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Personalised comfort systems: a novel approach based on localised two-phase water circulation

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Abstract

This work explores an approach to designing and constructing Liquid Cooled Garment (LCGs), compares the abilities and limitations of LGCs against other Personal Comfort Systems (PCSs), and evaluates the design's performance in the CORE-CARE facility.

PCSs have had a long history of research focusing on multiple approaches and applications. Most current designs show limitations regarding user agency, comfort, cost or complexity, while also having to contend with the vastness of the problem space. The work considers the various techniques available in the field and highlights LCGs as an underdeveloped field.

A series of designs for a simple LCG are described, a final prototype is devised and constructed, and its performance is evaluated in the CORE-CARE facility, with 9 tests of 90 minutes each, involving 9 participants.

The resulting design achieves promising results, with users reporting lowered global perceived temperatures at no cost of thermal comfort, highlights the advantages of a user controlled system and shows no issues of localized thermal discomfort; the low complexity of the design also shows ample space for future evolution.

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Introduction

This work will explore Personal Cooling Systems (PCS) and the various designed and approaches of this technology, propose a novel design for a Liquid Cooled Garment (LCG), compares its abilities and limitations with other Personal Comfort Systems (PCSs), construct a prototype of the design and evaluates designs performance in the CORE-CARE facility.

Technological development and design of Personal Cooling Systems started in the 1950s in the aeronautical fields for pilots and aircraft crews in extreme conditions. Research spread to other fields such as military, firefighting and office work. Current developments remain mostly in the research phase, as commercial solutions are few and far in between, focusing on specific needs in all fields beyond military aeronautics and space exploration. Some examples of research exist in the medical field but have limited development.

The technologies employed have expanded to newer and more complex systems such as custom-designed phase change materials, thermoelectric devices, vapour compression and others, using differing designs and technologies. Current designs are usually held back commercially by high complexity and high costs, linked to their novelty and lack of large scale production. Most of the research and designs are concentrated in the last 20 years, fuelled in part by growing concerns on energy consumption and changing climate patterns.

The work considers the various techniques available in the field and highlights LCGs as an underdeveloped field. Recent evolutions in electronics, hydronic miniaturization and decreased manufacturing costs have opened up potential for designs that focus on lower complexities and user control over the cooling action. These development have allowed to study the problem, build a prototype of this design and evaluate its performance, showing promising results regarding its impacts on thermal feeling and user experience. The design is simple enough that it can be tailored to various conditions and potential applications depending on user needs and use cases.

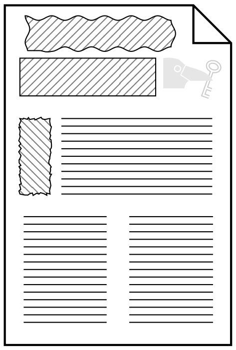
Chapter 1 aims to give an overview of thermal balance and comfort in humans, existing technologies and techniques used for personal cooling, advantages and disadvantages of each kind of personal comfort system, an introduction to liquid cooled garments and their development, and an overview of climate-controlled rooms used to measure human comfort.

Chapter 2 describes limitations of existing studies and devices, design and development of the liquid cooling garment tested, differences when compared to similar systems in literature, the trial and error process that took place, an overview of the climate-controlled room used to test its performance, and a description of the procedure used for testing.

Chapter 3 describes experimental procedure, dataset of participants, performance of the test chamber, numerical and subjective data obtained in testing, conclusions based on these data and potential future improvements for garment design.

Chapter 1

State of the Art



This chapter of the work aims to give an overview of thermal balance and comfort in humans, existing technologies and techniques used for personal cooling, advantages and disadvantages of each kind of personal comfort system, an introduction to liquid cooled garments and their development, and an overview of climate-controlled rooms used to measure human comfort.

The human body uses several mechanisms to regulate thermal balance. Sweating is the most prominent and the most distinctive of humans, vasodilation heats up the skin to improve heat dispersion, vasoconstriction inhibits heat exchange and enhances thermal resistance, metabolism is regulated to produce more or less heat and the use of clothes to help keep warm. Behaviour is the main way in which humans regulate their thermal balance [Gagge et al., 1967].

When these systems are not enough to deal with the surrounding environment, the body is forced to consume energy to heat up or cool down. This can have effects that range from light discomfort to severe conditions such as heat stroke or hypothermia.

Traditionally, humans have modified the conditions of their environments to keep a level of thermal comfort with technologies based on heating, ventilation, and more recently air conditioning.

Heating technologies raise temperatures in indoor spaces during the winter seasons. The most common heating systems include furnaces, boilers, and heat pumps. Furnaces burn fuel (such as natural gas or oil) to generate heat directly, boilers use fuel or electricity to heat water which is then circulated through radiators or pipes and heat pumps use electricity to transfer heat from the outside environment using a refrigeration cycle to warm the indoor space.

Air conditioning technologies that provide cooling include air handling units and mechanical ventilation systems. They are primarily utilized during summer in mild or warm climates, reducing temperature and humidity via the vapour-compression refrigeration cycle. Central air handling systems use ducts to distribute cool air throughout a building, split systems have a cold side in the building that exchanges heat with the hot side placed outside, and window units are self-contained and installed in individual windows.

The desire for a comfortable living and working environment, combined with large scale human development and industrialization has led to approximately one fifth of the energy consumption in developed countries being related to thermal comfort. [Pérez-Lombard et al., 2008]

The issue of energy consumption is even more important in situations and environments where traditional thermal comfort is not achievable or practical due to external conditions or resource limitations on site (e.g. very warm working environments or field hospitals which have difficulties in energy supply), and in those cases it would be beneficial to obtain comfort at the personal level.

By focusing on a single person or small group, heating or cooling efforts can be more precisely directed, allowing for greater efficiency and reduced energy consumption; in both extreme and everyday scenarios, personalized comfort systems can offer a viable alternative by targeting individual needs and lowering energy consumption.

Providing comfort to a single person or a few people instead of conditioning an entire room enhances energy efficiency by employing heating or cooling efforts on a smaller area or directly on the individuals who require it, focusing on individual needs rather than conditioning entire spaces. In medical settings, where patients may require specific conditions and workers are needed for long shifts in uncomfortable environments, adoption of personal comfort systems could improve patient health and professionals' productivity and well-being, enabling more efficient and comfortable work. In industrial settings such as foundries and steel mills where workers have to share spaces with heavy machinery and extreme heat, personal cooling systems could provide comfort, reduce short term heat discomfort and enhance productivity along with work time.

These devices can provide comfort without altering the overall environment, ensuring well-being and productivity of workers. The employment of personal comfort systems could result in safe and comfortable employees without the energy costs associated with cooling on a room or building scale. As the demand for energy consumption related to thermal comfort continues to rise and technologies become more widespread, it becomes increasingly important to explore innovative solutions that can provide comfort in different settings.

Most of the energy spent for thermal comfort is used in temperate climates, as developed countries in these areas typically have more resources to use for well-being; with the economic evolution of developing countries outside moderate climates, a sharp rise in energy consumption related to thermal comfort is expected. [Pérez-Lombard et al., 2008]

These requirements, along with growing concern for global warming, steadily rising temperatures, and the desire to reduce energy consumptions related to human comfort, have caused a steady grow in the research and development of devices that cool at the personal level in comfortable ways. [Makhoul et al., 2013]

1.1 Human thermal comfort

Temperature influences most of the chemical and biological processes inside the human body; maintaining a consistent internal thermal condition is therefore necessary for life. The nominal temperature of a human body is around 36.5°C when healthy. [Kenney and Munce, 2003] There are many ways for the body to maintain this consistent internal temperature: when cold, metabolism speeds up and muscles activate to burn off food energy into heat, and when hot, sweating makes use of water's high latent heat of evaporation to cool down the body. [Morrison, 2016]

Sweating is possibly the most important trait in human evolution: it is a bodily function unique to mammals and its use for cooling power is limited to humans, horses and some primates.[Jenkinson, 1973] It is, however, often uncomfortable, and in extreme cases requires the intake of a considerable amount of water to avoid dehydration.

Thermal *alliesthesia*, the pleasant sensation of one's body being comfortable in the environment [Parkinson and de Dear, 2015], is the objective of thermal comfort systems, be they centralized or personal.

Research on modelling the human body as a thermal system has been ongoing for the past decades, with proposed models that range from the relatively simple, like the single element one based on energy balance used by [Elson and Eckels, 2015a] and [Guo and Shang, 2015], to the extremely complex and detailed like that used by [Gordon et al., 1976] (figure 1.1) to capture the geometries and shapes of a specific person.

The model most suited for this work is based on the single-element human body used by

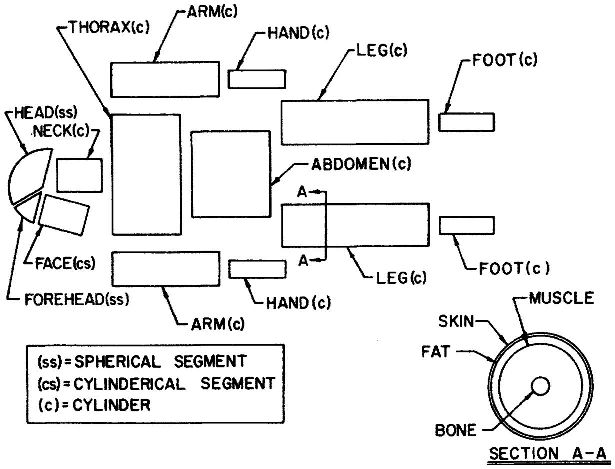


Figure 1.1: Example of detailed human thermal model [Gordon et al., 1976]

[Guo and Shang, 2015]; it was chosen because it is simple, fast to implement and to iterate on and represents a wide enough array of situations. The model aims to describes the relationships between metabolic heat produced inside the body, a person's surrounding and the thermal consequences, taking into account several effects:

- Metabolic energy consumption M or Q_m
- Storage of thermal energy S
- Mechanical work power generated W
- Heat exchange due to conduction Q_{cond}
- Heat exchange due to convection Q_{conv}
- Heat exchange due to radiation Q_{rad} or Q_r
- Thermal energy lost via respiration Q_{res}
- Thermal energy lost via sweat evaporation Q_{evap}

All of the heat exchange values are considered positive when thermal energy is leaving the body. Figure 1.2 shows these in a schematic way.

Following the first law of thermodynamics, a thermal balance equation can be so drafted:

$$M = S + W + \sum_i Q_i$$

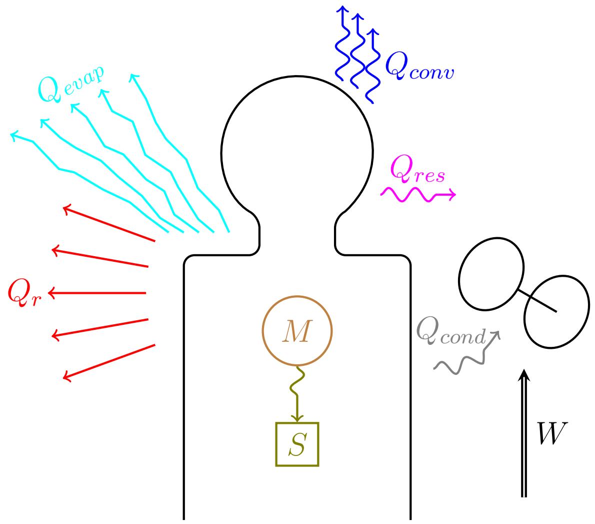


Figure 1.2: Schematic representation of heat exchange between a human being and their surroundings

with the storage element S made up of the changes in temperature of each part of the body i modelled as having mass m_i, specific heat capacity c_i and homogeneous temperature T_i:

$$S = \sum_{body} m_i c_i \Delta T_i$$

which can be made time-independent by taking into account heat and power instead of energy:

$$q_m = \sum_{body} m_i c_i \frac{\partial}{\partial t} T_i + \dot{W} + \sum_i q_i$$

In hot environments, the flow of some or all of these heat components can be negative, resulting in more heat entering the body than leaving: to prevent a rise in temperature that could lead to adverse effects up to heat stroke or death, the body activates systems of heat dissipation such as skin heating via vasodilation and, most perceivably, sweating. The increase in skin temperature causes a rise in thermal exchange with the environment, but increases discomfort.

Temperature is perceived via nerve endings on the skin whose sensations are sent via the nervous system to the hypothalamus in the brain [Zhao, 2022]. Some body segments are more susceptible to heat exchange with the environment than others, resulting in increased overall thermal sensation when acted on: in a warm environment, the face, hands and feet are reported to be en effective target for local cooling, while abdomen cooling is consistently the least preferred

[Luo et al., 2022].

It is generally believed that changes in thermal sensation are dictated by skin temperature, independent of core temperature [Schlader and Vargas, 2019]. The body reacts with stronger responses to cold than to heat no matter the location: autonomous bodily responses tend to heat up the body more readily and strongly than how it gets cooled down. The measurement of core temperature is often interpreted to reflect the status of central thermal receptors. There is a higher density of warm receptors than cold receptors in the central nervous system; this is likely advantageous because core temperature in humans is regulated closer to the upper lethal limit of $\geq 42°C$ than to the lower lethal limit of $\leq 26°C$ [Schlader and Vargas, 2019].

Efforts to classify and measure human thermal comfort have taken place in the last decades, starting from the 1960s[Gagge et al., 1967], and the most widely employed international standard concerning this is the *American Society of Heating, Refrigerating and Air-Conditioning Engineers'* ASHRAE 55. First published in 1966 and updated frequently up to 2020, ASHRAE 55 specifies conditions for acceptable thermal environments and is intended for use in design, operation, and commissioning of buildings and other occupied spaces. [ASHRAE, 2020]

A fundamental tool defined by ASHRAE 55 is the *Predicted Mean Vote*: taking into account metabolic heat production, clothing insulation and the surrounding environment it is capable of predicting the mean value of thermal sensation votes of a large group where sensations are expressed on a sensation scale ranging from -3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slight warm," "warm," and "hot". [ASHRAE, 2020]

Metabolic heat production is the rate of transformation of chemical energy into heat and/or mechanical work by the metabolism of an individual divided by skin surface area. It is expressed in units of *met*, where $1\,met = 58.2\frac{W}{m^2}$ approximately represents the metabolic rate of a seated person at rest [ASHRAE, 2020].

Clothing insulation is the thermal resistance provided by the clothes of an individual. In ASHRAE 55 it is expressed in units of *clo*, where $1\,clo = 0.155\frac{m^2 K}{W}$ approximately represents typical winter indoor clothing [Tartarini et al., 2020].

The Predicted Mean Vote is calculated via the formula described in [ASHRAE, 2020], or by using free tools like the open source online tool developed by [Tartarini et al., 2020] or the free Python package `pythermalcomfort` [Tartarini and Schiavon, 2020], which can be used in larger projects and does not require paid access to the standard.

The deliberate design of clothing and systems that target specific segments can minimize energy expenditure and potentially reduce the employment of traditional heating, ventilation, and air conditioning systems.

Applications in sports have seen a rise in the recent decades: material science and thermal design sees high end applications to such fields, where comfort results in better performance.

1.2 Personal Comfort Systems

A Personal Comfort System [Luo et al., 2022], often shortened as PCS, is a device designed to enhance user comfort without affecting the surrounding environment, as opposed to traditional comfort systems such as heating and air conditioning which act on the surroundings.

The majority of PCS can be subdivided by their operating principle:

- **Evaporative**, using the latent heat of evaporation of a liquid, typically water
- **Ventilation** systems, forcing circulation to employ air convection
- **Phase Change Materials**, based on the fusion of oils or water
- **Liquid cooled**, employing circulation of water or similar liquids into tubing
- **Thermoelectric cooled**, employing solid state elements typically called Peltier cells
- **Vapour compression**, based on a traditional refrigeration cycle
- **Hybrid**, employing two or more principles in superposition

These categories each have upsides and downsides, perform better under different conditions and require varied resources such as water or power to operate. Technical information available from manufacturers of commercial solutions is often incomplete, not provided or difficult to obtain. [Elson and Eckels, 2015a] Table 1.1 summarizes the main properties for each.

Evaporative cooling works thanks to the latent heat of evaporation that cools down a surface as liquid, typically water, vaporises off of it; evaporative garments require nearly constant re-wetting for longer cooling sessions and the total mass of water imbibed by the fabric is very low. The wet clothing can feel uncomfortable and wets other clothes, furniture, equipment and anything else it comes in contact with, potentially causing damage. The evaporation of water is most effective at low relative humidities, making the technology useless and uncomfortable in humid environments. Commercial systems exist, but are conceptually simple: they typically consist of clothing that holds up a larger than usual amount of water and have better heat conduction to the skin, enabling the user to stay in warmer conditions or have longer times between each refill compared to a regular garment. [Elson and Eckels, 2015a]

Ventilation systems force fresh air onto skin and use the evaporation of sweat to cool down the skin; they are considered amongst the most comfortable solutions as cooling is more intense at higher ambient temperatures as long as relative humidity is low. They perform best in dry environments such as deserts as they rely on sweat evaporation, and are therefore unsuitable

Table 1.1: Schematic analysis of different PCS properties

System	Complexity/cost	Resources	Tech maturity
Evaporative	Very low to low	Water or fluid	High
Ventilation	Low to medium	Power (low)	Medium
PCM	Medium	Swappable packs	Medium
Thermoelectric	High	Power (very high)	Low
Compression	Very high	Power (high)	Low
Liquid c.	Medium to high	Power (low), ice	Low
Hybrid	Variable	Variable	Low

for humid climates. Commercial solutions exist, but are often unwieldy and bulky due to the cross-sectional areas required for the passage of air. [Faming Wang, 2020]

Phase Change Material or **PCM solutions** use the fusion of materials such as water, which has amongst the highest specific latent heat of fusion for traditional materials but is extremely cold to the prolonged touch, or oils such as coconut oil or paraffin, which have much lower heat of fusion but can have comfortable temperatures at their melting point. Commercial solutions exist, are widespread and can be personalised on user requirements, thermal conditions and other factors; they are however either limited in duration by the lower latent heat capacity of oil-based systems or potentially uncomfortable due to the low melting point of water. [Hu et al., 2023]

Thermoelectric solutions make use of thermoelectric coolers, solid state heat pumps that generate heat flow using an electric current, often called Peltier cells. The lack of moving parts makes them easy to work with, very long-lasting and manufacturable a variety of geometries making implementation easier than for other systems. They are typically expensive and efficiencies are very low, providing typical values for *Coefficient Of Performance* not much higher than 1.5 compared to 5 and more being the standard for traditional compression cycles. They are widely employed in use cases where efficiency and heat throughput are not the main focus like portable refrigerators or temperature keeping for scientific purposes, but the high heat required for personal comfort limits their application in the field. Nonetheless, commercial solutions are becoming more widespread thanks to the decreasing costs of semiconductor technologies, electronic components and advancements in battery technology. [Elson and Eckels, 2015a]

The employment of **vapour compression cycles** in personal cooling systems is still under development as the miniaturization of electromechanical components such as pumps is not yet sufficient for the performance needed and weight limitations of personal systems. They require a large amount of energy as the heat dissipated is directly proportional to power needed, though efficiencies are much higher than those seen in thermoelectric coolers The high complexity of the system and high pressures required for high efficiencies result in bulky, heavy systems. No commercial consumer grade solutions exist as of yet, and even industrial or military grade devices struggle to get past the prototype phase. [Elson and Eckels, 2015a]

Liquid cooled garments, the main focus of this work, employ the circulation of a liquid to cool down the skin via conduction. They are going to be discussed and analysed in more detail in the following section.

Hybrid cooling solutions exist in research but typically inherit a superposition of disadvantages and reduced advantages compared to the singular principles they are born from. Most hybrid systems employ ventilation in combination with either evaporative, thermoelectric or PCM cooling. Commercial solutions exist but are not as widespread as single-principle devices. [Faming Wang, 2020]

The review from [Luo et al., 2022] separates the factors responsible for the performance (capacity to cool down the body) of a Personal Comfort System in three categories, listed in table 1.2.

Table 1.2: Variables affecting the performance of Personal Comfort Systems

Environment	User	System
Air temperature	Age	Segment targeted
Humidity	Sex	Cooling area
Air flow	Clothing	Cooling power
Radiant temperature	Fitness	Heat transfer mode
Evolution	Acclimation	Other factors
Other factors	Other factors	

High level PCS design is complex due to all the interacting variables that have to be taken into account [Luo et al., 2022]; the employment of complex systems makes multivariable optimization a lengthy process, and the lack of a standard method for evaluation and screening does not allow for straightforward comparisons [Elson and Eckels, 2015b], and comparative works must come up with their own scoring systems [Elson and Eckels, 2015a].

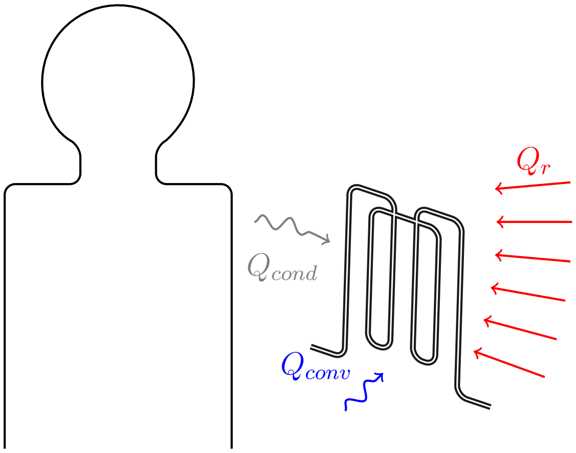


Figure 1.3: Schematic representation of heat exchange in PCS design
A liquid cooled system is taken into account, but heat fluxes to and from the body remain

In typical preliminary personal comfort system design, the heat equation is simplified as much as possible [Guo and Shang, 2015]: a steady quasi-static state is considered, heat storage components are removed, skin and garment are treated as two plates whose contact area is equal to the cooling surface, respiration and evaporation thermal effects are neglected, and air is thought to have no velocity so only natural convection is taken into account.

Introducing the heat removed by the garment (Q_w), it is possible to rewrite the heat balance equation as centred onto the garment [Guo and Shang, 2015], identifying heat incoming to the device as positive:

$$Q_w = Q_{conv} + Q_r + Q_m$$

and the heat fluxes as

$$q_w = q_{conv} + q_r + q_m$$

The heat flux to the garment is composed of body conduction, which is desired as it cools down the user, and ambient convection and radiation, undesirable as heat is absorbed with little to no advantage to the user.

Since it is desirable to split absorbed body heat q_m from parasitic heat received from the environment, this alternative notation is often used:

$$\begin{cases} q_1 = q_{conv} + q_r \\ q_2 = q_m \\ q_w = q_1 + q_2 \end{cases}$$

A simple parameter describing efficiency is then found as the ratio between these heat fluxes, with two limit cases:

$$\begin{array}{ll} q_1 \to 0 : \frac{q_1}{q_2} \to \ 0 & \text{No cooling effect} \\ q_2 \to 0 : \frac{q_1}{q_2} \to \infty & \text{No heat loss to environment} \end{array}$$

This simple efficiency ratio is higher for better insulation of the garment to the environment; however, insulating a wearable cooling system results in extra mass, restricts transpiration potentially resulting in high sweat condensation, and generally lowers comfort due to these effects [Kang et al., 2018].

Therefore, the ratio of heat exchanges is not a common parameter to see in research, as it is not a predictor of cooling performance by itself. It remains useful as a figure of how much energy is expended to cool down the user by a certain amount by taking environmental loss into account.

The individual components of heat are hard to estimate and verify as they are not linear and depend on several factors, but can be approximated [Guo and Shang, 2015] as follows:

$$\begin{cases} q_{conv} \approx f_{cl} h_c (T_{cl} - T_a) \\ q_r \approx f_{cl} h_r (T_{cl} - T_{mr}) \end{cases}$$

The clothed area factor f_{cl} represents the ratio of covered body surface to uncovered area, as clothes have different emissivity and thermal behaviour than uncovered skin. The two heat transfer coefficients h_c and h_r vary with subject, cooling system and boundary conditions, but they can be approximated.

The natural convection heat transfer coefficient h_c increases with the rise of the temperature difference between the human skin and the ambient, so its value will depend on clothing and air temperature. Assuming higher clothing temperature than ambient air, an approximate value is given by [Nielsen and Pedersen, 1953]

$$h_c = 2.38 \sqrt[4]{T_{cl} - T_a}$$

The radiation heat transfer coefficient h_r has a typical value of 4.7 $\frac{W}{K\,m^2}$ in most normal internal environments; this fulfils the accuracy requirements for indoor situations and can be employed for analysis. [Fanger, 1967]

1.3 Liquid Cooling Garments

Liquid Cooling Garments, typically shortened as LCGs, are a subset of PCS that employs the circulation of liquid to provide skin cooling. When compared to air-based personal cooling systems, LCGs use conduction instead of convection, enabling higher heat transfer.

The concept was proposed in the 1960s[Nunneley, 1970] for aircraft crews of the Royal Air Force, later adopted by the Apollo missions and the US Air Force[Guo and Shang, 2015]. Cooling garments in the Apollo suits were designed specifically for the vacuum of space, as the water could be boiled off when extra heat was produced. LCGs are employed in space today, remaining the most used systems to provide thermal comfort to astronauts.

The design of aerospace grade liquid cooling garments is not practical for use in other fields: these models cover the whole body, leaving only the face uncovered, and are designed for extreme environment and high metabolic rates. User comfort and system portability remain a secondary design goal.

This results in several challenges when designing liquid cooling garments for use outside fields related to aeronautics and space exploration [Nunneley, 1970]. The current designs are often bulky and not optimized for user comfort and freedom of movement. To be successful, the garments need to be lightweight, flexible, and non-restrictive to allow for easy mobility. The garments' cooling components should be integrated seamlessly and unobtrusively, minimizing any discomfort for the user. The design should allow for quick and straightforward recharging of the cooling system without interrupting the user's workflow.

Despite components and technologies becoming cheaper, smaller, lighter, and easier to use, the lack of industry interest in wearability, user friendliness and scale development left liquid cooled garments mostly limited to space applications despite the potential use cases outside extreme environments. This results in no commercial solutions based on liquid cooled garments available.

Research and industrial development are limited outside of aerospace applications: while research in the field exists, it is typically circumscribed to the aerospace field [Tanaka et al., 2014], where user comfort is secondary to survivability and duration of the cooling effect; this gap in research between the aerospace field and the rest of the PCS industry has not been patched despite potential fields of employment potentially benefiting from LCG technology.

The limits of liquid cooled garments remain the complex design, necessity of cooling the exchange medium via massive ice packs or complex and expensive cooling systems, limited portability potential for leaks during operation, and traditionally high costs of construction and maintenance.

The design of liquid cooled garments has not progressed enough to result in widespread adoption, which would be beneficial for workers in high heat environments (firefighters, metalworkers, etc.), those in high stress conditions (pilots, surgeons, etc.), and where high metabolism rates are obtained (athletes, construction workers, labourers, etc.).

The potential benefits of using liquid cooling garments in these and other industries are becoming increasingly recognized, which could drive further investment and progress in this field. Workers in these industries often face high temperatures and heavy physical exertion, which can lead to heat-related illnesses and decreased performance. Liquid cooling garments could help regulate body temperature, enhance comfort, and improve overall productivity and safety.

For a cooling garment based on liquid circulation where no phase change takes place in the tube, absorbed heat q_w can be easily calculated using the first principle of thermodynamics [Guo and Shang, 2015]:

$$q_w = \dot{m} c_p \left(T_o - T_i\right) / A_{cl}$$

where $\dot{m}$ is the mass flow of liquid, c_p is specific heat capacity, T_i is inlet temperature and can be considered equal to tank temperature, T_o is outlet temperature and A_{cl} is the effective cooling area of the device.

1.4 Environmentally controlled facilities

The last decade has seen a widespread rise in thermal comfort research; such research is often not developed in the wild, but rather in controlled environments and research labs. This is due to the necessity of providing vastly different thermal conditions depending on need, as well as providing repeatable and verifiable experiments.

Test rooms are useful because they allow researchers to control the environmental parameters of the investigated spaces. This control enables isolating the contribution of single environmental factors or specific combinations of multiple environmental stimuli on subjective responses, such as overall comfort perception or productivity. Test rooms also provide the ability to establish cause-effect relationships related to the comprehension of human comfort and occupancy behaviour by exposing different subjects to the same stimuli and elucidating the influence of subjective factors.[Pisello et al., 2021]

These labs widely employ highly controlled microclimate rooms to test and evaluate the performance of their projects and experiments. Test rooms are typically capable of controlling air temperature, relative humidity and air quality through ventilation and air exchange systems. A minority of them can also act on surface temperatures to account radiant heat.

Such properties create the ideal space to test the effect of changes in temperature on human comfort, thermal feeling and effects on productivity. The rooms should ideally have several sensors capable of monitoring temperature, humidity, air quality, CO_2 and other environmental parameters to thoroughly describe the environment, collecting experimental data and providing reliable and repeatable experiments. Such complexities tend to make each solution unique and customized to the needs of single teams or experiments, with the goal of providing repeatable environmental conditions and reliable experiments despite the environments and tools being different.

These test chambers have high cost and complexity, require specialized spaces, control rooms, separate HVAC systems and skilled technicians to operate, expert data analysts to understand the meaning of sensor output, and careful maintenance and monitoring. These compounding costs and complexities are one of the reasons such research is mostly focused on global thermal comfort systems, especially at an industry level.[Pisello et al., 2021]

A review of the facilities and experiments was conducted by [Pisello et al., 2021], selecting hundreds of research papers to better understand this topic's evolution in academic literature.

The review goes in great depth detailing on the properties of worldwide test chambers:

- most facilities are composed of a single room
- rooms are mostly similar to small offices
- few test rooms have equipment besides basic office furniture
- most chambers have the air temperature and humidity controlled
- less than 5% of rooms control radiant temperature
- basic personalized systems are sometimes present (fans, heated/cooled furniture...)
- most personalized systems are not part of the room, but temporary to specific experiments

- some specialized rooms have advanced lighting or acoustic systems
- more than 80% of facilities are located in regions with moderate climate
- costs and requirements are often not listed in published experiments

The review analysed experiments in literature as well as the facilities themselves, finding common patterns in experiment properties and outcomes:

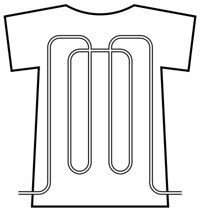
- most tests concerned global comfort and room-scale air conditioning
- PCS are well received by the occupants when provided
- the last 20 years have seen an increase in studies on local thermal systems
- lack of information makes it hard to replicate experiments
- most participants are students or faculty members
- most tests employ sedentary activities

Test chambers are expensive to build and maintain, distant from real world spaces and very different from each other; tests are unique and not standardized, without agreed on procedures even in similar industries and fields, as each individual product or hypothesis makes use of different settings and conditions. This makes comparisons between tests difficult when goals differ between projects, but individual experiments have high repeatability and can be described thoroughly. Rooms are mostly similar to small offices, making research difficult to extend beyond those spaces.

The review concludes that the field of indoor environmental comfort lacks standardization, starting from terminology and design guidelines, but test chambers are an essential tool in thermal comfort research and in testing thermal comfort devices.[Pisello et al., 2021]

Chapter 2

Experimental apparatus



This chapter of the work describes limitations of existing studies and devices, design and development of the liquid cooling garment tested, differences when compared to similar systems in literature, the trial and error process that took place, an overview of the climate-controlled room used to test its performance, and a description of the procedure used for testing.

2.1 Development of Liquid Cooled Garment

The focus of this project was to build a low complexity demonstrator liquid cooled garment to improve on the design of liquid cooled garments, specifically their low portability and high cost, by applying research findings in local thermal comfort and using available commercial components. The goal was construction of a water based liquid cooling garment up to the working prototype stage keeping complexity low and making the garment easy to reproduce and iterate upon. An important design choice was to give the user control over the behaviour of the system while avoiding complex feedback systems or sensor designs.

Liquid cooled garments are not widespread in research, with no examples of two phase designs found in literature. However, the necessary components have grown steadily in reliability, miniaturization, availability, while costs have dropped significantly, making the technology interesting and giving the right environment to produce new iterations.

The design phase started with a review on research on thermal comfort, with a focus on which body parts to target for a good performance: in the 2021 work [Luo et al., 2022], a review of recent studies is done with the goal of localizing winning and losing strategies for Personal Comfort System design. Both heating and cooling solutions are studied in the scope of office environment, therefore excluding extreme environments, to discuss the most relevant target body parts.

The aggregation work shows advantageous parts to target can be hands, face, back and feet. Specifically regarding the torso, it is shown that the back is more sensitive than the front, the chest is the torso's least thermally sensitive part, and more importantly that *local cooling of the abdomen should be avoided at all times*, as it is the least preferred[Luo et al., 2022]. Moderate local cooling of the head and torso is most associated with a better Local Thermal Sensation in non-cooled regions, resulting in pleasant cooling that spreads beyond the targeted zone.

The back was chosen as target area due to good performance in reviews[Zhao, 2022], large area and relative flatness resulting in ease of realization.

Thus the decision was made to develop the design around a coiled tube system around a regular t-shirt, connected to an external water circulation and cooling system running off of an external power source.

The base for the garment was purchased off-the-shelf, since bespoke manufacturing would have not given advantages; after testing on a synthetic fabric shirt and being dissatisfied with workability, glue performance and thermal comfort, a simple white cotton T-shirt was chosen.

A vertically coiled tube design with intake and outlet on the bottom part was chosen. Different tube layouts were tested to see if they had a noticeable difference in perceived heat exchange; after trying out different configurations (some pictured in fig. 2.1) and observing no significant difference in benchmark tests measuring fit, thermal feeling and thermal imaging; a layout that kept curvature radii high and stresses low was chosen. The tube pattern was chosen to minimize bending stresses from the tube and to avoid a wholly increasing temperature from left to right.

For the first prototype, the chosen method to attach tube and garment was self-adhesive insulating polyurethane foam sheeting, shown in figure 2.3; this would have had the added advantage of insulating the tube from the outside environment, minimizing heat intake from radiation and air convection. However, the adhesive strength proved insufficient on wet cotton even with minimal condensation (see fig. 2.2), resulting in destruction of the first prototype's tubing structure after a benchmark test.

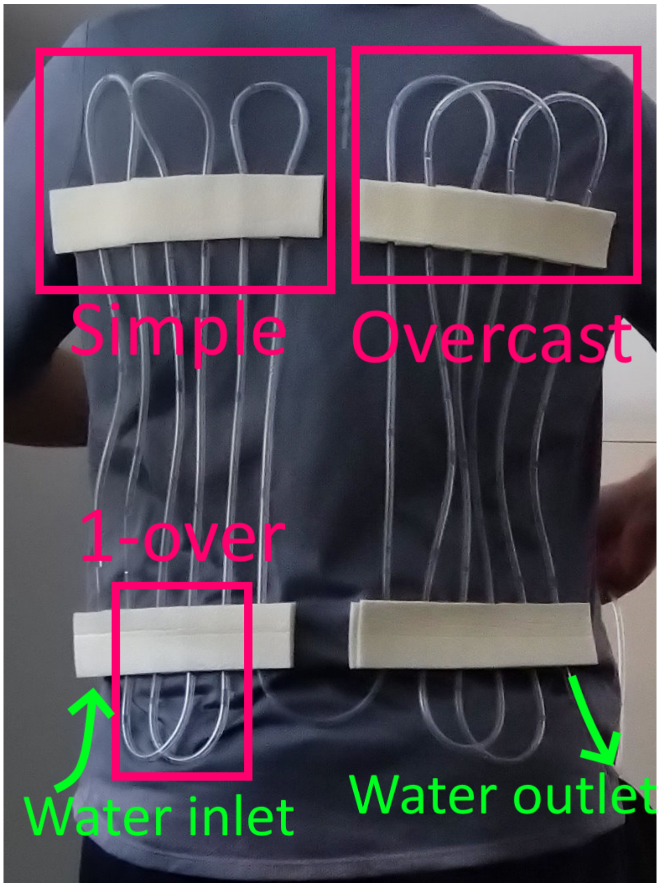


Figure 2.1: Tube configurations employing self-adhesive insulating foam, differences highlighted

The second prototype's main improvement was a better structure: instead of using adhesive sheets, the tube was sewn to the shirt using a blanket stitch. This proved much more robust, did not restrict movement, was not sensitive to condensation and did not result in out-of-plane stresses forced on the shirt's fabric. The blanket stitch was chosen for its large stitch length enabling quick construction via hand sewing. Structural connection between tube and shirt proved good even while moving, giving little restrictiveness in movement, proving resistant and offering good thermal contact. Figure 2.4 shows a close-up of the fixed tube in the final prototype.

An European size L was chosen to give a tight fit to larger test subjects, fitting up to XXL users; for smaller users, a thick thread running through sewn loops is used to ensure good thermal contact by keeping the garment tight.

The garment is designed to be worn over an undershirt, which can be any light piece of top clothing. This also keeps the garment cleaner, as it is not in direct contact with the skin.

The final prototype used for testing is visible in figure 2.5.

Figure 2.2: Pictures of adhesive de-bonding due to condensation in early prototypes; peeling is noticeable as adhesives are most sensitive to that failure mode

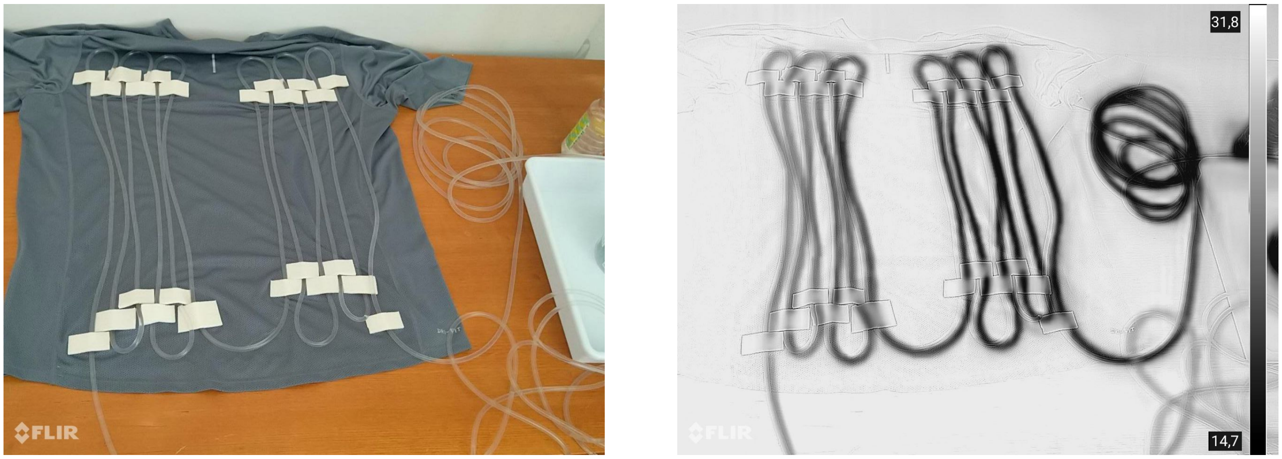


Figure 2.3: Optical and thermal image of the first prototype in a benchmark test; the coldest spot in the image is found in the tube coil before the garment, and a slight temperature gradient is observable in the tubes from right to left

Figure 2.4: Detail of the stitched tube in the final garment; black thread is used for contrast

Thermal imaging shows the tube temperature are much higher than the melting point of water: the ice-water mixture does not maintain freezing temperature when the liquid is circulated, the thermal resistance of the tube cause it to remain significantly warmer than the water circulated

Figure 2.5: Photo and thermal image of the working prototype during benchmark testing

inside, and major thermal losses happen between tube and environment at all points of the tube.

This results in the perceived temperature of the garment being significantly warmer than freezing, while delivering a consistent and pleasant cooling action.

2.2 Design of liquid circulation system

The primary purpose of an LCG is to increase thermal comfort by lowering the perceived temperature. As water circulates through the tubing, it absorbs heat from the person's skin, cooling them down. In the design, this role is done by the previously described tubing and garment, while the movement of the water and exchange for cooler water is managed by the liquid circulation system.

The liquid circulation system is primarily composed of three parts: pump, tubing and ice water reservoir. It requires an active powered component in nearly all cases, notable exceptions being some space-grade systems based on evaporation, and this design is no exception.

The main requirements were the ability to pump cold water uninterrupted for hours, modest size and weight, ease of availability and moderate power consumption. After several commercial solutions were considered, a small submersed pump designed for aquariums was chosen as it satisfied all requirements.

The standardization of electronics components of recent years has made available small and relatively powerful pumps that feed off a standard 5V USB socket. This enabled the design of a very simple controller: an off-the-shelf extension cord with a power switch turns on or off a small off-the-shelf mains voltage to USB adapter which powers the pump, enabling manual operation at no risk for the user without any bespoke parts. This allowed for low complexity user control over the system at no extra manufacture cost.

Silicone tubing was chosen for its flexibility, resistance and low cost; it is more soft and flexible than polyvinyl-chloride especially at lower temperatures, which is essential for a water cooling garment's comfort and good fit. The tube diameter was 4mm internal against 6mm external.

In recent years PVC tubing has taken the place of silicone in the making of most consumer-grade tubing thanks to its lower cost. This made finding a suitable tube more difficult than expected. Medical-grade tubing is most often made of silicone, but lengths of several meters are not easily sold to consumers. An approximately 13 meter tube of aquarium-grade silicone was found and chosen.

None of the prototypes found in literature have an active control system that can be acted on by the user; in the work by [Tanaka et al., 2014], employment of a user controlled system to act on temperature or flow rate of the cooling water is proposed but not built.

Turning on and off the pumping element is the easiest way to act on the cooling system: the flow of cold water is interrupted and cooling subsides as soon as the remaining water in the garment reaches a higher temperature. The simple design and low power pump do not require any other system to control backflow or pressure. Reliability and ease of use are therefore kept high, and the system is easy to construct, operate and maintain.

Most systems in literature use self-contained ice packs to store thermal energy through the latent heat of fusion; to enhance thermal exchange with the water, and reduce the amount of water required, it was decided to use free-standing ice instead.

The temperature of the ice bath is relatively cold and would be significantly uncomfortable if felt directly on the back; however the low flow of water and the significant length of tubing between pump and garment result in a pleasantly cool water temperature.

The necessity to refill the ice water reservoir with cold ice and drain it of water removed the possibility of completely insulating it during testing; to reduce unwanted heat losses between the ice water reservoir and the environment, a small insulated container made of polystyrene was chosen as housing during the experiments. Figure 2.6 shows this configuration.

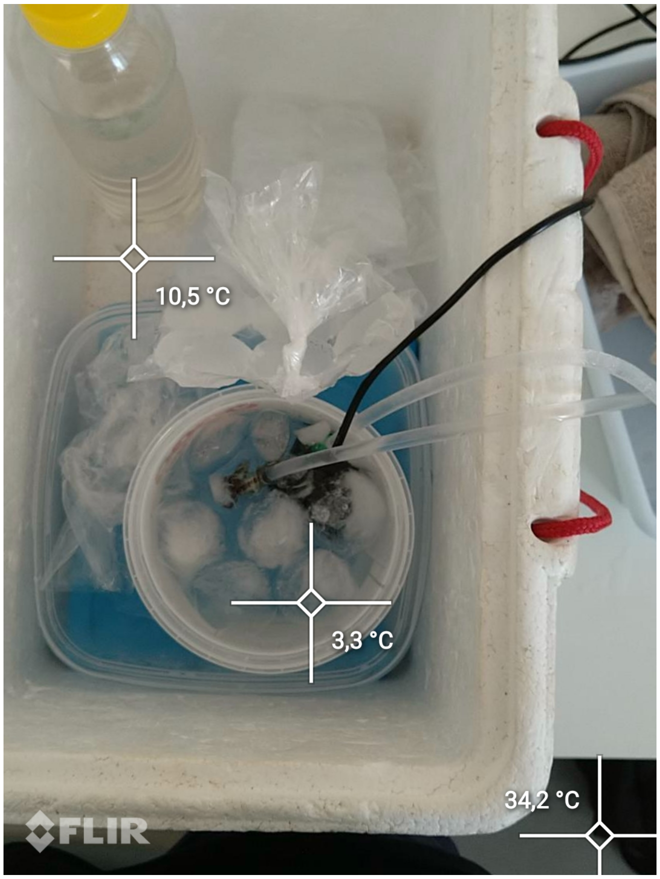


Figure 2.6: The insulated container for the ice water reservoir. Extra water and ice are ready for use.

Temperature in the container was kept low with ice packs (not in contact with water) and extra ice kept inside to quickly add more when needed.

Thermal imaging of the container showed that while internal temperature is far from that of the water and ice mixture, it is much colder than the outside room, minimizing thermal losses.

2.3 CORE-CARE room

The Department of Industrial Engineering of the University of Padova provided an **environmentally controlled room** for proper experimental testing of the prototype. The CORE-CARE laboratory (COntrolled Room for building Environmental Comfort Assessment and subjective human Response Evaluation)[Marigo et al., 2023] is a test room directly integrated with an existing building; it was not built *ex nihilo* as is common with test chambers but by refurbishing a space previously used as a meeting room. For this reason, its integration with an existing building give it characteristics similar to a frequently used room.

The laboratory consists of an 18.5 m^2 test room, where the experiments occur, and a control room to its south where the HVAC and monitoring systems are situated and controlled. Figure 2.7 shows a plan of the relevant angle of the building. Two windows equipped with double glass face east, unobstructed for most of the day.

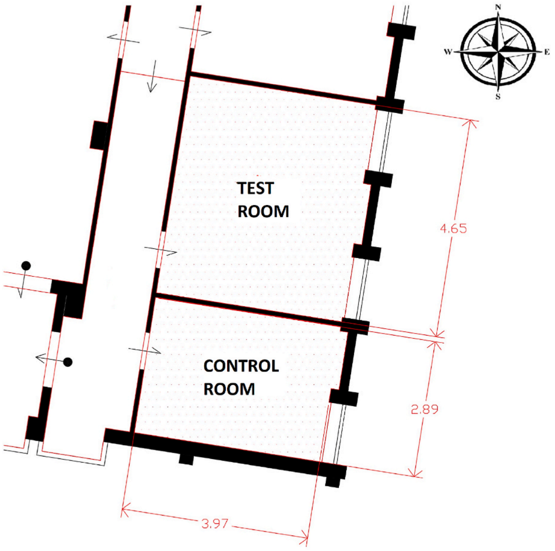


Figure 2.7: Plan view of the CORE-CARE laboratory

The facility is equipped with a mechanical ventilation unit and each surface of the test room can have its temperature set independently by commercial hydronic radiant systems. Heating and cooling can be provided via air circulation and/or by controlling the temperatures of each surface. Automated systems are set for each circuit and use water from an electrically heated 200L tank or cooled tank to act on surface temperatures.

The radiant panels in the room can be controlled independently, providing six hot or cold surfaces. Each surface is controlled by a circuit equipped with mixing valves and a circulator. From the control room the environment can be set by manually opening the valve of each desired circuit. The products and materials which make up this radiant system were supplied by different companies collaborating with the University of Padova, so each wall has different characteristics in terms of materials, design and shape of the panels, and diameter and pitch of the pipes.

The ceiling contains the mechanical ventilation system's ducts and *plenum* (positive pressure tube, as opposed to vacuum being negative pressure with respect to the atmosphere). The ventilation system can be set in five operation modes: only fresh air, heating and cooling integration, dehumidification and free cooling. [Marigo et al., 2023] The temperature can be set in a range of 15 to 45°C.

Figure 2.8 shows a layout of the systems embedded in each surface.

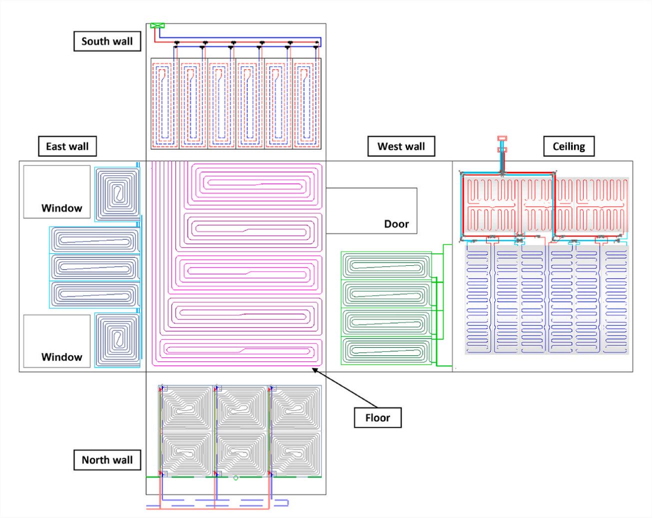


Figure 2.8: Layout of the panels installed on the different surfaces of the CORE-CARE test room

A thermal dummy capable of outputting 60, 120 or 180W depending on requirements was placed in the room for this test; it is most often to simulate the presence of people before their entrance to avoid increases in temperature caused by the added thermal load.

Each surface is equipped with four thermocouple-based temperature sensors, for a total of 24 surface temperature sensors divided amongst the six opaque surfaces of the test room. Air temperature is measured by 3 sensors located on the vertical column positioned in the centre of the room at three different heights of 0.1 m, 0.60 m and 1.70 m. All of these sensors are platinum thermistors, their tolerance is defined as Class F 0,15 according to [ECS, 2022], and the measurement range is between -50°C and 300°C. [Marigo et al., 2023]

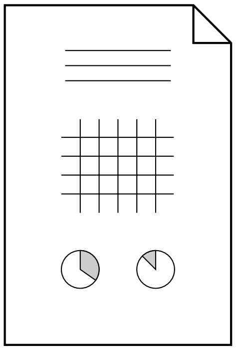
The mean radiant temperature is taken by a globe thermometer with 0.2°C accuracy and measurement range between -30°C and 70°C placed on a vertical column in the centre of the room at 0.6m of height; [Marigo et al., 2023] this is then averaged with the air temperature T_{AirAv}.

To represent the thermal environment in a meaningful way with a single number, operative temperature T_{OP} is chosen as the most significant parameter of the chamber:

$$\begin{cases} T_{AirAv} = \frac{1}{3}\sum_i T_{air,i} \quad \text{Average air temperature} \\ T_{OP} = \frac{1}{2}\left(T_{MR} + T_{AirAv}\right) \quad \text{Operational temperature} \end{cases}$$

Chapter 3

Experiment, results and conclusions



This chapter describes experimental procedure, dataset of participants, performance of the test chamber, numerical and subjective data obtained in testing, conclusions based on these data and potential future improvements for garment design.

3.1 Experimental procedure

To test the performance of the prototype, meaning its ability to improve thermal sensation and thermal comfort, a test campaign took place on September 2023.

The tests had the objective of measuring prototype performance by placing participants in an unchanging thermal environment, having them use the prototype for a section of the test and collecting thermal sensation and comfort data. A hot environment was chosen to provide a realistic use case for the LCG where the cooling effect is noticeable.

Nine healthy participants, seven males and two females, volunteered for the experiment. The mean age was 25.2 years with a standard deviation of 1.1 years, average height was 177 cm with standard deviation of 8.5 cm, and the average weight was 73 kg with standard deviation of 15.8 kg. None of the participants were on medication of any kind. All of them were asked to dress in long pants, short sleeved shirts and everyday sport shoes.

In each 90 minute experiment, the volunteers participated in prototype evaluation. An uncomfortably hot but not unbearable temperature of 31°C was chosen as the constant test condition for the whole duration of the test. 31°C is a temperature where local cooling of the back has been found to be sufficient in providing thermal comfort[Zhao, 2022].

Humidity was not explicitly controlled.

The clothing was chosen to represent typical office wear and provided a consistent thermal resistance between tests, giving a clothing insulation value of approximately 0.7 *clo* [Tartarini et al., 2020]. The sedentary activity offered a metabolic rate of circa 1.2 *met*; These values along with the operative temperature of the room relates to a Predicted Mean Vote of 2 (Warm) as calculated by the CBE Thermal Comfort Tool set to the ASHRAE standard. [Tartarini et al., 2020]

The experiment consisted of a 30 minute acclimation period followed by a 60 minute active testing phase. Participants entered the room and kept their regular clothes for the first 30 minutes, then wore the cooling garment on top of their clothes and remained in the room for 60 more minutes. Figure 3.1 shows the procedure and timestamps for each test. The duration was chosen to be long enough as to permit acclimation and testing.

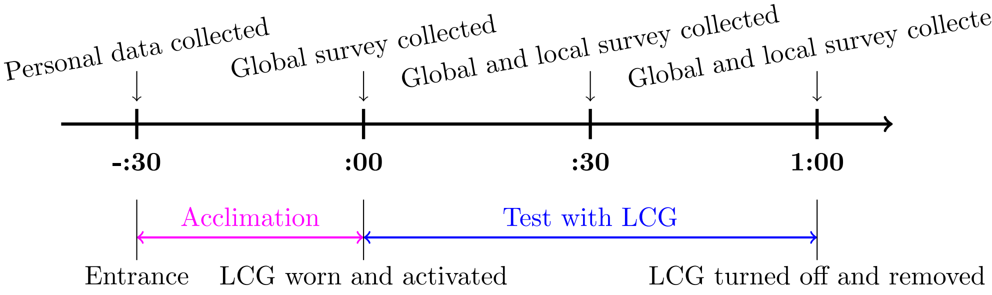


Figure 3.1: Timeline of each test showing events and type of collected data at each half hour

The main method for determining effectiveness was collecting subjective data through a series of questions. Participants completed questionnaires every 30 minutes to provide thermal comfort evaluation, both local and global. These questionnaires allowed data collection and evaluation throughout the experiment, allowing comparisons in the data analysis stage.

Referring to ASHRAE 55, sensations regarding temperature are expressed on a sensation scale ranging from -3 to +3 corresponding to the categories ”cold”, ”cool”, ”slightly cool”, ”neutral”, ”slight warm”, ”warm”, and ”hot”, identified as Thermal Sensation Vote or TSV. Comfort is divided in four levels, each corresponding to a different numerical value ranging from 0 to 3 corresponding to ”Comfortable”, ”Slightly uncomfortable”, ”Uncomfortable” and ”Extremely uncomfortable”, identified as Thermal Comfort Vote or TCV. [ASHRAE, 2020]

Since preferences regarding the thermal environment can be varied and different people can be comfortable in different situations without necessarily describing them as ”neutral”, thermal relationship to one’s environment is typically divided in three levels:

1. Temperature related: how cool or warm one feels globally or in a particular spot
2. Comfort related: how pleasant the global or local sensation is
3. Preference related: whether it would be desirable for the body or segment to feel cooler or warmer

The surveys concerned the first two levels: questions concerned thermal feeling (primary) and thermal comfort (secondary). The questionnaires are available in fac-simile in the appendix; global and local comfort were split, and local comfort was divided into warm and cold sensations. Table 3.1 contains the questions concerning global feeling and comfort. At no point did any participant choose the *I don’t know / I can’t define it* option.

Table 3.1: Questions concerning global sensations and the score they refer to

	How do you feel at this precise moment?		**How do you find this feeling?**
-3	Very cold	0	Comfortable
-2	Cold	1	Slightly uncomfortable
-1	Slightly cool	2	Uncomfortable
0	Neither cold nor hot, neutral	3	Extremely uncomfortable
1	Slightly warm		[**Thermal Comfort Vote**]
2	Hot		
3	Very hot		
X	I don’t know / I can’t define it		
	[**Thermal Sensation Vote**]		

The global questions follow the ASHRAE 55 standard from [ASHRAE, 2020] and they are consistent with decades of research, being first proposed by [Gagge et al., 1967].

Table 3.2 contains the questions concerning local feeling and comfort, separated between questions concerning cold and warmth.

Questions about air quality were included and are reported in table 3.3. They are not relevant to the test results

The tests took place on three different days, in the morning, early and late afternoon. An assistant was present in the chamber at all times to refill the ice bucket, turn on and off the

Table 3.2: Questions concerning local sensations

Do you feel hot or warm in one or more specific parts of the body?

- Yes
- No

In which one(s) do you feel a hot/warm sensation?

Head/Face Neck/Back of the head Chest Back Arms
Hands Thighs/Legs above knees Calves/Legs below knees Ankles/Feet

How do you feel that/those part/parts of the body in this precise moment?

1 Slightly warm
2 Hot
3 Very hot

Do you find this feeling...?

0 Comfortable
1 Slightly uncomfortable
2 Uncomfortable
3 Extremely uncomfortable

Do you feel cold or cool in one or more specific parts of the body?

- Yes
- No

In which one(s) do you feel a cold/cool sensation?

Head/Face Neck/Back of the head Chest Back Arms
Hands Thighs/Legs above knees Calves/Legs below knees Ankles/Feet

How do you feel that/those part/parts of the body in this precise moment?

1 Slightly cool
2 Cold
3 Very cold

Do you find this feeling...?

0 Comfortable
1 Slightly uncomfortable
2 Uncomfortable
3 Extremely uncomfortable

Table 3.3: Questions concerning air quality

Do you find the air to be...?
- Fresh
- Slightly stuffy
- Stuffy
- Very stuffy

Referring to your answer, how would you define the indoor air?
- Clearly acceptable
- Acceptable
- Just acceptable
- Just unacceptable
- Clearly unacceptable

Do you find the air smelly?
- Yes
- No

pump when asked and check on volunteers' needs. The activity chosen was sedentary activity akin to light office work.

The thermal dummy was set at 180W to simulate the presence of two people before the entrance of each participant and the assistant; once the two people entered the room, the dummy was turned off. This was done to maintain the thermal balance of the room before and after the entrance of the room occupants without needing to modify hydronic or ventilation parameters.

3.2 Room performance analysis

The surfaces used for the tests were the floor, north and south panels. Water inlet in all three hydronic circuits was set at 32°C to maintain the desired temperature and control the radiant heat environment.

Ventilation was set at 160 $\frac{m^3}{h}$, providing an estimated 3 ACH (air changes per hour) in the approximately 50 m^3 room to ensure good air quality.

Humidity was not explicitly controlled but was measured using three different sensors; it varied little between tests, with a mean value of 42.2% and standard deviation of 3.9% (measurement time-step 15 seconds).

The room needed several hours to reach thermal balance once set, but its consistency was noted and kept the numbers of tests to three per day.

The operative temperature was chosen to represent the thermal environment; obtained by averaging air temperature at the centre of the room and mean radiant temperature, it is the temperature most useful for PMV calculation [Tartarini et al., 2020]. Figure 3.2 and table 3.4 show the uniformity of the thermal environment: operative temperature does not deviate much from 31°C, with standard deviations always being lower than 0.2°C.

Results show the CORE-CARE room was perfectly suited for the experiments: as the figures indicate, it was able to maintain an extremely stable environment consistent between tests.

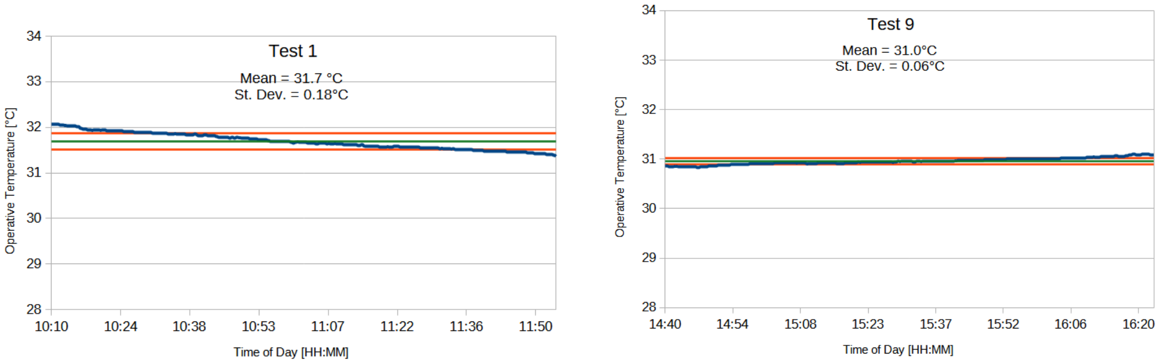


Figure 3.2: Temperatures measured during first and last tests, mean and standard deviation

Test	1	2	3	4	5	6	7	8	9
Mean t. [°C]	31.69	30.88	30.83	31.09	30.09	30.91	31.05	30.92	30.96
St. Dev. [°C]	0.18	0.16	0.03	0.03	0.07	0.09	0.07	0.10	0.06

Table 3.4: Mean and standard deviation of operative temperature in the room for all tests

3.3 Data and results

Every participant completed the full 90 minute experiment, filling out questionnaires (see Appendix) at required moments, describing global and local thermal perception, global and local thermal comfort and air quality evaluation.

The data was transcribed into spreadsheets by hand to enable digital data analysis and chart generation.

Responses regarding global feeling and comfort at acclimation were the first ones taken into account. After acclimation, most participants found the room *hot* and *slightly uncomfortable*, none of them found it *very hot* or *extremely uncomfortable*, three out of nine participants found it comfortable and one also found it to be thermally neutral. Figure 3.3 has the breakdown of the responses describing the environment after acclimation.

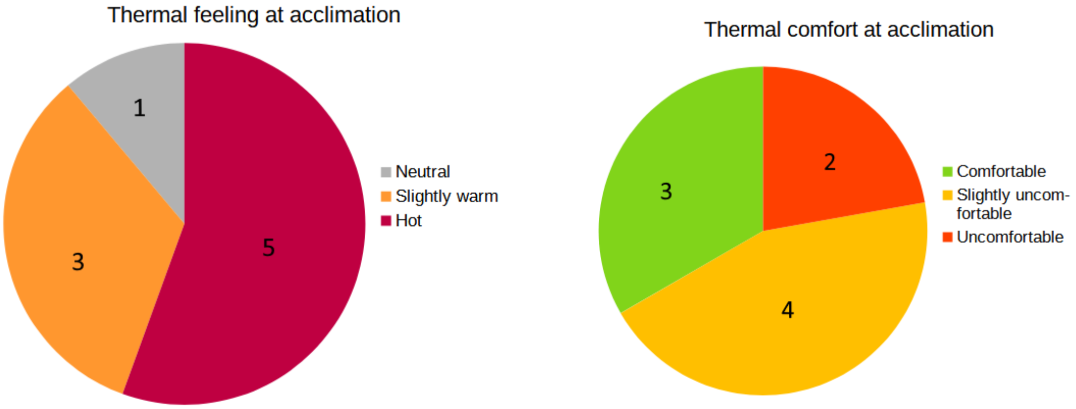


Figure 3.3: Responses describing global thermal feeling and comfort at acclimation

The thermal environment was set to provide an uncomfortable hot sensation, described by a Predicted Mean Vote of 2. This was done to provide a non neutral sensation and a realistic setting for LCG employment.

Most participants find the room hot, consistent with the PMV of 2; despite this, three out of nine participants found it comfortable and one of the three found it thermally neutral. This was unexpected and could be related to mid-term seasonal acclimation to heat, as the tests took place in early September after a hot and humid summer.

Bulk data was used to generate differential observations: since the environment remains constant during the experiment and participants are polled after having been given time to acclimate to the heat, the only significant differences are directly linked to LCG usage.

The objective of a PCS is to improve comfort, in the case of cooling garments by lowering the perceived temperature; numerically, this results in the decrease of the reported value. Hence the main parameter studied was the difference in feeling and comfort and its evolution over time: the first two rows of table 3.5 and 3.6 show the breakdown of response difference after 30 and 60 minutes wearing the LCG and figures 3.5 and 3.6 group the answers in positive, negative or neutral.

Water temperature was measured in two tests and is shown in figure 3.4. It remains significantly higher than the melting point of ice even as more ice is added during the course of the experiment. Temperature on the surface of the pipes remains significantly higher than the mixture temperature due to thermal losses and thermal resistance of the pipes themselves.

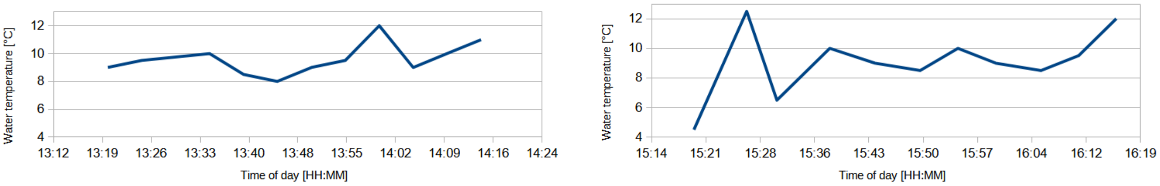


Figure 3.4: Water temperature during two tests, measured with an immersion thermometer

The results considered here concern the breakdown of response differences in sensation and comfort after specific time intervals. Responses from a single test were compared to analyse evolution of feeling and comfort. For example, a response evolving from ”warm” to ”neutral” is represented by a value of -1. Negative numbers indicate decreased hot sensations in table 3.5 and improved comfort in table 3.6, meaning negative numbers indicate a desirable outcome in both tables.

Asterisks indicate tests where the participant turned off the pump; in both cases the perceived temperature is lower at 60 minutes, despite the prototype being on for a small duration of the test.

It is clear that the effect on thermal sensation is more consistent and widespread compared to the effect on thermal comfort; this demonstrates the effectiveness of the prototype at cooling the user, and the increase in average comfort means it does so in a way that is not uncomfortable for most participants.

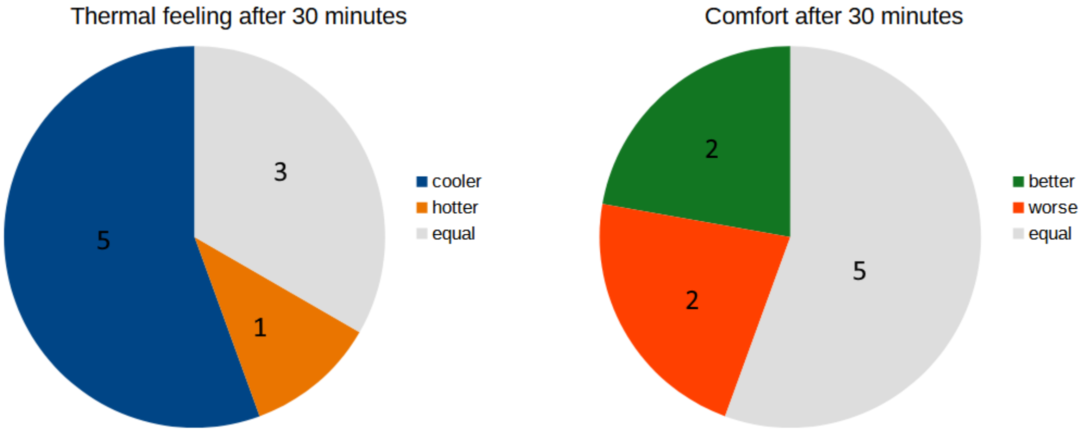


Figure 3.5: Thermal feeling and global comfort comparison between 30 minutes and the start

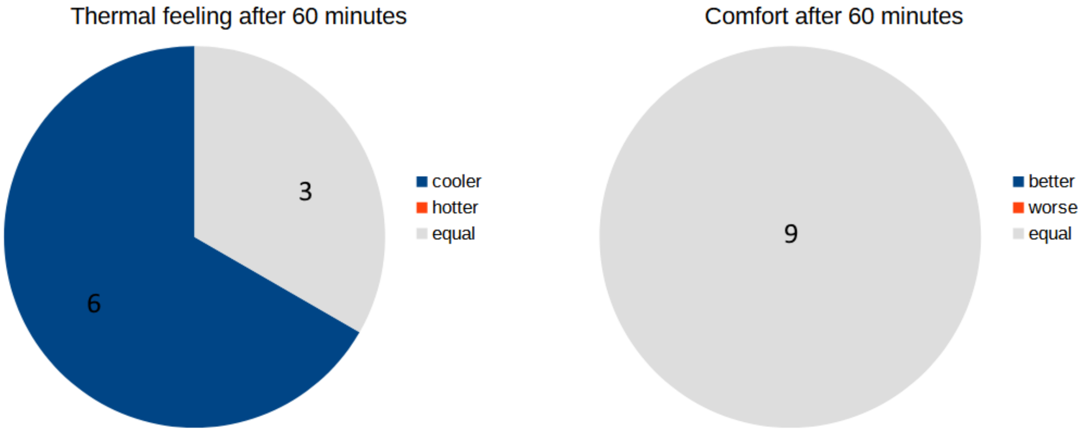


Figure 3.6: Thermal feeling and global comfort comparison between 60 minutes and the start

These results show the garment is generally well received: wearing it immediately impacted thermal feeling, causing individuals to feel cooler immediately, with measurable effects within the first 30 minutes.

Tables 3.5 and 3.6 are of particular interest: they compare different responses in different moments for each different test, showing minimal adverse effects and a generally positive cooling effect. The increase in thermal feeling seen in some tests could be related to an exaggerated bodily response to cold that causes a rise in metabolism.

Table 3.5: Difference in global thermal sensation between different moments of the test

	1*	**2**	**3**	**4**	**5**	**6***	**7**	**8**	**9**	
30min vs. start	0	-1	0	-1	-1	0	-2	1	-1	useful to judge initial cooling power
60min vs. start	-2	-1	0	0	-1	-1	-2	0	-1	useful to judge longer term cooling
60min vs. 30min	-2	0	0	1	0	-1	0	-1	0	useful to notice cooling power decrease

Table 3.6: Difference in global comfort between different moments of the test

	1*	**2**	**3**	**4**	**5**	**6***	**7**	**8**	**9**	
30min vs. start	0	0	0	0	-2	-1	1	1	0	useful to judge initial comfort increase
60min vs. start	0	0	0	0	-2	-1	1	0	0	useful to judge longer term comfort
60min vs. 30min	0	0	0	0	0	0	0	-1	0	useful to notice increase in discomfort

Using the LCG resulted in a lower thermal feeling score, which is expected and desirable, as well as causing average comfort score to evolve positively, which is desirable too. Histograms in figure 3.7 show the average and standard deviation in global feeling and comfort in the various stages of the experiment.

A noticeable trend towards cool and comfortable perception is immediately visible. The standard deviation of comfort lowers as different statuses of comfort at acclimation trend towards a more uniform, less uncomfortable condition.

The time frame is large enough to show progression in the perception of the garment: responses at 60 and 30 minutes can be compared to see how the perception of the garment evolves over time. Since the garment runs nominally for the whole experiment unless turned off, this comfort is expected to remain approximately constant. The third row of tables 3.5 and 3.6 show this evolution, as well as figure 3.8.

Part of the questionnaire concerned local sensations, and data analysis also concerned local

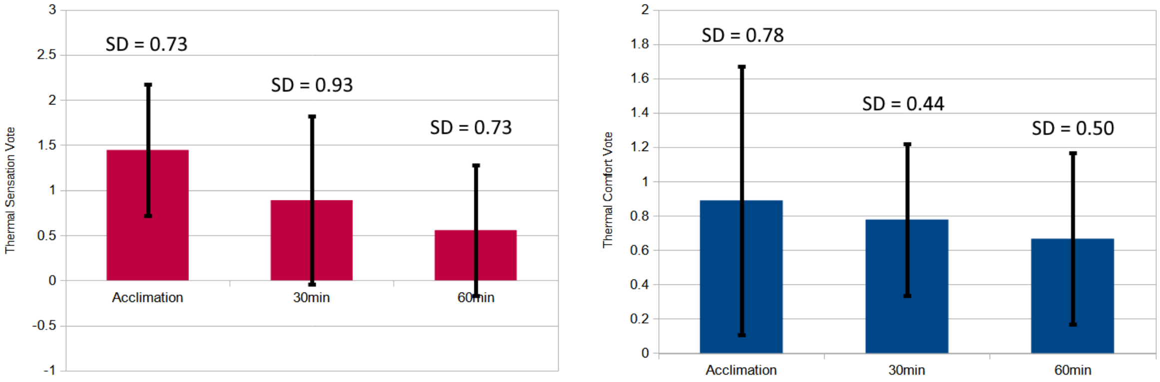


Figure 3.7: Average values and standard deviations for thermal feeling and comfort using ASHRAE scales of TSV and TCV

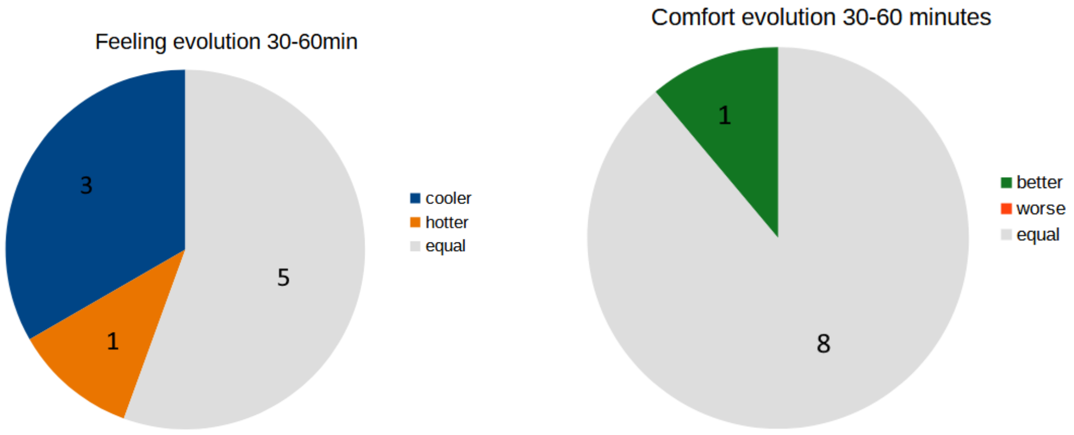


Figure 3.8: Evolution of thermal feeling and comfort at the global level
The garment does not become less effective or uncomfortable

feeling and comfort.

Only two data points per test concern local discomfort, but the granular nature of local data enables more detailed analysis: to analyse the evolution of thermal feeling related to warmth and cold, the thermal sensation on every body part is considered.

Each body part in each test is given a numerical value: considering cool sensations, the score is 0 for no response given, 1 for slightly cool, 2 for cold, 3 for very cold; considering warm sensations, the score is 0 for no response given, 1 for slightly warm, 2 for hot, 3 for very hot.

The sum of these sensations in all tests is then considered, and reported in tables 3.7 and 3.8. Notice that numbers above 9 are due to the fact several participants judged a sensation as ”hot” or ”cold”.

Table 3.7: Sum of warm sensations between tests

Warm sensations at 30 minutes

Head/face	6
Neck/nape	1
Chest	4
Arms	2
Thighs	10
Calves	7
Ankles/feet	3

Warm sensations at 60 minutes

Head/face	4
Neck/nape	4
Chest	2
Arms	2
Thighs	8
Calves	5
Ankles/feet	3

Table 3.8: Sum of cool sensations between tests

Cool sensations at 30 minutes

Chest	1
Back	12
Calves	2

Cool sensations at 60 minutes

Chest	1
Back	9

The evolution of local thermal sensations was analysed by taking the local answers for each test and analysing their evolution.

A positive trend in local sensation can be seen in figures 3.9 and 3.10: both sensations of local warmth and local cold tend to get less intense over time.

The body parts most reported as warm or hot were the thighs ($\Sigma = 10$ at 30min and 8 at 60min), calves at 7 and 5 and head at 6 and 4. The only consistently cold body part felt was the back, as it was the part directly targeted.

Part of the test concerned pump switching: all of the participants were informed that the device could be turned on and off at will, but only two out of nine turned it off for a significant amount of time. Operation of the switch was noted by the assistant with timestamps; figure 3.11 shows usage in these two tests.

To understand what could be related to choosing to deactivate the cooling effect, a subject analysis based on personal data and questionnaire responses took place. One of the two subjects was the shortest and lightest amongst men while the other was inside one σ of the average, and while it is no doubt related to the small sample size of the study, discrimination solely based on body size is not adequate.

Extracting the responses from these two participants shows that even with the cooling effect

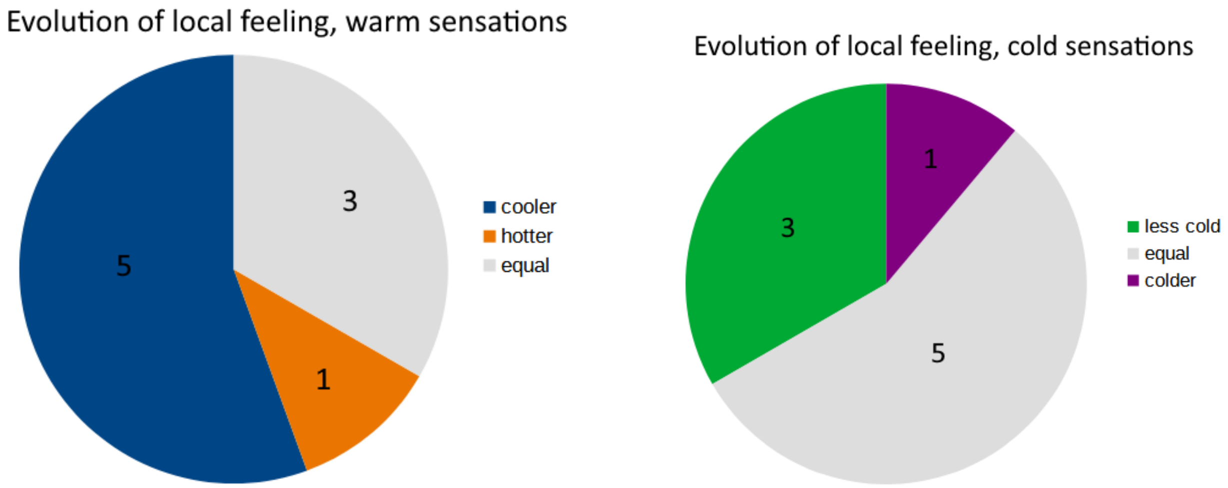


Figure 3.9: Evolution of local thermal feelings resulting from the analysis of hot and cold local sensations

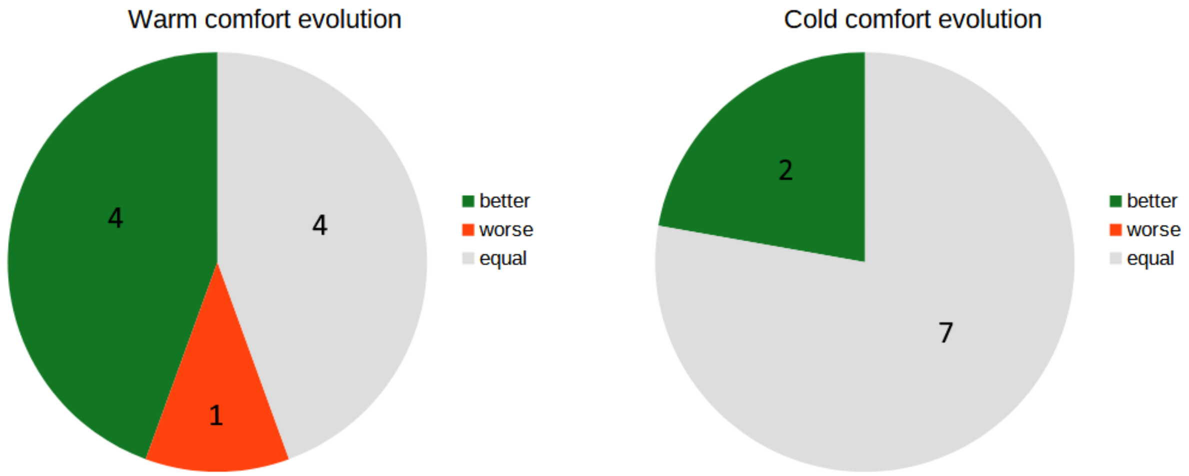


Figure 3.10: Evolution of thermal comfort regarding hot and cold sensations

switched off for the remainder of the test a positive effect on thermal feeling and comfort is present.

Three participants complained about an unpleasant smell in the test chamber, specifically 6, 8 and 9, with just participant 6 elaborating on that and describing the smell as chemical. Only number 9 noted the air as being smelly at the end of the test too. As the test was concerned with thermal feelings and not with air quality, these responses should have minimal impact on the other results.

None of the participants reported high levels of discomfort at any point of the experiment.

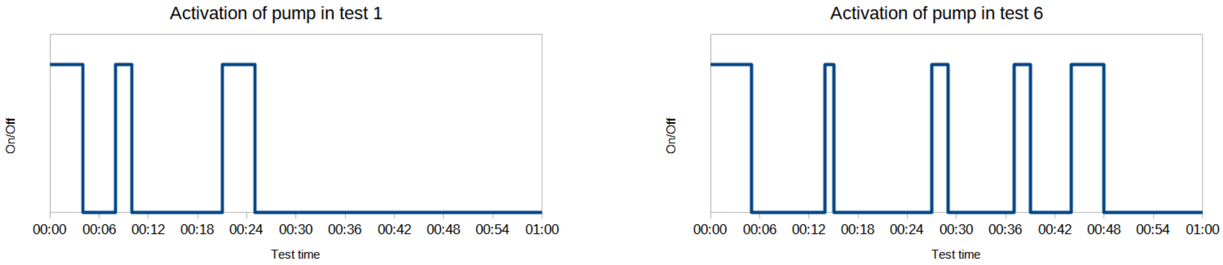


Figure 3.11: Pump activity in relevant tests

An expected source of discomfort was condensation, but most tests saw little to no wetness perception by volunteers. Some tests had visible condensation on tubes, but nobody reported feeling it. Clothes were checked after the test if water was visible on the garment; in none of these cases the underlying clothing got wet. This lack of condensation is caused by the relatively high surface temperature of the tubing and the low relative humidity.

Several participants complained about the thread used to maximize tube contact, specifically the upper one. No significant difference was seen based on gender or shirt size in this specific discomfort.

During testing, participants were welcomed to provide feedback and opinions regarding the prototype: all 9 mentioned a significant cooling effect immediately after the prototype was connected. Numerical responses did not reflect this even at the 30 minute mark, with several participants reporting the same TSV. Were the tests to be repeated, a questionnaire should be given at the 5 minute mark to take this immediate cooling into account.

Participants welcomed the idea of being able to turn on and off the cooling effect, though just two of them used it actively. The two subjects who did reported a positive effect on thermal feeling and comfort which lasted for the remainder of the test.

Several participants complained about uneven cooling, whether left to right, up to down or localised in corners. This could be improved with a different tubing configuration or a higher flow rate.

Participant 1 immediately described the cooling effect as too strong and specifically pointed to the top left as the coolest spot.

Participants 2 and 3 reported nothing of significance during the test.

Participant 4 wanted to walk a few paces during the test, and found the tubing not uncomfortable despite it limiting their movements.

Participant 5 was pleasantly surprised at the immediate cooling action and reported feeling the lower back as the cooler half.

Participant 6 described the cooling effect as pleasant and helpful towards concentration but too localised, specifically complaining about warm shoulders and arms.

Participant 7 immediately felt a pleasant freshness when the device was worn and the pump was turned on, but complained about garment fit.

Participant 8 complained about a cold feeling on the chest where the thread was, describing varying sensation on the back ranging from cold to almost warm.

Participant 9 reported nothing of significance during the test.

3.4 Conclusions

This thesis described the state of the art of human thermal comfort research, models for heat transfer between human bodies and their environment, different Personal Cooling System technologies and controlled environment facilities. It covered design and construction of a Liquid Cooled Garment using off-the-shelf components, properties of the liquid circulation system and CORE-CARE facility specifics. It also described the experimental procedure, participants, results and data analysis performed in the test campaign of the prototype.

The prototype consisted of a novel two phase approach to liquid cooling, focusing on proven areas of thermal comfort and exploring the possibility of user control over cooling action.

The performed tests involved nine participants subjected to a PMV of 2 for 30 minutes of acclimation and 60 of active testing, using the CORE-CARE facility.

Results show promise, as thermal feeling is positively affected while thermal comfort is not impacted in any negative way. Users also appreciated having control over the performance of the garment, although only a minority actually chose to act on this.

The main findings of the work are:

1. LCG design is still in its infancy
2. Technological advancement has lowered the barrier to entry to LCG design considerably
3. User control systems enhance LCG user experience
4. Thermal feeling is consistently improved even by simple LCG designs
5. The potential application space for LCGs is unbounded

Based on subjective responses, the sudden cooling offers relief and comfort in contrast to the pre-existing warmth. Over time, as the body adjusted to the garment's temperature, the body becomes used to the sensation and the perceived level of comfort returns to baseline because the individuals acclimated to the new conditions.

The study is mainly limited in the low number of participants, no comparative studies to draw references from and lack of design iterations. The experimental nature of the prototype leaves multiple avenues for improvement in future works.

Potential improvements could concern the garment itself, thermal design and the test campaign.

Garment comfort could be improved by using elastic bands for a tight fit and manufacturing models of differing sizes.

Better portability and maintenance could be achieved through a machine-sewn and washable design, a more compact and portable ice water reservoir and a fully battery powered pump.

Enhanced insulation to the environment would lower thermal losses, improving the efficiency of the device and enabling smaller designs or longer times between recharges.

Water-skin thermal resistance could be lowered by moving from the simple tube design for the liquid-user thermal interface to more complex geometries inspired by plate heat exchangers. These improvements would raise the cooling power of the device, potentially making throttling desirable to maintain user comfort. Improving thermal interface could also reduce cold and warm spots.

Concerning the test campaign, future research could obtain detailed information about participants habits, such as personal fitness, local feeling at acclimation, behavioural habits and AC usage. Comparative testing against other solutions would be ideal.

In conclusion, the garment works well. Thermal sensation is consistently cooler for most subjects with no added discomfort. Response from participants is positive, the garment is appreciated and this is reflected in the numerical results. The option of turning it off and on was appreciated, though just two participants made use of it. A consistent positive trend in both local and global thermal feeling and thermal comfort can be observed; it is reasonable to assume the body grows accustomed to the cooling action of the garment and reacts positively when the stimulus is not extreme.

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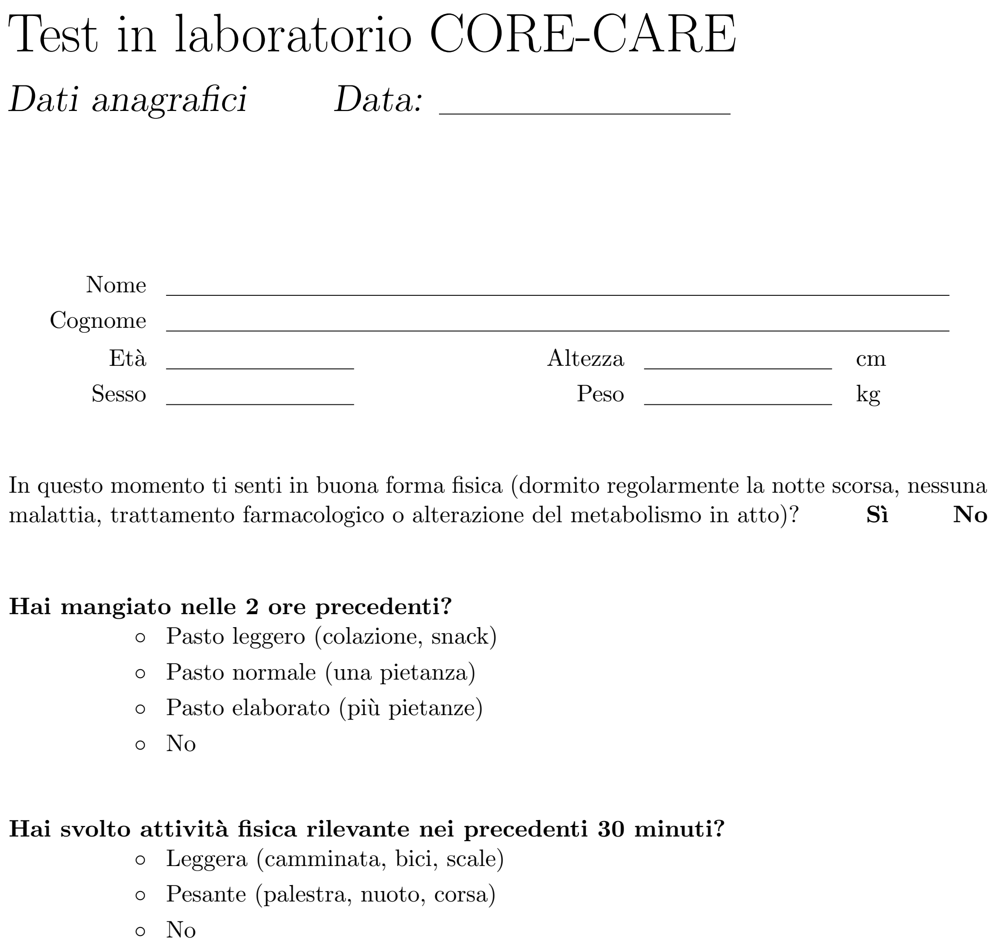
Appendix: questionnaires given to participants



Test in laboratorio CORE-CARE

Dati anagrafici *Data:* ________________

Nome ____

Cognome ____

Età ____________ Altezza ____________ cm

Sesso ____________ Peso ____________ kg

In questo momento ti senti in buona forma fisica (dormito regolarmente la notte scorsa, nessuna malattia, trattamento farmacologico o alterazione del metabolismo in atto)? **Sì** **No**

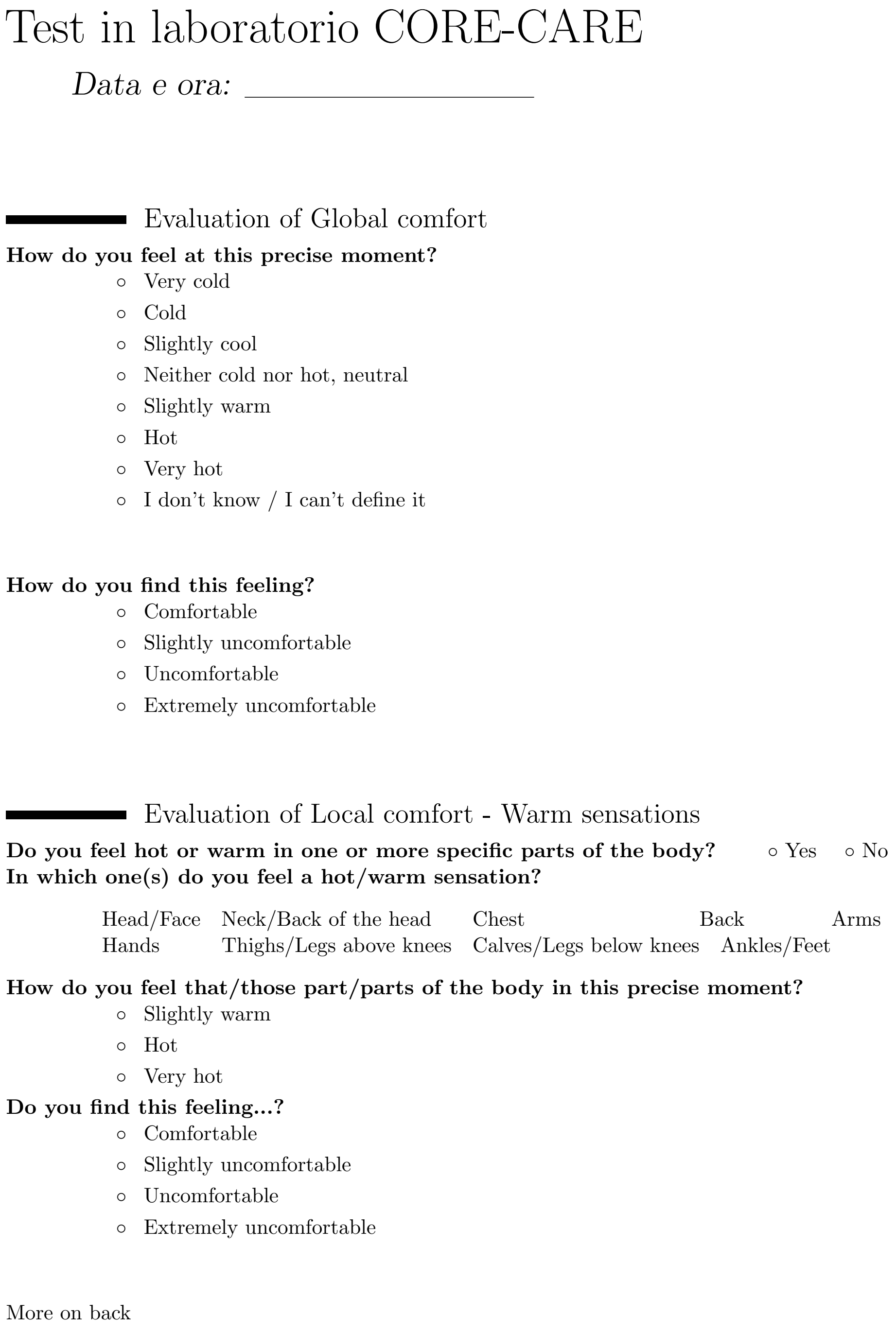
Hai mangiato nelle 2 ore precedenti?

○ Pasto leggero (colazione, snack)
○ Pasto normale (una pietanza)
○ Pasto elaborato (più pietanze)
○ No

Hai svolto attività fisica rilevante nei precedenti 30 minuti?

○ Leggera (camminata, bici, scale)
○ Pesante (palestra, nuoto, corsa)
○ No

Figure 3.12: Personal data, collected at start



Test in laboratorio CORE-CARE

Data e ora: ____________________

Evaluation of Global comfort

How do you feel at this precise moment?

- ○ Very cold
- ○ Cold
- ○ Slightly cool
- ○ Neither cold nor hot, neutral
- ○ Slightly warm
- ○ Hot
- ○ Very hot
- ○ I don't know / I can't define it

How do you find this feeling?

- ○ Comfortable
- ○ Slightly uncomfortable
- ○ Uncomfortable
- ○ Extremely uncomfortable

Evaluation of Local comfort - Warm sensations

Do you feel hot or warm in one or more specific parts of the body? ○ Yes ○ No

In which one(s) do you feel a hot/warm sensation?

Head/Face	Neck/Back of the head	Chest	Back	Arms
Hands	Thighs/Legs above knees	Calves/Legs below knees	Ankles/Feet	

How do you feel that/those part/parts of the body in this precise moment?

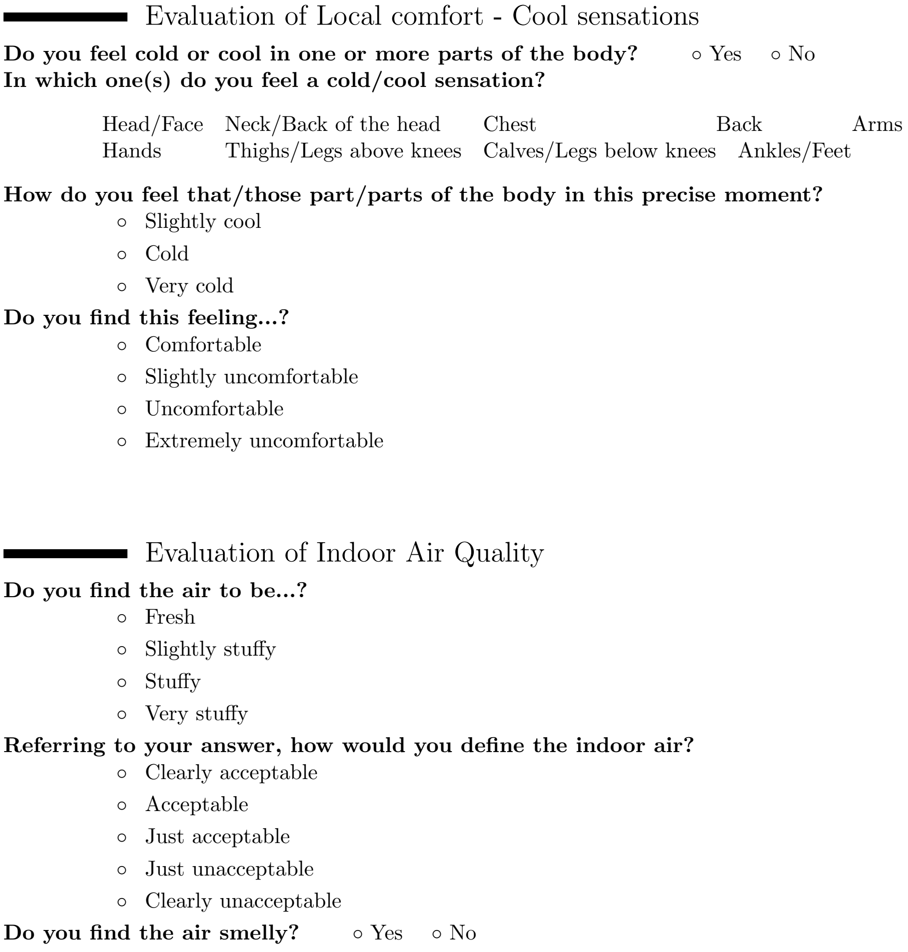
- ○ Slightly warm
- ○ Hot
- ○ Very hot

Do you find this feeling...?

- ○ Comfortable
- ○ Slightly uncomfortable
- ○ Uncomfortable
- ○ Extremely uncomfortable

More on back

Figure 3.13: Global and local survey for thermal feeling and comfort; global survey collected at 0, 30 and 60 minutes of test, local survey collected at 30 and 60 minutes of test; page 1



Evaluation of Local comfort - Cool sensations

Do you feel cold or cool in one or more parts of the body? ○ Yes ○ No

In which one(s) do you feel a cold/cool sensation?

Head/Face Neck/Back of the head Chest Back Arms

Hands Thighs/Legs above knees Calves/Legs below knees Ankles/Feet

How do you feel that/those part/parts of the body in this precise moment?

○ Slightly cool

○ Cold

○ Very cold

Do you find this feeling...?

○ Comfortable

○ Slightly uncomfortable

○ Uncomfortable

○ Extremely uncomfortable

Evaluation of Indoor Air Quality

Do you find the air to be...?

○ Fresh

○ Slightly stuffy

○ Stuffy

○ Very stuffy

Referring to your answer, how would you define the indoor air?

○ Clearly acceptable

○ Acceptable

○ Just acceptable

○ Just unacceptable

○ Clearly unacceptable

Do you find the air smelly? ○ Yes ○ No

Figure 3.14: Global and local survey for thermal feeling and comfort; global survey collected at 0, 30 and 60 minutes of test, local survey collected at 30 and 60 minutes of test; page 2

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