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**Review Article**

# Role of fibre, yarn and fabric variables in engineering clothing with required thermo-physiological properties

Y Jhanji[1], Deepti Gupta [2,a] & V K Kothari[2]

[1]Department of Textile Technology, The Technological Institute of Textile & Sciences, Bhiwani 127 021, India

[2]Department of Textile & Fibre Engineering, Indian Institute of Technology Delhi, New Delhi 110 016, India

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Designing and engineering clothing for an intended end use necessitates careful selection of fibre, yarn and fabric constructional parameters. Ideal clothing comfort can be achieved by designing clothing, considering high thermal resistance for protection from cold, low resistance to water vapour transfer in mild thermal stress conditions and rapid transfer of vapour and liquid moisture under high thermal stress conditions and rapid transfer of vapour and liquid moisture under hugh thermal stress conditions. Several studies have been reported on the influence of various fibre, yarn and fabric constructional variables on comfort properties of woven and knitted fabrics and the findings show that the fibre, yarn and fabric variables strongly influence the thermo-physiological properties of fabrics and determine the suitability for their particular end use. Several yarn variables, like yarn twist, yarn count, yarn spinning system and yarn types , have been reported to affect the properties of textiles. Change in any of these parameters ultimately changes the yarn structure, which, in turn, depends on the fibre geometry. Distriution of fibres in yarn dictates thermal as well as moistre transfer properties of fabrics. Fabric structure, thickness, cover factor, aerial desnity, bulk density, fabric porosity and finishing treatments affect the thermal and moisture management properties and hence determine the comfort properties of textiles. This paper reports a detailed study on the comfort characteristics of textiles and factors at interplay.

**Keywords:** Clothing, Comfort properties, Fabric, Fibre, Microclimate, Air permeability, Thermal properties, Thermo-physiological properties, Yarn

## 1 Introduction

The role and importance of clothing in providing thermal equilibrium with the surrounding environment and hence overall wearer comfort necessitates careful selection of all aspects involved in designing and engineering of clothing. Fabrics intended for applications like active sportswear, work wear and inner wears should have optimum thermo-physiological properties. The prime requirement of clothing for all such applications is the utilization of concept of moisture management to provide dry feel next to skin by preventing or minimizing the liquid accumulation on the wearer's skin. Ability of quick drying, permeability to air, rapid heat and moisture vapour transmission through clothing to environment are some other aspects that influence the performance and functionality of clothing. Ideal clothing comfort can be achieved by designing clothing taking into account high thermal resistance for protection from cold, low resistance to water vapour transfer in mild thermal stress conditions and rapid transfer of vapour and liquid moisture in high thermal stress conditions[1].

The thermo- physiological properties of clothing should, therefore, match the specific functionality in accordance with an individual's activity level and changing ambient conditions. Complex combination of various factors, such as fibre, yarn, fabric, garment design and fit, way clothing is worn, layers of clothing, human and environmental factors, all contribute to thermo-physiological properties and comfort of the worn clothing[2]. The desired thermo-physiological properties in the fabrics can be engineered by precise selection of fibre, yarn and fabric constructional variables. A lot of expertise is therefore involved in the selection of fibre, yarn and fabric variables to engineer fabrics intended for particular end use. The fibre, yarn and fabric variables affect the fabric's bulk properties and, in turn, have an influence on the thermo-physiological properties of the clothing. Several researchers[3-14] have studied the influence of various fibre, yarn and fabric constructional variables, like fibre fineness, fibre

[a] Corresponding author.
E-mail: deeptibgupta@gmail.com

cross-sectional shapes, fibre packing density, fibre orientation, yarn structure, yarn count, yarn twist, yarn spinning technologies & yarn types, as well as structural factors, like weave type, weave balance, different knit structures, cover factor, thickness and porosity, on comfort properties of woven and knitted fabrics. Reported literature suggests that fibre, yarn and fabric variables strongly influence the thermo-physiological properties of fabrics and determine the suitability for particular end use.

Although exhaustive studies have been carried out and reported to observe the effect of fibre, yarn and fabric variables on comfort aspects of textiles, however there is dearth of a systematic and comprehesive review on effect and interplay of factors on thermo-physiological properties of knitted structures, specifically plated knits. This study, thus, attempts to address the voids and provide an insightful review on the role of fibre, yarn and fabric variables in engineering clothing with required thermo-physiological properties.

## 2 Methodology

The research publications and PhD dissertations pertaining to thermo-physiological comfort properties of textiles were meticously searched and analysed. Researchgate database was used to find open access journals and otheronline articles relevant to studies. Accordinlgy, approximately one hundred thirty research and review publications werecollected and sumarised for the study and eventually the most relevant one hundred twelve papers were analysed to present a comprehensive outcome.

## 3 Role of Fibres in Thermo-physiological Properties

Fibre properties, like fibre type, cross-sectional shape, fibre fineness, fibre length, composition of fibre mix, friction, crimp, molecular orientation, are suggested as the major contributors to heat, moisture and liquid transmission and wearing comfort in textiles[10, 12, 14-19].

Role of fibres in providing thermal insulation is largely restricted to creation of three dimensional lattice in which air is immobilized. The small proportion of fibres present therein contribute to overall fabric conductivity to an extent related to fibre packing density[17]. Farnworth[18] gave the relationship between thermal conductivity of textile material with fibre and air thermal conductivity, as shown below:

$$K = (1 - f)K_a + fK_f \quad \ldots (1)$$

where $K$ is the thermal conductivity of fabrics; $K_a$, the fibre thermal conductivity; $K_f$ , the air thermal conductivity; and $f$, the part of air in textile material. Bogaty[19] gave model for thermal conductivity; by taking fibre orientation into account, as shown below:

$$K = x(V_f K_f + V_a K_a + \frac{y(K_a K_f)}{V_a K_f + V_f K_a} \quad \ldots (2)$$

where $V_a$ is the volume of air in textile material; $V_f$, the volume of fibre in textile material; x, the part of fibre parallel to heat flow direction; and $y$, the part of fibre perpendicular to heat flow direction.

### 3.1 Role of Fibre Type

Fibre type is reported to play a crucial role in determining the comfort properties of textile fabrics [20-23]. The most significant influence of fibre properties is believed to be manner in which fibre shape and surface reflect increased or decreased capillary formation in the fabric, which, in turn, causes an enhanced or diminished water uptake on wetting and water retention on drying[22].

A variety of natural and synthetic fibres are finding applications in functional clothing, like active wear, innerwear and sportswear, owing to unique characteristics and features of each fibre. Selection of natural or synthetic fibre will depend on the degree of activity contemplated. While natural fibres being hydrophilic owing to the bonding sites for water molecules [Fig. 1 (a)] are considered suitable for low activity levels, synthetic fibres are hydrophobic with no active sites for attachment of water molecules [Fig. 1 (b)] and are generally preferred choice as base layer for high activity levels. Hydrophilic fibres have a high surface energy and hence they pick up moisture

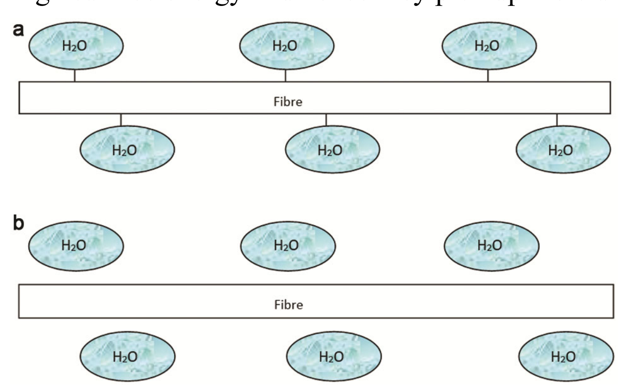


Fig. 1 — (a) Moisture vapour molecules on active sites of hydrophilic fibres and (b) Hydrophobic fibres with no active sites for bonding with water molecules

more readily than hydrophobic fibres which have low surface energy and repel moisture[22].

Diffusion process is delayed in hydrophilic fibres due to their affinity to water molecules, which when absorbed by the fibres cause fibre swelling and reduction of the air spaces. Therefore, hydrophilic fibres have poor moisture transportation and release, as water tends to be retained in these fibres. Synthetic fibres have an additional advantage of keeping garment lighter than natural fibres when wet, are quick drying and possess good shape retention property,thereby making them suitable for next to skin applications [23].

Cotton remains by far the most important natural fibre of the 20$^{th}$ century. It is characterized by good handle and hygiene properties. Additionally, cotton fibre has good water vapour and air permeability, so it is recommended for summer garments but is not a preferred choice as next to skin layer due to skin clinginess and chill feel when wet; also cotton fabrics are slow drying particularly in the conditions of high liquid sweat generation[23, 24]. Slow drying of vapour and liquid moisture in cotton fabric makes it clammy after sweating period, despite the smoothness and water absorption capacity of cotton fabrics.

On the other hand, synthetic fibres, such as polyester, polypropylene and nylon being hydrophobic, have an additional advantage of liquid transport and release by capillary wicking without liquid retention, as they do not form bond with water molecules[20, 25]. Polyester fibre owing to low moisture absorption and easy care properties is recommended in base fabrics for active wear. Excellent heat resistance, thermal stability, outstanding dimensional stability and durability are some other attributes of polyester fibre.

Polypropylene is claimed to be a proven performer in moisture management due to its hydrophobic nature and has the capability to provide insulation even when wet. It is more oleophilic than polyester and thus has a tendency to attract and hold oily body odors.

Nylon is often favorable choice in woven outer wears due to its low air permeability and ability to trap heat. Other characteristics include high moisture regain, lightweight, softness, durability and high strength. A combination of natural and synthetic fibres is an optimal solution when designing clothing for next to skin applications. However no single fibre or different fibre blends can ensure ideal clothing suitable for varied applications. The right type of fibre needs to be in the right place according to the fabric's end use. Any wrong selection of fibre combinations may lead to thermal and wetness discomfort to the wearer if water absorption and liquid transfer properties of the selected fibres are not according to level of sweat generated.

Polyester and cotton fibres in blended form are increasingly being used for specialized yarn production to achieve good wicking and low absorbency. Dri release yarn is composed of blend of 85-90% polyester and 10-15% cotton generally used in sportswear due to excellent moisture management properties[26]. Properties of individual components can be improved by blending two or more fibres into single yarns. Optimer has developed Dri release fibre blend consisting of 85-90% of hydrophobic fibre and 10-15% of hydrophilic fibre. Fabrics made from Dri release fibre show low absorbency, good wicking performance and quick drying[27, 28].

Several researchers[9,24,28-32] have attempted to study the influence of different fibre types and their blends on thermo-physiological properties of fabrics. Kandi *et al.*[9] studied the thermo-physiological properties of polyester-bamboo blended suiting fabrics and observed an increase in relative water vapor permeability, water absorbency and wick ability with increase in bamboo content. However, thermal resistance of fabrics decreased with increasing bamboo content which was attributed to inherent poor thermal insulation of bamboo fibre and its higher moisture regain compared to polyester fibre.

Oner *et al.* [16] observed higher overall moisture management capacity values for polyester fabrics compared to cellulose based fabrics and suggested that cotton fabrics caused wetness to be felt more than other fabrics.

Oglakcioglu[24] studied the thermal properties of different cotton and angora rabbit fibre blended fabrics and reported that as the angora rabbit fibre ratio increased, thermal resistance increased; however, thermal conductivity, thermal absorptivity and relative water vapor permeability decreased.

Bivainyte *et al.*[28] investigated the thermal properties of double layered fabrics knitted of cotton, bamboo and four types of synthetic threads. They found that fabrics knitted from yarns of cotton and synthetic fibres have higher thermal conductivity coefficient than those knitted from bamboo and synthetic yarns. Effect of synthetic fibre yarn on thermal conductivity coefficient was found to be low. Thermal resistance for fabrics knitted with coolmax in combination with cotton or bamboo was higher.

Jhanji *et al*.[29] compared the moisture management properties of plated fabrics with altering hydrophilic and hydrophobic fibres in top and bottom layers and different types of hydrophobic fibres in top layers. They observed that fabrics knitted with hydrophobic fibres (polypropylene, polyester) in top (next to skin) layers were moisture management fabrics owing to high values of accumulative one-way transport index and bottom spreading speed. Polypropylene on account of superior moisture management properties in the top layer was suggested to be more effective in providing dry feel next to skin and hence, seemed to be a preferred choice over polyester for such applications. Fabric knitted with nylon in top layer was classified as water penetration fabric due to poor liquid transfer properties. Fabrics knitted with cotton in top layer irrespective of the hydrophobic fibre in bottom layer (outer layer), were poor in moisture management properties.

Jhanji *et al.*[30] also investigated the effect of fibre type on the thermal properties, such as thermal resistance, thermal conductivity and thermal absorptivity, along with air permeability and moisture vapor transmission rate of single jersey plated fabrics. Plated fabrics with nylon in the next to skin layer seemed suitable choice for warm conditions as these fabrics would feel cooler on initial skin contact owing to high thermal absorptivity and were permeable to passage of air and moisture vapor.

Teyme *et al*.[31] investigated the thermo-physiological comfort properties of four selected knitted fabrics of different fibre blend ratios intended for cycling wear. Comfort-related properties of the fabrics, namely air permeability, moisture management properties, drying time, thermal conductivity, and water vapor permeability, were investigated. They found that polyamide/elasane fabric with good air permeability, thermal conductivity, moisture management properties, and short drying time was the preferred choice for summer cycling clothing.

Karthik *et al*.[32] investigated the effect of blend ratio on thermal comfort characteristics of cotton/bamboo blended fabrics and observed that thermal conductivity and thermal resistance of the blended fabrics decreased, while air permeability and water vapour permeability increased with increase in blend ratio of bamboo.

Nayak *et al*.[33] studied the effect of polyester content, pick density and fabric direction on handle and comfort properties of PV blended fabrics and concluded that the fabrics with higher viscose content showed lower thermal insulation but higher values of moisture vapor transmission and air permeability along with better handle properties. Rasheed *et al*.[34] studied the effect of fibres and weave design on comfort properties of summer headscarf fabrics and observed that matt weave in conjunction with micro polyester and tencel fibres was the best choice for summer scarf fabrics owing to their superior aesthetic, tactile, and thermal comfort properties.

Adamu and Gao[35] investigated the comfort properties of woven fabrics composed of nylon, cotton, and cotton–nylon mixtures with different yarn counts. They observed that fabric transfer wicking, longitudinal wicking, moisture regain and air permeability properties show an upward trend as the yarn became coarser for all woven fabric samples, however decrease in water vapor transmission property was observed. As the nylon fibre blend ratios increased, fabric transfer and longitudinal wicking capabilities improved. However, negative impact of nylon fibre composition on air permeability, water vapor transfer rate, wicking and moisture capabilities of the woven fabrics was observed.

Durur *et al*.[36] studied the comfort properties of gray and finished cotton and polypropylene terry-woven fabric structures and observed that the use of the polypropylene fibres yarns in high-pile fabrics and cotton yarn in ground yarns performed better in terms of comfort properties.

Yang *et al*.[37] investigated the physical and comfort properties of interlock knit structures composed of cool-touch nylon and common nylon fibres and concluded that former had better moisture absorption, wicking capacity, thermal transfer, and cooling properties but poorer drying performance and moisture permeability compared to latter.

Riaz *et al.* [38] compared the thermo physiological properties of 1/1 plain and 2/2 warp rib woven fabrics composed of cotton, bamboo, viscose and tencel fibres. They concluded that tencel fabrics exhibited the highest water vapor permeability index and overall moisture management capability values, whereas cotton fabrics showed the highest values of volume porosity %, air permeability, and thermal resistance. Comparison of weave design highlighted that 1/1 plain woven fabrics showed higher values of water vapor permeability index and OMMC values while volume porosity %, air permeability, and thermal resistance was observed to be higher for 2/2 warp rib woven fabrics.

Geraldes[39] suggested that percentage of hydrophobic component is crucial to the behavior of the functional knits and observed linear relationship between thermal absorptivity, thermal resistance and the percentage of hydrophobic component (polypropylene) in the functional knit structures. Majumdar *et al.*[40] studied the thermal properties of knitted fabrics made from natural and regenerated bamboo cellulosic fibres and observed that air and water vapor permeability increased but thermal conductivity decreased as the proportion of bamboo fibre increased.

Pac *et al.*[41] studied the influence of fibre morphology on warm-cool touch of fabrics. It was reported that fabrics made from pima cotton owing to less roughness and hairiness absorbed more energy and would feel cooler when compared to fabrics made from kaba cotton. However, cotton variety seemed to have less influence on warm-cool feeling as the fabric stitch length was increased.

Stankovic *et al.*[42] investigated the thermal properties of natural and regenerated cellulose fibres and suggested that heat transfer through the fabrics is highly related to both capillary structure and surface characteristics of yarns as well as air volume distribution within the fabrics.

Farnworth & Dolhan[43] noted no difference in heat loss between cotton and polypropylene underwear fabrics during period of heavy sweating and suggested that there was no evidence of thermal well-being of wearer enhanced by polypropylene underwear.

Supuren *et al.*[44] investigated the moisture management properties of the double face fabrics and suggested that polypropylene (back) and cotton (face) fabric had better moisture management property. Long[45] stated that liquid water transfer from the back to the face layer depends upon the water absorption of the fibre materials of the two layers and to a greater extent their difference. Fangueiro *et al.*[46] studied the wicking and drying ability of knitted fabrics produced from blends of wool- coolmax and wool- fine cool. It was reported that fabrics with coolmax fibres could transport perspiration quickly from the skin to environment and showed the best capillarity performance. Fine cool fabrics had higher drying rates, whereas wool fibre based fabrics showed low water absorption but good drying rate. Ozturk *et al.*[47] studied the influence of fibre type on wicking properties of cotton- acrylic yarns and fabrics and suggested that wicking ability of yarns and fabrics increased with the increase in acrylic content in the blends. Bedek *et al.*[48] evaluated the moisture management properties of knitted underwear fabrics and suggested that fibre type together with moisture regain and knitted structure characteristics appeared to affect comfort related properties. They observed that cotton underwear fabrics had the longest drying time which was correlated to the highest moisture regains and lowest air permeability of the fabrics.

Bertaux *et al.*[49] studied the influence of fibre type on sock comfort and suggested that fibre content determines the perceived comfort. They observed that socks containing cotton felt wetter and warmer to the wearers and were perceived less comfortable. Socks containing synthetic fibres like polyester and polyamide transported more perspiration from foot surface keeping it drier and thus were preferred for better comfort sensation and prevention of friction blisters on foot.

Kumar and Das[50] reported that polyester fabric exhibited the highest height raised by water during vertical wicking, however fabrics using viscose and cotton showed lower wicking height. They attributed reduced vertical wicking for cotton and viscose fabrics to hydrophilic nature of fibres and the gravity effect during vertical rise of water in fabric.

Weiyusan *et al.*[51] studied moisture transfer properties of knitted fabrics using different fibre combinations. They observed that polypropylene fibre knitted in inner side with hydrophilic fibre in outer side transferred moisture easily to outside. Greater moisture transport properties were shown by fabrics using polypropylene combined with viscose/cotton compared to fabrics with polypropylene in inner and silk/polyester on the outer side.

Hes *et al.*[52] studied the thermo-physiological properties of cotton and PP containing commercial socks. They observed that socks knitted in double layered and rib construction containing third by weight of PP fibres provided warmer feeling, had higher thermal insulation and lowest level of thermal conductivity as compared to 100% cotton socks.

Varshney *et al.* [53] suggested that short cotton fibres cause yarn of high cotton content to be fuzzier than yarns containing more synthetic fibres, yarns with greatest cotton content would have higher cover and less air permeability.

**3.2 Role of Fibre Linear Density**

The thermo-physiological properties of textiles have been reported to be influenced by fibre linear density, and several researchers have explored this field. Finer fibres possess higher surface to volume ratio. Fibres can thus form many small spaces for still air between them. High thermal insulation can be achieved due to large internal surface area provided by finer fibres for restricted air movement to limit heat flow by conduction and convection.

Air permeability, moisture and liquid transfer are also reported to be affected by fibre fineness owing to the impact of fibre size on the inter yarn pore spaces and capillary sizes.

Super fine fibres or micro fibres with filaments of linear density below 1 decitex have been used in fabrics to provide improved comfort. Fabrics using these fibres are dense owing to increase in fibre surface and reduced spaces between fibres. Increased capillary action for improved thermal regulation can also be achieved by the use of super fine fibres [22,26,27,46]. Sampath *et al.*[22] compared the fabrics made of different yarns and observed high thermal conductivity, high vapour permeability and low wet thermal resistance for micro-denier polyester fabric.

Varshney *et al.*[53] studied the effect of fibre linear density on physiological properties of polyester woven fabrics and observed an increase in thermal resistance, air and water vapor permeabilities and trans planar wicking with fibre decitex. However, they observed that thermal conductivity, thermal absorptivity and spreading speed of water drop decreased with increase in fibre linear density.

Ramakrishnan *et al.*[54] compared the comfort properties of micro denier and normal denier viscose yarn knitted fabrics and observed higher water absorbency and wicking for micro denier yarn knitted fabrics. Kim *et al.*[55] observed excellent water absorbency and moisture management properties for pile knitted fabrics made up of conjugate nylon polyester micro fibres characterized by high density of micro fibre loops and closely packed aligned capillary columns.

Karthik et al.[56] designed fleece single jersey knitted fabrics by blending super micro polyester (288 filaments) with polyester (34 filaments), cotton and modal in inner and outer layers. They observed that use of super micro polyester in outer layer resulted in fabrics of high spreading speed, overall moisture management capacity, absorption rate and less wetting time, while cotton and modal fabrics showed moderate overall moisture management capacity.

Gun[57] compared the thermal comfort properties of plain knitted fabrics with micro fibres and conventional modal viscose fibres. Micro fibre fabrics showed high thermal absorptivity, and maximum heat flux values but lower thickness, air permeability and thermal resistance as compared with conventional fibres.

**3.3 Role of Fibre Profile**

Fibres of varying cross-sections are finding applications in functional clothing owing to their effectiveness in heat, moisture and liquid transmission through fabrics. Incorporation of non circular fibre profile is characterized by increase in fibre's shape factor which influences the fibre capillary spaces, inter yarn pore spaces, packing density, specific surface area and, in turn, the thermo-physiological properties of fabrics[6,43]. Fibres with greater specific surface area possess good moisture absorption and release. The micro grooves present on fibre surface enhance capillary absorbency, cause siphoning of moisture which can thus be dissipated by spreading over fibre surface[52]. Figure 2 shows the different fibres and their cross-sections commonly used in functional clothing.

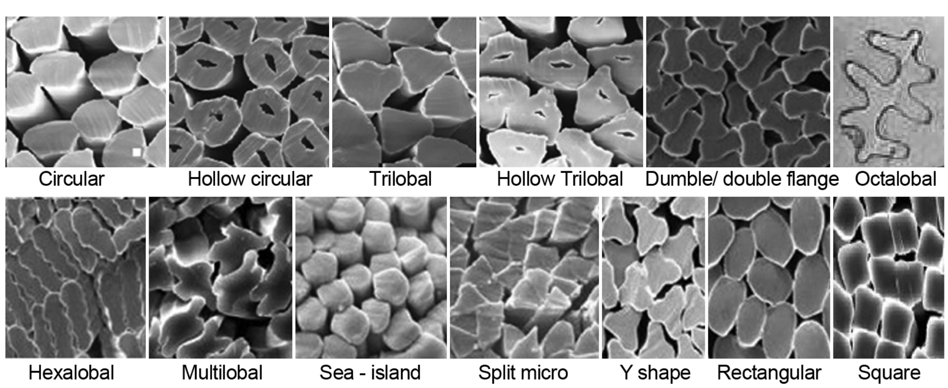


Fig. 2 — Fibres of varying cross-sections

Hollow fibres and fibres with different sized grooves are also used in active wear, sportswear and next to skin clothing to achieve good thermal insulation properties. Large trapped air volume in hollow fibres results in high thermal insulation of fabrics or garments made from these fibres. Hollow core fibres with twisted or convoluted surfaces are used for making Thermolite fabrics with improved thermal insulation and wicking properties[26]. Irregular capillaries are formed by cotton fibres within yarn, thereby inhibiting fluid flow due to flat, lima bean shaped cross-section and ribbon like appearance of cotton fibre[53].

Wicking and thermal resistance can further be improved by introduction of voids in fibre core. Welkey is fibre with hollow core and body of fibre has proliferation of small holes. Thermal resistance increases as a result of increased number of air spaces inside fibres. Wicking of sweat next to skin is possible by capillary action caused by small holes forming proliferations in fibre body. Coolmax is modified polyester fibre developed by Dupont. The fibre resembles double scallop with four channels having 20% more surface area than conventional polyester fibre, thus offering better wicking, moisture vapour permeability and water spreading over greater area in fabric [12,26, 27, 46]. 4 DG fibre is speciality fibre with eight legged cross-section made of polyester and other polymers and large surface area/volume and bulk as compared to round fibres. The fibre is capable of moving, storing and trapping the fluids owing to the unique grooved shape[26]. Changing the fibre cross-section results in creation of channels for liquid sweat removal from the body. Cross shaped, H- shaped, Y-shaped, W-shaped, I-shaped or five star cross-section, hexachannel, scalloped oval cross-section with longitudinal grooves in fibres are increasingly being used [53-54].

Bicomponent fibre are classified based on fibre cross-section into side- by side, sheath core, islands in the sea and segmented pie cross-section. Matrix of one polymer contains another polymer, and micro denier fibres can be generated by this type of bi component structure. Polyester, polypropylene and nylon form the island in the structure. Nylon and polyester form alternate pie or wedges in segmented pie structure[53,54].

Das *et al.*[6] studied the effect of fibre cross-sectional shape on moisture transmission properties of the fabrics and suggested that wicking rate through fabrics increased, while water vapour permeability reduced as the fibre shape factor increased.

Karaca *et al.*[10] compared thermal comfort properties of fabrics woven from different cross-sectional shaped polyester fibres and concluded that fabrics produced from hollow fibres had low thermal insulation, air permeability and water vapour permeability; however, fabrics using trilobal polyester fibres had higher air and water vapour permeability and lower thermal conductivity as compared to round fibre fabrics.

Behera and Singh[15] reported that low-stress mechanical properties and hand behavior of polyester multifilament yarn fabric were altered by change in cross-sectional shape of filaments. Varshney *et al.* [53] studied the effect of polyester profile on physiological properties of polyester fabrics and suggested that non-circular fibres made the fabric more voluminous, thereby increasing the mass flow rate and offered more resistance to heat flow.

Khoddami *et al.*[58] observed lower thermal conductivity for hollow fibre fabrics as compared to fabrics made of solid polyester fibres. However, they suggested that fabric structure affects the water vapour and air permeability more than fibre type.

Wang *et al.*[59] compared five leaf cross-section monofilament with circular cross-section yarn and observed that for the same twist level, fibres with five leaf cross-section formed five beads along length of fibre and larger number of capillaries in yarn than conventional yarns using circular cross-section fibres. Wicking height of five leaf yarns was observed to be higher than that of conventional yarns.

Jhanji *et al.*[60] engineered plated knit structures with such a combination of fibre cross-section in the back (inner/next to skin) and the yarn type in the face (outer) layer, so that rapid liquid transfer from back layer by wicking and quick liquid absorption and evaporation by the face layer could be achieved. Plated fabrics using the combination of triangular polyester fibre in the back and carded cotton yarn in the face layer showed the higher thermal resistance, higher absorbent capacity, and would be warmer to the initial touch. However, the combination of combed cotton yarn with triangular polyester fibre resulted in fabrics with the higher air permeability, moisture vapour transmission rate and transplanar wicking.

Gurudatt *et al.*[61] studied the absorption and drying behavior of textile using cotton and polyester of regular cross-section, polyethylene glycol modified polyester and scalloped oval cross-section fibre. It was suggested that absorption capacity of polyester enhances by cross-section and polymer modification. Knitted fabrics using scalloped oval cross-section had higher absorption rate compared to regular polyester fibre.

Su *et al*.[62] developed composite knitted fabrics by blending profiled polyester fibres and cotton fibres. Fabrics with decreasing cotton content showed higher diffusion rate and drying rate. Worst water absorption ability was shown by fabrics made of profiled polyester alone. They suggested that moisture absorption and release of fabrics could be improved by making fabrics from core and cover yarns of polyester profile filament, profile polyester spun and cotton in different blend ratios.

## 4 Role of Yarns in Thermo-physiological Properties

The role of yarns in contributing towards thermo-physiological properties and wearer comfort is very crucial. Several yarn variables, like yarn twist, yarn count, yarn spinning system and yarn types, are reported to affect the properties of textiles. Change in any of these parameters ultimately changes the yarn structure, which, in turn, depends on fibre geometry. Distribution of fibres in yarn dictates thermal as well as moisture transfer properties of fabrics.

Yarn structure is not rigid and capillary flow may produce lateral stress, which affects capillary sizes during liquid rise[56]. Disruption of the continuity, length and orientation of the capillaries occurs due to changing packing density throughout yarn structure. Heterogeneity of pore size, shape and orientation affects the penetration of liquid into the yarn structure and hence its liquid retention properties [57]. The effect of various yarn variables on thermo-physiological proeprties of fabrics has been discussed hereunder.

### 4.1 Role of Yarn Linear Density and Twist

Linear density of constituent yarns affects the radial spread of water in fabrics. Fast liquid flow through inter-yarn spaces in fine yarns is possible due to reduced capillary radius and low water retention in finer count yarns.

Heat and moisture transfer are affected by the degree of yarn twist; higher twist yarns improve capillary effect in moisture transfer as highly twisted yarns are compact and provide less air volume. Lower twist generally results in reduced water transport through fabrics due to reduction in number and continuity of inter-fibre capillaries. Twist in the yarn also affects the size of capillaries due to helical path of fibres in the yarn. More liquid on surface of twisted yarn is retained due to rough surface profile of these yarns as compared to filament yarns. Furthermore, twist level also influences the permeability of textile material to air, by the way it influences yarn hairiness. As the twist level increases, yarn hairiness shows a downward trend owing to binding of short and protruding fibres to the body of the yarn, thereby reducing obstacle for air passage through fabrics. Chidambaram *et al.*[4] studied the thermal comfort properties of bamboo knitted fabrics in relation to yarn linear density and observed that as the yarn got finer, thermal resistance decreased and air and water vapor permeability increased. Similar observations were reported for double layered weft knitted fabrics by Bivainyte and Mikkucioniene[20] and Bivainyte *et al.* [28] in their studies on rib fabrics.

Ozturk *et al.*[47] studied the influence of yarn count on wicking properties of cotton- acrylic yarns and fabrics and suggested that wicking ability of yarns and fabrics increased with the use of coarse yarns. Gupta *et al.*[63] studied the effect of yarn linear density in the inner and outer layer of single jersey plated knits on heat, moisture transport and air permeability of resultant fabrics. They stated that these three factors all together determined the wearer comfort and observed an increase in thermal reistance of the fabric with increase in yarn linear density. However, fabrics knitted with finer yarns and higher loop length were more permeable to air and water vapor and were found to have lower values of thermal absorptivity.

Ozdil *et al.* [64] studied the effect of yarn twist on different thermal comfort properties of rib knitted fabrics and observed that the thermal resistance decreased and water vapor permeability increased with the increase in yarn twist. Das *et al.*[65] studied the interactive effect of blend proportion, yarn count and twist level on in-plane and vertical wicking of polyester-viscose blended fabrics. They observed that wicking height and in-plane wicking of the fabrics reduced with the increase in yarn fineness and twist. An initial increase in wicking height and in-plane wicking up to a point and then reduction at later stage was observed with the increase in polyester proportion.

Raja *et al.*[66] investigated the influence of yarn linear density on liquid spreading of knitted fabrics and observed higher spreading rates for fabrics with low yarn linear density. They stated that water took longer to traverse thicker fabrics as water had to go through more number of fibres during traversing assembly of coarse yarns compared to those composed of fine yarns. Moreover low thickness and low water retention capacity of fine count yarns resulted in fast liquid spreading behavior of fabrics composed of finer yarns.

Sengupta and Murthy[67] studied the effect of yarn twist on wicking properties of ring and open end yarns and reported steep increase in wicking time with the increase in twist for ring-spun yarns.However, they observed gradual increase in wicking time with the increase in twist for open end yarns.

**4.2 Role of Number of Filaments**

Number of filaments, yarn tension and twist significantly affect the yarn wicking performance by influencing the way in which individual filaments can be packed in the yarn, thus determining the amount of void spaces between filaments. Sampath *et al.*[22] studied the effect of filament fineness on comfort characteristics of finished polyester knitted fabrics and stated that filament fineness and the number of filaments in the yarn play a vital role in determining the comfort characteristics of the micro-denier polester knitted fabrics.

Jhanji *et al.*[68] reported thermo-physiological properties of fabrics intended for next to skin applications, apparel, and functional wear to the heat and moisture transmission properties. The effect of loop length and filament fineness on the thermo-physiological properties of polyester-cotton single jersey plated fabrics had been reported. The thermo-physiological properties were correlated with structural parameters of knit structures, such as fabric tightness factor, thickness, porosity, stitch density, and loop length. Fabrics knitted with longer loop length (slack constructions) showed higher thermal resistance and would be perceived warmer on initial skin contact owing to lower value of thermal absorptivity, were permeable to air and moisture vapor transmission, had higher water evaporation percentage however water absorbency and transplanar wicking was lower. Fabrics knitted with finer filaments showed higher value of thermal resistance, lower value of thermal absorptivity, lesser permeability to air and moisture vapor transmission. The water absorbency and transplanar wicking increased and water evaporation percentage decreased as the filament fineness increased.

Ansary[69] studied the influence of number of filaments on air permeability of polyester woven fabrics and reported a decrease in air permeability with increase in the number of filaments in the cross-section of filling yarns.

Li and Joo[70] compared nano-scale filament, micro filament and normal filament knitted fabrics for their liquid transfer properties and concluded that nano-scale filament fabrics showed low porosity, high aerial density and increased water absorption properties like absorption capacity and absorption rate. Better water absorption ability of nano scale filament fabrics as compared to micro filament fabrics was attributed to smaller pore size of nano scale filaments compared to micro filaments. They observed that at initial stage, water had been rapidly absorbed by micro filaments and nano scale filaments followed by a stage of slow and prolonged wicking time till saturation level. Das *et al.*[71] varied the denier per filament for polypropylene knitted fabric to assess its influence on thermo-physiological comfort properties and observed that water uptake and wicking increased with increase in the number of filaments.

**4.3 Role of Yarn Spinning System**

The yarns produced on different spinning system play a crucial role in dictating thermo-physiological properties of textiles intended for varied applications. The difference in the yarn structure and packing density of yarns produced on different spinning systems account for different thermal, moisture and liquid transfer properties of fabrics made from these yarns. Physical features of yarns and fabrics produced from these yarns are influenced by the type of yarn production (ring-spun, compact, open end) and, in turn, affect the performance properties of fabrics. Yarn structural parameters by affecting the air pockets within the yarn body influence the bulk and comfort properties of textiles[3,8, 12, 13, 22, 39, 62].

A variety of yarns, like ring, rotor, friction, vortex and compact-spun yarns, are used for varied applications in textiles. Dimensions and structure of inter yarn and intra yarn pores, pore size and their distribution along fabrics are influenced by density and structure of yarn[68]. Ring and rotor-spun yarns vary widely in their structure which contributes to the entirely different properties of the two yarns. Ring-spun yarn has an ideal cylindrical helical structure with same number of turns per unit length in each helix, uniform specific volume and maximum packing density in the outermost zone of the yarn cross-section. Rotor-spun yarn has a bipartite structure with an inner core which forms the bulk of the yarn and an outer zone of wrapper fibres occurring irregularly along the core length. Rotor yarn shows maximum packing density in first zone from core. Core part of rotor yarn is relatively dense structure; sheath part is less dense structure with belly-bands [69,70]

Behera *et al.*[3] compared the comfort properties of ring, rotor and friction-spun yarn fabrics and suggested that ring and rotor-spun yarns were comparable in thermal comfort aspects, friction-spun yarn being the most suitable. They pointed out that in the normal wear conditions and in the absence of perspiration, rotor-spun yarn would be superior to ring-spun yarns.

Kane *et al.*[8] studied the comfort properties of ring and compact yarn single jersey fabrics and observed higher water absorbency and air permeability for compact yarn fabrics against ring yarn counterparts.

Tyagi *et al.*[12] studied the influence of yarn type on thermal comfort of woven fabrics and concluded that MJS yarn fabrics showed higher absorbency, air and water vapor permeability but lower wickability as compared to ring yarn fabrics.

Tyagi and Madhusoodhanan[13] compared the fabrics made of ring and MJS yarns and suggested that the presence of wrapper fibres in the MJS yarns compressed the core and impeded the freedom of fibre movement, making the yarns less bulky and more rigid than ring-spun yarns Accordingly, the MJS yarn fabrics exhibited higher thickness and bending rigidity compared to ring-spun yarn fabrics.

Raja *et al.*[66] compared single jersey knitted fabrics made of different yarns for their comfort properties. They reported that compact folded yarn fabrics showed higher air and water vapour permeability compared to ring and ring/compact folded yarn fabrics. Compact yarn fabrics showed higher air permeability compared to ring yarn fabrics which was attributed to better fibre migration and higher packing density and less hairiness of compact yarn, leading to easy passage into loops without any restriction to air flow. However, the thermal resistance of ring folded yarn fabrics was higher compared to compact folded yarn fabrics due to high hairiness of ring yarn fabrics.

Kumar *et al.*[72] compared ring, rotor and vortex yarns knitted fabrics and observed that ring yarn knitted fabrics showed good knitting performance and smooth feel, however abrasion resistance values of rotor- and vortex- spun yarn fabrics were higher than ring spun yarn fabrics. Lord[73] investigated the relative moisture uptake characteristics of ring and open-end yarns and reported that open end yarn wicked better and more evenly but for given yarn count elevated about the same volume of water as ring yarn. There was little difference in percentage water uptake for the two yarns.

Erdumlu and Saricam[74] studied the wicking and drying properties of vortex-spun yarns and knitted fabrics in comparison with ring-spun yarns and fabrics. They observed that yarn type significantly affected the yarn wicking, fabric wicking and water absorbency. Vortex-spun yarn owing to crimped yarn axis and tight wrappings along yarn length had lower yarn and fabric wicking values than ring-spun yarn fabrics. Fabrics knitted from ring-spun yarns wicked and absorbed water more evenly than fabrics knitted from vortex-spun yarns.

Mirdehghan *et al.*[75] compared solo, siro, single ply and two ply spun yarn worsted fabrics for their thermal behavior and observed that different spinning systems affected the thermal properties of worsted fabrics. Siro weft yarn fabrics had the highest thermal conductivity, while worsted fabrics made of single ply weft yarn showed the lowest thermal conductivity.

Water transport rate over yarn's length changed due to discontinuous capillary formed by randomly arranged natural fibres in the yarn.

Das *et al.*[76] stated that elite compact yarns had better compactness and thus resulted in fabrics of low thickness compared to fabrics of normal yarns. Elite compact yarn fabrics showed higher thermal conductivity and thermal absorptivity due to more amount of heat conducted and less fabric thickness. Moreover, higher fabric porosity resulted in higher air permeability, higher moisture vapor transmission rate and improved wicking properties of compact yarn fabrics compared to normal yarn fabrics.

Kulleman *et al.*[77] studied the air permeability of fabrics made from different yarns and concluded that maximum air flow occurred through fabric with twisted core wrapped yarns and open end yarns; ring-spun yarns were intermediate in permeability while cover-spun yarn with twistless fibre core and no twist yarn fabrics showed lowest value of air permeability.

**4.4 Role of Yarn Hairiness/ Uniformity**

Yarn types can significantly influence the performance properties of textiles by affecting the fabric's bulk properties. Yarn hairiness and roughness can bring about changes in thermal properties of fabrics by entrapment of still air layer. Likewise, the moisture and liquid transfer properties of textiles are significantly affected by yarn types owing to difference in yarn roughness and arrangement of fibres in yarns. Increase in yarn roughness results in reduced rate of water transport through fabrics due to increase in effective advancing contact angle of water on yarn. Yarns with more random fibre arrangement can retard the liquid transfer by wicking as a result of disruption in continuity of capillaries formed by fibres[24,33, 59, 68, 76].

Wicking of yarns and fabrics is affected by difference in yarn surface roughness. Rough yarns are formed by wool fibres with high apparent contact angle owing to random distribution of fibres in the yarns and the natural crimp. Yarns made of synthetic fibres have smooth surfaces and are well aligned[77]. Water transfer by capillary process is thus affected by two factors, viz (i) the increase in yarn roughness causes an increase in effective advancing contact angle of water on yarn, and (ii) randon fibre arrangement decreases the continuity of capillaries formed by fibres in yarn.

Oglakcioglu *et al.*[24] studied the effect of yarn type on thermal comfort properties of cotton knitted fabrics and observed that fabrics knitted with double plied yarn had higher thermal conductivity, thermal absorptivity and thermal resistance compared to single plied yarn fabrics. However, they found no significant difference between thermal comfort properties of fabrics knitted with carded and combed yarns.

Pac *et al.*[41] studied the influence of yarn structure on transient thermal properties of cotton knitted fabrics and observed that fabrics knitted with two ply yarns absorbed more heat and felt cooler when touched than those constructed from single yarns.

Ozdil *et al.* [64] studied the thermal comfort properties of carded and combed yarn rib knitted fabrics and observed an increase in thermal conductivity, thermal absorptivity and water vapor permeability of fabrics knitted with combed yarns.

Sengupta and Murthy[67] reported that open- end spun yarns showed lesser wicking time for any given vertical weight compared to ring- spun yarn fabrics. They observed that owing to dense core and less dense skin of open end yarns, it showed differential dyeing behavior in core and skin with dye wicking to greater height in the core than in surrounding sheath fibres.

Saricam and Kalaoglu[78] investigated the effect of yarn type, fabric thickness and air permeability on wicking and drying ability of polyester woven fabrics. They concluded that texturizing affected wicking performance, while fabric thickness, air permeability and yarn type influenced drying behavior of fabrics. Drying rate of fabrics made from filament yarns was higher as compared to texturised yarns. Jhanji *et al.*[79] studied the suitable combination of fibre and yarn variables for engineering polyester–cotton plated fabrics with good thermo-physiological properties. Categorical variables, i.e. outer layer yarn type and inner layer fibre linear density were found to affect the thermal, moisture vapour and liquid moisture transfer properties of developed test samples. Fabrics knitted with carded yarn and polyester fibre of high linear density showed high thermal resistance and would feel warmer on initial skin contact, owing to low thermal absorptivity. However, the air permeability and moisture vapour transmission rate increased with combination of combed cotton yarn in the outer and coarse polyester fibre in the inner layer. Combed yarn fabrics were superior in trans planar wicking as compared to carded yarn fabrics which showed higher water absorbency and would be slow drying fabrics.

Jhanji *et al.*[80] investigated the moisture management properties of polyester-cotton plated fabrics of ring vis a vis rotor yarns. They suggested that ring yarn fabrics exhibited higher moisture vapour transmission rate, trans planar wicking, lower wetting time and higher one way transport capacity as compared to rotor yarn fabrics. The ring yarn fabrics were thus deemed to be suitable where body needs to dissipate sweat both in vapour and liquid forms, with respect to fabrics using combination of rotor-spun cotton yarns, which exhibited higher absorbent capacity and would be slow drying with poor one way transport capacity. It was thereby concluded that yarn spinning system plays an important role in influencing moisture management properties of fabrics intended for next to skin applications.

Singh and Nigam[81]compared carded, combed and compact-spun yarn woven fabrics for their comfort performance and reported that carded weft yarn based fabric samples showed higher resistance against air drag than combed and compact weft filled fabric samples. Compact weft yarn fabrics showed high water vapor permeability and were reported to be suitable for summer wear shirting. Carded yarn woven fabrics showed high thermal insulation and were considered suitable for winter wear.

Nasrin and Nahida[82] observed that combed yarn fabric showed better colour fastness to rubbing, pilling resistance and shrinkage properties than carded yarns. They reported that combed yarns were stronger, less hairy and more uniform than carded yarns. Gudiyawar and Manjunath[83] studied the moisture transport properties of single jersey knitted fabrics produced from air jet texturized polyester filament yarns. They observed that increased bulk of texturized yarns resulted in improved wicking and moisture management properties of fabrics.

Karahan and Eren[84] suggested that yarn type significantly affected the static water absorption properties since they observed that higher water absorption was shown by two ply ring-spun yarn as compared to single ply ring-yarn and two ply open end yarn.

Shradhanjali *et al.* [85] investigated the effect of yarn type, yarn linear density and fabric loop length on the thermal comfort properties of knitted fabrics. They observed that the fabrics knitted with continuous filament yarn and micro denier yarn exhibited higher air permeability as compared to fabrics knitted with spun yarns. The water permeability of the fabric was observed to vary significantly between the spun yarn, continuous filament yarn and micro denier yarn knitted fabrics.The researchers concluded that yarn count and polyester yarn types had significant influence on comfort characteristics of single jersey fabrics.

Das and Ishtiaque[86] observed that plain woven fabrics with hollow viscose yarns showed higher water absorbency as compared to normal and twist less yarns in the weft.Chattopadhyay and Chauhan[87] compared ring and compact yarns for their wicking performance and suggested that ring yarns showed faster wicking compared to compact yarns as evident from higher equilibrium heights for ring yarns. They explained the lower wicking of compact yarn due to less average capillary size of compact yarn compared to ring yarn owing to higher packing coefficient of compact yarn.

## 5 Role of Fabrics in Thermo-physiological Properties

The thermo-physiological properties of textile materials depend on constructional variables and bulk properties of fabrics. Fabric structure, thickness, cover factor, aerial density, bulk density, fabric porosity and finishing treatments affect the thermal and moisture management properties and hence determine the comfort properties of fabrics. Woven and knitted fabrics are generally used for varied applications, like inner wears, outerwear, work wear and sportswear. Knitted fabrics owing to lower cover factor have more pores in their structure and the porous structure ensures good air, moisture and heat transfer properties, thus showing better liquid transmission properties than woven fabrics[18].

Different amounts of air can be entrapped in different fabric structures owing to difference in porosity; more air is generally entrapped in knitted fabrics as compared to that in woven fabrics. Thermal insulation is provided by fibres in fabric structure, mainly by (i) developing air spaces and preventing air movement and (ii) providing shield to heat loss by radiation[43, 77]. The trapped still air in the fabric structure thus affects the thermal insulation[86] and accordingly the structures which provide numerous spaces for dead air by perpendicular alignment of fibres and yarns to the surface like in pile or napped fabric construction results in improved thermal insulation.

Fabric thermal insulation reduces as more fibres are packed into the fabric; in other words as bulk density increases, heat transmission through fabric increases, thereby reducing thermal insulation properties[87]. About 70% by volume of fabric is composed of entrapped air and fibres account for only 30% by volume of fabric. Therefore, heat transfer through textile materials is mainly governed by properties of air.

Amount of water carried out by different fabrics varies mainly because of difference in basic structure of materials. Structural differences are related to fibre arrangement in yarn which affects yarn roughness factor (cos $\theta$), and structural differences can be related to difference in size and continuity of capillaries. Random arrangement of fibres results in high contact angle; while high degree of fibre alignment results in lower contact angle which is associated with faster movement of water in yarns and fabrics[77].

### 5.1 Role of Fabric Structure

Several researchers[20,26,31,44,71,88-91] have attempted to engineer different knit structures and compared the structures in terms of their comfort and performance properties. Innovative knit structures like plated fabrics, moisture management fabrics with different combinations of yarns in alternating courses, multilayered fabrics and fabrics mimicking the biometrics of plant structure have been developed for providing effective thermal and moisture management properties and sense of well- being to wearer.

Structured or engineered fabrics are used in application areas relevant to commercial interest. Class of structured fabrics is moisture management fabrics; utilizing two or more fibre types in layered structures rendering two sides of fabrics distinctly different in character. Each side of fabric has the ability to exhibit different performance characteristics and thermo-physiological properties. Light weight two-sided fabrics, finding applications in varied areas, are produced by plated knitted technique. Both hydrophobic and hydrophilic yarns can be fed to single set of knitting needles and two separate yarns, thus pass through each single needle of the set appearing distinctly on face and back sides of fabrics. Careful control of feed and positioning of two yarns is important to position distinct yarns in the two layers.

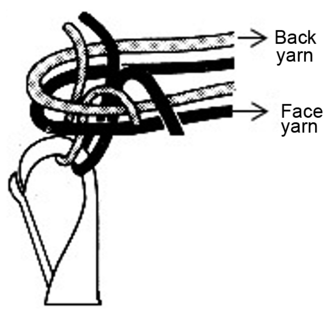


Fig. 3 — Plating relationship of two yarns

Figure 3 shows the plating relationship between two yarns used for plated fabric production.

Plated knit structure is a double layered construction characterized by distinct face and back layers. The two layers are composed of different materials and accordingly serve different roles in providing wearer comfort. One layer of plated fabric is the inner layer which is in direct contact with skin and serves the role of quick removal and transportation of sweat from body in vapour and liquid form. This layer serves as a separation layer and is composed of conductive and diffusive yarns. Another layer of plated fabric is the outer layer which is not in direct contact with the skin and prevents humidity build up near skin and vaporizes it to environment. This layer serves as absorptive layer and is composed of hydrophilic fibres and governs the liquid spreading and drying ability of fabrics[92]. Figure 4 shows the schematics of face and back layers of plated fabric. Selection of fibre and yarn combinations in the two layers can have a great bearing on the comfort properties, performance, aesthetic appeal and end use of the knit structures.

Fibres of different chemical nature and thus different water absorbing properties can be used in different combinations to appear in face and back layers of plated fabrics as shown in Fig. 5. Double layered knitted fabrics can be divided into following four types based on different fibre combinations and

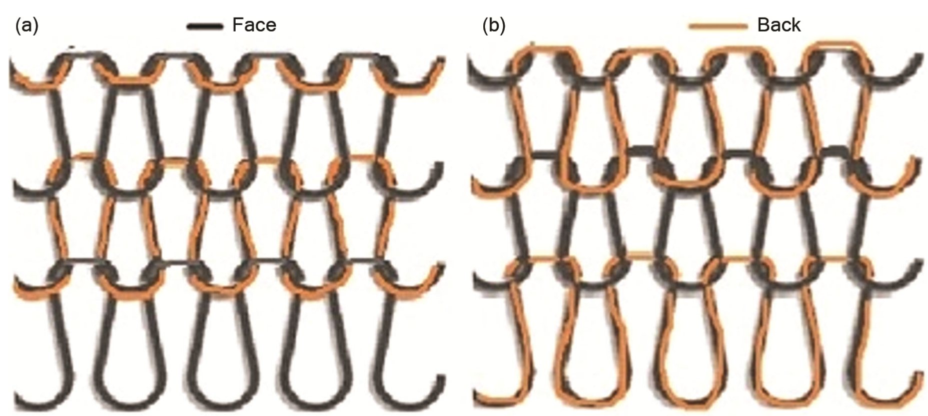


Fig. 4 — Schematics of plated fabric (a) face and (b) back layer

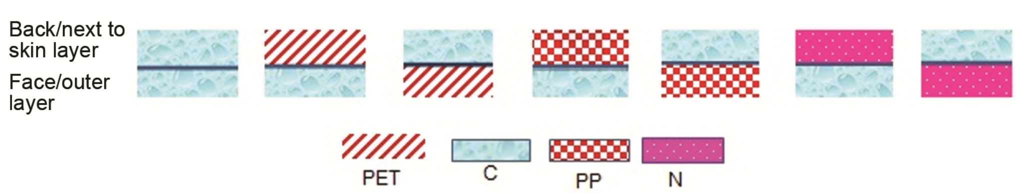


Fig. 5 — Combinations of hydrophobic and hydrophilic fibres in face and back layers of plated fabrics

difference in water absorption properties of different fibres used in the two layers[45]:

(i) Double layered fabrics with hydrophobic fibres in face and back layer

The fabric has hydrophobic fibre in both face and back layers as shown in Fig. 6 (a). Liquid sweat next to skin cannot be absorbed by inner layer owing to its hydrophobicity and the only means by which sweat can be removed from skin is water vapour diffusion through pores within fabric. The diffused water vapour will evaporate slowly from the face layer, in turn, causing thermal and wetness discomfort to the wearer.

(ii) Double layered fabrics with hydrophilic fibre in back and hydrophobic fibre in face layer

The fabric has hydrophilic fibre in back/next to skin layer and hydrophobic fibre in face layer as shown in Fig. 6 (b). Liquid sweat next to skin can be absorbed by the back hydrophilic layer but the transfer of sweat to the face layer is restricted owing to hydrophobicity of the face layer. Thermal insulation of fabric decreases and fabric gives sensation of wetness and coolness as the pores in the inner layer are filled with water, removing the static air from the pores.

(iii) Double layered fabric with hydrophilic fibres in face and back layers

Figure 6 (c) shows the fabric with hydrophilic fibre in face as well as back layers. Sweat from skin is picked up by hydrophilic fibres of back layer resulting in moisture accumulation and poor transfer to face layer. Water remains in the back layer and evaporation rate will be less, owing to smaller wet area. The fabric will feel cool and wet to the wearer.

(iv) Double layered fabric with hydrophobic fibre in back and hydrophilic fibre in the face layer

Figure 6 (d) shows the fabric with hydrophobic fibre in the back and hydrophilic fibre in the face layer. The back hydrophobic layer without absorbing the sweat itself transfers it to the face layer by means of capillary wicking. Face layer owing to hydrophilic fibres has good water absorption property and hence enables quick evaporation of sweat to environment by providing larger wet area.

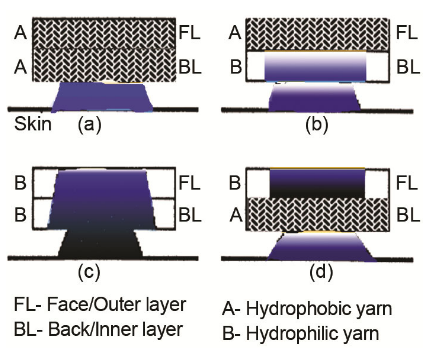


Fig. 6 — Water transfer from skin to different fabric layers

Based on classification of double layered fabrics, Lord[73] indicated that that structure (d) with hydrophobic fibre in the back and hydrophilic fibre in the face layer would be most effective in maintaining dry skin micro climate by rapid liquid transfer to face layer. In addition, researchers [7, 14, 26, 31, 44, 71, 88] have unanimously recommended the use of hydrophobic fibres in next to skin and hydrophilic fibres in the face layer to achieve desirable moisture management and comfort properties in plated fabrics.

Plated fabrics designed with contrastingly different fibre and yarns exhibit the push- pull effect. Layer of hydrophobic fibres repel the perspiration next to skin and pushes or wicks it into outer layer of hydrophilic fibres which absorb or pulls away the moisture. Structured arrangement of hydrophobic and hydrophilic fibres in the two layers of plated fabrics and large difference in humidity between inner layer and ambient environment cause moisture movement from skin to outer atmosphere. Figure 7 shows schematic of plated fabric with face layer of hydrophilic (cotton) fibre and back layer of hydrophobic (polypropylene) fibre. Correct selection of fibres in the distinct face and back layers of plated fabrics, therefore, appears to be crucial for effective liquid transfer and drying of fabrics for providing dry microclimate next to wearer's skin.

The structures are increasingly gaining popularity in apparels, next to skin applications, active wear and inner wears owing to freedom in selection of contrastingly different constituents in the two layers. Therefore, the functional clothing intended for such applications are often specially engineered or structured such that the fabrics are normally two sided and are produced from a minimum of two yarns of different fibre content or characteristics.

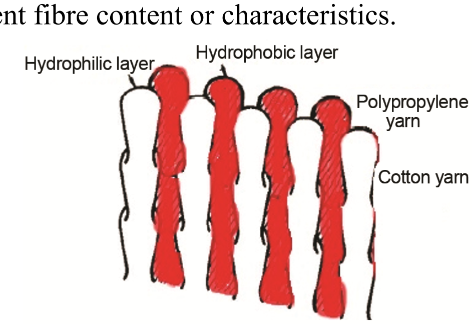


Fig. 7 — Schematic of plated fabric with face layer of hydrophilic (cotton) fibre and back layer of hydrophobic (polypropylene) fibre

Jun *et al.*[7] reported that layered fabric structures showed higher water vapor transport when hydrophobic fibre was exposed to high vapour pressure while hydrophilic fibre to lower vapour pressure. Hydrophilic fibres placed on surface towards high vapor pressure would cause swelling of fibres and blocking of pores and, in turn, prohibiting the moisture transfer through layered fabrics. Two layer fabric (sportwool) intended as sportswear has been developed with an inner layer of chemically modified fine merino wool fibres and an outer layer of 100% polyester filament yarns. Wool fibre in inner layer transfer heat and moisture from skin owing to good water vapour permeability to outer surface. Polyester filament yarn in outer layer enables escape of heat and moisture to environment aided by body movement and wind speed.

Mallikarajunan *et al.*[14] developed multilayered fabrics in different fabric structures using different fibres like lyocel, cotton, polypropylene and micro polyester (Fig. 8). They observed highest water vapor permeability for cotton/polypropylene plated knitted fabrics and recommended cotton/polypropylene and fleece knitted fabrics for winter wear due to their high thermal insulation and low conductivity. Transverse wicking for micro-polyester fabrics was observed to be higher owing to the low fabric thickness and smooth fibre surface. Cotton/polypropylene knitted fabrics showed higher transverse wicking compared to cotton/polyester fleece knitted, cotton/polyester and cotton pile structure fabrics.

Hes *et al.*[52] suggested that special knit structures can be developed consisting of two quasi separated fabric layers obtained by selection of needles adequately and knitting simultaneously on separate needle beds. The two fabric layers were linked by limited amount of binding loops. It was suggested that single layered cotton/PP knits can provide good physiological properties by the use of special rib structure. Plated fabrics with courses alternating between filament and spun polyester yarn (Fig. 9) have been reported to exhibit excellent moisture management properties.

Herath[88] compared cotton/spandex single jersey and 1×1 rib structures and observed that rib structures showed higher stitch densities compared to single jersey structure due to structure's ability to accommodate more number of stitches/ area of fabric. Further they observed higher air permeability for rib knitted fabrics compared to single jersey fabrics due to the two planar construction of rib knitted fabrics

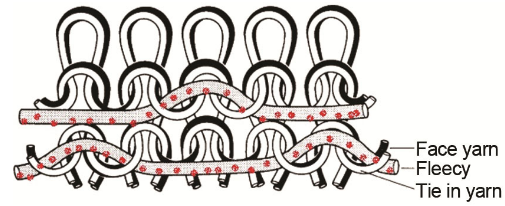


Fig. 8 — Fleece knitted structures[14]

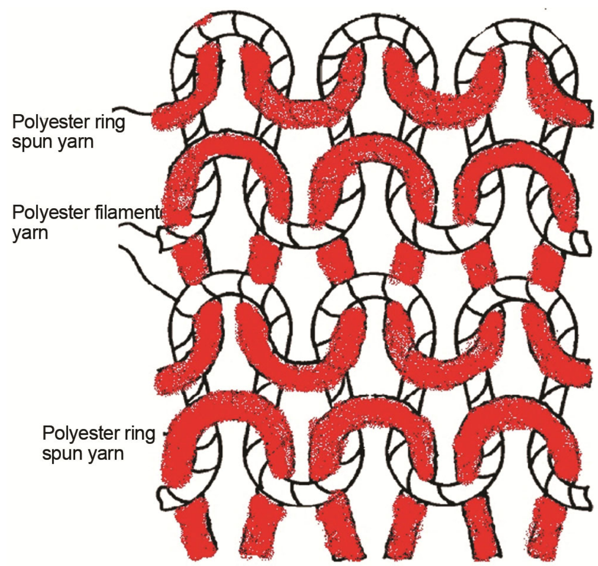


Fig. 9 — Plated fabrics with alternating courses of spun and filament yarns

which resulted in stretching in perpendicular direction to rib.

Tim and William[89] suggested the development of sandwich plated knitted technique where two hydrophobic yarns sandwich the hydrophilic yarn in b etween. They further suggested the use of composite yarn with hydrophilic fibres concentrated at the core and hydrophobic fibres at periphery. Mixture of hydrophilic and hydrophobic fibres lies in transition layer between centre and outer surface of composite yarn to obtain fabrics possessing properties specific to both fibres. Toda[90] developed multi-layered knitted structures composed of non-hygroscopic fibres. The structure was characterized by smaller inter fibre spaces in the face layer than in back layer by careful selection of fibre fineness, knitted structure and yarn type in face and back layers.

Mose *et al.*[91] observed that even distribution of moisture along outer fabric layer could be achieved by using yarns of higher denier in outer fabric layer as compared to the inner layer and improved insulation can be obtained by raising the inner layer in plated fabrics.

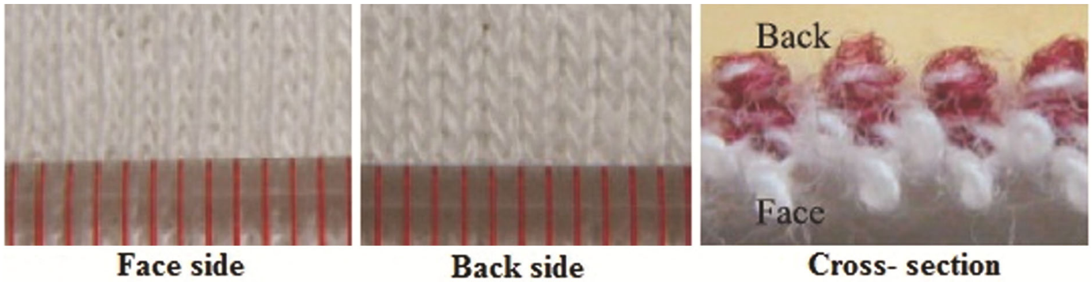


Fig. 10 — Knitted fabric mimicking plant's branching structure[94]

Chen *et al.*[92] developed double jersey knitted fabrics mimicking the biometrics of plant's branching structure from different yarn combinations with larger loops formed at back side and smaller loops at face side of fabric as shown in Fig. 10. The structure mimicked the tapering of water conduits in plants as a result of greater inter yarn spaces at back and smaller inter yarn spacesat face, thus providing greater exposed yarn surface area on face side compared to that on back side. They suggested that developed fabrics exhibited faster water absorption, improved moisture management property and air permeability.

Yang *et al.*[93] investigated the thermal comfort properties of bi-layer knitted fabrics to assess the impact of knitted structures and yarn composition on comfort characteristics. They concluded that bi-layer fabrics with asymmetric structure featuring meshes and composed of yarns with varied hydrophilicity in the two layer showcased excellent moisture management capacity.

Sarkar *et al.*[94] developed warp rib based woven fabrics to mimic plant's branching structure and observed fast water absorption, better wicking properties and liquid spreading over wider surface of fabric, thus recommending the use of developed fabrics for summer wear.

Onofrei *et al.*[95] studied the thermal and moisture management properties of plated knitted fabrics incorporating yarns with different thermo regulating effects. They concluded that the thermal properties and air and water vapor permeability are influenced by the raw material type and knitted structure.

Mishra *et al.*[96] studied the influence of structural variations in single jersey knit structures on the thermo-physiological comfort properties and observed that the percentage/number, location of tuck stitches and ratio of tuck to knit stitches strongly influenced the physical and thermo-physiological properties of single knit fabrics with all other knit parameters kept constant.

Akbar *et al.*[97] studied the comfort and anti-microbial properties of cotton, polyester, flax and polypropylene knitted denim designed by using 2/1 and 3/1 cross terry structure. Flax and polyester knitted denim exhibited higher values of moisture management indices and air permeability, however, thermal properties of former were observed to be inferior compared to polypropylene and cotton fabrics.

Qian *et al.*[98] investigated the thermal-wet and coolness related comfort properties of knitted fabrics developed as sandwich structure comprising middle layer of polyester multifilament and two asymmetric outer layers of polyethylene and polyester. They concluded that knit structures designed with tuck stitches exhibited higher air permeability, contact coolness, overall moisture management and dynamic cooling performance in contrast to knit fabrics designed with float stitches. The air permeability of fabrics showed an upward trend as the proportion of polyethylene increased. Furthermore, it was suggested that asymmetric knit structures featuring meshes in inner layer enabled effective moisture transmission.

Sledzinska *et al.*[99] studied the comfort characteristics of work wear for locomotor disabled employees and suggested that overall comfort in terms of clothing construction and material selection for disabled people was of utmost importance. The test results of fabrics designed for work wear of disabled employees suggested that twill 2/1 S with surface mass of 243, 204 and 175 g/m$^2$ respectivelywere most suitable candidates for designing work wear for employees with disabilities.

Limeneh *et al.*[100] investigated the effect of weave structures, namely plain, twill and satin on comfort properties of fabrics and observed that satin woven fabrics exhibited the highest values of water vapor permeability, water absorption rate and air permeability followed by twill and plain woven fabrics respectively. However, thermal resistance and stiffness of plain woven fabrics was observed to be the highest and lowest for satin woven fabrics.

Tahvildar *et al.*[101] studied the appearance and comfort properties of worsted fabrics woven with four varying weave structures (plain, twill 2/1, twill 2/2, and hopsack 2/2) and four groups of yarns spun on different yarn-spinning systems (solo, siro, single-ply ring, and two-ply ring). They suggested that the open structure and the mobility of yarns in the fabric improved the crease recovery angle, flexibility, air permeability, and water vapor permeability of the fabrics, whereas abrasion and pilling resistance showed downward trend. Furthermore, the researchers concluded that the comfort and appearance properties of fabrics composed of yarns spun on various spinning systems could be significantly affected owing to different level of compactness and fibre location in the yarn structure.

Shrivas and Patil[102] studied the effect of different weaves on thermal resistance properties of shirting cotton fabrics. They observed that thermal resistance was highest for plain woven structures, while crepe and 2/2 matt woven fabrics exhibited the lowest values of thermal resistance.

Kandhavadivu *et al.*[103] studied the thermal and moisture management properties of tri layer knitted and woven fabrics composed of bamboo charcoal, lyocell, bamboo and micro polyester yarns. They concluded that air permeability, water vapour permeability, transverse wicking and drying rate of tri-layer weft knitted fabrics were higher as compared to their woven counterparts. However, thermal conductivity, water absorption and vertical wicking of woven tri layer fabrics were higher as compared to former. The tri-layer fabric composed of bamboo charcoal/micro polyester/lyocell showed higher air and water vapour permeability, wicking, thermal conductivity, wicking and faster drying rate.

#### 5.2 Role of Fabric Tightness Factor

Fabric tightness factor dictates the heat, moisture and liquid transfer through the fabrics by the way it influences openness and the bulk properties of fabrics. Availability of inter yarn spaces for heat transmission, passage of air and moisture diffusion depend on the fabric's tightness factor. A number of researchers[4,8,27,42,48] have studied and established that fabric tightness factor strongly influences the thermo-physiological properties of textiles.

Chidambaram *et al.*[4] studied the effect of loop length on thermal comfort properties of bamboo knitted fabrics and observed an increase in air and water vapour permeability with the increase in loop length. Kane *et al.*[8] studied the influence of knit structure and structural cell stitch length on ring and compact yarn single jersey fabric properties and observed an increase in air permeability, water absorbency and spreading area of water with increase in structural cell stitch length. They stated that larger number of loops resulted in greater fabric density leading to high resistance to water absorption, thereby decreasing water absorption and spreading.

Wardiningsih and Troynikov[27] studied the relationship between cover factor and moisture management properties and suggested that the wetting time increased however a decrease in maximum wetted radius, rate of absorption, spreading speed and overall moisture management capacity was observed as the cover factor of the fabric increased.

Kumar and Das[50] suggested that tightness of knitted fabric structure affected the wicking nature of fabrics with tighter fabrics showing lesser amount of vertical wicking compared to loose fabrics. Herath[88] observed that fabric tightness was correlated with air permeability, aerial density and fabric thickness. Fabrics knitted with lower loop length showed higher thickness, weight and lower air permeability. Yanilmaz *et al.*[104] observed that slack fabrics knitted at longer loop length exhibited higher transfer wicking owing to higher porosity and pore size.

#### 5.3 Role of Bulk Properties of Fabrics

Fabric bulk properties like thickness, aerial density, bulk density and porosity are reported to affect thermo-physiological properties of fabrics. Accordingly, several studies[16, 68, 97, 98] are aimed at establishing relationship between bulk properties and the thermo-physiological properties of fabrics.

Oner *et al.*[16] studied the effect of fabric bulk properties on moisture management of fabrics and observed that fabrics with high thickness and mass per unit area showed lower values of moisture management indices. Saricam and Kalaoglu[78] found significant relationship between drying rate and fabric thickness in their studies on wicking and drying behavior of polyester woven fabrics.

Zhu and Takatera[105] studied the in plane capillary water flow for yarns and fabrics and suggested that wicking coefficient increases with the increase in fabric porosity. Increase in porosity increases the fibre spaces, thereby providing channel for transport of water and hence enhanced wicking. Hsieh[106] studied the liquid transport and retention in 100% cotton and polyester fabrics in relation to pore size. It was suggested that fast liquid spreading in fibrous material was prompted by small, uniformly distributed and inter connected pores while high degree of liquid retention was possible by increasing the number of pores or total pore volume.

## 6 Role of Fabric Dyeing, Printing and Finishing

Hayes *et al*. [107] studied the effect of new dye based on pyrido pyrimidine heptadinone derivative, as new colour dye on thermal properties of wool fabrics and observed significant decrease in thermal conductivity and q max values of dyed fabrics.

Said *et al*. [108] investigated the effect of ecological finishing treatments on the comfort properties of dyed cotton fabrics and observed that finished cotton samples showed lower air permeability and thermal conductivity compared to unfinished counterparts owing to sample compactness as a result of fabric shrinkage in finished samples.

Rathinamoorthy[109] studied the effect of alkali treatment on dyeing and comfort properties of modified polyester fabrics and observed significant increase in water absorbency, water vapour and air permeability but decrease in wicking values of alkali-treated fabrics in contrast to normal modified fabrics.

Ibrahim *et al*. [110] studied the effect of chemical finishing, namely soft-finish, bio finish, antibacterial and water-repellent finish, on comfort properties of cotton weft knit structures. They concluded that bio-finishing positively impacted the air-permeability and heat transmittance properties of treated cotton knits in contrast to other selected finishes.

Yilma *et al*.[111] studied the effect of plasma surface modification on comfort properties of polyester/cotton blend fabrics and concluded that plasma-treated fabrics showed higher wick ability & water vapor permeability, and lower air permeability, thermal & water vapor resistance as compared to unfinished samples.

Islam *et al*. [112] compared indigo and disperse dyed polyester fabrics for their comfort properties and found that after dyeing the air permeability reduced for both fabrics being studied however indigo dyed polyester fabric exhibited higher air permeability compared to disperse dyed polyester fabric.

## 7 Conclusion

The significance of clothing in providing thermal equilibrium with the surrounding environment and hence overall wearer comfort demands prudent selection of fibre, yarn and fabric variables for designing and engineering clothing for intended applications. Accordingly, optimum thermo-physiological properties are of paramount importance, while designing active sportswear, work wear and intimate wear. The challenging task for researchers and textile designers is thus comprehension of the varied factors at interplay and functional requirments of clothing to suit the intended application area.

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