Final report

1. Project details

Project title	Heat Pipe Spot Cooling
File no.	64017-05137
Name of the funding scheme	EUDP
Project managing company / institution	Ymer Technology APS
CVR number (central business register)	32074936
Project partners	Aalborg University Vestas
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2. Summary

2.1 English version

A wind turbine has power modules known as IGBT's that is used in the converter. Such power modules are mounted on cold plates to keep them cool to make them run effectively and prevent damage of the component. Since wind turbines are always increasing their power output for each generation, while keeping the turbine as small as possible to reduce footprint and cost, nacelle space will always be a limited. This project aims to develop a more effective cooling of the power modules, such that the cooling of the power modules does not become a bottleneck for the future development of wind turbines.

The main idea of this project is to utilize that when a cooling liquid is changing phase a larger heat transfer coefficient can be achieved. Furthermore, because the liquid is in a phase change, the liquid will not heat up passing under the power module, keeping the temperature distribution uniform on the power module, which makes them more effective. To keep the cooling liquid in a state where it is changing phase, the system needs to be controlled, and a control strategy for the system needs to be developed. The project thus has two main objectives: Developed a two-phase cooling plate and a control strategy to make it run stable.

Due to unforeseen challenges Ymer Technology has not been able to invest the amount of time needed to develop a working two-phase system. However, a one-phase system has been developed, which seems to improve the current one-phase system in wind turbines. This is demonstrated in the lab at Ymer Technology whit mock-up IGBT's and is awaiting real benchmark tests in Vestas lab.

If the tests in Vestas' lab are also successful the next step for this project is to reduce prototype costs, such that the new solution becomes viable.

2.2 Dansk version

En vindmølle har power moduler, kaldet IGBT'er, der bruges i konverteren. Sådanne power moduler er monteret på kølepladerfor at holde dem kolde, hvilket for dem til at køre effektivt og forhindrer beskadigelse af komponenterne. Da vindmøller altid øger deres effekt for hver generation, men samtidigt holder møllen så lille som muligt for at reducere fodaftrykket og omkostningerne, vil nacelle-pladsen altid være begrænset. Dette projekts formål er at udvikle en mere effektiv afkøling af power modulerne, således at afkøling af modulerne ikke bliver en flaskehals for den fremtidige udvikling af vindmøller.

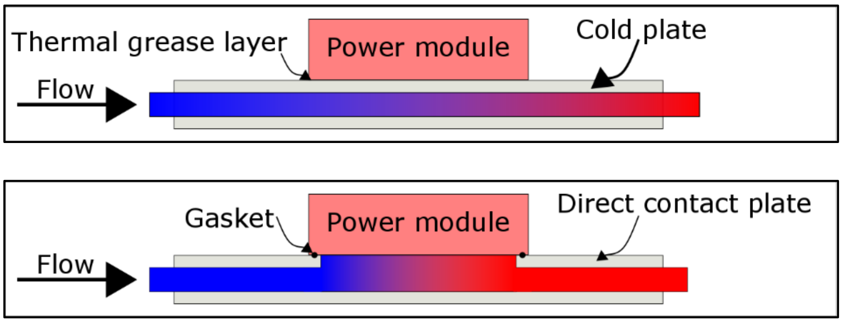
Hovedideen med dette projekt er at udnytte, at når en kølevæske skifter fase, kan der opnås en større varmeovergangskoefficient. Derudover vil væsken ikke varme under modulerne, da væsken er ved at skifte fase, hvilket holder temperaturfordelingen ensartet på effektmodulet som resulterer i et mere effektivt modul. For at holde kølevæsken i en tilstand, hvor den skifter fase, skal systemet styres, og der skal udvikles en kontrolstrategi for systemet. Projektet har således to hovedmål: Udvikle en tofaset køleplade og en kontrolstrategi så systemet kan køre stabilt.

På grund af uforudsete udfordringer har Ymer Technology ikke været i stand til at investere den tid, der er nødvendig for at udvikle et fungerende to-fasesystem. Der er dog blevet udviklet et en-fasesystem, som synes at forbedre det nuværende en-fasesystem i vindmøller. Dette er blevet demonstreret i laboratoriet hos Ymer Technology med mock-up IGBT'er, og afventer benchmarktest i Vestas lab med rigtige power moduler monteret.

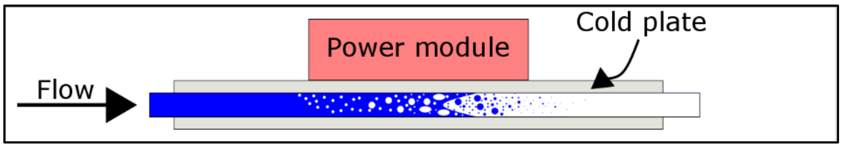
Hvis testene i Vestas' laboratorium lykkes, er det næste trin for dette projekt at reducere prototypeomkostningerne, således at den nye løsning bliver en brugbar løsning.

3. Project objectives

To keep the power modules in wind turbines cold, they are mounted on cold plates, which are plates with a cooling liquid running through them (normally glycol is used). There are two mainly used designs of these plates which are shown in the two figures below. In the top figure a closed plate is shown, and the bottom figure shows an open plate design. In the closed design the liquid is not directly in contact with the power module reducing the heat transfer, however the plate is more safe to use because leakage probability is reduced. The open design has a higher leakage probability but also a higher heat transfer.



The objective of this project was to create a system were the cooling liquid changes phase below the power module due to the heat transfer from the module. In the current designs the cooling liquid heats up, as it passes under the power module (illustrated by the change in colours above). In the new system there would be no heating of the cooling liquid as the transferred energy would be used on changing the phase of the liquid. Utilizing the phase change has two main advantages: Uniform temperatures of the power modules, as well as higher heat transfers of phase changing liquids.



Using phase changes in cooling is a well-known technology, however using it in cold plates is not. Because of the green profile of the wind turbine business as well as the safety of the persons working on the restricted space of a wind turbine's nacelle, it is not possible to use normal phase changing cooling liquids, and normal water or glycol had to be used. This makes the development more complicated and creates a need for developing a stable control strategy for the system. Because of the complexity of the full two-phase system it was decided to start with a one-phase system. The purpose of this is twofold: The one-phase system is needed to get a laboratory benchmark to compare two-phase results with, and the system is much simpler, such that it is easier to evaluate the control strategy. A developed control strategy for the one-phase system was then to be extended to a two-phase model.

During the development of the one-phase system several improvements to the one-phase cold plate has been made (which will be discussed further in section 5), and it was shown that a control strategy could be developed where it was possible to respond to outside influences of the system. Due to unforeseen challenges a two-phase system was never achieved, and some of these reasons will be discussed in section 4 below.

4. Project implementation

The project started out getting delayed because of the difficulties of finding a post doc for the project. Additionally, legal issues regarding the collaboration agreement between all three partners took some time to get in place. After the approval from EUDP the project started up with a new updated timeline and plan due to the delay. As mentioned earlier the work on the one-phase system was the starting point of the project. Different solutions to cold plates were designed and a one phase system was built.

The first real issue of the project was to get mock-up power modules made, where it would possible to measure a temperature that can be used for benchmarking. The only temperature that can be used for benchmarking of such a system is the temperature of the power modules because no matter what cold plate design is used, the water temperatures under the plate will always change the same amount, because it receives the same energy. A potential bad heat transfer between water and power module, will thus not alter the easy to measure water temperatures, but only increase the temperature of the power module. The mock-up power modules were chosen to be aluminium blocks with two heating rods placed inside of them to generate heat. Holes were drilled into the blocks where PT100 temperature sensors could be placed (See Figure 1**Fejl! Henvisningskilde ikke fundet.**).

Figure 1 - 6 IGBT mockups mounted on a cold plate in the laboratory.

However, it was quickly discovered that due to a large measurement area of the PT100 sensors, the temperatures measured were very inconsistent, and the solution was concluded not sufficient for benchmarking. To overcome this problem small thermocouples with a small area of contact were developed using a mold. These thermocouples (see Figure 2) could be placed more precisely in the blocks, in the very bottom of the drilling and could additionally be insulated on top to improve the reading even further. With this setup it was shown that reliable temperatures could be measured, and a benchmarking setup was completed (detailed results can be found in section 5).

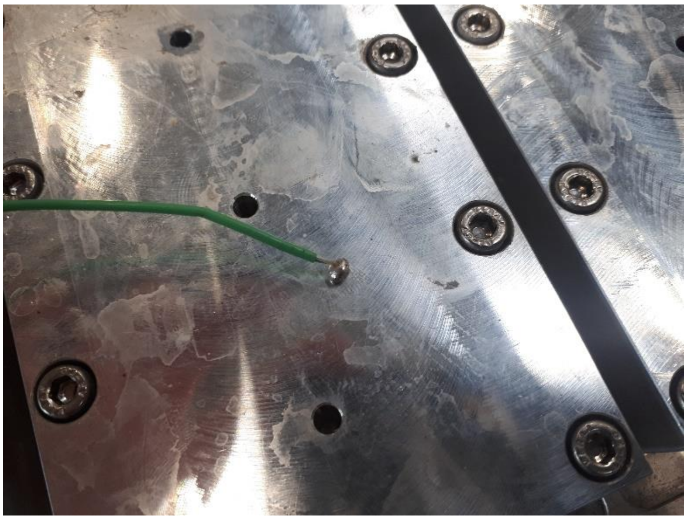


Figure 2 - New molded thermocouple.

Next benchmark tests were made on several different designs of the cold plate. The purpose was to show that two-phase cooling could not only outperform the current design but it could also outperform a perfected one-phase design. Only that way a conclusion could be made that the very complicated two-phase systems are better performing than any one-phase system that could be designed.

In parallel a system model and control strategy for the one-phase system was developed. The goal of this part was to get familiar with the experimental setup in the laboratory, and locate difficulties going from a computer model to a real-life model, for a system that is much simpler, and we have much more experience with. The lessons learned from this could then be used, when a more complicated control strategy needed to be implemented for the two-phase system.

After this work the project was hit hard by unforeseen challenges. The rapid growth of the wind business made it impossible to quickly enough get manpower into the company to keep the project up to speed. As a result, all R&D activities in the company were shifted to protect the core business. When the situation got under control and some of the initially planned resources could go back to the two-phase system project, the Corona virus hit making all lab activities nearly impossible. Even though the situation with manpower improved, the growth was still overtaking most of the R&D activities.

Development on the one-phase system was successful and great results was achieved (see section 5). Because of that a dialogue with responsible departments at Vestas was started. From these dialogues it was apparent that even getting in on sales of one-phase cooling plates would not be easy even though the improved one-phase system was interesting for the client. The power modules are such critical and expensive components that qualification of a new product is very difficult, and a lot of work needs to be put into this even when the new proposed product is nearly a 1:1 replacement to the old one and not bringing any different system pressures or other risks. This clearly shows that at the present time, the market is not ready for a two-phase system and will probably not be in the near future. Due to the limited amount of R&D time and the difficulties getting into the cooling plate business, it was thus decided to try to improve the one-phase plate even further. The strategy was to then get in on the cooling plate market with an improved product, that could help drive the green wind turbine business forward. If that could be achieved in the future, and Ymer Technology could become a main supplier of cold plates to the wind industry. Later-on the development of the two-phase system could be continued and much more probable to succeed when the market is more ready for such a big change, and the development could be driven inside Ymer Technology without support from EUDP and alike, as a natural development of the business. With the challenges described above, this was thought to be the most viable solution, where the project could end up with a product that could improve the wind turbines and generate job possibilities in the future.

5. Project results

5.1 Thermocouple designs

The original idea was to use standard PT100 sensors for measuring the block temperatures like the one shown on the figure below. However, as already mentioned the contact area of such sensors was too big and gave inconsistent results. For example, interchanging two sensors between two blocks, the two sensors would not measure the same temperature, even though they were placed in the same block, in the same position. With such unreliable temperature measurements, and these temperatures as the only mean to compare different cooling plates, a new solution needed to be found.

Figure 3 - Standard PT100 sensor.

From finite element analysis of the heat distribution in the mock up IGBT's it could be seen that the temperature of such a block was far from evenly distributed. The temperature was of course much higher close to the heat rods, and far less at the top of the block furthest away from the block. It was thus concluded that the unreliable temperature measurements were since the PT100 sensors had a large area of contact with the blocks and would thus depend a lot on at which area the best thermal contact between the block and the sensor was achieved. For example, if good contact was obtained at the bottom of the sensor (close to the heat rods) a high temperature would be measured. A quick fix of using thermal paste to ensure better contact was tried out, but no big improvement in consistency was achieved.

The solution was to produce small thermocouples in-house, which was done by casting small led blobs at the end of a thermocouple wire (see Figure 2). The cold plate consists of 6 IGBT's located in six different positions, and one thermocouple placed in each IGBT. For all benchmarking tests, each block and thermocouple will be numbered, and coupled together in such a way, that in all tests, a specific thermocouple is always placed in the same block. A good solution should thus be able to

1. Measure the same temperature, when put into the same block.
2. Measure the same temperature of a block when the block is at the same position on the cold plate.

1. ensures that all the self-made thermocouples function the same way, because it shows that when the thermocouple is placed at the same position it measures the same temperature. 2. Ensures that each block functions that same way, because it shows that when a block is placed at the same position of the cold plate, the same temperature is measured.

Table 1 shows the data for test 1. The data shows consistent temperature measurements of all the self-made thermocouples, and a maximum error between two measurements of 0.7 °C and a standard deviation between all the measurements of only 0.3 °C.

	Temperature	Abs error
T1	66.4	0.3
T2	66.3	0.2
T3	66.0	-0.1
T4	66.0	-0.1
T5	65.7	-0.4
T6	66.3	0.2
Mean	66.1	
STD	0.3	

Max error	0.7	

Table 1 - Interchanging thermocouples data (1)

Table 2 shows the data for the test where thermocouples are paired with a specific heater block, and then placed at the same position of the cold plate. From the data it can be seen that the error in this test is higher, which is expected. This because this test combines the error from test 1, with the errors arising from small differences between the different blocks. Furthermore, in this test the different blocks have to be placed at the same position of the cold plate, which means (unlike test 1) that the test setup needs to be stopped, drained and reassembled between each run, further increasing the errors.

	Temperature	**Abs error**
Block 1	59.3	0.4
Block 2	58.5	-0.4
Block 3	59.1	0.3
Block 4	58.5	-0.3
Block 5	59.5	0.7
Block 6	58.3	-0.6
Mean	58.9	
STD	0.5	
Max error	1.3	

Table 2 - Interchanging heater blocks data (2)

To try to correct for the fact that the setup has been taken apart and reassembled, it might be more appropriate to take the measured block temperature and subtract the average temperatures measured of all six blocks. That method accounts for the fact that the ambient conditions could have changed during the change in setup, resulting in an overall lower or higher temperature of the entire block. The data is shown in Table 3. As expected, this reduced the error between blocks.

	Delta T (ref Average)	**Abs error**
Block 1	1.1	-0.1
Block 2	0.9	-0.3
Block 3	1.4	0.2
Block 4	1.5	0.4
Block 5	1.2	0.0
Block 6	0.9	-0.2
Mean	1.2	
STD	0.3	
Max error	0.7	

Table 3 - Interchanging heater blocks data relative to average block temperature

The overall conclusion of the run-in of the self-made thermocouples is that the new solution gives reliable results, and is a big improvement compared to the PT100 sensors originally included. From the data in the tables above it is concluded that all temperature improvements in future tests above 1 °C should be considered as an actual improvement of a cold plate design. Below 1 °C the improvement is too small to conclude anything from, because of the margin of error of the temperature measurements.

5.2 Benchmark test of the two initial designs

The first design of the cold plate resembles Vestas' current design. The flow is across the IGBTs just as in Vestas' current design, and the main difference is that Vestas different, plastic, insert beneath the power modules to improve heat transfer, and Ymer Technology design uses normal aluminium turbulators, to increase turbulence and heat transfer between the water and the heater blocks.

The general benchmarking test consists of 25 test points. That consists of varying the liquid flow and input power to the heating rods systematically. Figure 6 shows the results from the benchmarking test compared to Vestas current design. It is clearly seen that the temperature of this design is much higher than the current design. The test had to be stopped at test point 10, because of the risk of reaching boiling temperatures in the plate. This design fails as a contender to be used for the future two-phase design as it is so much worse than the current design, and even though two-phase could improve heat transfer compared to one-phase, it starts from a much worse state.

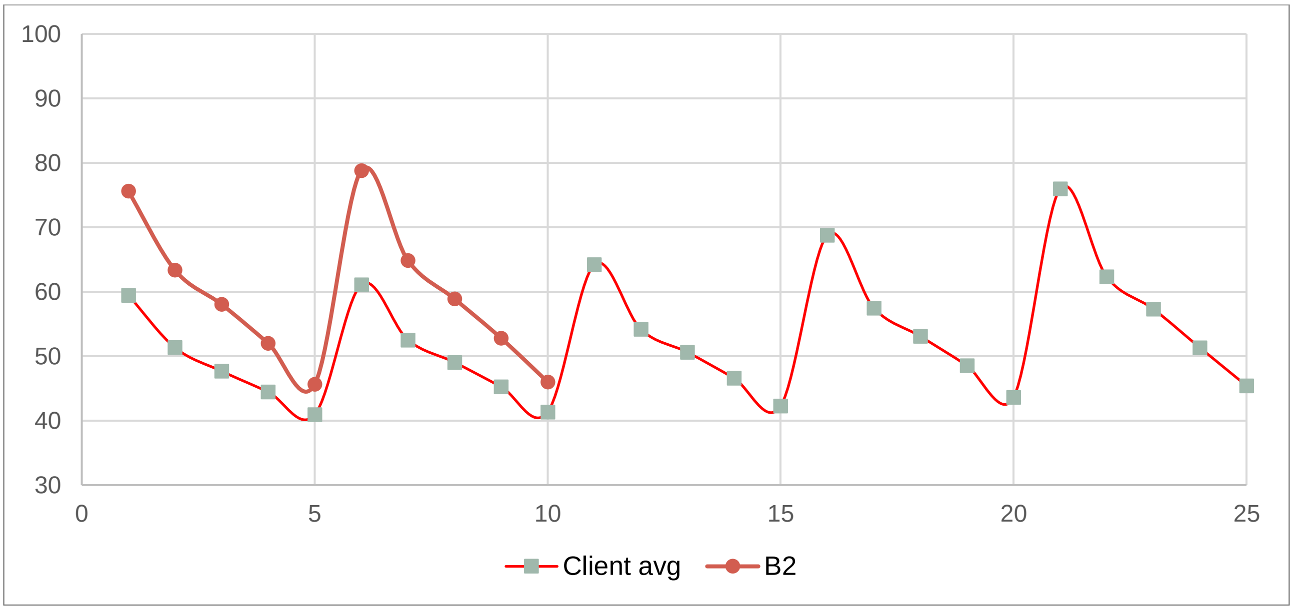


Figure 6 - Comparison between Vestas current plate and Ymer design for the 25 test points in the benchmarking test.

The worse performance of that plate than the Vestas current design was expected, since the aluminium turbulators are designed to work best at high flow rates where they create high turbulence a good heat transfer. In this design however, where the flow is across the IGBT the flow area is large, result in very low velocities in the turbulators.

To try and fix the design, higher flow velocities through the turbulators were needed. The results are shown in Figure 7. As can be seen in the figure, the temperatures are now comparable to Vestas current design.

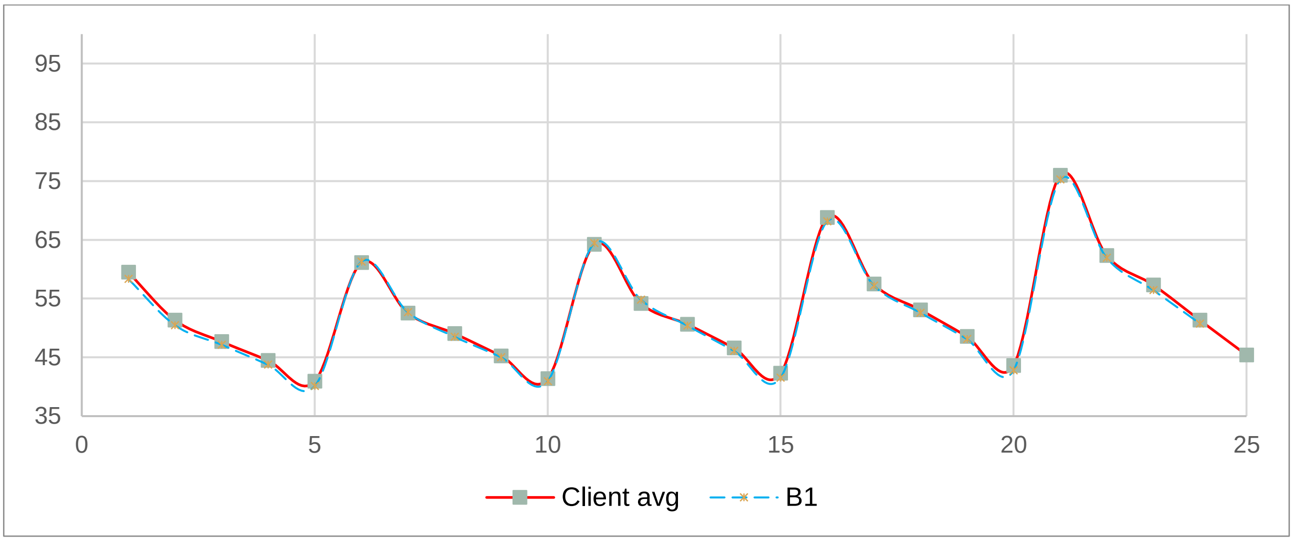


Figure 7 - Comparison between Vestas current plate, and new design allowing for high velocities.

Even though the new design improves the block temperatures and makes it comparable to the current design it has some other disadvantages. Increasing the flow velocities and flow length through the turbulators results in a pressure drop increase compared to the initial design, however, the pressure drop is still below Vestas' current design. Another issue is that an IGBT consists of several power units placed along the IGBT. For these power units to work optimally they need to be at the same temperature, so they experience the same conditions. When the flow is across the IGBT, as in the original design, the water temperature beneath each of these power units will be the same, however, with the new design, the temperature will increase along the IGBT resulting in a temperature gradient along the IGBT. If a two-phase system was achieved this will not be an issue, because when the heat is being used to make a phase change, instead of increasing the liquid temperature, no temperature change will be present beneath the IGBT. However, as already mentioned the pursuit for a two-phase system in this project was abandoned (discussed in more detail in section 5.5). We thus were left with two designs, one with much worse temperature than the current design, and one with comparable temperature, but with a gradient beneath the IGBT's. Thus, none of the solutions improve on the current design, and a new solution is needed.

5.3 New design and benchmark

A new design with multiple times higher flow and high flow velocity through the turbulators was designed.

Figure 8 shows the results from the benchmarking test for this design. As can be seen on the graph a significant improvement is observed. For the first test point the improvement is around 7 °C. The cooling water is 35 °C and so the maximum improvement possible to achieve is $60\,°C - 35\,°C = 25\,°C$. Using this as a reference this cold plate design is an improvement of 28 % which is a huge improvement. The improvement however comes at a cost of a higher pressure drop through the plate. To reduce the pressure drop the plate was tested without turbulators, and as can be seen from the graph, the temperatures were below target even without the turbulators. Furthermore, the pressure drop was now well below Vestas current design. It should though be possible to select a turbulator design that ends up with the same pressure drop as Vestas current design and has a better heat transfer (not 28% improvement though), or the extra pressure drop could be accepted and a small increase in pump power might be needed such that the full 28% increase could be utilized.

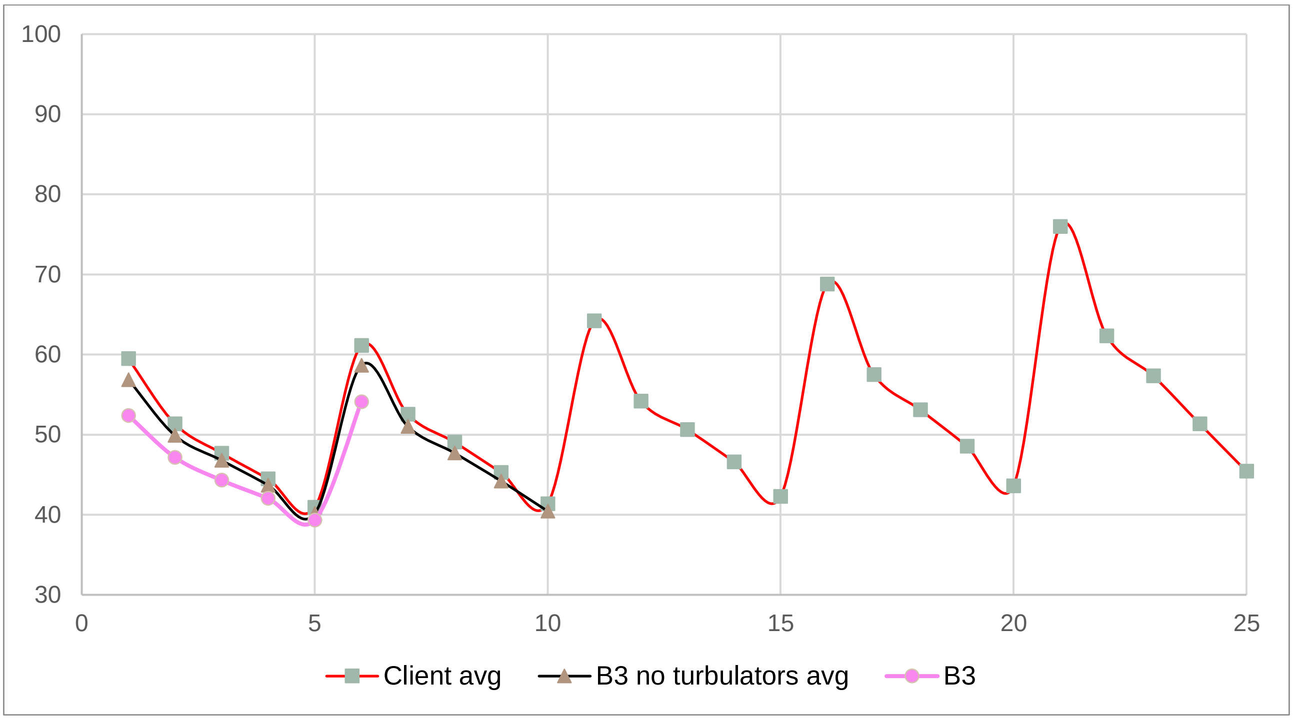


Figure 8 - Results for cold plate with highest flow beneath IGBT's

5.4 Control

A dynamic model for the two-phase system was needed to make a control strategy for the system. The initial system design is shown in Figure 9. In the system water in liquid phase starts to flow through the cold plate. Because of the heat added from the plate, phase change will happen and a mixture of liquid and water vapor will exit the cold plate. This mixture will enter a separator tank, where vapor is sent to the condenser, and the liquid to the cold plate. After the vapor has condensed it will recombine with the liquid flow and enter the cold plate as well. It is unknown if the system will need a pump to drive the flow, or if it can work as a thermosiphon (the pump may need to run in reverse if the thermosiphon effect is too great). As the temperatures of the water should be around 35 °C and we need a phase change, a vacuum pump is needed so the system can run at low pressures. The control strategy is to be designed such that the vapor percentage (quality of the water) can be controlled. This can be done by controlling the mass flow for example by controlling the pump. The mass flow will depend on the heat inputs from the IGBTs, which can vary in real applications, as well as on the liquid temperatures obtained which will depend on the ambient temperature. The thermosiphon effect may also depend on the ambient conditions, and this can affect the mass flow as well. The control model thus needs to take all these external effects into account to control the system.

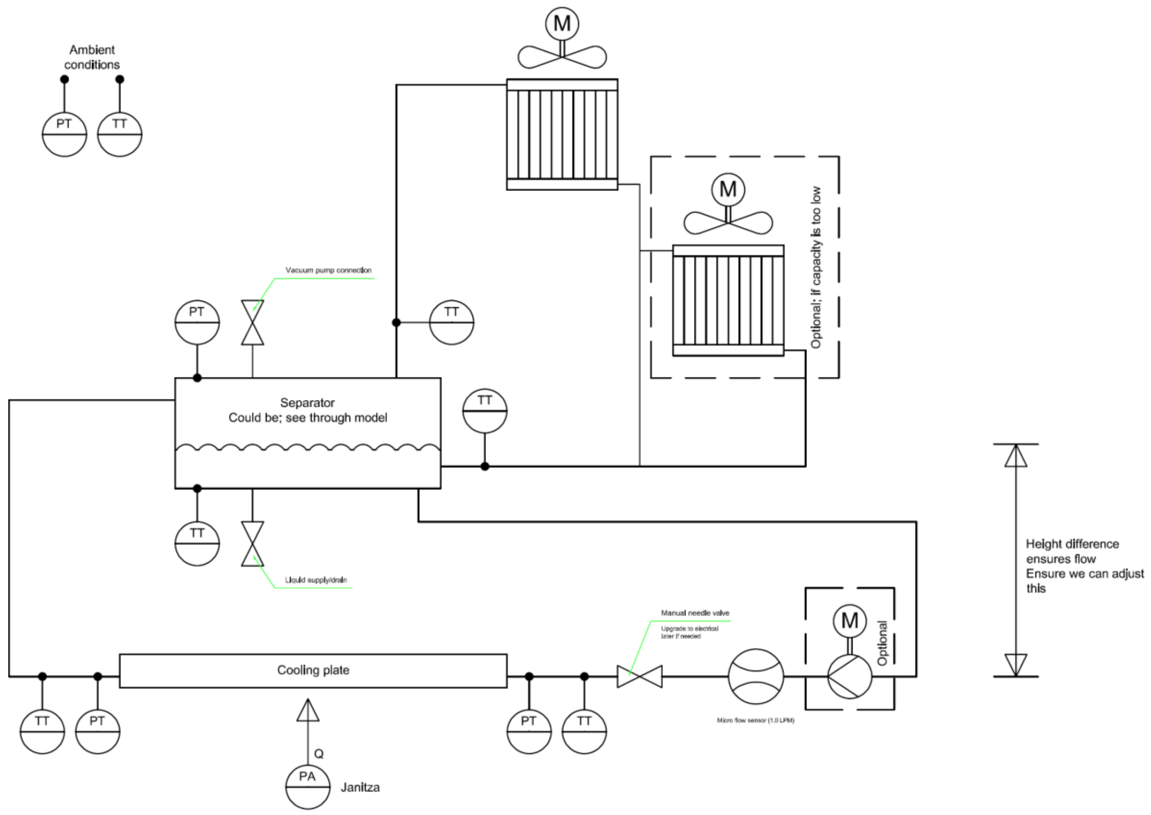


Figure 9 - Two-phase system diagram.

A dynamic model for the system above was developed, however, as already mentioned the project ran in to unforeseen challenges and, to get started with control of a real system and not only doing simulations, it was decided to try and make a basic dynamic model for the one-phase system, and then do laboratory control tests on this. This has two immediate benefits. First of all, we have the setup ready, because it was already used for the benchmark tests of the cold plates mentioned above, secondly the system is much simpler, which means that problems with relating the model to the tests can easily be understood, and knowledge of going from simulation to real system can be gained.

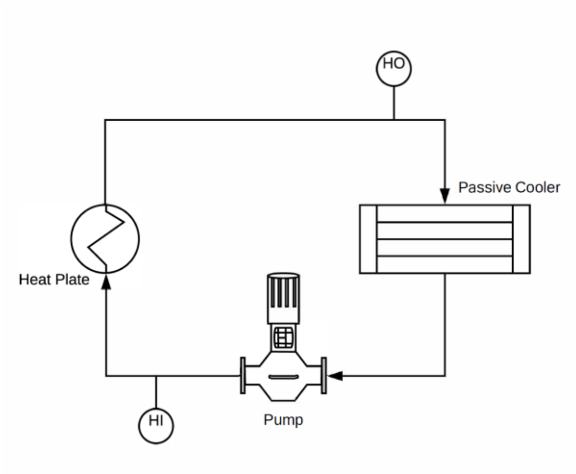


Figure 10 - Diagram of one-phase setup.

The one-phase model turned out to be successful and a good correlation between the system response and the model was obtained (see Figure 11). A paper describing this model and the comparison with the experiments was written, however, the findings was found too novel for the paper to be accepted in the journal. Mainly because similar models already exist in literature, even though this experiment was on a more real scale system compared to literature.

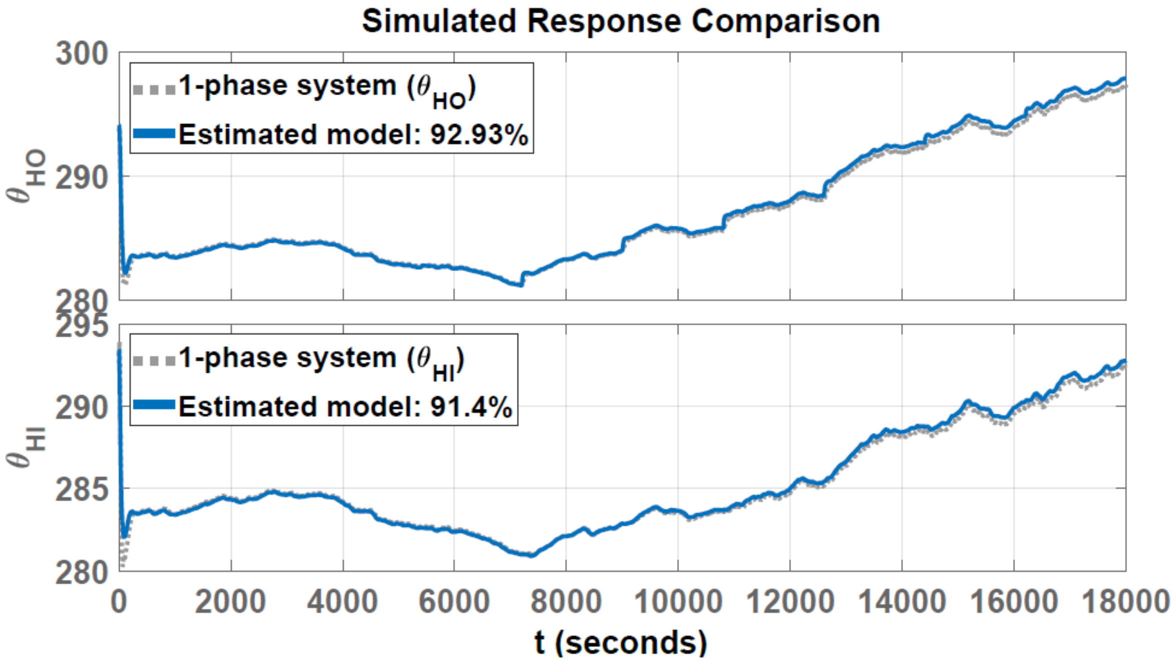


Figure 11 - Comparison between the measured outputs and the outputs obtained by simulating the model.

5.5 Conclusion

The original objective of the project was to deliver a two-phase cooling system, that could improve cooling of IGBTs in wind turbines. Due to extreme unexpected growth in customer projects in Ymer Technology, it was not possible to invest the needed number of hours in the project. This fact combined with the Covid-19 epidemic which made laboratory work restricted, a two-phase system was never developed. However, in the search for an optimal one-phase system to benchmark the two-phase system against, and interesting full-flow cold plate design was invented. This design shows promising results, and because of this direct talk about implementing this design in wind turbines has been initiated with customers. That stage was never expected to be reached within the timeline of this project (even though this is with the one-phase system). In the discussion with the final end-users that has been possible because of the promising results of the one-phase plate, it has become clear that IGBT’s are a very important component in the wind turbines, and getting new products approved that surround this component is not an easy task. This has further strengthened the decision to focus in the one-phase system, because getting an entirely new technology improved for these components in the near future is probably impossible. However, if the one-phase solution is implemented it will be possible to invest more time in developing such systems, and because we are then already a supplier getting a new technology approved will be easier. It is thus possible that the development of an improved one-phase plate, can turn into development of the intended two-phase system in the future, when the market is more ready.

From the control point of view a solid model of the one-phase system was made, and it showed great results compared to laboratory experiments. However, the findings were found too novel to get paper accepted, even though this was done on more realistic real-life systems. Furthermore, control of a one-phase system in a wind turbine is probably not needed in the final application, because IGBT's are critical components the highest cooling as possible is always wanted. The flow thus does not need to be controlled as it should always just be maximized. The only reasons to control a one-phase system could be to save pump power when full flow is not needed, or to try to even out temperature fluctuations of the IGBT's. However, because the lifetime of IGBTs depends so much on the cooling of the IGBTs and the IGBTs are so expensive, the saved power can probably not be justified over just reducing the temperature expanding on the lifetime of the components.

6. Utilisation of project results

The obtained technological result in this project is mainly an improved one-phase cold plate design. The improvement is so significant, that discussions about implementing the solution in upcoming wind turbine designs has already been initiated. There are two main difficulties in getting the new plate implemented. Firstly, the new design needs to be qualified, which is not easy because of the critical nature of the IGBT's. Secondly since cold plates are a relatively new product for Ymer Technology, a final design needs to be made that is cost-effective such that the new plate offers both better performance and a better or equivalent price point. If the new design is successfully implemented in new wind turbines, it is expected to generate both huge turnovers and the necessity for hiring additional people to improve and expand on the technology.

Today it is Vestas themselves that produce their cold plates and using a patented plastic insert solution to improve heat transfer. Vestas is thus the main competitor for our new product. However, it is a general strategy of Vestas to have sub suppliers supply more and more of the wind turbine. Therefore, if Ymer Technology can provide a cost-effective alternative to the current solution, the barrier into market should not be that hard, and there will not be an immediate competition on the product.

The benefits of this improved one-phase cold plate from an energy perspective, is mainly to improve the cooling of the IGBT's which can lead to bigger wind turbines and longer lifetime of the IGBTs. Two factors that will help drive down the cost of wind energy in the future, making this energy source even more competitive with fossil fuels. Moreover, should one-phase cold plates turn into a big business for Ymer Technology, it is entirely possible that the two-phase system will turn out to be very much relevant again in the future. Mainly because wind turbines need to always improve on the energy output while keeping the footprint small, and thereby improved cooling (even beyond what one-phase can offer) can be a necessity in the future.

7. Project conclusion and perspective

An optimized one-phase cold plate design was created, which improved the IGBT temperatures with several degrees. A two-phase cold plate was never achieved which was the original scope of the project, however the improved one-phase design has started a closer collaboration between Ymer Technology and Vestas on the cold plate development. Two-phase cooling may still be the next step for cold plates when further improvement is needed in the future. The improved design and closer collaboration could be a great starting point for developing two-phase cooling of cold plates.