Constant Power Drying Rate Tester: Measurement of Water Evaporation from Textiles with Heat

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Abstract: Water evaporation from textiles is important for wear comfort, especially for sportswear, casual wear and underwear. Constant Power Drying Rate Tester (CPDRT) offers fast (< 30 minutes) and versatile measurement of drying rate of fabrics. The operating temperature and water supply rate of CPDRT are adjustable to simulate required skin temperature and sweat rate, respectively. Change in weight of the fabric is continuously measured on a heated plate. This allows real-time observation of the entire drying process when fabric is placed on a heated plate supplied with constant power. This provides comprehensive information which is useful for fabric development. A set of 28 fabrics was tested by CPDRT. The temperature of bare sample stage is 37°C and water delivery rate is set at 10 ml/hr. The key parameter, drying rate (DRCP), ranges from 0.32 to 1.69 ml/hr. Statistical tests are conducted to verify the validity and repeatability of CPDRT.

Keywords: Drying, Evaporation, Fabric, Textile, Comfort

Introduction

Drying rate of fabric determines evaporation of sweat from skin surface and it impacts thermal-wet comfort directly. Evaporation of sweat can effectively cool human body [1,2], and a garment with good drying properties can help the user keep cool and dry [3,4]. Drying rate of fabric is actually related to absorption, spreading and evaporation of sweat. Therefore, high quality sportswear should offer good absorption, spreading and evaporation of sweat or water. This can maintain comfort feeling of the wearer [5-7] and prevent undesirable post-exercise evaporative cooling [8-10]. Although a variety of quick drying fabrics are put on offer every day, much of investigations has been focused on absorption and spreading properties of these fabrics (summarized by [11,12]). However, less attention has been paid to water evaporation from fabric. This implies the need to develop an efficient and simple fabric drying instrument.

Constant Power Drying Rate Tester (CPDRT) ensures that same thermal power per unit area is input to all specimens, at a constant rate, so the power output is irrespective of sample’s material, structure, geometry etc. This is fair for comparing drying rate of fabrics from the material perspective. This kind of testing for material comparison has apparently not been reported in extant literature. Against this research background, the newly developed CPDRT is introduced. It heats up fabric with constant power applied to dry fabric. The whole drying process can be monitored continuously in terms of weight change of fabric and this provides full information throughout the whole drying measurement. Furthermore, water absorption and spreading phenomena of fabrics are observed from its wetted area.

During fabric drying experiments, some researchers have applied air flow [13-16] to demonstrate various environmental conditions and body movements. However, the air speed has large variation in actual use. In order to offer simple and easy comparison to fabrics, zero wind speed at sample surface is applied in CPDRT. Since there is possibility of accumulating moist air in the enclosed chamber, a negative pressure ventilation system is deployed to keep air temperature and humidity constant. The ventilation system is able to exchange air between inside and outside of wind shield of CPDRT, with no wind (speed < 0.1 m/s) passing through or along the specimen’s surface that may affect drying of the fabric sample. Turbulence can be suppressed by introducing negative air pressure gradient [17]. Therefore, moisture evaporates from fabric is exhausted to outside of the wind shield steadily.

In the literature, quantity of water applied for evaporation measurement is commonly determined by fabric weight [18-21] or absorption capacity [14-16,22-25]. Different amounts of water can be applied to the fabric for measuring the drying rate for varying weight or absorption properties of fabrics. For example, a small amount of water should be applied to low absorption capacity fabrics. There can also be large variations in applied water amount due to the material density (unit: g/cm³; Also known as specific gravity: e.g.: cotton: 1.54, nylon: 1.14) [26]. CPDRT proposes to apply equal volume of water onto samples, and thus the textiles can be compared equally. A syringe pump is employed to deliver water to the back side of samples. The rate of water supply is adjustable to demonstrate different sweat rates based on end-uses. It suggests that CPDRT can provide valuable information during the early stage of product development and is capable of comparing fabrics made of different fibres, finishes and structures in terms of drying rate.

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Experimental

Setup of Tester
Figure 1 is schematic setup of CPDRT. The measuring system was covered by a wind shield and putted on a base platform. Inside of the wind shield, the weight of sample, sample stage and water supply system was monitored by an electronic balance (Shimadzu, UW4200H; resolution 0.01 g, repeatability ≤ 0.01 g). On the other hand, the heater did not have direct contact with electronic balance. The heater transferred heat to the sample holder by radiation and convection. This non-contact setup has solved previous research problem that the weight of a heated fabric is hard to measure accurately. Experimental details of CPDRT are described in next paragraph.

The syringe pump (SK Medical, SK-500I, accuracy±3 %) is equipped with a replaceable battery, so it does not need to connect with a socket with power cable. The battery can withstand two-day operation when it is fully charged. Instead, it was a stand-alone operation and contacted with the electronic balance and pipe directly. The syringe was connected with a silicon pipe and extended with a stainless steel pipe. The inner diameter of both pipes was 1.25 mm. The stainless steel pipe was then embedded and fixed at the centre of the sample stage, a printed circuit board (PCB). The top opening of stainless steel pipe was at the same level as the PCB. The syringe pump delivered water to the back side of the sample; the measured weight by the electronic balance did not change until water was evaporated from testing fabric sample. An unpatterned PCB was selected as the sample stage because it is thermal conductive and stiff. In addition, the contact angle of water-PCB was measured as 89°, by using a contact angle goniometer (ramé-hart, model-200). This is close to the value of water-unwashed skin interface [27,28].

Heater mat at 20×20 cm² was supported by a wooden board. The wooden board stood on the base platform and physically isolated from other parts of CPDRT. A circular hole at 5 mm diameter was drilled through the centre of the wooden board. This allowed the stainless steel pipe to pass through the wooden board for supplying water to the centre back of the sample. Finally, a fan was located at the top of the CPDRT to maintain steady air flow with negative pressure ventilation. Wetted area of fabric was captured by a camera from the top of CPDRT. This provides additional absorption and spreading information of sample. The correlation of the water transport properties against the drying rate of fabrics is investigated in Results and Discussion.

System Parameters of the Tester
The test of CPDRT was performed in standard condition room where ambient temperature and relative humidity were maintained at 20±1 °C and 65±5 %, respectively. The standard condition was widely employed in previous studies [6,14,18-22,24]. Since CPDRT was kept inside the condition room, the conditioned air outside of the wind shield can be regarded as a constant reservoir. Simultaneously, the ventilation system helps to maintain air condition of the CPDRT inside. Air speed through the fan is 2.7 ms⁻¹ (measured by Digitron, AF210 anemometer). This exchanges air between inside and outside of wind shield. Air speed at sample surface was found as below 0.1 ms⁻¹. Therefore, while negative pressure was introduced to remove evaporated moisture out of CPDRT, the slow and steady air flow did not make wind chilling to the fabrics or the sample stage.

The bare sample stage temperature (PCB temperature without placing sample on it) was set at 37 °C. This was set with reference to [29-34] and refers to the skin temperature when undertaking strenuous exercises. Another reason for selecting the upper limit of skin temperature in the current investigation is that the testing time can be as short as possible. In order to achieve selected bare sample stage temperature (37 °C), the required input power of the heater was found to be 11.3 W (applied voltage 6.5 V, current 1.74 A). The calibration procedures of sample stage temperature can be found in “Calibration and Uncertainty”.

The syringe pump was set at 10 ml/hr simulating the sweating rate during a high level of work, for example, high speed running [35]. The pump rate is adjustable to fit the aim of project or market requirements. A literature search was conducted against sweat rate in [35]. The amount of water delivered is 0.2 ml, the same as the previous investigation (3 layers of materials; 0.6 ml of water [35]).

Specimens
28 knitted and woven fabric samples with different fibre contents (Table 1) were measured by CPDRT. The size of fabrics was 12×12 cm². Before test, fabrics were ironed gently to get flat. Afterward, fabrics were conditioned for at least 12 hours in a standard atmosphere (20±1 °C and 65±5 % relative humidity). Water absorbency of fabrics was tested.
Detailed description of the test method was as follows: 0.2 ml of distilled water was applied to the back side of fabric. Auto-pipette (Finnpipette F2, 20-200 µl) was used to deliver water in 3±0.3 sec, by tilting it to nearly horizontal and putting its tip near the fabric surface, so water pressure was not applied to fabric by injection of water. Other procedures followed were in accordance with AATCC Test Method 79-2014 [36]. Results are listed as absorbency time (second), as shown in Table 1.

### Operation of CPDRT

Table 2 shows operating procedures of CPDRT. Steps 1 to 5 correspond to start-up of the system. The start-up takes less
than 30 minutes to stabilize CPDRT, which is reasonably fast as compared with other heat related equipment (e.g. water vapour resistance and thermal resistance). Steps 6 to 12 indicate general measuring procedure of CPDRT. These steps take 15 to 25 minutes in one test.

Measurement Parameters

Figure 2 presents a typical drying curve of CPDRT measurement. It is a plot of weight change of fabric versus time. It gives drying rate (DR<sub>CP</sub>) as key measurement of CPDRT. According to Step 10 (Table 2), the weight loss measurement of fabric was terminated when measured weight loss (WL<sub>CP</sub>) was larger than weight of applied water. However, the measurements were continued until there was no change in fabric weight. This aims at acquiring the most information.

Figure 2 shows the drying curve of a woven cotton fabric. It shows that measured weight change was -0.22 g, so that the weight loss (WL<sub>CP</sub>) of that woven fabric was 0.22 g. The discrepancy between water loss and water applied was induced by its moisture regain. It was a part of moisture regain, since fabric’s temperature was not raised to boiling point of water. In order to facilitate data analysis and comparison of fabric drying properties, data in linear region of drying curve were used for calculation. Therefore, only data of WL<sub>CP</sub> between 0.05 g to 0.15 g were selected to calculate DR<sub>CP</sub>. DR<sub>CP</sub> was defined as:

\[
\text{Drying rate, DR}_{CP} = (-1) \times \text{Slope of drying curve (0.05 g \leq WL}_{CP} \leq 0.15 g) \tag{1}
\]

by using linear regression, the slope can be found. The example in Figure 2 shows DR<sub>CP</sub> of the woven cotton fabric was 1.39 m<sup>3</sup>/hr., Density of water is assumed as 1 g/cm<sup>3</sup> for the ease of calculation (density of water at 20°C was 0.9982 g/cm<sup>3</sup> [37]). R<sup>2</sup> value of the linear fitting was 0.99, so the relationship between WL<sub>CP</sub> and time was linear at the selected region (0.05 g \leq WL}_{CP} \leq 0.15 g). This implies that the fabric dried at constant rate at the specified region. The effect of moisture regain to the drying experiment is further discussed in “Evaporation of Moisture from Fabric”.

Areas of water spot on fabric at (i) syringe pump just off (A<sub>CP0</sub>) and (ii) 60 seconds after syringe pump stopped (A<sub>CP60</sub>) are additionally recorded by CPDRT. These two parameters were obtained from photos of water spot from the fabric’s face side (Figure 3; step 9 of Table 2) at the corresponding time, and then pixel-counting. It is generally
believed that fabric will dry faster if water is spread wider on it. Therefore, wetted area is expected to be positively correlated with drying rate of fabric. When the syringe pump was switched off, water absorption and spreading were still ongoing. In order to obtain more stable and reliable picture, $A_{CP60}$ was considered instead of $A_{CP0}$. $A_{CP60}$ was regarded as stable reading for water-absorbing fabrics, and it was assumed to be the maximum area throughout each experiment. $A_{CP60}$ indicates water absorption and spreading features at fabric-PCB interface, where the PCB has water contact angle similar to unwashed skin surface (“Setup of Tester”).

Conventional Test – Water Evaporating Rate (WER)
Remaining Water Ratio (RWR) [38] and Water Evaporating Rate (WER) [18-21] are the most common parameters for evaluating drying rate of textile. The sum of WER and RWR equals 100 %. In order to measure WER, the fabric sample was placed in standard atmospheric conditions (temperature: $20\pm1 ^\circ C$ and relative humidity: $65\pm5$ %) and the amount of water applied to the fabric was equal to 30 % of the dry sample weight. Then, the weight of the wetted sample was measured regularly for an hour. WER is widely known as:

$$\text{WER} (%) = \left(\frac{\text{water evaporated}}{\text{water applied}}\right) \times 100 \% \quad (2)$$

In WER experiment, an auto-pipette was used to apply water onto a plastic card while the card was put on an electronic balance. Sample fabric was put on the water droplet, so centre back of the sample was in touch with the droplet. Then the sample was dried naturally in standard conditions. In the entire measurement, draft shields of balance at both sides were not closed. Air velocity near sample surface was measured by anemometer (Digitron, AF210). It was less than 0.1 ms$^{-1}$, occasionally hitting 0.15 ms$^{-1}$. The weight change of sample was recorded, so that the WER at 30th and 60th minute can be calculated by equation (2).

Results and Discussion

**DR$_{CP}$ of Fabric**

Figure 4 shows CPDRT result of the 28 fabric samples. The drying rate (DR$_{CP}$) ranges from 0.32 to 1.69 m/hr. This indicates that CPDRT is able to discriminate the drying rate between fabrics. Error bars on the plot indicate one standard deviation (SD) of the drying rate. Regarding DR$_{CP}$, coefficients of variation (CV) of most fabrics are below 3 %, indicating that the variation or dispersion of DR$_{CP}$ is low. In other words, measurement of DR$_{CP}$ is repeatable. The CVs of some fabrics are higher than 3 %, including “PET1”, “PET2”, “PET3” and “NYL”. High CVs are caused by slow water absorption and these cases are discussed in Limitations of CPDRT.

**Evaporation of Moisture from Fabric**

This section presents different drying curves measured by CPDRT. Four typical fabrics are selected for discussion,
WC1, WC3, K02 and P3M. The evaporated moisture is composed of water supplied from syringe pump and moisture regain from the fabric. Four typical drying curves are shown in Figures 5 to 8. These figures show raw data taken from the electronic balance during CPDRT measurements.

Plain weave cotton fabrics, WC1 and WC3, have different yarn count and fabric density (Table 1). Therefore, they have similar drying curves (Figures 5 and 6). The major difference between WC1 and WC3 is (i) slope; and (ii) water loss (WL_CP) at the end of the drying curves. The slope of WC1 is steeper than WC3 because WC1 is thinner and lighter and therefore it dries faster than WC3. The difference in final WL_CP is contributed by moisture regain. This is not exactly equivalent to moisture regain because fabric was not heated beyond 100°C. So the term intrinsic moisture content (IMC) is used to represent the partial evaporation of moisture instead of moisture regain. The black signs in Figures 5 and 6 represent CPDRT drying curves of WC1 and WC3 respectively, without applying water. These “without applying water” trials indicate IMC evaporates from the fabric during CPDRT measurement. It should be noticed that the contribution of IMC to the drop of measured weight from balance appears only at the beginning of measurement. Therefore, when calculating drying rate (DR_CP) of the sample, consider water loss (WL_P) from 0.05 g to 0.15 g can also help to reduce the effect of moisture regain from DR_CP.

When CPDRT measurement is near the end, fabric’s wetted area decreases and the rate of change of WL_CP also decreases. While all applied water evaporated from fabric, weight change measured by balance becomes constant.

As compared with WC1 and WC3, 95 % rayon and 5 % spandex knit fabric K02 has a larger weight loss in “without applying water” trial, which is around 0.09 g as represented by black signs of Figure 7. This is because the moisture carried on rayon (13.0 % at 21°C and 65 % RH) is larger than cotton (7 to 11 %) [39], and K02 is heavier than WC1 and WC3. Because of the large IMC of K02, WL_CP from 0.09 g to 0.19 g is used to predict DR_CP. The criteria to decide or modify WL_CP range for calculating DR_CP is the appearance of linear region, so that it is easy to compare and analyse against fabrics. The length of linear region of all tested fabrics in terms of weight change is longer than 0.10

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**Figure 5.** Weight change of woven cotton fabric WC1 against time.

**Figure 6.** Weight change of woven cotton fabric WC3 against time.

**Figure 7.** Weight change of knit rayon fabric K02 against time.

**Figure 8.** Weight change of woven polyester fabric P3M against time.
grams, therefore the range selected to calculate DR$_{CP}$ is representative.

Finally, drying curve of 96% polyester, 4% spandex (sport dry fit, 3M) woven fabric P3M (Figure 8) is different from the above discussed cases as evaporation rate of moisture is zero in the first 2 minutes of experiment. This is because the moisture regain of polyester is relatively low, only 0.4 to 0.8% (at 21°C and 65% relative humidity) [39]. In other words, IMC contributed almost zero to weight loss (WL$_{CP}$). No change in weight during “without apply water” trial also indicates CPDRT drying curves of P3M are independent of moisture regain. Also, all other synthetic samples present the same phenomena at the “without apply water” trial as P3M. Until temperature of applied water is raised and water spread through fabric, WL$_{CP}$ of sample increases obviously to achieve large DR$_{CP}$.

In fact, many other features can be found in a drying curve. These include “time to dry”, “turning points”, “length of linear region” etc. These provide much information to provide high flexibility for researchers and product developers to study drying phenomena of fabric comprehensively.

**Repeatability of CPDRT Result**

As shown in Figure 4, coefficient of variation of DR$_{CP}$ is smaller than 3% in most fabrics. This proves that DR$_{CP}$ has good repeatability. Figures 5 to 8 show raw data of all repetitions taken from electronic balance of WC1, WC3, K02 and P3M during CPDRT measurement. These measurements repeat well in each trial, and they overlap with each other. This verifies that CPDRT offers good repeatable results.

**Validity of DR$_{CP}$**

Pairwise comparison is further performed to check if there are significant differences between DR$_{CP}$ values of “WC” fabrics. These fabrics have different yarn count and fabric density, but same material. Therefore, they are suitable to be used for evaluating validity of DR$_{CP}$. The result (Table 3) suggests that three-fourths of the “WC” fabrics have significant difference in terms of DR$_{CP}$ (I-J) at 0.05 significance level which is relatively high. Figure 4 also shows that the differences between drying rates of the 28 tested fabrics are significant.

**Comparing CPDRT Result and Fabric Basic Properties**

Pearson correlation coefficient between DR$_{CP}$, thickness and fabric weight of WC1 to WC8 is shown in Table 4. It is found that DR$_{CP}$ has significant correlation with fabric weight (p=0.004<0.050) and thickness (p=0.038<0.050). Moreover, it suggests that thicker and heavier fabrics have slower drying rates (DR$_{CP}$). This observation matches the common understanding about drying fabric.

In addition to Table 4, Figures 9 and 10 show the correlation between all CPDRT drying rate (DR$_{CP}$) and fabric thickness and fabric weight. The points in these two plots are scattered and the R$^2$ values of linear regression of the plots are around 0.2. Apart from fabric weight and thickness, drying rate of fabrics is dependent on fibre content, type of finishing and

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**Table 3.** Pairwise comparison (Bonferroni) of DR$_{CP}$ of WC1 to WC8. Significance between samples is put at top-right section. Mean difference (I-J) of DR$_{CP}$ between samples is located at bottom-left section

<table>
<thead>
<tr>
<th></th>
<th>WC1</th>
<th>WC2</th>
<th>WC3</th>
<th>WC4</th>
<th>WC5</th>
<th>WC6</th>
<th>WC7</th>
<th>WC8</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC1</td>
<td>-</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
</tr>
<tr>
<td>WC2</td>
<td>.236*</td>
<td>-</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
<td>.000</td>
</tr>
<tr>
<td>WC3</td>
<td>.436*</td>
<td>.200*</td>
<td>-</td>
<td>.184</td>
<td>.037</td>
<td>1.000</td>
<td>.485</td>
<td>.000</td>
</tr>
<tr>
<td>WC4</td>
<td>.388*</td>
<td>.152*</td>
<td>-.048</td>
<td>-</td>
<td>.000</td>
<td>.002</td>
<td>.001</td>
<td>.000</td>
</tr>
<tr>
<td>WC5</td>
<td>.494*</td>
<td>.258*</td>
<td>.059*</td>
<td>.107*</td>
<td>-</td>
<td>1.000</td>
<td>1.000</td>
<td>.066</td>
</tr>
<tr>
<td>WC6</td>
<td>.468*</td>
<td>.232*</td>
<td>.032</td>
<td>.080*</td>
<td>-.027</td>
<td>-</td>
<td>1.000</td>
<td>.002</td>
</tr>
<tr>
<td>WC7</td>
<td>.477*</td>
<td>.241*</td>
<td>.041</td>
<td>.089*</td>
<td>-.017</td>
<td>.009</td>
<td>-</td>
<td>.018</td>
</tr>
<tr>
<td>WC8</td>
<td>.557*</td>
<td>.321*</td>
<td>.121*</td>
<td>.169*</td>
<td>.062</td>
<td>.089*</td>
<td>.080*</td>
<td>-</td>
</tr>
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</table>

*The mean difference is significant at the 0.05 level.

**Table 4.** Pearson correlation coefficient of DR$_{CP}$ against thickness, fabric weight, WER 30th minutes and WER 60th minutes of WC1 to WC8

<table>
<thead>
<tr>
<th></th>
<th>DR$_{CP}$</th>
<th>Thickness</th>
<th>Fabric weight</th>
<th>WER 30th min</th>
<th>WER 60th min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson correlation</td>
<td>1</td>
<td>-0.734*</td>
<td>-0.881**</td>
<td>-0.962**</td>
<td>-0.843**</td>
</tr>
<tr>
<td>Sig. (2-tailed)</td>
<td>0.038</td>
<td>0.004</td>
<td>0.000</td>
<td>0.009</td>
<td>-</td>
</tr>
<tr>
<td>Number of sample</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

**Correlation is significant at the 0.01 level (2-tailed) and *Correlation is significant at the 0.05 level (2-tailed).**
construction. For example, synthetic materials commonly dry faster than natural fibre.

Figure 11 shows \( \text{DR}_{CP} \) versus wetted area of fabric recorded at pump off \( (A_{CP0}) \) and 60 seconds after \( (A_{CP60}) \). It shows that \( \text{DR}_{CP} \) correlates much better with \( A_{CP60} (R^2=0.6) \) than with \( A_{CP0} (R^2=0.47) \). This is because the wetted area was still increasing when syringe pump was just switched off. Therefore, \( A_{CP60} \) is better than \( A_{CP0} \) to represent maximum wetted area of fabric that contributed to the evaporation process. The result shown in Figure 11 indicates that fabric with larger wetted area has larger drying rate. This is consistent with general understanding in the textile field.

In summary, this section suggests that drying of fabrics is a complicated phenomenon. A single factor, such as fabric weight or thickness cannot be used to predict drying property of fabrics. Instead, many factors interact with each other and so a drying instrument like CPDRT is needed.

Correlation between CPDRT Result and Conventional Test

In order to compare CPDRT with conventional drying tests, Water Evaporating Rate (WER), the results of conventional drying test, are plotted against \( \text{DR}_{CP} \) in Figure 12. It shows that these two parameters are positively correlated. This finding is rational because both \( \text{DR}_{CP} \) and WER represent the rate at which the fabric dries. WER at 30th minutes and 60th minutes correlates moderately well with \( \text{DR}_{CP} \) with \( R^2 \) value equal to 0.65 and 0.71 respectively. Finally, several fabrics completely dried before WER test end, i.e. WER became 100 % at 60th minute. Drying rate of such completely dried fabrics cannot be distinguished by WER, so this is a disadvantage of WER test.

Pearson correlation coefficient between \( \text{DR}_{CP} \) and WERs of WC1 to WC8 is shown in Table 4. Since material of the eight samples are the same, \( \text{DR}_{CP} \) has very high correlation with WER 30th minutes \( (p=0.000<0.050) \). As compared to...
WER 30th minutes, DR$_{CP}$ correlates with WER 60th minutes at a lower level ($p=0.009<0.050$). This is because WC1 and WC2 are completely dry at 60th minutes of WER test. The high correlation between DR$_{CP}$ and conventional WER is because of simple structured cotton fabrics are compared. The correlation reduces when other parameters are considered (Figure 12), such as fibre content and fabric structure.

Calibration and Uncertainty

In CPDRT, electronic balance, syringe pump, air speed and bare sample stage temperature should be calibrated. Shimadzu UW4200H electronic balance is internally calibrated by a built-in calibration weight. Internal timer of software LabVIEW is used as the system time of CPDRT. Therefore, the timing of CPDRT is based on computer’s clock. This is a common practice in research laboratories and the uncertainty is assumed to be negligible. Water delivered by syringe pump is verified by checking weight of water delivered to fabric. An anemometer is used to ensure the air speed at specimen surface is smaller than 0.1 m s$^{-1}$. The calibration of temperature of sample stage was conducted by attaching a thin film Pt100 platinum resistance thermometer (accuracy: ±0.35 °C with data logger) at the centre of the sample stage. The input power was tuned to maintain temperature of sample stage at 37±0.5°C. Table 5 summarizes the calibration and uncertainty related to CPDRT.

According to equation (1), the measurement of DR$_{CP}$ depends on WL$_{CP}$ and time. Uncertainty of DR$_{CP}$ (i.e. δDR$_{CP}$) can be found by:

$$\delta DR_{CP}/DR_{CP}=(\delta WL_{CP}/WL_{CP}) + (\delta time/time) \quad (3)$$

error of computer’s clock was assumed to be negligible. Therefore

$$\delta DR_{CP}/DR_{CP}=(\delta WL_{CP}/WL_{CP}) + 0 \quad (4)$$

and given that the electronic balance has uncertainty of 0.01 g, 0.10 g is the range selected for calculating DR$_{CP}$.

$$\delta DR_{CP}/DR_{CP}=(0.01 g/0.10 g) \quad (5)$$

so that δDR$_{CP}$ is at 10 % of DR$_{CP}$.

Table 5. Calibration and uncertainty of CPDRT

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Parameter</th>
<th>Calibration</th>
<th>Uncertainty (given by manufacturer)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic balance</td>
<td>Weight change on fabric</td>
<td>Execute the built-in calibration function</td>
<td>±0.01 g</td>
</tr>
<tr>
<td>Syringe pump</td>
<td>Water delivered</td>
<td>Confirm the weight of water delivered</td>
<td>±3 %</td>
</tr>
<tr>
<td>Timer</td>
<td>Time</td>
<td>Use internal timer of software LabVIEW to facilitate regular data acquisition from electronic balance</td>
<td>Assumed to be negligible</td>
</tr>
<tr>
<td>-</td>
<td>Air speed at specimen surface</td>
<td>Confirm air speed is smaller than 0.1 m s$^{-1}$ by using an anemometer</td>
<td>±0.1 m s$^{-1}$</td>
</tr>
<tr>
<td>-</td>
<td>Temperature of bare sample stage</td>
<td>Use a Pt100 temperature detector</td>
<td>±0.35 °C</td>
</tr>
</tbody>
</table>

Limitations of CPDRT

As shown in Figure 4, some samples demonstrate large CV in drying rate DR$_{CP}$ (e.g. PET1, PET2, PET3 and NYL). These samples are slow water absorbing samples (absorbing time larger than 60 seconds by modified AATCC 79 standard test, Table 1). But the prerequisite is that a sample should have absorbed water before it is dried. So measuring slow absorbing or non-absorbing samples is out of the scope of fabric’s drying rate. Besides, only the face side of fabrics is considered while measuring the maximum wetted area. However, wetted area is optional measurement parameter and does not affect accuracy of DR$_{CP}$.

Conclusion

CPDRT is capable of measuring the weight change of fabrics throughout the experiment. This is accomplished by equipping with non-contact heating component, so comprehensive information can be obtained. The power input to the sample stage is set at constant level. Therefore, this setup compares drying rate of fabrics from the material perspective. For the ease of comparison, zero air speed is applied to specimen. Moreover, the whole CPDRT setup is enclosed with wind shield to prevent unwanted or uncontrolled disturbances. The wind shield is equipped with ventilation fan to maintain negative air pressure gradient. This is an important design to steadily remove moist air within the chamber, and to maintain air condition within the setup.

The testing time of each sample is around 15 to 25 minutes. The validity of CPDRT is confirmed by comparing fabrics with different yarn counts and densities. Drying rate (DR$_{CP}$) is the key parameter obtained from CPDRT, which measures evaporation rate of moisture from fabric on a heated sample stage. DR$_{CP}$ results of 28 fabrics are found to be repeatable. DR$_{CP}$ ranges from 0.32 to 1.69 m/hr. Wetted area of fabric at syringe pump just stops (A$_{CP0}$) and at 60 seconds after syringe pump stopped (A$_{CP60}$) are additionally measured. The DR$_{CP}$ has moderate correlation with conventional method and A$_{CP60}$. This indicates DR$_{CP}$ is reasonable, and CPDRT has a uniqueness to evaluate drying rate with constant power applied to materials under real time conditions.
Comparing with existing drying rate measurements, the strengths of CPDRT include (i) short testing time to provide quick solution for drying rate of fabric. This can help product developer to catch rapid market changes; (ii) adjustable system parameters to demonstrate required testing condition i.e. skin temperature and sweat rate. The testing protocol of CPDRT is user-friendly and can be changed easily to fit different fabrics end uses; (iii) absorption and spreading properties of sample on skin-like surface are easily to fit different fabrics end uses; (iv) absorption and spreading properties of sample on skin-like surface are available. These properties affect drying rate of textiles. Researcher and manufacturer can obtain full water transport information (evaporation, absorption and spreading) of textiles by using CPDRT.

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