Liquid circulation cooling vest for factory- and warehouse workers

Sergio Fazzi
4458826
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Chair - Prof. dr. ir. K.M.B. Jansen

Mentor - Ir. G.P.M Hoekstra eur.erg

Company mentor - Rein Bokslag

Gratitude

I would like to express sincere gratitude to everybody who has made this project possible. The pandemic has made the graduation project even more difficult and impractical than it was supposed to be. Without the help of the following people I would not have been able to come to this result.

I would like to thank:

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With gratitude,

Sergio Fazzi

Summary

This graduation report describes the design of an ice cooled liquid circulation cooling vest for INUTEQ, a company specialized in personal cooling. The new design, the INUTEQ ICE, is made for warehouse and factory workers. They need cooling vests, because they work in large buildings with flat roofs. Large buildings cannot be cooled by air-conditioning anymore and the sun can heat them up to tropical temperatures. Additionally, the temperature may, in some cases, be increased by the production processes inside. Working in the heat can decrease productivity, performance, comfort and safety. The physical work these people perform also increases their chances of heat related illnesses such as: heat rash, heat cramps or heat exhaustion. In some cases, overheating can even lead to a heat stroke.

One of the solutions to cool people down is with cooling garments. The INUTEQ ICE is an improvement on traditional liquid circulation garments, which cool by running the water through silicone tubes. The new design makes use of open cell foam pads to increase the heat exchange between the cold water and the body. The developed cooling pad technology was found to have a nearly three times as high cooling capacity per unit area compared to liquid circulating cooling technology currently on the market. In the same experiment, the cooling capacity per unit area of the new pad technology was found to be similar to existing 6.5°C PCM packs and higher than 15°C and 21°C. The design has the potential to cool for longer than the 6.5°C PCM packs. Contrary to evaporation and air based cooling vest, the INUTEQ ICE is able to be used underneath enclosed clothing and in other high humid environments.

The project contained three phases, an analysis phase, a development phase and an evaluation phase. In the analysis phase, relevant information about cooling garments and the target group is gathered. This information is brought together in a list of requirements. In the development phase, the cooling pad technology is developed and the cooling method is defined. The development phase ends with the first concept of the INUTEQ ICE. In the evaluation phase, a working prototype was made and user tested in the appropriate context, which provided useful insights towards the final concept. The evaluation phase also contains the previously mentioned cooling capacity test and recommendations to continue the project.

The end result of the project is a promising final concept, with working prototype. The INUTEQ ICE has the potential to become a product that, in humid environments, performs better than alternative cooling garments. With further development it can be used by different target groups, not only factory and warehouse workers. It seems likely that a finished version of the INUTEQ ICE can add value to INUTEQ’s product range.

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1 Introduction

The human body uses energy for mechanical work, chemical reactions and transportation. Most of this energy, however, is converted into heat. Normally this heat is released to the environment, but when doing physical work in tropic temperatures (>30°C) the body can start to overheat. Overheating can negatively influence productivity, performance, comfort and safety and may even lead to a heatstroke. Because of rising global temperatures, due to climate change, this problem will probably increase in frequency and become relevant for a larger segment of the world's population.

One of the possible ways to cool down the body is with cooling garments. INUTEQ, a company specializing in cooling garments, has approached the TU Delft in search of a new type of cooling garment. The SDE department has done research into different kinds of cooling garments. This graduation project was set up to investigate the possibilities of one of these directions: an active liquid circulation cooling garment.

One of INUTEQ's main markets is construction- and factory workers. The development of this project's novel cooling garment has therefore been focussed on this target group. This group requires a large amount of freedom of movement and high user friendliness, which has been taken into account in the new design.

The project is separated into three distinct phases. In the Analysis Phase, relevant information about cooling garments and the target group is gathered. This information is brought together in a list of requirements. In the development phase, the cooling pad technology is developed and the cooling method is defined. The development phase ends with the first concept of the INUTEQ ICE. In the evaluation phase, the concept was evaluated based on the results of a working prototype, a user test in the appropriate context and a cooling capacity test.

2 Project definition

As stated in the introduction, INUTEQ has approached the TU Delft to find new technologies in the field of personal cooling systems. The SDE department of the Industrial Design Engineering faculty had been doing research on different cooling technologies already. Several possibilities were suggested to INUTEQ, of which a report by Joshua Stewart (2017) was selected. Stewarts report describes the design of a liquid circulating cooling garment for rowers.

Liquid circulating cooling garments are already sold on the market. However, these products have lots of tubing a large heat exchange box, and a heavy pump (see figure 1). Apart from that, the heat exchange between the cold water and the body is poor through the silicone tubes. Stewart (2017) aimed to improve this heat exchange. His cooling garment used open cell foam pads to create a large area of coverage with the body. These foam pads are also meant to passively circulate the water by movement induced compression. A protype cooling shirt was made and tested which will serve as a starting point for this project (see figure 2). A more detailed project brief can be found in appendix A.

Figure 1: Liquid circulating cooling shirt (eBay, N.D. A)

Figure 2: Stewart's prototype (Stewart, 2017)

2.1 Goal

The goal of this project was to design a liquid circulation cooling garment that had a higher cooling capacity than existing liquid perfused cooling garments. This garment was also aimed to cool throughout an entire workday, without having to take it off.

This goal was aimed to be achieved by improving the pads made by Stewart (2017), and designing a heat exchange apparatus, which could be comfortably carried together with a pump. This design was focussed on the predefined target group (see chapter 4), so it needed to have great freedom of movement and ease of use.

This project's aspired end result was a promising concept, including a user tested working prototype, which showed potential to become a valuable addition to INUTEQ's product range.

Analysis Phase

3 Analysis existing prototype

As stated before, Stewart's prototype (Stewart, 2017) was used as a starting point of this design project. He presents the design of a cooling garment for rowers, using water perfused foam pads. The function of these foam pads was to increase the area of the cooling surface and allow for a system where compression of the foam would circulate the water. This circulation function was possible due to the predictability of a rowers motion. Stewart made a prototype of the design which can be seen in figure 3. In this chapter this prototype will be analysed to gain a better understanding of it and to find potential challenges for further development.

In Stewart's design the water is pumped around using compression and relaxation of the foam in combination with one way valves. This feature was tested and proved to work, but did not provide enough circulation to provide effective cooling (personal conversation with Stewart). In the new design, the target group does not have such predictable movements as rowers. Therefore, an alternative water circulation method needed to be found for the new design.

Though the design and prototype looked promising, there are still a couple of problems that need to be solved.

Firstly, the pads were delaminating when subjected to a water pressure of a couple hundred millibar. Signs of this delamination can be seen in figure 4. It seems that the bonding between the fabric and the foam was not strong enough. A more recent prototype of a foam pad was examined and it was found that the glue used in this process had also completely come loose of the fabric (see figure 5). This delamination was a structural problem throughout Stewart's project (personal conversation with Stewart). The different types of glue that he used were: BISON fabric adhesive, HEMA fabric adhesive, BISON universal spray adhesive, Vliesofix and PU powder dot transfer coating on release paper (PU Dots). The PU dots were found to work best, but that was still not strong enough, as it was the method used in the delaminated pad in figure 4.

Secondly, the outside seal of the pad failed on multiple occasion. This seal consisted of multiple joining methods. The fabric was joined together using the PU dots and the connector was glued in using super glue.
During experimentation it became clear that both these methods were not waterproof. The fabric to fabric connection was not strong enough and leaks started to form. This was solved with silicon tape around the perimeter, which did not seem to be an effective long term solution.
The superglue seemed to damage the waterproof layer of the fabric, so water started leaking through (see figure 6).
During the examination of the more recent pad prototype in figure 5, it was also found that the seal broke easily by pulling the layers of fabric apart. Not only did the seal break, the fabric itself also started to delaminate because of the small applied force.

Thirdly, the proposed cooling method in the design, thermoelectric cooling, was not tested in the prototype. It can therefore not be known if thermoelectric cooling is powerful enough to provide enough cooling. Stewart proposed that the thermoelectric cooling unit would be placed in the rowing boat. In the new design all components have to be wearable, creating the additional challenge of the garments weight.

Figure 3: Stewart's prototype

Figure 4: Delamination of the pad

Figure 5: Opened delaminated pad

Figure 6: Leaking connectors

4 Target group

Together with INUTEQ it was decided that the target group to focus on for the new design would be construction- and factory workers. This target group is chosen because they work in hot conditions, either in old buildings or outside in the sun, and heat has a higher impact on people doing heavy physical work (see chapter 5). It is therefore not surprising that a great portion of INUTEQ products are sold to construction companies and factories.

The target group contains workers from two different sectors. Construction workers work in the construction sector and factory workers work in the industry sector. These two sectors have similarities and differences. Finding these could give a better view on the types of people containing the target group. The reason to look at sectors instead of workers is because research reports often compare sectors instead of individual jobs and because factory- and construction workers are diverse in their job description. Hence, a more general view can be given by looking at sectors.

4.1 Demographics

Both the construction and the industrial sector are dominated by male employees. For the industrial jobs just over 20 percent is female. In the construction sector this figure is even smaller at around 10 percent. This percentage already contains office personnel which is typically more balanced in gender (CBS, 2019).

The average age of workers across all sectors has strongly increased within the last ten years. The average age of the working class in the Netherlands has risen to 42 years. The industry more or less follows this average (UWV, 2020), while the construction sector has a slightly higher average age of 42.7 years (CBS, 2016).

Construction and industry are also similar on education levels. These are the two big labour sectors with the most workers who only have completed lower education (primary school). Roughly 35 percent of construction workers belong to this group. Over half of construction workers have completed a secondary level education (havo, vwo, mbo) (CBS, 2016). No percentages have been found on the education level of industry workers. However, CBS does state that the percentage of workers who have only completed a primary education is higher in the industry sector. It can therefore be assumed that the industry sector also contains a large amount of workers who completed a secondary education level.

The percentage of workers with a migration background is difficult to determine. This is because people working for less than 4 months in The Netherlands don't need to register (CBS, 2016). Only considering registered workers, the number of workers with a migration background are 12% and 18% in the construction and industry sector respectively (ABF, 2017).

It is not difficult to imagine that construction- and factory workers have jobs with a relatively high susceptibility to work related accidents. It was found that the percentages are similar for both sectors, though there are sectors with higher accident rates such as the transport and storage sector and the catering sector (CBS, 2019). People working in the industry sector do call in sick more than construction workers. Both groups score relatively high compared to other sectors but industry does have a considerably higher percentage (roughly 5.4% vs 3.8%). 24% of those cases are claimed to be (partially) work related (CBS, 2019). The high numbers of absenteeism could also be partially explained by the unhealthy lifestyles of people working in these sectors. Both have high numbers of obesity, smoking and alcohol usage (Jans, 2007).

A difference between the two sectors can be found in the number of freelancers. Construction is a labour sector containing relatively many freelancers and this has been increasing. Compared to that, the industry is a sector with relatively few freelancers (CBS 2019).
In 2019, roughly 26 percent of people working in the construction sector was freelancer. This is an increase of 15% since 2003 (CBS, 2021 A). In that same time, the number of freelancers in the industry sector grew from 2.7% to 5.3% (CBS, 2021 B). Though both sectors nearly doubled in the percentage of freelances, the percentages themselves lay far apart. This difference does not reflect on the workers income however. Workers from both sectors roughly have the same hourly income (CBS, 2019).

4.2 Clothing

Through online researching and observations (more on observations in chapter 4.4), the clothes of both groups have been roughly identified. The workwear may influence the design of the new cooling garment. Limitations and opportunities could be found when a cooling garment is combined with specific workwear.

4.2.1 Construction clothing

When construction workers work outside in the heat, they mostly wear shorts sleeves and long trousers in combination with high visibility vests for safety (see figure 7 and 8). Figure 8 also shows workers wearing safety harnesses, which are worn when work is done at heights. These harnesses could prevent waterflow in places where they are tightly strapped to the body. The same goes for shoulder protectors which are worn to more comfortably carry items on the shoulder.

Figure 7: Construction worker (Rodenburg , 2013)

Figure 8: Construction workers with harness (Worldsafety2018, 2019)

4.2.2 Factory clothing

Factory workers can work in all kinds of conditions. The work is more diverse than construction work, which can be seen in the clothing workers wear. Workers in high heat conditions (>70°C) usually wear thick heat protective outfits (see figure 9).

Other commonly worn outfits are coveralls. Coveralls also come in different shapes for different purposes, for instance a boiler suit for dirty work, antistatic for electrical work, flame retardant for work with fire hazards or sparks, etc. (see figure 10).

Factory workers without dirty or hazardous work often wear regular workwear. This includes long trousers and a separate top (see figure 11). In some cases this also comes combined with a safety vest. Factory work is more often done at a company, so clothes tend to be issued by the company including the company logo.

4.3 Selection

During a meeting with INUTEQ it was decided to narrow the target group. Past sales and future vision for the project led to the selection of a specific type of factory workers. This group consists of workers who do not wear closed suits or overalls but separated trousers and tops. They work in large open buildings with a flat roof. Due to the size of these buildings, air conditioning is not applicable or financially subordinate to personal cooling garments. Within this group, INUTEQ has experience selling to car manufacturers and tire factories (see figure 11 and 12). Other workers within this target group are people working in large warehouses (see figure 13).

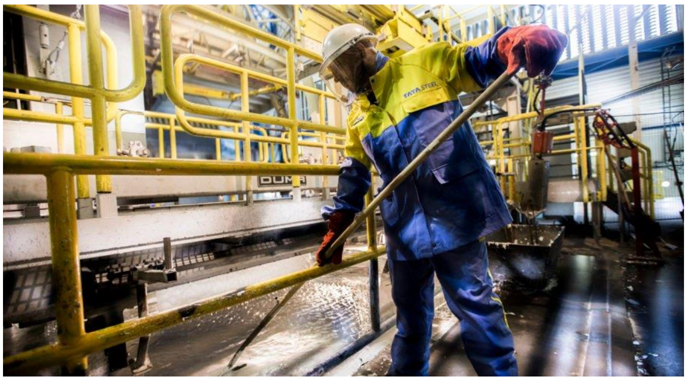


Figure 9: heat protective clothing (Beverwijk.nieuws.nl, 2015)

Figure 11: workers of car factory (Automotive News, 2014)

Figure 12: Tire factory (gumipiacmagazin, 2017)

Figure 13: Large warehouse (Romita, 2018)

Figure 10: Different types of Coveralls (Proforto, N.D.)

4.4 Interview

A large warehouse and a factory were visited to get a first-hand impression of the target group and the work they performed. The work was observed to better design the cooling garment with the required freedom of movement and the restrictions of the cooling pads in mind.

The cooling pads made by Stewart (2017) are flexible to better fit the shape of the body. However, when compressed too much, the water flow through them will stop. Compression can therefore stop the cooling pads from cooling. So, The main aim of the company visits was to find when and for how long a potential cooling pad could be compressed. Observations were done on the workers postures and movements, carrying items and standing against something. In case a body part is often obstructed, a cooling pad may not be placed on it in the new design.

To help observing the different postures the workers may have, an overview of the OWAS postures was brought along. OWAS (Ovako Working Posture Analysing) is a method to evaluate working posture and the load on different body parts (Motmans, 2017). Figure 14 shows the postures taken into account in the OWAS method. The method itself was not fully used, because the frequency of the postures was not the main concern. More important was how long the postures were held and whether or not they were done at all. The most critical postures are those where a pad could theoretically be compressed. These postures are back posture 2 and 4, and leg postures 1, 4 and 6. The arm postures may also be important for the fit of the garment on the shoulders, but they are unlikely to cause pad compression.

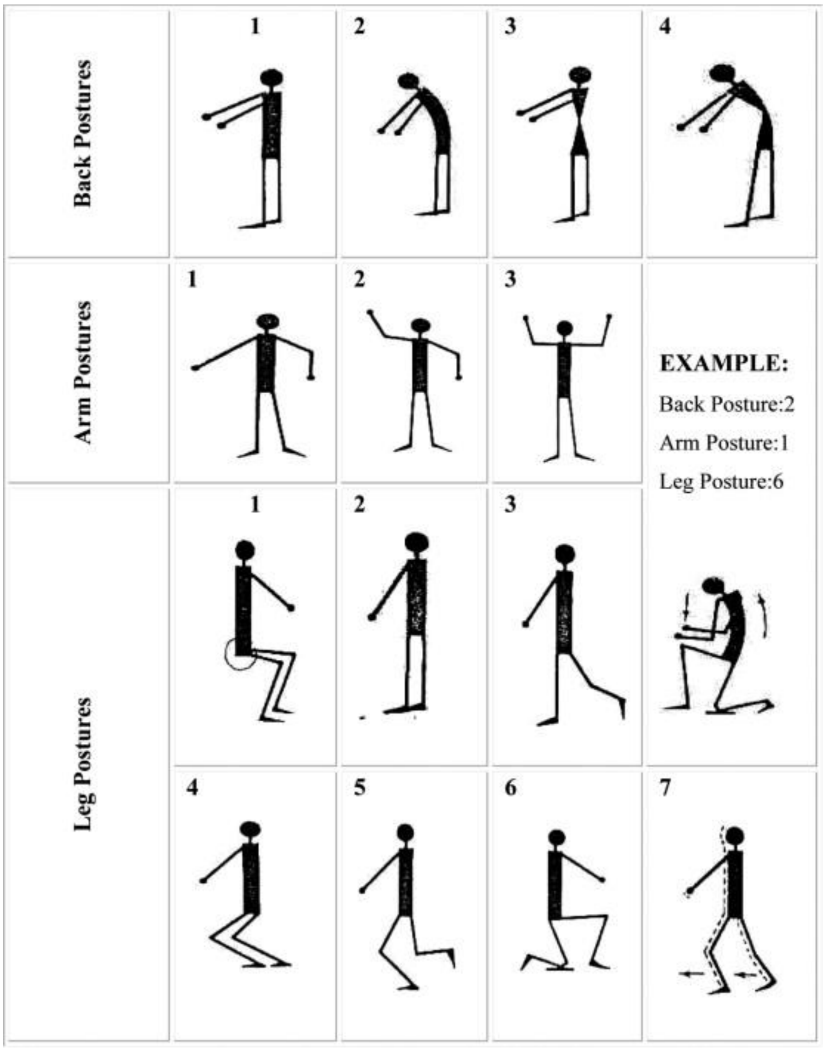


Figure 14: OWAS postures (Fığlalı, 2015)

4.4.1 Warehouse

The visited warehouse was the Quooker hub in Rotterdam. The hub was a new building, which at the time of the visit was not used during summer yet. Employees therefore had no idea how hot the building could get. Taking pictures of people was not allowed so the images shown are representations of the observed situations.

The main work activities of these workers was relocation of items, boxing items and the corresponding administration. Administration was mostly done on either a standing or sitting desk. Sitting desks had regular desk chairs. The relocation of items was performed in different actions. Boxes were either moved by vehicle or by moved to other pallets by hand.

Pallets of items were taken from the racking using reach trucks (see figure 16) and forklift trucks, while individual items were taken using an orderpicker (see figure 15). The forklift driver was sitting sideways in the machine, similar to figure 16. In the Quooker hub, the worker driving the forklift does this activity throughout the entire day. An argument could be made that these workers have less need for a cooling vest, as their job is less physically active. In smaller warehouses there may not be designated drivers, but there the cooling with air-conditioning may be more achievable.
The workers driving the reach trucks and orderpickers were not designated drivers. These were members of the general staff who got on these machines when they needed something from the racks.

Apart from the orderpickers and forklifts, items were also moved using different kinds of electrical pallet trucks. Some of them needed to be towed while walking (see figure 17), but these were also electrically supported. The ones on which the driver could stand (see figure 18 and 19), had the driver lean against side panels with either their hips or buttocks. When a truck is unloaded, a worker may stand on a pallet truck for an extended period of time (tens of minutes).

Figure 15: Orderpicker (Logistiek, 2015)


Figure 16: Reach truck (Jungheinrich, N.D. A)

Figure 17: Pallet truck (Jungheinrich, N.D. B)

Figure 18: Pallet truck (Heftruckaanbieding.nl, N.D.)

Figure 19: Pallet truck (Jungheinrich, N.D. C)

Most of the lifting by hand was to move boxes from pallets to other pallets. Boxes were also packaged into other boxes together with the description in the right language. The heaviest item the workers had to move was 22 kg. Each day two workers moved 180 of these boxes (~90 each) for 1-2 metres. These boxes were tightly pressed against the body with the workers hands on the far side of the box (see figure 20). Lighter items were carried with the hands underneath the box (see figure 21) or held at the handles. These lighter items are typically 5-7 kg. In both these situations the foam pads on the front of the cooling garment could be compressed, which hinders the flow.
The pallet truck from figure 17 could be raised to standing height, so the workers would not have to bend down that often. However, this was not always done. Especially with less heavy items the workers would bend over to pick them up.

When looking at the OWAS postures (see figure 22), all back postures were observed while carrying items. Only back posture 1 was used to carry the 22 kg boxes. Back posture 2 may cause foam pads on the abdomen to compress (see figure 23), hindering the waterflow.

No observations were made where items were lifted above the head, so only forearm posture 1 was observed when lifting/carrying items. Forearm posture 2 was only observed when placing stickers. The employee spoken with ensured that no items were lifted from above the head at other times either. Carrying items with the arms tightly pressed against the side of the abdomen may also compress pads placed there. As stated before, the boxes themselves could also cause interference with the flow due to compression of the foam pads.

The legs are more uncertain. 1, 2 and 7 were observed, but it is not unthinkable that the other leg postures could also occur. The observation time was limited and mostly done from the workstation of the workers carrying the 22 kg boxes. Other employees were also observed, but in lesser amount. Leg posture 1 could interfere with the foam pads on the lower back and buttocks, leg posture 4 and 6 with the pads on the abdomen and upper legs (see figure 24)

The worker which was spoken, was asked what he would find important on a cooling vest. He stated that it should have a discrete look and that the weight should be balanced. The worker also stated that he did not consider his job physically heavy. At no point during his job he would be out of breath. Maybe the workers carrying the 22 kg boxes would be tired at the end of the day, but not the general workers.
Another comment he made was that protruding edges would probably not be too much of a problem in warehouses. They only had XXL safety vests at the Quooker hub, so they would fit everyone. When worn by smaller people, these large vests leave room to get caught. The worker stated this has never been a problem or led to risky situations in the past.

Conclusion

The workers in the Quooker hub held many postures, but most of them either did not harm the use of a cooling pad or were held for a short time. Stopping the cooling effect of the pad for a short time should not be a problem temperature-wise. However, it may have consequences for the design due to pressure build-up. The new cooling garment, therefore, needs a way to release pressure.

The only long time blocks were found in using the vehicles. The forklift drivers constantly sit during the workday, so for them, their buttocks and back are constantly compressed. Drivers of pallet trucks may also have extended interference with a pad. For them, this concerns the hips and lower backs.

Figure 20: Carrying box

Figure 21: Carrying box

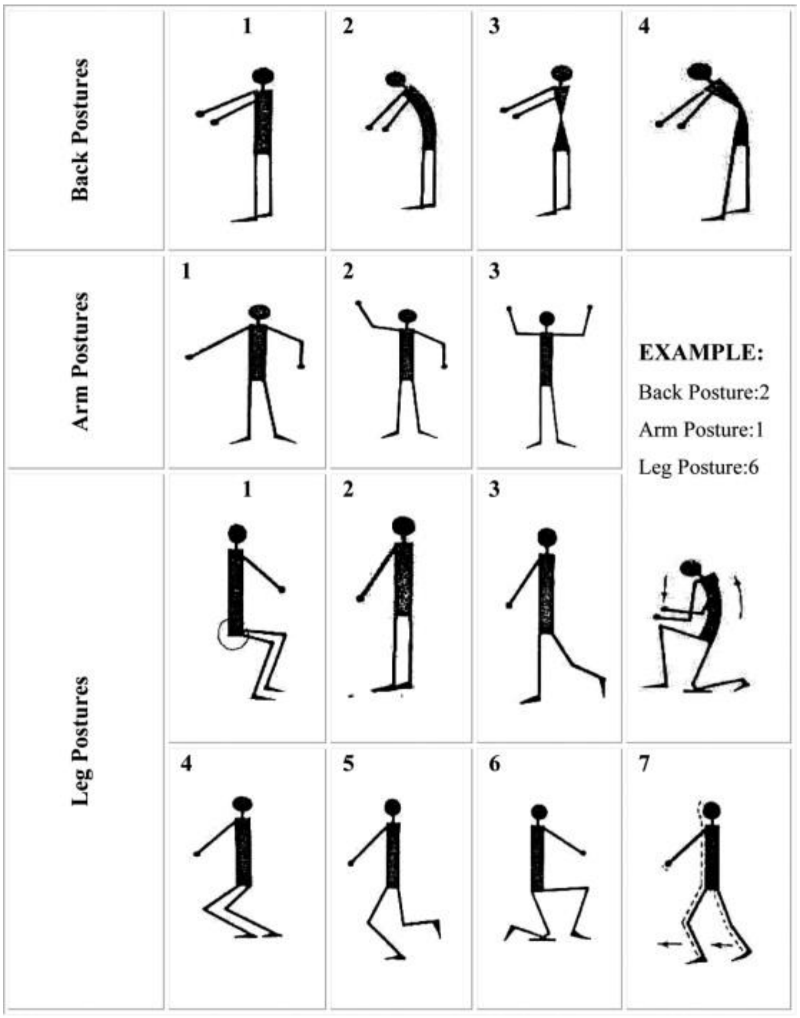


Figure 22: OWAS Postures (Fığlalı, 2015)

Figure 23: Bending over

Figure 24: Kneeling

4.4.2 Factory

The factory visit was to De Jong Verpakking. De Jong Verpakking is a factory that makes corrugated cardboard sheets and boxes and distributes them all over the world. They are the biggest producer of corrugated cardboard in north west Europe (De Jong verpakking, N.D. A).

The visited location was a large factory hall with multiple semi closed off cabins (see figure 25). In these cabins the paper is heated to raise up its fibres, which helped to strengthen the bond between the layers in the cardboard. Within these cabins, temperatures can range between 60°C and 90°C and the damp paper increases the humidity of the air. Employees constantly walk in and out these cabins throughout their shift. In case of a malfunction in these cabins, roughly twice a day, one or two employee(s) go in for a longer time (usually half an hour). The paper leaves these cabins still hot, which heats up the main factory hall. In the summer, the main factory hall can reach temperatures of roughly 40-45°C. Especially near the flowing paper this heat was already apparent during the spring time visit.

Employees of the factory already did a test with cooling vests, more specifically INUTEQ's PCM vests (see figure 26). Their main concern was that the cooling vests lasted for only 30 minutes. Because the packs had to be recharged after such a short cooling time, the employees discontinued the use of the vests. For them it is easier to submerge their shirt and cap in cold water than walking to the fridge and waiting for the PCM to reactivate.

Nearly all of the work is performed standing. Only in case of malfunctioning machinery or unsatisfactory product an employee has to kneel or crawl. When the paper leaves the hot cabins, it can tear, in which case an employee has to crawl underneath a table height platform (see figure 27). In case of a previously mentioned malfunction inside the heated cabins, an employee has to enter a space slightly lower than standing height. Here a combination of slight knee bending and/or slight bending of the torso is needed. Another reason to bend or kneel is when one or more sheets of cardboard leaves the machine teared or otherwise unsatisfactory. Employees then have to remove these sheets from the pile, which means restacking the entire 1.50-1.60m pile. This is similar to moving boxes from one pallet to another.

When looking at the OWAS movements again, different postures can be identified. Back posture 1 is standard at De Jong Verpakking. Back posture 2 occurs only sporadically and three and four don't generally occur at all. All forearm postures occur often. Especially when operating machinery, employees frequently have to use control panels above their head. As for leg postures, As previously discussed, anything other than standing (2) and walking (7) is rare and only happens for a short time. Employees will sometimes sit on a stool (1) or lean with one leg on a bar (3). However, this is not required for the work but to relax. In conclusion, no major problems were identified where a posture could block a pad from flow. Just like in Quooker's warehouse, the forklift drivers, who do have long term leg posture 1, are designated drivers with less need for a cooling vest (see figure 29).

Figure 25: De Jong Verpakking factory floor (De Jong verpakking, N.D. B).

Figure 26: PCM coolover (INUTEQ, N.D. A)

Figure 27: low space during repairs (AFG, N.D.)

Figure 29: Forklift truck (AFG, N.D.)

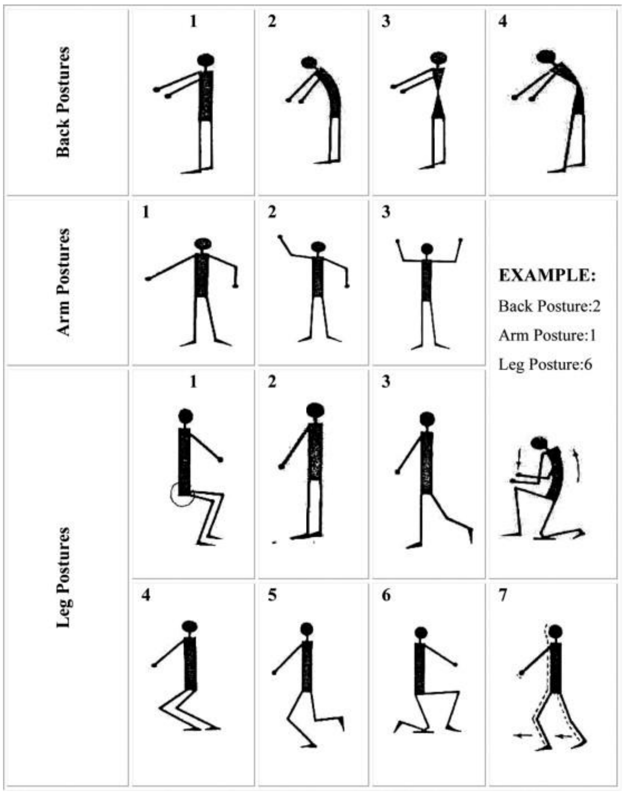


Figure 28: OWAS Postures (Fığlalı, 2015)

Another possible area of interference is when employees carry items against their body. The employees at the visited factory of De Jong Verpakking don't have to carry many items during the day. The main item to carry is an empty paper roll. When the roll seen in figure 30 runs out, it is taken out of the machine and carried on the shoulder to a bin roughly 20m from the machine. The new roll is brought with a forklift.

The last form of interference could be standing against something. This was not observed either during the visit. In figure 31 some employees are seen lightly standing against a control panel with their upper legs. This is probably not severe enough to stop water flow through a pad however.

In the conversation with the contact person, he was also asked where he would prefer a water container to be placed on his body. He said he would prefer the water container to be on his back, to hinder him the least.

Conclusion

The visit to De Jong Verpakking has yielded useful insights into the use of cooling garments in factories. It was found that ease of use is one of the most important aspects for the new cooling garment. If a cooling garment does not provide long-time cooling and/or if the recharging process is too tedious, the garment will not be worn. Cooling time cannot be stretched indefinitely, but for the recharging process of the new design focus should be laid on effortlessness.

Concerning the obstructions of the cooling pads, once again the forklift drivers were sitting all day. Because this is such a large body area and they perform this work the entire day, these drivers are excluded as a target group of the current project. The general workers were mostly standing and only carried light items for a short time. They did have the occasional repair job where pads could be compressed for an extended period of time. This is a similar time period that was observed during vehicle use in the Quooker hub. For these cases, multiple loops have to be made in the water circuit of the new design. A blockage of one specific location should not stop the water flow in the entire cooling vest.

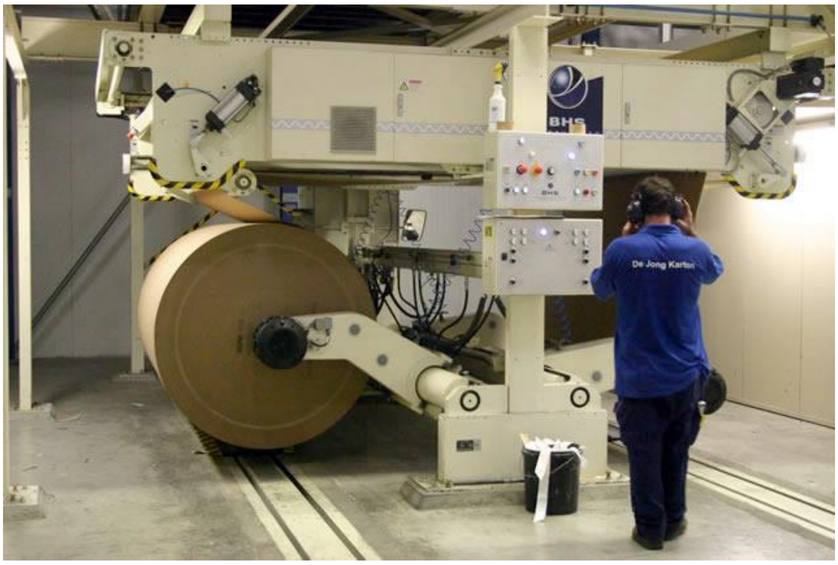


Figure 30: Factory worker with cardboard machine (AFG, N.D.)


Figure 31: Factory floor De Jong verpakking (Packonline, N.D.)

5 Impact of heat on workers

The body needs energy in the form of ATP to perform processes like transport, mechanical work and chemical reactions (Parsons, 1993). The production of ATP is rather inefficient however. Roughly 60 percent of the energy produced is in the form of heat (learning, N.D.). When using ATP, an additional part of the released energy is in the form of heat. When the body uses energy for exercise, a total of approximately 70 to 95 percent of energy is converted into heat (Kenny, 2014). All this heat energy is either released to the environment or used in a process called thermoregulation.

Thermoregulation is the process the body uses to maintain a constant temperature. It does so by activating several processes within the body to control the production of heat and the release of heat to the environment. When the body needs to cool down there are two processes at work: sweating and vasodilation.

- Sweating occurs when the skin releases fluid (sweat) through its sweat glands. The sweat evaporates and this phase change decreases the skin temperature.
- Vasodilation is when the body widens the blood vessels under the skin. The blood flow to the skin increases where it can release more heat to the environment.

(Healthline N.D. A)

Heat transfer between the body and the environment mostly goes through four mechanisms: Phase change, conduction, convection, and radiation. 20% Of the heat is released by sweating due to the phase change from liquid to gas. (Lumen learning, N.D.). However, sweating becomes less effective in humid environment. When the air is saturated with water, less sweat evaporates, decreasing the release of heat. (Dougherty, 2011)

The other 80% of heat is almost entirely released using vasodilation. Vasodilation makes use of convection, conduction and radiation to exchange heat with the environment. 3% of the total heat is released through conduction, 15% through convection, and 60% through radiation (Lumen learning, N.D.). In Conduction, convection and radiation, heat naturally flows from hot to cold (Perkins, 2016). The bigger this difference, the quicker the heat flow. Thus, when the ambient temperature increases towards or even above the body temperature, this vasodilation caused heat flow from the body to the environment decreases. Vasodilation therefore becomes ineffective at cooling the body.

Combining these two processes we can conclude that a hot and humid environment is the worst possible combination for the body to keep itself cool.

When the body loses the ability too cool itself we speak of hyperthermia. Hyperthermia mostly occurs when the body is subjected to a high temperature for an extended period of time. As stated before, a higher humidity can increase this condition. Doing (heavy) physical work can also increase the chances of hyperthermia because more muscle use generates more heat. Hyperthermia can have different stages depending on the conditions. They range from thirst and dizziness to serious conditions such as a heat stroke or a loss of consciousness. (Healthline, N.D. B)

These symptoms can have serious consequences, even more so for factory and construction workers. These people work with heavy machinery with large forces or fast moving parts (see for instance the paper machines in chapter 4.4.2). Loss of consciousness near such machinery can lead to serious physical harm. More common consequences of hyperthermia could also increase the work risk. Dizziness, for instance, can increase the mistakes people make at work. The dehydration caused by can also cause dizziness, as well as headaches, fatigue and loss of concentration (CM, 2020). Increased mistakes caused by these symptoms may lead to more accidents. It seems therefore that cooling workers is not only beneficial for comfort, but also to reduce risk.

5.1 Energetic overload

A different factor that also influences construction- and factory workers is energetic overload. Energetic overload occurs when the body cannot recover quick enough from physical effort. People suffering from energetic overload will experience a general sense of physical exhaustion. This is unlike mechanical overload, where muscle fatigue is felt locally. Especially if big muscle groups perform heavy work requiring a high amount of energy for extended periods of time, the risk of energetic overload increases. Working or exercising in high temperatures also has an increased effect on the occurrence of energetic overload, making it relevant for this research.

The primary symptoms of energetic overload are heavy breathing, high sweat- and heart rate and a higher heat production. The secondary symptoms have a more increasing effect on however. Especially the decrease of concentration and coordination can have serious consequences. These symptoms could lead to physical harm, by making mistakes or inadequate reaction to machine malfunction. Tempering the hot conditions may reduce the occurrence and severity of energetic overload which could partly prevent these consequences. (Railalert, N.D.) (SER, N.D.)

There is also an economic argument to be made. Workers with muscle fatigue will probably have a lower work pace than healthy workers. It has also been shown that an increased temperature in general will significantly reduce productivity (J. Tiesnitsch, personal conversation (webinar), 2021). Workers with energetic overload may even call in sick more. All these factors cause decreased productivity as a consequence of working in hot conditions. Thus, It could be stated that cooling workers down may increase productivity when working in hot conditions. In that case, a cooling garment may pay for itself.

6 Cooling garments

One of the ways to combat the cause of heat strain is through personal cooling garments. Personal cooling is when the body of a person is locally cooled in a hotter environment. INUTEQ does this by integrating a cooling technology into different garments. "In hot environments where air conditioning cannot be applied, personal cooling garments are the most effective method for cooling the body" (Yazdi, 2014). In this chapter, a benchmark is made to explore currently available personal cooling garments. After that, the effects of current products are discussed, followed by a literature review into the effects of cooling different body parts.

6.1 Benchmark

Within the market of personal cooling, more specifically cooling vests, several categories can be identified. Each category contains products using a different cooling technology. The categories that were identified are:

- Evaporation
- Passive PCM
- Active PCM
- Thermoelectric liquid circulation
- Vapor compression liquid circulation
- Air flow

These categories are loosely based on, but not limited to, the findings of Laprise (2005).

6.1.1 Evaporation

These products are sold by INUTEQ (see figure 32). The vests are either filled with water or completely submerged. The water inside the vest evaporates. The evaporation of water absorbs energy. This energy is taken from the heat of the body, cooling it down. This is also how sweating works (see chapter 5).
Just like sweat, this cooling vest will also not be effective in humid conditions, because the water cannot evaporate into saturated air.

6.1.2 Passive PCM

Passive PCM vest are also sold by INUTEQ. PCM, phase change material, works similarly to the evaporation garments. The PCM gel also goes through a phase change, but in these products it goes from solid to liquid. Different PCM's liquify at different temperatures, to provide the customer with a range of cooling options. The PCM gel is sealed into packs which are made into a vest or can be inserted into one (see figure 33 and 34). These packs need to be refrigerated to turn the PCM solid again. These vests will last for a few hours (personal conversation with Rein Bokslag).

6.1.3 Active PCM

In active PCM garments, the PCM is usually ice. A garment is covered in tubes (see figure 35). Water is circulated through these tubes with a pump. The water also flows through a box containing the ice (see figure 36). The melting ice will cool the water, which will in turn cool the body. The cooling time depends on the size of the icebox.

Figure 32: INUTEQ evaporation cooling vests (INUTEQ, N.D. [B-D])

Figure 33: PCM COOLOVER (INUTEQ, N.D. A)

Figure 34: BODYCOOL PRO (INUTEQ, N.D. E)

Figure 35: Active PCM coooling (eBay, N.D. A)

Figure 36: Active PCM cooling schematic(Triathlonaccesoires.nl, N.D.)

6.1.4 Thermoelectric liquid circulation

Thermoelectric Liquid circulating products also work with water that is pumped through a vest. However, in this product category the water is cooled using Peltier elements. Peltier elements are usually square flat electronic elements. When electricity is run through these elements, one side increases in temperature and the other decreases. This process requires energy so the average temperature of the element increases. The cold side of the Peltier element is then used to cool the water. The hot side is usually cooled with a fan to limit the effects of the average temperature increase. Thermoelectric cooling garments are rarely seen in the current market. The examples found are experimental research prototypes (see figure 37 and 38).

6.1.5 Vapor Compression Liquid Circulation

A vapor compression liquid circulating product also uses circulating water through a vest. This water is cooled using the same technology as a refrigerator. A refrigerant absorbs the heat from the circulating water. This refrigerant is then vaporized and compressed to release its heat to the environment. The refrigerant condenses again because its temperature lowers and it is returned to its initial position. The downside of these products is that the cooling unit is large and heavy and it requires lots of energy. In reality these systems are only used by the military, where the cooling unit is placed inside, and powered by, a vehicle. (Laprise, 2005) (see figure 39).

6.1.6 Air Flow

Compressed air flow

This vest is supplied with compressed air. A vortex tube is used to cool the air, which is then blown . These products are near exclusively used in industrial/factorial settings because they require a source of compressed air. Systems like these are non-portable, as the user is always tethered to the air supply. As long as the source of compressed air stays active, these vests cool indefinitely. (for example, see figure 40)

Thermoelectric air flow

Thermoelectric air flow products use the Peltier effect just like the thermoelectric liquid circulation products. Air is vented through a small device where it is cooled and dispersed into a shirt. These products are not (yet) commercially available. (see figure 42)

Uncooled air flow

The last category features products which use airflow without cooling the air. The body is cooled through just convection and the evaporation of sweat. They will not be effective in hot, humid conditions. (see figure 41)

Figure 37 : Thermoelectric liquid circulation vest (Lavanya, 2016)

Figure 38: Thermoelectric liquid circulation vest (Chi, 2008)

Figure 39: Vapor Compression Liquid Circulation vest (Compcooler, N.D.)

Figure 40: Compressed air flow vest (Dennisdeal, N.D.)

Figure 41: Uncooled air flow jacket (Amazon, N.D. A)

Figure 42: Thermoelectric air flow shirt (Sony, N.D.)

6.2 Effects of cooling garments

From the benchmark it can be concluded that there are lots of different personal cooling garments. To find if these cooling garments are effective at cooling the body, a literature study has been conducted. The findings of this study are presented in this chapter.

Bach (2019) tested four different cooling garments: Liquid perfused ice cooled, PCM, Ice vest (Ice as PCM) and the ice vest in combination with the ingestion of ice slurry. Participants had to walk for 120 minutes inside a closed chemical suit. For all cooling garments a significant decrease in heart rate, rectal-, mean skin-, and body temperatures were measured. All cooling garments except the liquid perfused ice suit also showed significant improvement in walking times. Bach (2019) states that the liquid perfused suit may have been slower because of an abating cooling capacity and a high thermal insulation. The fact that one single hose covered the entire body in the liquid perfused suit may also have been problematic. The temperature then rises inside the tube and by the end of the circulation the water may approach the body temperature, lowering the cooling capacity.

Chan (2015) found that wearing personal cooling garments cause significantly reduced temperature increase and sweat rate during work as well as increasing performance compared to a control. Performance increase was greatest with a cold air-cooled garment, followed by Liquid circulating and a combination of air and liquid cooling, natural air-cooled garments, and PCM garments. Chan (2015) observed performance improvement to be positively linearly correlated to the core temperature increase between the personal cooling garments and the control. They further state that an ideal cooling device balances cooling capacity, weight and mobility. Especially liquid cooling garments can be heavy, increasing metabolic rates and subsequently core temperatures.

Butts (2017) simulated industrial work in the heat with workers wearing PCM vests. They also found that the cooling garments significantly lowered the physiological strain index, heat storage and perceptual strain index. They state that personal cooling garments “could increase safety and reduce occupational heat illness risk.” Interestingly, the performance of the workers did not increase.

However, Teunissen (2014) found a different result. They tested two different cooling garments underneath a firefighting suit, one vest with cold water filled pads and one liquid perfused suit using ice to cool the water. These suits were compared to a control using a 30 min walking session with 10 min recovery, both in hot conditions. They found that neither the cold water pad, nor the water perfused suit provided a lower thermal strain, though they did provide a lower thermal sensation. Thermal sensation is highly related to skin temperature (Kato, 2001). Teunissen (2014) suggests that thermal comfort may have a closer link to core temperature. The perfused water vest they investigated did not lower core temperature or the heart rate. This was probably due to the additional weight of the suit. Carrying extra weight significantly increases metabolic rate (Grabowski, 2005), which leads to increased heat production. Finally, Teunissen (2014) states that “it remains questionable whether an improved thermal sensation and/or skin temperature alone provides significant benefits for worker safety and performance.”

Most studies mentioned above have been conducted on human subjects, so the perceived effects of a cooling vest may not be fully reliable. There is no clear, resolute answer on the effect of cooling garments, though most studies seem to suggest some reduction in temperatures and thermal strain when wearing a cooling garment. Yazdi (2014) conducted a more extensive literature review and also concluded that cooling garments are an effective way to combat heat strain when doing demanding work in high temperatures.

6.3 Where to cool

To make an efficient cooling garment it is useful to know what areas of the body to cool. Some areas produce more heat by having more muscle and/or mass. If a cooling garment is only applied to areas where cooling is most effective at lowering the total body temperature, it could save energy and therefore weight. Keeping the weight of the garment as low as possible is important, because carrying more weight increases muscle activity, which increases the chances of heat strain and energetic overload. The cooling garment therefore needs to find a balance between weight and cooling power. This chapter contains the results of the literature study that was done to find the body segments which are most effective when cooling.

Wang (2019) did a study inside a climate chamber to find the key local body segments for personalized heating and cooling. They measured the skin temperature using heat flow sensors on 7 locations on the body. What they found is that the lower leg, thigh and back were the key body segments to cool in hot conditions. This study did find differences between male and female participants, however this occurred mostly in cool environments.

Tamura(1993) did a similar research with inside a climate chamber. They measured ten body segments and found that cooling limbs only lowers local skin temperatures, while cooling the breast and back had a cooling effect on other body segments. This study is only done on female students. This means males are not taken into account and it can be assumed that the participants were younger than the average population. This study also did not include the abdomen

Shvartz (1974) also compared ten different body segments. They had three subjects performing moderate work at room temperature and in the heat. Similar to Wang(2019) this research was done to make the most efficient cooling suit, more specifically for liquid cooling. By finding the effectiveness of cooling on different body dimensions, they could determine the distribution of tubes through the liquid circulating suit. What they found is that the most effective segments to cool are the chest, the back and the thighs. Interestingly, this study also did not consider the abdomen as a cooling region.

Yang (2019) researched only the different segments of the torso, because the torso is the body part that generates the most heat. They also used a climate chamber to simulate a hot environment and a thermoelectric cooling device to cool separate segments. The segments they examined were the chest, abdomen, lower back and upper back. They showed that “the local cooling of the torso can significantly improve the overall thermal sensation and thermal comfort of the subjects in a hot environment”. The most effective segment was found to be the upper back, followed by the lower back and the abdomen. The chest was found to be the least effective of these four regions. This paper also states that they found almost no difference in thermal comfort and sensation between male and female participants.

In conclusion, these papers do not fully agree on the most effective body segments for cooling. However, all papers consistently state that the back is the best segment to cool. Furthermore, the arms and lower legs are uncontested as the least effective. The body segments with varying results are the chest, abdomen and thighs. This does not mean that these areas are ineffective for cooling. Some papers did not research the abdomen and in others these segments only differed a little in their effectiveness. It can therefore be stated that after the back, all three of these segments are relatively effective for cooling.

6.4 Weight

One of the main challenges for a liquid circulating cooling vest is the weight. More liquid in the vest increases the cooling capacity, but also makes it heavier. A heavier vest means more physical effort for the wearer. In chapter 5 it has been found that physical effort increases the chances of heat strain and energetic overload. Apart from that, a heavy vest will lead to discomfort decreasing the willingness of workers to wear such a garment. In this section, the (dis)comfort of a cooling vest's weight is analysed.

The biggest contributor to the weight of a liquid circulating vest is the liquid itself. For every litre of water, the vest becomes one kilogram heavier. The cooling pads from Stewart (2017) don't help in this regard either. The pads considerably increase the possible contact area with the body, but that also means that they hold a large amount of water, adding to the weight of the vest. The pad's thickness is one centimetre, meaning that a surface area of 0.5 m^2 holds 5 litres of water(=5 kg).

An experiment was done get a better sense of the effect of weight in hot conditions. Two cooling vests were worn inside of a climate chamber with a temperature of 32°C and humidity between 55 and 65%.

A PCM Coolover 21°C was put on (see figure 43), which weighed 1.3 kg. Then, a Bodycool Pro was worn on top of that, filled with twice the number of PCM cooling packs (see figure 44). The vest, including the packs, weighed 2.6 kg. Together with the PCM Coolover, the total weight was 3.9 kg. Additionally, four 1 kg weights could be added to further increase the weight to 7.9 kg (see figure 45). Tasks were performed without the vests, with the vests without the weights, and with the weights in various configurations: equally distributed, four on the back, four on the front, and four on the right side. In these configurations the weight was therefore 2 on one side kg and 6 kg on the other side.

Figure 43: PCM coolover

Figure 44 BODYCOOL PRO with double PCM packs

Figure 45: BODYCOOL PRO with double PCM packs and weights

Inside the climate chamber, common tasks observed during the company visit were performed (see chapter). These tasks were: walking, picking up items of the floor, carrying heavy objects, bending over and crouching (see figure 46 and 47).

The configurations of 3.9 kg and equally distributed 8 kg were tested for roughly ten minutes each. The configurations with unbalanced weight distribution were tested for only roughly five minutes as their effect quickly became clear.

Figure 46: Walking with the 8kg vest on

Figure 47: Picking up chair

6.4.1 Results

The results of this experiment were as follows: The 3.9 kg vest was easy to put on and reasonably comfortable during wear. It did not hinder too much during the activities and the added cooling effect made the vest pleasant to wear in the hot environment.

The equally distributed 8 kg vest was a less positive experience. The vest was heavy to lift and difficult to put on. Once worn for a couple of minutes the over encumbered feeling started to fade and the movements were doable. However, minutes later muscle pain in the shoulders started to develop. The muscle pain carried on the next day.

As for the unequally distributed weights, putting the extra (green) weights on the right side was clearly uncomfortable and undesirable. It created unbalanced walking and was a hinderance during the activities. It is assumed that putting the weights on the left will have the same effect.
Putting the four extra weights on the back was also undesirable, but for a different reason. The back-heavy vest would sag backwards, creating pressure of the collar on the throat. The sagging also required effort of the wearer to stay upwards.
Placing the weights on the front was a lesser issue. Only slight compensation was required to balance the frontal weights. The pain on the shoulders was still present though. It is also uncertain if long time wear of a front heavy vest has other consequences, in particular back issues.

For all the weight configurations the feeling of lifting the vest for the first time had a heavier weight sensation than when the suit was worn. This could cause an initial rejection towards the vest. It could be solved by filling the vest with water after it has already been put on. That way, the initial hurdle is taken down and the heavy sensation is only felt from the moment the vest also gives its positive sensation: the cooling.

6.4.2 Conclusion

In conclusion, a vest of 3.9 kg was found doable, while the 8 kg vest was clearly too heavy. This was just an indication to continue. The weight was be focussed on again in the user test (see chapter 13). Imbalanced weight distribution caused discomfort. Improper weight distribution should therefore be kept to a minimum in the design of the new cooling vest. The conclusion of chapter 6.3 states that the priority of cooling should go to the back for maximum cooling efficiency. However, as stated above, putting all the cooling on the back will disbalance the weight distribution, making the vest uncomfortable. Some cooling efficiency will therefore be lost by balancing the cooling pads on the front and back of the torso.

7 Safety

Safety is important in every product. Even more so for people working in factories, as some of them work with heavy machinery or at heights, for instance. The wear of a cooling vest should not introduce great risks or safety hazards in these professions. This chapter discusses the safety aspects of the new design, which may lead to new requirements.

In a conversation with Huub Agterberg, occupational hygienist and safety consultant at KLM, the safety of a cooling vest was discussed. Mr. Agterberg has experience regarding cooling vests: he conducted a test of cooling vests for airplane cleaners. He stated that the cleaners were not enthusiastic about the cooling vests. The cleaners were mostly female, while most cooling vests are made for men. The fit was therefore not right and the vests were also too heavy for the cleaners. The new design is mainly aimed towards men, so the weight and fit should be less of a problem.

On the subject of safety, Mr. Agterberg states that freedom of movement is the most important aspect. An additional clothing item is always going to limit the freedom of movement, the important factor is by how much. Workers need be able to comfortably move around and conduct their work otherwise they might get into risky situations.

Apart from the possible increased risk, workers don't like to wear clothing which inhibits their freedom of movements, Mr. Agterberg states. It also reduces the willingness of workers to wear such a garment. The previous example of the cleaners already validates this claim. Another example Mr. Agterberg gives is that of exoskeletons. Workers at KLM were given the opportunity to try an exoskeleton to help with heavy lifting. After a few tries the workers did not bother for the skeleton anymore. Though it helped with lifting objects, it was a hinderance during more variated work such as climbing or laying down in the hold of a plane.

Another subject Mr. Agterberg found important was the washability of the vest. In the warm conditions the vest is designed for people are likely going to sweat. This sweat will get into the vest causing a bad smell and salt stains, further reducing willingness to wear. The cooling vest should therefore be easily cleanable. Ideally machine washable. A cooling vest is also an item which is personally rolled out. Workers should not have to share cooling vests. In case of sharing, the smell and sweat would understandably become an even larger barrier.

Mr. Agterberg did not see any great risks in the different parts of the cooling vest. In case of a leak the water should not be of great concern. When it rains workers also carry water inside, he states. Leaking a litre of water should not be a problem. The electronic parts did not concern Mr. Agterberg either. The electric circuitry should not short circuit, but that is solvable in its design. The pump is probably water resistant and a small battery is not a great risk either. The battery can only be problematic in case it becomes large and heavy, which would not be necessary for a cooling vest.

An initial idea was to make to design a version of the cooling vest which also functions as a high visibility safety vest. In separate conversations with Prof. Kaspar Jansen and Rein Bokslag (INUTEQ) this idea was discouraged. A safety vest has specific recommendations on appearance, which may be difficult to meet in combination with the cooling system. It would be too time consuming to look into during this project. Implementing a safety vest feature in the future may also be discouraged. The vest would need extra certifications which are time consuming and costly. Rein Bokslag therefore recommends a regular appearance cooling vest with a separate safety vest worn over that.

In conclusion, during the conversation with Huub Agterberg, no *major* risks were identified. It did lead to insights in washability and once again confirmed the importance of freedom of movement.

8 Requirements

The requirements stated below were categorized using Pugh's checklist. Not all categories were used because they were irrelevant or not yet researched at this stage of the project.

Target group

- The design should be used by factory- and construction workers who:
  - Do not use closed suits such as hazmat suits, fire proximity suits or coveralls.
  - Can use common vehicles such as a forklift truck
  - Can use common equipment such as:
    - Helmet
    - Goggles/glasses
    - Ear protection
    - Respirator/dust mask
    - Gloves
    - Safety shoes
    - Safety vest
    - Knee protectors
    - Harness
    - Shoulder protector

Performance

- The design should be fully wearable.
- The design should not be tethered (to a source of cooling, liquid or energy).
- The design should cool the user in temperatures from 30 to 40 degrees Celsius
- The design should cool the body for 8 hours with the possibility of recharging during this time.
  - Recharging should happen a maximum of three times a day.
  - Recharging should last for a maximum of two minutes.
  - Recharging should be possible inside canteen, the recharge station will not be developed in this project.
- The cooling method of the water should be ice with possible addition of evaporation through the outer layer of the vest.
- It should be possible to simultaneously charge the battery and refill the vest.
- Cooling contact with the body should be done with foam pads.
- The water inside the vest should be circulated.
- During use, the external fabric of the product should remain dry.
- Priority of cooling should go to the back of the body, followed by the chest and stomach.
- The cooling vest should not lose all cooling function in case of a single local blockage of water.

Maintenance

- The battery should be replaceable
- The design should be (partly) machine washable
- The pump and battery pack should be separable from the vest section so either can be replaced upon failure.

Cost

- The product should cost the customer a maximum of €100,- per unit

Packaging

- The product should be packaged without the water inside.

Aesthetic, appearance and finish

- The appearance should be appealing to factory and warehouse workers

Ergonomics

- The product should be put on as a single piece.
- The pump and battery compartment should not be obstructive during common factory work.
- The design should be understandable by most factory workers.
- The product should allow bending over.
- The weight of the design should be balanced. A maximum of 1 kg difference between front and back, and left and right is allowed.

Reliability

- The product should stay functional in temperatures from 10 to 50 degrees Celsius.

Safety

- The design should not have any parts sticking out that could be caught in machinery.
- The electronic components should be protected from water

Initiation of use

- The initial filling of the vest should be similar to subsequent refills.
- The initial charge should be identical to later charges.

8.1 Wishes

- The design should be as light weight as possible
- The cooling capacity of the design should be as high as possible
- The design should allow as much freedom of movement as possible
- The cooling effect of the design should work as long as possible
- The design should be as easy to use as possible
- The cost of the design should be as low as possible (within reasonable standards)
- The design should be easy to understand
- Refill/recharge should be as quick as possible

Development phase

9 Pads

In chapter 1, it has been established that there were still some problems with the foam pads on the existing prototype. Selecting materials for the new foam pads therefore needed to be done carefully and thoroughly.

The initial plan for the pads was to start with one piece of laser cut foam and two larger pieces of fabric. The fabric was then glued onto both sides of the foam. Two connectors were glued to the fabric using super glue and the flanges of the fabric were connected using PU hot melt tape to seal the pad (see figure 48).

9.1 Glue

In Stewart's (2017) report it has become clear that a lot of options for gluing the fabric to the foam have been tried without success. 3M 80 glue spray was selected as the next possible option by Linda Plaude, textile expert at the faculty of design engineering, TU Delft. Four different fabrics were selected to bond to the foam (for information on these fabrics, see extremtextil, N.D. [A-D]). The fabric pieces were coated in a layer of glue, laid on the foam and covered by a weight (glass plate) (see figure 50, 51 and 52). The strength of the bond between the glue and the fabric was determined by peeling off the fabric after it had cured. In figure 53 it is clearly visible that the red fabric had the strongest bond with the foam. The foam itself tore when peeling off the red fabric, while the other three fabrics were easy to peel off.

Figure 48: PU hot melt tape

Figure 49: 3M 80
(Van Asperen Kleefstoffen, N.D. A)

Figure 50: Spraying fabrics with glue

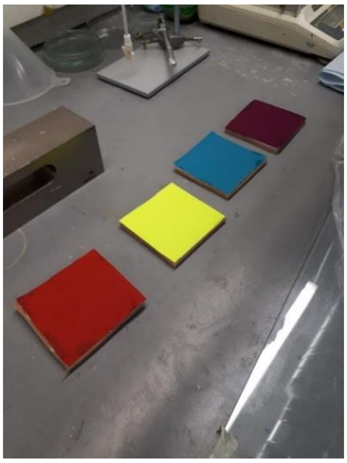


Figure 51: Bonding to foam

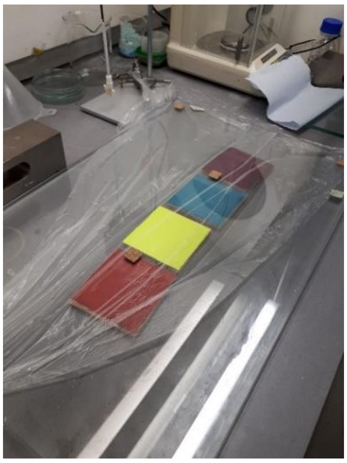


Figure 52: Covering with glass plate

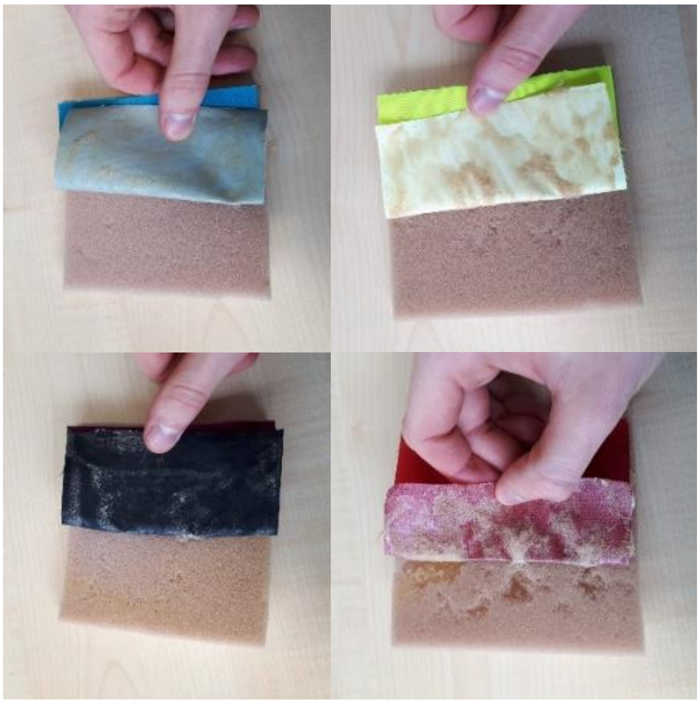


Figure 53: glue test result, the red fabric stuck most

9.2 Seal

As stated, the sealing of the pad was done with PU hot melt tape. A piece of each of the four fabrics was folded with a piece of the tape in between. This package was then covered on both sides with baking paper and heated with an iron (see figure 54).

Of the four fabrics again only the red one showed a promising bond (see figure 55). This bond was only breakable by ripping off the water tight layer of the fabric, which was also tightly connected to the fabric itself. The yellow fabric did connect using the tape as well, but the watertight layer easily delaminated from the fabric. The other two fabrics, blue and purple, did not bond together.

During a visit at INUTEQ, a second sealing method was tested using an impulse heater. An impulse heater is specifically made for sealing plastics. The impulse heater clamped down the material, heated it up to a specific temperature and also cooled down while still clamping onto the fabrics. An impulse heater can more precisely heat up to a certain temperature than an iron, together with the automatic clamping it was more reliable for sealing. A downside is that the typical machines can only seal in straight lines.

The four fabrics were sealed on the impulse heater (see figure 56). All of them were able to be sealed. Contrary to the other fabrics, the yellow fabric could even be sealed without the PU tape. The fabrics were sealed on three edges to create a bag (see figure 57). After sealing, these bags were filled with water and the open edge was rolled shut to increase the pressure (see figure 59 and 60). All of the bags remained sealed during this operation.

The fact that all of the fabrics were sealable with the impulse heater suggests that it should be possible to seal them with the iron as well. The method of sealing, heat, is the same for both processes. On the impulse heater the red fabric sealed at 180°C while the rest of the fabrics required 200°C. The heat of the iron could therefore have been too low to seal the other fabrics. The iron was not on max temperature during the initial sealing test so sealing all the fabrics with an iron should be possible.

The third sealing method which was tested, was high frequency welding (see figure 58). However, none of the four fabrics were able to be bonded with the high frequency welder at INUTEQ.

Figure 54: Bonding fabrics together with PU hotmelt tape

Figure 55: testing the bond

Figure 56: induction sealer

Figure 57: Sealed bags

Figure 59: Filling bag

Figure 60: Testing for leaks

Figure 58: High frequency welding machine

9.3 Recreating foam pad

A foam pad from Stewart's (2017) prototype was recreated to gain insights into the materials and the process he used. The fabric he used was no longer available. The red fabric from previous tests was used because it had the best results. The glue that Stewart used did not provide a solid bond so two other glues where tested: 3M 80 glue-spray and 3M 74 glue-spray (see figure 63). The 3M 80 was selected by Linda Plaude and the 3M 74 glue-spray was selected because it is specifically made to glue foams and fabrics.

The foam was laser cut into shape (see figure 61). The canals in the foam lower the flow resistance and distribute the water through the entire pad. The connectors were printed in agylus on the connex 3D printer (see figure 62).

The fabric was glued to the foam with the 3M 80 and 3M 74 glue. A sheet of cardboard with the negative pattern of the foam was used to contain the glue-spray in the right shape (see figure 64). A glass plate was used as a weight to hold the pieces together.

The 3M 74 stayed sticky for several days, so the channels of that pad remained stuck together after compression of the pad (see figure 65). When this happens, water cannot easily flow through the channels anymore. It was therefore decided to only finish the pad glued with 3M 80. The connectors were glued into place using superglue and the rest of the pad was sealed with the PU slide tape to complete the pad (see figure 66).

9.3.1 Water testing

The pad was tested with water to test the flow, pressure drop and leakages. It was connected to a pump that could create a maximum pressure of roughly 120mBar. The incoming pressure was measured with a manometer connected to the tube before the water entered the pad (see figure 67). The pressure drop was calculated by subtracting the atmospheric pressure from the measured pressure.

Figure 67 also shows the swelling of the canals on the pad. If the canals swell too much the rest of the pad will lose its contact with the body, making it ineffective at cooling while still adding to the weight. INUTEQ did indicate that one of the reasons for choosing Stewart's concept (2017) as starting point was the futuristic look of the visible canals.

At pressures lower than 100mBar the pad already started to leak. Several small leaks occurred because of improper sealing due to folds in the fabric. Figure 68 shows that the pad also leaked at the connection points. This is a more serious leak as the water is flowing through the fabric. The fabric is somehow damaged in these specific locations. The superglue either somehow weakened the watertight layer, or the watertight layer delaminated in high tension areas.

Figure 61: Lasercut foam

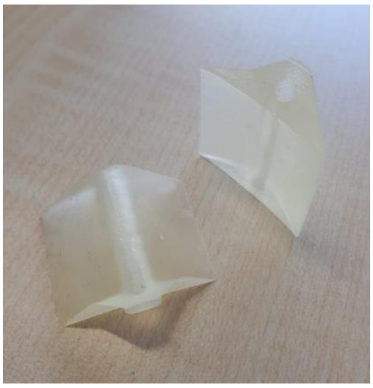


Figure 62: Connectors

Figure 63: 3M 80 and 3M 74 gluespray (Van Asperen Kleefstoffen, N.D. A and B)

Figure 64: glueing fabric to foam

Figure 65: Glued pads, left: 3M 74, Right: 3M 80

Figure 66: finishing pad

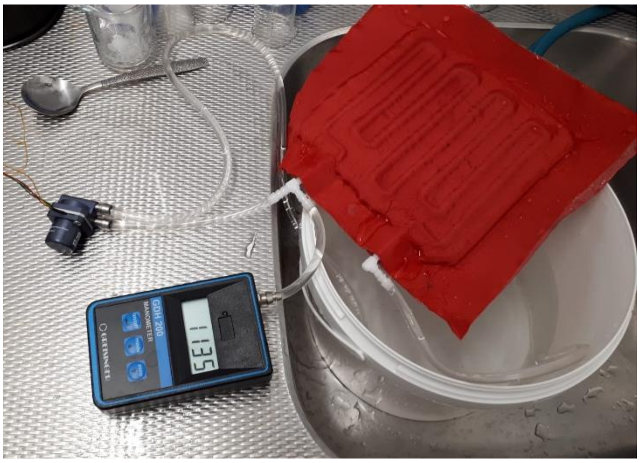


Figure 67: Water testing pad

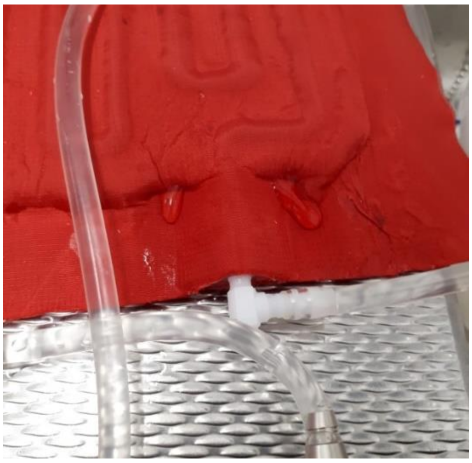


Figure 68: Leaks through fabric at connectors

9.4 New foam

As stated before, canals are cut into the foam to decrease resistance and increase distribution. The dense foam that was used however still limits the distribution of the water. Once the pad completely fills up, the water will follow the path of least resistance: through the channels. Only compression will replenish the water inside the foam itself, especially the regions further away from the canals.

To solve this issue, the water needs to flow directly through the foam. Using the fine foam from Stewart (2017) would then have too much resistance. A more coarse type of foam therefore needs to be found. A coarser foam has less resistance while still keeping the surface flat and creating turbulence in the water to increase distribution.

The newly selected material was reticulated polyether foam (see figure 69). This foam is usually used as an aquarium filter foam. It made to resist flowing water, similar to the intended use in the cooling vest. A density of 10- and 20 PPI (Pores Per Inch) was selected. Samples were ordered from two different suppliers, UXEM and Schuimplastic Brabant (SB).

9.4.1 Glue

The new foam also needs to be bonded to the fabrics to be a suitable material. Again, 3M 80- and 3M 74 glue spray were tested to join the two materials. The fabrics that were tested were the red and blue fabrics from previous tests, and a black TPU coated fabric that was provided by INUTEQ (see Confidential Appendix CA1 for specifications).

The red fabric preformed the best in previous tests. The blue fabric had a promisingly strong bond in the sealing test with the impulse heater. The black fabric is used in the INUTEQ's BODYCOOL SMART (see figure 70), is water tight, can be sealed with ultrasonic welding and it can also be heat sealed to itself without the use of PU tape.

A disadvantage of the black fabric is that it is thicker than the other materials. 4 stacked layers of each fabric were measured to more accurately find the thickness of the material. The red fabric is roughly .11 mm thick, the blue fabric .13 mm and the black fabric is .18 mm in thickness.

The glue test was similar to the previous glue test. In this case two pieces of fabric were glued to one piece of foam, on one side with 3M 74 and on the other side with 3M 80. Three fabrics and four types of foam led to 12 foam pieces with 24 pieces of fabric (see figure 71).

The pieces were glued and left to cure. After curing the fabric was pulled off the foam (see figure 72). The strength of the bond was rated on a scale of 0-10 where 0 is no bond whatsoever and 10 is a bond stronger than the foam itself. The results can be seen in table 1.

During the separation of the bond it was observed that the 3M 74 did not stick to the foam of the red fabric elements. This was remarkable because it did stick to the foams of the other elements. Since the red fabric was glued on the first and the method of doing so was not finetuned yet, it was decided that the test should be redone for the red fabric. The results of which can be seen in table 2.

The results of the retry differed greatly from the results of the initial test. It can therefore be concluded that the gluing process is an important factor in the bond strength. It can also be seen that 3M 74 always performs better than 3M80 and that 20 PPI generally bonds better than 10 PPI. This is logical because the glue has more material to hold onto with 20 PPI foam. However, testing continued with both 10- and 20 PPI because it was unclear if 20 PPI would have too much resistance. The final conclusion that can be drawn from the gluing test is that the red and black fabrics perform better than the blue fabric.

Figure 69: New foam

Figure 70: BODYCOOL SMART (INUTEQ, N.D. D)

Figure 71: Glueing samples

Figure 72: Testing strenght

Table 1: Results glue test

74	UXEM		Schuimplastic Brabant	
	PPI 10	PPI 20	PPI 10	PPI 20
Red	4	2	2	4
Black	7	8	8	10
Blue	4	8	3	6

80	UXEM		Schuimplastic Brabant	
	PPI 10	PPI 20	PPI 10	PPI 20
Red	6	4	7	7
Black	0	0	0	0
Blue	3	6	3	3

Table 2: Results glue test retry red

Retry red

74	UXEM		Schuimplastic Brabant	
	PPI 10	PPI 20	PPI 10	PPI 20
Red	9	10	8	10
Black	7	8	8	10
Blue	4	8	3	6

9.4.2 Water testing

The newly tested bond between the fabric and the blue filter foam was tested in wet conditions. Test pieces were made using the SB foam as UXEM was not willing to sell more foam in low quantities. The black fabric was used so its sealing capabilities could also be evaluated.

Two test pieces were made similarly to previously described pads (see figure 73). The black fabric is TPU coated, which means it seals to itself when heated. Both sealing with and without the PU slide tape was tried. No significant advantage was found in sealing this fabric with the tape. The tape creates extra work in cutting and aligning and the seal does not seem to improve with it.

The test pieces were connected to a pump and manometer. The pad with 10 PPI foam did not leak at all (see figure 75), while the 20 PPI had a water jet shooting out of the seam (see figure 74). The pressure difference and flow were therefore only tested on the 10 PPI pad. The results of this test can be seen in graph 1.

Interestingly, the trendline does not pierce the origin. This is probably due to a measuring error. After all, the pressure and flow are mathematically linked to the resistance: $Q = \frac{\Delta P}{R}$ (Ohm's law). The resistance (R) can be assumed as a constant, so if the pressure drop (ΔP) is zero then the flow (Q) should also be zero.

What can be concluded from the test is that the glue shows no signs of delamination at pressures up to 100 mBar. It is also possible to create a watertight seal with the black fabric.

9.4.3 Fabrication reconsideration

New pads were made with the red fabric, as it was thinner than the black fabric and would therefore have less resistance against heat exchange. This created three problems however.

Firstly, The red fabric needed to be sealed with the PU tape, while the connectors were sealed with super glue. The edge between these two bonding agents often improperly sealed, resulting in leaks.

Secondly, as a result of warping in the heating process the PU tape could bend away from the foam. This created a surplus of unbonded fabric on the side of the pad. The water flowed through this path with least resistance and it started to blow up like a balloon (see figure 76). A "balloon" as such decreases the cooling effectiveness of the pad and also looks untidy. Balloon forming should therefore be avoided.

Thirdly, as previously stated the superglue appeared to damage the watertight layer of the red fabric, also creating leaks (see figure 77).

The first two of these problems could be solved by using the black fabric. It does not require an additional bonding agent as it will melt to itself. This fabric can bond together at the edge of the superglue resolving the first problem. The ability of self-bonding also allows for sealing up to the edge of the foam, which solves the second problem of balloon forming. The third problem is not yet solved by the change of fabric, but the TPU coating does allow for new possibilities.

Figure 73: Test pieces black fabric

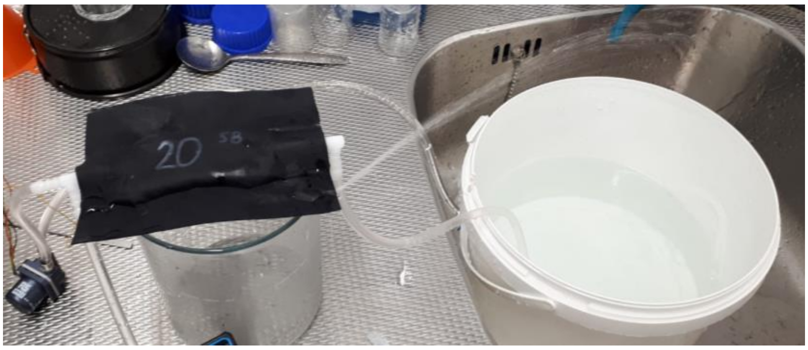
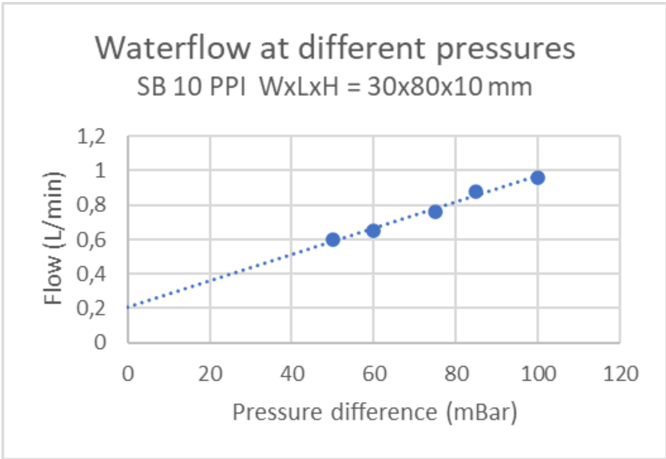


Figure 74: Jet stream from leak

Figure 75: Measuring resistance



Graph 1: Results measured resistance

Figure 76: baloon forming

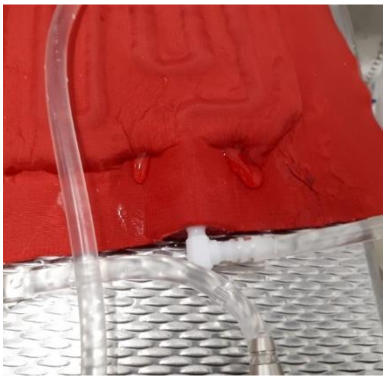


Figure 77: Leaks at connectors

Solving connector leakages

Two solutions were considered to solve the superglue damaging the fabric, both of which removed the need for the superglue itself.

The first solution was to use a transit (see figure 78). these transits are adapter pieces with a hose socket on one side and screw thread (generally inch based) on the other. The gray transit in figure 78 was ordered from Tameson.nl and the red transit was printed on the connex printer. The print allowed for smaller, metric screw thread and a wider flange to stop leakages. To place the transit the fabric is pierced, the adapter is placed on the outside with the screw end pushed through the hole. Then, a sealing ring (gasket) is placed around the screw end and the whole subassembly is tightened with a nut (figure 79 and 80).

The second solution used the TPU coating of the fabric. The already previously used connector pieces were printed in TPU instead of agylus (see figure 81). These connector pieces could then be fused to the fabric using the heat of a sealing iron (see figure 82 and 83). The idea for this solution was provided by Alice Buso who had previously used a similar method to place connectors in fabric bellows.

For both solutions prototypes were made and hooked up to a pump (see figure 84). This figure clearly shows that the gray transit piece created a leak. A greater downside of the transit pieces was their placement. Due to the assembly order, these pieces were placed before the seal was made. Getting the transit pieces to end up on the edge of the pad was therefore difficult. On the other hand, the TPU connector piece melted into the seal with relative ease. With this second method any leaks that did occur could simply be fixed afterwards by reheating the local fabric. The TPU connectors were also easily accessible, as they could be printed on an Ultimaker instead of the Connex printer. It was therefore decided to continue with the printed TPU connectors.

Melting of the TPU coating on the black fabric also inspired a new solution for the bond between fabric and foam. The thermoplastic polyurethane (TPU) layer of the fabric could be melted to the polyurethane (PU) foam. The foam itself is made of thermoset polyurethane so it does not collapse under heat. Test pieces were made with the 10- and 20 PPI foam (see figure 85). The fabric was heated using the sealing iron. The bond between foam and fabric was not as strong as with the 3M 74 glue, but still showed a foam breaking strength in many places. The prototyping of a pad which is fully bonded and sealed with heat is also significantly easier and quicker than one with several different processes. Moreover, a series production with the heating method will probably be quicker, cheaper and more reliable due to this single process and no glue curing time. INUTEQ also already has experience with heat-sealing. It was therefore decided to continue with this method.

Figure 78: Transits

Figure 79: Gasket and nut

Figure 80: Finished transit prototypes

Figure 81: TPU printed connector

Figure 82: TPU connector melted in pad

Figure 83: Sealing iron (Jamara, N.D.)

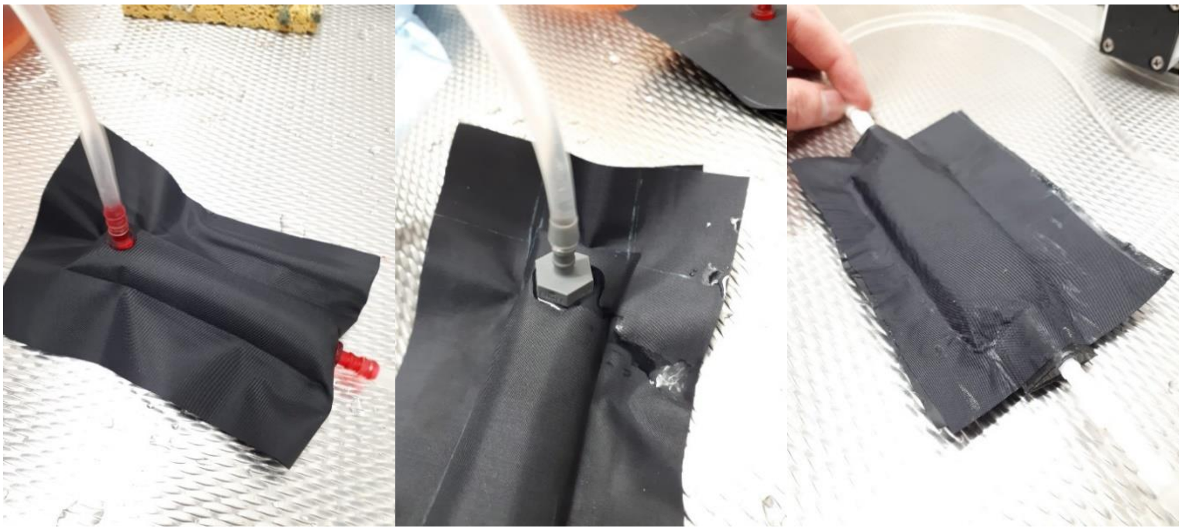


Figure 84: Three prototypes connected to a pump

Figure 85: testing bond between fabric and foam

9.5 Measuring resistance

In order to select a pump and battery for the complete cooling vest, it was necessary to estimate the required pressure drop and flow. The limiting factor of the water system was the strength of the pads. From a short test similar to previous pressure tests it was found that the bond between the foam and fabric broke between roughly 100 and 150 mBar above atmosphere (see figure 86). The seal, connectors and tubes remained intact when subjected to a pressure drop higher than 2 Bar. The subsequent flow (Q) belonging to these pressures could be found with Ohm's law: $Q = \frac{\Delta P}{R}$. The required pressure and flow determined the pump. To fill in Ohm's law the resistance of the system needed to be found.

The resistance of the eventual design could be estimated by finding the resistance of each part. Finding the resistance of each part separately also helped to find where improvements were most effective in case the resistance became too high. Different sized pads were made (see figure 87). These pads were hooked up to a pump. The ingoing pressure was measured and the flow was determined by capturing the water in a measuring cup (see figure 88). The full experiment can be found in appendix B.

9.5.1 Conclusion

In conclusion, the resistance of each element has been found. In the tested dimensions, the foam had an insignificant effect on the resistance. The 20 PPI foam has therefore been chosen to continue with, because it can form stronger bonds with the fabric. The white plugs (figure 89) had a resistance of 17,1 mBar/(L/min), the tubes had a resistance of 43.5 mBar/(L/min)/m and the pads themselves had a resistance of roughly 17,86 mBar/(L/min). Since the foam did not produce any significant resistance, the pad pressure is mostly produced by the connectors (entrance and exit) of the pad. It can be assumed the they produce 8.93 mBar/(L/min) each. These resistance values could be used to estimate the resistance of the new design. If the resistance was too high, because the pad delaminated, a part could be adjusted to lower the resistance.

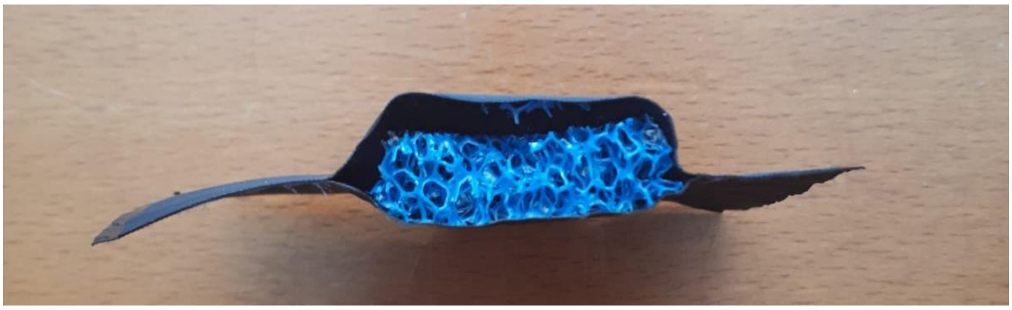


Figure 86: Delaminated pad

Figure 87: Different length pads

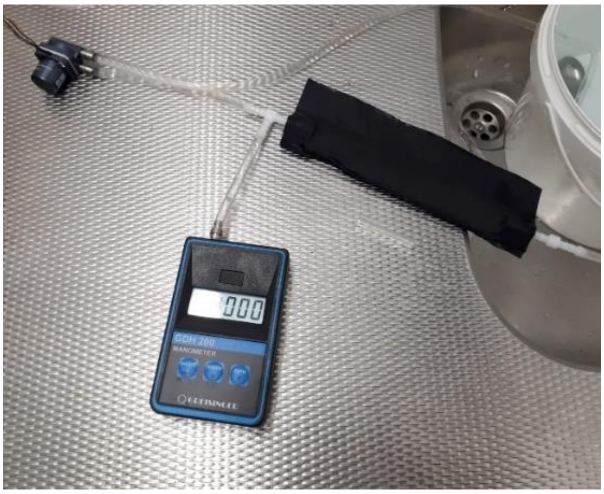


Figure 88: Resistance test

Figure 89: White plug

9.6 Flow pattern

When pumping water through a big sheet of foam it follows the path of least resistance. The foam itself may cause some turbulence in the water, but the stream of fresh water will still flow in a narrow path through the pad. The rest of the water inside the pad will therefore not be refreshed. The user will consequently wear a suit with warm water and one strip of cold water through it.

To solve this issue, the water had to be forced to flow along a desirable path. This path needed to cover the entire cooling surface to avoid "dead spots" without flow. The easiest way to create such a path is to fill the foam with bulkheads (see figure 90). These bulkheads guide the stream to cover the entire surface of the pad. To make these bulkheads, two concepts were tested (see figure 91). In the first concept PU hot melt tape (used previously in chapter 9.2) was placed inside slits in the foam (see figure 92). the fabric was then melted onto both the foam and the tape (see figure 93). In the second concept slots were cut in the fabric and the two layers of fabric were sealed together (see figure 95 and 96).

Two different water buckets with different temperatures and a thermal imaging camera were used to identify the flow patterns of the water. A more detailed description of the concepts and the experiment can be found in appendix C.

9.6.1 Conclusions

After the experiment it could be concluded that the bulkheads of the sealing concept work substantially better than the PU tape method. This method does have some drawbacks however.

One drawback was that the sealing method resulted in a pad that was less flat than the tape method (see figure 91). More flat surface area means more contact area with the body, increasing the heat exchange between the vest and the body. The edges of the pad also wrinkle more, making it less neat when integrated into the cooling vest. In later stages of the project, the bulkheads were made with a high frequency welding machine, which made them neater (see figure 94).

The second drawback was that the prototyping of the sealing method took longer than the tape method. However, when thinking ahead about larger-scale production, the sealing method could easily be simplified by pressing the layers together with a machined aluminium profile and bonded with a heat press.

Another result found in the experiments was that the water should ideally stream from the bottom to the top inside the pad. When flowing from the top to the bottom, the water flows in a more direct path, failing to cool the corners. When the water flows form the bottom to the top, these areas also occur, but in lesser amount. These areas of low flow are aimed to be minimized with the following test. The cooling area can also be reduced by trapped air inside 'dead spaces' (see figure 97). These should be avoided in the design.

Figure 90: Adding bulkheads

Figure 91: Bulkhead concepts

Figure 92: PU tape inserted in slits

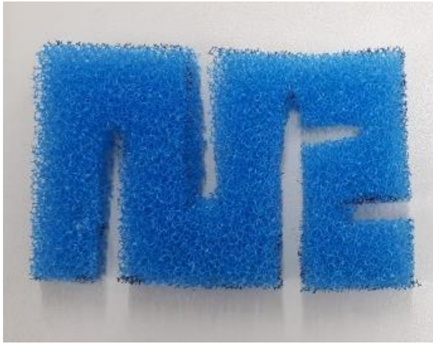


Figure 95: wide grooves cut from foam

Figure 93: Finished pad with PU tape bulkheads

Figure 96: Finished pad with sealed bulkheads

Figure 94: High frequency sealed pad

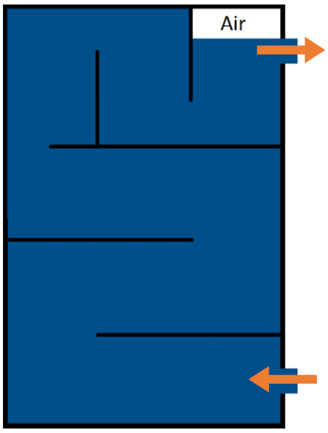


Figure 97: Trapped air

9.6.2 Pattern width

The previous test has shown that in a downwards stream, there are areas in the cooling pad where the water does not flow. To find out what this effect is when the channels are wider a new pad was made (see figure 98). This pad had 3cm wide channels where the previous pad had channels of maximally 2cm. This pad was once again suspended vertically and the test with the thermal imaging camera was performed once again.

Figure 99 shows the results of the test. In this case, the figure shows the pad was filled with hot water first and later with cold water. In the first four images, the hot water slowly fills the pad. It was clear that the water quickly flowed along the path of least resistance, after which it slowly fills the pad. When filling the pad with cold water again, it displayed the same effect (figure 99[5]-99[8]). In these last four images, the water flows through the previous hot stream. It was clear that even in straight sections of the pattern, the water was not quickly replenished at the edges. This behaviour was deemed unacceptable for the cooling vest. Channels of 3cm were therefore proven too wide.

With 3cm proven to be too large, a choice had to be made on the width of the channels. The water does not fully replenish in wider channels, so narrower channels will be more effective. However, with narrower channels, there are more bulkheads. Bulkheads take up the space of the foam, so more bulkheads means less foam for the water to flow through. Additionally, these bulkheads round off the edges of the foam, so a narrower channel will have even less contact area with the body.

A width of 2cm was chosen as a balance between good flow coverage and a high contact area. In the thermal test with the first prototype, only a few slow-flowing areas were observed in the corners. This suggests that wider channels will start to show these “dead spaces” on the straight sections as well. 2cm Wide channels, therefore, maximize the contact area with the body and the flow coverage. Subsequently, this channel width should have the highest heat exchange between the body and the cooling pad.

9.6.3 Filling

When observing the thermal imaging camera while filling the pad, a difference was found between filling from the bottom and from the top of the pad. When a pad is filled from the bottom, the water level slowly rises from the bottom to the top (see figure 102). However, when the pad is filled from the top, it will fall down the bulkheads like a waterfall (see figure 101). This downwards motion through the pad would trap air underneath the bulkheads. The air bubbles reduce the area of heat exchange with the body, decreasing the effectiveness of the cooling vest.

The bubbles want to rise to the top, as they are lighter than the water. However, the water is flowing downwards. The bubbles are trying to move against the stream. When the water eventually meets resistance at the end of the pad, it slows down. Some of the bubbles will then escape, but not all of them, resulting in a constant reduction of heat exchange.

When the water is flowing from the bottom to the top the water is flowing in the same direction as the buoyancy of the bubbles. Thus, even if air got stuck, it could more easily escape.

Figure 98: Prototype pad with 3mm wide pattern

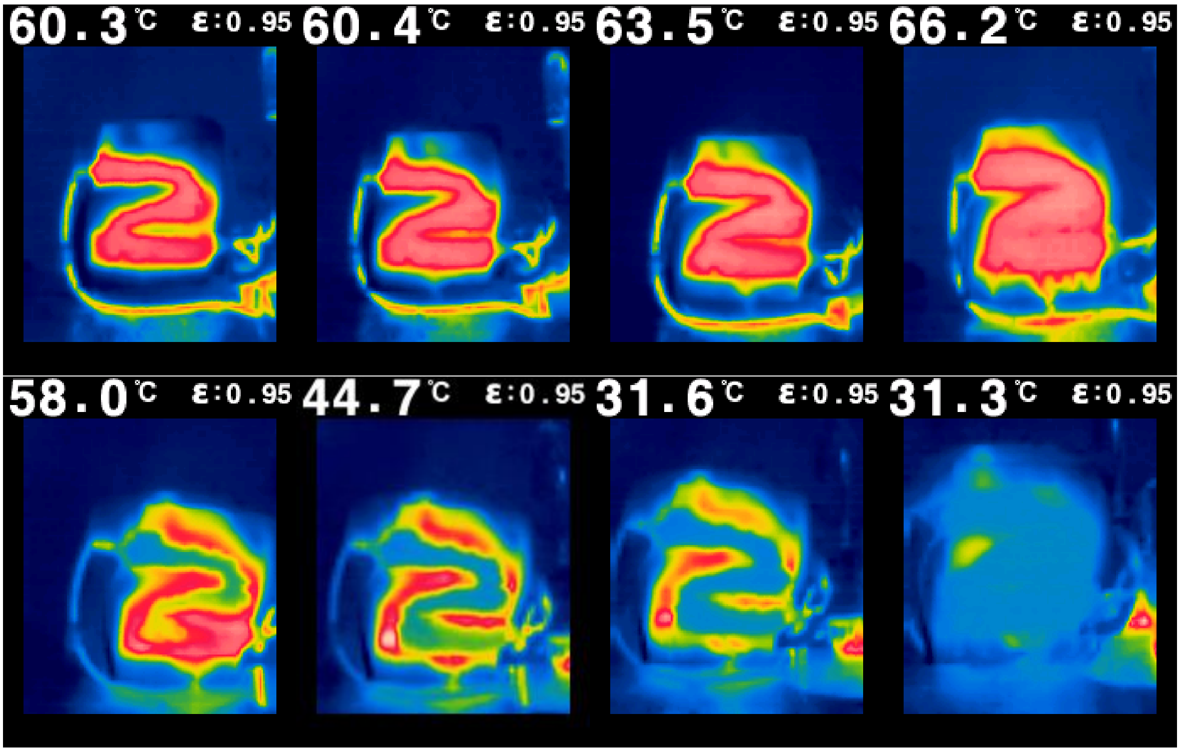


Figure 99: Thermal imaging of pattern width

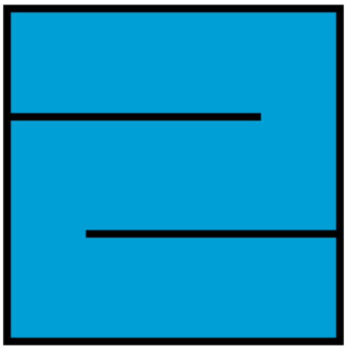


Figure 100: Empty pad

Figure 101: Filling from the top

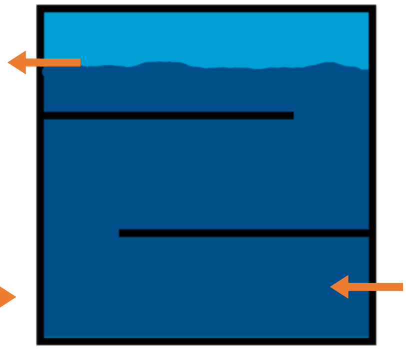


Figure 102: filling from the bottom

10 Cooling method

From the benchmark in chapter 6.1 it appears there are many different ways to cool the body. Stewart's concept (2017) uses a system of liquid circulation, which showed promising results. It was therefore decided to continue exploring this direction in this project. For an effective longer lasting cooling effect, the water needs to be cooled down during use. This chapter explores different methods to cool down the water.

10.1 PCM

The cooling method most familiar to INUTEQ is PCM cooling. Using PCM to cool the circulating water can therefore be easy implemented. PCM are most efficient around a narrow temperature range, which is when the PCM undergoes the phase change from solid to liquid. During this process, the PCM absorbs latent heat (Mondal, 2007). INUTEQ already produces PCMs with different activation energies to make cooling packs. The main drawback of using PCM is the activation process. The current packs need to be cooled in a refrigerator for several hours to be reactivated. When done incorrectly it can take even longer. So, unless there are multiple pcm packs available, a worker cannot be cooled constantly throughout a full workday.

The most common PCM is ice, which is not used by INUTEQ. When ice melts, it absorbs 335 kJ/kg (=335 J/g). Comparing that to the 4 kJ/kg water absorbs by heating up 1°C illustrates why PCM cooling is only effective during phase change (Mondal, 2007). Table 3 shows that the latent heat storage of other PCM's is substantially lower than that of ice. A cooling vest would therefore need less ice than other PCMs in weight to have the same cooling capacity. The reason INUTEQ does not already use ice is because the vests INUTEQ makes use the PCMs directly to cool the body. Ice is too cold to use in this manner. Using ice to cool the circulating water could be effective, however.

Table 3 Latent heat of adsorption and emission (Mondal, 2007)

Hydrocarbons	No of C atoms Ref. [24]	Latent heat of adsorption (ΔH) in J/g	Latent heat of emission ($-\Delta H$) in J/g	Crystallization temperature (T_c, °C)
n-Hexadecane	16	235.2	236.6	12.2
n-Heptadecane	17	176.4	182.6	16.5
n-Octadecane	18	244.8	246.4	22.0
n-Nonadecane	19	177.6	182.6	26.4
n-Eiscosane	20	242	230	30.4

Water to make ice is also easily available in factories, making it easy to use and cheaper. Current PCM packs are sold for €120 per suit. Together with the new foam pads and water circulation system, the new design may become too expensive. Factory workers are generally not a group which can count on high cost nonessential equipment from the company.

10.2 Evaporation

Another familiar technology for INUTEQ is evaporative cooling. They already use this type of cooling in other vests. The pads of the new cooling vest make evaporation possible by using a semipermeable fabric on the outside of the pad. Because water evaporates whether it moves or not, circulation becomes useless if evaporation is only used in the pads.

Evaporation vests use a phase change similar to PCM technology. At 30-40°C water will absorb between 2406 and 2430 kJ/kg of latent heat when it evaporates (Engineering Toolbox, 2010). Although it absorbs more than seven times the energy compared to melting ice, the evaporation rate of water is much lower than the melting rate of ice at 30-40 degrees. Evaporation rate is also influenced by air pressure and air humidity. The effectiveness of an evaporation vest therefore varies in different conditions.

Because the effectiveness of an evaporation vest is unpredictable and because using evaporation would be similar to designing an existing evaporation vest, it was decided that evaporation alone could not be used as cooling method. The easy integration of evaporative cooling in the cooling pads does make it an interesting option in combination with another cooling method.

A experiment was conducted to test if INUTEQ's evaporation fabric would work as part of a cooling pad. The evaporation fabric was melted to one side of the foam with the sealing iron. The other side was covered with the standard black fabric. These layers were then sealed together similarly to the creation of other pads. After connecting this pad to a pump it immediately started 'sweating' severely (see figure 103). The fabric had completely lost its watertight property, either because of the pressure or because of the bonding process to the foam.

Because INUTEQ spent years on developing this fabric, it is unlikely to find a fabric with similar evaporation qualities, which also does not leak after melting to the foam and put under pressure. Using evaporation as a cooling method was therefore discontinued.

Figure 103: Pad with evaporation fabric

10.3 Thermoelectric cooling

Thermoelectric cooling makes use of the Peltier effect. The Peltier effect occurs when electricity is run through a junction of two different (semi)conductors. Temperature rises in one of these conductors and falls in the other (Britannica, 1998). A Peltier element contains multiple junctions to increase the effect (see figure 104).

Because the Peltier element creates a temperature difference there is a conductive heat flow inside the element from the hot side to the cold side. Additionally, a Peltier element has a low efficiency. Some of the electrical energy passing through the element is converted into heat. These two effects result in the element, both the hot and the cool side, slowly heating up when it is activated. The Peltier element can therefore not continually cool down water (or anything else), without any additional heat extraction from the hot side. A heat sink in combination with a fan is usually used to cool down the hot end of a Peltier element.

Thermoelectric cooling is already used in cooling vests (see chapter 6.1). However, these vests are still experimental and not widely available. Besides, in these vests Peltier elements are used to directly cool the body instead of cooling a separate medium which subsequently cools the body.

The use of Peltier elements to cool down the water in the new cooling vest was discouraged by Dr. Kaspar Jansen and Ing. Martin Verwaal (electronics teacher and technician, faculty of design engineering, TU Delft). Their main reason was the heat development inside the element. The heat from the hot side needs to be extracted by a fan to prevent the cold side from heating up. This fan adds weight and also requires energy. The low efficiency of the elements means a cooling vest requires dozens of them. Continually powering and cooling all these elements does not seem like a realistic solution.

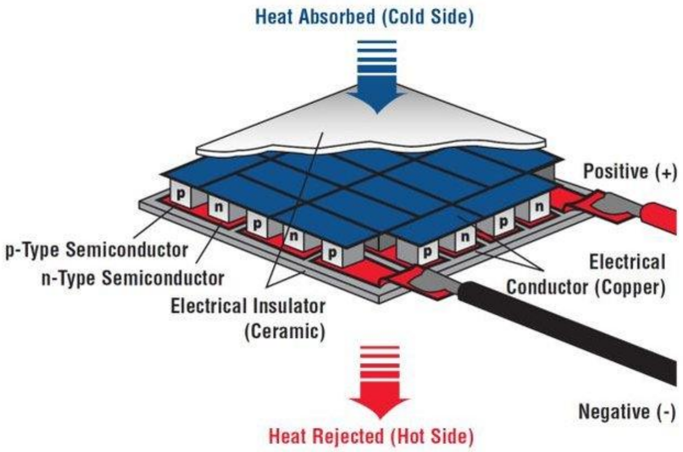


Figure 104: Peltier element (Nikolic, 2014)

10.4 Vortex cooling

A vortex tube is a device which creates a hot and a cold stream of air when supplied with compressed air (see figure 105). When compressed air enters the vortex tube it passes through a nozzle, which creates a vortex (1 and 2 in figure). When the air reaches the end of the nozzle it is forced to change direction back into the nozzle as a smaller vortex (3). The two vortices have the same angular velocity, but the inner vortex has a smaller radius. According to the conservation of angular momentum, the inner vortex should therefore have a higher angular velocity, but it does not. The inner vortex is slowed down by the outer and the lost kinetic energy is turned into heat. This heat is carried out of the vortex tube by the outer vortex (4 and 6). The inner vortex has cooled down and is released at the opposite side (5). (Harvard University, N.D.)

Cooling vests using vortex coolers already exist (see chapter 6.1), but they work by blowing the cold air directly onto the wearer. Cooling water with such a device may prove difficult. Efficient cooling will probably require a heat sink to increase the area of heat transfer. Apart from that, a constant supply of compressed air has to be available. Carrying a pressurized tank large enough to provide two hours of cooling in combination with the water in the suit will be heavy. An external supply, similar to existing cooling vests, means the wearer is tethered. INUTEQ has previously stated that the new design should be untethered, so an external air supply is out of the question. If water is fed into the vortex tube instead of air, a temperature difference can also be created. Unfortunately the water will heat up on both ends: one will become hotter than the other (Balmer, 1988).

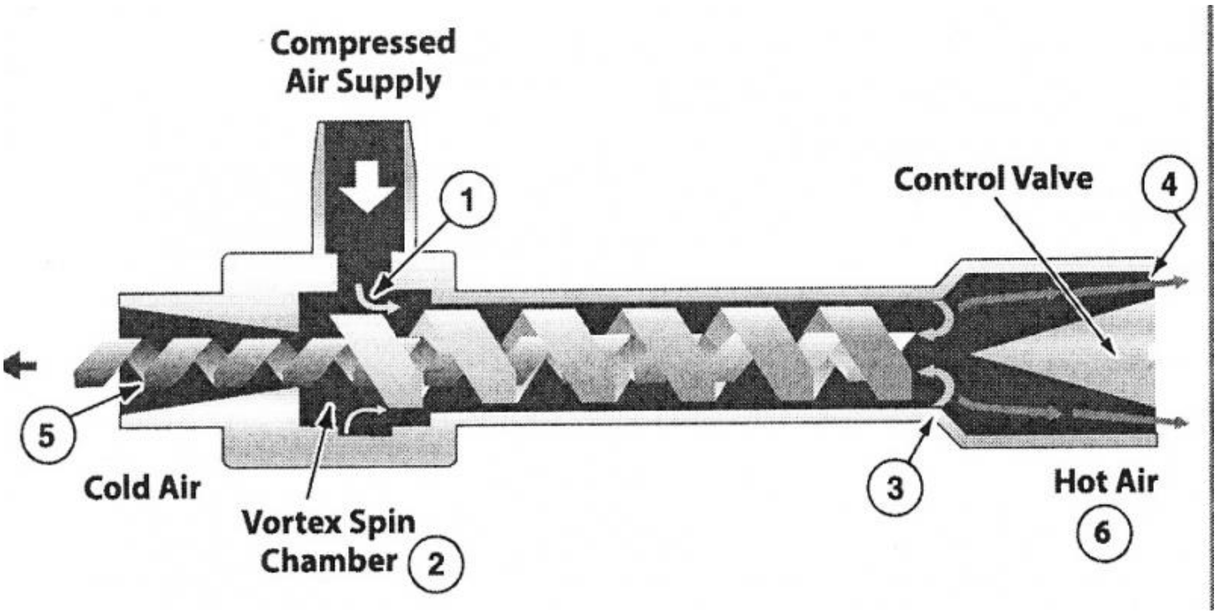


Figure 105: Vortex tube (Harvard University, N.D.)

10.5 Vapor compression

Vapor compression cooling is the technology used in air conditioners, refrigerators and heat pumps. Similarly to thermoelectric cooling this technology cools on one side and heats up on the other. It does so with a cycle of refrigerant (liquid and gas state). The hot side of the vapor compression system is called the condenser and the cold side the evaporator (see figure 106). The refrigerant is pressurized inside a compressor as a gas, causing it to heat up, becoming hotter than the warm environment. The hot refrigerant moves into the condenser where it condenses, giving off its heat to the warm environment. It is then expanded by an expansion valve, cooling it down again. Because the refrigerant has released energy to the warm environment, it is now colder than it was before it entered the compressor. Thus, the refrigerant becomes colder than the cold environment. The cold environment subsequently gives off energy to the refrigerant. The refrigerant starts to evaporate, absorbing more heat from the environment before returning to the compressor.
(Coolaction, N.D.)

Cooling vests using vapor compression cooling vest already exist (see chapter 6.1). These vests even use liquid circulation similarly to the new design. The drawback of this technology is that the compression unit is heavy and bulky. Current vests are mostly used by the military where the compressor is placed inside a vehicle so people do not have to carry them. Currently available air conditioning units currently do not have the desirable small size either. An entirely new compression unit will therefore have to be designed if vapor compression were to be chosen as cooling technology. Doing so is found too extensive for this project. Thus this technology is rejected.

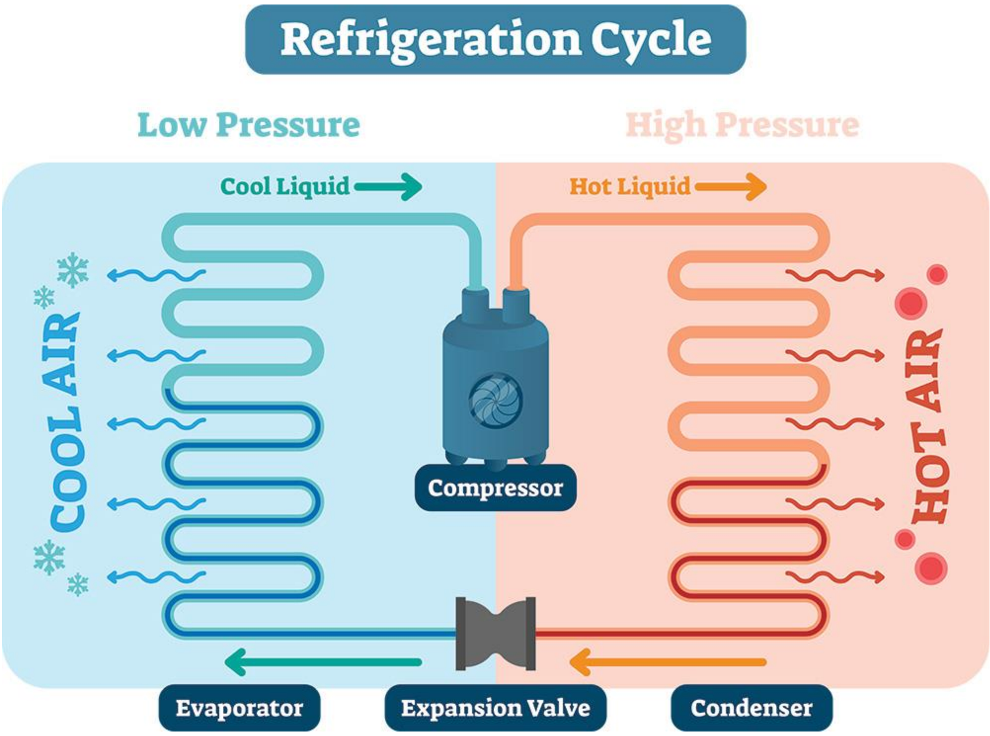


Figure 106: Vapor compression cycle (Learnmetrics, 2012)

10.6 Conclusion

In conclusion, the most suitable cooling method for this project is using ice. Unlike other PCMs it is easily available and absorbs more energy. Other cooling methods need too much development for this project, because they are currently too heavy, bulky or impractical to implement in a cooling vest directly.

11 Concept

This chapter explains the concept to solve the design challenge: The INUTEQ ICE (see figure next page). The subsections of this chapter explain the different parts of the new cooling vest.

INUTEQ ICE

11.1 Pad shapes

The pad shapes are designed in such a way that they minimize air getting stuck in the pads. The water enters the pads at the bottom and will fill the largest area of them while rising to the top. This filling direction avoids air getting trapped in the pads and therefore maximizes the area for heat exchange (see chapter 9.6.3). The back and forth lanes are oriented horizontally to also minimize trapped air. When the water has reached the top, it will fall though a single narrow strip downwards, forcing out as much air as possible.

The area of the pads is roughly equal. Though cooling is more efficient at the back (see chapter 6.3), it is important to balance the weight of the water. The pads are roughly $0.15m^2$ each, and 1cm thick. The total volume of $0.003m^3$ is partially filled with the foam and the rest is filled with water. A pad of roughly $0.01m^2$ (140x70mm) including bulkheads was weighed to be 68g. The pad area of the INUTEQ ICE is $0.3m^2$, meaning the pads will weigh roughly 2kg. The rest of the vest increases the weight to a total of 4kg.

When a worker is carrying a box or kneeling down, a pad could get compressed. Waterflow could then stop in this pad. When the whole cooling vest consists of a single water circuit, the entire cooling vest will lose its cooling capacity in case of a local block. To keep the wearer cooled, the two pads are therefore fed water separately, with one pump each. Thus, when one of the pads is (locally) compressed, the water flow will not stop in the other. This means the cooling vest keeps half of its cooling capacity in case of a block. From the observations in chapter 4.4 it appeared that a situation where both the front and the back are obstructed is highly uncommon.

11.2 Water container

The water container is a box containing the water reservoir, two pumps, two pressure relief valves and a battery (more on this in chapter 11.2). It sits tightly against the body, so it does not stick out too much. The water reservoir is filled with ice first and then the water is pumped in. The reservoir is 2L, but it can be filled with less water if it becomes too heavy for some people. The reservoir is smaller than the total volume of water inside the vest, to keep the reservoir compact, light and practical. Currently there is 2L in the reservoir, 2L in the pads and some water in the tubes. During the filling process, most of the volume in the tank is taken up by ice. To fill the complete vest, the pumps, therefore, need to be turned on while filling the reservoir.

11.2.1 Pumps

The pumps are centrifugal pumps and are placed below the water level, because they are not self-priming. A self-priming pump can pump water up a tube, even though the pump and part of the tube are filled with air. When the pump and its connecting tube are both completely placed below the water level, the water will automatically fill the pump.

Looking at the size and weight of the water container, two self-priming pumps were considered. A membrane pump and a gear pump. However, both these pump are not suitable for the cooling vest. The membrane pump creates a pulsating water flow. The peak pressures from this pump could break the pads, while the average pressures are not large enough to carry the water to the top of the pad. Apart from that, the pads vibrate when fed with a membrane pump, which is probably annoying for the wearer. A gear pump is also self-priming, but its drawback is that the gears need to be lubricated. Since water is not a lubricating fluid, a gear pump cannot be used for the cooling vest either.

Because the membrane pump and gear pump were not suitable, a centrifugal pump was chosen. Centrifugal pumps can be small and can produce high flowrates. They also work well at low pressures, which is what the cooling pads require. Since a centrifugal pump is not self-priming, the pump and the connections between the tank and pump were placed lower than the water level. This has another advantage, apart from automatically filling the pump. Warm water will rise to the top of the tank and cold water to the bottom. The pump, being connected to the bottom of the tank, will therefore always take in the coldest water from the tank. Although this effect may be outweighed by the turbulence of incoming water.

(The information on pumps is from a personal conversation with Martin Verwaal.)

11.2.2 Water flowchart

A flowchart was made to give a schematic overview of the water flow throughout the INUTEQ ICE (see figure 107). As stated before, the cooling vest contains two water loops with two pumps each to separately provide the front and back pad with water. The arrows represent tubes and the direction of the arrow shows the direction of flow. The P stands for pump and the R for a pressure relief valve.

Pressure relief valves have been placed between the pump and cooling pad, because the pads delaminate quickly if the pressure gets too high. A pressure relief valve is tuned to a specific pressure, in this case 100 mBar. If the incoming pressure is higher than the set pressure, the valve releases the excess into a separate exit (indicated as overflow in flowchart). This way, the valve insures that the water flowing into the cooling pad never has a pressure higher than 100 mBar. In case of a block of the pad, the valve immediately starts rerouting the water back into the reservoir. Apart from keeping the pads from delaminating, this valve will also prevent the pump from stress if the pressure gets too high.

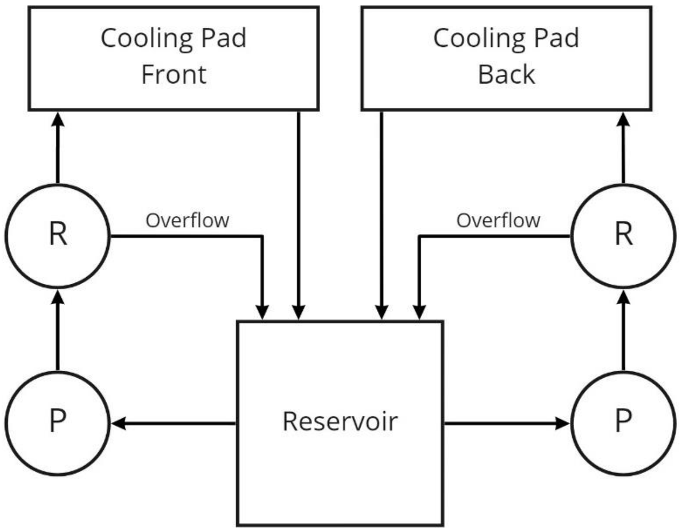


Figure 107: Water flowchart

11.2.3 Fixation

The water container of the INUTEQ ICE is fixated on a strap around the waist of the. It can be moved along this strap, so a worker can move out of the way and place it wherever they prefer. If a worker wants to sit down, for instance, he can move the water container to the side.

The inspiration for a movable container came from the conversation on safety with Huub Agterberg (chapter 7). In an anecdote unrelated to safety, he mentioned a respiration system he tested at KLM. The pump for this respiration system was placed on the waist and could be moved around, which was received positively by the workers. They mostly moved it to the back and side, which is why the area in the front could stay free to cover with cooling pads.

Another example of a waistband to carry a container can be seen in the 3M Versaflo (see figure 108). The Versaflo is a full face respirator face shield. Among other professions, it is used in industrial settings, indicating that the placement of a container on the lower back is appropriate for the target group. The contact person of De Jong Verpakking also stated that he would prefer a container with water to be on his back.

Because the water container is heavier than an air filter, the stap of the INUTEQ ICE is also using the waist as a support point. The weight of the cooling vest is therefore divided over the shoulders and the waist, instead of fully hanging on the shoulders. A solution like this can also be found in hiking backpacks to spread the weight over different support point and improve stabilization.

The straps on the side of the INUTEQ ICE can be adjusted with Velcro. Tightening the straps not only improves the support on the waist, it also presses the cooling pads against the body. This will increase the contact area, which aids heat exchange between the vest and the wearer. INUTEQ already uses straps to increase contact area, for instance in the BODYCOOL PRO (see figure 109).

Figure 108: 3M Versaflow (eBay, N.D. B)

Figure 109: BODYCOOL PRO (INUTEQ, 2019)

11.3 Cooling capacity

The cooling capacity depends on different factors. An accurate estimation of the cooling capacity is practically impossible. The water will flow through the ice, cool down, flow through the vest and heat up again. The speed of the water could be estimated because the resistance and pressure drop are familiar. However, the temperature of the water is going to vary depending on a number of unknown variables: heat exchange between the body and the vest, heat exchange between the vest and the environment, amount of surface area between the ice and the water. The cooling capacity of the vest therefore needs to be found using practical experimentation (see chapter 14).

11.4 Recharging

After a certain time using a cooling vest it needs to be recharged. The disadvantage of current INUTEQ cooling vests is that they need to be taken off completely to recharge or refill them. For PCM cooling vest this process is even more cumbersome, because the vests need to be recharged in a refrigerator for hours. Moreover, multiple PCM vests stacked on top of each other do not recharge easily, due to their insulating properties. A difficult or time consuming recharging process could demotivate users from wearing the vest altogether. The recharging process of the INUTEQ ICE aims for a greater ease of use in recharging. Due to time constraints of this project, the exact recharging interaction and recharging station have been left out of the scope. This chapter aims more to give an indication of the possibilities with a water perfused ice cooled vest.

The INUTEQ ICE could be rechargeable both by hand and with a recharging station. The different possibilities provide solutions for different size companies. If the number of workers with a cooling vest is low, the vest should be fillable by hand, but if there are many users in a company the possibility of a more expensive solution arises: a recharging station. At this station the user could plug a connector to his vest which simultaneously charges the battery and refills the suit with ice. It could also flush the entire suit with fresh water. This would help keeping the vest clean and could provide some increased cooling time by refilling with cold water. A key aspect for this recharging station is that recharging happens quickly. It helps to keep motivating workers to wear the vests, because they do not have to wait for their vest or other worker’s vests to recharge.

Refilling by hand seems more realistic if the reservoir is changed out for a new reservoir from a (shock)freezer. This still allows recharging without taking off the entire cooling vest. Having multiple reservoirs per worker seems realistic. After all, a separate water container is probably less expensive than a separate set of PCM cooling packs.

The water container possibly needs to differ from the container used with a charging station, but this situation seems almost unavoidable. A large company would probably need too much freezer space for all the extra reservoirs, while a smaller company would not be able to afford an expensive recharging station to provide cooling to a handful of workers.

As stated, this chapter describes possibilities and initial thoughts. In the future the action of recharging and refilling should be investigated further. Designing a system to refill by hand seems possible within a relatively short term design project. Developing a recharging station seems like a more long term goal.

Evaluation Phase

12 Prototype

As a proof of concept, the INUTEQ ICE was tested in a user research (see chapter 13). To do so, A full scale prototype needed to be made. This chapter expands on the process of making this prototype.

12.1 Patterns

Due to a lack of experience in textiles and patterning, the patterns of an existing cooling vest were copied. INUTEQ's BODYCOOL SMART was chosen because it is already used in a similar fashion, it is relatively flat compared to other cooling vests, and the area filled with water was roughly equal to the pad area in the INUTEQ ICE. The BODYCOOL SMART does have a zipper in the middle, however. The separation of pumps between the front and back pad (hereafter defined as front-back separation) in the INUTEQ ICE could therefore not be done with these patterns. Thus for the prototype it was changed to one pump for the left side and one for the right side (hereafter defined as left-right separation). A 100 mBar pressure relief valve was not found, so the water flow chart for the prototype looked like figure 110.

The flow was directed to the front panel first to keep the vest balanced. If the back would fill first than both the weight of the water reservoir and the full pad on the back would all weigh down the vest on one side. Chapter 6.4 explains why that would be undesirable. Another consequence is that the water needs to flow over the shoulder. That could become an issue because the fabric has to bend on the shoulder and the weight of the vest could compress the pads there. More on the shoulder solution can be found in chapter 12.2.

The patterns of the BODYCOOL SMART were first roughly traced on transparent plastic sheets (see figure 111). Then, these patterns were cleaned up and traced onto pattern paper (see figure 112). Next, the patterns were fitted with foam patterns (see figure 113). The zig-zagging foam strip had a width of 2cm, as defined in chapter 9.6.2. The foam- and fabric patterns were separately traced on a new sheet of pattern paper and cut out (see figure 114). These new patterns were used to trace the shape onto the fabric and foam.

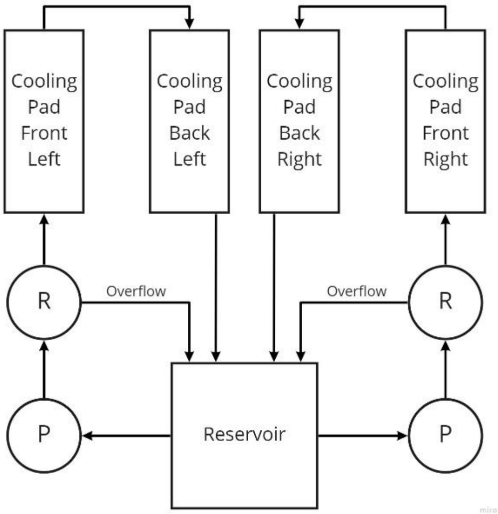


Figure 110: Flow chart of prototype

Figure 111: Tracing patterns onto transparent sheet

Figure 112: Tracing sheet patern onto pattern paper

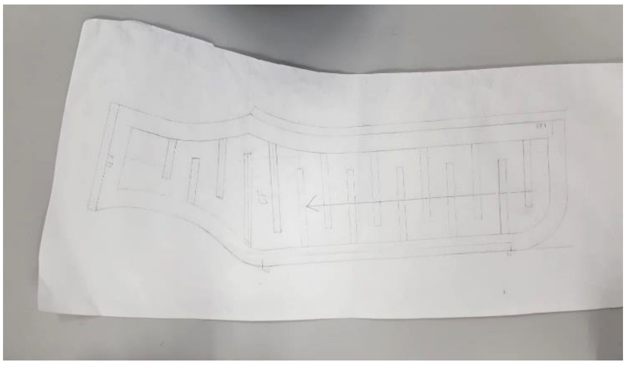


Figure 113: Pattern with foam drawn into panel

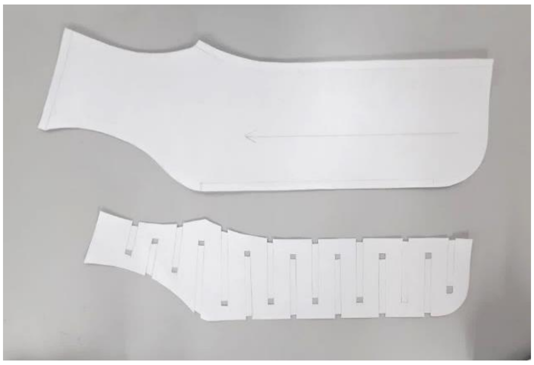


Figure 114: Separate patterns for foam and panel

12.2 Shoulder

Because the prototype had a left-right separation, the water needed to travel over the shoulder. Fabric falls over the shoulder in a curve (see figure 115). it was found that this curve was too tight for the zigzagged pad to make without buckling. The buckle would introduce a large amount of resistance which could delaminate the pad. Several concepts have been tried and tested to solve this issue (see appendix D), but none of these worked satisfactory. Eventually an idea was made up where a tube would be placed between the front and back pad (see figure 116). This tube would be longer than the fabric underneath so it would never carry the load of the vest.

However, during the green light meeting, it was discussed that this prototype could differ too much from the concept. The left-right separation could create a cooling vest where the front pads would be cold and the back pads lukewarm: The cold water was planned to enter the front pad first. There, it would warm up by cooling the body. Thus, it could have been possible that the water was already too warm to properly cool the back. The layout of the pads was therefore changed to better represent the concept (see chapter 11.2.2). A quarter of the initial layout was already made by this point. It was used to test if the pads were strong enough to withstand the added pressure of the vertical travel (see chapter 12.4)

There were still some positive takeaways from producing the shoulder concepts. Firstly, the method to create the pads on INUTEQ's high frequency welding machine was tested (see figure 117). With the high frequency welding machine, the pads could be made substantially neater than with the sealing iron alone (see figure 118).

Figure 115: Vest falling over shoulder

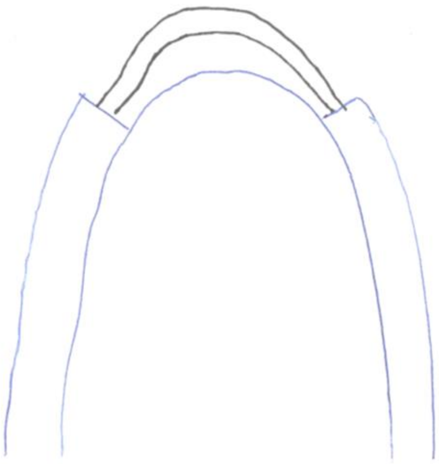


Figure 116: Shoulder solution idea

Figure 117: High frequency welding machine

Figure 118: Neat pad

12.3 Electronics

As stated before, the concept features two pumps to pump around the water in the two pads separately. The prototype therefore also needed two pumps. These pumps also required to be provided with power. These electronic components were selected in consultation with Martin Verwaal.

Chapter 11.2.1 already explains that the pumps will be centrifugal pumps. The RS Pro M400 was chosen (see figure 119), because of its small size and ability to still reach the required 100 mBar of pressure. The pump required 3 to 12V. When the pump was provided with higher voltage, the pump would create a higher pressure.

The pump was chosen to be powered by a power bank. The power bank selected was a Hama power bank which cold store 6000mAh (see figure 120). This power bank was selected because of its two USB ports, its on-off button and its low price.

A power bank provides a voltage of 5V, while the pump required 3 to 12V. An adjustable DC-DC converter was therefore required to step up the 5V to the required voltage. The “DC-DC adjustable step-up boost converter XL6009 4A” was found to fit the voltage requirements and was therefore selected (see figure 121). The outgoing voltage was adjusted when the prototype was finished to make sure the pump provided the right pressure.

A cut USB-C cable was used to connect the powerband to the DC-DC converter (see figure 122). The parts were soldered together and the DC-DC converter was encased in an electronics box to make the circuit waterproof (see figure 123). The power bank refused to run the two pumps simultaneously and turned itself off. A second power bank was used to solve this.

Figure 119: RS Pro M400 Pump (RS, N.D.)

Figure 120: Hama Powerbank (Action, N.D.)

Figure 121: DC/DC converter (Tinytronics, N.D.)

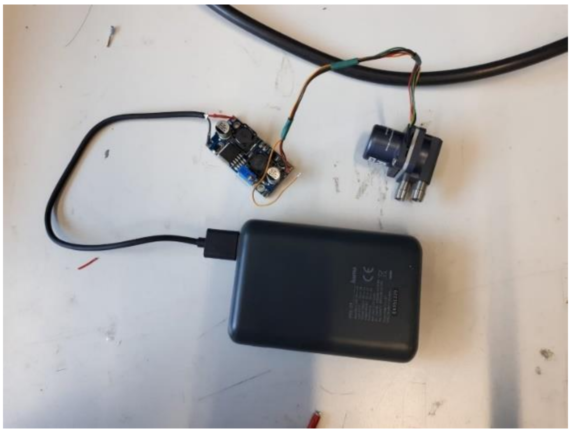


Figure 122: electronic circuit one pump

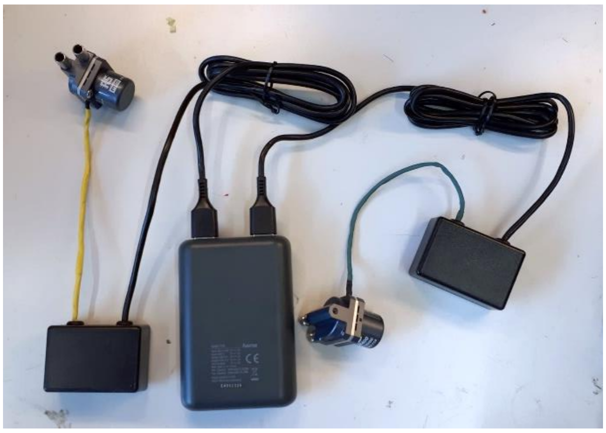


Figure 123: electric circuit finished

12.4 Test

As stated before, a quarter of the original prototype layout was made. This panel was not only made to test the pressure and flow of such a large piece, but also to practice making larger pieces.

When making smaller pieces, an optimal sequence to make a flat pad was slowly discovered. Firstly, the fabric is melted to the foam. Secondly, the fabrics are melted together to form the bulkheads without melting the outer edges together. These are kept separated with baking paper (see figure 124 [2]). Thirdly, the TPU connectors are loosely melted in place. At this point the TPU connectors were changed from the triangle shape to a smaller diamond shape (see figure 125). During fabrication of previous pads it was noticed that the fabric around the connector pieces had to stretch to form around the triangular shape. One side had to fully cover the gap between the two fabric layers. With the diamond shape the two fabric layers meet in the middle. The fourth step in making the pad was to melt the outer edges of the fabric together. The fifth step was to properly melt the connector into place. The last step was checking the pad for leaks, and fixing them.

It was expected that the panel would shrink in length due to the waving fabric, but it was not foreseen that the length of the foam also decreased. When comparing the panel with the original pattern on paper, it became clear that it had shrunk 5cm (see figure 124 [3]). In the final prototype this decrease in length should be taken into account.

The panel was tested to discover what the vertical distance does with the flow and structural integrity of the pad. The panel was suspended vertically and connected to a pump and manometer (see figure 126). the manometer was connected to measure the pressure of the water going into the pad. The voltage on the pump was increased until the pressure on the manometer indicated 100 mBar above atmosphere. Because the water had to rise 0.5m, 50 mBar of pressure was needed to reach to the top. The other 50 mBar and resistance determine the flow.

The water was able to make it up the pad and back down again. However, the outgoing flowrate of the water was deemed too low (see figure 127). Increasing the flowrate was only possible by reducing the resistance. Increasing the pressure was not possible, because the pads would delaminate. In chapter 9.5 it was determined what the resistance of each part was. It was also found that the resistance of cylindrical channels depends mostly on their radius. It was therefore decided to increase the inner tube width from 5mm to 6mm in the final prototype. This meant the resistance of the tubes, connectors and plugs would all decrease, increasing the possible flowrate. The final dimensions of the connector can be found in appendix E.

Figure 124: Making process of the pad

Figure 125: Improved connector

Figure 126: Testing pad

Figure 127: Resulting flow

12.5 Final prototype

Since it was proven that the water was able to rise 0.5m without delaminating the pad, it was time to make the final prototype. This prototype was made for user testing (see chapter 13).

12.5.1 New pad layout

In chapter 12.2 it was decided that the pad layout should be more representative of the concept. The final prototype should feature one central pad on the front and one on the back. To simplify the prototype, the shape of the garment was changed from a vest to a pullover. This pullover would have two tightening straps on each side to give good contact between the body and the pads. Figure 128 shows the simple idea sketch of the prototype plan.

The pattern of the front panel was mirrored and adjusted, to end up with one continuous front panel. The back panel was also made a bit wider to fit a larger pad (see figure 129). These panels were then extended to compensate for the shrinkage from sealing the pad (previous section). Then the patterns for the foam pieces were drawn in. The patterns of the foam were then retraced onto separate paper (see figure 130). Only the ends and corners of the bulkheads were cut out of the patterns, so they could be transferred to the foam. If the bulkheads were completely cut out, the pattern would become a long strip and the general shape would be lost.

These patterns were used to cut the fabric and foam into shape (see figure 131). The foam was melted to the fabric using the sealing iron (see figure 132). Then, the bulkheads were made with the high frequency welding machine (see figure 133). The connectors were ironed in, the outer edges of the pad were welded shut (see figure 134), and the pads were tested for leaks (see figure 135). Next, The two panels were ironed together. The placement of the tightening straps could now be located and they were welded on (see figure 136 and 137). Lastly, fabric was completely ironed together to complete the pullover (see figure 138).

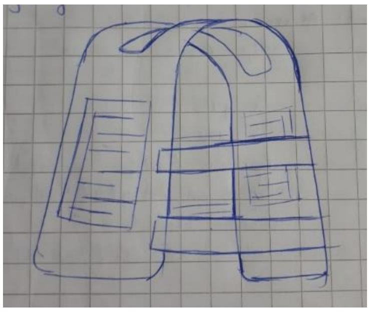


Figure 128: Prototype idea sketch


Figure 129: Panel patterns


Figure 130: Foam patterns


Figure 131: Panels with their foam pieces


Figure 132: Melting fabric to foam


Figure 133: Sealing bulkheads


Figure 134: Sealing outer edge


Figure 135: Testing for leaks


Figure 136: Fitting tightening straps


Figure 137: Tightening straps welded on


Figure 138: finished vest

12.5.2 Reservoir

In the original concept, the reservoir was a hard container. However, after discussing the prototype with Linda Plaude, it was decided that the reservoir should be a flexible bag. A flexible bag has two main advantages over a solid container: It can follow the shape of the wearer to make it more comfortable and, by squeezing the bag, the air can be released so the water does not slosh.

Again, a simple sketch was made to make a plan (see figure 139). Then piece of fabric was cut with the same width as the back of the pullover. It was folded in half and closed with clamps (see figure 140). This bag was filled with exactly two litres and the height of the water level was marked (see figure 141). Next, a lid was modelled and 3d printed (see figures 142). This lid was based on the old lid of the BODYCOOL SMART. The lid and connectors were ironed in, after which the bag was sealed on the sides (see figure 143 and 144). Figure 143 shows the lid leaking. Two new lids were printed, which did not solve the issue either. Eventually the porous 3d prints were covered in hot glue and the lid was fitted with a gasket from the PU hot melt tape. This reduced the leakage to an acceptable level. The reservoir was closed and the residual fabric was used to make the connection for the belt (see right side of figure 144). Figure 145 shows the finished reservoir.

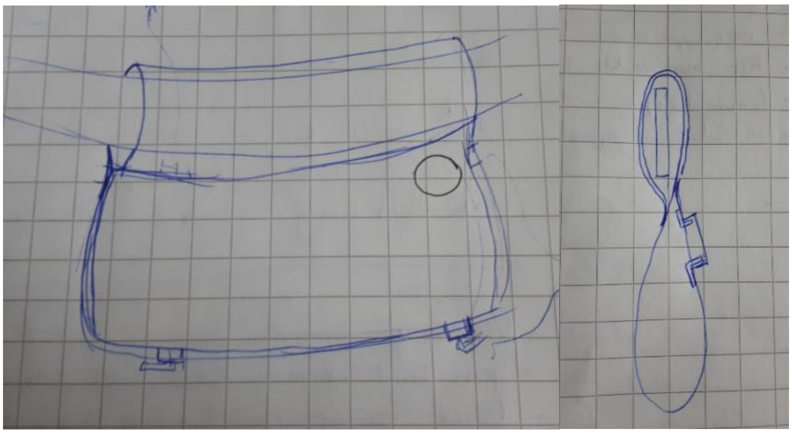


Figure 139: Reservoir Sketch


Figure 140: Fabric piece made into sack


Figure 141: Sack filled with 2L

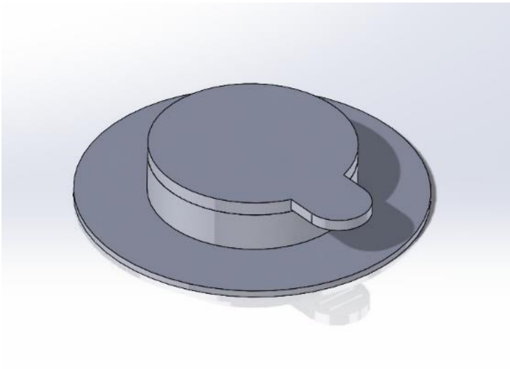


Figure 142: 3D model of lid


Figure 143: Leaking Lid


Figure 144: Reservoir sealed with connectors and lid


Figure 145: Finished reservoir

12.5.3 Belt

The belt itself was made from a 40mm cotton band. It was fitted with an adjustable clasp (see figure 146), so the wearer could adjust the belt to their size. In a meeting about the prototype, Linda Plaude put forth that it was not desirable to hang a 2kg weight on a belt that was attached to the pullover. It was therefore decided to make the belt a separate part, so the belt was better supported by the hips.

Apart from the reservoir, the electronics also needed to be attached to the belt. Two simple bags were made for the electronics, to hang on either side of the reservoir (see figure 147). These bags contain a hole for the tubes to go through and a hole on the other side for dewatering (see figure 148). The final assembly of the belt can be seen in figure 149.

Figure 146: Belt

Figure 147 Electronics bag

Figure 148: Tube exit in bag

Figure 149: Finished reservoir belt

12.5.4 Total assembly

With the pullover and the vest made, the tubes could be connected and the final prototype was finished. Figure 150 to 154 show the full prototype on a mannequin.

Figure 150: Detailed view of reservoir and tightening bands

Figure 151: Backside of prototype

Figure 152: Right tube arrangement

Figure 153: Electronics bag

Figure 154: Frontside prototype

12.5.6 Design changes

In the process of making the final prototype, several problematic aspects about the concept were ran into. Parts could either not be made, created warping, or were problematic for another reason. These aspects need to be changed in the concept of the INUTEQ ICE to improve the design. This subsection discusses the problems and offers solutions for future iterations of the INUTEQ ICE.

- As discussed before has the reservoir and belt been changed. It was preferable to make the reservoir a flexible bag, so it can follow the shape of the body and the water sloshes less. The belt needs to be fully wrapped around the body to offer better support.
- Because the belt goes all the way around, the pad on the front cannot cover the abdomen of the wearer anymore. The pad needs to be decreased in size at the bottom.
- As previously mentioned, the tube size has been increased from 5mm to 6mm to lower the resistance and the connectors have been changed from a triangle shape to a smaller diamond shape.
- The prototype was fitted with more tightening staps on the side. These straps enabled better contact between the body and the cooling pads. The concept should therefore also feature these straps.
- The pads have warped due to the shape of the foam. The zig-zagging strip causes the pad to shrink in the height direction (see figure 155), while the straight foam band on the other side wants to stay the same length (see figure 156). This causes the vest to warp and wrinkle. A solution for this problem would be to replace the vertical foam strip with a tube. This tube can be fitted to size after the pad has been made. If the pads only zig-zag, they should not warp and wrinkle less.
- Because the front pad decreases in size it will hold less water. The reservoir could be made bigger, while keeping the weight of the vest the same. A bigger reservoir could increase cooling time.
- The pads should be sown into a garment instead of the fabric of the pads forming the garment itself. Figure 157 shows that the garment is made from the same piece of fabric as the pads. A slight twist or warp from making the pads can cause great misalignment further away from the pad (see figure 158). In future prototypes, the pads should be made separately from the garment to avoid this issue. Doing so may also cause less wrinkling in the garment. It also enables the rest of the garment to be made of breathing sports fabric.
- Linda Plaude commented on the envisioned zipper of the INUTEQ ICE. A zipper needs to be straight to work, she said. An adjustment of the zipper in the concept is therefore in order.
- The pads still delaminate at low pressures. The 20 PPI foam does not seem to give much resistance. In the future an even denser foam could therefore be investigated. A denser foam will make more connections with the fabric, creating a stronger bond. The right balance should be found between foam density, structural integrity and resistance.

Figure 155: Shrinking and warping due to sealing lines

Figure 156: Vertical band warped

Figure 157: Pads are part of entire panel

Figure 158: Misaligned fabric pieces

13 User test
With the prototype finished, the concept can be presented to- and experienced by the target group in the form of a user test. This user test will form as one of the main points of evaluation for the concept. The results of this test can be used to modify the design to better suit the needs of the target group. This is a qualitative research, so the number of participants is low, but a large amount of information is gained per participant.

13.1 Goal
The goal of this user test was to validate if the INUTEQ ICE can be a suitable cooling vest for factory- and warehouse workers. This done by evaluating the prototype in the appropriate context. This includes the target group, their activities and the work environment. Important aspects of this test are the cooling, the comfort and the freedom of movement.

13.2 Research questions
- Is the INUTEQ ICE more appropriate than other cooling vests for workers in factories and warehouses?
- What is the thermal sensation and thermal comfort of the user while wearing the prototype?
    - What is the effect of intermitted cooling?
- What is the wearing comfort of the cooling vest?
    - How much freedom of movement do the users have while wearing the prototype?
    - Does the prototype hinder the user in their work activities?
    - Are the cooling pads ever compressed in such amount that the water flow noticeably stops?
- How much discomfort does the weight of the prototype give?
- Does the user consider the overall experience of wearing the prototype an improvement compared to other cooling vests or no cooling vest at all?
- What Improvements can the users think of?

13.3 Method
13.3.1 Participants
The participants consist of one worker from a factory and one worker from a warehouse. Both participants were men of average height. The working conditions and experience with cooling vests differed between these workers.

The factory worker worked for De Jong Verpakking in De Lier. Within this factory the temperatures are between 30 and 40 degrees. The building is heated by the production processes of making corrugated carboard (for more information see chapter 4.4.2). Because of the high temperatures in the building, tests with INUTEQ's cooling vests were already executed. The participant therefore already had experience wearing cooling vests during his profession.

The warehouse worker worked in the Quooker Hub in Heijplaat, Rotterdam. Heat in this warehouse mostly comes from the sun on the large flat roof. At the time of this research the Quooker hub had not been in use for a full summer yet (December-July). Within this period the workers did not yet experience high temperatures in the building. The participant did experience hot working conditions in the previous warehouse in Ridderkerk (for more information see chapter 4.4.1). He did not have experience with cooling vests.

13.3.2 Procedure

The reservoir of the cooling vest was filled with ice and regular tap water. The pumps were turned on during the water filling to fill the rest of the vest. When filled up, the air was pressed out of the reservoir before closing the lid. Participants put on the cooling vest and the reservoir (see figure 159 and 160). A stopwatch was set to keep track of the time. The participants were then asked for a first impression of the cooling vest and to think out loud during the entirety of the test.

Figure 159: Factory worker with the prototype

Figure 160: Warehouse worker with the prototype

Participants were asked to walk around their work environment and perform work they would normally do during their job. Together with the participant it was thoroughly discussed which activities were possible to minimize the introduced risk for people and equipment. If there were any movements observed during the first visit to these locations (see chapter 4.4) the participants were asked to execute these once more.

This research aims to find cooling perception rather than cooling capacity. After some time people start to lose the cooling sensation, even though their vest still provides cooling. a simple intermitted cooling setup was used to keep stimulating the cooling perception of the participants: once the participant perceived the cooling sensation to decrease, the pumps were turned off. After five minutes they were turned on again.

The participants wore the cooling vest for as long as it was perceived to provide cooling by the researcher. This was observed by feeling the temperature of the reservoir. Once it felt no longer cool the test was terminated.

The participants were interviewed both during and after wear (see appendix F for the interview questions). During the test they were also asked to continuously be aware of their thermal sensation (perceived temperature of the cooling vest) and their thermal comfort (overall comfort feeling of own body temperature). The participants were also called the next day to find out if they had additional feedback and if they experienced any discomfort afterwards (e.g. muscle pain). The comments and answers of the participants were written down and summarized in the results section.

The factory worker already had experience with other cooling vests of INUTEQ, the warehouse worker did not. The warehouse worker was therefore also asked to put on the PCM COOLOVER, the BODYCOOL PRO and the BODYCOOL SMART. This way these workers could both compare the prototype with existing cooling vests.

13.4 Results

Within this section, first the activities performed by the subjects are described. These are found in the results section, instead of the method, because prior to the test it was unclear which activities the participants were willing to perform. As stated before, the activities were not predetermined, but discussed with the participant to minimize additional risk.

After describing the performed activities, this chapter will continue describing the interview answers and remarks of the participants. These results have been divided into categories to give a more structured overview: cooling, comfort vest, comfort reservoir, comparison to other vests, and suggestions. These categories emerged from an analysis of the interview answers and remarks.

13.4.1 Activities performed

The factory worker walked through the factory hall and replaced a couple of paper rolls in the machine (see figure 161). During this activity, the postures and movements from chapter 4.4.2 also come into play. He Kneeled, bended over, worked with his hands above his head and carried items. Replacing these rolls is a large part of this factory worker's job. Other tasks may include repairs or maintenance, which did not occur on the day of testing, or operating a control panel in an airconditioned room.

The warehouse worker was also willing to perform most common tasks of his job. He drove a reach truck, pallet trucks, and an orderpicker (see figure 162). He also wrapped and unwrapped plastic foil around a pallet (see figure 162). Similar to the test with the factory worker, the postures and movements from chapter 4.4.1 were also observed here. The worker crouched, kneeled and bent over during the pallet unwrap. He sat down in the reach truck and carried boxes in the orderpicker. The worker did not perform deskwork during the test, because he already experienced the effect of sitting down with the vest on in the reach truck.

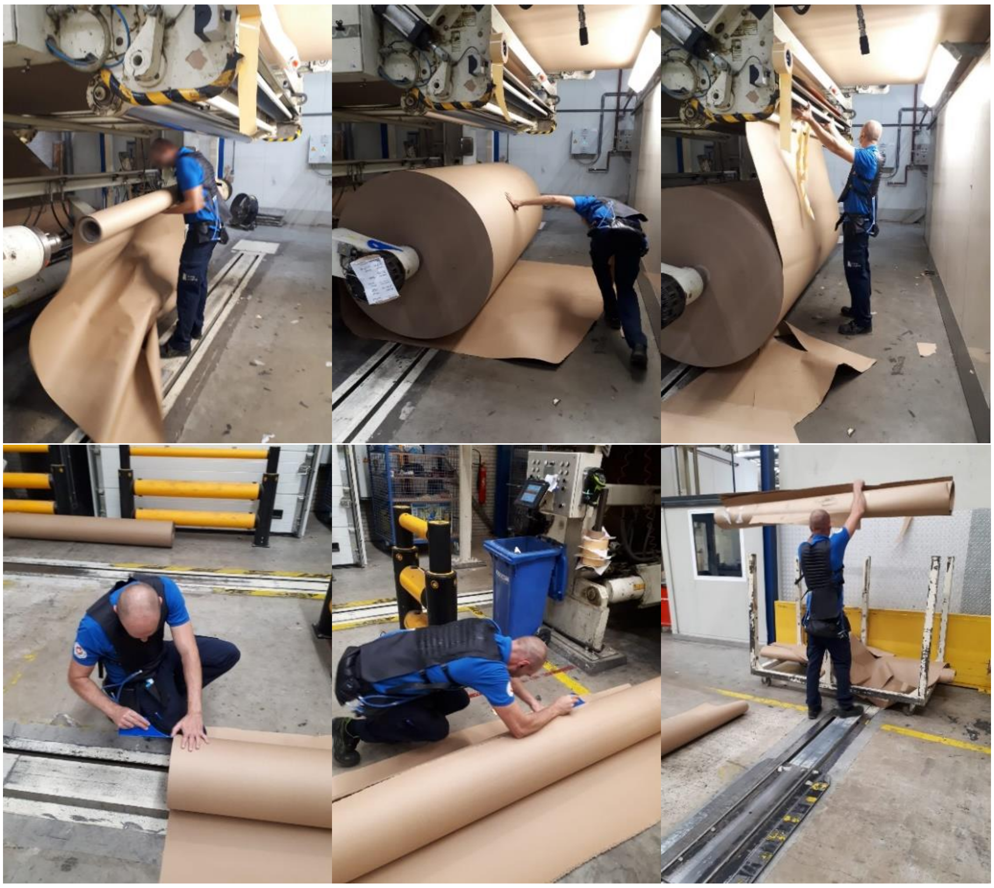


Figure 161: Activities by factory worker

Figure 162: activities performed by warehouse worker

13.4.2 Cooling

At the time of the test, the temperature in the factory was 33 °C and the humidity 40%. The factory worker put on the cooling vest in a cooler canteen of the building. Initially he did not feel the cold that much, but when stepping into the warmer factory hall he immediately felt the difference. Once he performed his tasks he remarked that he noticed less cooling. This was possibly because his mind was on the task and not the cooling, he later stated.

After twenty minutes, the factory worker indicated he did not perceive the cooling as much anymore. The pumps were turned off for five minutes. He then stated that the vest felt warm. The pumps were turned back on, and the test continued. The factory worker's perception of the cooling vest was that it never got as cold as before the break. Five minutes later, 30 minutes into the experiment, the reservoir was deemed no longer cool by the researcher and the test was terminated.

The factory workers cooling experience with the vest was that it was never too cold. It felt pleasant and helped against the heat, but he got used to the cooling quickly. A big drawback was the cooling time. He stated that he would want the vest to cool for two hours to weigh up against the trouble of refilling. The knowledge that refilling the product will be quicker and easier than the prototype, did not change his opinion.

The warehouse test was in different conditions. The temperature of the warehouse was roughly 18-20 °C. The humidity was unknown, but not perceived to be noticeably high. After putting on the prototype the worker described the cooling as nice. He perceived the cooling to be comfortable. After seven minutes he stated that the cooling was chilly and wondered if it would become too much after wearing the vest longer. That did not happen however: twelve minutes into the experiment he still found the vest cold, but not too cold. He also perceived his thermal comfort to go down. He often feels warm, he stated, which was not the case in the vest.

Sixteen minutes into the test, the warehouse worker said he perceived the impact of the cooling to start decreasing. The pumps were therefore turned off at minute seventeen. At minute 22, he stated that he perceived the cooling vest to increase in temperature. One minute later the pumps were turned on again. After some time the worker said he felt the effect of the cooling again, though the sensation was smaller than the initial peak when putting on the cooling vest at the start. The worker had performed all of his tasks, so he was interviewed while still wearing the vest. After 45 minutes the test was terminated due to time constraints. The vest was still perceived to be cold by the researcher, even though all of the ice had melted.

The warehouse worker's overall experience of the vest after wear was positive. He found the temperature in the first five minutes very cold, but never to the point where he would take off the vest. After the break, when the pumps were turned on again, he felt less cooling than at the start, but he found it comfortable. Again the cooling time was a limiting factor. Though the vest was still perceived to be cool after 45 minutes, the vest would probably not stay cool for more than an hour. The worker stated that he found that rather short and that 7 recharges in a day would be a lot.

13.4.3 Comfort vest

The factory worker had some issues regarding the comfort of the vest. When standing or walking, he only had trouble with the reservoir (more on that in the next section). Especially when bending down or kneeling, he found the top of the cooling vest was too tight around his body. When he was standing he said it was fine, and he had no trouble breathing. This would suggest that if the cooling vest was less tight the contact area may decrease.

The warehouse worker was positive about the comfort of the vest. He said the fit was lovely. The straps on the side provided great contact with the cooling pads. The worker also stated that he felt that he was wearing a vest, but that it was not disruptive.

13.4.4 Comfort reservoir

The most comfort related remarks were aimed towards the reservoir. Especially the factory worker had concerns. He already wore another belt for his trousers. He pointed out that the combination between the two was a bit uncomfortable. He also found the weight of the reservoir too high. In the interview after the test he stated that the reservoir was pushing on his tailbone and the belt was too tight when he bended over.

Another concern of the factory worker was the reservoir getting wet during the test (see figure 163). The reservoir was cold because it was filled with ice water. This, in combination with the thin fabric the reservoir is made of, resulted in moisture from the air condensing on the reservoir. The factoryworker remarked that his trousers were getting wet and cold.

The warehouse worker had less issues with the reservoir. He did not experience the same troubles as the factory worker regarding the belt and the weight of the reservoir. He only had issues with the reservoir when sitting in the reach truck (see figure 164). Because of the placement and thickness of the reservoir, he had to sit more forward on the chair. He needed to lean backwards to make his upper back touch the seat, which he found uncomfortable.

Figure 163: Wet reservoir

Figure 164: Warehouse worker on reach truck

13.4.5 Comparison to other vests

Both participants saw value in the wear of a cooling vest, compared to no vest at all. However, their opinions differed on which cooling vest would be the most preferable.

The factory worker drew a parallel between the prototype and the PCM COOLOVER in both thermal sensation and cooling time. He stated that the COOLOVER, and similarly the prototype, do not work for him. The cooling is good, but the vests need to be recharged too quickly. He and his colleagues had done tests before. Their preference was an evaporation shirt directly on the skin (see figure 165).

Figure 165: BODYCOOL T-SHIRT (https://INUTEQ.com/bodycool-t-shirt/)

The warehouse worker did not have experience with other cooling vests. He was therefore asked to put on INUTEQ's BODYCOOL SMART, PCM COOLOVER and BODYCOOL PRO with 21°C packs. He wore each of these vests for roughly ten minutes and was asked to compare them to the prototype.

He found the BODYCOOL SMART to cool too little. This could have been because of the lower temperatures in the warehouse, but when standing outside in the sun (23°C) he felt the same way. He was excited about the high comfort of this vest and was also positive about the ease of use.

A stark contrast was offered by the PCM COOLOVER. The warehouse worker found the cooling comfortable, but less effective than the prototype. He found the vest unpleasant to wear, because the hard elements were uncomfortable. He did not like that he could feel the vest so presently on his body.

With the BODYCOOL PRO, the comfort increased a bit, but the worker still found the hardness of the elements uncomfortable. The comfort of the BODYCOOL SMART and the prototype were still better. About the cooling he said that it was similar to the PCM COOLOVER.

The warehouse worker imagined that he would not like to wear a wet evaporation garment, such as the BODYCOOL T-SHIRT. Especially when working in the reach truck this would become undesirable. The next person would be presented to a wet chair.

Of all the vests the warehouse worker liked the prototype most and would prefer to wear it during his work. Positive points were the tight connection to the body and the (direct) cooling. However, the cooling time of the prototype does need to increase, he stated. Recharging every hour may be a bit too much. 90 Minutes or two hours would be a more workable situation. The BODYCOOL SMART was his second favourite. This was mostly due to the superior comfort compared to the other vests.

13.4.6 Suggestions

The workers had plenty suggestions to improve the cooling vest. One of the main points is that they both want the vest to cool longer. Seven or more recharges a day seemed too much for these men. A more realistic time would be one and a half to two hours. The warehouse worker suggested increasing the size and weight of the reservoir to increase the cooling time.

As stated before, the reservoir was found discomfortable. Subsequently there were many suggestions for improvement. The warehouse worker would like to see a flatter or movable reservoir to make it easier to sit inside the reach truck. The factory worker had more issues with the reservoir, so he suggested more drastic changes. Like the warehouse worker, he wanted the reservoir to be flatter, but he suggested it to be supported by the shoulders. Either that, or completely move the reservoir to the upper back or shoulders. He also suggested to remove the back pad entirely and replace it with a large reservoir. This reservoir could than cool the body, instead of the pad. The factory worker would also like the pad on the front to extend over the abdomen.

Neither participants had any additional comments in the phone call the next day. They did not experience any longer term pain or discomfort from wearing the prototype either.

13.5 Conclusion

Both participants saw the value of a cooling vest during their work. However, It is debatable whether the INUTEQ ICE is the most appropriate cooling vest for workers in factories and warehouses. It depends greatly on personal preference and the conditions of the location. It is clear that the prototype was perceived to give a cold thermal sensation and increased thermal comfort. On the other hand, the cooling time of the prototype was found too short and the initial cooling peak was perceived as rather intense. After the intermittent pump break, the cooling sensation returned, but not as intense as the initial cooling peak. The participants never stated that the cooling diminished due to a compression or blockage of the pad.

The cooling vest itself was perceived comfortable enough to wear and did not hinder the freedom of movement. The reservoir, however, was a point of concern. The strap of the reservoir got uncomfortable when crouching, kneeling and bending over. The reservoir also got wet and cold, which was found uncomfortable by one participant.

The weight of the prototype was disputed. The factory worker found the prototype too heavy, but that could have been because of his discomfortable experience with the reservoir. The warehouse worker suggested a higher weight to increase cooling time.

13.6 Discussion

The results of this study show that there are improvements to be made in the INUTEQ ICE. The largest of which are the increase of cooling time and the increase of comfort of the reservoir.

The cooling time can still be improved in several ways. Firstly, the reservoir needs to be insulated better. In the prototype it is made of a thin layer of fabric. Increasing this insulation not only decreases the heat transfer between the reservoir and the environment, it also decreases or fully stops the condensation on the reservoir. This means the wearer does not get wet and cold from the reservoir anymore.

Additionally, a second solution similar to the previous is increasing the insulation of the pads. Just like on the reservoir, condensation formed on the outside of the pads (see figure 166). The insulation on the outside could be increased to decrease heat exchange with the environment. The insulation on the inside could also be increased. Increasing internal insulation could be a solution in case the cooling vest is perceived to be too cold in a future experiment with a more participants.
A third improvement to increase cooling time could be to increase the size of the ice chunks. Bigger ice cubes filling the same volume have a smaller area than an ice slurry. Thus, the heat exchange between the ice and warmer water exiting the pads is decreased, slowing down the melting rate of the ice. This solution may also lower the initial cold peak when putting on the vest. This solution could even be extended to a situation where the entire reservoir is frozen. In that case the path of liquid water through this reservoir should be carefully considered.
A possible forth way to increase cooling time is to increase the size of the reservoir to carry more ice. This last improvement assumes that the comfort of the reservoir is improved enough to allow for more weight.

It is clear that the reservoir also needs improvement. This is not surprising, as the reservoir was the least thought out aspect of the concept and corresponding prototype. The prototype's reservoir also ended up lower than intended. The reservoir could be improved in several ways considering the remarks of the participants. It could be made movable like in the initial concept, it could be made flatter or be placed in a different location. It also remains unclear whether carrying the weight of the reservoir on the hips or shoulders is preferred. Perhaps a combination would even be possible similar to the heavy tool belt in figure 167.

A test with more participants may also yield more insights and increase the validity of this research. After all, thermal comfort is dependent on many situations and remains a personal preference. This research only had one participant who worked in hot conditions at the time of the test. More workers in hot conditions may have different preferences or work with different equipment, which could yield a more complete view of the advantages and shortcomings of the prototype.

Once the design improvements have been implemented in a new prototype, a quantitative study should be executed to determine if the cooling intensity ,especially at the start, is not perceived too high. The effects of long term wear (full work day) should also be studied to find what the long term effects of the cooling, weight and comfort are.

Figure 166: Condensation on the pad

Figure 167: Toolbelt with shoulder support
(eBay, N.D. C)

14 Cooling capacity

In the user test, the *perceived* cooling experience was found. The results do not say anything about the actual cooling capacity of the INUTEQ ICE. After all, Thermal comfort is down to personal preference and *perceived* cooling power differs per person. The cooling capacity is the amount of heat the vest is able to remove (in Watt). The true cooling capacity needs to be measured to find how much cooling this project's concept offers compared to existing vests. An experiment was therefore setup to find and compare the actual cooling capacity of different cooling vests.

One of the goals of this project was to improve the heat exchange between the vest and body, compared to existing water perfused garments. This research therefore tests the difference between a prototype cooling pad from this project (from here on described as "Pad") (see figure 168) and a representation of an existing water perfused cooling vest (from here on described as "Tube") (see figure 169). One participant from the user tests also *perceived* a similarity between PCM vests and the prototype. A 21°C PCM pack was therefore also tested (see figure 170). Measurements of a 6.5°C and 15°C PCM pack were already made by Joost Schootstra (Schootstra, 2020) (see graph 2) and are compared to the prototype also.

Graph 2 shows the measurements of 6.5°C and 15°C PCM packs. This graph has the time on the horizontal axis and the cooling power on the vertical axis. This cooling power is the amount of energy that is absorbed by a 15x15cm^2 PCM pack per second. The graph shows horizontal plateau's. These plateaus occur during the melting period of the PCM. Once the PCM is fully molten, the cooling power quickly decreases. In general, the lower the cooling power of the plateau, the longer the cooling time. It is expected that the graph of the INUTEQ ICE cooling pads will also show a plateau, because ice is used as a PCM in the concept. That will not be found in this experiment, however, because here the cold water is provided by a cooling thermostat (see method). If measurements with ice are done, the dimensions of the plateau greatly depend on the size of the reservoir, amount of ice, insulation of the reservoir and the conditions of the environment around the reservoir. The cooling thermostat was used to make measurements independent of these factors.

14.1 Goal

This research aims to find the difference in cooling capacity between this project's cooling pads and their most comparable existing cooling solutions. These solutions are a liquid perfused suit made of tubes and different PCM packs.

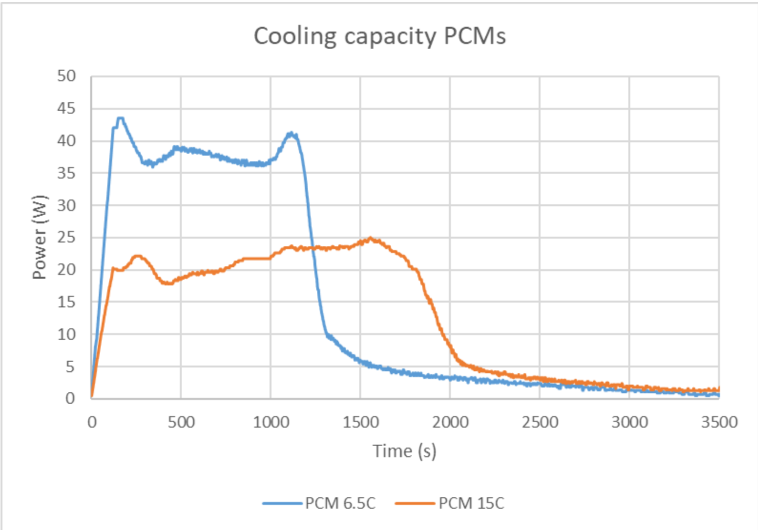
14.2 Research questions

- What is the difference in cooling capacity between samples of a water perfused cooling suit, PCM cooling vests and the INUTEQ ICE?
- What is the effect of the temperature of the water flowing through the two water perfused samples?
- What is the effect of the flowrate through the water perfused samples?

Figure 168: Prototype cooling pad sample

Figure 169: Tube sample

Figure 170: PCM pack sample



Graph 2: PCM pack measurements (Schootstra, 2020)

14.3 Method

The cooling capacity was measured with a hotplate (see figure 171). This $15x15cm^2$ plate heated itself up to a certain temperature and measured the energy it took to stay at that temperature. In this research, a temperature of 35°C was selected to represent skin temperature. The plate was surrounded by four plates that also heated up to this temperature. Their temperature was not measured. This was to avoid heat loss at the sides of the centre plate.

The samples were placed in the middle of the hotplate. Rubber bands were used to secure the samples and keep them flat on the plate (see figure 172). The samples were then covered with Styrofoam as insulation. The Styrofoam prevents heat exchange with the air (see figure 173). Lastly, the Styrofoam was covered with a glass plate to minimize gaps and keep it from shifting (see figure 174).

The two water perfused samples were connected to the pump from the prototype used in the user test (RS Pro M400). A manometer (see figure 175) was connected to the entrance of these samples to read the pressure flowing in (similar to resistance tests of chapter 9.5). The cooling capacity of three pressures was measured: 60, 80 and 100mBar above atmosphere. Higher pressures would have the risk of delaminating the prototype pad, while any lower pressure would result in a miniscule flowrate through the sample with the tubes. The cooling capacity was also measured at three different temperatures: 5, 10 and 15°C. The water was cooled by the LAUDA Alpha R8 (see figure 176). The temperature of the water flowing in and out were measured with a thermocouple (see figure 177). The flow was measured as a control: the outflowing water was caught in a measuring cup for one minutes and weighed afterwards to find its volume (see figure 178). Two pads with three pressures and three temperatures resulted in 18 measurements of cooling capacity. These measurements took 2-4 minutes each. This time is irrelevant, because with a constant pressure (so also constant flow) and constant water temperature, the cooling capacity should also be constant.

The cooling capacity of PCM changes as it melts. The PCM test, therefore, took longer. Due to time constraints, the test was terminated after just over 30 minutes. This was enough to identify a “plateau” in cooling capacity (see results). The PCM was frozen as flat as possible between two glass plates, covered with a weight (see figure 179). This was done to maximize the contact area between the PCM and the hotplate. The earlier measured 6.5°C and 15°C PCM were compared to the prototype pad with 5°C and 15°C water respectively. The 21°C PCM was also compared to the prototype pad with 15°C water, because the temperature difference is the smallest.


Figure 171: Hotplate


Figure 172: Sample on hotplate


Figure 173: Styrofoam cover

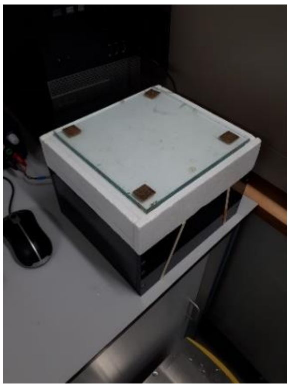


Figure 174: Glass plate for weight

Figure 175: Manometer

Figure 176: LAUDA Alpha R8 cooling thermostat


Figure 177: Thermocouple


Figure 178: Water weighing


Figure 179: Freezing pack flat

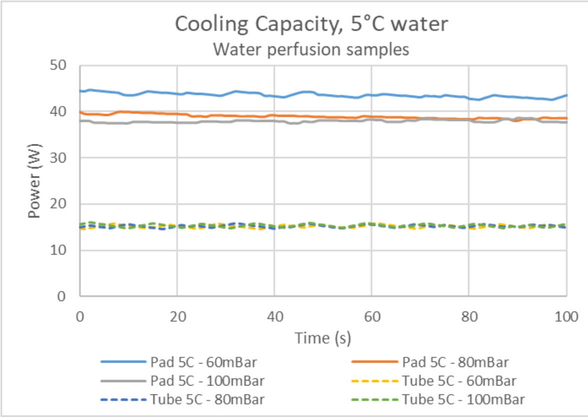
14.4 Results

14.4.1 Comparison with tube sample

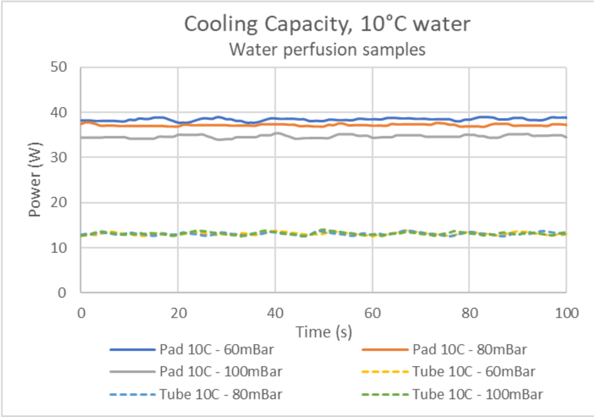
Graphs 3, 4 and 5 show the cooling power of the water perfused samples with water of 5, 10 and 15°C respectively. The measurements of the different pressures are presented by the different coloured lines. As expected, the lines follow a horizontal path, because the cooling capacity is expected to stay constant with unchanging water temperature and pressure. Not all measurements had the same length, so the first 100 seconds are presented. It can clearly be seen in all three graphs that the prototype pad sample was measured to have nearly three times as much cooling capacity as the tube sample. This means more than three times as much heat is extracted by the same area of the prototype pad compared to an existing cooling vest with tubes.

It was expected that a higher flowrate would result in a higher cooling capacity, because the water heats up less between the entrance and exit of the pad. The pad should, therefore, extract more energy near the exit, as the water is colder there at higher flowrates. However, The highest measurement of cooling capacity was the prototype pad with 5°C water with a pressure of 60mBar above atmosphere. Moreover, the tube suit does not seem to differ in cooling capacity at all with different flowrates. Graph 6 shows the average cooling capacity of each measurement of the prototype pads plotted against the measured flowrate of each combination. Contrary to the expectation, it can be seen that the cooling capacity slightly decreases with a higher flowrate. It was also found that the flowrate of the tube sample was considerably smaller than the flowrate through the prototype pad. A table with the flowrate and water temperature change of each measurement set can be found in appendix G.

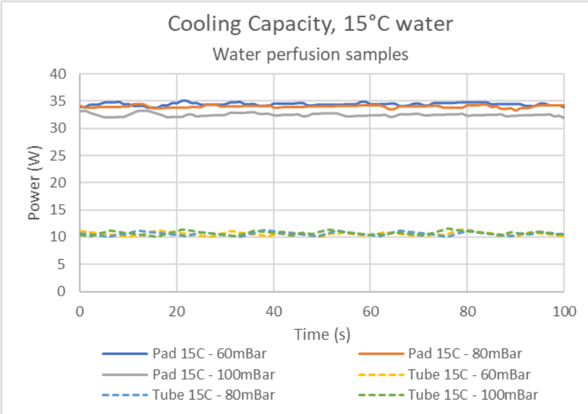
It was also expected that the cooling power would increase if the water temperature decreased. Graph 7 clearly confirms that expectation. Because the water inside the INUTEQ ICE is cooled by ice, the water could, in theory, be as cold as 0°C. It could then have an even higher cooling capacity. The graph features a linear trendline based on the 60mBar foam pad data. This shows the cooling capacity may reach up to 48W in 15x15cm^2. In practice, however, the water will probably not reach a temperature of 0°C inside the pads. No freezing of the tubes was observed in the four times the vest was completely filled with ice. The trendline in graph 7 is also extended forward to 21°C to compare with the 21°C PCM. The trendline shows a cooling capacity of roughly 28W at 21°C.



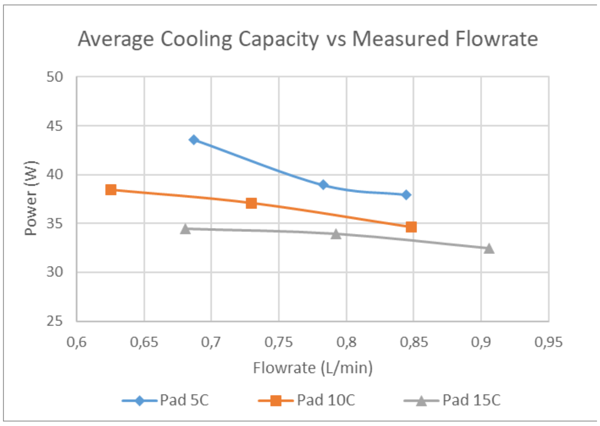
Graph 3: Cooling capacity foam pad vs tube sample, 5°C water



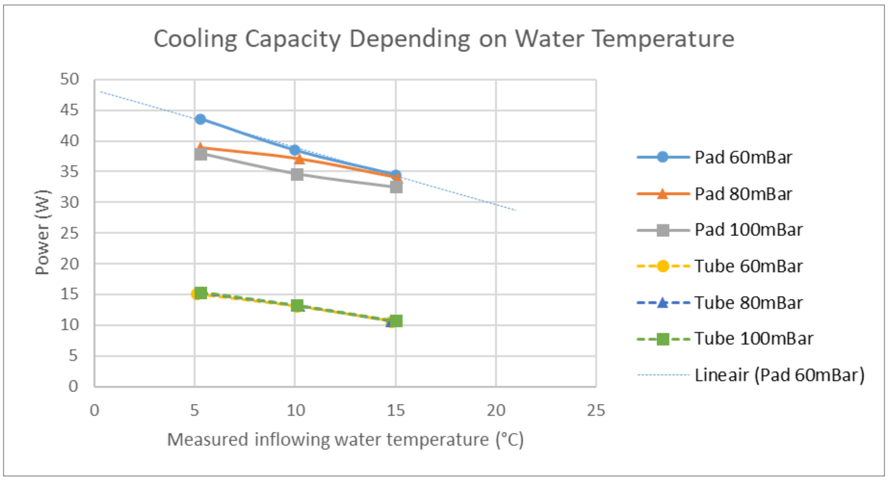
Graph 4: Cooling capacity foam pad vs tube sample, 10°C water



Graph 5: Cooling capacity foam pad vs tube sample, 15°C water



Graph 6: Cooling capacity vs flowrate



Graph 7: Cooling capacity depending on inflowing water temperature

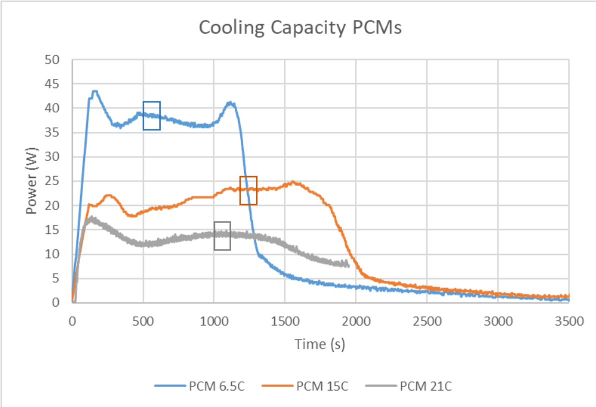
14.4.2 Comparison with PCM

The 21°C PCM pack was measured. The cooling power is presented in graph 8, together with the earlier measurements of a 6.5 and 15°C pack. Due to time constraints, the measurement of the 21°C was terminated early. The graph does show a horizontal plateau at roughly 13W. It can be seen that in generally, the higher the cooling capacity, the shorter the cooling time. The 6.5°C PCM is shown to have the highest cooling capacity, but is already fully melted after 1200 seconds (= 20min).

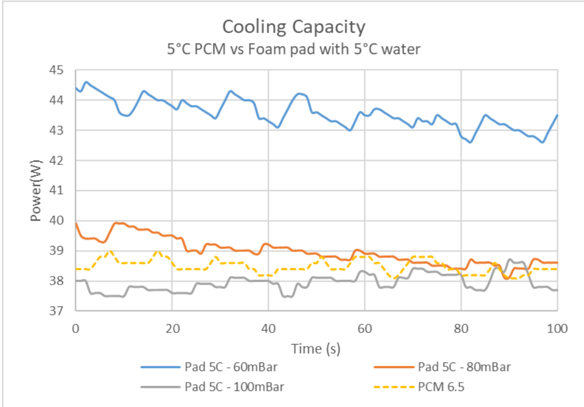
The PCM measurements were substantially longer than the prototype pad measurements. To compare the two, a section of the PCM measurements was taken. In the graph this section is indicated by the three rectangles. These timeframes were chosen as a representation of the height of the plateaus.

Graphs 9, 10 and 11 show the comparison in cooling capacity between the PCM packs and the prototype pad. It can be seen that the 6.5°C PCM pack had a similar cooling capacity to the prototype. However, In graph 7 (previous page), it was found that the foam pad with 0°C water may reach 48W, which is 10W higher than the 6.5°C PCM pack. The other two PCM's were measured to have substantially lower cooling capacities, even compared to the prototype pad with 15°C water running through.

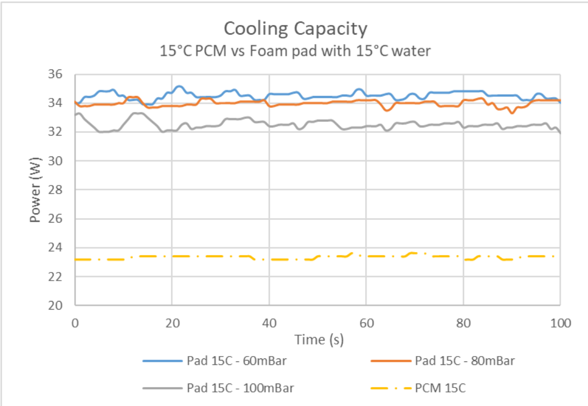
In graph 7 (previous page), the trendline of the cooling capacity of the foam pad was extended to 21°C to better compare it with the 21°C PCM. The trendline shows a cooling capacity of roughly 28W at 21°C. The cooling capacity of the 21°C PCM pack plateau is roughly 14W (see graph 11), which is half the amount of cooling capacity compared to the prediction of the foam pad.



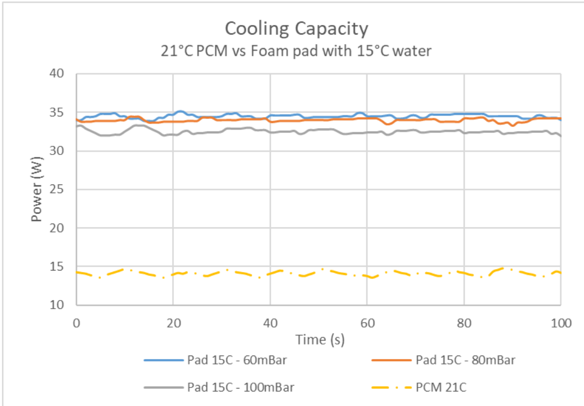
Graph 8: *Cooling capacity PCM's*



Graph 9: Cooling capacity 5°C water foam pad vs 5°C PCM



Graph 10: Cooling capacity 15°C water foam pad vs 15°C PCM



Graph 11: Cooling capacity 15°C water foam pad vs 21°C PCM

14.5 Conclusion

The measurements have shown that the cooling capacity of the prototype is relatively high compared to other cooling vests. It is able to extract nearly three times as much heat from the same area as an already existing water perfused cooling vest with tubes. It can provide intense cooling as high as a 6.5°C PCM pack and has a higher cooling capacity than the other PCM options. No correlation between the flowrate and the cooling capacity was found, but the flowrate of the prototype pad was found to be considerably larger than that of the tube sample. The water temperature was shown to have an effect. The colder the water, the higher the cooling capacity. When the graph was extrapolated to 0°C, the pad with 60mbar of pressure may be able to reach 48W of cooling power in the tested area.

14.6 Discussion

It was found that the cooling capacity of the prototype pad was nearly three times higher than the tube sample. This means the cooling of a cooling vest can be more intense and more concentrated on the body. Tube covered cooling vests often cover large areas in tubes to increase cooling capacity. The INUTEQ ICE could reach the same or higher cooling capacity with a much smaller surface concentrated in the areas of high cooling effectiveness (see chapter 6.3).

The cooling capacity is similar to that of the 6.5°C PCM pack. However, the water temperature of INUTEQ ICE may be lower than 5°C. It was shown that a lower water temperature increases the cooling capacity. The cooling capacity of a foam pad with water cooled by ice may reach 48W during a test similar to this test. That would be 10W higher than the 6.5°C PCM. In addition to that, with good insulation and a large enough reservoir, the cooling *time* of the INUTEQ ICE could probably be superior to that of the 6.5°C PCM vest. In the user research it became clear that the prototype cooled for 30 minutes in similar conditions to this test. A direct comparison may not be valid. It does provide an indication, considering the prototype could also still be improved on several aspects (mentioned in chapter 12.5.6 and 13.6). The only downside compared to a PCM vest would then be the weight of the INUTEQ ICE, which is twice that of the PCM vests.

No definitive correlation between the flowrate and the cooling capacity was found in this research. Further research may prove differently, but it is questionable whether this would result in a significant improvement for the cooling vest. The flowrate of the tube vest was shown to be substantially smaller than that of the prototype pad. This means that the prototype is not only able to extract the same heat with a smaller area, but it also needs less pumping per unit area of cooling surface. These two factors combined allow for a much smaller pump and battery to provide the same or more cooling, which makes the INUTEQ ICE lighter and more wearable. The possibilities of pump size are already clear in the prototype see (chapter 12.3). Less weight also means the possibility exists to carry more ice than in a tube covered vest, increasing the cooling time.

15 Final concept

Some aspects of the concept have changed due to results in the evaluation phase. Therefore a final concept was drawn. The changes compared to the original concept are based on insights from building the prototype, the user test and the cooling capacity test. The improvements visible in the drawing are:

- Change of the pad: the downwards strip is replaced by a tube. This tube is drawn covered by black fabric on the front and light fabric on the back.
- The reservoir is changed from a hard case to a flexible bag.
- The carrying belt of the reservoir goes fully around the body.
- The zipper is straightened.
- The previous two points required reshaping the cooling pad on the front.
- The cooling pads are sown into the garment instead of being part of the larger fabric pieces.

Some of the improvements cannot be captured in a drawing and/or have to be tested to confirm their effect. These improvements include:

- The connectors have been changed (but will possibly change again to make the connection neater).
- The tubes have increased size to 6mm.
- The insulation of the pads and reservoir needs improvement.

INUTEQ ICE

15.1 Desirability

The user test and cooling capacity test combined can give a good indication of the desirability for the INUTEQ ICE. From INUTEQ's sales, it becomes clear that there are lots of factory and warehouse workers who want to wear a cooling vest. What remains undiscussed is why they would choose the INUTEQ ICE in favour of other cooling options. This section discusses the advantages and disadvantages the INUTEQ ICE offers, compared to other cooling vests currently on the market. The benchmark of chapter 6.1 offers an overview of the different cooling garments that already exist.

A good starting point is perhaps the active PCM garments. This category houses tube covered cooling vests, which pump ice cooled water around the body. This project aimed to improve these vests with a new concept. The cooling capacity test has shown that the INUTEQ ICE has a cooling capacity nearly three times as high as a vest with tubes. Cooling can therefore be more intense and concentrated in the areas where cooling is needed. This will possibly result in more freedom of movement compared to a tube covered garment. The INUTEQ ICE will also require a smaller pump and battery to gain the same result, making it less cumbersome to wear. The user research has shown that freedom of movement and comfort was one of the most important aspects for workers to wear a cooling vest.

Passive PCM vests are familiar for INUTEQ. Similar to PCM vests, the INUTEQ ice is able to still work in humid conditions. The INTEQ ICE is shown to have a higher cooling capacity than most PCM alternatives. Only the 6.5°C PCM pack showed a similar cooling capacity, but the INUTEQ ICE has the potential to cool for longer. As stated in chapter 10.1, ice can store more latent heat than other PCMs. Especially if the improvements of chapter 12.5.6 and 13.6 are applied the INUTEQ ICE is expected to cool for longer than a 6.5°C PCM vest. As discussed in chapter 11.4, the envisioned charging process for the INUTEQ ICE is also significantly shorter than that of a PCM vest. A secondary reservoir, to charge while using the other, will also probably be cheaper than a second set of PCM packs. For factory and warehouse workers, this means they can quickly recharge their cooling vest without taking it off, which increases the willingness to wear the cooling vest. The only downsides of the INUTEQ ICE compared to a PCM vest are the higher weight and larger size, due to the reservoir. As discussed, the comfort and freedom of movement is important for these workers.

INUTEQ also sells evaporation based cooling vests. These vests are expected to cool longer, and are more comfortable. However, they are heavily dependent on the environmental conditions. With a humidity over 50% their cooling capacity starts decreasing and at 80% the function stops altogether. The cooling capacity was also perceived to be lower than the prototype in the user research. A wet shirt directly on the skin may cool more than a dry evaporation vest, but not all workers are willing to wear a wet shirt all day, especially if they have to share seats, e.g. in shared vehicles.

Air ventilation cooling garments have the same downsides as evaporation vests. They depend on evaporating the sweat of the wearer, which becomes less effective at a higher humidity. Some of these options also require a source of external air, which means the wearer is tethered. That is a clear disadvantage for factory and warehouse workers who have to walk around during their job. Other types of tethered cooling vests are unsuitable for the same reason.

The INUTEQ ICE has some clear advantages over other cooling garments. In the right conditions it can even potentially be considered the most suitable choice for factory and warehouse workers. It comes down to personal preference whether people find the weight and freedom of movement acceptable enough, but these aspects are not extremely out of proportion compared to other vests. The INUTEQ ICE is especially a large improvement over other liquid circulating cooling vests and can be a valuable addition to INUTEQs product range.

15.1.1 Opportunities

This project focussed on a target group of factory and warehouse workers specifically. However, the INUTEQ ICE could be suitable for a whole range of other target groups. This subsection discusses the opportunities the INUTEQ ICE provides.

Especially in hot and humid conditions, the INUTEQ ICE performs better than other cooling vests. One of the biggest opportunities is, therefore, to wear it underneath an enclosed suit. Firefighters, Explosive Ordnance Disposal Service, surgeons, people who have to wear chemical/heat isolation suits or even theme park entertainers all have to work in hot suits with little to no ventilation. Due to their sweat, the air inside the suit can also quickly become saturated with humidity. The INUTEQ ICE could therefore be a highly suitable solution to keep these workers cool.

Within the Netherlands, a good example of hot and humid conditions can be found in greenhouses. The workers there have to work in highly humidified air, which is good for the plants. Similar conditions are also experienced by zookeepers having to clean enclosures of tropical animals. In general the humidity is usually high in the Netherlands. On hot summer days, people doing physical work could benefit from the INUTEQ ICE. One example could be waiters and waitresses working on terraces. Construction workers laying asphalt are subjected to even higher temperatures, because of the heat radiating from the freshly laid asphalt. All these people could benefit from the INUTEQ ICE. The only extra thing they would need is a freeze, which could be placed in the canteen, for example.

Outside of the Netherlands it is clear that the possibilities become endless. Countries with tropical climates will have many workers who could benefit from the INUTEQ ICE. INUTEQ provided cooling vests for the Olympic games in Tokyo, for example. In the case of pre-workout cooling the INUTEQ ICE may also play a role in such markets. INUTEQ could even think about bigger external reservoirs to place on the ground. Users would then be tethered, but for stationary work this could provide intense long term cooling for longer periods of time.

A completely different opportunity that a water perfused cooling vest has, is that it could also circulate warm water. By using warm water, the INUTEQ ICE suddenly becomes a heat vest. (The name should perhaps be reconsidered in this case.) This would be ideal for surgeons, who sometimes have to operate in a warm- and sometimes in a cold environment. A way to heat up the water would still need to be figured out, should INUTEQ want to pursue this direction.

In conclusion, the INUTEQ ICE has plenty of directions to expand its target group. With a few small additional extras, the possibilities become even more plentiful.

15.2 Recommendations

The main goals of this project were to investigate if a water perfused cooling vest with cooling pads would be an improvement over other solutions and to find out if this vest would then be suitable for factory and construction workers. Both these statements can be answered positively. The INUTEQ ICE has a high cooling capacity and given the right circumstances, it has the potential to be more suitable than other cooling vests. This is also true for factory and warehouse worker. However, the INUTEQ ICE is still only a concept and still needs development to become a proper product. This chapter discusses the next steps that need to be taken.

INUTEQ does not have a full time development department, so another student/graduation project could be considered for the following suggestions. When moving further towards production, a professional designer should be hired to pick up the project.

The reservoir needs to be further developed. The reservoir has already been adjusted in the final prototype, but this was not tested. It became clear during user testing that the reservoir was the main point of concern for the participants. A new prototype of only the reservoir could be made to quickly review the entire concept again with a new user test. This new test could feature more participants to get a better overview of the preferences regarding the cooling intensity. For some people the initial cooling spike may be too cold. In that case the cooling pads need a thicker inner lining. In this new user test, the weight could also be better evaluated.

The INUTEQ ICE needs proper insulation. The condensation on all cooling parts of the cooling vest was an indication that it was losing a high amount of cooling capacity to the environment. The reservoir is once again the main part to be improved in this regard, which is not surprising considering it is the coldest part of the cooling vest. By incorporating the insulation in a prototype, the cooling time can be better evaluated. A more realistic cooling time estimation can serve as a proper go/no go moment on further developing the project. The full value of the concept is then known and its placement in the product range can be determined.

If the project is continued, the recharging process should be developed. In this project it became clear that there are multiple recharging scenarios depending on the size of the company and the work environment. It should therefore be considered whether a single recharging process is going to cover most scenarios. The idea of a recharging station was conceived during this project, that would be a more long term project. It would probably require a full time designer working for INUTEQ to design such a station.

A pressure relief valve needs to be found or created. The problem is that 100mBar is not a pressure where pressure relief valves are commonly used. Most systems can withstand higher pressures. Luckily, a pressure relief valve is not overly complicated. They are basically a valve with a spring inside. Perhaps an existing relief valve could be used with a weaker spring.

The weakest link in structural integrity was still the bond between the foam and the fabric. A denser foam could be considered, to increase the bonding strength. A denser foam would add more resistance, but the current foam inside the pads did not add any significant resistance at all. A balance between resistance and structural integrity could therefore be investigated. Another way to improve structural integrity, could be to develop a fabric with a thicker TPU layer. The thicker TPU would hold on to the foam better, but also decrease heat exchange. Decreased heat exchange might be useful if more people find the initial cooling peak too cold. Less heat exchange will also increase cooling time, so again there is a balance to be found there. Together with an external partner, INUTEQ has developed fabrics before for the BODYCOOL SMART.

A promising addition for the INUTEQ ICE is the introduction of intermitted (=periodic) cooling. In the user tests this was already experimented with. The thermal sensation of a cooling vest starts to drop after 20-30 minutes, while the vest is still working. Intermitted cooling could be applied by turning the pump on and off every so often. When the pumps are turned off, the water inside the pads heats up. When the pumps are then turned on again, the user experiences the cold sensation again. Intermitted cooling could be done on a time base (e.g. 20min on 5 min off), or on a temperature base. INUTEQ has already stated that the ultimate goal is to have a cooling vest with sensors to measure environmental- and skin temperature and a cooling system that reacts accordingly. The INUTEQ ICE could be designed to have these functions.

Another way to notify wearers whether the vest is still cooling is by means of thermochromic paint. Thermochromic paint changes colour once the temperature changes. The user could therefore get visual feedback on the activity of the cooling vest.

Lastly, The complete manufacturing process needs to be developed. Melting all the parts of the cooling pads together may be a challenge, but should be doable with a heat press. Apart from that, the textile work (including details) needs to be finalized. The patterns of the cooling vest need to be redrawn, the materials need to be chosen and decisions need to be made on the stitching.

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DESIGN FOR our future

TU Delft

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT
Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy".
Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name	Fazzi 4694
initials	S. A.
given name	Sergio
student number	4458826
street & no.	
zipcode & city	
country	
phone	
email	

Your master programme (only select the options that apply to you):

IDE master(s):	★ IPD / ◯ Dfl / ◯ SPD
2nd non-IDE master:	
individual programme:	- - (give date of approval)
honours programme:	◯ Honours Programme Master
specialisation / annotation:	◯ Medisign
	◯ Tech. in Sustainable Design
	◯ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair	Prof. dr. ir. Jansen, K.M.B.	dept. / section:	SDE / EM
** mentor	Ir. Eur.Erg. Hoekstra, G.P.M.	dept. / section:	HCD / AED
2nd mentor	Rein Bokslag		
	organisation: Inuteq		
	city: Deventer	country:	the Netherlands
comments (optional)			

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

TU Delft

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Prof. dr. ir. Jansen, K.M.B. date 10 - 02 - 2021 signature Kaspar Jansen

Digitally signed by Kaspar Jansen
Date: 2021.02.10 15:52:24 +01'00'

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 27 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 27 EC

List of electives obtained before the third semester without approval of the BoE

(★) YES all 1st year master courses passed

( ) NO missing 1st year master courses are:

name J. J. de Bruin date 10 - 02 - 2021 signature J. J. de Bruin, SPA

Digitally signed by J. J. de Bruin, SPA
Date: 2021.02.10 16:37:57 +01'00'

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: (★) APPROVED ( ) NOT APPROVED

Procedure: (★) APPROVED ( ) NOT APPROVED

comments

name Monique von Morgen date 16 - 02 - 2021 signature

Initials & Name S. A. Fazzi 4694 Student number 4458826

Title of Project Design of an active liquid cooled garment for workers in hot conditions

Personal Project Brief - IDE Master Graduation

TUDelft

Design of an active liquid cooled garment for workers in hot conditions — project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 08 - 02 - 2021   20 - 07 - 2021 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Doing heavy physical work in the heat will cause a workers body temperature to rise. Overheating of the body (hyperthermia) can negatively influence productivity, performance, comfort and safety. A prolonged exposure to these conditions can even lead to thermal injuries. Due to climate change and the subsequent rise in global temperature, this problem will increase over time and become relevant for a bigger portion of the worlds population.

A possible solution for this problem is a personal cooling system integrated into a garment. This project will therefore be done in collaboration with Inuteq, a company that specializes in cooling garments (mostly vests) for professional, sports, leisure and militairy purposes. Current technologies that inuteq uses are all passive, using either water evaporation or phase changing material (PCM) pads that have to be cooled in the refrigerator. The limiting factors of these solutions are the two hour cooling time and the usability: Users fill up the water vests too full or don't refrigirate the PMC pads correctly (feedback given to Inuteq).

Together with Inuteq it has been decided that the target group for the project will be factory and construction workers. The design therefore needs to be worn outside and inside. Currently, inuteq already sells to this targetgroup. Mostly in the Middle East, where temperatures are higher than in Europe. With temperatures rising, it is expected that the demand in Europe will also increase. These workers conduct heavy work and require freedom of movement which will be taken into account in the new design.

The SDE department has been doing research into active cooling integration into garments. It was found that cold liquid flow is a promising technology for effective long lasting cooling. Shirts and vests using liquid cooling are already sold on the market. However, these products have lots of tubing, a big pump and a bulky heat exchange box, which make them inefficient and unpractical (see figure 1).

A prototype of a liquid cooling shirt for rowers was recently developed at the TU Delft (see figure 2). It uses open foam pads to increase the effect of liquid cooling. The water flows through channels in the foam after which it will spread out inside it. This technique is promising with a greater contact area than products on the market, so the prototype will serve as a starting point for this project. In the current prototype, the water cooler and batteries are external. The water was circulated using the rowers movement. In the new design a pump probably needs to be added to take over this function. The pump, batteries and water cooler all need to be integrated in the design. The design needs to be wearable with enough freedom of movement, low enough weight and be safe to wear.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: Liquid cooling system currently on the market (source: https://www.ebay.com/c/668577771)

image / figure 2: Current prototype with open foam pads

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Construction and factory workers have to work in hot conditions (both outside and inside), which negatively influences productivity, performance, comfort and safety. A personal cooling garment could serve as a solution to this problem. However, current products do not function long enough and are not user friendly enough for this target group.

The recently developed prototype from the TU Delft shows promise, but is far from being a usable product for construction and factory workers. The issues that need to be adressed are as follows:
- The size and shape of the foam elements were determined specifically for rowing. Rowers perform a low range of motions at high intensity, while construction workers use a wider range of motions. Their cooling needs may therefore differ. In the new design the pad configuration has to be reevaluated to fit the cooling needs of heavy fysical work.
- The water was pumped around using the rowers body movement. The movement range during work is more diverse than rowing, so a new circulation system needs to be added to circulate the water.
- This circulation system, together with the cooling solution and a battery, needs to be wearable. Freedom of movement and comfort during wear need to be taken into account for these items.
- A cooling solution needs to be found that can release the heat of the water to a warm environment, whilst also being close to the body.
- The entire garment needs to be durable enough for factory and construction proffessions. Especially the electrical components and water system need to be highly damage resistant when lifting heavy items and working with machinery.
- The aesthetics of the new garment needs to be desirable for the targetgroup.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

Research needs to be done on the size, shape and placement of the foam pads to find the most effective and comfortable cooling configuration for the given situation. Then, the flowrate and amount of heatexchange needs to be determined to select the electrical components. Ergonomic user research will help to determine the place of these components on the body.

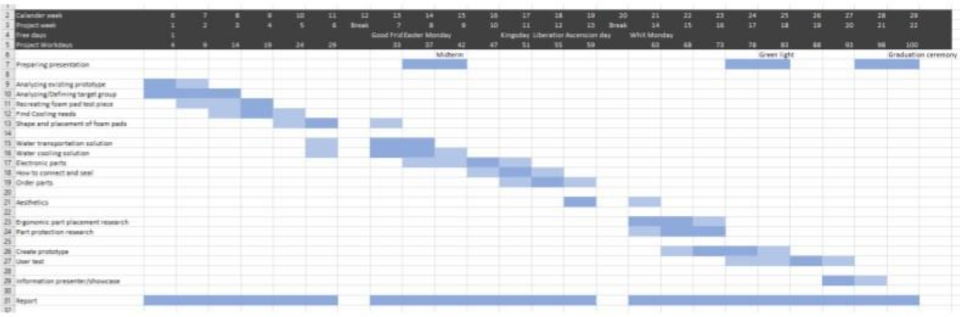
The outcome of the project is expected to be the design of a cooling garment in combination with a working prototype. This prototype will be tested to prove that it does work and is also comfortable enough to wear during heavy physical work in hot conditions. Proven components in the design will be the water circulation and cooling system, the comfortable placement of components, the safety during wearing and the willingness of workers to wear such a garment.

The feasability of the product can be directly evaluated by research and prototyping of the components of the garment. A statement about the products desirability will be made by doing a user test with the prototype. In this user test, the comparison of comfort will be made between physical work in the heat with and without the prototype. And the viability can be determined together with inuteq by looking at costs and an expected price for the garment.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 8 - 2 - 2021 20 - 7 - 2021 end date



The first 6 weeks will be a research phase. Then 9-10 weeks of design phase, followed by 6 weeks of evaluation phase. This period contains 22 weeks because there are some scedualed holidays in the planning. There are 100 total project workdays.

Meetings with chair and mentor will generally be helt on a weekly basis. The project may require more or less input from the chair and/or mentor at times. In that case these meetings scedule will change accordingly. Meetings with employees of Inuteq will be held whenever necessary.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

During this project I expect to make a lot of prototypes. This is an opportunity for me to increase my prototyping skills. I feel that the development in 3d printers have limited the attention towards other prototyping techniques. Therefore I hope that during this project I get the chance to widen my skillset. The biggest prototyping challenge I see in this project is working with textiles. I have never worked with these materials and cannot operate a sowing machine. However, textiles are not often used at IDE, so it may become knowledge I can use to distinguish myself as a professional designer.

If succesful, this project will be the last one I will do before I start my career as design engineer. I expect that this project determines, more than previous projects, the early career path I will take. I therefore want to pay extra attention during this project to find the aspects of industrial design engineering that I like. Part of this exploration is organising my own project. The graduation project is the first time I am going to lead a project all by myself. It will be interesting to see how I handle such a responsability.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

B – Measuring Resistance of the Pads

It was assumed that the foam pads are the parts with the greatest resistance, as they were in Stewart's prototype (2017). To measure the foams resistance, 3 pads with different lengths were made of 10 PPI and 20 PPI foam (see figure 180). The pads were 50, 100 and 150 mm long, 30mm wide and 10 mm thick. The resistance of the tubing and connectors could be found by extrapolating the resistance of these three lengths to the resistance of a foam piece with zero length. Subtracting the tube resistance from the total resistance gives the resistance of the foam. The pressure and flow were measured similarly to previous experiments: a manometer was placed before the pad to measure pressure difference (see figure 181) and the flow was measured with a measuring cup. The pump was set to 50, 75 and 100 mBar above atmosphere. For each test pad two measurements were made of each pressure, so a total of six measurements were made for each pad. It was hypothesized that longer pads and denser foam (20 PPI) would have higher resistance resulting in a lower flow at equal pressures.

Figure 180: Different lengt pads

Figure 181: Measuring pressure

The method and hypothesis were tested by replacing the pads with a thin tube (see figure 183). The flow through this tube was measured at 100 mBar of pressure difference. Then it was cut shorter to lower the resistance and the flow was measured again. Two cuts were made resulting in three measurements (see table 4). Table 4 shows the clear increase in flow when the tube gets shorter, validating the method.

Figure 182: Two sizes of tubes

Figure 183: Connected tubes

Table 4: Flow through thin tube at ΔP = 100 mBar

Length	Flow (L/min)
Original	0.46
Cut 1	0.53
Cut 2	0.68

The measuring started with the 50 mm pieces of the 10 PPI and 20 PPI foam. The results of which can be found in table 5. In this table it can clearly be seen that the flow measured through the 10 PPI pad is nearly identical to the flow through the 20 PPI pad. This result would suggest that the difference in resistance of these two foam types does not influence the flow.

Table 5: Flow (L/min) through 50 mm pads

L = 50 mm	ΔPressure (mBar)		
Density	50	75	100
10 PPI	0,7	1,01	1,26
	0,725	1	1,265
20 PPI	0,7	1,01	1,23
	0,705	1,02	1,27

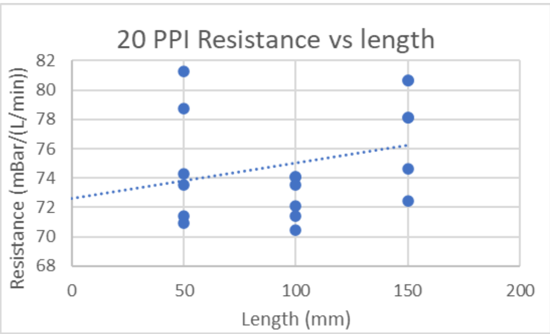
Because of the notable results of the two 50 mm pieces, the experiment was continued with the 20 PPI foam pads. The other two 20 PPI foam pieces were tested and together with the 50 mm pad their results can be seen in table 6. Using Ohm's law the pressure (ΔP) was divided by the measured flow (Q) to give six values for the resistance (R) of the pads ($R = \frac{\Delta P}{Q}$). Table 7 shows these outcomes, which are plotted in graph 12.

Table 6: : Flow (L/min) through 20 PPI pads

20 PPI	Pressure (mBar)		
Length (mm)	50	75	100
50	0,7	1,01	1,23
	0,705	1,02	1,27
100	0,71	1,02	1,35
	0,7	1,04	1,35
150	0,67	0,96	1,24
	0,69	0,96	1,24

Table 7: Resistance (mBar/(L/min)) of 20 PPI pads

Length (mm)	50	100	150
Resistance (mBar/(L/min))	71,42857	70,42254	74,62687
	70,92199	71,42857	72,46377
	74,25743	73,52941	78,125
	73,52941	72,11538	78,125
	81,30081	74,07407	80,64516
	78,74016	74,07407	80,64516



Graph 12: 20PPI resistance vs length

Similarly to the previous results, the values of this test were similar to each other. When looking at the graph, no reliable trendline could be found. The resistance did not seem to be influenced by the length of the foam either. It could therefore be concluded that the resistance of the foam was significantly smaller than the resistance of the rest of the system between the manometer and the orifice. This result justifies using the 20 PPI foam rather than the 10 PPI foam. The denser 20 PPI foam consistently scored better in all previous glue tests and the resistance is not significantly higher either. Testing needed to be continued to find the resistance of other elements in the system.

Finding resistance of other elements

As the rest of the system was made of tubular parts, it can be assumed that the Hagen-Poiseuille equation for laminar flow can be applied: $Q = \frac{\pi \Delta P r^4}{8 \eta L}$ (Q is the flow rate, ΔP is the pressure difference, r is the radius of the tube, η is the viscosity and L is the length). Since $R = \frac{\Delta P}{Q}$, this equation can be rewritten to find the resistance: $R = \frac{8 \eta L}{\pi r^4}$. From this equation it appears the radius has the largest effect on the resistance. The first resistance test was therefore done to the part with the smallest radius, the white plugs (see figure 184). These plugs were made for 5mm tubing, and had an inner diameter of 3.1mm

Plugs

The resistance of the plugs was found similarly to previous resistance measures. Instead of a pad, connectors were placed behind a manometer (see figure 185). The pump was set to create a pressure of 50 mBar above atmosphere. The flow was measured by catching the water in a measuring cup for 1 minute. 1-4 connectors were placed in the system and each number of plugs was tested twice. The resistance was then calculated using $R = \frac{\Delta P}{Q}$, results of which can be seen in table 8 and are plotted in graph 13.

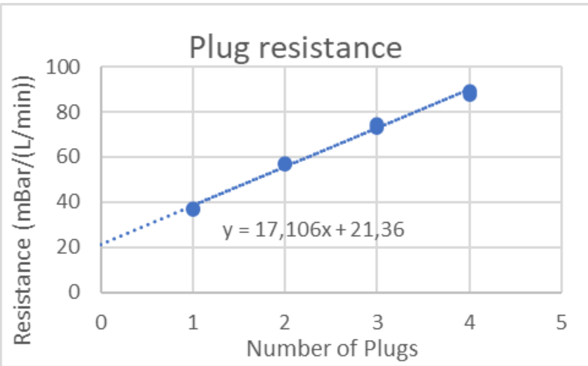
The graph clearly shows a linear function, indicating that the measurement was done correctly and the number plugs had an effect on the resistance of the system. The slope of the line gives the resistance per plug, which is *a* in the function $y = ax + b$, giving a resistance of 17,1 mBar/(L/min) per plug.

Figure 184: Plug

Figure 185: connectors behind manometer

Table 8: Plug resistance

Plugs	System resistance
1	36,76
1	37,31
2	56,82
2	57,47
3	72,99
3	74,63
4	87,72
4	89,29



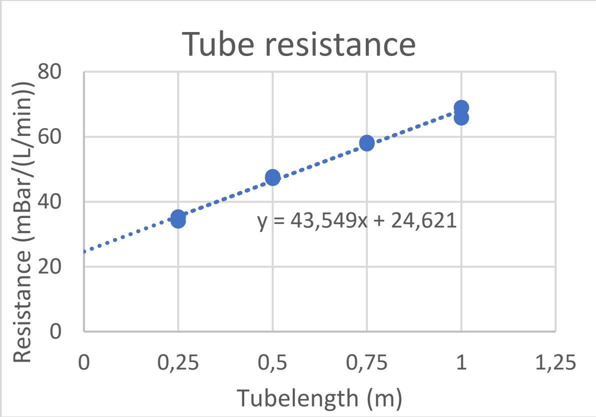
Graph 13: plug resistance

Tube

A similar test was done to find the resistance of the tube. The plugs were switched out by a meter of tube. The rest of the test was kept the same, including the 50 mBar pressure drop. One plug was kept in the system to be able to reach 50 mBar in all tests, so the test setup looked like figure 185. After two measurements, the tube was cut to 0.75m, then to 0.5m and finally to 0.25m. The resistance was calculated from the measurements resulting in table 9 and graph 14.

Table 9: Tube resistance

Length (m)	Total Resistance
0,25	34,01
0,25	35,21
0,5	47,17
0,5	47,62
0,75	57,80
0,75	58,14
1	68,97
1	65,79



Graph 14: Tube resistance

The resistance per meter tube can be derived from the slope of this function. The slope of the function gives the resistance per meter tube. It can again be found in the equation $y = ax + b$. In the function of the tube resistance the value of a is 43.549, meaning the resistance of the tube is 43.5 mBar/(L/min)/m.

The tube resistance per meter is higher than the resistance per plug. Though the design of the cooling vest requires multiple plugs and probably less than a meter of tube. If the resistance of the system will be too high, a careful consideration could be made which part to change and how.

Pad

Because the resistance of the other elements has been found, the resistance of the pad can be tested. Previous tests could not be used because there may have been a difference in tube length elsewhere in the system. The height difference between the entrance and exit could also differ between these tests. As the previous pad test has shown that increased length or density of the foam does not increase resistance, only the 150mm pad was tested twice. The 50mm pad was also tested once to control whether the foam truly had no effect. During the tests, the system of the 25mm tube resistance test was kept the same, the only difference was that the small tube between the plugs was replaced by the pad (see figure 186). The resistance of the pad itself could therefore be isolated by subtracting the total resistance of the 25mm tube resistance test. The resistance of the replaced short tube (below the pad in figure 186) was neglected. The results of the test can be found in table 10.

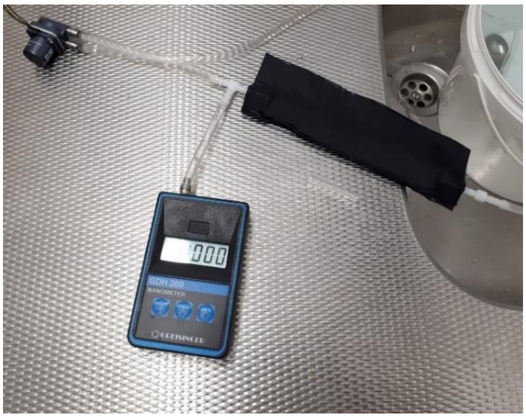


Figure 186: measuring pressure and flow

Table 10: Foam resistance in pads

Length (m)	Total resistance	Pad resistance
0,15	53,19	18,58
0,15	51,02	16,41
0,05	53,19	18,58
Average		17,86

The total resistance in table 10 is the resistance of the entire system. The pad resistance was found by subtracting the average of the two 25 mm tube length resistances. These resistances were 34.01 and 35.21 mBar/(L/min). the average, 34.61, was subtracted from the pad measurement to find the pad resistance (third column in table 10). The average resistance of the pad was found to be 17.86 mBar/(L/min). Since the foam itself does not significantly influence this value, it can be assumed that the two printed connectors produce roughly 8,93 mBar/(L/min) of resistance each.

C - Testing Bulkhead Concepts

Concepts

Two concepts were made to create these bulkheads (see figure 187). In the first concept PU hot melt tape (used previously in chapter 9.2) was placed inside slits in the foam. In the second concept slots were cut in the fabric and the two layers of fabric were sealed together.

Figure 187: bulkhead concepts

Concept 1 – PU Tape

In the first concept the bulkheads are made with PU hotmelt tape. A pattern was made with potentially challenging corners, as well as narrow and wide sections. Slits were cut into the foam where the bulkheads needed to come (see figure 188). Strips of PU tape were then inserted into these slits (see figure 189). The PU tape was cut slightly wider than the thickness of the foam so a small edge was sticking out (see figure 190). This edge would then melt to the black fabric in the bonding process between the fabric and the foam. Before the pad was closed with the second piece of fabric, the pattern of the bulkheads was marked on the pad (see figure 191). Once the pad was finished, the pattern could not be seen apart from the marking.

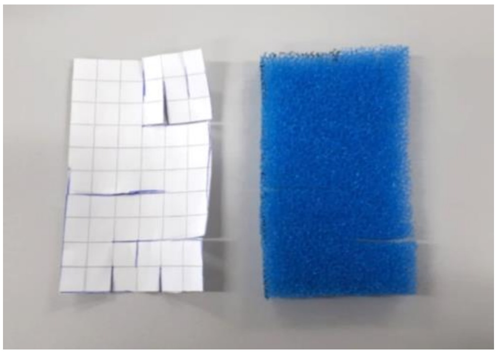


Figure 188: Bulkhead pattern

Figure 189: Slits cut in foam

Figure 190: Slits filled with PU tape and melted to fabric

Figure 191: Finished pad

Concept 2 – Sealing

In the second concept, the bulkheads were made by sealing the top and bottom layers of fabric together (see figure 193). Wider slots were cut into the foam (see figure 192). These allow the layers of fabric space to move towards each other and create a contact area. Because the pattern was made with wider grooves instead of single slits, the patterning takes more space. Consequently, the pattern of this concept could not have the same complexity as the first concept's pattern. The fabric was bonded together with a combination of the sealing iron and a constant heat roller sealer (see figure 194).

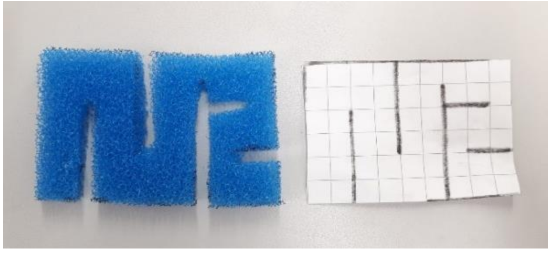


Figure 192: Bulkhead pattern with grooves cut in foam

Figure 193: Finished pad

Figure 194: Roller sealer (Amazon, N.D. B)

Thermal Testing

A test using a thermal imaging camera was done to find how effective the two bulkhead concepts were. The test pads were hooked up to a pump and suspended vertically like they would be oriented in a cooling vest (see figure 195). Two buckets were filled, one with cold and one with hot water. A thermal imaging camera was placed on a tripod pointing at the pad.

Figure 195: Pad suspended on bucket

The pad was filled with water from the cold bucket. Then, the inlet of the pump was moved to the other bucket to change the temperature of the water flow. This temperature change could then be visualized with the thermal imaging camera, to find the path of the water through the pad. The water temperature was alternated until the effect was clear.After a couple of temperature alternations, the bulkhead effectiveness of both pads was clear. The bulkheads of concept 1 – PU Tape did not have the desired blocking effect. Figure 196 shows the water following the pattern leftwards at first (figure 196[2]), but later the water starts leaking from the entrance upwards (196[4]). In the later images, it can also be seen that the water stream does not quite follow the pattern. It appears the PU tape bulkheads have many leaks where water can pass. It appeared the longer the water streamed through, the worse these leaks got. Figure 196 does show that the water eventually fills the whole pad (except for the top), but it cannot with certainty be stated that this will still happen in a wider pad.

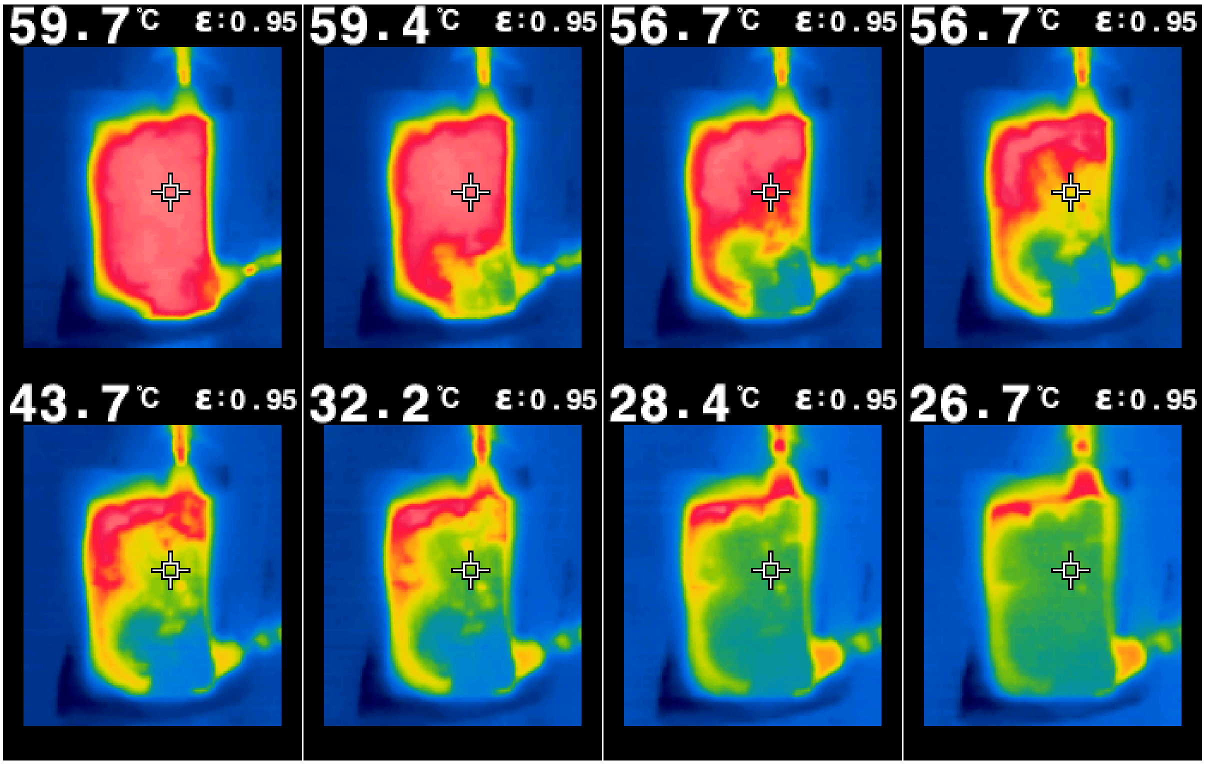


Figure 196: Thermal imaging concept 1

The thermal imaging of concept 2 – Sealing tells a different story. Looking at the flow of the water in Figure 197, it becomes clear that the water follows the desired path. The water zigzags through the pad and quickly replaces the hot water in the pad. However, in the final image of figure 197, there is still an area at the top which remains hot. This happens because the exit of the pad is lower than its highest point, resulting in trapped air inside this area (see figure 198). If the exit were on top of the pad this would not happen.

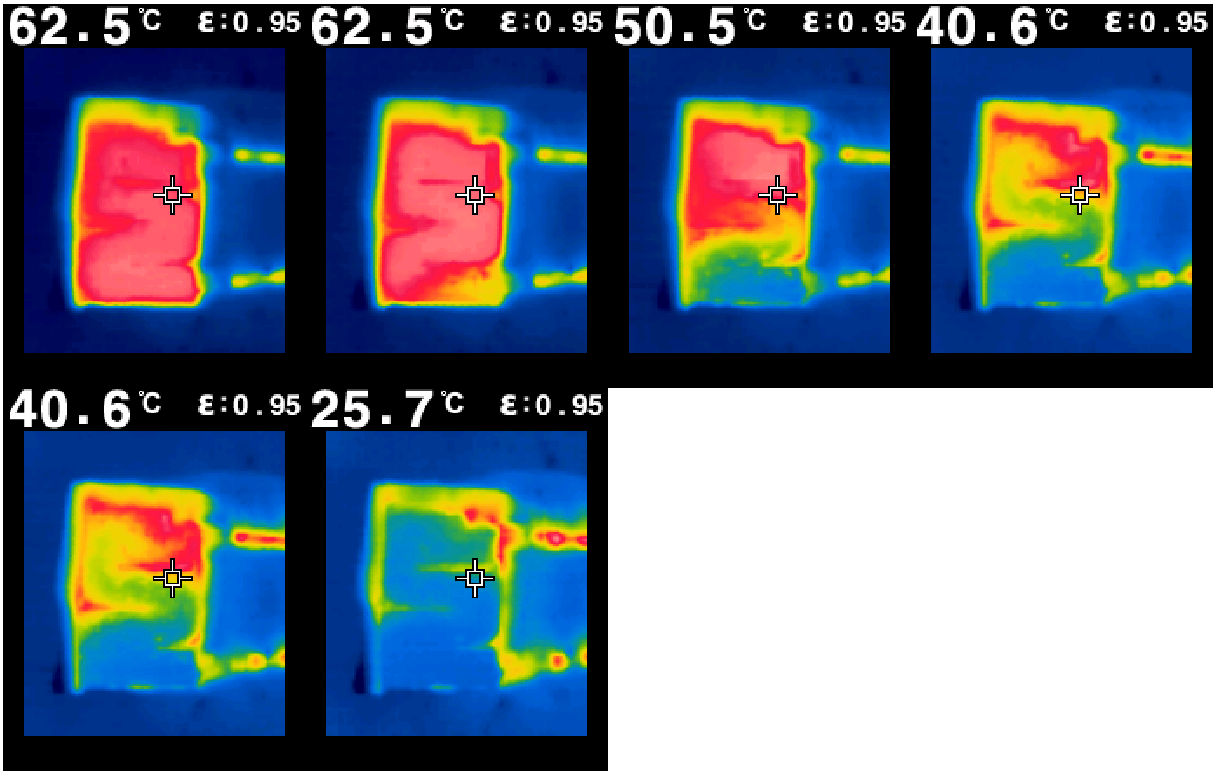


Figure 197: Thermal imaging concept 2

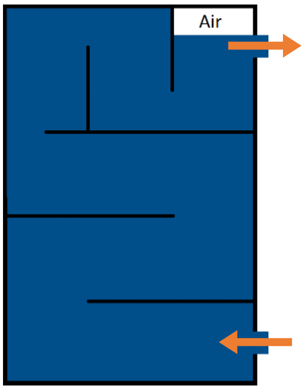


Figure 198: Trapped air

After the test with the thermal imaging camera, it could be concluded that the bulkheads of the sealing concept work substantially better than the PU tape method. The sealing concept also has some drawbacks, however.

The sealing method resulted in a pad that was less flat than the tape method (see figure 199). More flat surface area means more contact area with the body, increasing the heat exchange between the vest and the body. The edges of the pad also wrinkle more, making it less neat when integrated into the cooling vest.

Another drawback was that the prototyping of the sealing method took longer than the tape method. However, when thinking ahead about larger-scale production, the sealing method could easily be simplified by pressing the layers together with a machined aluminium profile and bonded with a heat press. With this process, the entire pad could be sealed and provided with bulkheads in the same action. Moreover, INUTEQ already has experience using machined aluminium profiles to seal vests. They use this method for instance in the production of the PCM Coolovers (see figure 200). Because of the efficient production opportunities and the superior functioning of the bulkheads, the sealing method was chosen to continue.

Figure 199: Prototype pads with bulkheads

Figure 200: PCM COOLOVER (INUTEQ, N.D. A)

In a later stage of the project (chapter 12.2), high frequency welding was used to create both the bulkheads and the outer seal of the pads (see figure 201). This method resulted in a neater pad and flatter flanges (see figure 202).

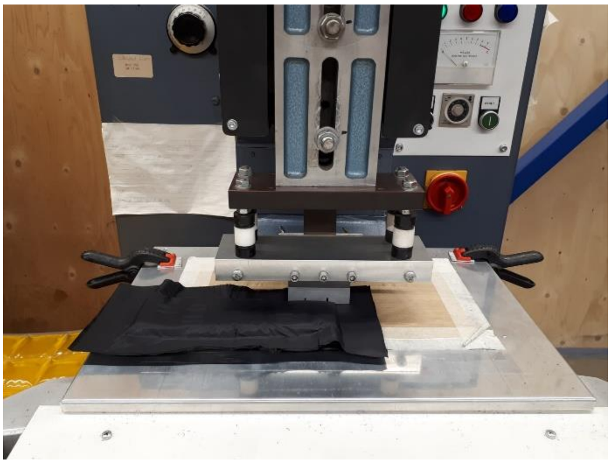


Figure 201: High frequency welding machine

Figure 202: Neater pad

So far, the water stream was tested when flowing from the bottom to the top. However, in a cooling vest it may occur that the stream also flows from the top to the bottom. Thermal testing where the water flowed downwards was therefore also done using the thermal camera and the same setup.

The images taken in this test can be seen in figure 203. They show the water following the pattern downwards. This time, the water seems to skip the outer corners of the pattern, however. In figure 203[4] the water has taken the fastest route through the pad, with some cool areas in the lower left and middle right of the pad. The later figures show that these areas slowly adjust to the new temperatures. These areas may possibly occur due to bubbles or because of a low water flow through them. It was hypothesized that the wider the stream, the bigger this effect would be. A third thermal imaging test was therefore done.

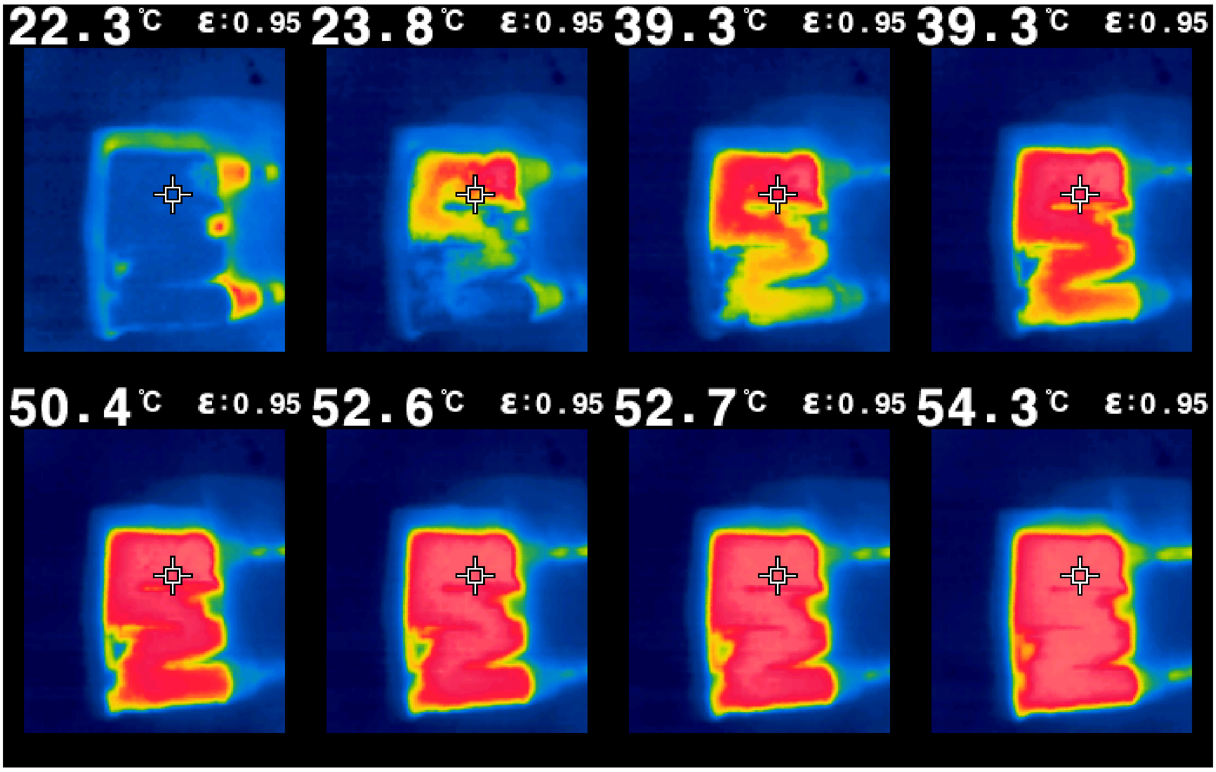


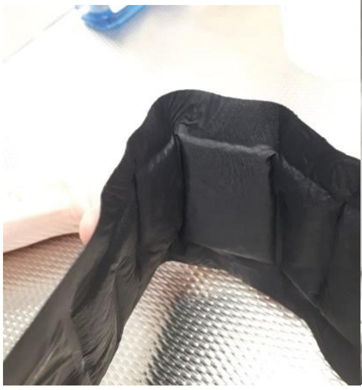
Figure 203: Thermal imaging downwards flow

D – Shoulder buckling solution

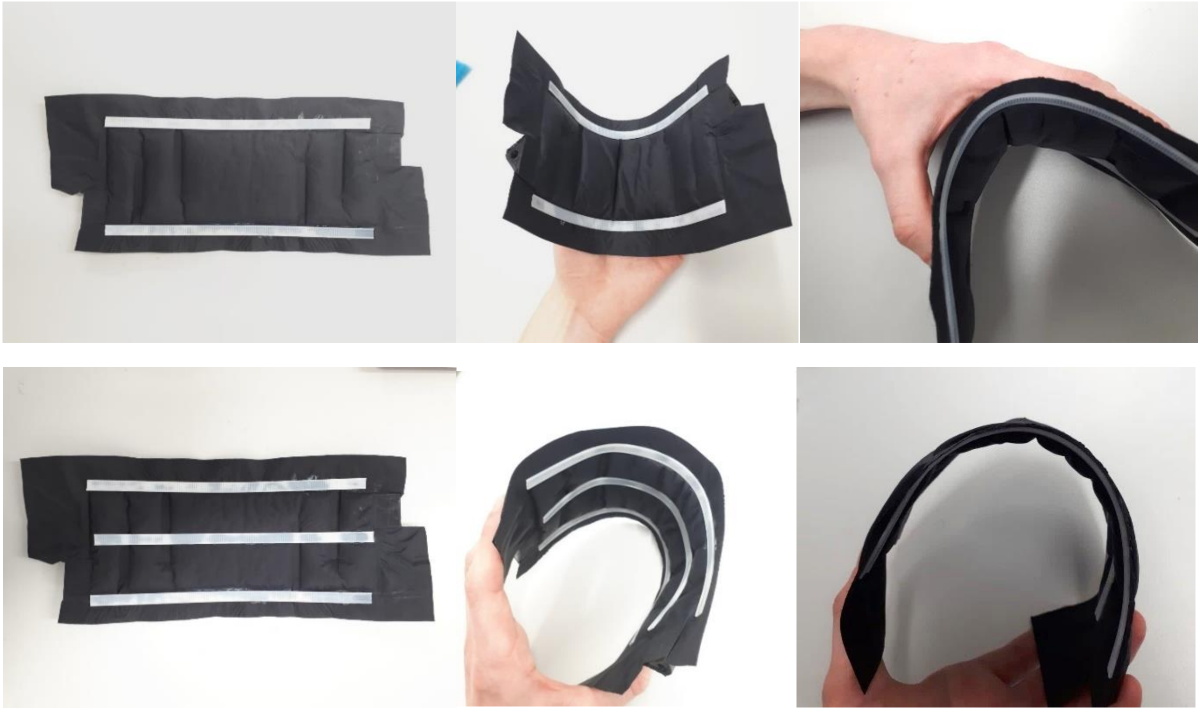
To find a solution for the buckling problem of the shoulder, the shoulder of the BODYCOOL SMART was first traced on paper. The pattern was then simplified into a rectangle with the minimum width of the shoulder pattern.

Two concepts were made, one simple zig-zag, and one where the bulkheads were removed on the location of the bend.

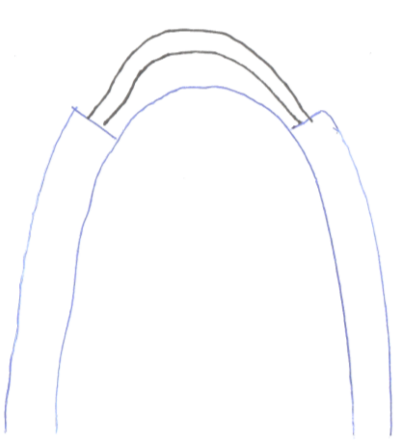
They were then bent to get an initial idea of what would be the effect. As can be seen in the figure below, the samples buckled in a single spot. Later they were rolled around a radius and connected to the water. It quickly became clear that bending the samples massively increased the resistance to the point of delamination.



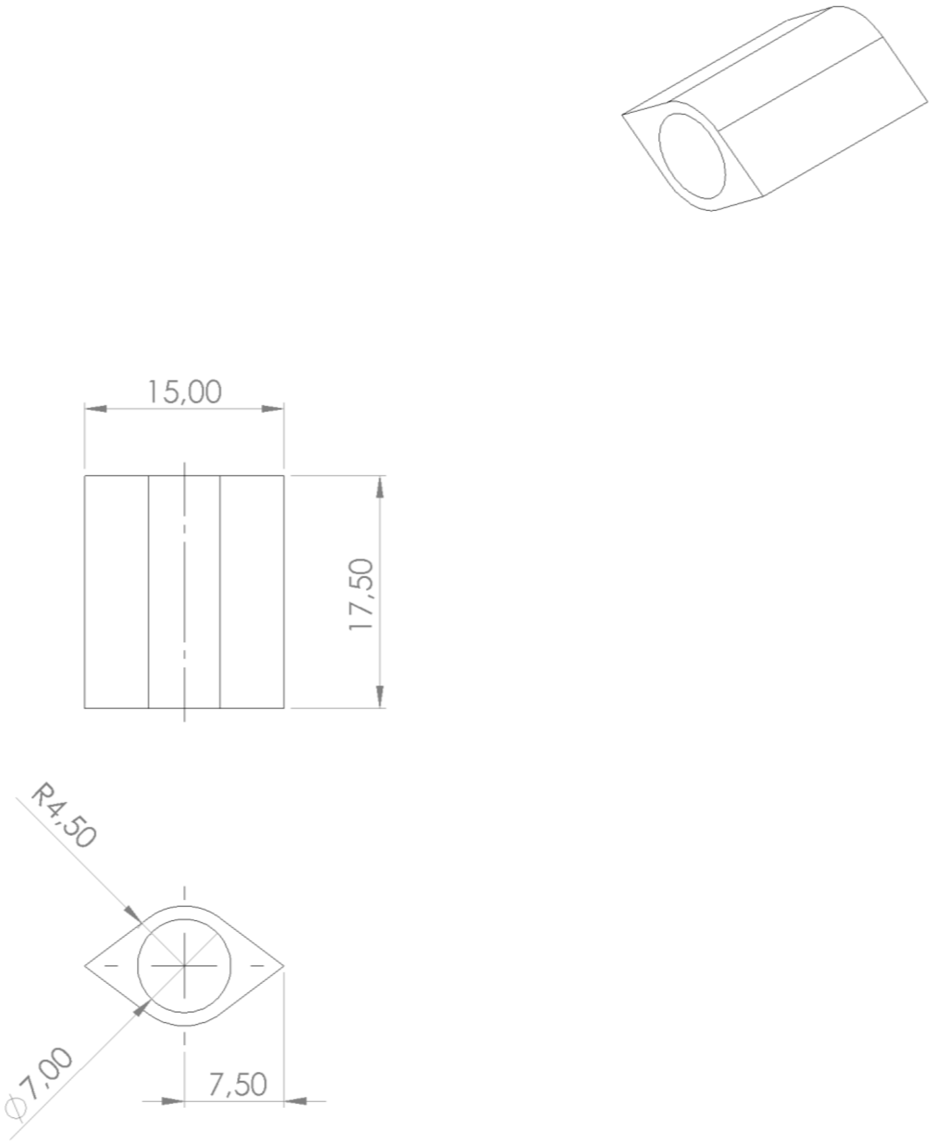
To maybe stop the buckling from happening, ribs were added made from zip-tie’s. Two and three ribs were tried, the samples became more difficult to bend, but the buckling did not disappear. When connected to the pump again the resistance was not decreased. It was therefore decided to scrap these ideas.



A new idea to solve this problem was to have a tube carrying the water over the shoulder. This idea was never tested, because the plans for the prototype changed, where the water was no longer flowing over the shoulder.



E - Drawing of Connector



	units mm	scale 2:1	quantity 2	date 5-8-2021	remark -
material				mass gr	TU Delft University of Technology
author	Sergio Fazzi - 4458826			group -	
name	Connector TPU square 7mm			format A4	drawing no. 1

F - Interview questions

As this research aims to gain qualitative results, these interview questions are handles to start in-depth conversations about subjects. The researcher will ask follow-up questions accordingly.

During wear:

- Wat is je eerste indruk?
  What is your first impression?
- Hoe comfortabel vind je koeling?
  How comfortable is the cooling for you?
  - Voelt het nog te warm of te koud aan?
    Does it feel too cold or too warm?
  - Gedurende de test periodiek blijven vragen. Ook vergelijking trekken met eerdere momenten in de test.
    Throughout the test periodically keep asking. Also compare to earlier moments of the test.
- Hoe comfortabel voel je je qua volledige lichaamstemperatuur? (Heb je het warm/koud/comfortabel).
  How comfortable is your full body temperature? (are you feeling warm/cold/comfortable)
  - Gedurende test doorvragen. Begin je het kouder te krijgen?/ Blijft het warm?
    Throughout the test periodically keep asking. Are you starting to get cold(er)?/ Do you stay warm?
- Voel je je beperkt in je bewegingsvrijheid? Op wat voor manier?
  Do you feel limited in your freedom of movement? In what way?
  - Welke bewegingen zijn moeilijker?
    which movements are more difficult?
  - Komen deze bewegingen vaak voor tijdens je beroep?
    Are these movements common in your profession?
- Tijdens taken: Hoe erg wordt je in je taken beperkt door het koelvest?
  During tasks: How much are you limited in your tasks by the cooling vest?
  - Heb je het gevoel dat je de taken nog steeds makkelijk genoeg kunt uitvoeren?
    Do you feel you can still execute these tasks
  - Ook gedurende de hele dag?
    Also throughout the entire day?
- Hoe ervaar je het gewicht?
  how do you experience the weight?
  - Waar liggen de grootste drukpunten?
    where are the biggest pressure points?
  - Zou je dit gedurende de volledige werkdag kunnen dragen?
    would you be able to wear this thoughout the entire workday?

After wear:

- Wat was je algehele ervaring met het vest?
  what was your overall experience with the vest?

- Hoe heb je het ervaren qua temperatuurverloop?
  how did you experience the temperature progression?

    - Eerst snel afkoelen en dan steeds minder? Of steeds koeler gedurende de test? Hoe ziet dit verloop er uit?
      First quickly cool down and then less and less? Or cooler and cooler throughout the test? What does this progression look like?

- Zou je dit aandoen tijdens je werk, waarom wel/niet? Combinatie met concept tekening.
  Would you wear this cooling vest during your work? Why (not)? Show concept drawing.

- Wat zijn positieve en negatieve punten van dit koelvest in vergelijking met andere typen koelvesten?
  what are positive and negative aspects of this cooling vest compared to other cooling vests.

    - Welk koelvest zou je het liefst aandoen tijdens je werk en waarom?
      Which cooling vest would you prefer to wear during your work and why?

        - Waarom beter dan prototype?
          Why is this better than the prototype?

- Denk je dat een koeloplossing als deze geschikt zou zijn voor meer mensen met dit beroep? Waarom wel/niet?
  Do you think a cooling solution like this is appropriate for other people with this profession? Why (not)?

- Zijn er nog verbeterpunten die je in het concept graag zou willen terug zien.
  Can you think of improvements for the concept?

Next day (phone call):

- Hoe heb je het dragen van het koelvest achteraf ervaren?
  How did you experience wearing the cooling vest?

- Heb je nog ergens last van gehad vandaag/gisteren? Denk aan spierpijn/pijn in schouders door gewicht.
  Did you have any physical discomfort today/yesterday? Think of muscle pain/pain in shoulders due to weight.

- Zijn er nog verbeterpunten te binnen geschoten?
  Can you think of any further improvements?

G – Hotplate measurements

	T_in	T_out	ΔT	Flowrate	ΔT*flowrate
Pad 5C - 60mBar	5,3	6,8	1,5	0,6872	1,0308
Pad 5C - 80mBar	5,3	6,6	1,3	0,7827	1,01751
Pad 5C - 100mBar	5,3	6,5	1,2	0,8446	1,01352
Pad 10C - 60mBar	10	11,5	1,5	0,6254	0,9381
Pad 10C - 80mBar	10,2	11,5	1,3	0,7299	0,94887
Pad 10C - 100mBar	10,1	11,2	1,1	0,848	0,9328
Pad 15C - 60mBar	15	16,1	1,1	0,6805	0,74855
Pad 15C - 80mBar	15,1	16	0,9	0,7921	0,71289
Pad 15C - 100mBar	15	15,7	0,7	0,9061	0,63427
Tube 5C - 60mBar	5,1	7,7	2,6	0,2	0,52
Tube 5C - 80mBar	5,3	7,5	2,2	0,2282	0,50204
Tube 5C - 100mBar	5,3	7,5	2,2	0,2451	0,53922
Tube 10C - 60mBar	10,1	12,2	2,1	0,2172	0,45612
Tube 10C - 80mBar	10,2	11,8	1,6	0,2375	0,38
Tube 10C - 100mBar	10,1	11,7	1,6	0,2708	0,43328
Tube 15C - 60mBar	14,8	16,1	1,3	0,2392	0,31096
Tube 15C - 80mBar	14,8	16	1,2	0,2589	0,31068
Tube 15C - 100mBar	15	16,1	1,1	0,2942	0,32362