UK Heat Transfer Conference 2021
UKHTC2021

17th UK Heat Transfer Conference (UKHTC2021)
4-6 April 2022, Manchester, UK

LIQUID METAL – MORE THAN COOLING?

Y. Yerasimou[1], V. Pickert[2*]

[1]PV Technology Laboratory, FOSS Research Centre for Sustainable Energy, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, 1678, Cyprus
[2]School of Engineering, Discipline Electrical and Electronic Engineering, Electrical Power Group, Newcastle University, Newcastle NE17RU, United Kingdom

1. ABSTRACT

The advancement of electrified transport requires smaller and lighter power electronics converters. In power electronics there are various aspects in achieving these goals such as increasing the switching frequency, using new materials for passive components or using advanced control methods. A relatively new technique is called multi-objective design, where one power converter is sufficient to do different tasks which were previously carried out by individual power converters. The same approach is proposed in this paper with the focus on cooling systems. The duo liquid metal and magnetohydrodynamics (MHD) pump has so far received limited attention in power electronics. This paper presents two examples demonstrating that the duo does not only show excellent cooling capabilities but also provides additional functions outside cooling. In one example the lifetime of power modules is extended by reducing actively the temperature swing of the junction temperature of power switches and in the other example the duo removes the use of deionised water from high voltage dc transmission lines. The paper also highlights other functions that can be embedded using liquid metal and MHD.

2. APPLICATIONS FOR LIQUID METALS

Power electronics is the technology that delivers energy in a controlled manner. The estimated global power electronics market for 2025 is $44.2 billion [1]. Power electronics control the energy in every area of our lives such as household applications [2], aircrafts [3] or electric vehicles [4] to name a few. Power electronics require power semiconductor switches which when in operation produce losses. All power semiconductor switches must therefore be cooled to prevent overheating. Various cooling heatsinks have been proposed over decades [5]. The use of liquid metals as cooling agent has received less attention so far but have gained attention in recent years. Liquid metals have excellent thermophysical properties, including very high thermal conductivity and low melting point. In addition, they own very high electrical conductivity; an important attribute for driving the fluid with an electromagnetic pump without any moving parts [6, 7]. Comparisons between liquid metal and water for mini– and micro–channels show that liquid metal can achieve up to 40% reduction of the heat sink's thermal resistance [8]. Moreover, heat fluxes greater than 1500 W/cm^2 have been successfully dissipated [9]. Therefore, liquid metals are ideal for applications where high heat fluxes need to be dissipated and high reliability is required. The design and development of thermal management systems based on liquid metal for central processing units (CPUs) has been reported on multiple occasions in the past decade, demonstrating significant increase in the cooling performance compared to commercial heat sinks [10–13]. Liquid metal heat sinks have also been utilised for cooling high–power laser diodes and adjusting their wavelength by controlling the coolant's flow rate [14]. Moreover, they have been used for cooling high–power light emitting diodes (LEDs) [15]. Liquid metals are also ideal for integrated cooling mechanisms for electronic devices in spatial restricted applications with local hotspots [16], as well as an alternative to heat pipes utilised as heat spreaders for orientation sensitive applications [17]. In addition, a liquid metal coolant has been proposed for reducing the weight of the power electronic cooling system for an aerospace application while maintaining similar cooling performance, in spite of its higher density [18]. Experimental investigations of liquid metal mini–channel heat sinks aimed at power electronic applications have been reported on a few occasions, however, the experimental

*Corresponding Author: volker.pickert@newcastle.ac.uk

validation is performed by using power resistors rather than power electronic devices [19, 20]. As liquid metals are considerably more expensive than other cooling mediums, the cost of a pure liquid metal cooling system can be rather high. In order to develop a more cost–effective thermal management system without compromising the cooling performance, liquid metal has been used as an intermediate stage for dissipating the excess heat of power converters in hybrid electric vehicles (HEVs). As the cooling loop of power electronics in HEVs is often shared with the internal combustion engine, thus leading to elevated fluid temperatures, liquid metal has been used to dissipate the excess heat of the power electronics to the main cooling loop [21]. An alternative solution to reduce cost for liquid metal cooling applications involves the use of a liquid metal droplet that activates the circulation of a secondary fluid through a variable frequency signal based on the Marangoni effect, which is defined as the mass transfer across an interface between two fluids due to surface tension difference [22, 23]. Despite that the majority of liquid metal cooling applications use externally supplied electromagnetic or peristaltic pumps to drive the coolant, the excess heat can be harvested in order to drive an electromagnetic pump via a thermoelectric generator [24] or by exploiting the thermosyphon effect [25].

Table 1: Thermophysical properties of various fluids used for power electronics cooling

Property	Unit	$Ga_{68}In_{22}Sn_{10}$	Mercury	Water	Ethylene glycol*
Density	kg/m^3	6400	13593	998	1107
Melting point	°C	-19	-38.89	0	-52.8
Boiling point	°C	>1300	357.3	100	111.1
Specific heat capacity	J/(kg·°C)	365	140	4181	3284
Volumetric heat capacity	J/(°C·m^3)	$2.34\cdot10^6$	$1.9\cdot10^6$	$4.07\cdot10^6$	$3.63\cdot10^6$
Dynamic viscosity	Pa·s	0.0024	0.0017	0.001	0.009
Electrical conductivity	S/m	$3.46\cdot10^6$	$1\cdot10^6$	$5.5\cdot10^{-6}$	$3.2\cdot10^{-6}$
Thermal conductivity	W/(m·°C)	16.5	8.2	0.606	0.52
Prandtl number	-	0.027	0.013	6.62	23.2

* The physical properties of the fluid are based on a 60/40% ethylene glycol/water mixture.

There are different types of liquid metals available on the market mainly, mercury and gallium based liquid metal alloys either as gallium, indium and tin or as eutectic gallium and indium. Table 1 provides a comparison between $Ga_{68}In_{22}Sn_{10}$, mercury, water, and a 60/40% ethylene glycol/water mixture. Water and ethylene glycol are commonly used for single phase cooling of power electronics, however, they require a conventional liquid pump for driving the fluid that relies on moving parts and can compromise the reliability of the cooling system. In addition, the thermal conductivity of liquid metals is much higher and can therefore achieve higher heat flux removal, in spite of the lower volumetric heat capacity. On the other hand, mercury can be used for cooling applications, however, compared to $Ga_{68}In_{22}Sn_{10}$ it has about half of its thermal conductivity and lower volumetric heat capacity. Also, it is a toxic material that requires extra precautions when used. Considering the advantages and disadvantages of each cooling medium, $Ga_{68}In_{22}Sn_{10}$ can provide high cooling performance and be driven through a reliable, non–moving pump.

3. MAGNETOHYRDODYNAMICS (MHD)

The physical laws governing the MHD phenomenon for a Newtonian fluid flow are a combination of electromagnetism and classical fluid dynamics that include Maxwell's equations, Ohm's law and Navier-Stokes conservation of mass and momentum, as well as energy equations. As the focus is to use liquid metal as heat sink for power electronics components, the presented governing equations are only limited to Newtonian fluids. The simplified Maxwell's equations that include magnetohydrodynamic components are:

$$\boldsymbol{\nabla} \cdot \boldsymbol{E} = \frac{\rho_e}{\varepsilon_0} \tag{1}$$

$$\nabla \cdot \boldsymbol{B} = 0 \quad (2)$$

$$\nabla \times \boldsymbol{E} = \frac{\partial \boldsymbol{B}}{\partial t} \quad (3)$$

$$\nabla \times \boldsymbol{B} = \mu_0 \boldsymbol{J} \quad (4)$$

where $\boldsymbol{E}$ is the electric field, $\boldsymbol{B}$ is the magnetic field strength, $\boldsymbol{J}$ is the current charge density, ρ_e is the charge density, ε_0 is the vacuum permittivity and μ_0 the vacuum permeability. In these equations, it is assumed that the magnetic field is solenoidal and therefore, magnetic monopoles do not exist. In addition, magnetic fields could be generated by currents and electric fields could be generated by varying magnetic fields. Moreover, according to Ohm's law, the current charge density $\boldsymbol{J}$ is proportional to the force experienced by free charged particles. For a conductive fluid with an electrical conductivity σ moving with velocity $\boldsymbol{u}$ in a magnetic field $\boldsymbol{B}$:

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{u} \times \boldsymbol{B}) \quad (5)$$

For liquid metal pump applications, the cross-product $\boldsymbol{u}\times\boldsymbol{B}$ in (5) can be interpreted as an apparent electric field. Considering the case of electrical machines, $\boldsymbol{u}\times\boldsymbol{B}$ is analogous to the back EMF of electric motors, whereas the fluid flow is analogous to the armature voltage. The power produced by the pump is maximised when B, E and u are mutually orthogonal, in which case $\boldsymbol{u}\times\boldsymbol{B}$ is in the opposite direction of J. Moreover, a Lorentz force is acting on a particle with a given charge that is moving with velocity u, which is the sum of electrostatic Coulomb forces and magnetic forces. In MHD, the bulk forces acting on the medium are dominating the fluid flow, hence the force per unit volume acting on the conductor is:

$$\boldsymbol{F} = \boldsymbol{\rho_e E} + \boldsymbol{J} \times \boldsymbol{B} \quad (6)$$

As the fluid used in most cases has a very high electrical conductivity and its velocity is very small compared to the speed of light, the Coulomb force is negligible and can be ignored. Therefore, only the magnetic force is considered:

$$\boldsymbol{F} = \boldsymbol{J} \times \boldsymbol{B} \quad (7)$$

In addition to the electromagnetic equations, the MHD phenomenon also involves fluid dynamics equations to characterise the flow of the medium. Fluid dynamics is a subset of fluid mechanics and deals with the motion of fluids systems. It has a large spectrum that includes both aerodynamics and hydrodynamics, for gases and liquids, respectively. The fundamental laws of fluid dynamics are based on the conservation of mass, momentum and energy and the governing equations describing the fluid flow can be written as:

$$\nabla \cdot \boldsymbol{u} = 0 \quad (8)$$

$$\left(\frac{\partial \boldsymbol{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}\right) = -\nabla \mathrm{p} + \mu \nabla^2 \mathbf{u} + \boldsymbol{\rho_e E} + \boldsymbol{J} \times \boldsymbol{B} \quad (9)$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)\mathrm{T}\right) = \mathrm{k}\nabla^2 \mathrm{T} + \frac{\boldsymbol{J}^2}{\sigma} \quad (10)$$

where ρ is the fluid density, p is the pressure, μ is the dynamic viscosity and C_p is the specific heat capacity of the fluid. The term $\boldsymbol{J}^2/\sigma$ in (10) accounts for Joule heating caused by the injected current. In (9), the momentum equation is modified for MHD applications by including the electromagnetic force component, $\rho_e\boldsymbol{E}+\boldsymbol{J}\times\boldsymbol{B}$. As mentioned earlier, the Coulomb force is negligible for liquid metal pumping and thus, can be omitted:

$$\rho \left(\frac{\partial \boldsymbol{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u}\right) = -\nabla \mathrm{p} + \mu \nabla^2 \mathbf{u} + \boldsymbol{J} \times \boldsymbol{B} \quad (11)$$

4. EXAMPLE 1: COOLING AND ACTIVE LIFETIME ENHANCEMENT

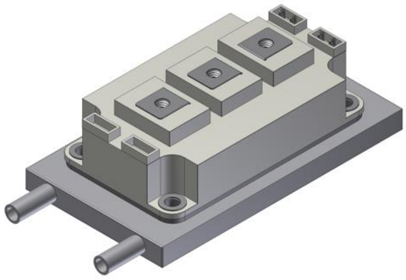
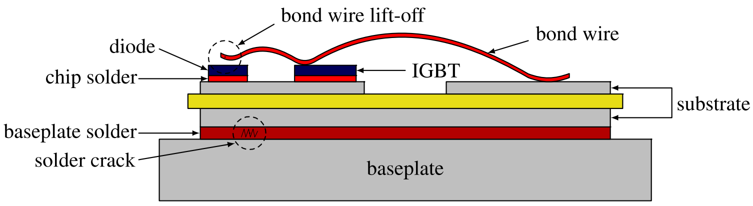
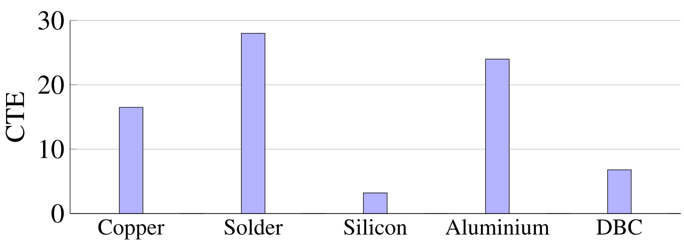


Fig. 1. Typical cold plate for power module cooling

A typical cold plate for power modules cooling is shown in Fig. 1. Despite the simplicity and superior heat dissipation properties compared to forced-air cooling, standard cold plates are not able to dissipate heat fluxes in excess of 300 W/cm^2. Consequently, continuous development of cold plates that focused on increasing the heat transfer coefficient and therefore, further enhancing liquid cooling effectiveness by increasing the contact surface of the coolant has led to the introduction of techniques such as mini–channel [26] and micro–channel [27] based heat sinks. Mini–channel and micro–channel cooling methods are able to cope with heat fluxes as high as 1000 W/cm^2.



(a)



(b)

Fig. 2. Power module structure: (a) typical failure modes and (b) CTE value of each material in the power module.

Fig. 2 shows the schematic of a common Insulated Gate Bipolar Transistor (IGBT) power module. Its structure consists of many layers of different materials, each one owning a different coefficient of thermal expansion (CTE). During large temperature fluctuations, a shear force is generated between the layers because of the mismatch in the CTE of the power module's materials. Hence, the thermomechanical stress within the layers consequently leads to devices' failures such as bond wire lift–off [28] and solder joint fatigue [29]. Thus, reducing the thermal stress within the power module structure can prolong the lifetime of power modules and reduce the possibility of a failure [30].

Fig. 3 illustrates an example mission profile and the different temperature variations caused by each time constant. Power modules are subjected to cyclic thermomechanical stresses resulted from the superposed temperature deviations mentioned above. They are mostly stressed because of load changes with regards to the mechanical system requirement, which is always accompanied by large temperature swings occurring at a substantial frequency [31]. Changes associated with environmental temperature contribute to the module ageing, however, they are outperformed by the load cycling [32]. On the other hand, temperature cycles caused by the device switching action and circuit topological alternations result in very small amplitude that does not greatly impact the lifetime of a healthy power semiconductor module [33]. That is partly because the thermal variation caused by higher frequencies is absorbed by the capacitance of the thermal circuit, and partly because the thermal strain is counterbalanced by the elastic deformation of the power module's materials.

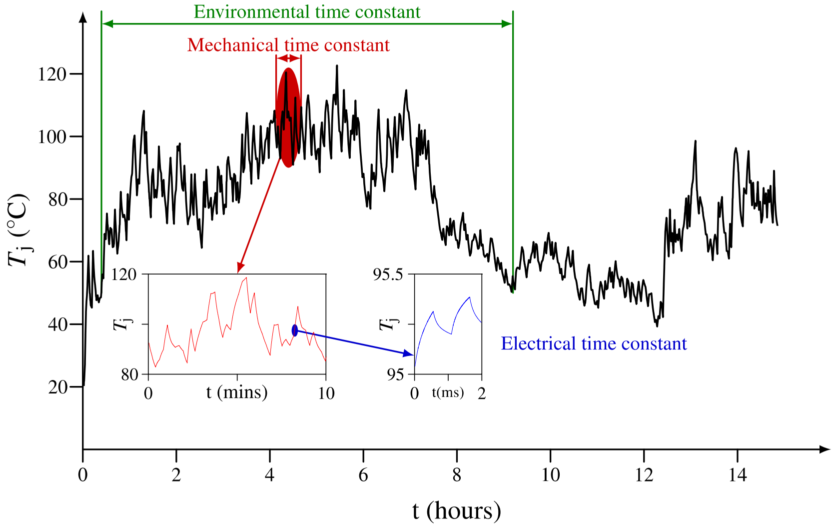


Fig. 3. Example junction temperature mission profile

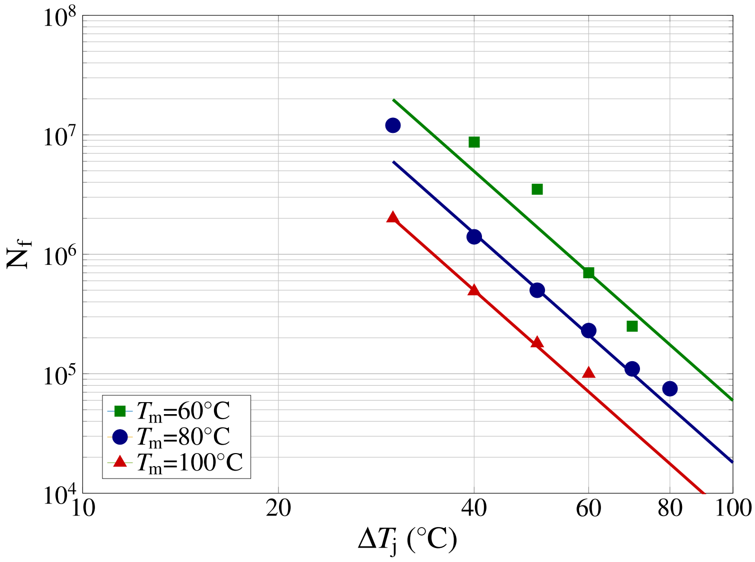


Fig. 4. Power cycling results from LESIT project, showing the dependency of power modules lifespan on junction mean temperature and junction temperature swing [34]

The lifetime of power electronic devices is associated with the temperature cycles of the device during operation. Numerous lifetime models have indicated that the cycles to failure of the device is directly affected by both the junction temperature swing, ΔT_j, and the average working temperature, T_m. Several lifetime models have been proposed. One of the most cited lifetime model was developed in the late 90s by Held et al. [34] during the LESIT research program, in which the lifetime consumption of power modules is calculated based on the junction temperature swing, ΔT_j, and the mean junction temperature, T_m. Hence, the number of cycles to failure, N_f, is expressed as:

$$N_f = m(\Delta T_j)^{-n} e^{\left(\frac{E_a}{k_B T_m}\right)} \tag{12}$$

where m and n are material dependent coefficients and k_B is the Boltzmann constant. The outcomes of the LESIT study are illustrated in Fig. 4, clearly showing that the most influencing factor for power modules failures is ΔT_j.

A junction temperature control method for IGBT power modules based on a liquid metal heat sink was proposed in [35], in which the thermal stress between the device's layers is decreased by reducing the chip's temperature fluctuations. Fig. 5 shows the schematic. The junction temperature T_j is measured using a Temperature Sensitive Electrical Parameter (TSEP) [36] and compared with a reference temperature. The error is converted into a demand current for the pump I_{pump} which drives the amount of cooling Q resulting in the junction temperature T_j.

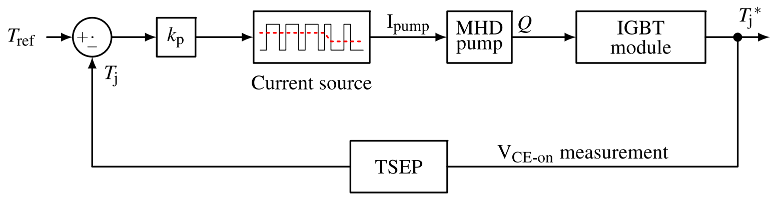


Fig. 5. Schematic diagram of junction temperature control.

The working principle of the MHD pump is shown in Fig. 6. As there is a constant magnetic field in ***x*** plane, injecting current through the electrodes in ***y*** plane, generates Lorentz force in ***z*** plane that is used for driving the conducting fluid in the channels of the pump. When a current is applied across the width of a channel filled with a conductive fluid subjected to an orthogonal magnetic field, the Lorentz force exerts body force on the fluid that is proportional to both the generated current density ***J*** in the fluid and the magnetic flux density ***B***.

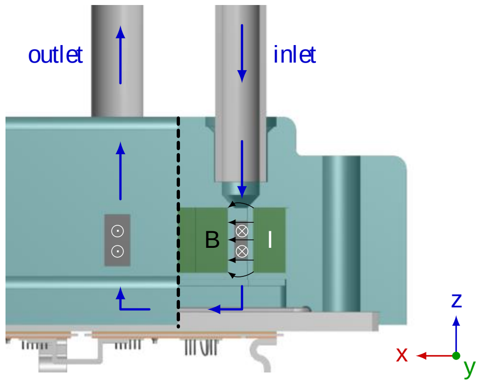


Fig. 6. Working principle of MHD liquid metal pump

The self–contained liquid cooling system consists of two parts; a MHD pump head with direct immersion cooling and a U–type tubular liquid–to–water heat exchanger with connection pipes. The Semikron power module, which is used as the device under test (DUT), is bolt on the pump head and there is a direct interface between the backside of the baseplate and the liquid metal coolant. The coolant flowing is confined to the designed liquid block and directed by two narrow slots in the nylon housing, as shown in Fig. 7. The liquid block of the heat sink is sealed with an o–ring. The heat source is in direct contact with the liquid metal, which impinges the baseplate. Two MHD micro–pumps are integrated in the plastic housing, where totally five magnets are embedded in ***x*** direction and a pair of nickel electrodes is embedded in ***y*** direction and thus, perpendicular to the magnets. The U–type heat exchanger and the pump head are connected with two short pipes to form a closed loop. The pump is positioned beneath one IGBT chip. The 3–D printed housing of the pump head is made of engineering plastic (VeroWhite).

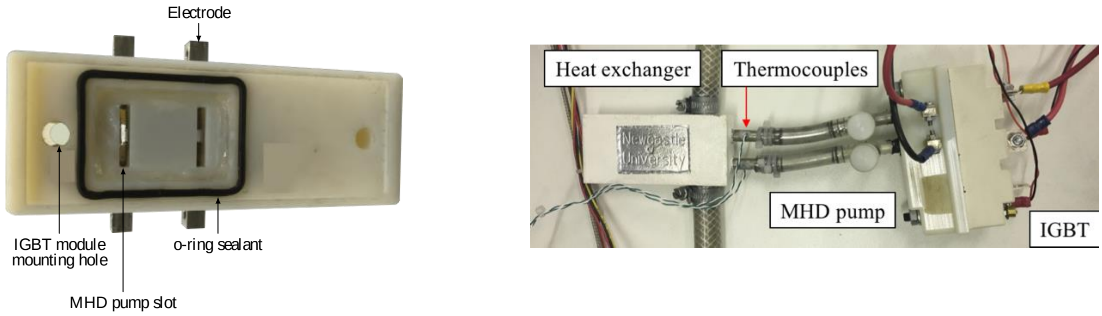


Fig. 7. Left: Bottom view of the MHD prototype, Right: Cooling connection between MHD pump and heat exchanger

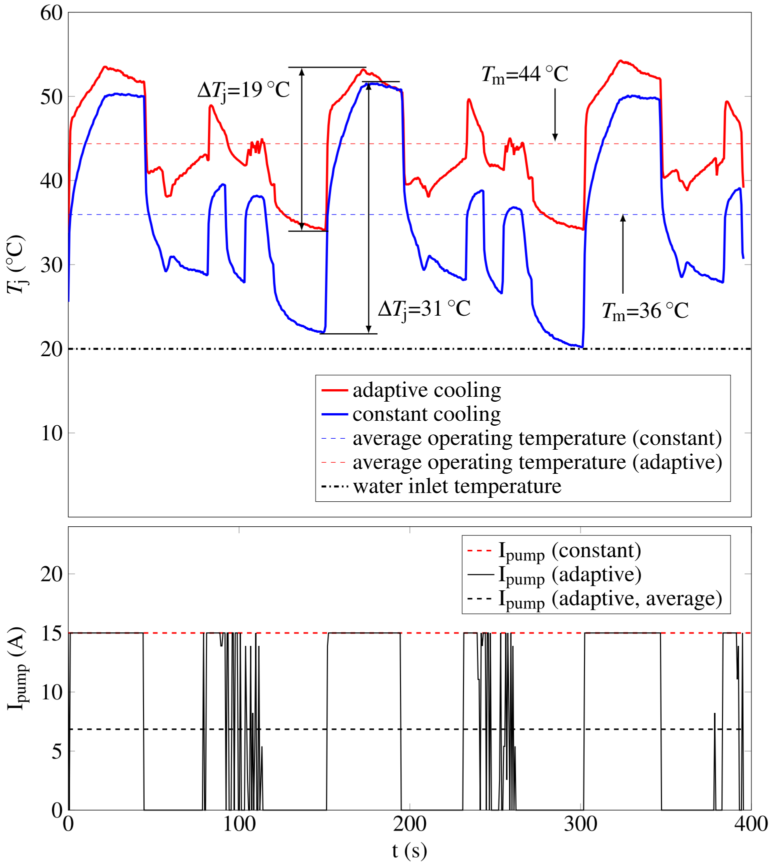


Fig. 8. Junction temperature, T_j, results and liquid metal pump supplied current, I_{pump}, with and without thermal controller

The IGBT power module was subjected to the heat mission profile of Fig. 8 for two tests. In the first test the MHD pump is supplied with the maximum pump current I_{pump} of 15 A throughout the whole experiment. This test emulates a typical heat sink used for protecting the IGBT device from thermal runaway. For the second test, the MHD pump is adaptively controlled by varying I_{pump} from 0 A to a peak current up to 15 A. This test represents a combination of cooling and extending the lifetime of the power module by reducing large temperature swings. The results for both tests are shown in Fig. 8. In both experiments the water temperature is fixed at 20 ◦C. Therefore, the inlet liquid metal temperature, has approximately the same value as the water temperature due to the effective heat transfer properties of the heat exchanger. Fig. 8 shows that the junction temperature swing is greatly reduced with the introduction of the adaptive controller. The largest variations of the temperature are observed during the accelerating and braking phases, as there is a large amount of heat losses during those intervals. The temperature swing ΔT_j is reduced while the adaptive temperature controller is activated, in comparison to the case where maximum constant cooling is applied over the full metro–mission profile. Thus the combination of MHD and liquid metal does not only cool the power module effectively but also increases the lifetime of the power module.

5. EXAMPLE 2: COOLING AND INHIBITING CORROSION

Press–pack is an alternative packaging technology for high–power IGBT modules. In contrast to the conventional power modules, where soldered bond wires are used for the electrical connections, press–pack devices achieve electrical and thermal contact by applying pressure, which is typically from 10 to 20 N/mm^2 [37]. Press-packs are commonly used in high voltage dc transmission lines (HVDC) where hundreds of press-pack devices are connected in series to achieve the required blocking voltage of ten thousands of volts. Traditional cooling for HVDC systems requires deionised water flowing through copper heat sinks that are configured in either typical "S" meander or "Archimedes" spiral structures [38]. The heat sink housing is made of copper due to its high electrical and thermal conductivities, which is nickel plated for protection against corrosion. The heat sinks are series or parallel connected and supplied through a liquid pump, as shown in Fig. 9.

Fig. 9. Water–cooled PP stack configurations: (a) series and (b) parallel

Deionised water is an electrolytic conductor, hence, its chemical composition varies as current conducts through it. More specifically, the free oxygen produced due to the electrolytic activity contributes to the oxidisation process of the cooling system [39]. In addition, any electrical potential imbalance between metal components of the cooling circuit, such as the heat sink body and pipe fittings, leads to chemical reactions on the metals. Therefore, in order to reduce the electrolytic currents flowing in the cooling medium, techniques such as limitation of the coolant's electrical conductivity via a chemical filter placed in a bypass parallel to the main circuit, minimisation of the hydraulic diameter of the piping system and placement of grading electrodes at predefined locations, should be employed. In addition, due to deionised water's aggressiveness irrespectively of whether current is flowing through it, the system should be pressurised so as the free oxygen content is limited. Even when plastic tubing, fittings or sealants are used, contact with deionised water could lead to embrittlement and thus, to premature failure. Also, there is a risk of pit corrosion in areas where there is a contact of rubber sealants with metal surfaces [40].

In [41] research was conducted on the design and development of a heat dissipation system for HVDC that eliminates the disadvantages of deionised water coolant. A liquid metal heat sink is proposed that transfers the excess heat generated by the press-packs to a liquid metal–to–water heat exchanger.

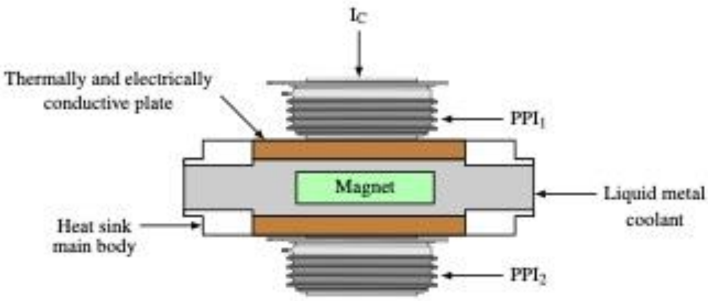


Fig. 10. Schematic of proposed heat sink

Fig. 10 shows the principle of operation of the proposed heat sink. The collector current, I_C, drives the liquid metal coolant in the presence of a magnetic field provided by permanent magnets. Each side of the heat sink contains a plate that its inner and outer surfaces come in direct contact with the press-pack and the liquid metal coolant, respectively. Therefore, the excess heat generated by the press-pack is transferred via the liquid metal. The material selection for the heat sink components are based on their chemical compatibility with $Ga_{68}In_{22}Sn_{10}$. In addition to that, the top and bottom plates of the heat sink should be a good electrical and thermal conductor. On the other hand, the material used for the main body of the heat sink should be an electrical insulator, thus ensuring that I_C conducts solely through the liquid metal.

A pre–assembled commercial press-pack stack that consists of a pressure clamp and two press-pack devices (Westcode T0360NB25A), which are double–sided cooled by water heat sinks, was used for demonstration. The schematic representation of the press–pack stack is illustrated in Fig. 11.

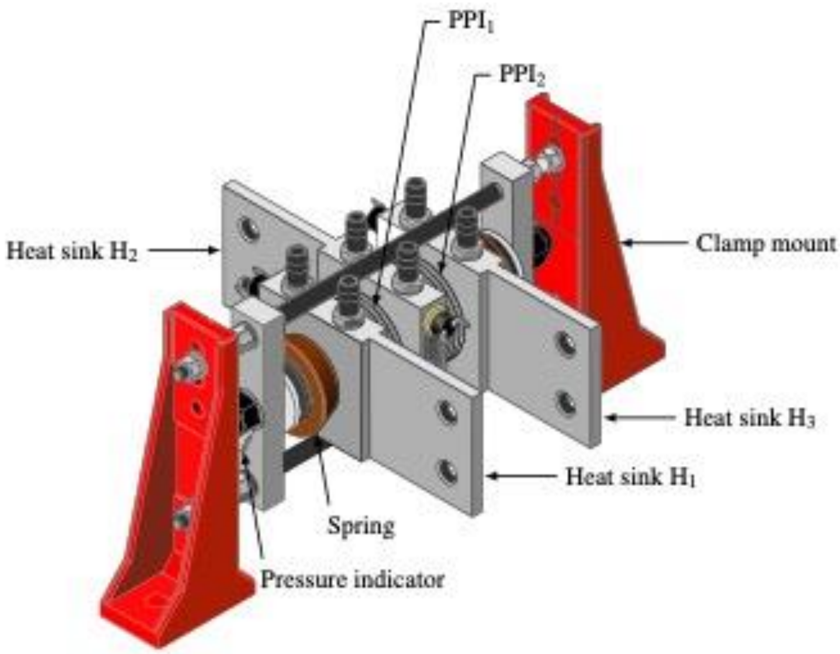


Fig. 11. Schematic of press–pack stack

Fig. 12 illustrates a detailed view of the cooling system for one side of the press-pack. As shown, the collector and emitter lids of each PPI come in direct contact with the copper plates of the heat sink, which forms a closed loop with a heat exchanger. The system is filled with the liquid metal Ga68In22Sn10 and the excess heat is transferred from the copper plates to the heat exchanger, where it is then dissipated to the ambient through water cold plates that are attached to the heat exchanger copper surface.

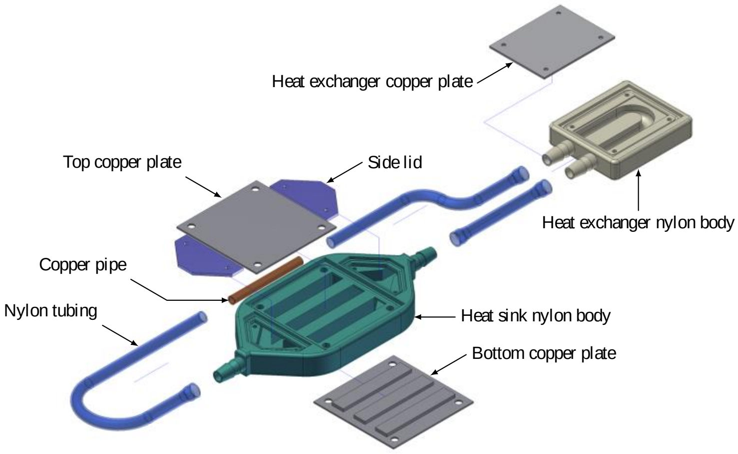


Fig. 12. Exploded view of press-pack heat sink

Press-packs were electrically powered and cooled using the press-pack assembly shown in Fig. 11excpet the classical heatsinks shown in the figure were replaced with the MHD pumps shown in Fig. 12. The heat dissipation performance of the liquid metal heat sink is evaluated through a steady state heat transfer experimental test and is compared against a conventional water–based commercial heat sink for press-packs. The proposed liquid metal cooling system provides lower thermal resistance for identical water flow rates. Thus, higher heat loads can be potentially rejected without the risk of thermal runaway, although the difference between the two cooling methods in not large. Moreover, based on the uncertainty analysis, the error bars in Fig. 13 indicate that the difference in the thermal resistance of the two heat sinks is not significant, as their error ranges intersect. The heat exchanger in Fig. 12 was cooled by standard (ionsied) water. Thus, the combination of MHD and liquid metal does not only cool the press-pack effectively but also eliminates the use of deionised water.

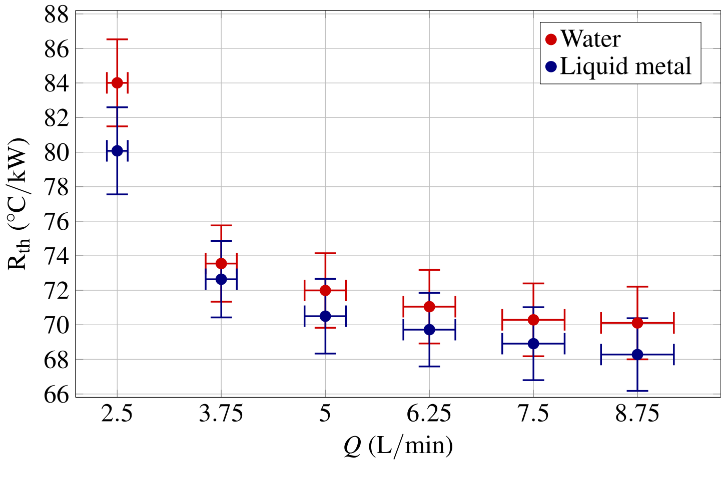


Fig. 13. Thermal resistance of cooling systems as a function of the water flow rate

6. COOLING AND MORE

The two examples show that thermal systems should not only be selected based on cooling capabilities by improving material, using new mini and micro cooling topologies or making use of advanced phase change cooling, but should also be selected on the base of additional contributions such as lifetime enhancement -as demonstrated in example 1- by reducing the junction temperature swing or replacing deionized water that is often used in HVDC applications in order to avoid corrosion with standard ionized water (example 2). In order to provide additionality to a cooling system the two above examples propose the combination of liquid metal and MHD pumps. MHD liquid metal pumps offer not only efficient cooling but also additional benefits that classical thermal systems cannot offer.

The duo liquid metal and MHD is not only limited to the two examples but can also address other additional functionalities. For example, it can be used as Lorentz force velocimetry where the flow of the liquid metal is measured by the magnetic field that is generated by eddy currents within the liquid metal. In example 2 the liquid flow is proportional to the average current flowing through the press-pack. Thus Lorentz force velocity can be used to measure the current in HVDC eliminating expensive current sensors. Liquid metal and MHD are bidirectional meaning the MHD can operate as a pump or as a generator. Therefore, if the MHD is used to cool power electronics components it can be designed to produce enough power, to power a second MHD that is embedded in the same liquid metal cooling circuit. The second MHD operates as a generator producing electric power. This electric power can be used to power ancillaries within the power electronics system like a controller board or a safety circuit board for example. If sufficient power is provided it can also operate the cooling fan for the liquid metal heat exchanger. Another option is to operate the MHD as a rotating induction pump that could cool an electric motor. An MHD rotating induction pump uses a rotor with magnets attached to the outer surface of the rotor. A tube filled with liquid metal is wrapped around the rotor. This tube is static (as the stator of an electric motor). When the electric motor rotates it is spinning the rotor with the magnets that produces a mechanical force in the liquid metal due to the rotating and changing magnetic field cutting through the metal liquid. The changing field produces current within the liquid metal and the force of the magnetic field and the produced current within the liquid metal propels the liquid metal within the tube. The liquid flow can now cool the stator of the electric motor or cool power electronics systems. This would avoid the use of any mechanical pump. This short section highlights that liquid metal and MHD promise many opportunities to cool power electronics systems and electric motors efficiently and to provide additional functionality helping to increase lifetime, reducing the number of components. reducing size and weight.

7. CONCLUSIONS

In power electronics the demand to reduce size and cost at increased power requires the use of efficient and small heat transfer techniques. So far liquid metals received little attention as heat transport agents, despite their excellent thermophysical properties. Their high electrical conductivity allows for driving them with a magnetohydrodynamics (MHD) pump, which is a reliable and low-power device. Hence, a thermal management system based on liquid metal coolant is able removing high heat fluxes, requires low operating power and provides high reliability, all desirable attributes for modern power electronic applications. Thus, the combination of liquid metal and MHD opens new opportunities in achieving smaller power systems by allowing liquid metal not only to be used as heat transport agent but also giving liquid metal other functions such as lifetime enhancement, eliminating mechanical pumps or using it as current sensing for example. This paper shows two selected examples how liquid metal in combination with MHD provide two functions: cooling and non-cooling. The paper also discusses briefly other ideas how this duo can provide additional functionality. The paper therefore concludes that the future of cooling systems in power electronics should not only answer the question "How good can I cool a component?" but also "What more can I do?". Thus, the future of cooling platforms must do more than cooling.

ACKNOWLEDGEMENTS

This paper includes extracts from the main author's PhD thesis: Heat sinks based on liquid metal for power electronics cooling applications, May 2020, Newcastle University.

REFERENCES

[1] marketsandmarkets.com, Power Electronics Market worth $44.2 billion by 2025, *https://www.marketsandmarkets.com,* Press release, Accessed 9-4-2021.

[2] S. Pal, B. Singh & A. Shrivastava, novel distortionless dimming in high power LED lighting using isolated SEPIC converter, *IET Power Electronics*, 13 (2020) 3234-3242.

[3] GJ. Atkinson, JW. Bennett, BC. Mecrow, DJ. Atkinson, AG. Jack, V. Pickert, Fault tolerant drives for aerospace applications, *6th International conference on Integrated Power Systems (CIPS),* Nuremberg, Germany, (2010).

[4] P. James, A. Forsyth, G. Calderon-Lopez & V. Pickert, DC-DC converter for hybrid and all electric vehicles, *24th International Battery, Hybrid and fuel Cell Electric Vehicle*, Stavanger, Norway, (2009).

[5] E. Laloya, O. Lucia, H. Sarnago & J. Burdio, Heat Management in Power converters: From State of the Art to future Ultrahigh Efficiency Systems, IEEE Transactions on Power Electronics, **31** (2016) 7896-7908.

[6] Y. Deng & J. Liu, Hybrid liquid metal–water cooling system for heat dissipation of high power density microdevices, *Heat and Mass Transfer*, **46** (2010) 1327–1334.

[7] Y. Hayashi, N. Saneie, Y. J. Kim, & J.-H. Kim, Thermal performance and pressure drop of galinstan-based microchannel heat-sink for high heat-flux thermal management, *ASME 2015 13th International Conference on Nanochannels, Microchannels, and Minichannels*, San Francisco, USA, *(*2015).

[8] M. Hodes, R. Zhang, L. S. Lam, R. Wilcoxon, & N. Lower, On the potential of galinstan-based minichannel and minigap cooling, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, **4**, (2014) 46–56.

[9] R. Zhang, M. Hodes, N. Lower, & R. Wilcoxon, Water-based microchannel and galinstan-based minichannel cooling beyond 1 kW/cm2 heat flux, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, **5**, no. 6, pp. (2015) 762–770.

[10] U. Ghoshal, D. Grimm, S. Ibrani, C. Johnston, & A. Miner, High-performance liquid metal cooling loops, *Semiconductor Thermal Measurement and Management IEEE Twenty First Annual IEEE Symposium*, (2005) 16–19.

[11] Y. Deng & J. Liu, Design of practical liquid metal cooling device for heat dissipation of high performance cpus, *Journal of Electronic Packaging*, **132** (2010) 1-6.

[12] Y. Deng & J. Liu, Optimization and evaluation of a high-performance liquid metal cpu cooling product, *IEEE Transactions on Components, Packaging and Manufacturing Technology,* **3** (2013) 1171–1177.

[13] T. Li, Y.-G. Lv, J. Liu, & Y.-X. Zhou, A powerful way of cooling computer chip using liquid metal with low melting point as the cooling fluid, *Forschung im Ingenieurwesen*, **70** (2005) 243–251.

[14] J. Vetrovec, D. A. Copeland, R. Feeler, & J. Junghans, Testing of active heat sink for advanced high-power laser diodes, *Proc.SPIE*, vol. 7918 (2011) 7918 – 7918 – 6.

[15] Y. Deng & J. Liu, A liquid metal cooling system for the thermal management of high power leds, *International Communications in Heat and Mass Transfer*, **37** (2010) 788 – 791.

[16] M. Luo, Y. Zhou, & J. Liu, Blade heat dissipator with room-temperature liquid metal running inside a sheet of hollow chamber, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, **4** (2014) 459–464.

[17] R.Wilcoxon, N. Lower, & D. Dlouhy, A compliant thermal spreader with internal liquid metal cooling channels, *26th Annual IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM)*, Santa Clara, California, (2010).

[18] A. Sakanova, C. F. Tong, K. J. Tseng, R. Simanjorang, & A. K. Gupta, Weight consideration of liquid metal cooling technology for power electronics converter in future aircraft, *IEEE 2nd Annual Southern Power Electronics Conference (SPEC)*, Auckland, New Zealand (2016).

[19] M. Tawk, Y. Avenas, A. Kedous-Lebouc, & M. Petit, Numerical and experimental investigations of the thermal management of power electronics with liquid metal minichannel coolers, *IEEE Transactions on Industry Applications*, **49** (2013) pp. 1421–1429.

[20] M. Luo & J. Liu, Experimental investigation of liquid metal alloy based mini-channel heat exchanger for high power electronic devices, *Frontiers in Energy*, **7** (2013) 479–486.

[21] J. Vetrovec, High-performance heat sink for hybrid electric vehicle inverters, *12th International Conference on Advanced Vehicle and Tire Technologies,* Tuat, Japan (2010).

[22] J. Y. Zhu, S.-Y. Tang, K. Khoshmanesh, & K. Ghorbani, An integrated liquid cooling system based on galinstan liquid metal droplets, *ACS Applied Materials & Interfaces*, **8** (2016) 2173–2180.

[23] S. Tan, Y. Zhou, L.Wang, & J. Liu, Electrically driven chip cooling device using hybrid coolants of liquid metal and aqueous solution, *Science China Technological Sciences*, **59** (2016) 301–308.

[24] K.-Q. Ma & J. Liu, Heat-driven liquid metal cooling device for the thermal management of a computer chip, *Journal of Physics D: Applied Physics*, **40** (2007) 4722-4729.

[25] P. Li, J. Liu, & Y. Zhou, Design of a self-driven liquid metal cooling device for heat dissipation of hot chips in a closed cabinet, *Journal of Thermal Science and Engineering Applications*, **6** (2013) 8-11.

[26] K. Yuki & K. Suzuki, Applicability of minichannel cooling fins to the next generation power devices as a single-phase-flow heat transfer device, *Transactions of The Japan Institute of Electronics Packaging*, **4** (2011) 52–60.
[27] S. T. Kadam & R. Kumar, Twenty first century cooling solution: Microchannel heat sinks, *International Journal of Thermal Sciences*, **85** (2014) 73–92.
[28] B. Ji, V. Pickert, B. Zahawi, & M. Zhang, In-situ bond wire health monitoring circuit for IGBT power modules, *6th IET International Conference on Power Electronics, Machines and Drives (PEMD)*, Bristol, UK, (2012).
[29] B. Ji, X. Song, W. Cao, V. Pickert, J. Hu, J. W. Mackersie, & G. Pierce, In situ diagnostics and prognostics of solder fatigue in IGBT modules for electric vehicle drives, *IEEE Transactions on Power Electronics*, **30** (2015) 1535–1543.
[30] M. Andresen, K. Ma, G. Buticchi, J. Falck, F. Blaabjerg, & M. Liserre, Junction temperature control for more reliable power electronics, *IEEE Transactions on Power Electronics*, **33** (2018) 765-776.
[31] D. Zhou, F. Blaabjerg, M. Lau, & M. Tonnes, Optimized reactive power flow of dfig power converters for better reliability performance considering grid codes, *IEEE Transactions on Industrial Electronics*, **62** (2015) 1552–1562.
[32] M. Ke, M. Liserre, F. Blaabjerg, & T. Kerekes, Thermal loading and lifetime estimation for power device considering mission profiles in wind power converter, *IEEE Transactions on Power Electronics*, **30** (2015) 590–602.
[33] W. Lai, M. Chen, L. Ran, O. Alatise, S. Xu, & P. Mawby, Low ΔT_j stress cycle effect in igbt power module die-attach lifetime modeling, *IEEE Transactions on Power Electronics*, **31** 92016)6575–6585.
[34] M. Held, P. Jacob, G. Nicoletti, P. Scacco, & M. H. Poech, Fast power cycling test of IGBT modules in traction application, *Second International Conference on Power Electronics and Drive Systems*, Singapore, Singapore, (1997).
[35] Y. Yerasimou, V. Pickert, B. Ji & X. Song, Liquid Metal Magnetohydrodynamic Pump for Junction Temperature Control of Power Modules, *IEEE Transactions on Power Electronics*, **33** (2018) 10583-10593
[36] R. Mandeya, C. Chen, V. Pickert & R.T. Naayagi, Prethreshold voltage as a Low-component count Temeratur Sensitive electrical Parameter without Self-Heating, *IEEE Transactions on Power Electronics*, **33** (2018) 2787-2791.
[37] E. Deng, Z. Zhao, Z. Lin, R. Han & Y. Huang, Influence of temperature on the pressure distribution within press pack igbts, *IEEE Transactions on Power Electronics*, **33** (2018) 6048–6059.
[38] S. Wang, Z. Song, P. Fu, K. Wang, X. Xu, W. Tong & Z. Wang, Thermal analysis of water-cooled heat sink for solid-state circuit breaker based on igcts in parallel, *IEEE Transactions on Components, Packaging and Manufacturing Technology*, **9** (2019) 483-488.
[39] S. Fang, W. Luo, H. Wang & H. Hu, Operational performance of the valve cooling system in guangzhou converter station, *11th IET International Conference on AC and DC Power Transmission*, Birmingham, UK, (2015).
[40] J.-S. Kwak, C.-K. Kim & B.-E. Koh, Cooling system of haenam-jeju hvdc system [power convertor], *2001 IEEE International Symposium on Industrial Electronics (ISIE) Proceedings,* Pusan, Korea, (2001).
[41] Y. Yerasimous, V. Pickert, S. Dai & Z. Wang, Thermal Management system for Press-Pack IGBT based on Liquid Metal Coolant, *IEEE Transactions on Power Electronics*, **10** (2020) 1849–1860.