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Heat transfer and critical heat flux for two-phase immersion cooling of an inverter power module

I T'Jollyn^{1,2}, J Nonneman^{1,2} and M De Paepe^{1,2}

¹ Department of Electromechanical, Systems and Metal Engineering, Faculty of Engineering and Architecture, Ghent University, Sint-Pietersnieuwstraat 41, Ghent, Belgium

² FlandersMake@UGent – Core lab EEDT-MP, Leuven, Belgium

Ilya.TJollyn@UGent.be

Abstract. Heat transfer and critical heat flux measurement are reported for pool boiling cooling of the base plate of an inverter power module. Novec 649 is used as refrigerant. Heat fluxes up to 14.6 W/cm² were applied with refrigerant saturation temperatures of 36 °C, 41 °C and 46 °C. The measured boiling curves are comparable to those reported for similar refrigerants. The critical heat fluxes range from 12.1 W/cm² to 14.6 W/cm², which corresponds within 10% to the correlation of Zuber. The critical heat flux is significantly lower than the highest heat fluxes expected from the power module, indicating that methods to increase the critical heat flux are needed to enable two-phase power module cooling.

1. Introduction

Electrification in the transport sector is globally on the rise. To increase the efficiency and range of electric vehicles, drivetrains need to become ever more power dense [1]. By increasing the power rating of components while reducing their volume, cooling requirements become more stringent to avoid overheating and failure. The power module of the inverter is one of the critical components in the drivetrain, with heat fluxes exceeding 30 W/cm². The state-of-the-art cooling method for the power modules is forced liquid cooling, usually with a water-glycol mixture. In this study, cooling with boiling refrigerants is experimentally investigated. This method features high heat transfer coefficients, low pumping power and can possibly reduce the size of the heat sink [2]. Although pool boiling is thoroughly studied for electronics cooling, most studied feature refrigerants such as FC-72 and R-113, which have high global warming potentials (GWP). Recently, low-GWP alternatives have been introduced, such as Novec 649. An important limiting factor in boiling heat transfer is the critical heat flux (CHF) [3]. If the heat flux becomes higher than the CHF, a vapour film will be formed on the surface which will cause immediate overheating of the modules. It is thus the maximal heat flux that can be transferred from the boiling surface.

The goal of this paper is to experimentally investigate the heat transfer and critical heat flux of pool boiling cooling of the base plate of an inverter power module.

2. Experimental setup

The inverter power module used in this research is an Infineon HybridPACK type FS400R07A1E3, shown in Figure 1. It consists of a six-pack with IGBTs and diodes. This is a typical module used in the inverter of a drivetrain, with a rated voltage and DC current of respectively 650 V and 400 A.



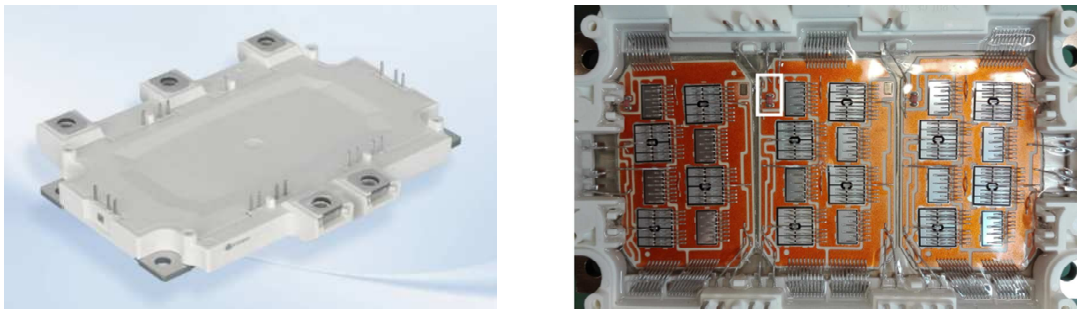


Figure 1. Infineon power module (left) and its interior (right).

In a previous study, a three-phase current waveform was applied to the module to provide losses in the IGBTs and diodes [4]. This approach was accompanied by some drawbacks. As the losses in the power module are two orders of magnitude smaller than the electrical power, a circuit containing a second power module and inductors was needed. This allowed for the three-phase power to be circulated between the components and thus only the electrical losses needed to be supplied by a power source. However, due to the current limitation of the inductors of 50 A, the power dissipation in the module was limited. This power dissipation in the module was only able to be measured indirectly through the heat balance, as the high switching frequency of the waveform required a too high sample frequency for accurately determining the power from voltage and current measurements. In this study, power dissipation in the module is achieved by applying a DC current to the IGBTs. The gate voltage of the IGBTs is chosen such that it operates in the active region. In this region, the current remains quasi constant while the voltage can be adjusted to vary the power losses in the module. With this method, heat dissipation rates up to the critical heat flux can be applied to the module. Furthermore, the electrical power can be accurately measured from the module voltage and current. In this configuration, all current will flow through the IGBTs and no current through the diodes. This is thus the worst case for thermal load of the IGBTs.

The base plate of the power module is cooled by direct contact with a refrigerant. For this study, $C_2F_5C(O)CF(CF_3)_2$ or 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-pentan-3-one is chosen as coolant. This fluid is also commonly known by its trade name Novec 649. It is fluoroketone with a boiling point of 49 °C at atmospheric pressure, making it viable for immersion electronics cooling. Its main advantages are the high dielectric strength, non-flammability and non-toxicity and low global warming potential equal to 1.

The refrigerant is contained in a leak-tight stainless steel reservoir, shown in Figure 2. The power module is bolted to the bottom plate with a silicon mat in between to avoid leakage of refrigerant between the plates. The bottom plate has a rectangular cut-out with dimensions 108 mm by 47 mm to form the boiling surface on the base plate. The bottom plate is made of 8 mm thick polyoxymethylene (POM). This material was chosen to avoid additional heat flows from the base plate to the bottom plate, as it has a low thermal conductivity (0.35 W/mK) compared to metals. The reservoir is cooled by a spiral condenser at the top. This copper tube carries a water-glycol mixture which is pumped through it to provide cooling. Before starting the measurements, air is removed from the reservoir with a vacuum pump connected to the top. More details on the reservoir can be found in [4].

To analyse the cooling performance, the temperature difference between the base plate and the refrigerant (or surface superheat temperature) and the heat flux have to be measured.

The base plate temperature is measured by five K-type mineral insulated thermocouples. These thermocouples are placed in between the base plate and the silicon mat, providing direct contact with the base plate but not with the refrigerant, as shown in Figure 3. With this configuration, the base plate temperature can be measured without affecting the boiling phenomenon. The five thermocouples are equally spaced along the long side of the boiling surface.

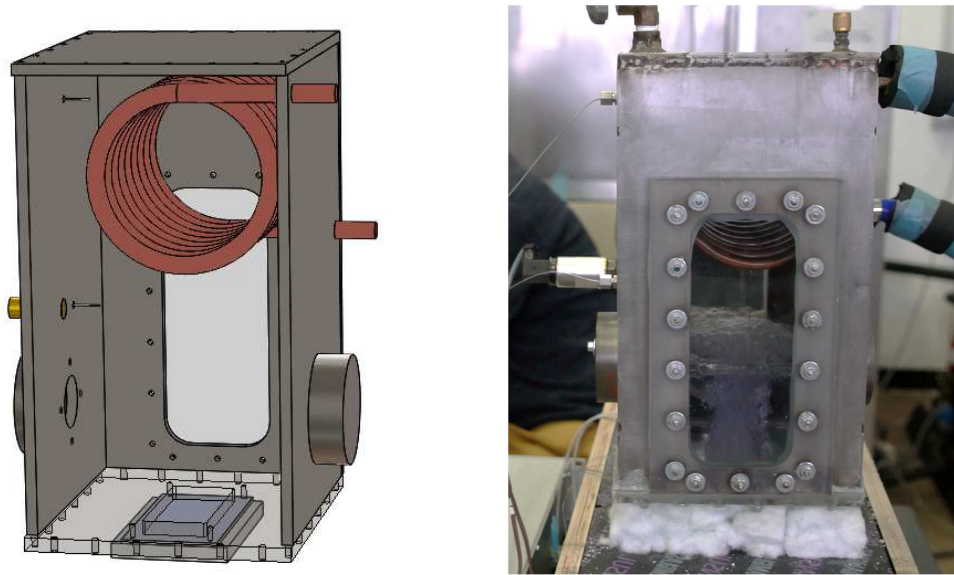


Figure 2. Refrigerant reservoir: CAD drawing without front plate (left) and picture (right).

The refrigerant temperature is measured at two locations by type T mineral insulated thermocouples. However, as significant thermal gradients are measured in the vapour phase, these measurements are not always a good indication of the refrigerant saturation temperature. The pressure in the reservoir is monitored by a pressure transducer. As there always exists a two-phase state within the reservoir, this pressure can be linked to the saturation temperature through the refrigerant saturation curve. To determine the surface superheat temperature, the thermocouple measurement is used when it is in direct contact with the liquid refrigerant. If it is not in direct contact, the saturation temperature derived from the pressure measurement is used.

The heat flux is determined from the voltage and current measurements. The voltage is measured directly at the module terminals to avoid inaccuracies due to voltage drops in the connecting cables. The current is measured by the DC source used to supply the power.

An overview of all the sensors and their measurement uncertainties is given in table 1.

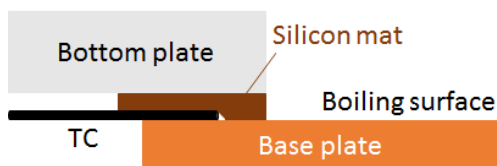


Figure 3. Thermocouple (TC) location.

Table 1. Sensors and their measurement uncertainty.

Sensor	Uncertainty
Thermocouple	± 0.07 °C
Pressure transducer	± 720 Pa
Current	± 0.24 A
Voltage	± 50 μ V $\pm 0.003\%$

3. Results and analysis

The boiling curve for a saturation temperature of 36 °C is shown in Figure 4. Furthermore, several measurement points at high heat fluxes for saturation temperatures of 41 °C and 46 °C are plotted. All measurement points are taken during boiling, so no measurement points of natural convection heat transfer were included. The boiling curves are consistent with those expected, both in trends and absolute values. Heat transfer is enhanced at higher saturation temperatures, which is also expected from previous studies.

The critical heat flux is shown as a function of saturation temperature in Figure 5. The critical heat flux increases with saturation temperature. The full line shown on the figure is the correlation for CHF

by Zuber with the correction by Lienhard and Dhir [3]. The correlation is able to predict the CHF within 10%, making it a good method for assessing the maximal heat flux that can be transferred by pool boiling cooling.

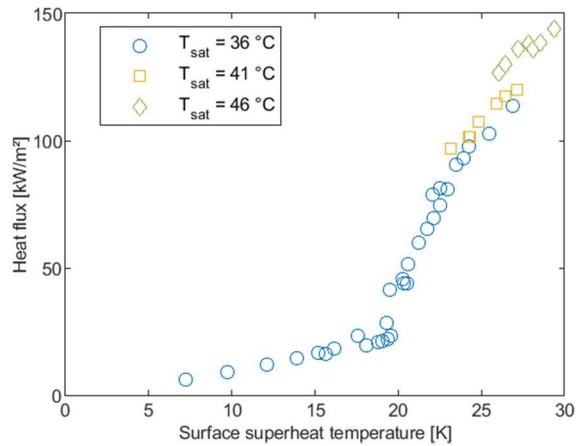


Figure 4. Heat flux as a function of surface superheat temperature for three refrigerant saturation temperatures.

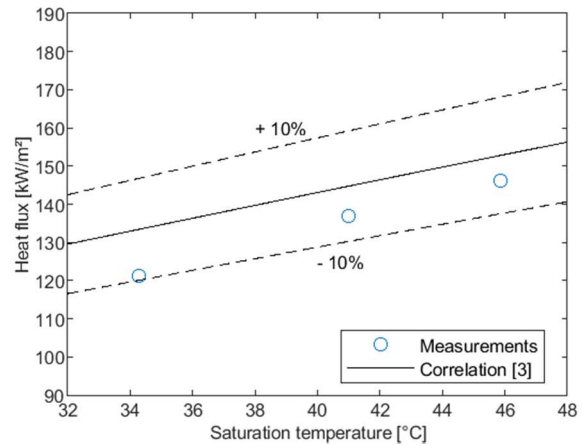


Figure 5. Critical heat flux as a function of refrigerant saturation temperature.

The largest CHF measured is equal to 14.6 W/cm^2 , which is significantly lower than the maximal heat fluxes expected from the power module (around 30 W/cm^2). It can be concluded that although the surface superheat temperatures for pool boiling on a flat base plate are low for heat fluxes below the critical heat flux, the method is not sufficient for cooling power modules at the highest loads. Other strategies to increase the CHF should be investigated, such as using subcooling the liquid, forced two-phase cooling and increasing the heat transfer area.

4. Conclusions

An experimental measurement campaign is done to determine the heat transfer and critical heat flux of pool boiling cooling of an inverter power module. Novec 649, a low-GWP refrigerant is used as coolant. Boiling curves were determined which are consistent with previous studies of other refrigerants. The critical heat flux is adequately predicted by correlations from literature. Although high heat transfer coefficients are measured, heat fluxes at high loads of the power module exceed the critical heat flux. Further research should be concentrated on overcoming this obstacle, for example by applying flow boiling cooling or by increasing the heat transfer surface.

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