



Thermophysiological and compressional properties of fleece-knitted fabrics for extreme cold weather clothing

Ranjna Kumari^a, R S Rengasamy & R Chattopadhyay

Department of Textile and Fibre Engineering, Indian Institute of Technology Delhi, New Delhi 110 016, India

Received 10 October 2023; revised received and accepted 4 March 2024

Thermo-physiological comfort is related to the body's heat balance at different activity levels. In extremely cold weather conditions, it is essential that the inner layers of the ensemble transport the liquid sweat and water vapours generated by human skin away from the body and keep the skin dry. The soldiers must carry heavily loaded bags, so the fabric's compressional recovery property is vital to regain its thickness and insulation. Fleece fabric is one of the components of clothing in extreme cold climates. The major function of the fleece fabric is to transport the liquid from the skin side to the base side of the fabric and entrap still air to provide some insulation. The incorporation of air channels in the fleece fabric is responsible for the vapour transmission and air entrapment, as well as reducing the weight of the fabric. In the present work, we have developed a few grid fleece fabrics by varying the combination of filament and spun yarns, differing in yarn and fibre fineness in the base and fleece parts of the fabrics. The effect of fibre fineness, yarn fineness and yarn structure (spun or filament) on moisture transport, thermal insulation and compressional properties are studied. The findings suggest that fleece fabric with filament yarn on the base side and spun yarn on the fleece side have better moisture management properties.

Keywords: Compression and recovery, Evaporative resistance, Fleece, Liquid moisture transport, Thermal resistance

1 Introduction

Thermo-physiological comfort in humans is intrinsically linked to heat balance, which seeks to maintain a core body temperature of approximately 37 °C. During routine activities, the human body generates heat in varying amounts depending on the level of physical exertion. The heat production rates during resting, walking, and running are estimated to be 65, 100, and 290 W/m², respectively¹. As physical activity intensifies, sweating occurs, facilitating evaporative cooling due to the latent heat of vaporisation. Consequently, the fabric should be designed to efficiently transport sweat from the skin to the fabric's outer surface, where it can readily evaporate. In extreme cold conditions, moisture transport is required along with thermal insulation. Moisture absorption by polyester fabric displaces air voids with water, thereby reducing insulation due to water's higher thermal conductivity than fibre and air. Thus, it is essential that liquid sweat is efficiently transferred to the fabric's exterior for evaporation to maintain optimal thermal comfort.

Literature suggests that finer fibres provide greater surface area and enhanced air entrapment, leading to superior thermal insulation. The effect of yarn fineness on the thermal insulation of knitted fabrics has been investigated under constant loop length conditions, revealing an increase in insulation with coarser yarns²⁻⁵. Coarser fibres in yarns contribute to greater fabric porosity due to their higher bending rigidity, enhancing insulation⁶. Additionally, increased loop length in knitted fabrics has been reported to facilitate greater air entrapment, further improving thermal insulation⁷. Similarly, insulation increases with fabric thickness and areal density⁸. Comparative studies indicate that fleece fabric exhibits superior thermal insulation relative to single jersey, woven, and felt fabrics of similar thickness⁹. Since fabric porosity and still air entrapment are primary determinants of insulation in extremely cold conditions, compressional behaviour analysis is vital. Compression reduces fabric thickness, leading to insulation loss. The bending rigidity of constituent fibres and yarns influences thickness recovery post-compression. Research has demonstrated that yarn bending rigidity is governed by fibre fineness and the application of twist, with coarser fibres exhibiting higher bending rigidity, which translates into stiffer yarns and fabrics¹⁰⁻¹². When yarn count remains

^aCorresponding author.

E-mail: ranjna14817@gmail.com

constant, and only fibre fineness varies, fabrics composed of finer fibres exhibit reduced compressibility¹³. Notably, the flexural rigidity of yarn increases significantly with fibre and yarn diameter¹⁴.

Apart from insulation, moisture transport is critical in extremely cold, hot, and humid environments. The human body continuously produces insensible sweat as vapour at a rate of 15 to 25 g/h¹⁵ and sensible sweat generation at 0.7 – 3.4 $\mu\text{L}/\text{cm}^2/\text{min}$ ¹⁶. Effective moisture transport ensures thermophysiological comfort by preventing excessive heat retention or rapid cooling. Fabrics function as a "second skin," shielding the body in adverse climatic conditions. A comprehensive investigation into the influence of fibre and yarn parameters on moisture transport is, therefore, imperative. Studies on the vertical wicking behaviour of polyester fabrics have demonstrated that finer fibres enhance wicking height and rate. However, in in-plane wicking tests, initial water uptake is higher for fabrics composed of coarser fibres, but finer fibres dominate over time¹⁷. Similarly, investigations on microdroplet absorption under simulated sweating conditions reveal higher initial wicking in yarns containing coarser fibres, followed by dominance of finer fibre yarns at later stages¹⁸. Knitted structures with increasing tightness factors, attributed to higher machine gauge, exhibit reduced vertical wicking height and rate¹⁷. Moisture management tester evaluations indicate that coarser fibre yarns yield lower wetting times, higher absorption rates, and superior one-way moisture transport. In contrast, finer fibre yarns display greater maximum wetting radius, spreading speed, and overall moisture management capacity¹⁹. The higher specific surface area of finer fibres facilitates enhanced moisture management and rapid drying²⁰. Yarn twist and fineness also affect moisture management properties, with increased twist reducing absorption rate, spreading speed, and maximum wetted radius while prolonging wetting time. Conversely, finer yarns demonstrate higher absorption rates, larger wetted areas, and shorter wetting times²¹. Plaited double-knitted fabrics exhibit excellent moisture management when composed of a finer-yarn/coarser-fibre inner layer and a coarser-yarn/fine-fibre outer layer²².

Water vapour transmission from the skin to the environment through fabric has been extensively studied. Findings indicate that decreasing fibre diameter while maintaining yarn fineness constant and increasing loop length reduces water vapour permeability⁷. The moisture vapour transmission rate declines with finer fibres⁴ and increased yarn linear

density (tex)⁶. Researchers have additionally examined the correlation between water vapour resistance and material thickness^{23,24}.

The thermophysiological properties and compressional behaviour of the inner layer of extreme cold-weather clothing are of paramount importance. Considering these factors, the fleece-knitted fabric having air channels emerges as an optimal structural choice, as the entrapped air in fabric channels improves insulation and water vapour permeability. However, no prior research has examined channelled fleece fabric's insulation, vapour transport, and compressional resiliency properties. This study investigates the effect of yarn fineness, fibre fineness, and yarn type on the liquid transport, vapour transmission, insulation and compressional properties of grid fleece fabric having air channels.

2 Material and Methods

Polyester yarns were produced using staple fibres and continuous filaments. The details of the yarns are given in Table 1. Grief fleece-knitted fabrics were produced using these yarns on a circular knitting machine. Fabric structural parameters are given in Table 2.

The stitch density was kept constant across all fabrics, leading to minor variations in areal density due to differences in yarn fineness in the multifilament yarns (C1 and C2). Figure 1 shows the technical front, back, and cross-section of grid fleece-knitted fabric with air channels on the fleece side.

2.1 Bending Rigidity

The bending rigidity of yarns was measured using a "Shirley weighted ring yarn stiffness tester." The yarn was wrapped around cylindrical formers to form loops of a specific perimeter. These loops were removed from the former surface and placed in a gripper, allowing the yarn ring to hang vertically. The initial scale reading was recorded (R1), followed by a second reading (R2) after attaching a weighted hook to the yarn ring. The weight was selected to ensure a deflection between 0.35 and 0.7 cm.

Table 1 — Yarn parameters

Code	Type	Fineness, tex	Fibre fineness, dtex
C1	Continuous multifilament	16.6	1.1
C2	-do-	8.3	2.2
S1	Spun	17	0.89
S2	-do-	17	1.33

Table 2 — Fabric structural parameters

Fabric code	Base yarn	Fleece yarn	Course density (courses/cm)	Wale density (Wales/cm)	Areal density, g/m ²	Thickness (mm) at 20 cN/cm ²
F1	C2	S2	13.6	12	240	1.43
F2	C2	S1	13.6	12	240	1.38
F3	C1	S1	13.6	12	270	1.33
F4	C1	S2	13.6	12	270	1.39
F5	S1	C2	13.6	12	235	1.15
F6	S2	C2	13.6	12	235	1.13

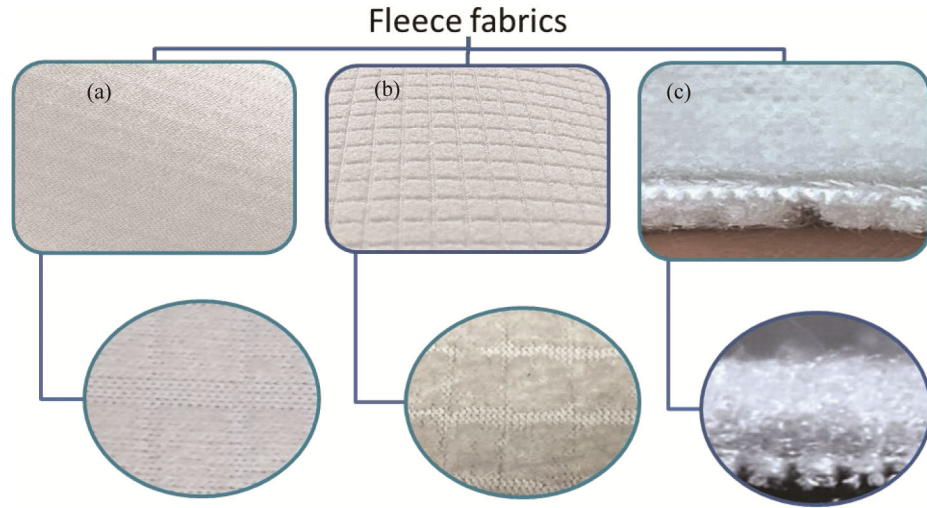


Fig. 1 — Fleece knitted fabric’s (a) technical front, (b) technical back, and (c) cross-section

Deflection, d (cm) = $R_2 - R_1$

Flexural rigidity G is calculated as

$$G \text{ (N/m}^2\text{)} = 9.81 \frac{ML^2}{z} \dots(1)$$

where M is applied mass; L , circumference of former or yarn ring (7.75 cm); z , reference table value corresponding to the ratio of d/L .

2.2 Vertical Wicking

Vertical wicking of yarns was measured using the AATCC 197 standard test method. Yarn samples were suspended vertically in a deionised water reservoir containing 1% reactive dye to track the liquid path. The height of the coloured liquid wicking in the yarn was recorded over time.

2.3 Moisture Management

Moisture management properties of the knitted fabrics were assessed using a moisture management tester. Fabric samples were placed between the top and bottom plates. A controlled volume of 100-120 μL of liquid was applied for 20 s, with each drop measuring approximately 10 μL . The upper fabric surface, considered the skin-contacting side, was analysed for liquid movement in horizontal and

vertical directions over 100 s. Electrical resistance changes due to liquid presence were recorded to assess liquid movement and wicking behaviour. Wetting time (s), absorption rate (%/s), maximum wetted radius (mm), spreading speed (mm/min), accumulative one-way transport index and overall moisture management capability terms were used to express results.

2.4 Compression and Recovery

Compressional properties were examined using an Essdiel thickness gauge with a pressure foot diameter of 2 cm. Fabric samples were placed on the holder plate, and pressure was applied incrementally from 2 kPa to 100 kPa, with thickness recorded after 30 s at each pressure level. Once the maximum pressure was reached, the pressure was gradually reduced in reverse order, and corresponding recovery thickness measurements were noted²⁵. Compression and recovery percentages were calculated using the following equations:

$$\text{Compressibility } (c) = \frac{\text{Initial thickness } (Z_0) - \text{Compressed thickness } (Z_c)}{\text{Initial Thickness } (Z_0)} \dots(2)$$

$$\text{Compression (\%)} = \text{Compressibility} * 100 \dots (3)$$

$$\text{Recoverability (r)} = \frac{\text{Recovered thickness (Zr)} - \text{Compressed thickness (Zc)}}{\text{Initial Thickness (Zo)} - \text{Compressed thickness (Zc)}} \dots (4)$$

$$\text{Recovery (\%)} = \text{Recoverability} * 100 \dots (5)$$

2.5 Thermophysiological Comfort

The thermophysiological comfort of the fabric was evaluated by the parameters ‘Thermal- and Evaporative- resistances’ on a sweating-guarded hot plate following ISO 11092 standard. The guarded hot plate was maintained at 35 °C, with atmosphere conditions at 20 °C with 60 % relative humidity. The thermal resistance was calculated using the below equation:

$$R_{ct} = \frac{(T_s - T_a)}{Q/A} \dots (6)$$

where R_{ct} is the thermal resistance; T_s , skin temperature; T_a , ambient temperature; and Q/A , area-weighted heat flux.

The evaporative resistance was determined during the sweating test using the formula:

$$R_{et} = \frac{(P_s - P_a)}{\frac{Q}{A} - [(T_s - T_a)/R_{ct}]} \dots (7)$$

where R_{et} is the evaporative resistance; P_s , saturated skin vapour pressure; P_a , ambient vapour pressure; Q/A , area-weighted heat flux; T_s , skin temperature; T_a , ambient temperature; R_{ct} , thermal resistance; and $(T_s - T_a)/R_{ct}$, dry heat loss.

3 Results and Discussion

3.1 Yarn Bending Rigidity

Coarser filament yarn with finer fibres (C1) exhibits greater bending rigidity than the finer filament yarn with coarser fibres (C2). The bending rigidity of yarn is the sum of the bending rigidity of constituent fibres¹². Fibre bending rigidity depends on the elastic modulus and second moment of inertia of fibre, which is proportional to the fourth power of the fibre diameter. Fibre fineness (dtex) is proportional to the square of fibre diameter. Consequently, the bending rigidity of C1 is the sum of the bending rigidity of 144 filaments of 1.1 dtex, whereas that of yarn C2 is derived from 36 filaments of 2.2 dtex. The elastic modulus of filaments in yarns C1 and C2 are 65.9 cN/dtex and 77.9 cN/dtex, respectively. Theoretically, the bending rigidity of yarn C1 would be about 15% lower than yarn C2 if inter-filament friction forces are neglected. However, the bending rigidity of coarser yarn, C1, is about twice that of C2, indicating the significant contribution of inter-filament friction due to greater frictional contacts when more filaments are used. This keeps the filaments together while bending the yarn, contributing to more bending rigidity to the yarn.

In the case of spun yarns, S1 and S2, which have the same linear density and twist level, the bending rigidity remains similar despite differences in fibre fineness. This is due to the discrete length of fibres in spun yarns, which are twisted to form a relatively less compact structure than filament yarns. During bending, the fibres in spun yarns exhibit greater freedom of movement, unlike those in filament yarns, where inter-filament is more dominant.

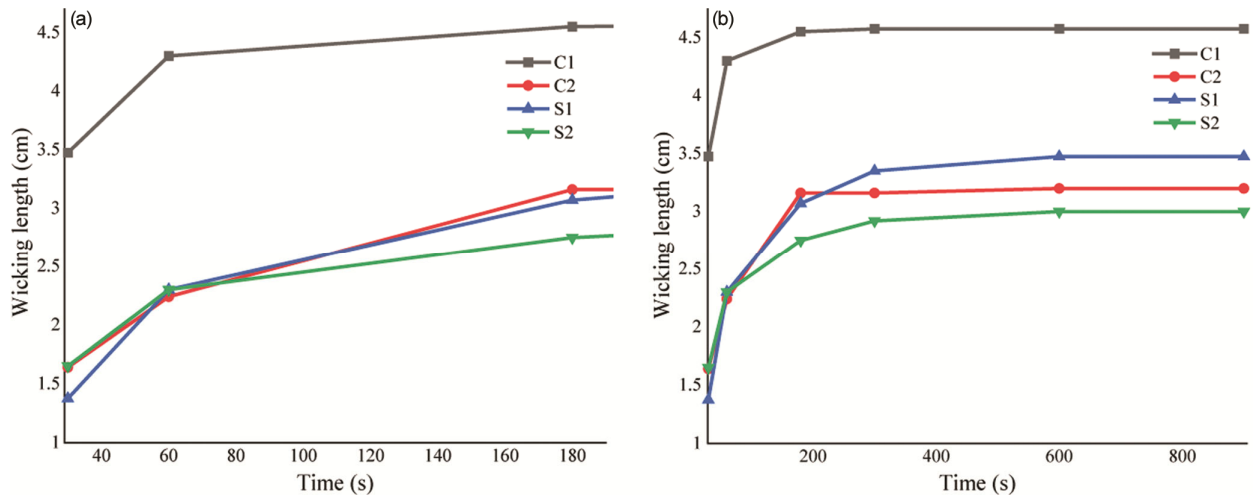


Fig. 2 — Liquid transport through spun and filament yarns (a) initial wicking up to 180 seconds, and (b) wicking up to 900 seconds

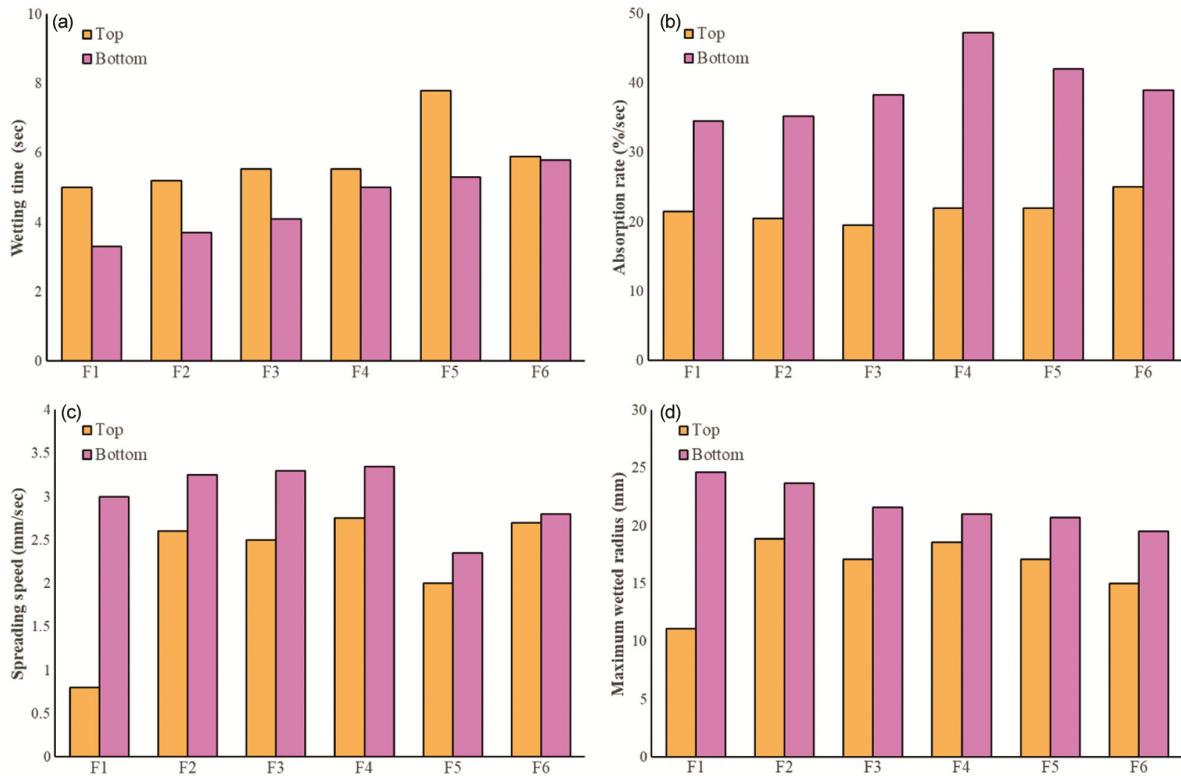


Fig. 3 — Moisture management properties of fleece knitted samples (a) Wetting time (b) Absorption rate (c) Spreading speed, and (d) Maximum wetted radius

3.2 Yarn Vertical Wicking

Vertical wicking results for the yarns are presented in Fig. 2. Filament yarn with finer fibres (C1) demonstrates the highest vertical wicking due to numerous fine capillaries, facilitating liquid exchange and exerting high capillary pressure. In contrast, yarn C2, having fewer but larger capillaries, exhibits lower capillary pressure, resulting in slower liquid movement and reduced wicking height.

For spun yarns (S1 & S2), the initial wicking height (up to 60 s) is longer for coarser fibre yarn (S2) than for finer fibre yarn (S1). However, at later stages (900 s), the finer fibre yarn (S1) achieves greater wicking height due to the higher capillary pressure exerted by its numerous fine capillaries. The gravitational force acting on the liquid column is greater in the coarser fibre yarn, reducing its final wicking height compared to the finer fibre yarn.

3.3 Moisture Management Testing

Fleece fabrics are used in extremely cold conditions, with the fleece side either in direct contact with the skin or layered beneath outer garments (or vests) to optimise insulation via air channels. While testing the moisture management properties, water droplets were

applied to the fleece side (top surface), and liquid transport was analysed as it moved towards the base layer (bottom surface). Liquid travels along the fleece as well on the base of fabric simultaneously in a complex manner due to a variety of factors such as capillary size and numbers, volume of pores/yarns, tortuosity of fibres, and continuity of capillaries present in both the yarns at the fleece and base part of fabric.

Moisture management properties were evaluated based on wetting time (WT), absorption rate (AR), spreading speed (SS), maximum wetted area (MWA), accumulated one-way liquid transport (AOLT), and overall moisture management capacity (OMMC).

3.3.1 Wetting Time

Wetting time, the duration required for fabric wetting to commence, is shown in Fig. 3 (a). Samples F5 and F6, which contain spun yarns in the base, exhibit the longest wetting times. Sample F2 and F1 have the same combination of fibre/yarn fineness as in F5 and F6, but when spun yarn is used in the base rather than the filament, the wetting time increases by more than 15%. This is because in these fabrics, spun yarns were used in the base and filament yarns in the fleece part of the fabric. In the spun yarn, staple fibres

(of finite length) follow the helical path along the yarn axis due to twist, and the fibre ends protrude mostly as hairs on the yarn surface, contributing many partially opened capillaries on the yarn surface. The spun yarn takes longer to transport the liquid due to the tortuous path of capillaries because of the segmental migration of fibres across the yarn cross section and the poor capillary pressure exerted by the surface capillaries, thus exhibiting longer wetting time. When F1 and F2 having 8.3 tex filament yarn (coarser fibres) in the base of the fabric, compared with F3 and F4 having 16.6 tex filament yarn (finer fibres) in the base of fabric, it is found that wetting time for sample F1 and F2 is lower than F3 and F4. This is because the filament yarn having coarser fibre has a larger hydraulic pore diameter. When liquid encounters the yarn, these capillaries quickly transport the liquid across and along the yarn. When the samples F1 and F4 consist of spun yarn with coarser fibres (1.33 dtex) on the fleece part are compared to F2 and F3, it is noticed that coarser fibres on the top is showing lower wetting time, but the difference is less than 10%.

3.3.2 Absorption Rate

Top and bottom absorption rates for all the samples are shown in Fig. 3 (b). A higher absorption rate is found a little bit more in the case of F1 and F4 when compared with F2 and F3, respectively. This may be because of the coarser fibres on the top; the absorption rate is higher due to the larger pore size (as per the Hagen Poiseuille equation¹⁸). For the bottom absorption rate, it is found that coarser yarn with finer filaments gives an absorption rate higher than finer yarn with coarser filaments, although the porosity of both yarns is the same. This is because, in coarser yarn, the air space to be replaced by liquid is more than the finer yarn because of the larger yarn diameter. The amount of liquid dropped on fabric is limited (100-150 μm). So, coarser yarn absorbs more liquid, resulting in a higher absorption rate. Samples F5 and F6 also show a higher bottom absorption rate when compared with F2 and F1, respectively. This is because in F5 and F6, the base yarn is spun yarn (17 tex), which is bulkier due to more yarn diameter and hence more air space to be replaced by liquid than filament yarn F2 (8.5 tex). This results in the absorption of more liquid within the structure in spun yarn.

3.3.3 Spreading Speed

Figure 3 (c) reveals that in the case of top spreading speed, no specific effect of fibre fineness is

observed. The bottom spreading speed is higher in samples F3 and F4 (coarser yarn with finer filament) compared to F1 and F2 finer yarn with coarser filaments) due to the presence of finer filaments in the base yarn, which generate higher capillary pressure. However, differences in spreading speed remain within 2–12%. When filament yarns are used in the base, as in F1 and F2, spreading speed is higher compared to spun yarn-based samples (F5 and F6), due to the more uniform and straight capillaries in filament yarns.

3.3.4 Maximum Wetted Radius

There is no trend on the effect of fibre fineness in the fleece part on the maximum wetted radius, as shown in Fig. 3 (d). But in most cases, the top wetted radius is more when the bottom wetted radius is more. When the bottom maximum wetted radius of samples F1 and F2 are compared with F3 and F4, it is found that the maximum wetted radius is always more in the case of finer yarn with coarser filaments. This is because the volume available for holding the water in the finer yarn is limited; hence, in the case of finer yarn (yarn with a lower diameter), the length of wicking is longer, resulting in a greater wetted radius. When samples F5 and F6 are compared with F2 and F1, respectively, for the wetted radius at the bottom, it is observed that the wetted radius is lower for F5 and F6. This is because the base yarn is spun yarn, and due to distorted and irregular capillaries, the maximum wetting length is lower.

3.3.5 Accumulative One-Way Transport Index

The accumulative one-way transport index (Fig. 4 (a)) is highest in sample F1, followed by F4. In both F1 and F4, the top fleece part consists of coarser fibre spun yarns; hence, as the liquid falls on the top of the fabric, it is immediately transported to the bottom surface. F1 base yarn is finer yarn and has a lower absorption rate than F4; hence, more liquid is transported to the bottom plate. At the same time, samples F4 and F3 showed almost the same values because coarser filament yarns were used in the base. Coarser fibre on the skin side (fleece side) and finer fibre on the other side (base) is an ideal structure for moisture management fabric²², therefore as the liquid comes in contact with the fleece layer, the high capillary pressure generation in the base side pulls more liquid to the bottom. The lowest values are observed in F5 and F6 due to spun yarn in the base, which impedes efficient liquid transfer.

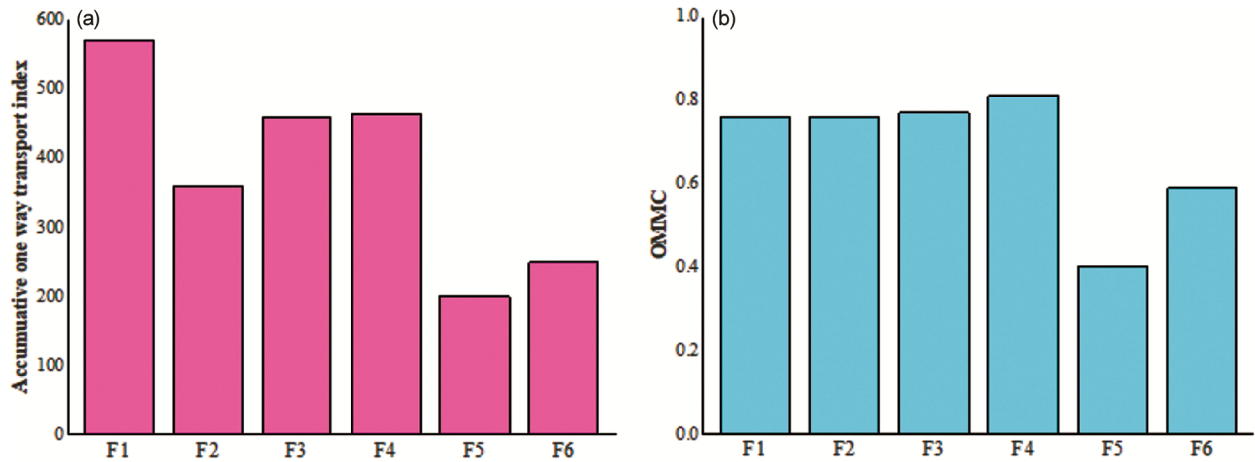


Fig. 4 — Fleece knitted fabrics (a) accumulated one way transport index, and (b) overall moisture management capacity

3.3.6 Overall Moisture Management Capacity

The overall moisture management capacity is highest in F4 due to superior bottom absorption and spreading [(Fig. 4 (b)]. In this fabric, the water first contacts the coarser fibre spun yarn on the fleece which rapidly imbibes the water, from there, the coarser yarn having finer filaments on the base swiftly transport due to the presence of many finer capillaries One-way transport is also better than other F2, F3, F5 and F6 samples. Samples F5 and F6 exhibit the lowest OMMC, as spun yarn-based bases hinder effective moisture transfer.

3.4 Compression and Resiliency

Table 3 shows the compression and recovery percentages of fleece samples. It is observed that samples F1 and F2, having finer yarn in the base of the fabric, undergo more compression than other samples having coarser yarn. These fabrics have a fleece with longer projections due to finer base yarn. The long fleece can get compressed to a greater extent, resulting in more compression. The recovery is found more in sample F4, which has coarser yarn on the base and coarser fibres on the fleece part. All the samples (F3 and F4) having coarser yarn (C1) on the base give lower compression and more recovery due to the more bending rigidity of the coarser yarn. The presence of spun yarn in the fleece (F5 and F6) have lower compression than the others due to crimps in the staple fibres.

3.5 Thermal and Evaporative Resistance

Thermal resistance values [(Fig. 5 (a))] depict that fabric samples with finer fibres on the fleece part exhibit more thermal resistance due to enhanced air entrapment by finer fibres. Sample F2 and F3 show

Table 3 — Compressibility and recovery percentage of fleece fabrics

Sample	Compression, %	Recovery, %
F1	59.26	77.34
F2	61.32	83.4
F3	55.98	85.47
F4	56.56	93.64
F5	53.45	84.95
F6	56.04	83.43

more thermal resistance because of the large number of smaller pores on the fleece part; hence, air entrapment would still be more. The fibre surface area of fleece fibres for F2 and F3 is greater (the presence of fine fibres in tortuous form in spun yarns) when compared with fleece parts in other samples, so radiative heat transfer through F2 and F3 will be less. F3 has higher dry thermal resistance than F1 by 14.2% despite the former having more thickness. The F2 has higher thermal resistance than F4 by 27%, respectively; both have similar thicknesses. From these observations, it may be stated that finer fibre in fleece enhances the thermal resistance of the fabrics. When base yarn is compared while keeping the fleece yarn the same in the fabric (F1 vs F4 and F2 vs F3), It is found that the thermal resistance for F4 is 24% lower than F1, and the thermal resistance of F3 is 11.5% lower than F2 fabric despite having coarser filament yarn (C1) in the base of F4 and F3 fabrics.

In F5 and F6 samples, thermal resistance is found to be at a minimum. Samples F5 and F6 consist of spun yarns (S1 and S2, respectively) in the base of the fabric and finer multifilament yarn (C2) in the fleece part. Due to this, the fabric thickness is lower and less bulky than that of other fabrics. Hence, less air

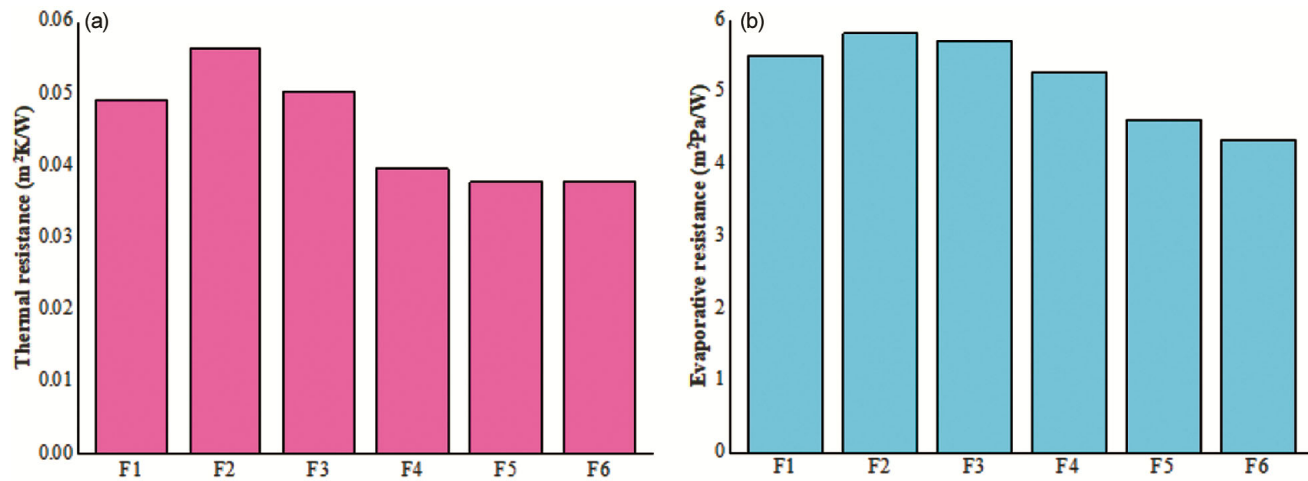


Fig. 5 — Fleece fabrics (a) Thermal resistance, and (b) Evaporative resistance

entrapment in these fabrics is lower, resulting in lower thermal resistances.

The evaporative resistance of all the samples is shown in Fig. 5 (b). F2 and F3 show maximum evaporative resistance as compared to other fabrics. This is because of more surface area of fine fibres in the fleece which hinders the diffusion of water vapours through the fabric. This results in higher evaporative resistance. When spun yarn is used in fleece and filament yarn in the base of the fabric, the difference in evaporative resistance of samples (F1, F2, F3 and F4) does not exceed 10.5%. Samples F1 and F4 have coarser fibres, and F2 and F3 have finer fibres in the fleece. The difference between F1 and F4 & F2 and F3 is in the base yarn fineness. It is observed that the difference in the evaporative resistance is 4.5% and 2%, respectively, which is not significant. Sample F1 & F2, and F3 & F4 are having filament yarns in the base but with different fibres (fine and coarser) on the fleece part. This indicates that minimum evaporative resistances are found in F5 and F6 fabric samples because of the lesser fabric thickness. Therefore, water vapour can easily move from the skin side to the outer environment through the fabric. F5 and F6 show 14-34% lower evaporative resistance than the other samples.

Conclusion

This study investigates the thermo-physiological properties and compressional behaviour of grid fleece knitted fabrics with air channels. The findings reveal that yarn and fibre fineness significantly influence bending rigidity, wicking length, moisture management, thermal resistance, and compressional

resilience. Due to its straight and continuous capillaries, filament yarn exhibits a faster wicking rate and longer wicking length than spun yarn. Among spun yarns, those with coarser fibres display faster initial wicking, whereas those with finer fibres achieve greater wicking height over time. Finer fibres enhance thermal insulation by increasing air entrapment, while coarser fibres improve moisture transport due to larger capillary diameters. Spun yarns in the base layer exhibit longer wetting times and lower one-way liquid transport, whereas filament yarns enable more efficient moisture transfer. Compression and recovery properties are largely determined by yarn fineness, with coarser yarns exhibiting greater resilience. The highest thermal and evaporative resistance is observed in fabrics with finer fibres in the fleece layer, as finer fibres provide greater surface area and smaller pores, impeding infrared radiation and moisture vapour transmission. This results in reduced radiative heat loss increased dry thermal resistance, and greater resistance to moisture vapour diffusion through the fabric. Among the essential attributes of fleece fabrics used in inner layers, moisture management and resiliency are paramount. Based on these findings, fleece fabrics with filament yarn in the base and spun yarn in the fleece layer are highly preferable for optimising both thermal comfort and moisture management in extreme cold conditions.

Acknowledgement

This research work was funded by the Defence Research and Development Organisation, India (JATC under MI01618).

References

- 1 Kumar D S, *Int J Res Appl Sci Eng Technol*, 10 (2022) 1799, doi: 10.22214/ijraset.2022.48303.
- 2 Ozdil N, Marmaralı A & Kretzschmar S D, *Int J Therm Sci*, 46 (2007) 1318, doi: 10.1016/j.ijthermalsci.2006.12.002.
- 3 Kumar S T, Kumar R M & Kumar S B, *Ind Text*, 72 (2021) 31, doi: 10.35530/IT.072.03.202032.
- 4 Varshney R K, Kothari V K & Dhamija S, *J Text Inst*, 101 (2010) 495, doi: 10.1080/00405000802542184.
- 5 Chidambaram P & Govind R, *AUTEX Res J*, 11 (2011) 102.
- 6 Manshahia M & Das A, *Res. J Text Appar*, 17 (2013) 50, doi: 10.1108/RJTA-17-03-2013-B006.
- 7 Jhanji Y, Gupta D, & Kothari V K, *J Text Inst*, 106 (2015) 383, doi: 10.1080/00405000.2014.923594.
- 8 Mishra G, Kumari R & Baheti V, *Polym*, 25 (2024) 4033, <https://doi.org/10.1007/s12221-024-00709-y>.
- 9 Das A & Biswas B, *Indian J Fibre Text Res*, 36 (2011) 410.
- 10 Platt M M, Klein W G & Hamburger W J, *Text Res J*, 29 (1959) 611, doi: 10.1177/004051755902900802
- 11 Kumari R, Rengasamy R S & Chattopadhyay R, *Fibre Polym*, 25 (2024) 357, doi: 10.1007/s12221-023-00404-4.
- 12 Dhingra R C & Postle R, *J Text Inst*, 67 (1976) 426, doi: 10.1080/00405007608630161.
- 13 Varshney R K, Kothari V K & Dhamija S, *J Text Inst*, 102 (2011) 31. doi: 10.1080/00405000903453661.
- 14 Walker E M and Doyle P J, *J Text Inst Proc*, 43 (1952) 19, doi: 10.1080/19447015208663954.
- 15 Gates D M, *Bioscience*, 23 (1973) 55, doi: 10.2307/1296372.
- 16 McCUTCHEON L J, Geor R J, Hare M J, Ecker G L, & Lindinger M I, *Equine Vet J*, 27 (2010) 153, doi: 10.1111/j.2042-3306.1995.tb05022.x.
- 17 Das B, Das A, Kothari V K, Fanguiero R & Araújo M, *Fibers Polym*, 9 (2008) 225.
- 18 Kumari R, Mishra G, Rengasamy R S & Chattopadhyay R, *Colloids Surfaces A Physicochem Eng Asp*, 665 (2023) 131273, doi: 10.1016/j.colsurfa.2023.131273.
- 19 Choudhary A K & Ramratan, *J Inst Eng Ser*, 101 (2020) 77, 10.1007/s40034-020-00157-2.
- 20 Sampath M, Mani S, & Nalankilli G, *J Ind Text*, 41 (2011) 160, doi: 10.1177/1528083711400774.
- 21 Ozdil N, Supuren G, Ozcelik G & Pruchova J, *Text Appar*, 19 (2009) 218.
- 22 Rock M, Haryslak C, Lie W K & Vainer G, & Richardson P C, *United States Patent*, 1 (2007) 12.
- 23 Grayson M, *Encyclopedia of composite materials and components*, (1983).
- 24 Havenith G, *Exog Dermatology*, 1 (2002) 221, doi: 10.1159/000068802.
- 25 Kothari V K & Das A, *J Text Inst*, 84 (1993) 16, doi: 10.1080/00405009308631243.