Measurement of In-plane Capillary Water Flow of Fabrics by Thermocouples

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Abstract: - A new wicking test for measuring the in-plane capillary water flow in fabrics was developed, and three different types of woven fabrics were examined. The method is based on the temperature changes, when fabric absorbs water, the temperature will be decreased. The equipment is composed of the thermocouple array, measurement equipment and PC. The thermocouple array was set on the foam polystyrene, with the space of each measurement point of 1cm. Due to the wicking of water, the temperature changes of appointed distance of fabric can be measured as function of time. Plain woven fabric samples with different cotton and polyester blending ratios were examined. Compared with the result measured by the Byreck method, it confirmed the feasibility of developed temperature measurement. The device is suitable for measurement of in-plane capillary water flow automatically by recording the temperature change.

Key-Words: - Wicking; In-plane capillary; Water flow; Thermocouple; Measurement; Fabric

1 Introduction

Liquid transport in textiles is relevant for a number of applications, such as sports wears, industrial uniforms, dyeing, finishing and filtration. In general, wicking takes place when a liquid travels along the surface of the fiber but is not absorbed into the fiber. Physically, wicking is the spontaneous flow of a liquid in a porous substrate, driven by capillary forces. The type of flow in any porous medium, caused by capillary action, is governed by the properties of the liquid, liquid-medium surface interactions, and geometric configurations of the pore structure in the medium\cite{1,2}.

There are many test methods for wicking test \cite{3}. The longitudinal wicking is to measure the height of rise of water in a fabric strip, which can be taken as a direct indication of the wickability of fabric. The transverse wicking plate test is to record the position of the meniscus along the capillary tube at various time intervals to calculate the mass transfer rate of water into the fabric. The areal wicking spot test is to measure the elapsed time of reflection before it disappeared by a drop of liquid delivered onto a horizontal specimen of fabric. The syphon test is to weigh the collecting beaker to determine the amount of liquid transferred at successive time intervals.

The traditional test method for liquid flow is Byreck method, which is visual investigation decided by the height of dyes. There are some disadvantages of Byreck method, for example, the influence of the dyes on the liquid absorption of fabric, the variances of water front of different observers, the effect of gravity. Considerable effort has been channeled into the development of meaningful test methods to determine the absorptive properties of the fabrics. The methods developed generally fall into two broad categories, i.e. absorption and wicking \cite{4}. The previous measurements of wicking were mostly based on the visual observations of dye-water penetration \cite{5}, electrical capacitance techniques \cite{6}, the mass of liquid retained in the sample \cite{7}, and electrical resistance technique \cite{8}. Yoneda\cite{9} developed the dew sensor array for water flow measurement of thin fabric, by monitoring the relative humidity of the microclimate around the sensor point. However, the relative humidity of microclimate would be affected by adjacent space when fabric sample absorbed a lot amount of water, or in low humidity. Wicking of liquid into fabrics is a very complicated problem with big significance and is much dependent on fabric porosity. It is important to investigate on the relationship between wicking and fabric porosity.

In this paper, based on the Seebeck effect, the thermocouple has been fabricated and used for measurement of in-plane capillary water flow of
fabrics automatically by measuring temperature of fabric with the sensor array.

2 Basic Theory

According to the Washburn equation [10], capillary penetration rate depends on the rheological properties of the liquid such as surface tension, viscosity, density, fiber wetting characteristics, and geometry of the capillary spaces, as shown in Fig.1.

Fig.1. Capillary water flow in cylindrical capillary

The horizontal wicking distance of water is given by

\[ L^2 = \left( \frac{r\gamma \cos \theta}{2\eta} \right) t \]  

(1)

Where \( L \) is the liquid advancing distant, \( \gamma \) is the liquid vapor surface tension, \( \theta \) is the contact angle of solid liquid system, \( \eta \) is the viscosity of liquid, \( t \) is time, and \( r \) is the equivalent radius of capillary spaces. This equation has been widely applied by many researchers to evaluate the wicking behavior in fibrous assemblies [11].

If the horizontal wicking length, which is already measured, is plotted vs. the square root of wicking time, the slope of this plot \( \frac{dL}{dt^{0.5}} \) is defined as the wicking rate \( W_c \):

\[ W_c = \frac{dL}{d\sqrt{t}} \]  

(2)

\( W_c \) can be calculated directly from experimental data.

3 Experimental Method

3.1 Description of Test Equipment and Method

The measurement device is shown in Fig.2. The 9 points of temperature sensor, which can be seemed as sensor array, have been set on the foam polystyrene for heat insulation, and the distance between the adjacent measurement points is 10mm. The water level of fluid reservoir is always keeps the same, for a slight hole is drilled in the reservoir.

The originating end of the fabric strip was clipped by tension of 5.0gf/cm to keep the fabric end immersed in the fluid and keep the fabric strip contact with the sensor array. It is important that the tension be no larger than needed since it could affect the size of fabric and therefore the wicking performance. The other end of the fabric is fixed to keep it taut throughout the whole experiment.

Experiment was conducted on fabric strips of 3cm width and about 25cm length. The fabric strip was carefully cut with long axes parallel to weft. The fabric strip sample is shown in Fig.3. The originating end is 5cm, and then the next 9cm was lined in each centimeter.

![Testing equipment](image)

The T-type thermocouple has been used, with copper and constantan as materials for the temperature measurement. The circles in Fig.2 represent the measurement points of thermocouple. As hygroscopicity fabric, the temperature of the fabric rises slightly once because of heat generation by absorbing water. Afterwards, because of evaporation which brings heat from fabric, the temperature of fabric at the measurement point will decrease straightly. In this experiment, temperature changes of the 9 points occur in turn. In order to analyze, the time when it reaches to the peak value of temperature is seemed as the absorbing starting time. One of the temperature change of the fabric by the influence of the water as a sample is shown in Fig.4. The temperature decreasing time marked with circle in Fig.4 can be seemed as the moment for the liquid flow to the appointed point. In this experiment, the time \( t \) is calculated by:

\[ t = t_{n+1} - t_n \]  

(3)

Where, \( t_{n+1} \) is the time at the distance of n+1, \( t_n \) is the time at the distance of n.
Fig. 4. Sample of the temperature change of fabric caused by wicking. Moreover, in order to contrast, the horizontal Byreck method was used to verify the developed temperature measurement device.

### 3.2 Test Samples

Three different kinds of woven fabrics were used in this experiment, with the specification shown in Table 1.

Experiment was conducted in the constant temperature and relative humidity of 20°C, 65% RH. Samples were washed with soap for 35 min. Each type of fabric was cut to 5 pieces at five different places for test strip in the warp and weft directions, and the average of the 5 strips was calculated to be the result.

Table 1. Specification of fabric samples

<table>
<thead>
<tr>
<th>Property</th>
<th>C</th>
<th>C/P-1</th>
<th>C/P-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yarn content</td>
<td>100% Cotton</td>
<td>35% Cotton</td>
<td>65% Polyester</td>
</tr>
<tr>
<td>Yarn count (tex)</td>
<td>28</td>
<td>12.5</td>
<td>13.5</td>
</tr>
<tr>
<td>Weave density (cm⁻¹)</td>
<td>27</td>
<td>56</td>
<td>56</td>
</tr>
<tr>
<td>Area Weight (g cm⁻²)</td>
<td>153.52</td>
<td>114.60</td>
<td>111.02</td>
</tr>
<tr>
<td>Fabric Thickness (mm)</td>
<td>0.745</td>
<td>0.442</td>
<td>0.569</td>
</tr>
<tr>
<td>Porosity</td>
<td>86.62</td>
<td>82.53</td>
<td>86.41</td>
</tr>
<tr>
<td>Weave</td>
<td>Plain</td>
<td>Plain</td>
<td>Plain</td>
</tr>
</tbody>
</table>

### 4 Result and Discussion

#### 4.1 Verifying of Temperature Measurement

For contrast, the horizontal Byreck had been used to measure the time of liquid flow. The one example of the results is shown in Fig. 5.

![Fig. 5. Contrast between two results measured by thermocouple and Byreck](image)

From Fig. 5, the result measured by thermocouple is almost as the same as the result measured by the horizontal Byreck. Even though there is a little difference between the two results, it can be seemed as error during the experiment.

#### 4.2 Wicking Performance of Different Types of Fabrics

The wicking performance of three fabrics in warp direction and the weft direction are shown in Fig. 6 and Fig. 7 respectively.

![Fig. 6. The relationship between L and l² in warp direction](image)
Fig. 7. The relationship between $L$ and $t^{0.5}$ in weft direction.

From the slopes of Fig. 6 and Fig. 7, the wicking rate of the three fabrics in two different directions can be received, listed in Table 2.

<table>
<thead>
<tr>
<th>Fabric</th>
<th>C</th>
<th>C/P-1</th>
<th>C/P-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp</td>
<td>0.3099</td>
<td>0.4618</td>
<td>0.5915</td>
</tr>
<tr>
<td>Weft</td>
<td>0.2463</td>
<td>0.3202</td>
<td>0.5618</td>
</tr>
</tbody>
</table>

During the three fabric samples, wicking rate of cotton is the lowest, whenever in warp or weft directions. The fabric woven with cotton/polyester blending fiber as 35/65 has the highest wicking rate. This may be caused by the bending ratio and the count of fibers which affected the different porosity.

As the same fabric, the wicking rate in warp direction is higher than in the weft direction; this is mainly because of the different weave density, which causes different porosity.

4.2 Application on the wicking rate

The horizontal wicking rate of fabric can be applied for liquid flow estimation on fabric.

As the cotton fabric shown in Table 1, in the warp direction, the function of liquid advancing distant as the square root of time elapsed is $L=0.3099t^{0.5}-0.7008$.

From this formula, the square root of time elapsed can be calculated in a confirmed distance. For example, if $L$ is 1.5cm, then $t$ can be calculated to be about 50s; if $L$ is 3cm, $t$ is about 143s. It takes 93s for liquid flow from 1.5cm to 3cm on fabric.

Fig. 8. Temperature changes around dropped point for cotton fabric

In this experiment, the thermocouple cotton fabric as introduced in other paper [12], was investigated at 20°C, 65%RH, with a drop of liquid (0.5ml) dropped on the cotton fabric, and at the same time, recorded the temperature of every point. As a hygroscopic fiber, the contact angle between cotton fabric and the liquid is small, so it can be ignored. Meanwhile, the point which is 1.5cm away from the dropped point can be seemed as the basic point, shown in Fig. 8 of $L=0$. By recording and calculating the past time, it can get the data for liquid flow from $L=1.5$cm to $L=3$cm, and the time is 90s, which is almost the same as the calculated data by the in-plane capillary liquid flow. It demonstrated that the results of in-plane capillary measured by thermocouple can be used for liquid flow estimation of fabric.

5 Conclusion

The developed temperature measurement-thermocouple array can be used for in-plane capillary measurement of water flow on fabric automatically. Different from the Byreck method, the develop method can be used without dyes, and it can get objective results. Moreover, it can be used not only for thin fabrics, but also for thick fabrics, by setting two rows of sensor array on and under the fabric sample. It makes the device flexible by setting measurement points of sensors to investigate on the liquid flow of two or more layers of fabrics.

The distance $L$ and the square root time $t^{0.5}$ is linear, and the slope can be applied to evaluate the wicking rate of fabric. The result of wicking rate of cotton and cotton-polyester blend fabric showed that cotton-polyester (35/65) had the highest wicking rate; however, cotton is the lowest. This is mainly because of the different types of fibers and the porosity. The wicking rate in warp and weft direction is different from each other. It can be presumed that yarn is the unit of liquid flow in fabric.

The result of dropped test verified that the function of distance $L$ and the square root time $t^{0.5}$ of cotton fabric can be applied to estimate the liquid flow of fabric.

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References:


