A Meta-Analysis on the Advancement on the Thermodynamic Properties of Clothing in Extreme Cold Environments

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Abstract: When two systems with different energies are in contact, the heat from the higher energy system will move into the lower energy system and the two will reach equilibrium. Humans in extreme cold environments will perish if they do not keep appropriate heat contained within their system and thus it is the object of much historic research to maintain heat within a system for as long as possible. Research and development of cold weather clothing focuses on a range of methods regulating heat flow between clothing layers. Modern research focuses on air gaps between layers of clothing, development of new conventional insulating textiles and contemporary solutions such as the use of Phases Change [1]. The purpose of this paper is to conglomerate all of the current research into one meta-analysis highlighting the gaps in the research and potential areas in need of further study, and to propose a new article of cold weather apparel utilizing the most effective advancements from the papers collected in this study. It was found that each component of cold climate clothing affects an aspect of thermal resistivity. Thickness affects the windchill resistance, the specific heat increases thermal resistance of the fabric, while humidity increases thermal conductivity, air gaps reduce it and the rigidity affects all of these factors. Our findings suggest if the air gaps are above 8 mm, natural convection currents can occur which increase the thermal and moisture transfer between clothing layers. By analysing all of these factors, a new prototype garment was able to be proposed.

Keywords: Cold environment; clothing; thermoregulation.

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1. Introduction

Since its inception, clothing has been used to protect humans from the environment. As people encountered new, colder and harsher environments, new advancements came in the form of naturally available insulating materials such as fur or wool. Since then, synthetic materials have been developed in place of traditional insulators, and recent research in the scope of this paper has focused on developments such as Phase Change materials, materials with a high heat of fusion that make them able to store large amounts of energy [2,1]; Chemical solutions that can be applied to the outer layer of clothing to increase the thermal resistance of the clothing [3]; and advancements in conventional insulating materials, determining the effect of different parameters on the effectiveness of an article of clothing as an insulator.

The thermal properties of a material are largely dependent on the size of air gaps within the textile, as the transfer of heat is slowed down by air gaps compared to solid materials [4]. A large number of the papers focus on methods of measuring or predicting the size of air gaps in clothing using a variety of methods, such as an artificial neural networks.

By finding the optimal methods of insulating against the cold, and combining these findings into a proposed article of cold weather apparel, we can use mathematical modelling to predict the efficacy of this theoretical apparel and compare it with existing clothing.

2. Methods

In order to undertake a meta-study on the topic of cold climate clothing, an investigation was undertaken to determine the largest contributing factors of thermal insulation in clothing. The literature for this Meta-study was sourced from multiple databases including Scopus, Proquest, Web of Science, Google Scholar and Elsevier using keywords such as thermoregulation, cold climate clothing and multilayer clothing. To ensure the most relevant information was sourced, no literature older than 10 years was considered. The meta study was then conducted on the factors which have the greatest effect on the thermal resistivity of apparel. The 6 factors were; thickness, specific heat, humidity, convection currents, rigidity and air gap size. Each paper was tabulated based on which of these factors they considered in their research (Appendix A) so a comparison could be drawn. Each factor was then broken down, and solutions to each of them were compared systematically and quantitatively to ascertain the most effective method to solve each factor. Once the optimal solution for each factor had been determined, a prototype garment was suggested for further research based on these solutions which utilises the most effective aspect of all the components. Papers that dealt with topics not strictly related to the materials in clothing were also considered where they were relevant to thermodynamics, addressing other factors related to thermal insulation such as optimal air gap size and humidity.

Data tables given in the papers were collated and examined to see if there were any existing relationships between variables that could be assessed, and the different papers' methods of insulation against the cold were quantitatively analysed to determine which of the materials in development were the most promising, and therefore in warrant of further research.

3. Results and Discussion

In multilayer clothing, there are two main aspects which affect thermal conductivity. As such, the results have been broken down into these two sections, Material thermal properties and Non-material thermal properties.

3.1 Material properties

3.1.1 Thickness

Modern cold climate clothing is affected minimally by the thickness of the material, due to the fact that most layers of clothing are ~1 mm thick [5]. When compared to contemporary counterparts, which had an average compressed thickness of a 1-2 cm (and uncompressed, up to 15 cm), it becomes clear that the thickness of modern clothing has a minimal effect on the overall thermal resistivity. Modern clothing is an order of magnitude thinner, and as such plays a very small role, instead aspects such as specific heat, water retention, and weight become of more concern.

In a certain polyester-cotton blends, the thickness of the fabric only accounted for 1% of the thermal resistivity of the textile, whereas the specific heat of yarn contributed to 29% of overall thermal resistivity [4]. Air is a better thermal insulator than fabric as less energy is required to maintain the skin temperature [6] due to it air having a lower density. Due to its minimal effect on the system most papers assessed used the material thicknesses as a control or standard for other calculations in the experiment, where their effect on the thermal resistivity is too negligible to merit measurement. This aligns well with the information gathered and supplies an explanation for how modern apparel are both thinner and more effective than older cold climate clothes. [4,6]. Alternatively, thicker materials have been found to increase protection against wind chill, including a web-style layering, which was an effective way for increasing thermal insulation, since it increased air layer size without adding proportionally to the weight or to the thickness of the wadding [7], so whilst not being in the scope of this meta study it could potentially warrant further investigation. However, when wind chill is investigated, it is often found that, archaic apparel held the heat better against the wind than modern clothing, even with the batting method outlined previously [7]. It is well established that the best method to combat windchill is to supply a buffering layer.

3.1.2 Specific heat

The thermal properties of a material (specific heat, latent heat and porosity) greatly affect the total thermal resistivity of a material [6]. As mentioned previously, 29% of all contributions to thermal resistance come from the specific heat of the material [4]. Aiming to address the issue of overheating in cold climate clothing, researchers investigating the use of Phase Change Materials in cold weather apparel found that using n-Octa-decane within a PMMA-Silica shell suspended inside the apparel affected the latent heat. Another major parameter that determines the thermal insulation is the porosity of the material. Porosity was used in one of the focus papers to simulate how quickly warm air escapes cold climate clothing based on the porosity of the material [8]. It was found that porosity only affects heat radiation and mass diffusion properties. Other researchers used an equation to calculate the effective thermal conductivity of the fabric layer [6], which equates the effective thermal conductivity of the fabric layer to porosity and the thermal conductivity of clothing fibers and air, illustrating the effect that porosity has on thermal resistivity.

Although porosity has a demonstrable effect on the thermal regulation of apparel, it's often overlooked in experimentation, due to it being an innate property of a material. The only way to change porosity in most cases, is to change the material. We found that the only researchers interested in this property are those constructing mathematical or statistical models of clothing who require accurate values for different porosity values [9].

As mentioned above, the reason that specific heat has such a large effect on the thermal resistivity of the fabric is due to the relative thickness of the fabric being so small [4]. The specific heat determines how much fabric is required to maintain a surface body temperature above the surrounding environment [5]. By having a larger specific heat less material is required to achieve the same result and thus modern materials with high specific heats allow garments to shrink dramatically in thickness. This can however lead to an overheating issue inside the garment, which is the issue that had been resolved in one of the papers [1] . PCMs are a relatively new research area, however with modern clothing becoming more and more effective at insulating people from the cold, overheating in cold climate clothing is quickly becoming a legitimate concern [1]. The PCMs allow a deeper level of control to be maintained within the clothing system by using the heat to change the phase of the SiO_2 from solid to liquid. With this incorporated into clothing, it is possible to create apparel which is suited for unpredictable weather conditions or for winter sport athletes, making this potential research into this field very valuable.

3.1.3 Rigidity

Rigidity of the clothing plays a huge role in the thermal retention of clothing indirectly by affecting various other properties. Rigidity has been found to have a significant effect on the thermal retention of the apparel, due to the fact that air gap size is directly related to rigidity [10,5]. It was also found that plain woven fabrics are stiffer than jersey(rib) and interlock knitted fabrics (figure 1), which in turn resulted in larger air gaps, higher drape coefficients and a lower contact area, encouraging the generation of convection currents, which further diminish the thermal resistivity [11].

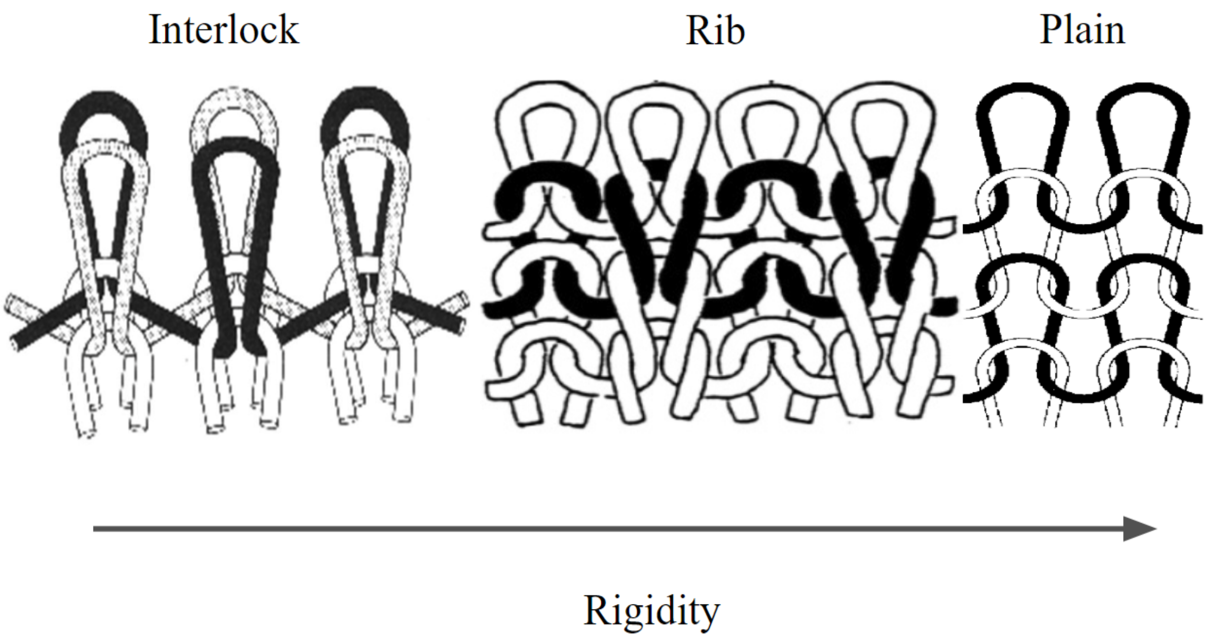

Figure 1. *Schematics of the different weave variations from least to most rigid. original images sourced from "knitted fabrics and their properties - slideshare' (interlock, rib), "research gate - schematic of plain knitted fabric"(plain).*

An increased workload from wearing less ergonomic, more stiff clothing has been found to result in an increased sweat output, increasing the humidity in the clothing [12]. If this is left unaccounted for, it can have drastic effects on the thermal conductivity of the material. These finding were quantified with mathematical models and calculations which further go to support the results, and also suggests that stiffer fabrics are more prone to shearing [13]. This concept is applied in another] study which assesses the rigidity of a new prototype material based on the fibres of bamboo. By studying the fiber's rigidity, a drape coefficient can be found and thus, an average air gap is then able to be modelled. It was also found that the individual fibers have a lower rigidity, resulting in a thinner fabric with the same thermo-resistive properties [14]. It was also observed that zippers alter the draping of the clothing due to its inherent stiffness, a concept only discussed in one paper [15]. Conversely, one paper assessed stated that there was no distinguishable correlation between rigidity and air gap size, which was the only assessed paper which came to this conclusion [16].

Rigidity plays an important role in air gap thickness due to how it affects the way the garment sits on the body [10,5]. A rigid fabric (such as one which has been pain-woven) will fall straight down the body, assuming straight, angled shapes [11]. An interlocked woven fabric follows the curves of the body more, 'hugging' the body much closer than the stiff plain-woven structure. the ribbed weave fits in between these two, allowing for moderate air gaps, while still following a reasonable amount of the body's natural curves [11]. Additionally, the increased rigidity increases workload, increasing the humidity due to sweating. This property can be utilised to create a more thermally resistant garment in extreme weather conditions where overheating is rare, however more commonly, it is going to be an issue worth avoiding as added humidity to the system will reduce the overall thermal resistivity [7]. In most cold work environments, a more flexible material is recommended as it's less prone to shearing if it gets caught on an object. A more flexible material will simply fold around the object instead of tearing or shearing. For this reason, Regenerated Bamboo Cellulose Fibers are an excellent clothing choice, as they're flexible, lightweight, thin and breathable [14]. Additionally, it has a high specific heat, meaning the fabric can be thinner than many modern alternatives, further reducing the weight and therefore workload. The concept of zippers complicates the system further, by adding a rigid strip down the length of the material, which may have unwanted effects on the thermal resistivity of the material [15].

3.2 Non-material Properties

3.2.1 Air gap:

It has been shown that thermal resistance increases with air gap thickness in a predictable manner [18]. It has been concluded that the optimum size for air gaps for clothing is 17 ±2.5 mm [3,9,18]. Considering that the average air gap size is 25-30 mm [19], new articles of clothing should have a smaller air gap, despite the data suggesting otherwise at an initial glance. By controlling the size of the air gap, the relationship between ease, the loosening of clothing due to excess material, can be quantitatively measured [20]. However, as mentioned above, the material plays a role in the air gap peak/plateau which would perhaps account for the air gap size disparity found in these studies. Further research into this area would allow us to determine the optimal air gap size for thermal resistance with greater certainty. It was also found that most regions of the body have a larger air gap when the humidity is at 40%. The abdomen had a peak thickness at 40%, and the lumbar at 60% humidity [10].

Air gap size is perhaps the single most important factor of modern cold climate clothing, directly affecting the thermal resistivity, humidity and size of the garment. It is also affected by almost all of the other parameters mentioned prior, with material thickness perhaps being the only exception. Because of this, being able to accurately measure the air gap of a garment is crucial to the testing of a new cold weather garment. Convective properties also play a significant role in determining the optimal air gap size in clothing. Although this likely varies slightly with different clothing materials, We were unable to find any current research into the effect that different materials have on optimum air gap size. Further research should be undertaken on this area to fully understand and quantify the relationship. The reason for the disparity between the results of our focus papers could potentially be explained through convective properties, suggesting that without convective properties, a larger air gap (up to 30 mm) would be ideal. However in a real-world scenario were natural convection occurs, the air gap should be between 17 ±2.5 mm [3,9,18].

3.2.2 Convection currents:

Convection is the result of moisture evaporation from the surface of the material or skin, and increased convection results in a larger loss of heat in cold climate clothing [6,21]. The lower air gap threshold for natural convection was 8-14 mm [20,22]. Natural convection can serve to transport humidity away from the body, however in turn, it is also responsible for heat loss in the system [11]. The upper threshold for convective phenomena to dispel twice as much heat as is retained is a 30 mm air gap [15], implying that the optimum size of air gap when convection is taken into account is equidistant between 5 and 30 mm (~17.5 mm). This extrapolation is consistent with the results of other papers which state that the optimal air gap between fabric layers is 17 mm [9]. As natural convection only occurs between a difference of air temperatures [11], and the temperature difference between layers of fabric is minimal, the intensity of convective currents are greatly reduced. The reduction of convection currents is a potential method of limiting heat loss through the fabric, however, currently the only way known to accomplish this is by shrinking the air gap of the garment down to below 8 mm. Future research should investigate alternative methods to limiting convection currents in clothing to generate a better insulated garment. On the contrary of that point, there are some uses for convection currents in clothing, including the removal of humidity from the system [11], which is an imperative process for thermoregulation. All of these factors end in convection currents being a complex factor of cold climate clothing, and convection currents are usually limited in intensity due to the fact that temperature differences between the fabric layers are only a few degrees [13]. This means that the optimal air gap size for convection is dependant on which layer of the clothing the gap is situated between. For a layer closer to the body, a larger gap is required as it will more effectively remove moisture, however further from the body (between layer 2 and 3 for example) a smaller gap is better as it allows less heat to be lost through convection.

3.2.3 Humidity:

It was found that humidity, and by extension damp clothing increases the thermal conductivity of both air and the materials, thus reducing the overall effectiveness of the cold climate clothing. An alternative solution to this issue is to create clothing which provides optimal insulation based on the scenario, rather than generating maximum insulation, thereby limiting the risk of intensive sweating in cold weather [23]. This conclusion is supported by other papers which state that the moisture barrier increases thermal conductivity in the clothing system [17]. Hydrophobic materials were also found to greatly reduce the thermal conductivity caused by humidity [7]. This is reinforced by other papers which state that if the moisture is absorbed from the skin before it can evaporate, an overall increase in skin surface temperature can be obtained [12]. Furthermore, regenerated bamboo cellulose fibers created a very absorbent fabric which is ideal for absorbing sweat from the skin surface before it can evaporate [14]. A new level of complexity was added to this issue when their results found that moisture rises upwards when a person undertakes activity, meaning the top half of the chest will have a more humid environment than the lower half [24]. This supplies a rather unique opportunity, naturally accumulating the moisture into one area. An alternative solution from is to vent the moisture into the surrounding air to remove the thermal conduction that the humidity provides. This could be achieved by allowing the moisture to travel up and out of the neck hole, or via a porous ventilation system. Such a system could be as simple as a metal zipper, which allows small amounts of air flow, letting the moist air escape [25].

The primary issue with humidity in the cold climate clothing system is that it acts as a thermal conductor through the insulating clothing, and as such the most beneficial way of handling it is to contain the moisture in one place within the clothing instead of letting it permeate through the clothing [8]. Using hydrophobic materials to contain the moisture allows the humidity to be 'sectioned off' from the rest of the garment, reducing the effect that the water vapour has on the thermal resistivity of the garment. By placing this 'moisture trap' in the middle of the garment, greater heat can be gathered from the skin surface, eliminating the small thermal conducting effect the 'moisture trap' would have [26]. Alternatively, venting the moisture into the surrounding air provides the opportunity to maintain a dry, warm environment inside the clothing, which is ideal for cold climate apparel. The biggest issue with this method is the need for some type of ventilation, which acts as a break in the insulation of the clothing, allowing the warm, moist air out, and the cold air in. In order to fully ascertain the nature of this process, more research will need to be conducted to determine how best to enact this particular solution.

3.2.4 Limitations:

This research has all been conducted in a ideal, lab environment where real-world situations are not all considered. Only one of the papers assessed studied clothing on live fit models, however their results were fairly inconclusive [27]. Most of the papers used Manikins, which were only one shape and size, not accounting for the various different body shapes and sizes that people have. Additionally, the sweating/heated manikins produce specific amounts of heat and moisture, which fails to account for the variations in body heat/ sweating variations present in the human population. Furthermore, all of these experiments were performed in stationary positions (some in walking positions, but always still), which fails to account for the added convection caused by motion, nor the added external wind. These measurements are of the garments working under ideal conditions and the results will differ in real-world scenarios. Further research should be undertaken into testing cold climate clothing under natural conditions to gain a more accurate measurement of the true properties of the clothing.

Calculation of the thermal resistance for the proposed cold weather apparel:

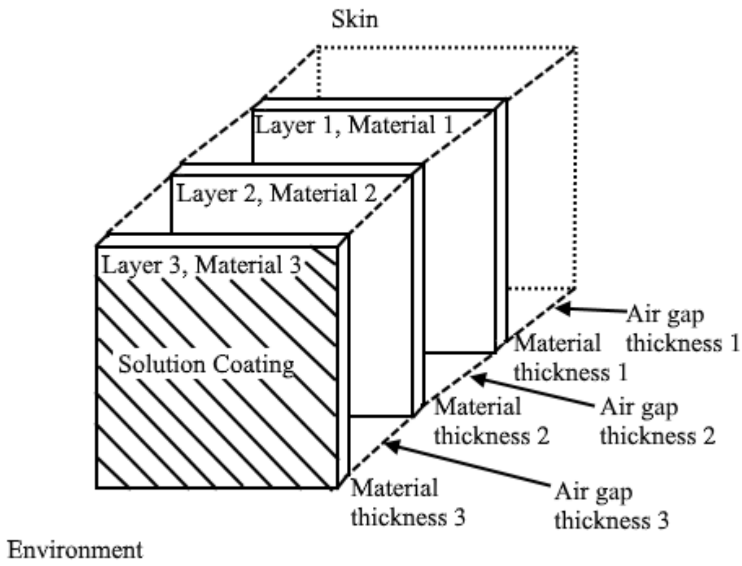

Figure 2. *Example of a segment of clothing with 3 layers*

By varying air gap thickness and material composition, we can create an article of clothing with a theoretical thermal resistance predicted using the following equation: $R_t = R_{m1} + R_{a1} + R_{m2} + R_{a2} + R_{m3}$

With R_t being the total thermal resistance, R_{m1},R_{m2},R_{m3} being the thermal resistances of interlock woven cotton (0.008) [4], textiles containing PCM's (taken to be 0) and bamboo cellulose fiber coated in polyester respectively (0.027+0.22=0.247) [6,27], and R_{a1},R_{a2} being the thermal resistance of the air gaps between the middle layer, and the inner and outer layers respectively. The air gap between the skin and the innermost layer considered to be negligible and not taken into consideration in this equation.

Since there were no values we could use for the thermal resistance at the desired air gaps, we have calculated the thermal resistance of a 7 mm air gap with natural convection and extrapolated the results to approximate the thermal resistance of a 8 and 17 mm air gap using the following equation to calculate the linear gradient:

$$\frac{1}{2}(R_2 - R_1)$$

Where R_1 is the thermal resistance of a 3 layer article of clothing [18] with no gap between the layers, and R_2 is the thermal resistance of the same article 2 uniform gaps of 7 mm each. Using this equation, we found that air gaps of size 8 mm have a thermal resistance of 0.0537 and 0.1141 respectively.

Using all of these numbers, we find that the thermal resistance of our proposed article of clothing is 0.4228 m²K/W

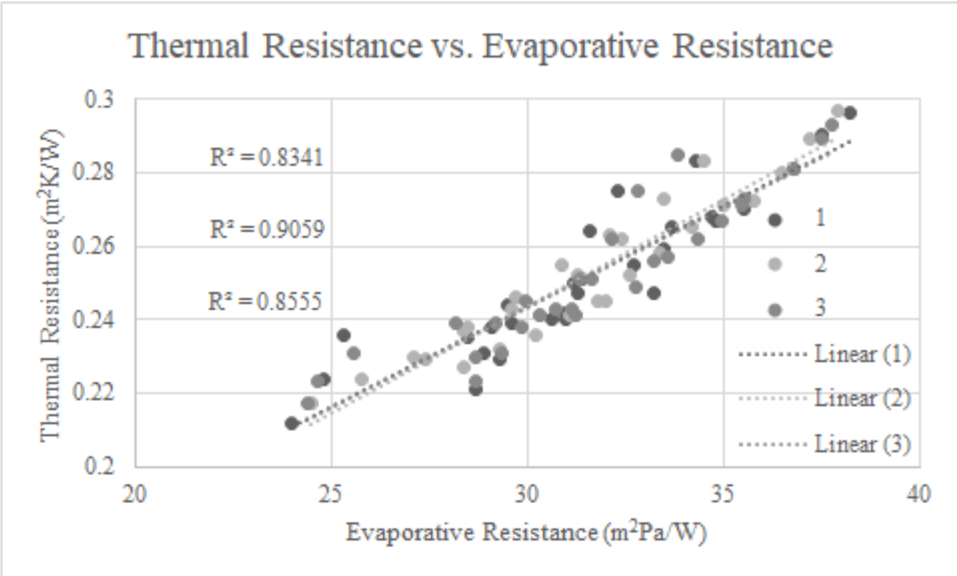

Figure 3. *Graph detailing the thermal and evaporative resistances.*

[28] R^2 of the set is 0.8635. Series 1 is the experimental values, Series 2 are the values predicted by the statistical method, and Series 3 are the values predicted by the Artificial Neural Network. As an R^2 of 0.86 is a strong correlation, Thermal resistance of a material could be predicted with reasonable accuracy if we knew the evaporative resistance.

4. Conclusions

Through an analysis of all the components above, it can be ascertained that the most effective cold climate clothing is a hybrid between the designs currently being used. Such a hybrid is detailed below:

By utilising the regenerated bamboo cellulose fiber from article [14] and coating it in polyester, a material can be constructed that is both strong and thermally insulating while remaining thin and light. This polyester coated bamboo fiber would be most beneficial as an outer layer to the clothing, acting as a windbreak and moisture barrier from the weather. Underneath this, a second phase change material layer should exist with an air gap of 17 mm from the outer layer. The PCMs explained in article [1] allow for thermoregulation inside the garment, keeping the person from overheating as well as acting as an insulator from the cold. The PCMs should be

SiO_2 suspended in the fabric. An 8 mm air gap should be between this layer and the innermost layer of the garment to prohibit convection currents in this microclimate which would whisk the warmth away from the body. This final layer should be an interlock woven cotton which sits close to the surface of the skin, having a minimal air gap (exact value is dependent on necessary ease fabric for each clothing size). Regenerated Bamboo Cellulose fabric is a breathable and warm layer which pulls the humidity immediately away from the body. For this to be most effective, it must be close to the body. It is for this reason that an interlock woven pattern is recommended. Fastening aspects such as zippers and buttons will need to be researched more before a conclusion can be made, however with the knowledge gained from this study, a zipper would be recommended as it allows less airflow.

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Appendices:

Appendix A:

Criterion	Rigidity	specific heat of materials	Thickness of material	Convection currents	Humidity	Air gap size
Name of paper which looked at this	1,3,11,12, 19,23,24, 27,36,41, 48	1,3,4,6,8,9,10, 15,17,18,20,23, 29,37,38,43,45	1,3,4,5,6,8,9,10, 12,13,14,15,17,19, 21,23,24,25,26,27, 33,34,36,37,38, 39,41,42,43,44,47, 48	5,6,7,9,10,12,13,14, 16,17,18,23,29,33, 34,35,36,37,38,40, 42,45, 46,49	6,7,8,13, 17,18,19, 27,28,37, 39,42,48	5,6,8,9,10, 11,12,13,15, 16,17,18, 23,24,25,26, 33,34,35,36, 40,42,48,49
Used as a control			3,4,5,6,8,9,12,13, 14,19,23,24,25,26, 27,29,33,34,36,42, 43,44,47,48		1,3,9,10,11,12, 14.16,20,23,26, 33,35,38,44,46, 49,50	