MedCrave
Step into the World of Research
Journal of Textile Engineering & Fashion Technology

Review Article
Open Access
CrossMark

Thermophysiological clothing comfort

Abstract

The clothing is not worn only for protecting the human body, but it helps to obtain comfort during high level activities or in unfavorable environmental conditions. Heat generated by the working human body in hot climate or high physical activity, which must be dissipated to the environment. Similarly, in the cold environment, the body is going to be shielded from cold feeling. Thermophysiological clothing comfort related to warmth and moisture transport behaviour of clothing. Good clothing helps to maintain body temperature during various level of physical activities and surrounding environmental condition. Therefore, some improved functional properties are desirable in the clothing. For clothing comfort, thermophysiological comfort properties of fabrics which are related to heat and moisture transport properties play very vital role. These properties can be introduced in the clothing by using various fibrous material and modifying the structure of yarns, fabrics and garments.

Keywords: comfort, heat transport, moisture transport, thermophysiological comfort, sportswear

Volume 7 Issue 3 - 2021

Devanand Uttam, Ramratan
Department of Textile Engineering, Giani Zail Singh Campus College of Engineering & Technology, Maharaja Ranjit Singh Punjab Technical University, India

Correspondence: Dr. Devanand Uttam, Professor, Department of Textile Engineering, Giani Zail Singh Campus College of Engineering & Technology, Maharaja Ranjit Singh Punjab Technical University, Bathinda, Punjab-151001, India, Tel +91-9417233925, Email d_a_uttam@yahoo.co.in

Received: April 11, 2021 | **Published:** May 26, 2021

Introduction

In the present era, the choice of clothing comfort may be a main attribute for general consumer as well as sportsmen.[1,2] Clothing is essential material that we use every time to obtain psychological and physiological comfort to ensure physical conditions around our body which is require for survival in distressed environment condition or activity level.[3] The consumers are keen on the clothing that not only looks good but have some functional properties and feel comfortable to physical body.[4,5] Such fabrics help to sportsman in breaking the record. The consumers of sportswear and other functional fabrics are able to pay huge money during the acquisition of the fabrics which make market more attractive to textile manufactures. Many industries and research workers are engaged to develop the functional fabrics that are highly suitable for the comfort point of view.

General perception on comfort

Comfort may be a pleasant state of psychological, physiological and physical combination between a person and environment.[6] Garment is worn not just for aesthetic and ethical reasons, but it protects physical body against climatic influences and supports the body's own thermal control operation under variable external environment conditions and altering physical loads in such how that the body's heat and moisture management is balanced and a 'microclimate' is made next to the skin which we perceive as comfortable.[7,8] This physiological effect is very important, especially within the case of functional fabrics or sportswear. Need of consumer on comfort are changing with products and wear situations. No single clothing system is suitable for all situations: a fabric that is suitable for one climate is typically completely unsuitable for other environment.[9]

The clothing comfort has been assumed to be in both psychological and physiological states and has following aspects[4,5,7,10] as shown in Figure 1:

i. **Thermophysiological comfort:** It is attainment of a comfortable thermal and wetness state. It concerns the heat and moisture (both liquid and vapour) transmission properties of clothing and the way that clothing helps to maintain the thermal balance of the body during various level of activity and different environment conditions.

ii. **Sensorial or tactile comfort:** Sensorial comfort is concerned with the elicitation of various neural sensations when a fabric comes into contact with skin. In other words, it is associated with how a cloth feels when it is worn next to the skin. It is related to the mechanical contact of the clothing with the human body, softness and its pliability during movement. The good clothing lacks of irritation, prickle and cling when damp.

iii. **Body movement comfort:** Ability of a fabric to permit freedom of movement, reduced burden and body shaping as needed decides the body moment comfort.

iv. **Aesthetic comfort:** Aesthetic appeal or comfort is related to beauty or art of the clothing. It is subjective perception of apparel to eyes, ears and nose and provide feeling of general comfort to the bearer. The parameters which contribute in aesthetic comfort are color, luster, pilling and crease etc.

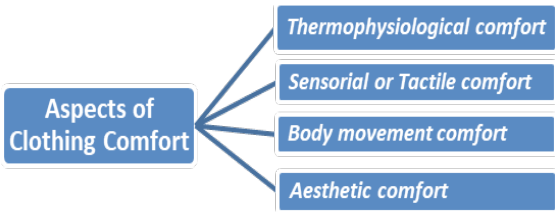

Figure 1 Aspects of clothing comfort.

The clothing comfort is affected by low stress mechanical, thermal and moisture transfer properties of the fabrics.[4,11] It is assumed that heat and moisture transmission through a cloth is perhaps the most important for clothing comfort.[4,11,12] Clothing comfort is governed by interplay of three components: human body, climate, and clothing as shown in Figure 2. The human body, microclimate and its clothing form a mutually interactive system. The body and its microclimate are constant, only the clothing system is variable. Therefore, modification in fabric enhances the comfort and functional properties of clothing.

Concept of thermophysiological comfort

The human body is fit to function within a narrow temperature range. Generally, the body keeps its own temperature constant at 37±0.5°C under different climate.[7,8,13] Thermophysiological comfort

means the body core temperature of about 37˚C is maintained; rise or fall of 5˚C are often fatal. Hypothermia and hyperthermia may result due to the variation of heat in the body, which may limit the work performance. Excessive physical activity above that required to maintain body heat will result surplus heat generation which must be transported to environment, otherwise the body temperature will increase. Although some of the surplus heat dissipation is done through breathing, most of this heat must flow out through the clothing via the surface of the body. On one way, this is often achieved through dry-heat transfer by conduction, convection and radiation. On the other way, with greater workout, and thus a greater level of warmth generated by the body itself, dry heat transfer through the clothing is, however, insufficient to catch up on the body's energy balance. In this situation, human body begins to sweat, the aim being to cool the body through evaporation of the sweat from the skin. The prerequisite for cooling is that this sweat is often evaporated. Clothing must therefore always ensure a high level of moisture transmission. This kind of clothing comfort entails both thermoregulation and moisture management. This is often achieved by using clothing to take care of the body temperature and moisture output as far as possible to its normal level under different climatic conditions.

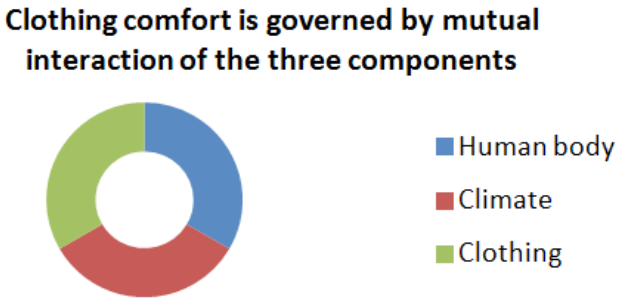

Figure 2 Components governs the comfort.

Thus, there are four mechanisms of heat transmission[7] from the body to the environment via clothing; so as to take care of its thermal balance: conduction, convection, radiation and evaporation (Figure 3). In conduction process heat loss is accomplished through direct contact with another substance. The temperature difference between the two materials and the conductivity of these materials are determining the rate of heat transmission. In convection mechanism, the heat is transferred by a fluid transmission (liquid/gas). In radiation mechanism, the heat is transferred through electromagnetic waves. The waves can pass through air without imparting much heat to it; however, when these waves strike an object, their energy is largely transformed into heat. The mechanism of evaporation process is very effective in a hot dry. Transforming liquid water into vapour needs huge amount of heat energy. When water is evaporated from the surface of skin, then the heat energy taken from the skin, thus cooling it.

Person sometimes feels uncomfortable as a result of their excess physical activities and due to the change of external environmental conditions. The body is suffering from various external conditions within the winter and summer seasons. These external conditions can include alteration in ambient temperature, air speed, vapour pressure, and clothing insulation, among other factors that affect skin temperature.[13]

The temperature and humidity of the environment may strongly influence the body's skin and interior temperature.[13] On the other hand, the body continuously produces heat by its metabolic processes, which must be transferred to the environment.[7,13] The efficiency of human organism is such that of the energy taken in as food, only 15-30% is converted into useful work and remaining 70-85% of the energy being wasted as heat.[7] This production of heat is quite considerable. When the body is at rest it is already as high as 100W, rising to approximately 300W during physical work with a medium degree of difficulty, and attaining values of over 1000 W for short period at maximum physical performance in the case of a sportsman.[8]

According to Watikins et.al.,[14] the upkeep of thermal balance is perhaps the foremost important physical comfort attribute of clothing and has occupied the eye of the many textile research workers. An air temperature of 28-29˚C would be required for an individual to be ready to sit in comfort without wearing any clothes.[6] At air temperatures less than this, the body will lose temperature without the added insulation given by fibrous material. If air movement is controlled, it will act as heat insulator which is merely slightly less than that of a vacuum. Convection losses arise because the body transfers heat to the air in touch with it. This heated air is then immediately replaced with cold through natural convection or through air currents generated by body movement or air flow. Morris[15] classified thermal properties as under:

a) **Thermal insulation of fabrics:** This is the property of fabric to keep the thermal balance of the human body.

b) **Cold feel of fabrics:** The warm/cool feeling of individual when the fabric touched first.

c) **Chill proofness of fabrics:** This is power of a cloth which reduces the effect on the human body due to sudden variation in atmospheric conditions.

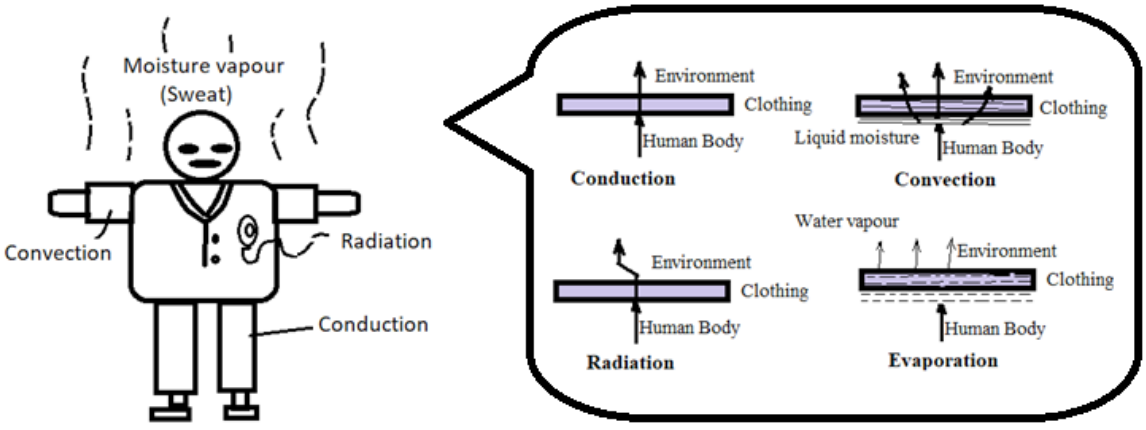

Figure 3 Mechanism of heat transport from the body to the environment.

Thermal comfort depends on combination of clothing, climate and physical activity.[4] The human body converts the energy of its food into work and warmth. The quantity of warmth generated and lost varies markedly with activity level and type of clothing. The heat produced is transferred from the human skin to the environment. During a steady-state heat balance, the heat energy produced by the body equals the speed of warmth transfer from the body by respiration, conduction, convection, radiation and evaporation.[16] Therefore, clothing is required to guard the body against climatic influences and to help its own thermal control functions under various combinations of environmental conditions and physical activities.[4] In each environment, the feeling of comfort depends upon heat loss by body which is affected by type of clothing worn.[17] Clothing plays a crucial role in the maintenance of heat balance of the human body. Figure 4 exhibits the factors that influence the thermal comfort for a person[3,18]:

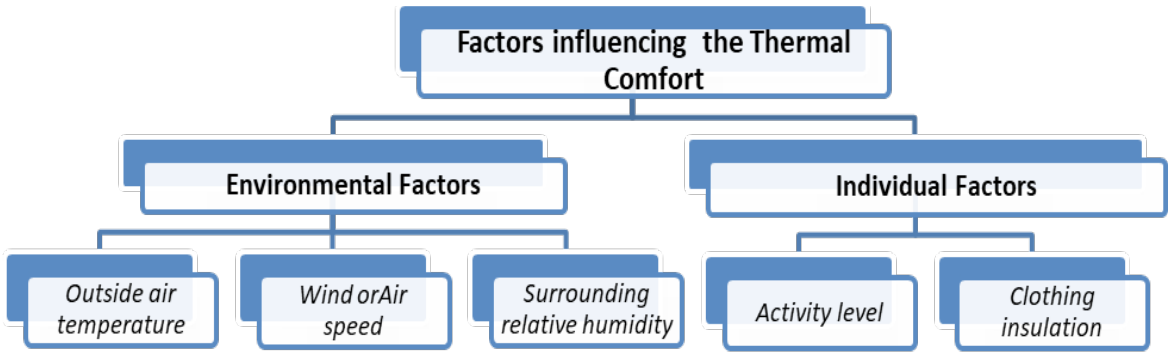

Figure 4 Factors affecting thermal comfort.

A. **Environmental factors**

i. **Outside air temperature:** The outside temperature has direct relation with the thermal insulation of clothing. If, outside air temperature is lower the thermal insulation of clothing decreases.

ii. **Wind/Air speed:** Air speed has reverse relation on clothing insulation value mainly because of breakup of air layer.

iii. **Surrounding relative humidity:** With the increase of relative humidity of surrounding the thermal insulation value of clothing increases.

B. **Individual factors**

i. **Activity level:** Thermal insulation value of individual decreases at higher activity levels.

ii. **Clothing insulation:** Clothing is a device that regulates or resists the transfer of heat energy from one body to environment. A high insulative fabric will be helpful in reducing body heat loss via conduction and radiation.

In above-mentioned factors, the environment factors aren't within the control of man; only individual factors are often controlled. In individual factors clothing insulation is main parameter. Most insulation systems that applied to reduce heat loss from the body are made from textile structures that are mixtures of textile fibre and air. In these structures, fibre dominates by weight and visibility whereas air dominates by volume. Textile fibres obstruct the flow of radiant heat and stabilize the air within the textile structure to attenuate convection heat losses since air features a lower conductivity than fibres.

Thermoregulation through clothing system

By the metabolic processes, the human body continuously generates heat. The warmth is lost from the surface of the body by convection, radiation, evaporation and respiration. In a steady state condition, the heat produced from the body is balanced through the heat loss to the environment. The body has very intelligent thermoregulatory system to make sure the body core temperature (37˚C). When the body heat increases higher than the set value, vasodilatation of blood vessels is activated to increase the blood flow to the skin for the aim of accelerating heat loss. If the body heat continues to rise, the sweating mechanism will be activated to accelerate heat loss by evaporation of the liquid sweat. In contrast, when the body detects its temperature decreased less than the set value, vasodilatation of blood vessels is going to be activated to decrease the blood flow to the skin to reduce heat loss, and metabolic rate will be increased by stimulating the muscles, which ends up in shivering.[13,19]

A person can live comfortably only during a very narrow thermal environment from 26-30˚C without wearing clothing.[13,20] With clothing, a person can live and perform various physical activities comfortably in a wide range of thermal environment from -40˚C to 40˚C. Therefore, clothing plays a crucial role in providing thermal protection for the body and creates a pleasant thermal microclimate in order that one can live and survive in unfavorable thermal environment in which human body cannot cope up alone. Functional design of clothing is very important for comfort point of view as well for survival in unfavorable conditions and it will be the matter of life and death.

The thermoregulation mechanism through clothing depends primarily on the thermal behaviors in human body and transmission characteristics of clothing and can be summarized as[13,21,22]:

a. The biological thermal activities in the human body.

b. The heat transmission through clothing.

c. The moisture transfer process in clothing.

d. The thermal barrier between the human body and the environment formed by the clothing.

Heat and moisture transport properties

The thermal and moisture transport behavior of a cloth critically important for survival of human being and plays a significant role in maintaining thermophysiological comfort.[4,11,13,23,24] Heat transmission through the clothing can take place in three ways.[3,5,6,24,25]:

i. Dry heat transmission through conduction and radiation

ii. Diffusion of insensible perspiration (water vapour); and

iii. Diffusion of liquid perspiration

Yoo et al.[26] stated that once we wear a garment, heat and moisture generated from the body stay within the air layer before transfer to the ambient air, leading to the characteristic microclimate between the skin and therefore the garment and determining comfort sensation. Heat and moisture are suffering from the environment as well as human factors and clothing factors such as fabric and garment openings.

Dry heat transmission

There are many thermal measurements possible for fabrics, but, in general, they can be divided into two groups: transient-state and steady state thermal properties. The steady state properties of thermal conductivity and resistance are perhaps the most widely understood and provide information on the warmth of a fabric. Transient heat transfer occurs when contact between the skin and a surface first takes place. Measurements classified as transient include the thermal diffusivity, which characterizes the temperature flow through the fabric; thermal absorptivity, which is the quantity of heat penetrating a fabric during the time period when the temperature is raised rapidly, and q_{max}, which is the maximum heat flow while heat is still being transferred.[27]

Thermal resistance

Thermal insulation property of a textile fabric was defined by Miller[28] as its ability to resist the transmission of heat by all modes. Morris[15] also defined thermal insulation as the effectiveness of a fabric in maintaining the normal temperature of the human body under equilibrium conditions. The thermal resistance is used to measure of thermal insulation and it reciprocal of thermal conductivity. In the measurement of thermal resistance, the thickness of the fabric is not considered. The unit of thermal resistance in SI unit is degree Kelvin square meter per watt.[7]

The insulation value of a fabric is in fact mainly dependent on its thickness and entrapped air within the yarn and fabric structure.[7] If the losses by convection can be prevented, the entrapped air offers a very high resistance to heat conduction having a value of thermal resistance which is only slightly less than that of a vacuum. In fabrics majority of the bulk is composed of air (for example, about 75% and 90% air in worsted suiting fabric and knitted underwear fabrics respectively). In windy atmosphere, the insulation of fabrics is inversely proportional to the air velocity. The air in contact with the body is heated by conduction and is then carried away from the body by convection. It disturbs the trapped air in the clothing system by both the movement of the fabric and by penetration through the fabric; which reduces insulation value.

Thermal conductivity

It is another familiar term applied to materials that conduct heat. Thermal conductivity is defined[28] as the heat flux divided by the temperature gradient where heat is transferred by conduction only and has units of $Wm^{-1}K^{-1}$. It gives the rate of flow of heat by conduction through unit area of material of unit thickness when a difference in temperature of one degree Celsius exists between its opposite faces. Thermal resistance (R), thermal conductivity (K) and thickness of the material (d) are related as under:

Thermal resistance (R)=d/K

The thermal conductivity (K) is roughly constant for various fabrics While thermal resistance is approximately proportional to thickness of fabric. Therefore, thickness of a garment mostly determines its thermal resistance.[24]

Warm/Cool feel (transient-state heat transfer)

The warm or cool feel of fabric during first touch is due to its transient heat transfer in between hand and fabric in which thermal conduction makes the most important role.[27,29,30] The intensity of the warmth and cold feeling is depend upon the of change in temperature sensed by the thermo receptors in the skin and the total magnitude of the change.[31] A fabric that dissipates heat quickly will feel cooler than one that transfers heat slowly. The transient transfer of energy depends on the contact interface between the skin and the fabric, and the contact interface depends on many morphological and structural parameters like fiber morphology or yam and fabric structure. The 'warm/cool feel' is therefore mainly determined by the thermal conductivity.[11]

Moisture transmission

The clothing to be worn should allow the perspiration to be transferred to the atmosphere so as to maintaining the thermal balance of the body.[7,32,33] The moisture transmission of fabric affects significantly on thermophysiological comfort of the human body which is maintained by perspiring both in liquid form or vapour form.[7,34]

The two sorts of perspiration raise different problems: one is that the ability of water vapor to undergo the fibrous material, particularly the outer layer; and other is that the ability of the fibrous material in touch with the skin of absorbing or otherwise handling the liquid sweat. Perspiration is a crucial mechanism by means of which the body uses to lose heat when its temperature starts to rise. Heat is taken from the body so as to provide the required latent heat to transform liquid moisture into water vapour from the skin. Some workers[25] consider that the extent to which the wet fabric clings to the skin is additionally important to the comfort of a garment. The moisture transmission by diffusion of water vapor (insensible perspiration) and wicking of liquid water (sensible perspiration) away from the skin largely depends on fabric structure.[7,34] In addition to heat and moisture transport properties; water absorbency and drying rate are vital factors affecting the physiological comfort of sports garments and normal clothing.[7,11,35–37]

Diffusion of insensible perspiration (water vapour permeability)

Fabric's water vapour permeability is very important property of fibrous material that helps in maintaining thermal equilibrium for the wearer. During the exercise or very hot climate, the human body maintains thermal balance by sweating and evaporation. To reduce the degradation of thermal insulation due to moisture build up and to maintain comfort specially in cold environments, the clothing must be able to remove this moisture. A fabric of low moisture vapour permeability is unable to pass sufficient perspiration and this leads to sweat accumulation in the clothing and hence discomfort.[4] Water vapour transmission can be done through textile layers by different processes, e.g. diffusion, absorption-desorption and forced convection.[10,11,34,38] The overall moisture vapour transmission of clothing depends on the whole clothing system.

Diffusion of liquid perspiration (Wicking)

Wicking (liquid moisture transfer) plays an important role in moisture transmission, when the moisture content of clothing is very high, and the body is producing large quantities of liquid perspiration.[7] Water generated at the body surface as perspiration should be removed as quickly and as efficiently as possible if comfort is desired.[39] Wicking in clothing significantly influences the wearer's perception of moisture comfort sensations.[36,40] Fabrics to be worn as workwear in tropical climates, or as sportswear, should possess very high wicking properties.[36,41] Hollies et al.[42] stated that yarns are responsible for the main portion of capillary action and wicking of liquid in fabrics. For movement of liquid in a fabric, the liquid must wet the fabric surface before being transported by capillary action through the fabric pores formed between fibres and yarns.

Water absorbency and drying property

Moisture handling properties of textile during intense physical activities have been regarded as major factor in the comfort performance. Actually, the comfort perceptions of clothing are influenced by the wetness or dryness of the fabric and thermal feeling resulting from the interactions of fabric's moisture and heat transfer related properties. For a garment that is worn next to the skin should have good sweat absorption and sweat releasing property to the atmosphere, and fast drying property for getting more tactile comfort.[43] Water absorbency (retention) is a quality of fabric to absorb water.[44]

Air permeability

Air permeability is a critical propertie by which fabric is assessed for upto which extent fabric allows the passage of air through it.[7] Air permeability of a fabric can influence its comfort behaviour of apparel, functional sportswear and leisurewear in several ways.[5,35,39] A fibrous material that is permeable to air is also, in general, likely to be permeable to water, in either the vapour or the liquid phase. Air permeability can be important in both hot and cold climates.[6] High permeability allows freer access of air to the surface of the skin which thus enhances the removal of moisture in hot weather and reduces discomfort. Conversely, this easy access can destroy comfort in cold weather, since any cold air that is allowed to reach the body surface will remove heat at high rate.

Approaches to enhance thermophysiological comfort

Thermophysiological comfort properties of fibrous material depends on some factors such as structure of component fibres, structural characteristics of yarn and fabrics and the way of these factors interact with each other.[3,11,22,32] Different raw materials and fabric structure have their own merits which are inherent and determine the comfort behaviour of the material. Some approaches to increase the clothing comfort are as under:

i. **Use of various types of fibres and modification of fibre structure:** The various type of fibres such as natural and manmade and structure (such as fibre type, shape and size, internal and external structure, density, crimp and hygroscopic nature etc.) influence the thermophysiological properties of clothing.

ii. **Type of yarn and modifying yarn structure**: Yarns manufactured by using various type of material such as mono-component, multi-component yarn; and structure of the yarn like core yarn, hollow/micro-porous yarn, bulked yarn etc. plays important role in achieving the thermophysiological comfort.

iii. **Type of fabrics and modification of its structure:** Type of fabric and its structure (such as woven, knitted, nonwoven and layered fabrics etc.) play a vital role in regulating thermo physiological comfort.

iv. **Applying various types of finishes:** By applying various types of finishes in the fabric such as water repellent finish, wicking enhancer finish, hydrophobic finish and nano-finishes etc.; thermophysiological comfort can be enhanced.

Conclusion

The thermophysiological comfort is main attribute of the clothing which includes the heat and moisture transport properties. Feeling of comfort depends on combined effect of physical activity, climate and clothing. The heat transmission through the fabric is done by four mechanism: conduction, convection, radiation and evaporation. Thermophysiological clothing comfort can be achieved by dry heat transmission through conduction and radiation, moisture transmission (water vapour permeability, liquid water transmission or wicking, water absorbency and drying property) and air permeability. These properties of the clothing can be improved by using the different fibrous material, modifying the structure of fibre, yarn, fabric and garment; and applying suitable finish in the fabric which can enhance the heat and moisture transport properties.

Acknowledgments

None.

Funding

None.

Conflicts of interest

The authors report no declarations of interest.

References

1. Meinander H. Heat stress in sportswear. *Textile Asia*. 1995;26(8):108–110.
2. Uttam D. Active sportswear fabrics. *International Journal of IT, Engineering and Applied Science Research*. 2013;2(1):34–40.
3. Uttam D, Sethi, R. The effect of repeated washings on the total hand value of cotton fabric. *International Journal of Advanced Research in Engineering and Applied Sciences*. 2016;5(7):29–36.
4. Li Y. The science of clothing comfort. *Textile Progress*. 2001;31(1/2):1–135.
5. Li Y, Wong ASW. *Clothing biosensory engineering*. The Textile Institute, Cambridge, England: Woodhead Publishing Limited; 2006:1–391.
6. Slater K. The assessment of comfort. *Journal of the Textile Institute*. 1986;77(3):157–171.
7. Saville BP. *Physical testing of textiles*. The Textile Institute, Cambridge, England: Woodhead Publishing Limited; 2002:1–310.
8. Umbach KH. Aspects of clothing physiology in the development of sportswear. *Knitting Technique*. 1993;15(3):165–169.
9. Farnworth B. Mechanism of heat flow through clothing insulation. *Textile Research Journal*. 1983;53(12):717–725.
10. Das A, Alagirusamy R. *Science in clothing comfort*. New Delhi: Woodhead Publishing India Pvt. Ltd; 2010:1–175.

11. Mukhopadhyay A, Ishtiaque SM, Uttam D. Impact of structural variations in hollow yarn on heat and moisture transport properties of fabrics. *Journal of the Textile Institute*. 2011;102(8):700–712.

12. Asta B, Daiva M. Influence of shrinkage on air and water permeability on double-layerd weft knitted fabric. *Material Science*. 2012;18(3):271–274.

13. Mukhopadhyay A, Sikka M, Karmakar AK. Impact of laundering on the seam tensile properties of suiting fabric. *International Journal of Clothing Science and Technology*. 2004;16(4):394–403.

14. Watkins DA, Slater K. The moisture vapour permeability of textile fabrics. *Journal of the Textile Institute*. 1981;72(1):11–18.

15. Morris GJ. Thermal properties of textile materials. *Journal of the Textile Institute*, 1953;44:T449–T476.

16. Stocker WF, Jones JW. *Refregeration and Air Conditioning*. 2nd edn. Singapore: McGraw Hill; 1982:1–439.

17. Ogulata RT. The effect of garment on man's thermal comfort. *Association for the Advancement of modeling and Simulation Techniques in Enterprises*. 2001;70(1,2):15–26.

18. Yadav AK, Gupta KK, Kureel GL. Studies on thermal insulation values of different insulating material. *Man Made Textiles in India*. 2005;48(4):145–149.

19. Li Y, Mao A, Wang R, et al. P-smart-a virtual system for clothing thermal function design. *Computer Aided Design*. 2006;38:726–739.

20. Fanger PO. Thermal environment - human requirements. *Sulzer Technical Review*. 1985;67:3–6.

21. Mao AH, Li Y, Luo X, et al. A CAD system for multistyle thermal functional design of clothing. *Computer Aided Design*. 2008;40(9):916–930.

22. Ogulata RT. The effect of thermal insulation of clothing on human thermal comfort. *FIBRES & TEXTILLES in Eastern Europe*. 2007;15(2):61.

23. Uttam D, Sethi R. Impact of repeated washings on the thermal insulation properties of woven cotton fabrics. *International Journal of Advanced Research in Engineering and Applied Sciences*. 2016;5(3):1–9.

24. Uttam D. Objective measurement of heat transport through clothing. *International Journal of Engineering Research and Development*. 2012;2(12):43–47.

25. Smith J. Comfort in Casuals. *Journal of the Textile Institute*. 1985;5(8):35–38.

26. Yoo HS, Hu YS, Kim EA. Effect of heat and moisture transport in fabrics and garments determined with a vertical plate sweating skin model. *Textile Research Journal*. 2000;70(6):542–549.

27. Weedall PJ, Goldie L. The objective measurement of the 'cool feeling' in fabrics. *Journal of the Textile Institute*. 2001;92(4):379–386.

28. Ukponmwan JO. The thermal insulation properties of fabric. *Textile Progress*. 1993;24(4):1–57.

29. Pac MJ, Bueno MA, Renner M, et al. Warm-cool feeling relative to tribological properties of fabrics. *Textile Research Journal*. 2001;71(9):806–812.

30. Yoneda M, Kawabata S. A theoretical consideration on the objective measurement of warm/cool feeling. *The Textile Machinery Society of Japan.* 1982:393–406.

31. Hensel H. *Thermoreception and Temperature Regulation*. New York, London: Academic Press; 1981:144–145.

32. Hyun SO, Hollies NRS, Spivak SM. Skin sensations perceived in apparel wear part I: Development of a new perception language. *Journal of the Textile Institute.* 1991;82(3):389–397.

33. Sachdeva RC. *Fundamentals of engineering heat and mass transfer*. 2nd edn, New Age International Publisher; 2005.

34. Das B, Das A, Kothari V K, et al. Moisture transmission through textiles, part – I process involved in moisture transmission and factors play. *AUTEX Research Journal*. 2007;7(2):100–110.

35. Haberstock H. Special polyester yarn knitted fabric for sportswear with optimum functional and physiological properties. *Milliand*. 1990:E125–E127.

36. Fangueiro R, Filgueiras A, Soutinho F, et al. Wicking behaviour and drying capacity of functional knitted fabrics. *Textile Research Journal*. 2010;80(15):1522–1530.

37. Arai K. Wearing comfort of water absorbent acrylic fibres. *Journal of Textile Machinery Society of Japan (English Edition)*. 1984;30(3):72–81.

38. Das B, Das A, Kothari V K, et al. Moisture transmission through textiles, part – II evaluation methods and mathematical modelling. *AUTEX Research Journal*. 2007;7(3):194–216.

39. Slater K. Comfort Properties of Textiles. *Textile Progress*. 1977;9(4):1–70.

40. Ghali K, Jones B, Tracy J. Experimental techniques for measuring parameters escribing wetting and wicking in fabrics. *Textile Research Journal*. 1994;64(2):106–111.

41. Miller B, Tyomkin I. Spontaneous transplanar uptake of liquids by fabrics. *Textile Research Journal*. 1984;54(11):706–712.

42. Hollies NRS, Kaessinger MM, Bogaty H. Water transport mechanism in textile materials, part I: The role of yarn roughness in capillary type penetration. *Textile Research Journal*. 1956;26(11):829–835.

43. Hill R. Fibres and fabrics in sports. *Textiles*. 1985;14(2):30–36.

44. Das A, Ishtiaque SM. Comfort characteristics of fabrics containing twist-less and hollow fibrous assemblies in weft. *Journal of Textile and Apparel Technology and Management*. 2004;3(4):1–7.