Dynamic Transportation of Water Vapor through Cotton and Polyester-Cotton Blended Fabrics

Part I: Indices Characterizing Moisture Buffering and their Interrelationships

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ABSTRACT

The water vapor transport (WVT) through a set of cotton and polyester cotton fabrics has been analyzed under dynamic conditions using the CIRCOT WVTR Apparatus. The hygrograms obtained for cotton fabrics from the experiment show three distinct phases in water vapor transport rate (WVTR) with time, in which the first slower phase may be attributed to the moisture buffering by the fabric. In addition to the parameter $T_{82.5\%}$ defined by earlier authors, five more parameters (α, β, R_{30}, R_{90} and T_b) have been defined out of which β, R_{30} and T_b may be considered to represent moisture buffering in fabrics. In the case of P-C blended fabrics, the hygrogram was strongly influenced by the cotton content in the fabric apart from the parameters mentioned earlier.

Keywords: fabric, water vapor permeability, water vapor transport, environmental buffering, moisture buffering, thermo- physiological comfort, dynamic moisture transport, WVTR.

INTRODUCTION

Water vapor transportation through a fabric is one of the most important fabric attributes that contributes to wear comfort. It is generally defined as a measure of the mass of water vapor that is transported across unit area of the fabric under specific conditions of temperature and vapor pressure gradients between the two sides of the fabric under study. Many methods have been proposed by researchers to measure Water Vapor Transport Rate (WVTR) or its variants in the literature [1] [2]. Each of these methods is based on different experimental conditions and hence cannot be compared with each other [1].

Many of the experimental methods used for characterizing WVTR through fabrics are under steady-state or static conditions [3]. WVTR results measured based on static conditions have only limited use in deducing clothing comfort due to the fact that in real wear conditions the moisture transfer processes are dynamic in nature. In fact, the reported gap between WVTR test results and clothing comfort performance may be attributed to the steady state methods of measurements of WVTR which are widely used in reported studies [3]. Consequently, dynamic moisture vapor transport through fabrics has received special attention in comfort assessment of textile fabrics [4] [5] [6].

In the year 1939 Cassie et al. [7] postulated the concept of moisture buffering in clothing and subsequently restated phenomenon to moisture sorption and desorption and exchange of heat when hygroscopic fibers are exposed to humidity transients [8]. During humidity transients, hygroscopic fibers can absorb or desorb moisture from or to the adjacent air, which can delay the moisture change in the clothing microclimate. Moisture buffering during humidity transients leads to stability of clothing microclimate and thereby helps to maintain clothing comfort. Many investigations conducted to prove significance of moisture buffering in clothing comfort did not provide any conclusive proof for its existence [9]. Works by Scheurell et al. [6] showed the importance of a fabric property named dynamic surface wetness which correlated well with wear comfort. Fabrics made of hygroscopic fibers like cotton and wool were studied to understand their influence on dynamic surface wetness. Hong et al. [5] found that minimum moisture build up over the inner surface facing the moist skin was a minimum for cotton compared to cotton polyester blend and all polyester fabrics. Wehner et al. [10] found that the duration of humidity transient heavily depended on the moisture sorption abilities of the fabrics. While a moisture flux across an inert porous fabric can reach steady state within seconds, a similar flux across wool fabrics took over an hour to reach steady state.

Available information in the literature shows that the dynamic nature of the moisture exchange between the skin and outer environment through clothing is the key to understand the role moisture plays in clothing comfort. To improve the understanding on this complex topic; a reliable method for quantification of the buffering property of the fabric is very much crucial. The present study envisages analyzing dynamic moisture transport through both cotton and polyester-cotton blends using the CIRCOT WVTR Apparatus and quantifying the moisture buffering that takes place both in cotton and cotton rich fabrics.

The CIRCOT Method [11] [12] relies on the continuously changing moisture flux in a fabric, conditioned in standard atmospheric conditions, when instantaneously brought in contact with high humidity environment on one side. These conditions are very close to typical real life situation where a fabric comes in contact with changing microclimate between the clothing and human skin. The modified form of the CIRCOT WVTR Apparatus used in the present study can digitally record changes in humidity transients across the fabric and hence can help in a detailed study of the moisture transport process including the buffering that takes place in a fabric.

MATERIALS AND METHODS

The present study consisted of two parts; first, moisture transport measurements were made on plain woven cotton fabrics prepared from varieties and hybrids possessing different fiber length and within each length category; varieties having different fineness levels. The second part of the study, intended to focus on water vapor transport through polyester-cotton blended fabrics made from yarns spun by varying blend ratios.

Selection of Raw Materials and Preparation of Fabrics

Cotton fabrics for this study were prepared from a few major cultivated varieties of cotton in India. The varieties for this study were chosen to cover three length categories viz. medium to medium-long (23-27 mm SL), long staple (27-32.5 mm SL) and extra-long staple (>32.5 mm SL). Each of these length groups had varieties that possessed different fineness (micronaire) values. The range of micronaire values of cotton under each length category was 3.2-4.9 for medium staple, 3.0-4.3 for long staple and 2.8-3.3 for extra-long staple. These cottons were spun by using ring spinning procedure into yarns belonging to three nominal counts viz. 20s Ne, 50s Ne and 80s Ne. These yarns were used to prepare plain woven fabrics.

Similarly, polyester-cotton blends were prepared by blending MCU.5 cotton (2.5% span-length: 31mm, micronaire: 3.7) variety with polyester staple fiber (38mm, 1.2 d) by following the drawframe blending procedure. Yarns having counts 20s Ne and 40s Ne were prepared by ring spinning method. Three different twist levels were applied to each count category mentioned above. Blend composition was varied and 100% cotton, 67% cotton and 33% polyester, 50% cotton and 50% polyester, 33% cotton and 67% polyester and 100% polyester blends belonging to two count category were made available for the study. For every blend ratio, both 20s and 40s count yarn were produced by using the ring spinning system. Each count of yarn produced was spun using three different twist multipliers (4.2, 4.4 and 4.6 for 20s count and 4.0, 4.3 and 4.6 for 40s count). Both cotton and P-C blended yarns were used for preparing plain weave fabrics by using an automatic sample loom and the fabrics were desized, scoured and bleached before taking up any transmission studies.

Measurements of Water Vapor Transport Rate (WVTR) of Fabrics

WVTR was measured by using both the CIRCOT Method and Dish Method [13] by following established procedures.

WVTR by CIRCOT Method

Water vapor transport through cotton fabrics was measured by using the CIRCOT WVTR Apparatus [11], [12]. The apparatus consisted of a wet-chamber (100%RH), dry-chamber (65%RH) and a separating wall with a circular opening. The specimen fabric was mounted over the circular opening of the separating wall. Shutter separating the sample from the wet-chamber can be opened by turning a knob attached to it. A digital humidity probe fitted inside the dry-chamber measured the humidity inside the chamber and transmitted to a data logger for digitally recording its change with passage of time. During the experiment, the wet chamber was brought to 100% RH by circulating moisture saturated air through it. The shutter separating mounted sample was opened so that the one side of the fabric is exposed to air saturated with moisture and data logging of the humidity inside the dry chamber was simultaneously started. Due to the existence of concentration gradient between two sides of the fabric water vapor stars diffusing towards the dry-chamber and with the result the RH in the dry chamber increased. The original paper suggested that the time taken to reach dry-chamber RH to 82.5% as the only measure to characterize the average rate of water vapor transportation through the sample.

Measurement of WVTR by Dish Method

The dish method [13] measures WVTR under static conditions. Aluminium cups having diameter 10cm and a height of 2.5cm were used for the experiment. An air gap of 10mm was maintained above the water filled in the dish and its mouth covered with the sample fabric was kept in controlled environment chamber maintained at 65%RH and 25°C temperature. The dish assembly was placed over a turn-table revolving at 5 - 6 RPM and weight of the dish assembly was taken after 1 hour. Weighing was repeated after every 2-3 hours to find the rate of vapor transport through the fabric until consistency in weight was achieved.

RESULTS AND DISCUSSION

The hygrogram obtained from the CIRCOT WVTR Apparatus is shown in *Figure 1*. Since the change in relative humidity inside the dry chamber (ΔRH) is approximately proportional to quantity of moisture transported across the fabrics [12] the RH at a given point on the curve may be assumed to represent water vapor passed through the fabric after the sample is exposed to a vapor pressure gradient. *Figure 1* shows hygrogram obtained from three cotton fabric samples, belonging to thick, medium thick and thinner categories. Relative humidity (RH) in the dry-chamber of the apparatus was 65% when the time=0. The humidity in the dry-chamber increased with time and data logging continued till the RH in the dry-chamber was slightly above 82.5% which is the average RH of both the wet-chamber (100%) and the dry-chamber (65%). It may be noted that Sreenivasan et al. [11] had suggested time taken to reach 82.5%RH ($T_{82.5\%}$) inside the dry-chamber as a measure of WVTR of the sample.

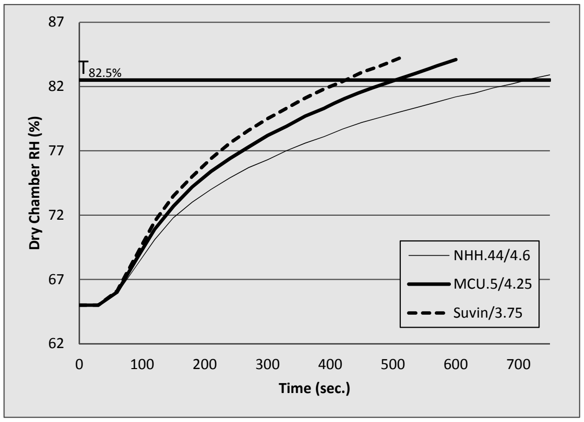

FIGURE 1. Typical Time-RH curves obtained from CIRCOT WVTR Apparatus.

A Close Look at the Hygrogram

A close look at the shape of the hygrogram obtained by using the CIRCOT WVTR Apparatus reveals three distinct phases, each having different WVTR, during the course of moisture diffusion through the fabric after it is subjected to a vapor pressure gradient. Presence of these three phases of moisture diffusion process can be more clearly observed if we plot the rate of change of RH with time $(\Delta RH/\Delta t)$ against time (see *Figure 2*). The first phase of the curve lasts up to 20-30 seconds after the shutter is opened (up to the dotted line 1). This region is characterized by relatively low rate of vapor transport. After this stage, there is a sudden increase in $(\Delta RH/\Delta t)$ and it reaches a maximum after passage of 90-100 seconds. Most of the moisture transport through the fabric happens during the third phase that starts approximately 90 sec after the fabric is exposed to high humidity and the rate of water vapor transport during this stage decreases with time. The initial slow rate of change of RH in dry-chamber could be attributed to two factors; (a) time taken by the vapor flux to reach RH-sensor (about 3mm from the fabric surface) which is constant and (b) buffering of moisture by the fabric when it is exposed to a high moisture gradient resulting in a reduction in the effective transfer of moisture to the dry-chamber. Buffering of moisture may be either due to absorption of moisture by the fiber mass or due to retention within the inter fiber space in the fabric structure.

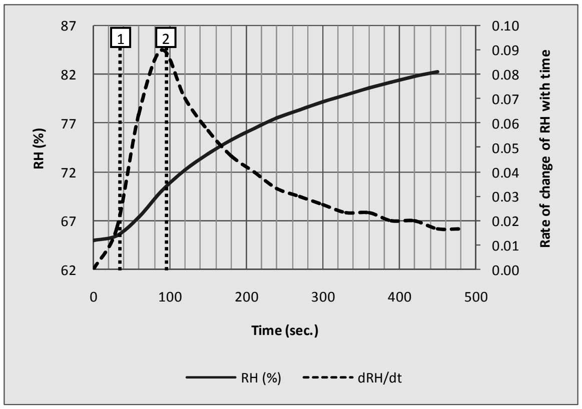

FIGURE 2. Plot showing RH variation with time and rate of change of RH with time.

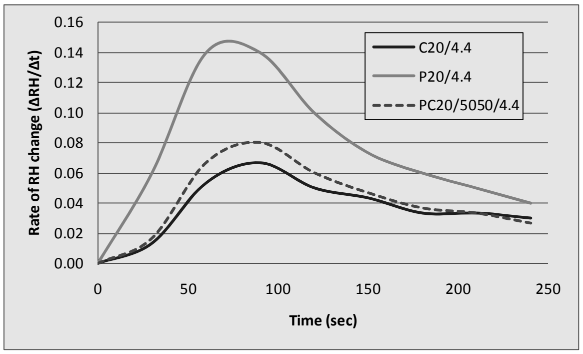

FIGURE 3. Hygrogram obtained from 100% cotton, 50:50 PC blend, and 100% polyester fabrics.

If the initial phase of the time-RH curve is indeed reflecting the buffering capability of the fabric as postulated earlier, we must see noticeable differences in the shape of time-RH curve of fabrics made from hygroscopic cotton and hydrophobic polyester fibers when tested on the CIRCOT WVTR Apparatus. To prove this point, the hygrograms were recorded for 100% cotton, polyester-cotton blend (50:50) and 100% polyester fabrics. These fabrics were similar in every respect, except blend composition (20s Ne, 4.4TM ring spun, desized, scoured and bleached). The $(\Delta RH/\Delta t)$ of the hygrograms from these fabrics (*Figure 3*) clearly show that while 100% cotton and PC blended fabric have the initial slow phase, the 100% polyester fabric does not. The slope of this initial portion of the curve is found to decrease as cotton content increased. While dry-chamber RH reached the highest for 100% polyester fabrics in shorter time, 100% cotton was the lowest and 50:50 PC blend fabrics have slope in between the remaining two samples. This proves that the initial slow WVTR phase in the hygrogram directly relates to the nature of the blend.

Transient absorption of moisture by the fabric and its contribution to moisture transport has been reported by many authors [14], [15], [16], [17]. According to reported literature the fabric retains a portion of the moisture inside the inter-fiber air spaces and within the fiber by way of both absorption and adsorption. Only after both the air space and the fibers are saturated with the moisture, the fabric can achieve its full capacity to transport moisture across. During the second phase (*Figure 3*), an increased transportation of moisture is noticed and hence RH inside the dry chamber increases rapidly (*Figure 1 and Figure 2*). Since the rate of transfer of moisture across the fabric sample depends on the vapor pressure gradient that exists on either side of the fabric barrier, the curve becomes less steep during the third stage as RH inside the dry-chamber increases.

The initial region of the time-RH curve is important because it reflects the buffering property of the fabric when the humidity/temperature changes across the fabric [9]. Environmental buffering by the clothing is an important fabric property from comfort point of view. Influence of moisture buffering by fabrics on wear comfort during temperature and humidity transients has been documented by many authors [18] [19] [20] [21] [22]. A fabric that can buffer a lot of moisture during sudden changes of temperature and humidity will be more comfortable to the wearer [23]. The transients of vapor pressure changes can be due to changes in the environmental conditions that exist outside the clothing system and also due to changes happening inside the skin-cloth microclimate that arises due to the sudden changes in activity levels of the wearer. During higher activity level situations, the skin surface becomes wet due to onset of perspiration. Evaporation of sweat leads to sudden increase of RH inside the skin-clothing microclimate. If the clothing allows easy passage of moisture, it may lead to sudden chill feeling under cold climate. This phenomenon, known as 'after chill' may be uncomfortable to the wearer. Many textile fibers exchange heat in the form of heat of sorption during absorption or desorption of moisture and this process protects the wearer of clothing from sudden change in the climatic conditions.

The second part of the time-RH curve, which is characterized by a steeply increasing RH with time, can be ascribed to the fast Fickian diffusion of moisture through pores of the fabric. During the third and final stage of time-RH curve the moisture transfer rate goes on reducing as time advances due to two possible reasons (1) reduction in vapor pressure gradient as the RH in the dry-chamber increases and (2) swelling of fibers and resulting decrease in porosity of the fabric. The second and third phases of the time-RH curve could be closely related to what is suggested by Li et al. [24] that in hygroscopic fibrous materials the mechanism of moisture diffusion during humidity transients have a two stage moisture diffusion process consisting of a fast Fickian diffusion with a concentration-dependent diffusion coefficient and a slow diffusion with a time dependent diffusion coefficient. Contrary to this, weakly hygroscopic fibers follow a single Fickian diffusion process with a constant diffusion coefficient.

The third phase of time-RH relationship contributes to most of the moisture transport in quantitative terms (80-85% of the total transport) and fits well with a logarithmic equation of the type:

$$\textit{RelativeHumidity}\ (RH) = \alpha \ln t + \beta \qquad (1)$$

where, t is time and α and β are constants. Significance of the above constants in the context of dynamics of water vapor transportation through the fabric needs a detailed analysis. In addition to these parameters the rate of RH changes that take place during the first and second phases of the time-humidity curve also need a detailed analysis.

Unlike the third phase, the Time-RH relationships during first and second phases are linear in nature and hence the slope of the time-RH curve at 30 seconds and 90 seconds after the start of the experiment (R_{30} and R_{90} respectively) may also be used for understanding the dynamic nature of the WVTR through fabrics. While R_{30} may be considered as a truly dynamic property, R_{90} comes in between dynamic and static conditions. *Table I* and *Table II* show different parameters of water vapor transport of cotton and polyester-cotton blended fabrics measured by using the CIRCOT WVTR Apparatus.

Physical Meaning of Constants α and β

The hygrogram obtained by using the CIRCOT WVTR Apparatus superimposed with the logarithmic trend-line obtained by curve-fitting humidity data corresponding to time >90 sec is shown in *Figure 4*. It may be argued that had the logarithmic relationship held true throughout the experiment, the hygrogram would have looked like the one shown by the dotted line. But the actual curve followed a different shape, primarily due to moisture buffering property of the fabric.

In a logarithmic function of the type discussed above, the constant-α decides the rate of increase of RH and, the constant-β is the limiting value of RH when time approaches zero (i.e. at RH=65%). The deviation of β from 65% is partly due to the buffering of moisture by fabric and partly due to the concentration dependent part of the Time-RH curve.

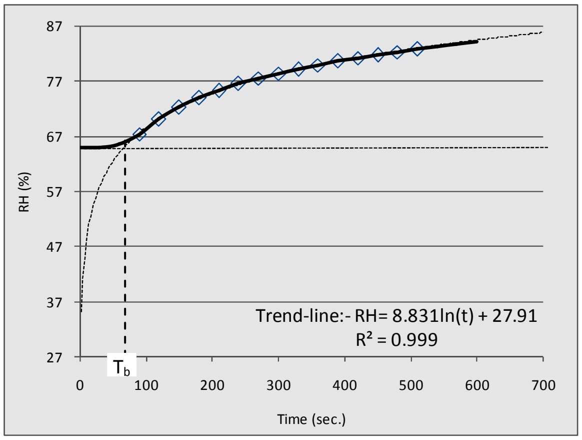

FIGURE 4. Time-RH Relationship for fabric DHH.11/4.6 superimposed with the logarithmic trend-line fitted over the data corresponding to time > 90 sec.

Definition of the Parameter: Buffering Time (T_b)

Since environmental buffering by fabrics manifests itself as delayed transport of moisture on the Time-RH hygrogram, we may define the parameter "buffering time" (T_b) as the time value corresponding to 65%RH on the logarithmic trend-line discussed earlier. It may be argued that unlike β, the parameter T_b is derived from the overall shape of the hygrogram and hence is a better measure of the physical phenomenon of environmental buffering. The value of T_b may be calculated from the logarithmic relationship derived earlier as $T_b = e^{(65-\beta)/\alpha}$.

The parameter T_b has a linear relationship with cotton content in P-C blended fabrics (R^2=0.83 and 0.96 for fabrics made from 20s and 40s count fabrics respectively). The slope of the trend-line between cotton content and T_b increases with thickness of the fabrics, and the difference between the slopes rises with increase in cotton content.

Relationship Between Parameters $T_{82.5}$%, α, β, R_{30}, R_{90} and T_b in Cotton Fabrics

The different parameters of WVTR through a fabric defined as above are obviously interdependent. However, it is apparent that $T_{82.5}$ and α provide an average value of WVTR, much closer to what we get from a static experiment like the dish method, without accounting for the dynamic nature of the process. The parameters β, R_{30}, $R_{90,}$ and T_b, on the other hand, are more related with the dynamic nature of the WVTR out which the parameters β, R_{30} and T_b are expected to represent moisture buffering by the fabric under dynamic wear conditions.

Relationships between $T_{82.5}$, α and β

As expected the parameters α and β obtained from cotton fabrics are inversely correlated (R^2=0.97). The relationship between $T_{82.5\%}$ and α is linear but negative (*Figure 5*). Thicker fabrics made from 20s count yarns have relatively lower value for α compared to fabrics made from 50s and 80s count yarn. Similarly, fabrics made from 20s count yarns are having a relatively higher β implying the greater buffering of moisture in these fabrics. Thicker fabrics made from 20s count yarns showed a relatively higher α compared to other fabrics with same $T_{82.5}$ value. This is due to the fact that in spite of having steep rise in time-RH curve during the third stage of dynamic transport, time required to reach 82.5% RH was high for these fabrics. Such a situation is possible only if there is holding of moisture by the fabric during initial stages. The parameter β is positively correlated with $T_{82.5\%}$ But deviation of thicker fabrics is even more prominent in the case of parameter β. This once again confirms the assumption that β is more sensitive to moisture buffering compared to α (see *Figure 6*).

Relationships between $T_{82.5\%}$, R_{30} and R_{90}

The parameters R_{30} and R_{90} are slopes of time-RH curves at 30 sec and 90 seconds after the shutter of CIRCOT WVTR Apparatus is opened. These two values represent slope of time RH curve during first and second phases of dynamic moisture transport process. While both R_{30} and R_{90} have shown negative linear relation with $T_{82.5\%}$, the correlation with R_{90} is better (R^2=0.79) than R_{30} (R^2=0.23). This difference is expected in that as R_{90} was more a static phenomenon compared to R_{30} which is purely dynamic in nature.

Relationships between $T_{82.5\%}$, α, β and T_b

Buffering time (T_b) has a relatively weak positive linear relationship with $T_{82.5\%}$. The relationship of T_b with α and β, on the other hand is not significant. This indicates that influence of hygroscopic nature of cotton subdues the influence of fabric structure in 100% cotton fabrics.

Relationship Between Parameters $T_{82.5}$%, α, β, R_{30}, R_{90} and T_b in P-C Blended Fabrics

The P-C blended fabrics are prepared in such a way that their blend composition successively changed from 100% cotton to 100% polyester. The major variable within these fabrics is the blend composition; where, as the hygroscopic cotton component was reduced, the hydrophobic polyester component increased.

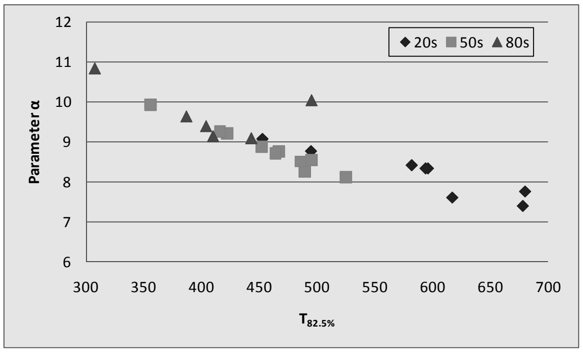

FIGURE 5. Relationship between $T_{82.5\%}$ and α

Relationships between $T_{82.5}$, α and β: In *Figure 7* the parameters α and β are plotted against $T_{82.5\%}$ for both 20s and 40s count blended fabrics. Unlike mono-component cotton fabrics, where this relationship was a linear type, in the case of blends both α and β have a curvilinear relation. While variation of α is relatively low, β is found to increase steeply as $T_{82.5\%}$ increased and gets saturated for high $T_{82.5\%}$. Similarly, variation in α, and β is plotted against variation in cotton content in the fabrics (*Figure 8*). From the plot it may be found that while variation in α is minimal, the parameter β decreases as cotton content diminishes. It may be concluded that, as expected, β is very sensitive to cotton content in the fabric.

TABLE I. Moisture transport properties of cotton fabrics measured by using CIRCOT WVTR Apparatus.

Sample Id	$T_{82.5\%}$ (Sec)	Constant α	Constant β	R_{30} (g/sec)	R_{90} (g/sec)	T_b(sec)
NNH.44/4.6	596	8.340	29.190	1.287E-06	3.861E-06	73.2
DHH.11/4.6	453	9.077	27.070	5.940E-07	4.455E-06	65.3
V.797/4.6	678	7.400	33.985	8.910E-07	5.841E-06	66.1
J.34/4.6	495	8.770	28.105	1.386E-06	4.455E-06	67.2
NHH.44/5.0	594	8.339	29.190	1.386E-06	3.960E-06	73.3
DHH.11/5.0	617	7.609	33.465	1.386E-06	3.960E-06	63.1
V.797/5.0	680	7.761	31.745	1.386E-06	4.851E-06	72.6
J.34/5.0	582	8.420	28.915	1.089E-06	4.257E-06	72.6
MCU.5/4.25	489	8.259	31.455	1.980E-06	4.950E-06	58.1
Surabhi/4.25	486	8.511	29.775	1.683E-06	5.148E-06	62.7
LK.861/4.25	356	9.932	24.190	1.683E-06	4.851E-06	60.9
Mech.1/4.25	467	8.768	28.555	1.683E-06	5.346E-06	63.9
LRA.5166/4.25	495	8.543	29.470	1.782E-06	6.138E-06	64.0
MCU.5/4.75	422	9.214	26.835	1.881E-06	4.554E-06	62.9
Surabhi/4.75	416	9.265	26.745	1.683E-06	4.752E-06	62.1
LK.861/4.75	525	8.112	31.660	1.485E-06	4.950E-06	60.9
Mech.1/ 4.75	452	8.888	28.080	1.584E-06	4.653E-06	63.7
LRA.5166 4.75	464	8.709	29.140	1.782E-06	4.950E-06	61.4
Suvin/ 3.75	410	9.140	27.585	1.980E-06	5.346E-06	60.0
DCH.32/3.75	404	9.395	26.325	1.881E-06	5.445E-06	61.3
Varalaxmi/ 3.75	308	10.845	20.490	1.683E-06	5.643E-06	60.6
Suvin/4.25	387	9.641	25.120	1.782E-06	5.049E-06	62.6
DCH.32/4.25	443	9.090	27.180	1.485E-06	7.326E-06	64.1
Varalaxmi/ 4.25	495	10.047	23.135	1.683E-06	5.148E-06	64.5

Relationships between $T_{82.5}$, R_{30} and R_{90}

The parameter R_{30} is high for 100% polyester fabrics and after cotton is added in the blend R_{30} value drops considerably. Addition of more cotton in the blend mix does not alter the R_{30} value. Significantly, parameter R_{90} on the other hand decreases nonlinearly as cotton content increased. As discussed earlier, relationships of R_{30} and R_{90} with $T_{82.5\%}$ in 100% cotton fabrics had a linear trend. It may be noted that $T_{82.5\%}$ increases (reduction in WVTR) along with increase in cotton content in the fabrics and hence this nonlinearity found in the relation between $T_{82.5\%}$ and R_{90} may be attributed to change in cotton content among the samples.

Figure 9 shows a plot indicating relationships between $T_{82.5\%}$, R_{30} and R_{90}. It is interesting to note that even though $T_{82.5\%}$ depends on count of yarn used in the fabric, both R_{30} and R_{90} are insensitive to count of yarn used (thickness) in the fabrics. It appears that R_{30} and R_{90} depend only on the blend composition of the fabrics. As seen earlier, presence of cotton, even in small quantities influences moisture buffering.

Relationships between $T_{82.5\%}$, α, β and T_b

The buffering time (T_b) has a positive linear correlation with $T_{82.5\%}$

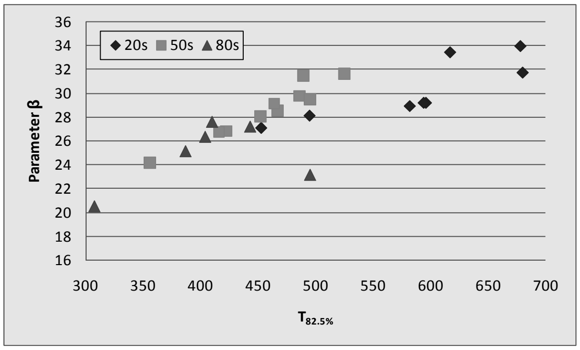

FIGURE 6. Relationship between $T_{82.5}$ and constant β.

TABLE II. Moisture transport properties of PC blended fabrics measured by using the CIRCOT WVTR Apparatus.

Sample Id	$T_{82.5\%}$ (sec)	Constant α	Constant β	R_{30} (g/sec)	R_{90} (g/sec)	T_b (sec.)
C20/4.2	681	7.650	32.130	1.188E-06	3.564E-06	73.5
C20/4.4	671	7.665	32.530	9.900E-07	4.158E-06	69.1
C20/4.6	807	7.140	34.325	1.386E-06	3.267E-06	73.4
PC20/3367/4.2	600	7.657	33.380	2.178E-06	3.465E-06	62.2
PC20/3367/4.4	614	8.007	31.110	1.188E-06	4.158E-06	68.9
PC20/3367/4.6	614	7.881	31.670	1.188E-06	3.663E-06	68.7
PC20/5050/4.2	645	7.819	31.525	1.287E-06	3.960E-06	72.3
PC20/5050/4.4	645	7.547	33.420	9.900E-07	4.554E-06	65.7
PC20/5050/4.6	519	8.251	30.985	1.485E-06	5.049E-06	61.7
PC20/6733/4.2	545	8.409	29.430	1.089E-06	4.356E-06	68.7
PC20/6733/4.4	545	8.511	28.760	9.900E-07	4.554E-06	70.7
PC20/6733/4.6	455	8.954	27.500	1.584E-06	4.950E-06	65.9
P20/4.2	227	12.310	15.770	3.465E-06	7.920E-06	54.6
P20/4.4	294	11.815	16.880	2.772E-06	6.039E-06	58.7
P20/4.6	275	11.245	19.385	2.871E-06	6.732E-06	57.8
C40/4.0	561	8.128	30.830	1.782E-06	3.960E-06	67.0
C40/4.3	500	8.445	29.930	1.782E-06	4.455E-06	63.6
C40/4.6	614	7.663	33.055	1.584E-06	4.158E-06	64.6
PC40/3367/4.0	519	8.291	30.790	1.881E-06	4.554E-06	61.9
PC40/3367/4.3	479	8.417	30.625	2.079E-06	5.445E-06	59.4
PC40/3367/4.6	455	9.998	20.950	1.881E-06	5.247E-06	81.9
PC40/5050/4.0	474	8.283	31.325	1.881E-06	5.049E-06	58.3
PC40/5050/4.3	492	8.275	31.050	1.881E-06	4.950E-06	60.5
PC40/5050/4.6	482	8.263	31.178	2.079E-06	4.950E-06	59.9
PC40/6733/4.0	261	11.590	18.330	3.168E-06	7.227E-06	56.1
PC40/6733/4.3	363	9.965	23.825	1.782E-06	5.841E-06	62.3
PC40/6733/4.6	323	9.970	24.825	2.277E-06	5.742E-06	56.2
P40/4.0	207	12.745	14.225	3.762E-06	8.118E-06	53.7
P40/4.3	272	11.340	19.025	2.673E-06	6.930E-06	57.6
P40/4.6	233	11.905	17.210	3.366E-06	7.425E-06	55.4

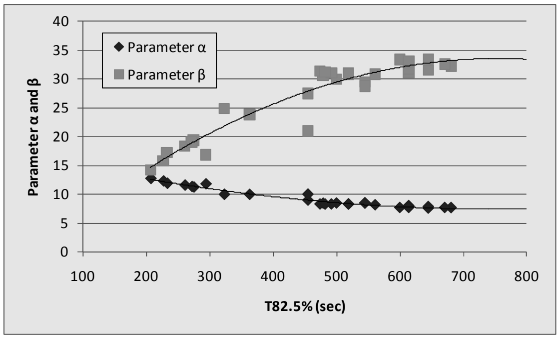

FIGURE 7. Variation of α and β with $T_{82.5\%}$ in P-C blended fabrics.

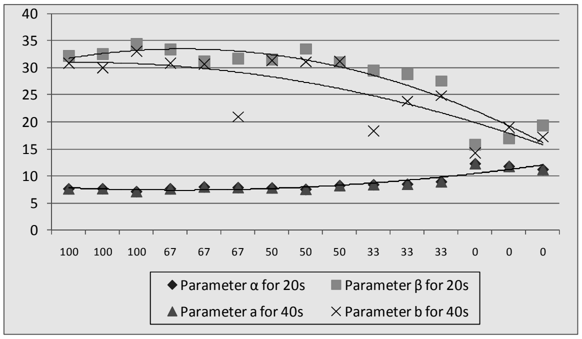

FIGURE 8. Relationship of α, β with cotton content in P-C blended fabrics.

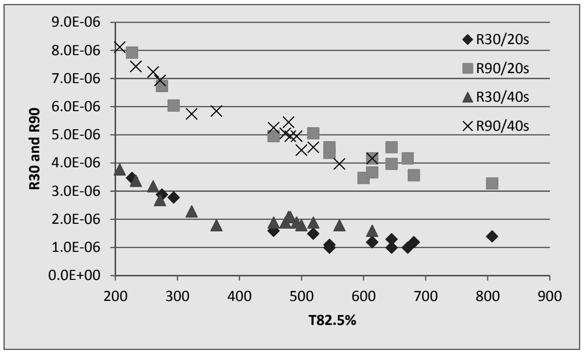

FIGURE 9. Relationship between T82.5% and R_{30} and R_{90} in P-C blend fabrics.

(R^2=0.77) unlike the curvilinear relation shown by β with $T_{82.5\%}$. While the relationship of T_b with both α and β are linear and positive (R^2=0.67and 0.61), R_{30} and R_{90} showed a negative linear correlation (R^2=0.74 and 0.71).

Comparison of Results from CIRCOT WVTR Apparatus with Dish Method

Dish Method is an industry standard and accepted and used worldwide for evaluation of WVTR through fabrics. Dish Method quantifies the rate of water vapor transport ($WVTR_{dish}$) through the sample under equilibrium conditions of temperature and humidity. Measurement of WVTR using CIRCOT WVTR Apparatus, on the other hand, is relatively dynamic and expected to provide an insight into the transient behavior of a fabric exposed to vapor pressure gradients across its two faces.

Comparison in the Case of Cotton Fabrics

Relationships between different measures of WVTR have been compared in the case of cotton fabrics.

a) *Comparison $MVTR_{dish}$ with $T_{82.5\%}$*: Water vapor transportation measured using the Dish method ($WVTR_{dish}$) of cotton fabrics is compared with $T_{82.5\%}$ value obtained from the CIRCOT method. As expected, these two measurements are well correlated (R^2=0.84) with each other. The two measurements are found to be related by the regression equation:

$$WVTR_{dish} = \frac{T_{82.5\%} - 3136}{1.49} g/m^2.24hr \tag{2}$$

b) *Comparison with α*: Parameter α and corresponding WVTR from dish method are found to be linearly related (R^2=0.82) and equation of the straight line fitted over the data is:

$$\alpha = 0.014 \times WVTR_{dish} - 16.49 \tag{3}$$

We can get WVTR equivalent to dish method by rearranging the above equation as:

$$WVTR_{dish} = \frac{\alpha + 16.49}{0.014} \tag{4}$$

c) *Comparison with β*: The parameter β has a negative linear correlation (R^2=0.76) with WVTR by dish method which is slightly poorer compared to the other two constants.

We can calculate WVTR equivalent of dish method from the regression equation as:

$$WVTR_{dish} = \frac{\beta - 114.8}{0.048} \tag{5}$$

d) *Comparison with R_{30} and R_{90}*: Both R_{30} and R_{90} have poorer correlation values with WVTR by dish method. It is understandable that R_{30}, that represents water vapor transport rate 30 seconds after the fabric came in contact with saturated air of wet chamber, does not follow the same trend as dish method which is a steady state method. R_{90} on the other hand shows reasonably good correlation (R^2=0.55).

Comparison in the case of P-C blended fabrics: Unlike cotton fabrics the relationship between $WVTR_{dish}$ and $T_{82.5\%}$ depends on the blend composition of the fabric. None of the regression equations developed for cotton fabrics relating Dish Method and CIRCOT Method can be applied to blended fabrics with varying blend compositions. Further, comparison of fabrics that differ in their material properties, using dish method as being currently done, will lead to incorrect and misleading conclusions. The CIRCOT Method, on the other hand, is more sensitive to dynamic environmental conditions and fabrics response to such changes during real-wear conditions. This method is also sensitive to changes in material composition of fabrics.

CONCLUSIONS

The present study leads to the following significant observations:

a) Dynamic moisture transport through cotton and polyester-cotton blended fabric has been explored by digital data logging of RH variation using the CIRCOT WVTR Apparatus.
b) The shape of the hygrogram obtained reveals three distinct phases, each having different WVTR, viz. a low slope initial phase, a steep Fickian second phase and a time depended non—Fickian third phase, during the course of

moisture diffusion through the fabric after it is subjected to a vapor pressure gradient.

c) Hygrograms obtained for 100% cotton, 50:50 P-C blend and 100% polyester show that while 100% cotton and PC blend fabric have the initial slow phase, the 100% polyester fabric does not have such a phase.

d) The slope of initial portion of the curve is found to decrease as cotton content increased. This portion represents the ability of a fabric to buffer moisture during humidity transients and hence very important from clothing comfort standpoint.

e) The third phase of time-RH relationships, which contributes to most of the moisture transport in quantitative terms, fits well with a logarithmic function of the type: $RelativeHumidity\ (RH) = \alpha \log t + \beta$, where, t is time and α and β are constants.

f) While the constant α determines the rate of increase in RH, the constant β is the limiting value of RH when time approaches zero (i.e. at RH=65%). The deviation of β from 65% is partly due to the buffering of moisture by the fabric and partly due to the concentration dependent part of the Time-RH curve. Additional parameters R_{30} and R_{90}, i.e. slopes of hygrogram at time=30 sec and time=90 sec respectively, are also defined.

g) Parameters $T_{82.5\%}$ and α represent the overall variation of RH with time. The parameters β, R_{30} and R_{90} specifically represent dynamic aspects of WVTR. The parameter 'buffering time' (T_b), which represents time delay in moisture transport due to buffering of moisture by the fabric, is a better and direct measure of environmental buffering. While the relationships between $T_{82.5\%}$, α, β, R_{30} and R_{90} are linear in mono-component cotton fabrics, in P-C blends these relationships are nonlinear and depend strongly on cotton content in the fabric.

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