THERMAL INSULATION WEAR – A REVIEW

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ABSTRACT

This review paper discusses the innerwear used as thermal insulation wear to protect from cold weather conditions. Thermal insulation is of high importance especially for military garments, aiming to enhance soldiers' comfort and performance in diverse environments. Key challenges in development of thermal wear is to include integrating effective thermal insulation and moisture-wicking properties, achieved through a deep understanding of heat transfer mechanisms between the body and the atmosphere. This review paper explores various knitted fabric structures, particularly plated ones, to optimize heat retention and moisture management. The structure of the fibres used, their dimensions, thermal conductivity, moisture absorption properties play a major role in deciding and developing thermal insulation wear.

Keywords: Innerwear, Thermal Insulation, Moisture Absorption, Microdenier Polyester, Plaited Jersey Fabrics, Silk, Knitted Fabrics

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1. INTRODUCTION

In the realm of modern military operations, soldiers often find themselves facing extreme environmental conditions, ranging from freezing cold to scorching heat. Ensuring the well-being and performance of military personnel in such diverse climates is paramount. One of the critical challenges faced by soldiers is maintaining optimal body temperature, which directly impacts their comfort, endurance, and overall operational efficiency. To address this challenge, the research and development of specialized thermal insulation wear has become imperative, aiming to provide military soldiers with enhanced comfort and protection against temperature extremes.

This research initiative focuses on the development of an innovative innerwear solution that acts as an additional thermal supportive layer beneath the primary military garment. The core objective of this project is to integrate advanced thermal insulation and effective moisture-wicking properties into the innerwear, ensuring superior thermal regulation regardless of the environmental conditions. Achieving this goal requires a comprehensive understanding of the intricate mechanisms of heat transfer between the human body and the surrounding atmosphere, with the fabric acting as a vital medium in this process.

This study seeks to unravel the complexities of heat transfer mechanisms to design innerwear that efficiently retains body heat in cold environments while facilitating heat dissipation in warmer climates. A crucial aspect of the research involves exploring various knitted fabric structures, particularly plated structures, to discern their impact on the heat transfer mechanism. Through systematic analysis and experimentation, this project aims to identify the most suitable fabric configurations that optimize thermal insulation, moisture management, and overall comfort for military soldiers.

The successful development of this advanced thermal insulation wear not only promises enhanced comfort and performance for military personnel but also holds the potential for broader applications across various industries and sectors. By advancing our understanding of thermal regulation in extreme conditions and leveraging innovative fabric technologies, this research endeavor strives to make a significant contribution to the well-being and operational efficiency of military soldiers and, by extension, to the success of military missions worldwide.

2. LITERATURE REVIEW

2.1. COLD WEATHER CLOTHING

The design and development of cold-weather protective clothing is a critical endeavor, especially for military personnel and paramilitary forces who face extreme environmental conditions during combat and operational activities. These protective garments must not only offer thermal insulation but also address various challenges such as combat hazards, rain, snow ingress, and extreme cold and windy conditions while ensuring the wearer's comfort and freedom of movement. The selection of appropriate textile materials and their strategic use are crucial in minimizing physical stress on the wearer while providing effective protection from the cold.

Historically, wool and woolen pile fabric have been utilized as protective materials against cold. With the advent of synthetic fibers, acrylic and polyester fibers in different forms have been explored for making cold protective clothing. Research studies have shown that polyester batting offers a favorable insulation-to-weight ratio against extreme cold, making it a significant component in protective garments, especially in glacier and Siachen regions. Manufacturers have also developed various synthetic insulating materials to enhance protection against cold weather conditions.

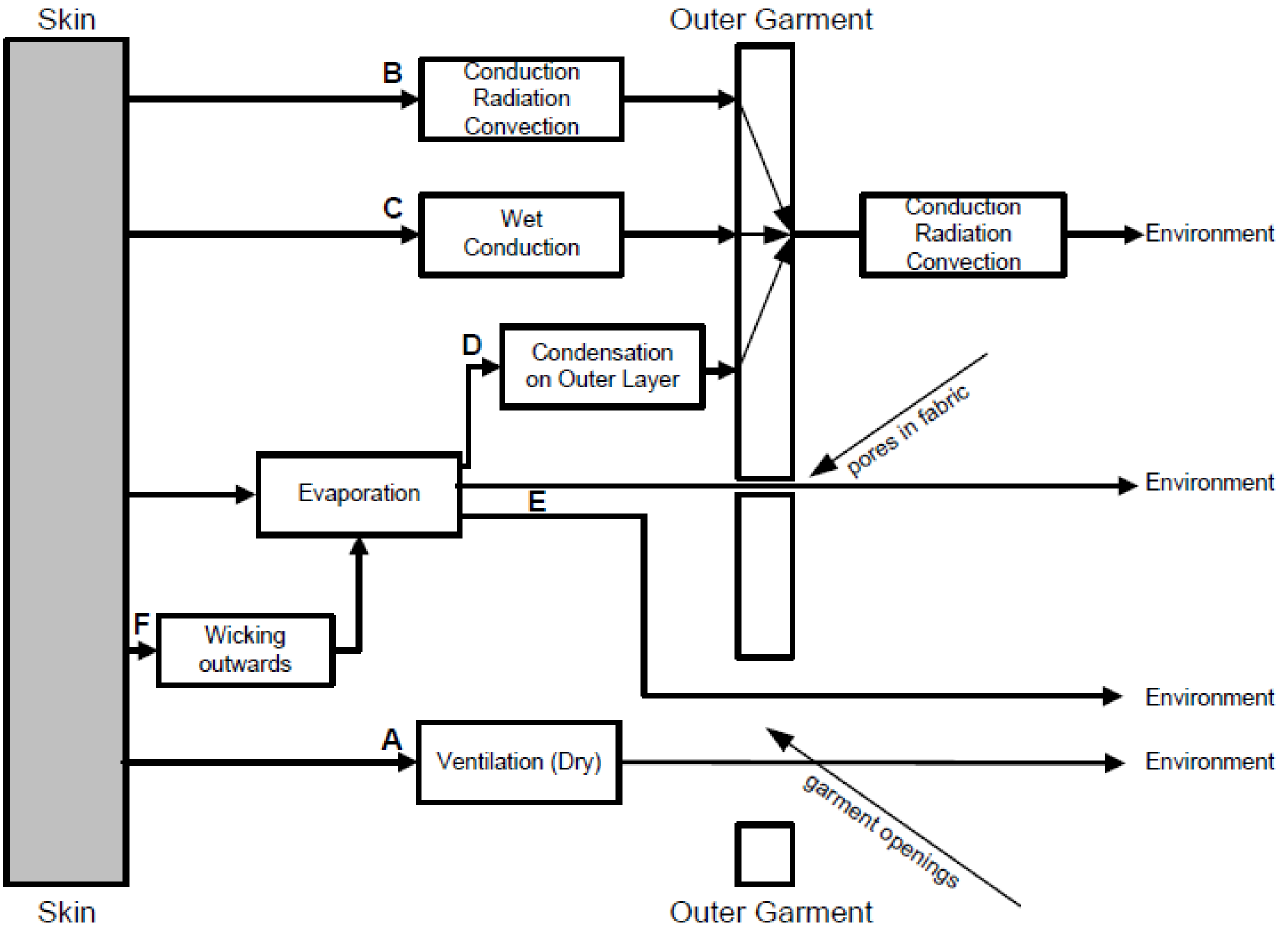
The choice of material for cold weather protective clothing primarily revolves around minimizing heat loss from the body to the environment while allowing the evaporation of sweat. Preventing the rapid dissipation of body heat is essential to provide comfort to the wearer, and the material's heat resistance plays a crucial role. Moisture, such as sweat, can increase the rate of heat conduction. Hence, clothing must allow moisture vapor to flow out to prevent condensation inside the clothing, particularly in low-temperature conditions.

The system design of protective clothing for extreme cold weather focuses on repelling water and snow while retaining body heat. The efficiency of a soldier in the field under cold climates is significantly affected by the clothing worn. The protective clothing must be compatible with rigorous operations as well as periods of inactivity. Numerous insulating materials are available in the market, requiring careful consideration of all functional requirements before selecting suitable materials for designing clothing. The combination of materials is a critical aspect of system design, with organizations like DMSRDE (Defense Materials and Stores Research and Development Establishment) specializing in the development of protective clothing for use in extreme cold regions. These clothing systems, based on multilayer principles, have undergone rigorous laboratory evaluations and field trials, establishing their superiority over existing protective clothing options. Through continuous research and development, these protective garments ensure the safety, comfort, and effectiveness of military personnel operating in harsh cold weather conditions.

2.2 HEAT TRANSFER MECHANISM

The discussed system involves human skin, fabric, and an air layer between them, arranged horizontally. The air layer, referred to as the microclimate, is characterized by a small gap distance. Heat and moisture transport in this system are assumed to be mostly one-dimensional. The microclimate, when the temperature difference is small, is stagnant without natural convection. Moisture is transferred to the fabric surface based on Fick's law, assuming a low Rayleigh number to prevent convective motion in the microclimate. Heat transfer involves conduction through solid fibers and air in the fabric, radiation between skin and fabric, and vapor transport through the microclimate. The fabric is considered a porous medium with two mechanisms for moisture transfer: pore diffusion and surface diffusion. Conduction through fibers and air, along with moisture transport, contributes to heat transfer to the fabric surface. The research excludes explicit consideration of radiation heat flux inside the fabric, assuming it is already accounted for in the effective thermal conductivity. Surface diffusion is influenced by adsorption and desorption processes, assumed to be in local equilibrium, and is expressed in terms of moisture concentration in pores.

Fig.1 Heat Transfer Mechanism in Textiles



2.3 REQUIREMENTS FOR INNER GARMENT

The requirements for the inner garment in the context of developing thermal insulation wear for military soldiers are multifaceted and must address various critical factors to ensure the well-being and performance of soldiers in extreme environmental conditions. The inner garment designed for military soldiers must fulfill several critical requirements to ensure optimal comfort and performance in a range of environmental conditions. It should provide efficient thermal insulation, retaining the body's natural heat in cold climates, while also incorporating effective moisture-wicking properties to keep the skin dry and prevent discomfort during physical activities or in warm weather. The garment must offer breathability, allowing moisture vapor to escape, and it should be constructed for a comfortable and ergonomic fit that does not restrict movement. Durability is paramount, requiring materials that can withstand rugged conditions and regular wear, even after frequent laundering. Additionally, the innerwear should be adaptable for layering purposes, enabling soldiers to adjust their clothing based on specific climate conditions. Antimicrobial properties are beneficial to prevent the buildup of odors, especially in situations where regular laundering might not be possible. Quick drying capabilities are essential in wet conditions to prevent prolonged exposure to moisture. The garment should be lightweight and compact to minimize bulk, taking into account the weight soldiers already carry. Compatibility with the primary uniform and other protective gear is crucial for seamless integration into the overall clothing system. Environmental considerations, such as the use of sustainable materials, should also be considered.

2.4 INNER WEAR USED BY SOLDIERS AT HIGH ALTITUDE.

2.4.1. COTTON KNITTED FABRIC.

The research focused on investigating the properties of a weft knitted fabric made from new cotton non-twisted hollow yarn, with a specific aim to develop an innerwear product. The fabric's weight, thickness, thermal characteristics, tensile strength, shear properties, bending properties, and surface properties were meticulously analyzed using a KES-FB system. In this comparative study, four commercially available innerwear fabrics were also assessed to provide a comprehensive understanding of the new fabric's potential for innerwear applications.

The results revealed several noteworthy findings. The knitted fabric crafted from non-twisted hollow yarn exhibited distinct advantages over the commercially available innerwear fabrics. It was significantly lighter and fuller, enhancing comfort and wearability. The fabric displayed comparable or lower shear stiffness and bending rigidities, indicating its flexibility and ease of movement, crucial factors for innerwear comfort. Moreover, the fabric's surface properties closely resembled those of existing innerwear fabrics, ensuring a smooth and comfortable texture against the skin.

In terms of thermal properties, the new fabric demonstrated superior performance. It had a lower Q-max value, signifying a reduced peak heat transfer, making it warmer to the touch and providing enhanced thermal insulation when worn. The fabric's lower thermal conductivity and higher heat retention rate further emphasized its excellent warmth-retaining capabilities. Additionally, the fabric's unique construction allowed it to achieve superior heat retention with a lighter mass, a valuable attribute for innerwear where both warmth and lightweight comfort are paramount.

Furthermore, the new fabric exhibited comparable ventilation resistance to commercially available innerwear fabrics, ensuring adequate breathability while maintaining its insulating properties. These combined features highlighted the fabric's suitability for innerwear applications, positioning it as an innovative and promising choice for the development of high-quality, comfortable, and thermally efficient innerwear products. The study's findings underscored the potential of the knitted fabric made from cotton non-twist hollow yarn, offering a compelling solution to enhance the comfort and thermal performance of innerwear products.

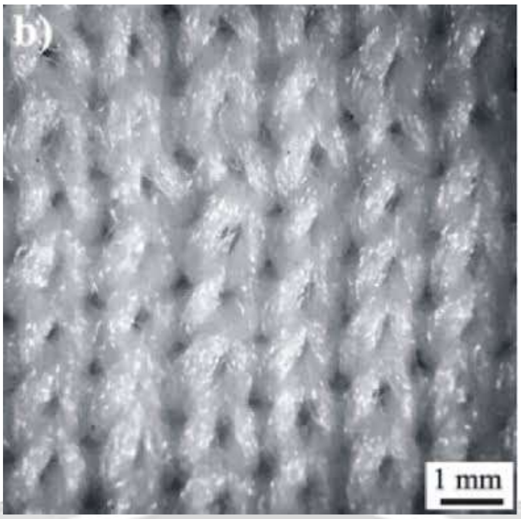


Fig.2 Cotton knitted fabric.

2.4.2. POLYESTER KNITTED FABRIC.

Du Pont makes three polyester fibers which are engineered for innerwear (as well as other) fabrics - Thermax, Coolmax, and Thermastat. Thermastat and Thermax use round hollow polyester fibers and have inherent wicking properties. Coolmax uses a four-channel solid fiber which forms conduits to move moisture and must be in direct contact with the skin to be effective. DuPont claims all of these fibers provide good breathability, wick moisture (perspiration) away from the body thus retaining body heat and preventing the "chilling effect" and can be machine washed and dried without shrinking. Thermastat, the "new generation of Thermax", uses microdenier fibers 0.5 - 0.7 dpf providing the same insulating properties as Thermax (1.2 - 2.0 dpf), but providing a lighter weight, less bulky material. According to DuPont, because there are more fibers/inch the wickability of the Thermastat material is also improved. Thermax/Thermastat fabrics come in varying weights and thicknesses: light, medium and heavy (fleeced). Test data on Thermax and Thermastat, as well as other samples, evaluated for the lightweight cold weather underwear can be found in the Table. Note that different test methods were used to evaluate these materials.

Lightweight Cold Weather Underwear Data:

Material	**Fiber Content Construction**	**Weight (oz/sq. yd)**	**Clo**		**Im/clo**	
			Before Launder	**After Launder**	**Before Launder**	**After Launder**
Thermax	100% polyester rib knit	4.7	0.71	0.79	0.715	0.639
Thermastat	100% polyester rib knit	5.4	0.68	0.72	0.778	0.658
Thermax	50/50 poly/wool bi-ply, jersey knit	6.9	0.71	0.86	0.691	0.544

2.5. SILK FOR MOISTURE ABSORPTION AND THERMAL INSULATION:

Clothing comfort, which is determined by the wearer's experience in specific environmental conditions and can be categorized into three main dimensions: Thermal, Aesthetic, and Tactile comfort. Thermal comfort is particularly significant, as it revolves around a garment's ability to regulate the body's core temperature by efficiently managing heat dissipation and insulation. The fabric creates a microclimate between the skin and the environment, aiding the body's thermoregulatory system to maintain a stable temperature, even when external temperature and humidity levels fluctuate. During physical activity, heat is produced by metabolism and released through conduction, convection, and radiation. The body also perspires, with insensible perspiration occurring under normal conditions and sensible perspiration in response to excessive heat, both serving to cool the body. It is crucial for the fabric to allow perspiration to pass through; otherwise, discomfort arises. Slow moisture transfer can lead to increased humidity levels within the clothing microclimate, hindering sweat evaporation and causing heat stress. Along with heat transmission, moisture transmission, in both vapor and liquid forms, plays a vital role in determining wearer comfort. Factors such as thermal insulation, thermal absorptivity, air permeability, water vapor permeability, wetting/wicking, and water absorbency influence the fabric's hot/cool feeling and moisture management properties, crucial for thermophysiological and thermal clothing comfort.

Silk, renowned for its natural beauty, drapability, and comfort, has become a coveted fiber in high-fashion clothing. Its remarkable properties extend to its ability to retain warmth during winters and compete with advanced synthetic polymers. One of the key attributes of silk is its high hygroscopicity. Mulberry raw silk fiber exhibits a moisture regain of 11%, decreasing to approximately 9% after degumming, owing to the removal of hygroscopic sericin during the process. Wild silk fibers, such as tasar, muga, and eri, display even higher moisture to regain values. Silk's moisture absorption capacity is noteworthy, allowing it to absorb up to 30% moisture from the air without feeling damp. This, coupled with its high heat of wetting (69 J/g) and a regain of about 10%, gives wearers ample time to acclimatize to changing weather conditions.

However, silk's moisture absorption properties also have their implications. The fibers swell about 30% of their volume under wet conditions, leading to lower dimensional stability compared to other natural fibers. Prolonged exposure to steam or boiling water can result in hydrolysis of peptide bonds, damaging the silk fiber. Despite these challenges, silk remains thermally stable below 100°C due to its highly oriented molecular structure. However, exposure to higher temperatures causes yellowing and degradation, with initial weight loss occurring around 250°C and degradation starting at 280°C.

Silk's insulation properties are another notable feature. It boasts a specific heat of 1.38 J/gK, slightly better than cotton (1.3 J/gK) and wool (1.36 J/gK). The thermal conductivity of silk in longitudinal (KL) and transverse (KT) directions is 1.49 and 0.119 W/(mK) respectively, resulting in a high anisotropic ratio (KL/KT) of 12.64. This high orientation of fibroin molecules along the fiber direction contributes to its insulating properties. However, due to its lower thermal conductivity and high moisture regain, silk's comfort level decreases in hot and humid conditions.

In summary, silk's exceptional moisture absorption properties, coupled with its thermal stability and insulation capabilities, make it a versatile and sought-after material in the realm of textiles, balancing comfort, and style for wearers across various environmental conditions.

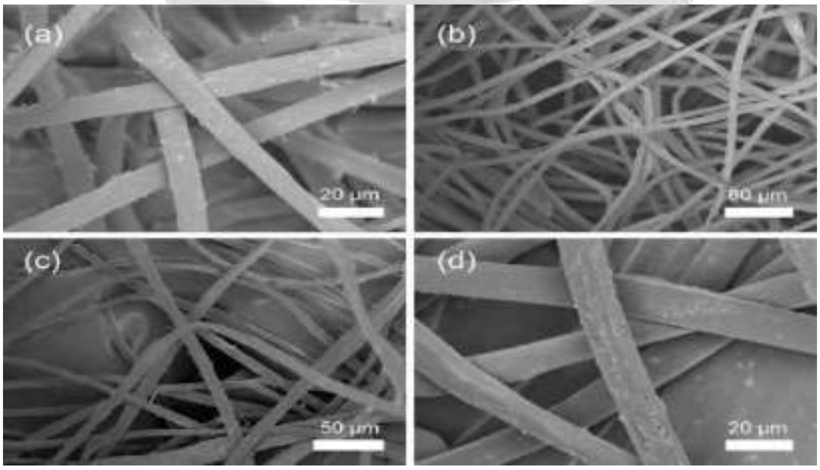


Fig.3 Silk fiber after degumming

2.6. MICRODENIER POLYESTER- MOISTURE WICKING & THERMAL INSULATION

Microdenier fibers, characterized by exceptional flexibility, play a pivotal role in the textile industry due to their numerous advantages. These fibers exhibit superior regularity and elongation, contributing to seamless knittability and resulting in fabrics with enhanced softness, drape, dimensional stability, and wicking properties. The inherent low hairiness of microfiber yarns significantly reduces lint shedding during knitting, enhancing the efficiency of knitting machines. The larger number of fibers in the yarn cross section and their better packing within the yarn structure led to improved yarn tenacity and uniformity, attributes crucial for high-quality textiles.

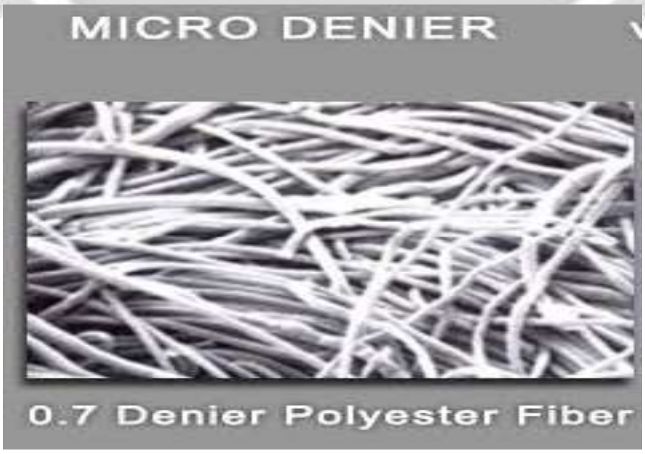
The production process for microfibers, often conducted at lower speeds, has substantially reduced imperfections in microfiber yarns. The higher flexibility of microfibers enables a more coherent yarn structure, reducing hairiness and lint shedding. Additionally, microdenier fabrics exhibit exceptional dimensional stability, with minimal changes in loop lengths compared to normal denier fabrics. This stability is attributed to the lower twist in microdenier yarns, resulting in decreased strain and improved fabric integrity. Identical single jersey knitted structures were employed for both microfiber and normal fiber fabrics, revealing noteworthy differences. Polyester microdenier fabrics exhibited superior drapeability, approximately 21% better than their normal denier counterparts. This improved drape is a consequence of the finer fibers, which mold more easily to the wearer's shape, ensuring a better fit.

Despite these advancements, essential fabric properties such as thickness, bursting strength, abrasion resistance, and pilling resistance remained consistent between microdenier and normal denier fabrics. Furthermore, the spirality of microfiber yarns met garment manufacturing standards and exhibited lower levels than normal denier yarns. This difference in spirality can be attributed to the lower twist multiplier employed during the ring spinning process for microfiber yarns.

In addition to these attributes, microdenier spun yarns boast a higher packing coefficient compared to their normal denier counterparts. Consequently, microdenier yarns feature smaller average capillary sizes, enhancing capillary pressure and accelerating water absorption. This increased capillary action results in higher wicking heights for microdenier yarns compared to normal denier yarns at any given time, demonstrating their superior moisture-wicking capabilities.

In summary, microdenier fibers offer an array of advantages, including enhanced flexibility, reduced lint shedding, improved dimensional stability, superior drape, and exceptional moisture-wicking properties. These qualities make microdenier fabrics invaluable in various applications within the textile industry, ensuring high-quality, comfortable, and functional end products.

Fig.4 Microdenier polyester



2.7. PLAITED JERSEY FABRICS

The provided paragraphs underscore the paramount importance of thermal and moisture management properties in functional garments, such as sportswear, active wear, and inner wear. Comfort in clothing is intricately linked to how efficiently it dissipates heat and moisture generated by the body's metabolic processes. Achieving thermal equilibrium involves balancing environmental parameters like air temperature, radiant temperature, air velocity, and humidity, with human physiological factors. The human body naturally loses heat through conduction, convection, and radiation, and under normal conditions, it cools itself through insensible perspiration, where water vapor is lost. However, excessive heat production leads to sensible perspiration or sweating.

Clothing inherently acts as an insulator, resisting the transfer of excess heat and moisture from the body. When a stagnant layer of air is trapped between the skin and fabric layers, or between two fabric layers, it creates a barrier effect, making the wearer extremely uncomfortable. Similarly, perspiration in the form of water vapor is transmitted from the skin through the fabric to the outer surface via diffusion. If this transmission does not occur at the same rate at which it is generated, the wearer feels suffocated and uncomfortable. The circulation of air due to clothing's pumping effects can also be harnessed to keep the wearer cool and comfortable.

Hence, the primary purpose of clothing is to provide a stable microclimate next to the skin by maximizing the rate of heat and moisture loss from the body. Textile engineering plays a pivotal role in achieving this by manipulating the structural features of fibers, yarns, and fabrics to engineer the desired properties related to heat and moisture transport.

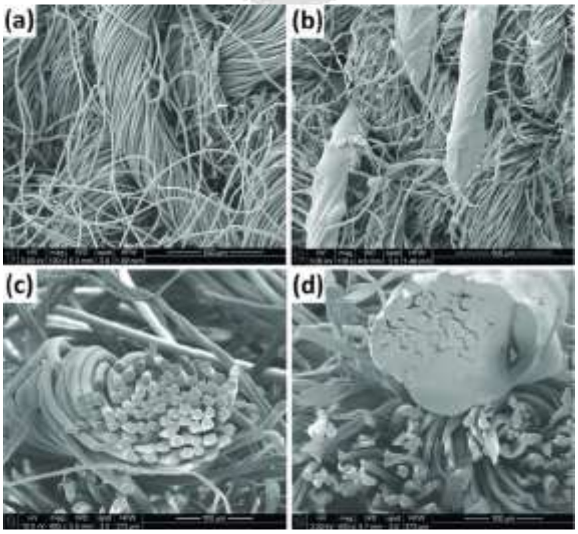
Plated fabrics, characterized by distinct face and back sides made from different yarns, offer a versatile platform to create fabrics with varied properties, such as hydrophilic/hydrophobic or fine/coarse textures. Researchers have conducted studies investigating the influence of yarn and fabric construction variables on thermal properties. Findings have indicated that factors like raw material type and knitted structure significantly affect thermal properties, air and water vapor permeability. For instance, fabrics with higher loop lengths exhibit increased air and water vapor permeability but minimal change in thermal resistance.

However, systematic studies on factors affecting heat and moisture transport characteristics of plated structures remain limited. The effect of varying yarn linear density for both inner and outer layers of plated fabrics on comfort properties has not been extensively explored. Current research focuses on investigating the influence of fabric characteristics such as loop length and yarn characteristics like yarn linear density on heat transfer, water vapor transfer, and air permeability in single jersey plated fabrics. Plated structures produced with yarns of different linear densities in inner and outer layers are evaluated to understand their properties comprehensively.

For instance, PET/C fabrics knitted with higher loop lengths exhibit higher air permeability and relative water vapor permeability, along with lower thermal conductivity and thermal absorptivity. Fabrics with higher loop length, due to their slacker construction, are perceived as warmer, emphasizing the intricate relationship between fabric structure and wearer perception. These findings open avenues to design and engineer plated structures where variations in inner and outer layer yarn linear density and loop length can influence thermal and moisture management properties. This research is crucial for determining the suitability of fabrics for next-to-skin applications and low activity levels, ensuring optimal comfort and performance for the wearer.

Fig.5 Heat exposure on fabric a) before heat exposure b) after heat exposure

Heat exposure on yarn c) before heat exposure d) after heat exposure



2.8. EVALUATION OF COLD WEATHER CLOTHING

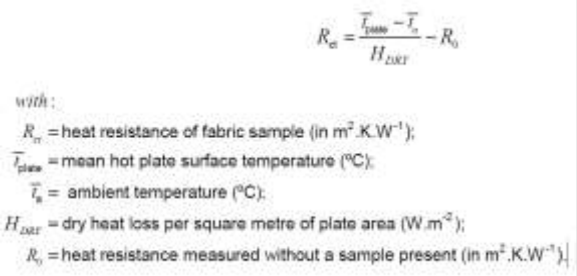
The development of cold weather protective clothing has evolved from natural materials like fur and down to manmade fiber and textile solutions. The complexity of material combinations available necessitates a systematic approach in clothing development. The five-stage approach proposed by Goldman and Umbach is widely used in the clothing research community. It begins with a detailed analysis of the user's tasks and environmental conditions, leading to a pre-selection of fabrics and materials based on physical properties, with a focus on thermal protection (stage one). Predictions for overall clothing characteristics are made using fabric properties and thermal models, accounting for heat balance and human thermoregulation (stage two). This approach reduces the number of potential materials for further testing. Prototypes of selected materials are then tested on manikins and eventually on human wear-testers (stage two). Stage three involves wearing the clothing in a climatic chamber under defined conditions, collecting detailed wearer data. This stage helps narrow down choices and leads to small or large-scale field trials. The testing complexity, time, and cost increase through these stages, but they provide crucial objective data for development, evaluation, and quality control of cold weather protective clothing.

The relevant measures for the above would therefore be:
- Heat resistance (convection/radiation)
- Vapour resistance/Permeability index
- Water tightness
- Air permeability (affecting heat resistance in wind)
- Wicking

Heat and vapour resistance:

For heat resistance measurement, typically a guarded hot plate apparatus of some form is used, which measures the amount of heat lost through a sample at a certain temperature gradient between the plate and the environment. From this, insulation of the fabric can be calculated as:

Air permeability:



$$R_{ct} = \frac{\overline{T}_{plate} - \overline{T}_{a}}{H_{DRY}} - R_{0}$$

with :

R_{ct} = heat resistance of fabric sample (in $m^2.K.W^{-1}$);
$\overline{T}_{plate}$ = mean hot plate surface temperature (°C);
$\overline{T}_{a}$ = ambient temperature (°C);
H_{DRY} = dry heat loss per square metre of plate area ($W.m^{-2}$);
R_{0} = heat resistance measured without a sample present (in $m^2.K.W^{-1}$).

When wind speed increases, a fabric’s heat and vapour resistance may decrease in relation to its air permeability. This can be quantified via the fabric air permeability that can be determined e.g. by EN ISO 9237.

Water proofness / water penetration:

Material resistance to water penetration can be assessed using standards like EN 20811 (1992), where a higher number indicates better performance. Newer tests, such as EN 14360 (2004), evaluate the entire garment, accounting for design features. It's essential to consider the fabric's application range; in extremely cold conditions where no liquid is present, omitting waterproof layers can widen the clothing's temperature range by improving vapor permeability. However, these layers also enhance wind proofness, requiring a balance, as seen in wind-stopper fabrics, which maintain wind proofness with minimal impact on vapor permeability.

Wicking/buffering:

The wicking/buffering effect can be measured on the sweating guarded hot plate, allowing the liquid water to touch the fabric, and looking at overall moisture loss, or by measuring the microclimate response to a short sweating burst. Other methods look at the wicking of liquid into vertically hanging strips of fabric after fixed time periods (BS 3424; 1996 and DIN 53924), or looking at the dispersion of a drop of liquid on a fabric (visual test). Trying to make this more objective, electrical conductivity of fabrics has been used to define the water absorption speed.

Thermal character:

Examples of instruments for assessing parameters related to this sensation can be found in the Kawabata system and e.g. in the Alambeta tester, the latter looking at the 'warm-cool feeling' in the first two seconds of skin contact.

Insulation:

For dry heat insulation (the prime parameter for cold protection) the manikin surface is controlled at a set temperature and the energy (heat) required keeping this set temperature is then directly related to the manikin's insulation:

$$I_T = \frac{\overline{t_{sk}} - t_a}{H_{sk}} = \frac{\sum \alpha_i . t_i - t_a}{\sum(\alpha_i . H_i)} = \frac{\sum \alpha_i .(t_i - t_a)}{\sum(\alpha_i . H_i)}$$

[4

$$with\ \alpha_i = \frac{surface\ area\ of\ segment\ i}{total\ surface\ area\ of\ manikin}$$

I_T = insulation of complete ensemble including enclosed and surface air layers (in $m^2.K.W^{-1}$);

$\overline{t_{sk}}$ = average skin temperature (°C);

t_i = temperature of segment *i* (°C);

t_a = ambient temperature (°C); (if radiation is present, this is replaced by operative temperature);

H_i = heat loss of segment *i* (W).

Vapour resistance:

For the measurement of vapour resistance, usually the ambient temperature is set equal to skin temperature to eliminate any DRY heat loss (Isothermal conditions). Then the calculation becomes:

$$R_{e,T} = \frac{\overline{p_{sk}} - p_a}{H_{sk}} = \frac{\sum \alpha_i \cdot p_i - p_a}{\sum (\alpha_i . H_i)} = \frac{\sum \alpha_i .(p_i - p_a)}{\sum (\alpha_i . H_i)} \qquad [6]$$

If the measurement is performed with a uniform skin vapour pressure over the body, i.e. $p_i = p_{sk}$ = constant, then equation [6] becomes :

$$R_{e,T} = \frac{\overline{p_{sk}} - p_a}{\sum (\alpha_i . H_i)} \qquad [7]$$

If, instead of measuring heat flux, a measurement of mass loss due to sweating is performed, no regional resistances can be calculated. The calculation becomes:

$$R_{e,T} = \frac{\overline{p_{sk}} - p_a}{H_{sk}} = \frac{\overline{p_{sk}} - p_a}{massloss \cdot \lambda} \qquad [8]$$

$R_{e,T}$ = vapour resistance of complete ensemble including enclosed and surface air layers (in $m^2.Pa.W^{-1}$);
$\overline{p_{sk}}$ = average skin vapour pressure (Pa);
p_i = vapour pressure of segment i (Pa);
p_a = ambient vapour pressure (Pa);
H_i = heat loss of segment i (W);
mass loss = amount of moisture evaporated from ensemble per unit of manikin surface area per second ($g.m^{-2}.sec^{-1}$);
λ=latent heat of evaporation at skin temperature (approx. 2430 $J.g^{-1}$).

Fig.6 Thermal Manikin

CONCLUSION

This review paper extensively explores the possibilities of constructing textiles using a plated knitting model, incorporating diverse fibers such as cotton, microdenier polyester, and Eri silk, while thoroughly discussing their properties. The study also delves into the model of heat transfer through fabrics and evaluates cold weather clothing by assessing key properties like air permeability, wicking, and insulation. Within this context, the paper highlights the significance of innerwear as a specialized form of thermal insulation clothing designed to protect against cold weather conditions. The advancement of thermal wear hinges on the integration of efficient thermal insulation and moisture-wicking properties, necessitating a profound understanding of the heat transfer mechanisms between the body and the surrounding atmosphere.

REFERENCES

1. Nishkam Kasturiya, M.S. Subbulakshmi, S.C. Gupta and Hans Raj. System Design of Cold Weather Protective Clothing. Defence Science Journal, Vol 49, No 5, October 1999, pp. 457-464.

2. KyoungOk Kim[a], Toko Manabe[a], Masayuki Takatera[a], Nagisa Hirata [b], Kyosuke Kanda [b], Masatoshi Kawakami [b]. Thermal and Mechanical Characteristics of Cotton Knitted Fabric Made of Non-twisted Hollow Yarn for Inner Wear. Journal of Fiber Bioengineering and Informatics 13:2 (2020) 89–99.

3. Margaret A. Auerbach and Regina D. Jugueta. CANDIDATE FABRICS FOR THE 2ND GENERATION EXTENDED COLD WEATHER CLOTHING SYSTEM. December 1997.

4. Brojeswari Das, Naveen V. Padaki, K. Jaganathan, H. M. Ashoka. Comparative Studies on Thermal Comfort Properties of Eri Silk, Mulberry Silk, Wool and Linen Fibres. J. Inst. Eng. India Ser. E.

5. N.V. Padaki, B. Das, A. Basu. Advances in understanding the properties of silk. Central Silk Technological Research Institute, Bangalore, Karnataka, India; Northern India Textile Research Association (NITRA), Ghaziabad, Uttar Pradesh, India.

6. J. Srinivasan, G. Ramakrishnan, S. Mukhopadhyay & S. Manoharan. A study of knitted fabrics from polyester microdenier fibres. Published online: 08 Jul 2010.

7. Deepti Gupta, Vijay Kumar Kothari & Yamini Jhanji. Heat and moisture transport in single jersey plated fabrics. Indian Journal of Fibre & Textile Research. Vol. 39, June 2014, pp, 115-121.

8. Laboratory assessment of cold weather clothing. © Woodhead Publishing Limited, UK. Havenith, George. 2019.

9. Ibrahim, N. A., Khalifa, T. F., El-Hossamy, M. B., Tawfik, T. M. Effect of knit structure and finishing treatments on functional and comfort properties of cotton knitted fabrics. Journal of Industrial Textiles: 2010; 40(1), 49-64.

10. Chen, Q., Tang, K. P. M., Ma, P., Jiang, G., Xu, C. Thermophysiological comfort properties of polyester weft-knitted fabrics for sports T-shirt. J Text I: 2017; 108(8), 1421-1429.

11. CAN/CGSB 4.2 NO. 70.1-94 (1994) [withdrawn] 'Textile Test Methods - Thermal Insulation Performance of Textile Materials', Canadian General Standards Board

12. CAN/CGSB 4.2 NO. 78.1-2001 (2001) 'Textile Test Methods - Thermal Protective Performance of Material for Clothing', Canadian General Standards Board.

13. Mathur, G.N.; Hans Raj & Kasturiya, Nishkam. Protective clothing for extreme cold region. Indian J. Fibre Textile. Res., 1997, 88. 292- 96.

14. Hans Raj, Nishkam, Anita; Subbulakshmi, M.S., Batra, B.S. & Nishkam, Kasturiya. Thermal insulation studies of protective clothing. Mannzade Textiles India, April 1998, 153-58.

15. Gupta, V.B., Rajkhowa, R., Kothari, V.K., 2000. Physical characteristics and structure of Indian silk fibres. Indian J. Fibre Text. Res. 25, 14–25.