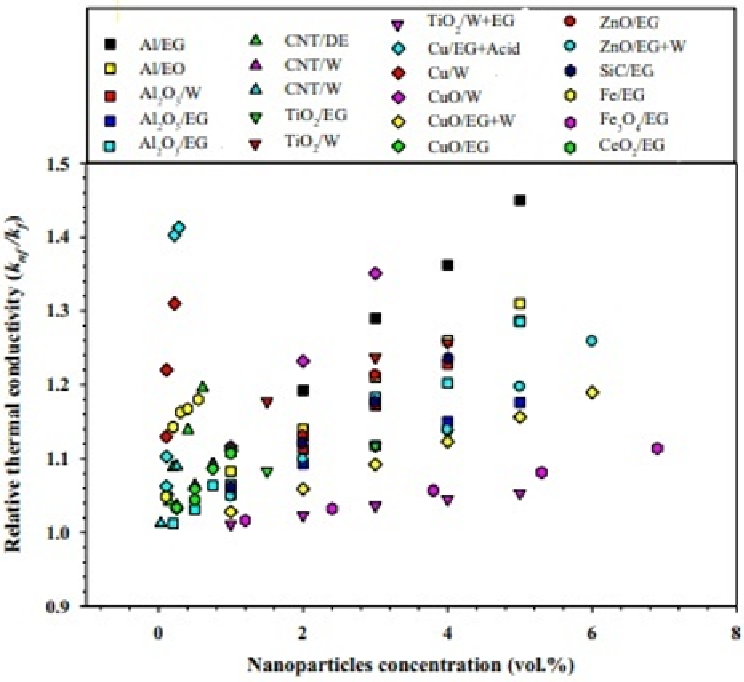


Figure 7.1: Enhancement of thermal conductivity of various types of nanofluids as a function of concentration of nanoparticles [141]

But the added value of particles is not related just to thermal conductivity improvements but even in the CHF increasing, if we are in a boiling regime obviously. As can be seen in Fig.7.2, the enhancement is mainly at lower particle concentrations and experimentally was shown that there is a sort of critical concentration of particles until there is the increase in CHF, after this threshold it will decrease. In figure, for the same type of particles and base fluids there are different pointers because even other parameters influence CHF like the deposition of nanoparticles on heater wall, roughness of wall surface, addition of surfactants but this kind of analysis is not done in this work.

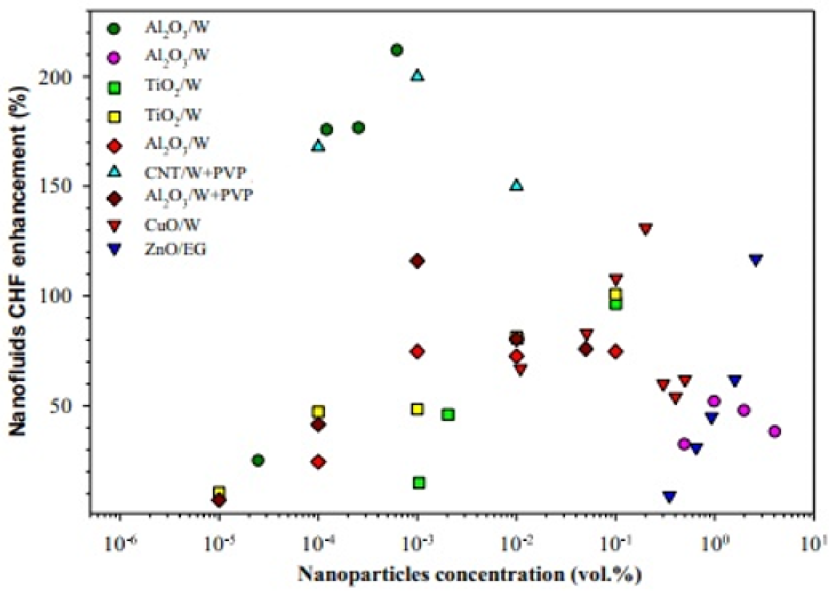


Figure 7.2: Boiling CHF of various nanofluids as a function of concentration of nanoparticles [141]

7.4 Conclusion and discourse for choosing the optimal fluid for immersion cooling of power electronics

As said in the introduction of this chapter, for cooling electronic devices with a direct immersion is necessary the dielectric characteristic of the fluid. This solution could seems the optimal one because shows the elimination of the thermal resistance of the package that classically seal the board in indirect cooling solutions, but in reality there are some disadvantages, or better, some factors to consider to choose the optimal solution.

The mayor one disadvantage is that for direct immersion cooling, there is the necessity of dielectric fluids used (or should be founded solutions to make the board electrically insulating), so is eliminated the possibility of using water (the fluid with the highest thermal aspect in absolute but with even an electrically conductive nature).

Indeed dielectric liquids possess, in comparison to water, lower thermal aspects in general caused by different chemical characteristics.

Even regarding the vaporization process they are thermally poor too in comparison to water and show an higher wetting nature (almost zero static contact angle in surfaces) and this is a negative aspect for the nucleation process because they tend to be more incline to non easy evacuation in the cavities of the surfaces; this reason causes that dielectric liquids have the CHF point at a super-heat temperature (Twall-Tsat) higher (in the range of 30-72°C) in comparison to water (around 30°C) plus a consequently lower drop down of surface temperature after the start of boiling. Anyway even for the low latent heat of vaporization of dielectric liquids, in comparison to water, they exhibit a lower CHF (to have a general order of magnitude example, dielectric liquids in simple pool boiling of horizontal flat surface at atmospheric pressure show a CHF of around 15–25 W/cm^2, 100–150 W/cm^2 for water in the same configuration).

Just in the last twenty years the problem of environmental impact of refrigerants must be keep under study and attention, so no one of the best thermal performance fluids can be used if not Low-GWP and near zero-ODP declared.

Was not deeply analyzed the simple compatibility of the board or wires elements with the fluid considered but odiously this aspect is highly important. There are already in literature compatibility tables for liquid/materials coupling but must be keep attention to the fact that boiling phenomena can accelerate drastically the degradation process of the board materials because with pure condensate in contact with plastic materials can extract oils similar with it, so faster degradation process, plus a consequently accumulation of this oil on the boiling surface (and inside the surface pores) limiting heat transfer. Is suggested for this aim do tests, like the soxhlet test, that needs as an accelerated prove of compatibility for the board/fluid coupling. Anyway even if the compatibility is good and the oil dissolved is low, is suggested (in particular if used HFE fluids) to put in the bath an absorbent to remove all the contamination, like activated carbon that "cleans up" the fluid [182].

Chapter 8

Review of surface types for pool boiling

As explained theoretically in the chapter 5.2, one parameter that is of fundamental importance to increase the heat transfer in pool boiling is the type of coupling heated surface-two phase fluid.

The necessity to achieve increasingly high heat dissipation rate in recent electronics modules, has pushed the researches of last decade mainly, thought enhancements of heated surfaces as can be seen in Fig. 8.1, where is showed the exponential trend of documents published last years on the Scopus database typing ”boiling” and ”enhancement”.

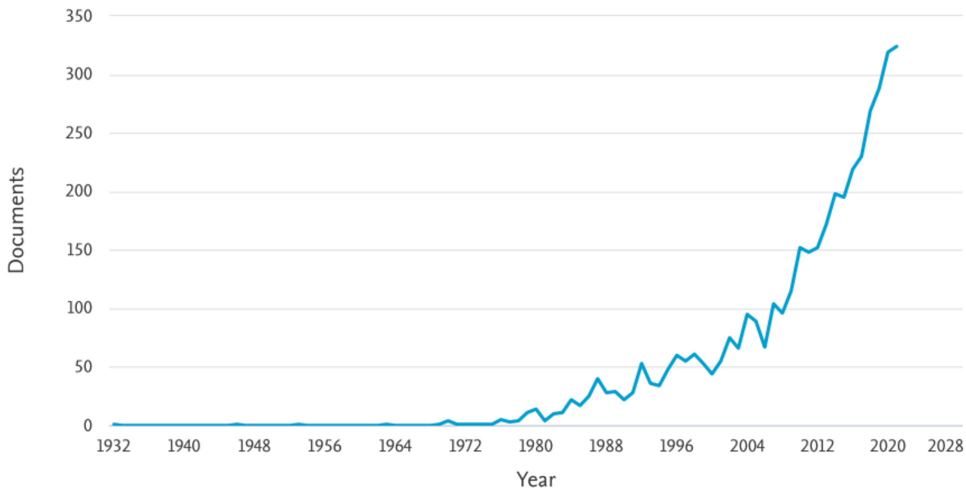


Figure 8.1: Trend of documents published by year on Scopus database, searching ”boiling” and ”enhancement”

With the purpose of making an exhaustive review of different combinations fluid-surface types [1], is following done a work of subdivision and analysis of maximum critical heat fluxes (CHF) (and heat transfer coefficients if are reported in citations) and the related wall super-heat ΔT_{CHF} for the published studies.

[1]The lists of references of this chapter are mainly viewed in the review work of M.M. Mahmoud and T.G. Karayiannis [130].

To have more uniform parameters for doing comparisons, the papers discuss the boiling performances of horizontal upward facing surfaces with pure liquids at atmospheric pressure.

8.1 Surfaces types for water pool boiling

Water is mainly studied with surfaces coupling because is the liquid with the highest thermal properties, as explained deeply many times in this thesis work.

8.1.1 Smooth surfaces with water

In Tab.8.1 are listed the heat transfer performances from most relevant articles for the coupling water-planar heated surface of different materials.

All the surfaces here reported are defined "smooth" even if there is not an universal standard for this definition which gives the explanation of the different values reported in the table for the same types of couplings (Is needed a standard to "smooth surface" to avoid this type of discrepancy in results).

Article	Fluid	Material	Surface preparation	Roughness value [µm]	HTC [kW/m^{2}K]	CHF [W/cm^2]	ΔT_{CHF} [K]
[93]	W	Si	Not reported	0.00175	18.1	99.3	35.9
[124]	W	Si	Not reported	Not reported	21.8	98	28.3
[125]	W	Si	Not reported	Not reported	11.9	70	45
[192]	W	Si	Not reported	Not reported	14.5	72	43
[109]	W	Si	Not reported	Not reported	21	150	47
[120]	W	Si	Not reported	Not reported	15.2	80	36
[156]	W	Cu	Not reported	0.068	38.3	124	21.3
[81]	W	Cu	Not reported	Not reported	41.8	130	19.45
[49]	W	Cu	EDM	2.9	31.75	104	20.8
[165]	W	Cu	Not reported	Not reported	72.1	110	10.7
[173]	W	Cu	Abrasive AlO	0.05	30.9	77.2	17.1
[168]	W	Cu	Not reported	Not reported	19.74	85.3	30.5
[106]	W	Cu	Not reported	0.05	72.3	125	11.3
[157]	W	Cu	Not reported	Not reported	37.8	123	24
[64]	W	Cu	Sand paper	0.2	51.8	85	13.9
[35]	W	Cu	Not reported	Not reported	47.9	111	21.3
[68]	W	Cu	Emery paper 2000	0.2	38.8	106	20.1
[127]	W	Cu	CNC machining	0.25	40	118	19.1
[102]	W	Cu	Not reported	Not reported	45.74	170	23.9
[91]	W	Cu	Not reported	Not reported	19.6	77.1	36.2
[188]	W	Cu	CNC	Not reported	61.1	170	17.1
[132]	W	Cu	Not reported	Not reported	43.3	121	19
[93]	W	Al	Sandpaper 2000	0.11	28.4	160	43.16
[73]	W	Al	Not reported	Not reported	43.1	126	23.5
[65]	W	Al	sandpaper 600	Not reported	39.8	182.2	30.96
[103]	W	SS	Not reported	Not reported	15.52	90	40
[196]	W	SS	Not reported	Not reported	45.8	86	12.3

Table 8.1: Thermal aspects of coupling smooth surfaces with water [130]

So for the reason seen before and for the different ΔT_{CHF} of the different articles, the values are defined in a range even for the same type of coupling, in particular:

- Water-Silicon: CHF (70-150 W/cm^2); HTC (11.9-21.8 kW/m^{2}K).

- Water-Copper: CHF (77.1-170 W/cm^2); HTC (19.6-72.3 kW/m^2K).
- Water-Aluminum: CHF (126-182.2 W/cm^2); HTC (28.4-43.1 kW/m^2K).
- Water-Stainless Steel: CHF (86-90 W/cm^2); HTC (15.52-45.8 kW/m^2K).

8.1.2 Rough surfaces with water

In Tab.8.2 are listed, like the previous sub-chapter, the heat transfer performances but this time for the coupling of rough surfaces with water. In the ranges of roughness analysed in each article, is chosen the "best roughness" that is the one that achieves high enhancement factors in CHF and HTC.

Article	Fluid	Material	Surface preparation	Roughness [µm]	Best roughness [µm]	CHF [W/cm^2]	ΔT_{CHF} [K]
[94]	W	Cu	Sandpaper	0.041–2.36	2.36	160	18.1
[93]	W	Cu	Sandpaper coated with 50 nm PTFE layer	0.042–1.54	0.042	67.4	13
[185]	W	Cu	Sandpaper	0.106–4.03	4.03	169	12
[146]	W	Cu	Nanosecond laser	0.171–0.29	0.271	-	-
[102]	W	Cu	Femtosecond laser	17–69.9	17	135	17.4
[56]	W	Cu	Sandpaper and femtosecond laser	0.045–1.22	1.2	125	11.6
[131]	W	Cu	Picosecond laser grooves, width 100 µm	30, 70, 100	100	226	23.2
[95]	W	Al	Sandpaper and oxidization	0.11–2.93	2.93	175	25.3
[103]	W	SS	Femtosecond laser	1.4–7.8	7.8	226	18.3
[101]	W	SS	Femtosecond laser	8.2–11.8	9.2	138	29

Table 8.2: Thermal aspects of coupling rough surfaces with water [130]

Roughness in surfaces (industrially created by chemical and vapor deposition, electrochemical deposition, sintering, selective laser melting, etc...) generally increases the CHF if compared to the smoother ones, like seen in [56] (not always, like can be seen in [93] where the CHF and HTC decrease as roughness increases considering even the same coupling and sandpaper used to create roughness; the reason to this opposite trend can be: 1 Different size of the test section which can, in larger surfaces, creates bigger bubbles that reduce the free nucleation in nearest holes, 2 Different methods to change the surface wettability [130]).

Let's see now in detail the main conclusions:

- Water-Copper: maximum CHF reached with surfaces roughened by sandpaper (at 4.03 µm) is of 169 W/cm^2 at a ΔT_{CHF} of 12 K and maximum CHF using laser grooves is 226W/cm^2 at a ΔT_{CHF} of 23.2 K.
- Water-Aluminum: maximum CHF reached with surfaces roughened by sandpaper (unidirectional) and oxidation (at 2.93 µm) is of 175 W/cm^2 at a ΔT_{CHF} of 25.3 K.
- Water-Stainless Steel: maximum CHF reached with surfaces roughened by Femtosecond laser (at 7.8 µm) is of 226 W/cm^2 at a ΔT_{CHF} of 18.3 K.

8.1.3 Enhanced surfaces with water

Surfaces with finned structure

- Non-porous fin/channels

  Are compared, in Tab.8.3, researches on pool boiling of water on non-porous copper surfaces enhanced with pin-fins or parallel channels created using CNC or WEDM machines.

Article	Fluid	Material	Surface microstructure	Characteristics	CHF [W/cm^2]	ΔT_{CHF} [K]
[42]	W	Cu	Microchannels of width (197–400 µm), depth (100–445 µm), effect of channel geometry	Channel width 0.375 mm, depth 0.4 mm	244	9
[34]	W	Cu	Interconnected microchannels (0.8 × 1.6 mm) with re-entrant cavities	Interconnected with re-entrant cavities	164	21.3
[66]	W	Cu	Parallel microchannels (0.4 × 0.45 mm) versus segmented channels	Surface with segmented fins	200	11
[69]	W	Cu	Square pin-fins of height 0.2 mm, pitch 0.1 mm and cross section 0.4 × 0.4 mm, 0.8 × 0.8 mm and 1 × 1 mm	Fin cross section 0.8 × 0.8 mm	151	5
[161]	W	Cu	Inclined interconnected meso-fins, effect of fin size, geometry, inclination angle on the vertical direction	Fins with inclination angle 450 and height 1.2 mm	122	5.7
[49]	W	Cu	Channels of -shape cross section versus the same geometry but cut in a sintered copper plate	The porous channels	117	61

Table 8.3: Thermal aspects of coupling water on non-porous copper surfaces enhanced with fins or parallel channels [130]

  As a clear deduction, the article [42] shows the highest performances (maximum CHF of 244 W/cm^2 at a wall superheat of 9 K) using a copper surface with rectangular parallel channels (0.375mm of width and 0.4mm of depth).

  The good aspect of this kind of surface is even the simplicity of manufacture.

- Porous fins/channels

  Are compared, in Tab.8.4, researches on pool boiling enhancement using this time porous fins/channels of copper.

Article	Fluid	Material	Surface microstructure	Characteristics	CHF [W/cm^2]	ΔT_{CHF} [K]
[80]	W	Cu	Microchannels of width 0.762 mm, depth 0.4 mm; effect of sintered copper coating (channels walls only, only the fins, fully coating)	Fully coated surface	313	7.6
[81]	W	Cu	Microchannels; effect of channel width (0.3–0.762 mm) and sintered coating (fully, channels only, fins only)	Channel width 0.3 mm, only walls coated	420	2
[197]	W	Cu	Microchannels of width 0.8 mm, depth 1.5 mm with sintered copper plate on top of the channels (thickness 2, 3, 4 mm)	Sintered plate thickness 4 mm	650	53.5
[152]	W	Cu	Selective laser melting (SLM)	SLM -shape channels	167	35.8
[36]	W	Cu	Micro-patterned surface consisting of square micro-pin fins 0.1 × 0.1 mm, pitch 50 µm and height 0.1–0.38 mm fabricated by powder injection molding	Pin-fins with the shortest height	142	26
[188]	W	Cu	Porous channels of width 0.3 mm and depth 0.5, 1 mm fabricated by selective laser melting. The fins were hollow with hexagonal holes.	The surface with fins height 1 mm	455	27.8
[53]	W	Cu	Low conductivity porous polymer fixture fabricated by additive manufacturing. The texture consisted of square cavities.	Cavity size 4.3 × 4.3 mm and height 2 mm	171	24.3

Table 8.4: Thermal aspects of coupling water on porous copper surfaces enhanced with fins or parallel channels [130]

The highest CHF reached by this kind of porous fins/channels is of 650 W/cm^2 with a wall superheat of 53.5 K in a microchannel (0.8 mm width) with sintered copper plate on top of the channels [197].

Surface Coating

In Tab.8.5 are reported the maximum CHF achieved in different articles with enhancement of copper surfaces in different ways.

Article	Fluid	Surface microstructure	Surface characteristics and preparation	CHF [W/cm^2]	ΔT_{CHF} [K]
[87]	W	Cu particles	Copper particles (25 µm) mixed with a binding past of thickness 50–280 µm; effect of coating thickness	210	8
[127]	W	Cu-diamond mixture	A mixture of diamond and copper of coating thickness 0.4 mm	160	7
[91]	W	CuO nanoparticles	Surfaces uniformly coated with CuO nanoparticles (25–50 nm), sintered modulated (V-shape) copper particles, hybrid coating (Cu modulated structure and deposited Cu nano-particles)	142	40
[156]	W	Sintered Cu	Acid etched surface, surface with uniform sintered copper layer (0.5 mm diameter and 1 mm thickness), surface with modulated sintered particles on top of which there are sintered cylindrical pillars and 3 mm height, hybrid structure (etching and sintering).	378	21.3
[173]	W	Aluminium oxide	Smooth and rough surfaces coated with aluminium oxide	74	17
[132]	W	Graphene oxide	Graphene oxide nanocoating of thickness 0.8 µm	214	24
[83]	W	Silver nanowires	Surface coated with silver nanowires with thickness 35–255 nm	65	76
[137]	W	Titanium oxide nanoparticles	Surface coated with titanium oxide nanoparticles and on top of the surface there is a commercial honeycomb plate of pore size 1.4 × 1.4 mm and 1 mm thickness. Test section diameter was 10, 30, 50 mm	310	24.7
[68]	W	Cu-Al composite	Surface coated with copper–aluminium composite nano-coating with coating thickness 13–45 µm	185	9.9
[35]	W	Cu-nanowires	Surface with micro grooves of width 0.262 mm, depth 0.518 mm and pitch 0.5, 1 and 4 mm (similar to square pin fins) coated with copper nanowires of height 5, 15, 25 µm	264	16.8
[157]	W	Graphene nanoplatelets	Surface coated with graphene nanoplatelets-cupper porous coating. Concentration of the graphene nanoplatelets (from 0.25% to 2.5%)	286	14.2

Table 8.5: Thermal aspects of coupling water on particular coated copper surface [130]

In the previous Tab, the article of Rioux et al. [156] shows the highest CHF of this category (378 W/cm^2 at a ΔT_{CHF} of 21.3 K) with an hybrid structure of nanostructure created by acid etching and microstructure created by sintered copper particles.

8.2 Surfaces types for dielectric liquids pool boiling

Are in this chapter compared the CHF reached with smooth surfaces and enhanced ones in contact with the most used dielectric liquids. In comparison to the previous part (using water as fluid) are here, for simplicity and even for the higher number of dielectric fluids, analysed only the studies with the higher CHF reached for different coupling dielectric fluid-material surface.

8.2.1 Smooth surfaces with dielectric liquids

Article	Fluid	Material	Surface preparation	Roughness value [µm]	HTC [kW/m^{2}K]	CHF [W/cm^2]	ΔT_{CHF} [K]
[121]	FC-72	Si	Not reported	Not reported	3.39	16.5	36.2
[114]	FC-72	Si	Not reported	Not reported	3.22	16.3	36.3
[194]	FC-72	Cu	EDM machining	Not reported	5.04	17.8	26.9
[104]	FC-72	Cu	Mechanical and chemical polishing	Not reported	3.39	18.1	35.8
[96]	FC-72	Al	Alumina compound	0.09	3.85	15.9	31.6
[134]	HFE-7300	Cu	Mill-grade finish	Not reported	4.77	17.3	22.9
[189]	HFE-7200	Cu	Emery paper Grit 2000	0.1	3.6	19.1	39.6
[32]	HFE-7200	Cu	Emery paper Grit 2000	0.085	3.62	19.2	39.6
[50]	HFE-7100	Al	Sandpaper Grit 1200	Not reported	3.26	12.7	46.3

Table 8.6: Thermal aspects of coupling smooth surfaces with dielectric liquids [130]

8.2.2 Rough surfaces with dielectric liquids

Article	Fluid	Material	Surface preparation	Roughness [µm]	Best roughness [µm]	CHF [W/cm^2]	ΔT_{CHF} [K]
[84]	FC-77	Al	Electrical Discharge Machine (EDM)	0.027–10	10	19	15.1
[7]	HFE-7100	Brass	Sandpaper	0.023–1.878	0.884	30	34.6
[96]	FC-72	Al	Mechanical (unidirectional) and sandpaper (random)	0.09–0.86	0.37	22	21.6
[63]	HFE-7000	Cu	Emery paper	0.039–0.58	0.58	29.5	15.2

Table 8.7: Thermal aspects of coupling rough surfaces with dielectric liquids [130]

8.2.3 Enhanced surfaces with dielectric liquids

Surfaces with finned structure or particular coatings

Article	Fluid	Surf.	Surface characteristics and preparation	CHF [W/cm^2]	ΔT_{CHF} [K]
[98]	FC-72	Si	Surfaces with micro-pinfins (30 × 30 × 60 µm and 60 µm pitch) in different configurations at subcooling 15–35 K. Surface fully finned, surface with fins distributed at parallel strips (width 0.7 and 1.4 mm) separated by smooth un-finned strips of width 0.3 and 0.5 mm, surface with fins distributed at square areas (0.7 × 0.7 mm and 1.4 × 1.4 mm) separated by smooth strips of width 0.3 and 0.3 mm.	52	8.2
[33]	FC-72	Si	Surfaces with micro-pinfins (30 × 30 × 60 µm and 60 µm pitch) uniformly distributed with staggered arrangement and other surfaces with fins aligned and distributed at selective square areas on the surface. The effect of nanocoating (FeMn oxide) was studied and sub-cooling was 15–35 K.	56	12.5
[114]	FC-72	Si	Cylindrical micro-pin fins of fixed height 120 µm. areas on the surface with a blank circular area at the middle. The fin diameter increased in the radial direction (diameter range 25–255 µm). Saturated and subcooled boiling up to 35 K.	53	20.8
[194]	FC-72	Cu	Rectangular pin–fin array of height 0.5–4 mm, pitch 0.5–2 mm and fin width 1 mm	96	33.6
[105]	FC-72	Cu	Surface coated with hybrid graphene-carbon nanotube coating	25	20
[31]	FC-72	Cu	Surface enhanced with porous structure created by electrochemical deposition (porosity 0–60.8%, Ra =0.09–17 µm)	27	25
[189]	HFE-7200	Cu	Microporous surface created by electrochemical deposition	27	17
[162]	HFE-7300	Cu	Nanofibers layer created by electrically-assisted supersonic solution blowing technique	27	12.1
[105]	HFE-7300	Cu	Nanofibers layer created by supersonically-blown	28	17

Table 8.8: Thermal aspects of coupling dielectric liquids on particular coated copper surfaces [130] [117]

8.3 Surfaces with water based nanofluids, augmentation in CHF

As can be seen in the Chapter 7, of the possible fluids that can be used for pool boiling, apart to the traditional ones there are, as a last frontier for enhancing the thermal fluxes that can be dissipated, the so called nanofluids.

These are created from a base of one traditional fluid (here are viewed just the water based ones) plus metal or metal oxide nanoparticles in an optimal percentage (the enhancement in heat transfer is mainly at lower particle concentrations and experimentally was shown that there is a sort of critical concentration of particles until there is the increase in CHF).

So, even a small concentration in volume (see Tab.8.9) can increases the CHF, giving a possible and not so costly solution of optimization.

Article	Nanofluid	Surface	Particle size [nm]	Concentration	Maximum CHF enhancement
[13]	Al_2O_3/Water	Cu	10-100	0.5-4% vol.	32%
[43]	Al_2O_3/Water	Cu	45	0.003% vol.	37%
[110]	Al_2O_3/Water	Cu	140	0.001% to 1 g/l	80%
[37]	ZrO_2/Water	Cu	20-25	0.005-0.15% vol.	-
[97]	Al_2O_3/Water	SS	100-200	0.001-0.1% vol.	50%
[97]	SiO_2/Water	SS	25-45	0.001-0.1% vol.	80%
[97]	ZrO_2/Water	SS	120-260	0.001-0.1% vol.	75%
[89]	Cu/Water	SS	10	0.25-1% weight	48%

Table 8.9: CHF augmentation of nanofluid pool boiling [171]

8.4 General conclusions of surface types for pool boiling

Selecting the optimal coupling surface-fluid, evaluating the thermal/compatibility/disadvantage/ costs/etc... and many others aspects is really challenging, but in Tab.8.10 are briefly schematized the general advantages and disadvantages of different types of enhanced surfaces for pool boiling.

Surfaces	Advantages	Disadvantages	Remarks
Macro-structured surfaces	Manufacturing process is simple; related technology is mature; low cost.	The degree of improvement of boiling performance is not large.	Heat transfer surface area is enlarged, or hydrodynamics is improved.
Micro-structured surfaces	Significantly enhance HTC and CHF.	High manufacturing cost.	The ONB (oneset of nucleate boiling) decreases and the nucleation sites and surface area increase, hydrodynamics is improved.
Heterogeneous surfaces	HTC can be considerably enhanced.	The intensification of CHF is not obvious; the manufacturing process is relatively complex.	The bubble growth and departure frequency are promoted; the ONB decreases. The proportion and collocation of hydrophobic part and hydrophilic part are particularly important.
Micro-nano particles coated surfaces	The boiling performance can be drastically augmented; related technology is mature and cost is relatively low.	The service life is severely limited.	The nucleation sites increase, the hydrodynamics and wicking capacity are significantly improved; the composite coating may peel off after several experiments.
Nano-wire/ fiber/tube coatings	The CHF and boiling HTC can be enhanced; the morphology of the coating is controllable.	Manufacturing cost is high and the process is complex.	The nucleation site density and capillary effect are improved; the ONB decreases.
Metallic oxide film coated surfaces	Boiling performance is improved owing to the changeable wettability; related technology is mature; high stability of coatings.	The required temperature for adaptively altering wettability is high.	The required temperature for changing wettability is high which means used in high pressure;it is normally more thermo-sensitive oxide film coatings should be developed.

Table 8.10: Principal characteristics of enhanced surfaces in pool boiling [117]

Chapter 9

Conclusions

This thesis work was started after six months of internship in the Huawei Nuremberg Research Center (GE), where I have had the opportunity to study and research the latest technologies in Data Center cooling. In that period I continued to get more and more passionate on the field of electronics cooling and in particular on the last frontier for the high dense systems so the two-phase immersion cooling.

For this reason I went on, staying and deepening this field in this master thesis.

In particular, the electronic devices analysed for designing the cooling systems were the power electronic converters even if the thermal/material/system/etc conclusions are valid also for cooling electronics devices in general, just keep attention to the different heat fluxes and to the maximum temperature allowed in base of the specific device.

Starting from a first introduction to power electronic classification with relative applications and market size view, were introduced the thermal aspects of these devices like the heat losses causes and the related failure types to avoid with an efficient cooling system.

Before the introduction to the real cooling systems used were studied the thermodynamic basis not only of traditional heat transfer but mainly of boiling and condensing phenomena (with all the relative parameters to improve heat transfer) because the main aim is the analysis of two-phase immersion cooling systems.

Going deeply on these devices, was done an historical overview of cooling solutions for power electronics and a thermal/cost/feasibility/etc comparison of all these possible technologies.

A final comparative histogram of heat fluxes dissipated (W/cm^2) for each technology was done, comparing the newest end most innovative scientific articles in a really complete overview.

From chapter 5 was started the principal subject of this thesis, so the two-phase immersion cooling of power electronics; even here was started the research with the historical systems (that applied boiling cooling) and after was done a deep analysis of the lasts and most advanced patents and scientific articles that developed these kind of systems,in order to have a global knowledge of all the sub-parts and their influence on the others (even to know the criticisms commonly get in these prototypes).

The finals two chapters were dedicated to the thermal and feasibility application of the most used fluids for this kind of cooling (dielectric and non) and a comparison view of the possible couplings heated surface-fluid for compare the different heat fluxes dissipated in the boiling process with different couplings.

Giving a personal vision at the and of this thesis work, the two-phase immersion cooled systems and related technologies are, and will be, the optimal solution to cool highly dense electronics even if being a relatively novel field of study, the thermal dissipation goals will be even more high in the next years.

The real added value is not only the possibility to create tanks with many boards in parallel, so the need of really less space in comparison to the traditional solutions (up to 50% reduced space), but in particular the extremely low yearly consumption of energy (usually just the condenser is the consuming device, are not present pumps/compressors/fans/etc...) and the cost reduction in maintenance and replacements even for the same reason of less working parts (even the fact of a more uniform cooling of electronic thanks to immersion, and no particular hot spots, influences the failure rate of the board itself).

So, even if up to now the maximum heat flux removed using two-phase immersion cooling systems using water (thermally the best fluid) and enhanced surfaces is of 500-600 W/cm^2 (low values in comparison to microchannels/sprays/jets impingement cooling), for the lower heat fluxes devices remains the best one solution.

Others advantages, already deeply explained in this thesis, are the extremely low noise production in comparison to recirculating liquids solutions (pumps are present) and to air ones (fans have high noise production in particular if there are many in big plants) and the possibility of work in harsh environments because the fluid protects the electronics from different external conditions like high humidity, dust or debris on industrial sites, etc...

Instead, regarding the researches status from universities and from the research centers of the biggest tech companies, is a reality that data center two-phase immersion cooling is highly pushed; considering that two-phase immersion cooling of electronic converters is a new field of deepening, scientific materials and validated systems are limited but the increasing trend of interest is moving absolutely in this direction.

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