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Water vapour and air transmission of multilayer fabric ensembles

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The present study is aimed at finding out an optimum combination of various fabric layers, so that the fabric ensemble will show maximum water vapor permeability along with lowest air permeability. Yarns of different blend ratio of wool/acrylic fibre are used to knit fabrics of different structures. Polypropylene yarns having different number of filaments are also used to knit samples. These fabrics are then layered with cotton fabric and breathable fabrics. Various fabric ensembles are formed and tested for water vapour and air permeability. The results conclude that the fabric having 70:30 wool/acrylic blend with pile knit structure, layered with cotton and breathable fabric shows maximum (303.46 g/m^2/24h) water vapor transmission rate and zero air permeability. Fabric ensemble produced by layering polypropylene fabrics (plain knitted with yarn having 24 filaments), cotton fabrics and breathable fabric shows maximum water vapour transmission rate (527.87 g/m^2/24h) along with zero air permeability.

Keyword: Acrylic fibre, Air permeability, Breathability, Cotton, Cup method, Knitted fabric, Multilayer assembly, Polypropylene, Water vapour transmission, Wool

1 Introduction

Designing fabrics for extremely cold weather has always been a challenge for the scientists. Chilling air from outer atmosphere must not penetrate the clothing so that the wearer remains warm. But at the same time moisture generated from the body must be released into atmosphere. Moisture comfort is extremely important for a person to work efficiently. A single type of fabric can never solve is issue. The assembly of fabrics for inner layer applications where water vapour permeability is one of the most important factors may depend on the selection of fibre yarn and fabric construction systems. Fabric can be prepared using knitting, weaving or nonwoven technologies. Water vopur can be transferred through any fabrics due to either diffusion or wicking. Breathable fabrics are readily available to protect the wearer from outside chilling air as they are not permeable to air. At the same time, the moisture vapour can be transferred to the outer environment through the breathable fabrics.

Water vapour diffusion could be affected by fabric structure. The measurements of air flux through the fabrics can be used as standard to the quantity of water vapour which can be transferred through the fabrics. The textile material that is permeable to air is in most of event permeable to water vapour. Notwithstanding, water vapour permeability should be managed to ensure that the required clothing comfort is reached to target.[1-3]. Water vapour permeability is very delicate property of fabrics that must maintain the thermal balance for user. Textile materials with high water vapour transmission permit the human skin to take benefit of its capacity to provide cooling due to sweat output and evaporation. The water vapour collection (condensation or absorption) within clothing system is a serious problem of thermal undergarment, sportswear and clothing worn in cold weather[4-8] .The interaction of water vopur with fabric involves basic physical concept, such as wetting of the fibre surface, passover of water vapour into the assemblies of fabric , adsorption of the fibre surface , diffusion of water vapour into the inner portion of the fabric[9,10]. The mechanism by which water vapour is transported in fabrics is similar to the wicking of liquid in capillaries. Capillary action is determined by two properties of the capillary, viz its diameter and surface energy of its inner surface. The smaller the diameter or the greater the surface energy, the higher is the tendency of a liquid to move up the capillary. In fabric structures, the spaces between fibres effectively

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form capillaries. Hence, the smaller the spaces between these fibres, the greater will be the ability of the fabric to wick water vapour. Fabric constructions, which effectively form small capillaries, pick up water vapour easily. The surface energy in a fabric structure is determined largely by the chemical structure of the exposed surface of the fibre, and therefore hydrophilic fibres have a high surface energy. Knitted fabrics are the most common fabric structures for underwear garments and sport wear. Knitted fabric mainly possesses good tightness and recovery, providing good freedom of movement, shape retention, and tailored fit. With the possibility of various combinations of fabric constructions and yarns used, knitted fabric appears to be the ideal base for functionally thermal undergarment. And commonly, a knitted double-layer construction is selected to obtain a functional fabric design because of its ductility due to fibre selection and properties[11,12]. In double layer fabric structures, the connecting yarn acts as a bridge between the two layers of fabric and improves the comfort level of double-layer knit ted fabric[13,14]. There are a number of fibres that are currently used in underwear and sportswear garment, both natural and manmade fibre, but polyester is the single most popular and common fibre used in thermal undergarment, active wear and sportswear. Some other researchers have studied geometric distribution of capillaries in manmade fibre assemblies, which affects the volume of water vapour and the wicking time of capillary action[15,16]. When water vapour saturates the inner layer of the fabric, various processes take place. The water vapor may permeate through the clothing system to its outermost fabric surface which is then taken away by the air[17].

Water vapor permeability through fabrics influences thermo-physiological comfort of the human body, which consider sweat both in vapor and liquid forms. The clothing to be worn should permit this sweat to be transferred to the surrounding atmosphere in order to maintain the thermal balance of the human body. The fabric being worn should allow the sweat to pass through it, otherwise it will result discomfort. The perception of discomfort in the active case depends on the degree of skin wetness. In case of sweating, if the clothing water vapor transfer rate is slow the relative and absolute humidity levels of the clothing microclimate will more suppress the evaporation of sweat. The water vapor transmission properties of a fabric are essentially governed by inter-fibre or inter yarn spaces[18]. The vapour diffuse through the air spaces between the fibrous materials and the open fabric structure promotes the diffusion process. Water vapour permeability through the textile fabrics is followed by the following Fick's Law[19].

$$M_1 = -D_{12}\frac{\partial C1}{\partial x} \qquad \ldots (1)$$

where M_1 is the rate of water vapour flux; $\frac{\partial C1}{\partial x}$, the concentration gradient; and D_{12} , the diffusion coefficient. Water vapour resistance mainly depends on the air permeability of the fabrics and indicates it's ability to transfer the sweat coming from the human skin[18,20].

According to wearing condition, the movement of the heat and water vapour through an undergarment fabric is probably the most important parameter that affects clothing comfort. The higher air permeability and higher water vapour permeability of fabric can provide higher degree of comfort, as they can facilitate the transfer of water vapour and insensible heat [21].

Today's thermal undergarment clothing are engineered to maximize comfort through enhanced moisture management and temperature regulation. Basic properties are included into garments, using specialized fibres, yarns, fabric structures and fabric finishes[22-24]. A thermal undergarment clothing that is worn next to the skin should have[25,26] a good sweat absorption and sweat releasing property to the surrounding environment, as well as a fast drying property for getting more tactile comfort. Many research studies have shown that the raw materials and structural properties of fabrics are important in the assessment of moisture management properties of fabrics[27-31].

Multilayer fabrics are chosen for extreme cold weather condition to provide adequate comfort characteristics (i.e. thermal insulation, water vapur permeability). The usage of a multilayer clothing ensemble is better than the single layer clothing due to the fact that comfort properties provided by several layers can be easily adjusted. One layer is taken off or put on without disturbing the whole clothing ensemble. The body temperature increases at high activity level in ECW (extreme cold weather). Multilayer fabrics have been widely used for thermal comfort protective clothing, which is important in hot environment to protect the wearers from solar radiation. Thermal protection clothing consists of the inner layer, middle layer and out layer[32-34]. Polypropylene filament fabrics may give better transmission properties than wool/acrylic fabric which has not been studied yet to the best of our knowledge.

In this investigation, authors have studied the water vapor and transmission behavior of the multilayer clothing system along with various factors affecting it. The designed multilayer clothing system includes a series of wool/acrylic knitted fabrics, polypropylene knitted fabric, and cotton knitted fabric and breathable fabric. The study will also point out the effect of blend proportion, number of filaments in yarn, and fabric structure on water vapour transmission rate and air permeability of multilayer fabric ensemble (MLFE).

2 Materials and Methods

2.1 Materials

Fabrics were prepared by using V-bed flat knitting machine. Details of the samples are given in Table 1. WA, CWA and CWAB stand for wool/acrylic, cotton/wool/acrylic, cotton/wool/acrylic/breathable respectively. P, CP and CPB stand for polypropylene, cotton/polypropylene, cotton/polypropylene/breathable respectively. Nine samples of wool /acrylic with different knitting structure (plain, rib and pile) and blend ratio (30:70, 50:50 & 70:30) were produced, keeping count of yarn (70 tex) same. Nine samples of polypropylene (PP) with different knit structure (plain, rib and pile) and yarn having different number of filaments (24, 48 & 66) in PP yarn are produced. One sample of 100 % cotton fabric and one sample of light weight, water proof, and breathable fabric membrane were prepared. The breathable fabric is composed of three layer, i.e. expanded polytetrafluoroethylene protected by knitted fabric layer from one side and woven fabric layer from the other side.

2.2 Methods

2.2.1 Fabric Physical Properties

The fabric samples were conditioned in a conditioning chamber at standard atmospheric

Table 1─Constructional parameters of wool/acrylic and polypropylene fabrics

Fabric code	Structure of fabric	Composition of No. of filament in yarn fabric (Wool: Acrylic)	Wale/inch	Courses / inch	Arial density g/m^2	Thickness mm (Under pressure of 7g/cm^2)
			Wool: Acrylic			
1	Plain	30:70	14	17	161.58±0.42	1.23±0.021
2	Rib	30:70	17	27	438.04±0.47	1.93±0.016
3	Pile	30:70	13	24	467.34±0.49	3.21±0.030
4	Plain	50:50	13	16	162.52±0.47	1.24±0.020
5	Rib	50:50	15	26	409.35±0.47	1.94±0.022
6	Pile	50:50	14	27	452.41±0.43	3.39±0.044
7	Plain	70:30	13	16	163.9±0.50	1.25±0.017
8	Rib	70:30	17	26	408.69±0.31	2.04±0.026
9	Pile	70:30	14	25	458.04±0.43	3.42±0.025
10	Plain	–	16	22	181.01±0.38	1.21±0.023
			Polypropylene			
11	Rib	–	16	28	344.99±0.37	1.54±0.016
12	Pile	–	17	28	351.81±0.30	2.43±0.030
13	Plain	–	15	23	239.41±0.36	1.31±0.023
14	Rib	–	15	28	445.688±0.26	1.82±0.025
15	Pile	–	15	28	345.94±0.35	2.36±0.031
16	Plain	–	16	24	202.51±0.39	1.11±0.028
17	Rib	–	14	25	377.02±0.44	1.58±0.025
18	Pile	–	14	24	348.70±0.43	2.21±0.035
Cotton	Plain	–	26	35	126.78±0.30	0.41±0.003
Breathable fabric [a]	–	–	–	–	193.76±0.31	0.4±0.002

[a] Breathable fabric is composed of three layer, i.e. expanded polytetrafluoroethylene protected by knitted fabric layer from one side and woven fabric layer from the other side.

conditions (20 ± 2°C, 65 ± 2% RH) for 24 h. Knitted fabric's stitch densities were measured using counting glass according to ASTM D3775-03 & ASTM D-3887 standards. Yarn linear density and fabric weight per unit area were measured according the ASTM D 1059 standard. The thickness of fabrics was measured as per the ASTM D 1777-96(2002) standard test methods using Shirley thickness gauge at a pressure of 7 g/cm^2 with an accuracy of 0.01mm. An average value of ten readings was taken for each sample in case of each test and calculated standard error was calculated.

2.2.2 Water Vapor Permeability

Water vapor permeability is the ability to transmit vapour from the human body. The water vapour permeability of the sample was measured through the cup method, according to ASTM E96 standard and BS 7209 (1990) (Fig. 1). This technique is very simple and it determines the weight loss (evaporation of water) with time of water contained in a cup. The sample fabrics are mounted on top of the cups and tighten with ring & maintained in an air tight manner. The experiment was performed in triplicate for three continuous days. The dimensions of the cup were determined to give a 1.90 cm deep layer of air between surface of the water and inside of sample. The weights of the cups were measured firstly at the starting of the test and then after every 24 h for three days. The weight of cups with samples was measured quickly at the starting of the test and then periodically after a fixed interval using the balance with resolution of 0.001, to calculate how much water has been evaporated in each step. The difference in water loss in the cup indicated water vapour evaporation though the fabrics and the water vapour permeability of the samples was calculated[35-37]. The water vapour permeability was calculated using the following formula:

$$WVT = \frac{24W}{AT}\, g/m^2/day \qquad \dots (2)$$

where W is the loss in mass (g); T, the time; and A, the internal area of the cup (m^2). A was calculated using the following relationship:

$$A = \pi\left(\frac{d^2}{4}\right) \times 10^{-4} \qquad \dots (3)$$

where d is the internal diameter of cup (m).

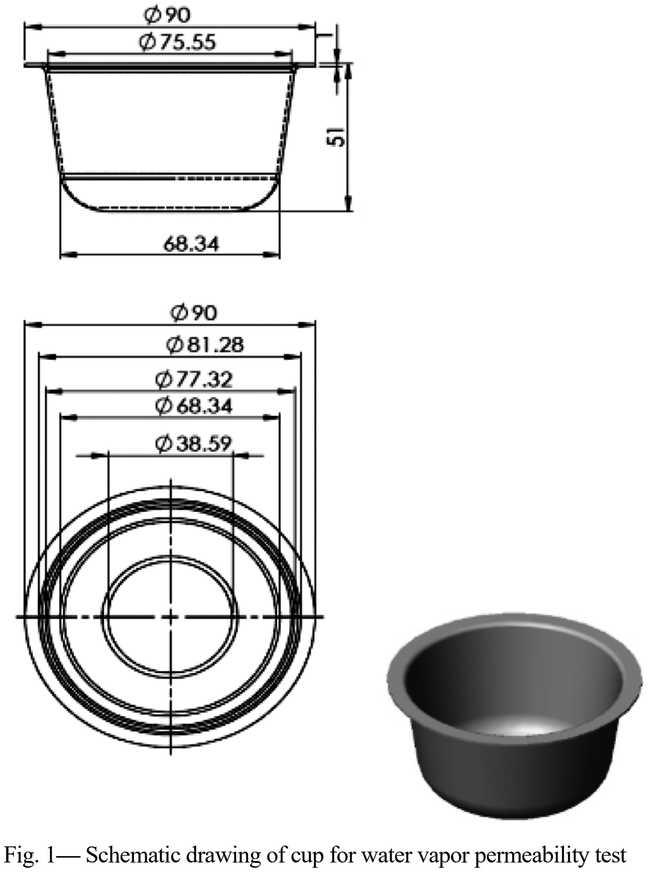

Fig. 1— Schematic drawing of cup for water vapor permeability test

2.2.3 Air Permeability

Air permeability determines the ability of airflow through the fabric. It is mostly affected by the porosity of the structure and pore characteristics. Air permeability of the all six samples of knitted fabrics was measured using profilic air permeability tester at 10 mm water pressure using ASTM 737-18 test standard. The air permeability is expressed in cc/cm^2/s, keeping the test area 5.07 cm^2 and pressure 98 Pa.[38]

3 Results and Discussion

3.1 Water Vapor Transmission Rate

The prepared samples are tested for water vapor transmission rate (WVTR) and the results are plotted in Fig. 2. The study reveals that the higher percentage of wool content in the samples exhibits high value of WVTR. The presence of more curly & scaly wool fibres in the yarn may have created longer and narrow size pores across the diameter of the yarns. This will lead to the high value of WVTR. The samples having pile structure of wool/acrylic knitted fabric also exhibit high WVTR. This is because with increase in thickness, more air is entrapped inside the fabric. This will facilitate more amount of water vapour in the fabric and give high WVTR. Hence, the pile knitted fabrics has shown the highest value of water vapour permeability followed by rib and plain knitted fabrics. So, the fabric ensemble 9 (sample number nine), which has layers of cotton fabric in the inner side, wool/acrylic (70:30) pile knitted structure in the middle layer and water proof breathable fabric in the outer layer, shows the highest WVTR. This is because of the more thickness of the all three layers assembly and more air inside the layer. The breathable fabric also have pores in the micro porous membrane. Molecules of the water vapour can pass through this membrane which increases the water vapour permeability. In addition the molecular structure of the membrane is so complex that most of the air molecules get scrambled and cannot penetrate through the membrane of the fabric.

Figure 2 (b) shows the results of WVTR of single layer polypropylene, two layers (polypropylene with cotton) and three layers (polypropylene, cotton and waterproof breathable fabric) fabric ensembles. The results show that the fabric having polypropylene yarn (24 filaments) and plane structure gives high WVTR. MLFE made by taking cotton fabric in the inner layer, polypropylene fabric (24 filament yarn and plain structure) in middle layer, and water proof breathable fabric in the outer layer, gives highest WVTR.

3.2 Air Transmission Rate

The air transmission rate (ATR) of the single, double and triple layer fabrics are shown in the Figs 3(a) and (b). Single layer wool/acrylic fabric having 70 %wool and 30% acrylic (knitted with pile structure) shows lowest ATR. The pile structure gives higher thickness and that is the reason for the decrease in air permeability. Layering this fabric with cotton fabric shows further lower value of ATR, which is due to the increase in fabric thickness and layer. Three layer fabric assembly, made with cotton fabric in inner layer, wool/acrylic fabric (70:30) in middle layer and water proof breathable fabric in out layer, shows zero air transmission rate. The breathable fabric is a multilayer structure consisting of woven fabric, EPTFE membrane and knitted fabric. This breathable fabric does not allow air to pass through it, i.e. zero air permeability. The fabric ensemble having breathable fabric, wool/acrylic fabric and cotton

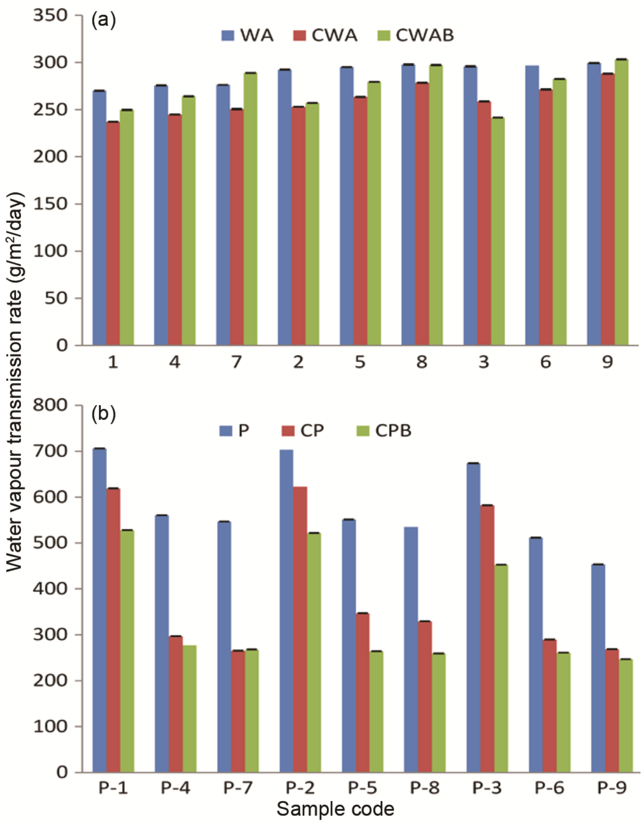

Fig. 2 — WVTR of (a) wool/acrylic and (b) polypropylene, cotton and breathable multilayered fabric ensembles

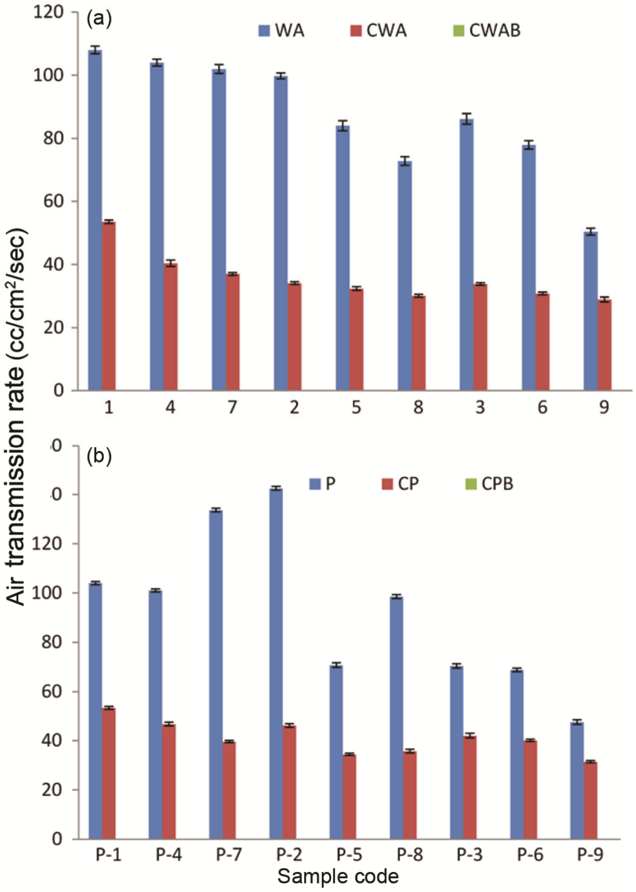

Fig. 3 — ATR of (a) wool/acrylic and (b) polypropylene, cotton and breathable multilayered fabric ensembles

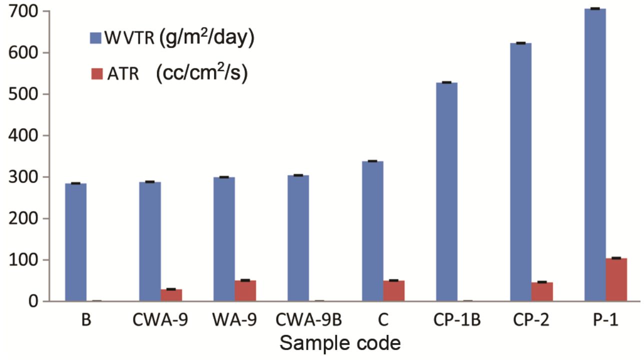

Fig. 4 — WVTR & ATR of wool/ acrylic, polypropylene, cotton and breathable multilayered fabrics

fabric, gives zero air permeability but higher MVTR than the water poof breathable fabric layer only. The more moisture vapor will be accumulated in the middle layers which will help to transfer more moisture vapor through the breathable fabric. Hence, this fabric ensemble will increase the comfort level of the wearer for protective clothing.

The results of ATR of polypropylene fabric ensemble are shown in Fig. 3(b). ATR of single layer polypropylene fabric (66 filaments in yarn and pile structure) is minimum due to pile height and deformation of pile loop. Deformation of pile takes place due to the minimum diameter of multifilament yarn. Multilayer fabric ensemble with cotton in inner later, polypropylene (66 filaments & pile knitted structure) in middle layer, water proof breathable fabric in outer layer shows zero air transmission rate.

3.3 Selecting Best Multilayer Fabric Ensemble

Looking at the requirements, we find that the maximum water vapor transmission rate and minimum air transmission rate are needed for the best multilayer fabric ensemble. This kind of MLFE can save the wearer from outer chilling air and at the same time it will allow the moisture vapor to go into the atmosphere. Scrutinizing the results obtained, we selected samples that show minimum air permeability. The findings are plotted in Fig. 4. Sample number 9 (CWAB) shows the best possible combination because its air transmission rate is zero and the WVTR is 303.96 g/m^2/24h. In case of polypropylene fabric combination, sample number 1 (CPB) gives the best results because its air permeability is zero and WVTR is 527.87 g/m^2/24h.

4 Conclusion

Present study shows the water vapor transmission rate and air transmission rate of multilayer fabric assembly having cotton knitted fabric as inner layer (next to skin), wool/ acrylic and polypropylene knitted fabric as middle layer and waterproof breathable fabric as outer layer. It has been found that wool: acrylic (70:30) and polypropylene both (pile knitted structure) fabrics show higher WVTR and lower air permeability. Layering this two layer fabric assembly with water proof breathable fabric, as outer layer, helps in minimizing the air transmission rate. The moisture and water vapor produced by the body is absorbed by the skin friendly, thin cotton fabric layer. Due to very light weight of the cotton fabric, water is easily gets converted in to water vapor by body heat. Then, this water vapor is transferred into the middle layer of the fabric assembly. High bulk of this middle layer of fabric assembly helps in transferring the water vapor into the atmosphere through the impervious outer waterproof breathable fabric layer. WVTR of the three layer fabric assembly is higher than the single layer of waterproof breathable fabric. The WVTR of the three layer fabric assembly having polypropylene layer is high as compared to that having wool/acrylic layer. Since, the fabric ensemble is designed for high altitude wear, high WVTR and zero ATR are considered as one of the important comfort characteristics. Therefore, better comfort properties is shown by three layer fabric ensemble having thin cotton fabrics (inner layer), polypropylene (having less number of filaments) fabric (middle layer) and waterproof breathable fabric (outer layer).

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