DEVELOPMENT OF ADVANCED INSTRUMENTATION FOR EVALUATING DRYING AND STICKINESS OF TEXTILE MATERIALS

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Development of Advanced Instrumentation for Evaluating Drying and Stickiness of Textile Materials

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CERTIFICATE OF ORIGINALITY

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Abstract

Constant Power Drying Rate Tester (CPDRT) offers fast (< 30 minutes) and versatile measurement for fabrics. The operating temperature and water supply rate of CPDRT are adjustable to simulate required skin temperature and sweat rate, respectively. The feature that weight change of the fabric is continuously measured on a heated plate is new. It allows real-time observation of the entire drying process when fabric is placed on 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 platform was kept at 37 °C while water delivery rate was set at 10 ml/hr. The key parameter, drying rate (DR_{CP}), ranges from 0.32 to 1.69 ml/hr. Statistical test are conducted to verify the validity and repeatability of CPDRT.

A prototype of Constant Temperature Drying Rate Tester (CTDRT) was built to evaluate the drying rate of fabrics. The sample platform controlled at constant temperature, was placed onto the balance. Its temperature is adjustable to simulate different skin temperature. The heater was placed underneath the sample platform but it did not have any contact with the sample platform. This novel non-contact heating system demonstrated real-time measurement of water evaporation in the sample throughout the whole experiment. In addition to drying rate, comprehensive information can be obtained from CTDRT, ranging from absorption, spreading and other fabric drying features. In addition, negative pressure gradient system of CTDRT helps to maintain constant atmospheric condition at negligible wind speed, so enhancing stability and sensitivity of measurement. The drying rate (DR_{CT}), a key

parameter of CTDRT, of 28 fabrics investigated are found to range from 0.36 to 2.56 ml/hr at skin temperature of 37 °C. This range offers a high resolution to differentiate drying properties of fabrics. Validity and repeatability of CTDRT are also confirmed with statistical proofs. The testing duration for CTDRT ranges from 15 to 40 minutes, which is similar to other drying methods where heat is applied, but is much faster than the conventional non-heating methods.

In comparing the drying rate testers, CTDRT is able to eliminate the contribution of moisture regain of fabric during measurement. However, CPDRT captures evaporation of moisture regain in drying curve. Without the effect of moisture regain, CTDRT gives better observation on water absorption and spreading properties of fabric than CPDRT. Based on comparing coefficient of variation of DR_{CT} and DR_{CP}, DR_{CT} has better repeatability than DR_{CP}.

A subjective wet sensation assessment was conducted. 20 subjects participated in the assessment. They were presented with fabrics at different drying time. The fabrics at different drying time simulated garments dry during recovery period. The recovery period refers to the garment being dried after conducted light activities. A 2-arm fabrics driver was built to simulate human's daily movements. The driver is synchronized to drive specimen and reference fabrics on both forearms of the subjects. The 2-arm configuration can help to enhance reliability of assessment result. Since a garment should "dries fast" and "offers dry sensation" to offer the best wet comfort to wearer, a wetness factor (WF) is developed to include these two factors. WF is the area under curve of wetness rating against drying time of fabric. The smaller WF indicates that a user suffers less from wet sensation. WF ranges from 6190 to 9510 among seven tested fabrics.

Fabric Drag Force Measurement System (FDFMS) was built to study the interaction between fabrics and a wetted simulated skin. It is equipped with a novel free-end dragging type sample holder. The sample holder facilitated intimate contact between fabric and simulated skin, and external pressure is not required to apply on fabric during measurement. This simulates natural elongation of fabric on skin in actual wear condition. FDFMS acquires drag force curve to show a full profile of "drag force against water applied to fabric". Therefore, FDFMS is a convenient tool to measure drag force at various water levels in a single trial. Static drag force (F_S) from the curve simulates the force required for a wetted fabric started to be dragged along human skin. A large F_S implies strong adhesion between fabric and skin. The F_S and adhesion deform skin and muscle to evoke stickiness sensation. The peak drag force (F_P) from the drag force curve is another parameter to compare stickiness between fabrics. The larger F_P implies the stronger stickiness feel can be evoked by a fabric. 28 fabrics were tested by FDFMS. The F_S ranges from 0.29 N to 2.37 N for simulated skin wetness at 6 mg/cm^2. Four of the 28 fabrics have no F_P. The F_P of remaining 24 fabrics is found to be between 0.51 N and 1.98 N. Validity and repeatability of FDFMS are also confirmed. A subjective stickiness sensation assessment is conducted. Its result, stickiness rating, represents the real stickiness sense against wetted fabrics. FDFMS results are correlated with stickiness rating. A multiple linear regression is conducted to predict stickiness rating by FDFMS's results. The R^2 value of linear regression is 0.79, so that FDFMS is able to predict stickiness sensation. It is found that stickiness and water absorption properties of fabric are closely related.

In considering the drying and stickiness properties by the developed instruments, result of CTDRT and FDFMS may be used. In applying DR_{CT} of CTDRT and a stickiness rating predicted by FDFMS, the fabric with the best drying and stickiness performance can be identified. A polyester fabric with mesh structure is found to have the best drying and stickiness performance among knitted fabrics in this study.

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List of Abbreviations and Symbols

Abbreviation/ Symbol	**Full Form**	**Unit**
AATCC	American Association of Textile Chemists and Colorists	/
ANOVA	Analysis of variance	/
A_{CP0}	Area of water spot on fabric at syringe pump just stop (CPDRT)	cm^2
A_{CP60}	Area of water spot on fabric at 60 seconds after syringe pump stopped (CPDRT)	cm^2
A_{CT60}	Area of water spot on fabric at 60 seconds after water applied (CTDRT)	cm^2
CPDRT	Constant Power Drying Rate Tester	/
CTDRT	Constant Temperature Drying Rate Tester	/
CV	Coefficient of Variation	%
ΔW	Weight change measured by balance (CTDRT)	gram
DR_{CP}	Drying rate of CPDRT	ml/hr
DR_{CT}	Drying rate of CTDRT	ml/hr
FDFMS	Fabric Drag Force Measurement System	/
F_P	Peak drag force (FDFMS)	Newton
F_S	Static drag force (FDFMS)	Newton
IMC	Intrinsic Moisture Content	/
MIU	Average of the coefficient of friction (KESFB4-AUTO-A)	/
PET	Polyethylene terephthalate	/
PID	Proportional-Integral-Derivative	/
RH	Relative Humidity	%
SD	Standard Deviation	/
SMD	Mean deviation of fabric surface roughness (KESFB4-AUTO-A)	μm
WER	Water Evaporating Rate under conventional drying test	%
WF	Wetness factor (dimension: wetness x time), in subjective wetness sensation assessment	/
WL_{CP}	Weight loss of fabric (water) (CPDRT)	gram
W_P	Amount of water supplied to fabric at F_P (FDFMS)	mg/cm^2

Chapter 1 Introduction

1.1 Background and Scope

The continuous search for comfortable apparel has attracted increasing amount of research in the textile and clothing industry worldwide since people are comfort-conscious nowadays and the expectation on clothing comfort is rising. Thermal-wet comfort is one of the most important factors dominating wear comfort. More specifically, the water absorption, transport properties and evaporation of fabrics are key contributors to thermal-wet comfort. Human sweats when exercising or staying in extreme environment. Five water transport phenomena occur within the fabric when body sweats: (i) absorption of sweat from skin to fabric, (ii) spreading of sweat along the plane of fabric, (iii) spreading of sweat across the plane of the fabric, and finally (iv) evaporation of sweat from the fabric. Plus additional but common phenomenon (v) stickiness (adhesion) at the skin-textile interface. Stickiness is due to sweat accumulated at skin-textile interface. The absorption and transport of sweat affects immediate response to the wearer whilst evaporation and stickiness can cause severe discomfort feeling in long-term. Each absorption and transport phenomenon has specific implication on clothing comfort. Therefore, it is important to find effective evaluation methods for studying specific water transport behaviour.

For the five water transport phenomena, it can be understood as a feedback cycle (Figure 1.1). The quantity of sweat produced varies with internal/external stimulation (i.e. activity level, the thermal and moisture transport abilities of the garment and the ambient environmental conditions). If sweat cannot be dissipated quickly, the humidity in the space between the skin and the fabric rises. This increases humidity in the microclimate close to the body. The poor moisture transport limits the evaporation of moisture from perspiration on skin producing a hot and sweaty sensation. The body then responds with increases sweating to attempt to dissipate the excess thermal energy. As we can see, the effectiveness of sweat transport will lead to the difference in evaporation rate and so varying the sweating rate. For example, when people are exercising at light activity level, like jogging, slight amount of sweat may be secreted. In this case, if a high quality sportswear with good sweat transport properties is worn, sweat rate can be maintained at low level (Casa, 1999a). Conversely, if clothing with poor sweat transport property is worn, the sweat evaporation rate is low and body cannot cool down through sweat evaporation effectively. Eventually, much sweat will be secreted due to hyperthermia (Casa, 1999a; Arens and Zhang, 2006). In addition, quick drying clothing able to prevent undesirable post-exercise evaporative cooling or chill sensation (Gavin, 2003; Splendore et al., 2011; Kim and Na, 2016; Neves et al., 2017). Sweat undergoes evaporation from wetted garment, the attractive force at the wet skin-fabric interface is higher than the dry skin-fabric interface (Kenins, 1994; Adams et al., 2007; Gerhardt et al., 2008; Derler and Gerhardt, 2012). The extra amount of attractive force experienced from the wet interface is named as stickiness. Stickiness, human’s daily activities plus surface tension of water induce drag force, at the skin-textile interface is often associated with a clingy or clammy sensation. This is considered by researchers to be a major source of fabric-evoked discomfort (Wang et al., 2012). Besides, friction on skin is a critical factor for skin injuries like irritations, abrasions and blisters (Derler et al., 2007; Derler and Gerhardt, 2012; Falloon, 2014; Jayawardana et al., 2017). Therefore, this cycle of sweating, absorbing, spreading, adhering and evaporating is an important study area of clothing comfort.

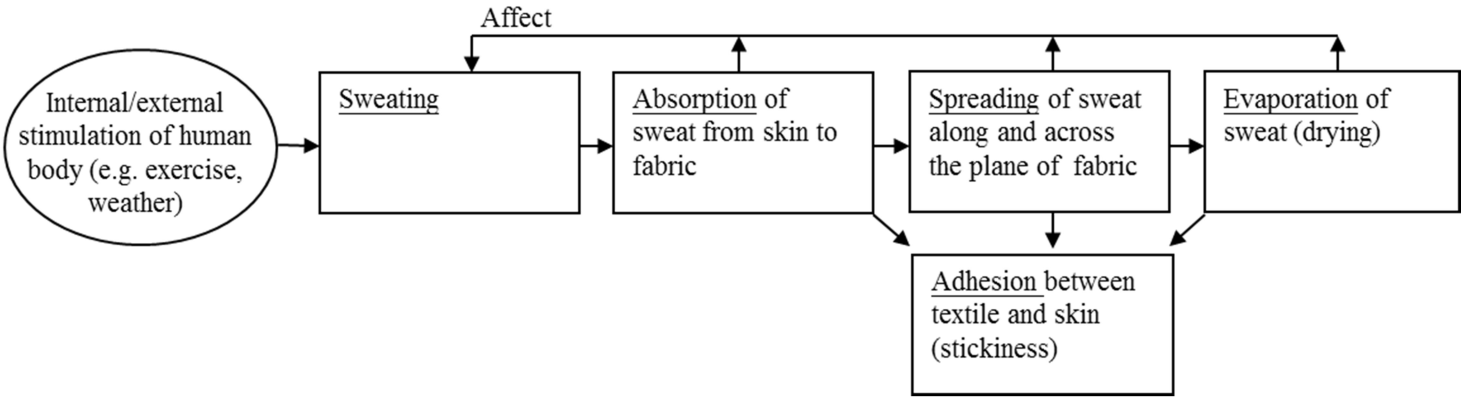


Figure 1.1 Interaction between external environment, human body and fabric/garment.

For the measurement of absorption property of fabric, it is relatively simple and this research area has been investigated extensively. From the simplest wettability/absorbency tests (BS 4554 (British Standards Institution, 1970b) and AATCC 79 (American Association of Textile Chemists and Colorists, 2014a)), contact angle measurement for slow water absorbing fabric, to gravimetric absorbency testing system (GATS) (McConnell, 1982). As water absorption properties of fabric have been well studied (Tang et al., 2014; Tang et al., 2017), this study is not intended to have further investigation on water absorption.

The spreading of sweat within fabric is generally termed as water transport of fabric in the literature. Many literatures (British Standards Institution, 1970a; Hu et al., 2005; Sarkar et al., 2007; American Association of Textile Chemists and Colorists, 2011a; American Association of Textile Chemists and Colorists, 2011b) have attempted to characterise the in-plane and transplanar direction of fabrics. However, there are several limitations for the conventional methods and none of them can effectively differentiate the direction of water transport. In order to facilitate investigation of transplanar and in-plane water transport properties of fabrics, two comprehensive water transport testers based on gravimetric and image analysis technique were developed by our research team. While one of the testers was equipped with force flow water supply (Tang et al., 2015a), and spontaneous water uptake technique (Tang et al., 2015d) was applied on another tester. Since absorbing and spreading of sweat on fabric were well studied, and the absorbing and spreading phenomena had already included in the process of evaporation and stickiness tests. Therefore, this study focused on evaporating of sweat and stickiness phenomenon to achieve a comprehensive study of sweat transport throughout fabric.

In the study of evaporation of sweat from fabrics, several standard testing methods are available and some of them were recently developed by American Association of Textile Chemists and Colorists (AATCC). Section 2.1 summaries the principle, advantages and limitations of these standard methods. Those new AATCC drying test methods were introduced with air flow or heating on fabric samples, so the testing time may be shortened as compared with the traditional drying test methods. However, AATCC standards only give "time to dry" of fabrics, the information throughout drying processes was not provided. Among previous researches and current standards listed in Section 2.1, it is difficult to find out an informative measuring method that can simulate actual use of garment. Method with ventilation of moist air, with stable and steady sample chamber environment was not found in previous works. This study is going solve above mentioned issues, and to develop accurate, reliable and effective experimental methods for sweat/water evaporation/drying measurement.

While sweat is secreted, absorption, transport and evaporation are in progress, stickiness can be induced. The previous researches on fabric's stickiness (frictional properties) were mainly on dry fabric with metal or plastic. The level of stickiness depends on amount of sweat secreted, movement of wearer and fabric's properties. The focuses of the stickiness study are amount of sweat secreted and fabric's properties. In the experiment, the amount of sweat is represented by the water applied to fabric. The discussion on fabric is mainly about water absorption properties. The contact material against fabric is selected as simulated skin, instead of metal and plastic. This study is going to develop accurate, reliable and effective experimental method for stickiness measurement.

1.2 Research Objectives

For drying rate (evaporation of sweat) test method, AATCC 199 has lack of ventilation during drying process. AATCC 200 and AATCC 201 can only provide overall drying rate, i.e. time spent to completely dry the fabric, all information during experiment was absent. Therefore, there is demand to develop drying rate test method which provides comprehensive information throughout the entire drying process. The first objective of present project is:

(i) To develop measurement method(s) which can accurately characterise the drying property of fabric

There were some studies on friction between fabric and skin, however, they were focused on frictional properties at dry state. While sweat accumulates at the skin-fabric interface, the frictional force increases dramatically as compare with dry state, the phenomenon of extra friction at wet is called stickiness. As there were seldom studies on stickiness measurement, therefore the second objective of this study is:

(ii) To develop measurement method(s) which can accurately characterise the stickiness of fabric on skin

Clothing comfort is a psychological judgment about the garments being worn under the prevailing environmental conditions. Comfort property cannot be described comprehensively by the physical parameters measured in the objective evaluation methods. So, there is insatiable desire on efficient subjective assessment method and the last objective of the present study is:

(iii) To develop a subjective evaluation method for assessing wetness and stickiness sensation of fabrics

1.3 Originality, Significance and Value

Sweat evaporation and stickiness properties are two of the most important factors dominating wear comfort. These properties are fundamental for sportswear, intimate apparel, uniform, workwear and hygiene products. Five water transport phenomena occurs after sweating. As discusses in Figure 1, fabrics with poor water transport trigger much sweating and so severe discomfort sensation. Sweating rate depends not only on activity level and outside environmental condition, but also on the type of garment worn. The first three water transport phenomena and stickiness contribute to immediate response of the garment. On the other hand, evaporation rate of sweat from the fabric and stickiness at skin fabric interface gives information regarding wear comfort for a longer term. When the garment is worn for several hours, the importance of evaporation and stickiness are dominant. Hence, it is worth studying these two sweat transport phenomena in instrumental and subjective sensation aspects.

For newly developed drying rate testers, novel setups are introduced to dry fabric on a heated plate and continuously measures weight change of the fabric. So these setups can monitor the whole process of drying. This offers informative drying curves for fabric developments and researches. First of the setups applied constant power to fabric, the result drying rate depends only on its materials and structure; The second setup maintains constant temperature to a heated sample platform, this simulates constant skin temperature. These two systems are able to exchange dry air from outside to inside of setup. At the same time, air flow through sample surface is negligible. Therefore, these systems can keep air temperature and humidity within wind shield at constant all the time, with no chilling effect contributes on fabric sample.

Subjective wet sensation of drying fabric was investigated against time. There was not previously studied wet sensation in the recovery period in fabric test. Therefore, fabrics with various dry times were assessed by subjects for simulating wet sensation against extended drying period. A 2-arm fabrics driver was built to offer repeatable fabric movements against subject's forearms. This driver also enables direct sample and reference fabrics comparison to ensure reliable subject response.

A novel setup was constructed to demonstrate wet skin-fabric interaction, stickiness. The setup equips with a free-end drag type sample holder, so that intimate contact is established between fabric and a simulated skin. This intimate contact does not require pressure applies onto fabric, so that real wearing condition is simulated. Each single fabric drag force scanning offers a full drag force profile, "drag force curve". The profile contain drag force against all amount of water applied to fabric. Therefore, a quick method is developed for capturing full wet drag force information of a fabric-simulated skin interface.

1.4 Methodology

Constant Power Drying Rate Tester (CPDRT) is based on applying constant power to sample platform. This is using non-contact type heating method. While a springe pump is used to deliver water to sample platform, then water evaporates through specimen fabric. An electronic balance is used to capture the change in weight through fabric. The weight change against time in a linear region gives drying rate of the fabric.

In addition to the technique of CPDRT, the Constant Temperature Drying Rate Tester (CTDRT) has a temperature sensor connected with wireless data logger. This setup allows remote temperature monitoring of sample platform and real time measurement of weight change through specimen fabric. A computer receives data from the logger and transfers data to a Proportional-Integral-Derivative (PID) controller. The PID controller controls power output onto sample platform to maintain platform's temperature at constant.

The subjective wet sensation assessment of fabric over time is based on evaluating wetness of fabric at various dry time. The level of wetness suffered by subject and expected time of fabric dries are both considered as the discomfort feel against subject. The wet sensation was assessed by a ratio scale without upper and lower limits.

Fabric Drag Force Measurement System (FDFMS) drags sample through a pre-wetted simulated skin. The drag force is captured by a digital force gauge. The water amount apply to fabric accumulates when fabric is dragged along the simulated skin. The drag force against applied amount of water is the profile of fabric-simulate skin interaction.

IBM SPSS Statistic 22 is used to conduct the statistical tests in this study.

Chapter 2 Literature Review

2.1 Objective Drying Measurements on Fabric

Since this study focus on drying of fabric which in contact with human, literature search about drying of textile during manufacturing and after washing are excluded. Academic studies on fabric drying measurements are summarised in Table 2.1. Discussions below are mainly classified in wetting method, drying method and parameter evaluated.

In the literature, many wetting methods applied different amounts of water to different fabrics. These methods wetted fabrics according to absorption capacity or weight of fabrics. These can cause drying rate result largely depends on absorptive capacity or fabric weight. For example, little amount of water was applied to low absorption capacity fabrics, or large variation in applied water amount due to material's density of fabric (unit: g/cm^3; Also known as specific gravity: cotton: 1.54, nylon: 1.14) (Collier et al., 2009). In order to compare fabric's drying properties equally, fixed amount of water had applied onto fabric for experiments (Crow and Osczevski, 1998; Petrulyte and Velickiene, 2011).

Table 2.1 Details of current objective fabric drying measurements

Principle of the test	Parameter evaluated	Advantages	Limitations/Potential problems	Reference
Water applied to the fabric, equal to 30 % of the dry sample weight. Then measured weight of sample regularly for an hour at ambient or in oven.	Water Evaporating Rate (WER) in terms of % evaporation of applied water	Simple	- Tested at ambient temperature, did not correlate with skin temperature - Tested at ambient temperature was time consuming - Tested in oven causing sample and air at same temperature, which was also not the real case - Since the amount of water applied depended on fabric's weight. WER can be distorted by special fabric, e.g. heavy and light fabrics.	(Fangueiro et al., 2010; Yanılmaz and Kalaoğlu, 2012; Saricam and Kalaoglu, 2014; Yu et al., 2015)
Water saturated fabric was mounted on a rotating shaft. The rotation speed was variable to demonstrate different wind speed.	A time profile of temperature change of fabric, time between turning points of the profile was studied	Multiple wind speed can be applied to fabric	- Tested at ambient temperature, did not correlate with skin temperature - Water applied to fabric depended on fabric's absorption capacity, this may cause distortion against result.	(Wang et al., 2014)
Fixed amount of water was applied to the fabric. Then measure weight of sample regularly for three hours at ambient	Remaining Water Ratio (RWR) in terms of remain % of applied water	- Simple - Fixed water amount applied to fabric was easy for comparing fabric	- Tested at ambient temperature, did not simulate actual skin temperature - Time consuming	(Petrulyte and Velickiene, 2011)

Principle of the test	Parameter evaluated	Advantages	Limitations/Potential problems	Reference
Water saturated sample laid on flat surface at the standard atmospheric conditions of 20 ± 2 °C, 65 ± 2 % R.H.	Remaining water on fabric was recorded every two hours until fabric dry	- Simple - Can simulate drying rate at profuse sweating	- Tested at ambient temperature, does not simulate actual skin temperature - Time consuming - Water applied to fabric depends on fabric's absorption capacity, this may cause distortion against result.	(Beskisiz et al., 2009)
Wet fabric by using wascator, then (i) line dried fabric on a balance with glass draught shield to prevent air movement. or, (ii) put wetted fabric on sweating guarded hotplate with airflow across fabric surface	Drying time in minutes	- Can simulate drying rate at profuse sweating Principle (i): Simple Principle (ii): Sweating guarded hotplate with suitable air flow can simulate on-skin drying time	- Water applied to fabric depends on fabric's absorption property, this may cause distortion against result. Principle (i): - Time consuming - Zero air movement inside of glass shield would cause accumulation of moist air that prolong and bias the drying time Principle (ii): - Only time spent to completely dry the fabric was known, all information during experiment were absent - Expensive (around USD 100 k) sweating guarded hotplate followed ISO standard (ISO 11092)	(Laing et al., 2007)
(i) Soaked fabric in water, squeezed by hand and blotted on paper towels, then dried on a 30 °C guarded hot plate.	Heat flux x time to dry, in terms of kJ/m^2	- Can simulate drying rate at profuse sweating -Guarded hot plate can simulate on-skin drying time	- Water applied to fabric depends on fabric's absorption property and fabric weight, result of special fabrics may be distorted, e.g. heavy or absorptive fabrics.	(Crow and Osczevski, 1998)

Principle of the test	Parameter evaluated	Advantages	Limitations/Potential problems	Reference
(ii) Drops of distilled water from a full 2.5 ml hypodermic syringe were placed in decreasing circles onto the test surface. Whole experiment was conducted on a 30 °C guarded hot plate	Heat flux x time for 2.5 g water to dry, in terms of kJ/m^2	- Guarded hot plate can simulate on-skin drying time - Fixed water amount applied to fabric was easy for comparing fabric	- Resolution of result was not high (result range from 387 to 491 kJ/m^2, while samples were cotton, polyester and polypropylene fabric with thickness between 0.30 to 1.45 mm)	(Crow and Osczevski, 1998)
Fabric fully soaked with water, then suspended vertically for 15 seconds and laid flat on a double thickness of dry paper towel for two minutes on each side. Afterward, samples were weighted at half-hour and one-hour intervals, test end when the measured value was 105% of dry weight	Drying rates were expressed as average weight loss over the initial water content per unit area per unit hour.	- Simple - Can simulate drying rate at profuse sweating condition	- Tested at ambient temperature, which was not correlated with skin temperature - Time consuming	(Coplan, 1953; Duru and Candan, 2013)

For drying method, drying fabric freely at standard atmospheric condition did not simulate actual garment wearing condition. Moreover, this method was time consuming. Some researchers (Crow and Osczevski, 1998; Laing et al., 2007) employed guarded hot plate to simulate skin temperature during drying process. This on-skin drying method allowed ventilation to fabric. The large and expensive experimental setup may be the major drawback of using guarded hot plate. A guarded hot plate setup is shown in Figure 2.1.

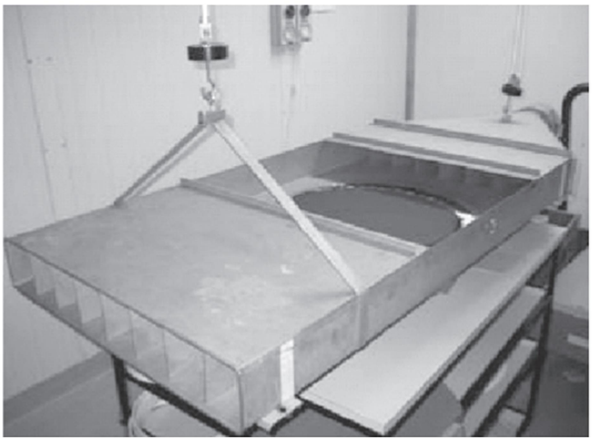


Figure 2.1 Guarded hot plate with a circular sample (Laing et al., 2007)

Table 2.1 also shows experimental parameters evaluated by previous researches. Some researchers used Water Evaporating Rate (WER) or Remaining Water Ratio (RWR) to study drying rate of fabric. The relationship between WER and RWR was "WER + RWR = 100 %". WER and RWR were recorded regularly to construct a plot against time. This method was able to investigate whole drying process, but it may involve lots of manpower to conduct the experiment. Additionally, WER and RWR against time can be converted to drying rates in terms of weight change of water per unit area per unit time (Coplan, 1953; Duru and Candan, 2013). Lastly, the parameter "heat flux multiply time to dry" may not have high enough resolution to distinguish various types of sample. This was because the result range between 387 and 491 kJ/m^2, while samples were cotton, polyester and polypropylene fabric with thickness between 0.30 to 1.45 mm (Crow and Osczevski, 1998).

In addition to academic researches, there were several test standards about objective drying measurement on fabric (Table 2.2). Elevated temperature and air flow were introduced by test standards AATCC 199, AATCC 200 and AATCC 201. AATCC 199 conducted in a moisture analyser chamber at 37 °C. This can have temperature control problem as moisture analyser was designed for measurement at higher than 100 °C. Also, ventilation of sample chamber of moisture analyser was not good. Therefore, moist air can possibly accumulate to affect result. AATCC 200 projected drying rate at absorbent capacity. This was achieved by conducting several drying rate tests at various amount of applied water to sample. This method simulated profuse sweating at room temperature, but its operating procedure was rather complicated. AATCC 201 was another test method for drying rate. It applied fix amount of water to fabric and tested on a 37 °C heated plate under air flow. Water was applied to fabric and evaporated, latent heat of evaporation caused drop in fabric temperature. An infrared sensor was used to check temperature change on fabric surface. Therefore, only overall "drying time" was recorded by the infrared sensor. Drying time was the time spent to completely dry the fabric. All information during experiment was merged as a single parameter "drying rate". It was calculated by dividing total "drying time" with water applied. Information in various drying stages was absent. Test standard JIS L1906 used line drying at ambient to obtain drying time, which was similar to academic studies listed in Table 2.1.

Table 2.2 Details of current fabric drying test standards

Test standard	Principle of the test	Parameter evaluated	Advantages	Limitations/Potential problems
Drying Time of Textiles: Moisture Analyzer Method, AATCC 199 (American Association of Textile Chemists and Colorists, 2013)	Completely wetted fabric was dried in a moisture analyzer at 37°C.	Drying time	- Simple - Can simulate drying rate at profuse sweating	- Due to the design of moisture analyzer, ventilation at sample chamber was low - Moisture analyzer was not designed for low temperature measurement, high power heating element was difficult to control sample temperature at 37 °C accurately.
Drying Rate of Textiles at their Absorbent Capacity: Air Flow Method, AATCC 200 (American Association of Textile Chemists and Colorists, 2015)	Fabric was wetted according to their absorbent capacity. They were then dried with air flow through fabric. The change in fabric temperature was used to estimate drying time of fabric.	Overall drying rate in term of mL/hr. It was calculated by dividing total drying time with water applied	- Can simulate drying rate at profuse sweating	- Time consuming - Test cannot be conducted at absorbent capacity, drying rate at absorbent capacity was just a projection of other wetting amount - Tested at ambient temperature, which was not correlated with skin temperature
Drying Rate of Fabrics: Heated Plate Method, AATCC 201 (American Association of Textile Chemists and Colorists, 2014b)	0.2 ml of water was dispensed under testing fabric, which was placed on a 37 degree C heated plate with air flow along sample surface. The change in fabric temperature was used to estimate drying time of fabric.	Overall drying rate in term of mL/hr. It was calculated by dividing total drying time with water applied	-Relatively simple (compare with AATCC 200) -Repeatable result	- Only overall drying rate can be studied, i.e. time spent to completely dry the fabric, all other information during experiment were absent -

Test standard	Principle of the test	Parameter evaluated	Advantages	Limitations/Potential problems
Drying time, JIS L1906 (Japanese Industrial Standard, 2010)	Line-drying of wetted fabric	Drying time	Simple	- Tested at ambient temperature, which was not correlated with skin temperature

2.2 Subjective Drying and Wetness Assessments

There were two types of subjective test, wearing test and fabric test. Principle and details of the studies are listed in Table 2.3. Wearing tests were mainly focused on wet sensation during exercises, and commonly extended to recovery period. Wearing tests gave real sense from subjects. They commonly included acclimatisation, and cycles of exercise, rest and recovery in various atmospheric conditions. These protocols simulated daily activities and exercises depended on the aim of each experiment. The experiment can last for 30 minutes to around 2 hours for a sample. This was time consuming for conducting subjective assessment, so that the number of subject would seldom be more than 10. Reliability of wearing subjective test may be limited by the number of subject. Fabric tests spent shorter test and operation time than wearing test. However, studies on fabric test were focusing on wet sense against pre-wetted fabric. Therefore, it is a research gap on wet sensation at the recovery period using fabric test.

Table 2.3 Details of current subjective fabric drying and wetness sensation assessments

Principle of the test	No. of subject	Site for assessment	Rating/scaling method	Reference sample	Acclimati-sation	Reference
10 x 10 cm^2 foot sweat pads were wetted with 50 % capacity by artificial sweat, then pads were in contact with forearm for 5 seconds	14	Forearm	5-point ordinal rating scale: 1: Dry 2: Slightly damp 3: Moderately damp 4: Very damp 5: Extremely damp	Dry sample tested separately	20 minutes	(Kaplan and Aslan, 2016)
12 x 12 cm^2 fabric was held on embroidery loop, and then applied 0.1 ml of water and wait 1 minute. After that, forefinger glided and swept around the wetted portion of fabric	22 out of 24 (2 rejected)	Forefinger	5-point ordinal rating scale: 1: Dry 2: Barely wet 3: Slightly wet 4: Moderately wet 5: Very wet	Wet: fabric with the worse water absorbency Dry: a fabric without water added	30 minutes	(Tang et al., 2015b)
12 x 12 cm^2 fabric was moved left and right, water applied by pipe between skin and fabric	12 out of 15 (3 rejected)	Volar forearm	Time required to trigger wet sensation (Psycho-physical measurement)	Dry fabric	30 minutes	(Tang et al., 2015c)

Principle of the test	**No. of subject**	**Site for assessment**	**Rating/scaling method**	**Reference sample**	**Acclimati-sation**	**Reference**
260 cm^2 fabrics were wetted with 2 ml of water, and evaporated to certain wetness. Then, these fabrics were put on forearm for 30 seconds.	12	Forearm	ASHRAE 7-point scale(*):	Dry sample was included as a specimen	30 minutes	(Niedermann and Rossi, 2012)
Subject wore knee "legging tube" to lift knee for 30 seconds. Wetness rated before and after knee-lift	8	Knee area with length of 30 cm	0 to 5, from very slight to very strong feeling	Not specified	30 minutes	(Zhou et al., 2011)
Subject wore jacket to conduct rest-exercise-recovery process in 100 minutes. Subject gave rating every 10 minutes.	3	Area covered by a jacket	7-point ordinal rating scale: +3: Very humid +2: Humid +1: A little humid 0: Not either -1: A little dry -2: Dry -3: Very dry	Humid rating at first 30 minutes rest time was defined as "0" of rating scale	30 minutes	(Ahn et al., 2011)
Subject wore long-sleeved round neck T-shirts and exercised on a treadmill at speed 5.5 km/hr for 25 minutes. Subjects gave rating every 5 minutes.	25	Area covered by long-sleeved round neck T-shirts	5-point ordinal rating scale: 1: None 2: Slightly damp 3: Moderately damp 4: Very damp 5: Extremely damp	Humid rating at start of exercise was defined as "1" of rating scale	15 minutes	(Wu et al., 2009)

Principle of the test	**No. of subject**	**Site for assessment**	**Rating/scaling method**	**Reference sample**	**Acclimati-sation**	**Reference**
10 x 10 cm^2 fabrics were applied with 10 % or 20 % excess amount by a pipette, and then sealed to condition for 24 hr. Fabrics were in contact with forearm for 10 sec with a standard weight 15 g.	7	Forearm	5-point ordinal rating scale: 1: Dry 2: Slightly damp 3: Moderately damp 4: Very damp 5: Extremely damp	Dry sample tested separately	20 minutes	(Kaplan and Okur, 2009)
10 x 10 cm^2 fabrics using hands	20	Hands	5-point ordinal rating scale (details of the scale was not specified)	Not specified	30 minutes	(Choi and Lee, 2006)
Subject wore coverall to go through preconditioning-rest-exercise-rest-stretch-rest process within 70 minutes. Subjects gave rating for each part of the process.	30	Area covered by a coverall	7-point ordinal rating scale: 1: Totally felt 7: No sensation	Not specified	10 minutes	(Yoo and Barker, 2005)
Subject wore long-sleeved, loose fitted jacket and long pants to sit on a chair. Subjects gave rating every 5 minutes.	9	Area covered by jacket and pant	ASHRAE 7-point scale(*):	Not specified	10 minutes	(Choi et al., 2005)

Principle of the test	No. of subject	Site for assessment	Rating/scaling method	Reference sample	Acclimati-sation	Reference
Subject wore long sleeve shirt to complete backpacking on a treadmill for 30 minutes. Subjects gave rating every 5 minutes.	5	Area covered by long sleeve shirt	4-point ordinal rating scale: 1: Dry 2: Slightly wet 3: Wet 4: Very wet	Not specified	Not specified	(McCormick and DeVoe, 2004)
Subject wore protective mask and clothing to perform intermittent step exercise. Subject rated every 1 minute.	5	Area covered by mask	7-point ordinal rating scale: 1: Very wet 2: Wet 3: Slightly wet 4: Neutral 5: Slightly dry 6: Dry 7: Very dry	Not specified	15 minutes	(Hayashi and Tokura, 2004)
Subject wore long-sleeved, loose fitted jacket and long pant to conduct a 5-session exercise protocol within 40 minutes. Subject rated every 5 minutes.	11	Area covered by jacket and pant	ASHRAE 7-point scale(*)	Not specified	5 minutes	(Chung and Cho, 2004)

Principle of the test	No. of subject	Site for assessment	Rating/scaling method	Reference sample	Acclimati-sation	Reference
Subject wore long-legged/long-sleeved underwear as part of a 3-layer clothing system to conduct two bouts of 40 minutes exercise and two 20 minutes rest. Subject rated every 10 minutes.	8	Area covered by underwear	4-point ordinal rating scale: 1: Dry 2: Slightly damp 3: Damp 4: Wet	The beginning of exercise was defined as "Dry"	10 minutes	(Bakkevig and Nielsen, 1995)
Subject wore long-legged/long-sleeved underwear as part of a 2-layer clothing system to sit at rest for 60 minutes. Subject rated every 10 minutes.	8	Area covered by underwear	4-point ordinal rating scale: 1: Dry 2: Slightly damp 3: Damp 4: Wet	The beginning of exercise was defined as "Dry"	Not specified	(Bakkevig and Nielsen, 1994)

*ASHRAE 7-point scales: Adopted from ASHRAE standard 55, which divides sensation "satisfied" points and "dissatisfied" points with a middle point "neutral" (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2013)

Previous studies commonly employed ordinal point scale with verbal descriptions as wetness rating method (Table 2.3). There were chances that verbally misunderstand the definition of verbal description, such as "barely", "slightly" and "moderately". Yoo's study (Yoo and Barker, 2005) only fixed the both ends of rating scale, so this rating scale did not affect by language or understanding of definition of labels. Psychophysical measurement can be used to replace those typical rating scale. For example, time required to trigger wet sensation. This was an absolute threshold that easy to be rated by subject (Tang et al., 2015c). Reference fabric was important for subjects to rate the wetness of fabric. Most of the previous researches used dry fabric as reference (for those reference sample was employed), so that the wet end of rating scale were unreferenced. This can cause difficulties to subjects for determining fabric's wetness near the wet end. Tang et al. had solved the problem by using two references that covered the range (of specimens) of wet sensation (Tang et al., 2015b).

For the body site of subjective assessment, wearing test should follow the end-use of garment. Forearm was frequently selected as the site for assessment in fabric tests (Kaplan and Okur, 2009; Niedermann and Rossi, 2012; Tang et al., 2015c; Kaplan and Aslan, 2016). The reason to use forearm as test site was because forearm is hairless, so forearm is less sensitive to prickle that may affect subject's judgement. The forearm was chosen also because it has a similar numbers of cold spots in human skin as the back (Parsons, 2014). Therefore, the back would have similar wetness sensation with forearm.

2.3 Objective Fabric Friction and Stickiness Measurements

A summary of previous fabric friction and stickiness measurements are shown in Table 2.4. There were two major types of contact materials to test against fabrics. The first type was human skin, forearm was frequently selected to rub against fabric. In vivo test is always the most representative to show the friction at skin-fabric interface. However, skin condition changes from time to time. The changes may due to weather, age, physical condition of subjects, etc. Therefore, in vivo measurement may have reproducibility problem for long term comparison. In contrast, non-in vivo tests used stable contact materials (metal or plastic) to rub against fabric. The drawback of using non-in vivo test was that it may not be able to simulate skin-fabric interaction. In order to simulate human skin with repeatable measurement, several materials were used for rubbing against skin. Such as, poly (dimethyl-siloxane) (PDMS) simulates Young's modulus of human tissue (Mondal et al., 2016); artificial finger with elastomeric skin with a fingerprint (Chen et al., 2015; Tang et al., 2015e); and Lorica Soft to simulate surface properties of skin (Amber et al., 2015). On the other hand, fabric's wetting condition is important factor to be studied. Only one of the study listed in Table 2.4 studied fabrics frictional properties at various wetting level (Wang et al., 2012). This can enable the study of effect of water to frictional properties at skin-fabric interface. The remaining reference summarised in the table of previous stickiness tests (Table 2.4) had studied on dry fabric or one level of wetting only.

Table 2.4 Details of current objective fabric friction and stickiness measurements

Principle of the test	**Type of contact materials/ fabric's condition**	**Parameter evaluated/ used equipment**	**Advantages**	**Limitations/ Potential problems**	**Reference**
A Poly (dimethyl-siloxane) (PDMS) indenter was scanned through a fixed fabric forward and backward at 0.5 mm/s	PDMS/ dry fabric	Frictional force/ shear force load cell	PDMS simulated Young's modulus of human tissue	-Only dry state was studied -Entanglement may happen between indenter and fabric	(Mondal et al., 2016)

Principle of the test	Type of contact materials/ fabric's condition	Parameter evaluated/ used equipment	Advantages	Limitations/ Potential problems	Reference
A rotary type "custom-made fabric-to-skin applicator" (abb.: SOFIA) was used to apply fabric to subject's skin at 5 cm/s	Forearm and palm/ dry fabric	Frictional force/ SOFIA	In vivo test was used	-Only dry state was studied	(Hoefer et al., 2016)
An artificial finger was mounted with a horizontal angle of 30 degree. The artificial finger was controlled by the tribometer to scan single track on the samples at different normal loads (0.5 N, 1 N, 1.5 N, and 2 N), different velocities (1, 5, 10, 15, and 20 mm/s), and a scanning distance of 30 mm.	A commercial artificial finger consisted of a rigid core that contained sensory transducers and was covered by an elastomeric skin with a fingerprint. /dry fabric	Frictional force/ force sensor	An artificial finger was used for simulating human finger	-Only dry state was studied	(Chen et al., 2015; Tang et al., 2015e)
The test was based on the principle of rectilinear motion of a sled over a platform. A sled connected to a constant rate of tensile tester slides over the platform. The sample was loaded with pressure.	Lorica Soft platform/ dry and damp fabric	Frictional force/ tensile tester	Lorica soft was used for simulating human skin	-Only fixed amount of moisture can be tested at a time	(Amber et al., 2015)
	Aluminium platform/ dry fabric		/	-Aluminium platform did not simulate human skin. -Only dry state was studied.	(Ajayi, 1992)

Principle of the test	Type of contact materials/ fabric's condition	Parameter evaluated/ used equipment	Advantages	Limitations/ Potential problems	Reference
Fabric was mounted on a hand-held probe, and it was scanned against subject.	Ventral face of the forearm and palm/ dry fabric	Frictional force/ cantilever type load-cell	In vivo test was used	-The probe should be scanned steadily by operator -Only dry state was studied.	(Ramalho et al., 2013)
Both end of the fabric was mounted with clamp. The fabric was then pulled across forearm and a roller. The friction equipment pulls forearm up and down and the dragging friction between fabric and skin was measured.	Forearm/ dry or wet fabric at various level	Frictional force/ force sensor	In vivo test was used	-Only fixed amount of moisture can be tested at a time	(Wang et al., 2012)
	Forearm/ dry fabric			-Only dry state was studied	(Wang et al., 2010)
Subjects rubbed their inner forearm in a reciprocating and uniform motion against the textiles on a triaxial quartz force plate and the rubbing force in terms of friction was measured.	Inner forearm/ dry and wet fabric	Frictional force/ triaxial quartz force plate	In vivo test was used	-The subjects should maintain steady motion during test to ensure reliable result can be obtained. -Only fixed amount of moisture can be tested at a time.	(Gerhardt et al., 2008)

Principle of the test	Type of contact materials/ fabric's condition	Parameter evaluated/ used equipment	Advantages	Limitations/ Potential problems	Reference
Fabric was rotated against an aluminium disk (ring). The torque at the fabric-disk interface was measured. Linear speed at middle radius of disk was 1.77 mm/s. Fixed pressure was applied on sample.	Aluminium disk (ring)/ dry fabric	Torque/ torque sensor	Rotating sample measured overall resistive force of sample at all orientations	-Aluminium platform did not simulate human skin -Only dry state was studied	(Lima et al., 2005)
Fabric was pulled against a plastic platform for measuring friction. Fixed pressure was applied on sample.	Poly(methyl methacrylate) (PMMA)/ dry fabric	Frictional force/ tensile tester		-Platform materials did not simulate human skin -Only dry state was studied	(Hermann et al., 2004)
	Stainless steel, nylon, and synthetic rubber/ dry fabric				(Virto and Naik, 1997)
A polyvinylsiloxane sledge was driven to and fro on fabric to acquire friction. Fixed pressure was applied on sample.	Polyvinyl-siloxane sledge at 25 mm long and 10 mm wide/ dry fabric	Frictional force/ tensile tester	Simulated continuous fabric/skin motion	-Only dry state was studied	(Ramkumar et al., 2003)

Principle of the test	Type of contact materials/ fabric's condition	Parameter evaluated/ used equipment	Advantages	Limitations/ Potential problems	Reference
The subject's forearm or hand was placed in a support and a strip of fabric was draped across the skin. One end of fabric was suspended with a dead weight while another end was attached to a strain gauge.	Forearm or index finger/ dry and wet (water applied to the skin) fabric	Frictional force/ strain gauge	In vivo test was used	-Only fixed amount of moisture can be tested at a time.	(Gwosdow et al., 1986; Kenins, 1994; Jayawardana et al., 2017)
A metal probe with a fix pressure was scanned through fabric. Frictional force and surface roughness of fabric were measured simultaneously	The commonly used testing probe of KES-F-4 surface tester was made of steel wire (0.5 mm diameter)/ dry fabric	Frictional force/ frictional force sensor	Displacement sensor was equipped for fabric roughness measurement	-Steel wires did not simulate human skin at wet -Only dry state was studied	(Kawabata et al., 1994)

There were many types of mounting methods for fabric sample (Table 2.4). Mounted at fixed pressure was the most common mounting method (Ajayi, 1992; Ramkumar et al., 2003; Hermann et al., 2004; Lima et al., 2005; Amber et al., 2015). The dimensions of fabric generally remain unchanged during experiment. This can help to keep sample flat during test, but this did not follow actual wearing condition about stretching of textile. Mounted sample with clamp or suspended with dead weight at the end of fabric (Kenins, 1994; Wang et al., 2010; Wang et al., 2012) was a good alternative to fixed pressure. This allowed fabric to stretch for simulating body movements, but the choice of clamping force would largely affect friction at skin-fabric interface. Therefore, the clamping force should be chosen carefully. Lastly, for in vivo test, fabric can be mounted firmly on a platform, then rubbed by subject (Gerhardt et al., 2008). Alternatively, the scanning may be manually operated by operator (Ramalho et al., 2013). For such methods, subject and operator should maintain steady motion during test to ensure reliable result can be obtained. In order to perform repeatable fabric-skin movement, motorised scanning was used in some researches (Wang et al., 2010; Wang et al., 2012; Hoefer et al., 2016).

Dragging speed of sample was also named as sliding speed. The dragging speed referred to relative motion between of sample and sample platform. According to the literature (Ajayi, 1992; Falloon, 2014), sliding speed had a limited effect on the frictional properties. In addition, Benenson's research showed that sliding friction coefficient of materials was independent with velocity of the motion (Benenson et al., 2002). Therefore, dragging speed would not be an important issue to be considered. The main influence of dragging speed to friction measurement would be stability and efficiency of experiment only. The dragging speed of sample in previous research was put in first Column of the summary table of stickiness measurement (Table 2.4).

KES-F-4 surface tester (Kawabata et al., 1994) is a famous fabric friction and roughness tester for dry fabric. The roughness testing probe of KES-F-4 surface tester was made of a steel wire, 5 mm in length with 0.5 mm of diameter. The friction testing probe was made of ten parallel steel wires, each of the wires were 5 mm in length with 0.5 mm of diameter. A fix pressure was applied vertically on the steel probes, and the probes were set to scan through dry fabric sample (Figure 2.2). Then, frictional force and surface roughness of fabric were measured simultaneously. The KES-F-4 surface tester was designed for testing dry fabric, so the steel probe may not simulate human skin at wet.

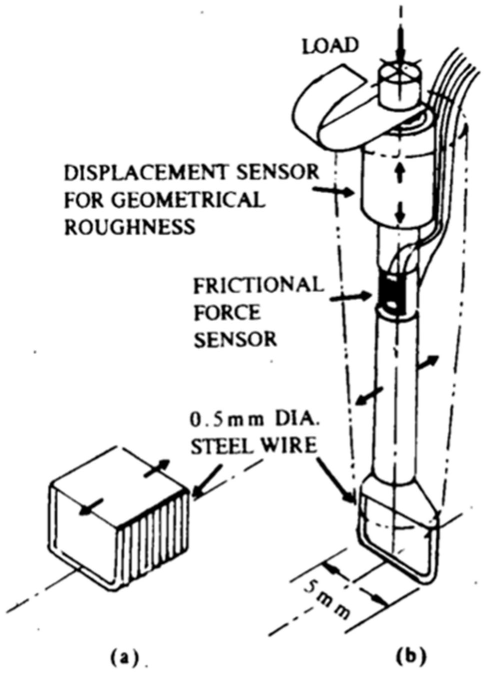


Figure 2.2 Surface friction sensor built by Kawabata et al. (a) Standard KES-F system, (b) the new "U-type" sensor (Kawabata et al., 1994)

2.4 Subjective Stickiness Assessments

Table 2.5 lists current subjective stickiness sensation assessment. Half of previous researches required subjects to rub or touch fabrics sample by finger or hand (Wu et al., 2009; Bacci et al., 2012; Tang et al., 2015e; Zhang et al., 2017). This method did not need complicated equipment and can be easily operated. However, the subject should be well trained for touching sample properly to ensure reliable result. The active touching can be replaced by passive motion. The passive motion was enabled by mounting fabric on a hand-held probe, and then scanned against forearm and palm (Ramalho et al., 2013). Therefore, only the operator of subjective assessment was required to be trained for assessment's operation. There were also wearer trial type stickiness assessment (Yoo and Barker, 2005; Bogerd et al., 2012). The wear trial is the best way to assess subject's sensation, but time consuming. The number of specimen was commonly limited by the duration of assessment in wearer trial.

Table 2.5 Details of current subjective stickiness sensation assessments

Principle of the test	No. of subject	Site for assessment	Rating/scaling method	Reference sample	Acclimati-sation	Reference
Subjects rubbed their middle finger against micro-structured stainless steel sheet	16	Middle finger	11-point scale: 0: Least sticky 10: Most sticky	Unpattern sample was employed as reference	Not specified	(Zhang et al., 2017)
Subjects used their right index finger to scan the material surface.	20	Right index finger	A 0 to 100 rating scale between sticky and slippery	Not specified	Not specified	(Tang et al., 2015e)
Fabric was mounted on a hand-held probe, and it was scanned against subject.	19	Ventral face of the forearm and palm	5-point scale: 1: Slippery 5: Adhesive	Not specified	Not specified	(Ramalho et al., 2013)
Subject wore two different socks, one on each foot, friction was rated after a daily 6.5 km march on 4 days.	37	Feet	Visual analogue scale:*	No	Not applicable	(Bogerd et al., 2012)
Laid fabric sample on a flat surface and subject's hand moved horizontally across the surface.	12	Hand	0 to15 scale: 0: No drag 15: High drag	Not specified	Not specified	(Bacci et al., 2012)

Principle of the test	**No. of subject**	**Site for assessment**	**Rating/scaling method**	**Reference sample**	**Acclimati -sation**	**Reference**
Subject touched the test clothing to give stickiness rating.	25	Hand	5-point scale: 1: None 2: Slightly sticky 3: Moderately sticky 4: Very sticky 5: Extremely sticky	Not specified	0 minute	(Wu et al., 2009)
Subject wore coverall to conduct a 5-session exercise and stretch protocol within 60 minutes. Subject rated once per session.	30	Area covered by a coverall	7-point scale: 1: Totally sticky 7: No sticky	A 100 % cotton control	10 minutes	(Yoo and Barker, 2005)

* Visual analogue scale: The scale consisted of a horizontal, 10-cm-long line. On both ends of the line, both extreme answers were given, e.g. for friction very low and very high.

For those fabric stickiness sensation assessment summarised in Table 2.5, experiments were conducted in dry fabric state. Therefore, it is a research gap for wet stickiness sensation studies. Regarding the rating scales and rating methods, subjective wetness and stickiness assessments shared similar experimental design. However, most of the researches about stickiness had not mentioned reference fabric. Therefore, there is room for improving the subjective stickiness assessment. Many researches (Yoo and Barker, 2005; Bacci et al., 2012; Bogerd et al., 2012; Ramalho et al., 2013; Tang et al., 2015e; Zhang et al., 2017) just fixed the both ends of rating scale. Therefore, the intermediate points were not constrained by language or understanding of definition of labels.

2.5 Physiological Parameters

2.5.1 Skin Temperature

Skin temperature measured at various body sites under different activity level and environment are summarised in Table 2.6. The upper limit of skin temperature under exercise was found as 38 °C and the majority highest skin temperature for playing sport were reported as 37 °C.

Table 2.6 Summary of skin temperature from the literature

Body site	Activity level/environment	Skin temperature	References
Axilla	General	About 35.2 to 36.7 °C	(Scratcherd and Gillespie, 1997)
Not specified	Not specified	25 to 37 °C	(Parsons, 2014)
Distal skin temperature: average of ankles, wrists and thighs Proximal skin temperature: average of infraclavicular regions, sternum and stomach	Normal daily activities (without sporting activities), during summer and winter in Basel, Switzerland	Distal skin temperature: 30.5 to 35.5 °C Proximal skin temperature: 34.2 to 35.6 °C	(Martinez-Nicolas et al., 2015)
Mean temperature of face and chest	Cycling, work intensity was adjusted to induce a heart rate of 125 to 130 beats min^{-1} at condition i: 20 °C, condition ii: 40 to 42 °C and 10 to 15 % RH	Condition i: 32 to 33 °C Condition ii: 37 to 38 °C	(Nielsen et al., 1993)
/	(i) Severe running exercise (ii) Light-intensity exercise (metabolic rate around 450 W)	(i) 30 to 36 °C (ii) 32 to 37 °C	(Sawka et al., 2012)

Body site	Activity level/environment	Skin temperature	References
Upper arm, forearm, chest, back, thigh, and calf with using weighting	Cycle ergometer exercise (258 ± 20W, 87 ± 2 rpm, 66 ± 3% VO_{2max}) in the heat (41 °C, 17 % RH) until volitional fatigue.	34 °C at beginning 37 °C at fatigue (40 to 45 minutes)	(González-Alonso et al., 1999)
Mean torso skin temperature	Wore interceptor body armour to walk on a treadmill at speed 1.34 m/s for 2 hours at: (i) 40 °C, 20 % RH (ii) 35 °C, 75 % RH (iii) 30 °C, 50 % RH	(i) 36.7 ± 0.2 °C (ii) 36.8 ± 0.2 °C (iii) 36.3 ± 0.7 °C	(Chinevere et al., 2008)
Mean skin temperature		(i) 35.7 ± 0.4 °C (ii) 36.2 ± 0.8 °C (iii) 34.3 ± 0.1 °C	

2.5.2 Sweat Rate

The sweat rate of human body is summarised in Table 2.7. The sweat rate corresponded to low activity level at various atmospheric conditions. For studies on strenuous activities and tough environmental condition, they are not applicable for the studies on subjective wetness sensation assessment (Chapter 6). The sweat rate of human body at low activity levels and common atmospheric conditions are listed in Table 2.7. Some of the previous studies used “litre/hour” to describe sweat rate. This referred to sweat rate contributed by the whole body. Another unit for sweat rate was “gram meter^{-2} hour^{-1}”. This unit included the term “per unit area”. The units are converted to “mg cm^{-2} min^{-1}” for enabling comparison between literatures. The sweat rate found from previous studies was between 0.158 to 0.423 mg cm^{-2} min^{-1}.

Table 2.7 Sweat rate of human body at low activity levels.

Air temperature (°C)	**Relative Humidity (%)**	**Exercise/ activity level**	**Sweat rate (litre/ hr)**	**Sweat rate (g m^{-2} hr^{-1})**	**Sweat rate (converted to mg cm^{-2} min^{-1})**	**References**
26.7	/	Light activity	0.237	/	0.228#	(McArdle et al., 2015)
32.2			0.378	/	0.364#	
15	50	1.34 m/s, 5 % grade	0.307	/	0.269*	(Cheuvront et al., 2007)
20		1.34 m/s, 0 % grade	0.220	/	0.193*	
20		1.34 m/s, 5 % grade	0.397	/	0.348*	
25		1.34 m/s, 0 % grade	0.337	/	0.296*	
25		1.34 m/s, 5 % grade	0.482	/	0.423*	
20	40	1.34 m/s, 0 % grade	/	95	0.158	(Shapiro et al., 1982)
22	30	1.34 m/s, 0 % grade	/	126	0.210	

(*) Calculated value as the author stated body surface area of subjects were 1.9 m^2

(#) Calculated value by taken body surface area of subjects as 1.73 m^2 (Go et al., 2004)

2.5.3 Liquid-Skin Interaction

Contact angle at liquid-contact material interface is important to consider. This is because when considering drying rate and stickiness on skin, surface tension takes an important role. This also applies to drying rate and stickiness instruments, because water always presents at the fabric-contact materials interface. Therefore, contact angle at water-unwashed skin interface is studied for a reference. Mavon et al. measured advancing contact angles (the maximum value of the contact angle when the drop was increasing in volume) was 88° and 55° on the untreated forearm and forehead respectively (Mavon et al., 1997). Schott had reported similar contact angle at 87.8° and 84.3° on untreated finger and forearm respectively (Schott, 1971). Therefore, contact angle of untreated forearm was roughly between 84° and 88°.

Randall and Calman measured surface tension of chemically pure water and sweat by using capillary rise method. They found that surface tension of sweat (73.5 dynes per cm) only slightly greater than that of pure water (71.8 dynes per cm) (Randall and Calman, 1954). Since the surface tension between pure water and sweat is similar, it is reasonable to replace sweat by pure water in the instruments. This is because salty sweat causes maintenance problems to equipment.

2.6 Summary

The conventional objective drying rate measurements can either use heated plate measurement or real time measurement. There are common to apply water to fabrics which depended on fabric weight and fabric absorption capacity. However, fabrics with special weight, absorption capacity and material density can distort drying rate result. For the wind speed applied to drying fabric, there is no well-defined value found in the literature.

In subjective drying and wetness assessment, rating scales mostly employed ordinal point scale. The ordinal point scale had fixed end that may limited subject's rating. Most of the previous researches used dry fabric as reference (for those reference sample was employed), so that the wet end of rating scale was unreferenced. Forearm was frequently selected as the body site of assessment in fabric tests. Previous studies on fabric test focused on wet sense against pre-wetted fabric. Therefore, it is a research gap on wet sensation at the recovery period using fabric test.

Most of the previous studies on friction between skin and fabric had studied on dry fabric or one level of wetting only. Only one literature was found that studied fabrics frictional properties at various wetting level. For the contact materials against fabric, human skin (in vivo test) is the most representative. However, in vivo test may involve reproducibility problem of test. Therefore, researchers used various types of materials to simulate human skin, such as PDMS, artificial finger and Lorica Soft (simulated skin). Mounting fabric at fixed pressure was the most common mounting method for fabric friction test, but this is not practical for wet stickiness test. This is because fabrics always deform when they are dragged on wet skin. Finally, sliding speed has a limited effect on the frictional properties

For those fabric stickiness sensation assessment found in literature, experiments were conducted in dry fabric state. Therefore, it is a research gap for wet stickiness sensation studies. The use of rating scale, body site and reference fabric in subjective stickiness sensation assessment is similar with wet sensation assessment in the literature.

Physiological parameters are reviewed in Section 2.5. The upper limit of skin temperature under exercise was found as 38 °C and the majority highest skin temperature for playing sport were reported as 37 °C. The sweat rate found from previous studies was between 0.158 to 0.423 mg cm^{-2} min^{-1}. Contact angle of water against untreated forearm was between 84° and 88°. Finally, the surface tension between pure water and sweat is similar.

Chapter 3 Fabrics Used and Their Basic Properties

3.1 Fabric Specifications

Specifications of 28 fabrics are shown in Table 3.1. Fabric codes are assigned for easy of identification. All knitted fabrics are assigned with the prefix K. A series of woven cotton fabrics is assigned with prefix WC. Except WC6 is twill fabric, all other WC fabrics were in plain structure. WC fabrics are in different yarn count and fabric density. Remaining woven fabrics are in plain structure. These fabrics are labelled with the short form of fabric materials. K06, K07, K08, PMJ and P3M are treated with finishing by manufacturers. The finishing used is specified under the Column of fibre content in Table 3.1. No finishing was further applied to the 28 fabrics after purchased. Fabric weight in Table 3.1 was calculated from measuring the weight of 100 cm^2 circular fabric swatch. Fabric thickness is measured by a thickness gauge (AMES, BG1110-1-04) under a pressure of 4 gram force per square centimetre.

Table 3.1 Fabrics specification

Fabric code	**Knitted / woven**	**Fabric structure**	**Fibre content (*)**	**Yarn count (*)**	**Fabric density (Ends/wales x picks/course per inch) (*)**	**Weight (g/m^2)**	**Thickness (mm)**
K01	Knit	Single jersey	40 % cotton, 60 % polyester	32s	/	144.6	0.56
K02	Knit	Single jersey	95 % rayon, 5 % spandex	32s	/	259.0	0.86
K03	Knit	1x1 rib	Cotton	32s	/	231.2	1.08
K04	Knit	Single jersey	Cotton	32s	/	126.8	0.64

Fabric code	Knitted / woven	Fabric structure	Fibre content (*)	Yarn count (*)	Fabric density (Ends/wales x picks/course per inch) (*)	Weight (g/m^2)	Thickness (mm)
K05	Knit	Double jersey mesh	Polyester	/	/	228.1	0.97
K06	Knit	Pique	95 % polyester 5 % spandex (dry fit)	/	/	182.1	0.89
K07	Knit	Pique	DuPont Coolmax yarn (Dry fit, permanent)	/	/	140.6	0.67
K08	Knit	Pique	Polyester Bamboo Charcoal (Dry-fit and anti-odours)	/	/	152.2	0.56
K09	Knit	Single jersey mesh	Polyester	/	/	202.6	0.60
K10	Knit	Double jersey mesh	Polyester	/	/	173.9	0.80
K11	Knit	1x1 rib	Acrylic	/	/	245.0	0.94
WC1	Woven	Plain	Cotton	80s x 80s	90 x 88	56.6	0.37
WC2	Woven	Plain	Cotton	60s x 60s	90 x 88	78.6	0.40
WC3	Woven	Plain	Cotton	40s x 40s	133 x 100	156.9	0.42
WC4	Woven	Plain	Cotton	40s x 40s	120 x 100	145.9	0.43
WC5	Woven	Plain	Cotton	40s x 40s	133 x 72	135.9	0.48
WC6	Woven	Twill	Cotton	40s x 40s	133 x 72	132.4	0.56
WC7	Woven	Plain	Cotton	40s x 40s	120 x 60	114.8	0.48
WC8	Woven	Plain	Cotton	21s x 21s	60 x 60	157.0	0.66
PMJ	Woven	Micro jacquard	Polyester (Breathable)	/	/	97.5	0.31
P3M	Woven	Plain	96 % polyester, 4 % spandex (sport dry fit, 3M)	/	/	89.1	0.28
WOL	Woven	Plain	Wool	/	/	283.2	0.64
SIL	Woven	Plain	Silk	/	/	57.9	0.16
PET1	Woven	Plain	Polyethylene terephthalate (PET)	/	/	63.3	0.10
PET2	Woven	Plain	Polyethylene terephthalate (PET)	/	/	66.8	0.12

Fabric code	Knitted / woven	Fabric structure	Fibre content (*)	Yarn count (*)	Fabric density (Ends/wales x picks/course per inch) (*)	Weight (g/m^2)	Thickness (mm)
PET3	Woven	Plain	Polyethylene terephthalate (PET)	/	/	156.2	0.38
NYL	Woven	Plain	Nylon	/	/	45.0	0.08
CHI	Woven	Plain	Polyester	/	/	78.5	0.22

(*) Given by manufacturer.

3.2 Water Absorbance and Absorption Capacity of Fabrics

Modified AATCC 79 was adopted to measure the water absorbency of fabrics. The modifications include: Auto-pipette (Finnpipette F2, 20 – 200 µl) was used to transfer 0.2 ml of distilled water in 3 ± 0.3 sec onto back side of fabric. The auto-pipette was tilted to nearly horizontal and putting its tip closed to the back side of fabric. This prevented water pressure applied on fabric due to injection of water. Other procedures followed AATCC Test Method 79-2014 (American Association of Textile Chemists and Colorists, 2014a) and the absorbency time (second) of various fabrics was measured. Absorbency time refers the time since all water applied, until no reflectance was observed from the water spot, i.e. all water absorbed by fabric. The results are summarised in Table 3.2. The water absorbency time of fabrics relates to several parameters in the drying rate and stickiness studies.

Table 3.2 Water absorbency time and absorption capacity of fabrics

Fabric code	**Modified AATCC 79, absorbency time (sec)**	**Absorption capacity (mg/cm^2)**
K01	15	37.2
K02	< 1	61.5
K03	< 1	71.0
K04	6	41.2
K05	< 1	55.9
K06	13	24.6
K07	5	45.6
K08	58	41.4
K09	3	36.5
K10	< 1	56.4
K11	45	57.8
WC1	32	14.6
WC2	9	17.1
WC3	13	18.3

Fabric code	**Modified AATCC 79, absorbency time (sec)**	**Absorption capacity (mg/cm^2)**
WC4	10	16.6
WC5	4	22.6
WC6	2	26.0
WC7	3	22.2
WC8	2	30.8
PMJ	> 60	13.4
P3M	> 60	16.5
WOL	> 60	25.3
SIL	> 60	12.4
PET1	> 60	3.51
PET2	> 60	7.27
PET3	> 60	9.21
NYL	> 60	3.94
CHI	> 60	8.88

In order to measure the absorption capacity of fabric, dry weight of 100 cm^2 circular fabric swatches was measured by an electronic balance (Mettler Toledo, ME403E; resolution 1 mg, repeatability 0.7 mg). The fabric swatch was put into a breaker of distilled water for 5 minutes. A glass rod was used to remove bubbles from the surface of fabric. The wetted fabric was then hanged on specimen stand (Figure 3.1). While no water dropped from the fabric for 1 minute, the wet weight of fabric was measured by the balance. Dividing the net amount of water on fabric by 100 cm^2 gives the absorption capacity of fabric. Absorption capacity of fabrics is shown in Table 3.2. It is compared with instrumental and subjective experiment's results.

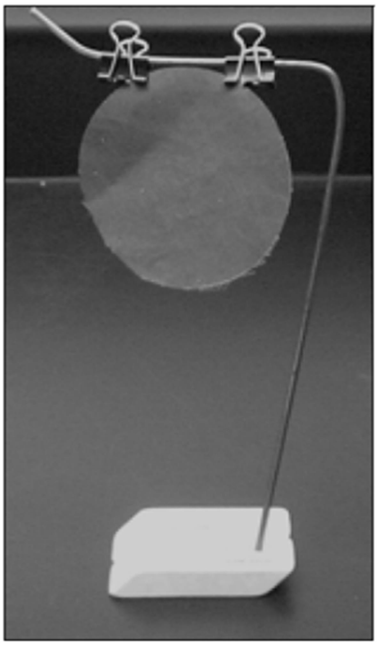


Figure 3.1 Specimen stand for water absorption capacity measurement, adopted from AATCC Test Method 199-2013 (American Association of Textile Chemists and Colorists, 2013).

3.3 Fabric Drying Properties by Conventional Method

In the conventional way, researchers frequently used Water Evaporating Rate (WER) (Fangueiro et al., 2010; Yanılmaz and Kalaoğlu, 2012; Saricam and Kalaoglu, 2014; Yu et al., 2015) or Remaining Water Ratio (RWR) (Petrulyte and Velickiene, 2011) to study drying rate of fabric. The relationship between WER and RWR is simple where "WER + RWR = 100 %". Therefore, only WER is considered in the following analysis and it is selected to compare with the new fabric drying rate testers. In order to acquire and calculate WER, fabrics were wetted with water to 30 % of its dry weight, and then placed at the standard atmospheric condition (ambient temperature at 20 ± 1 °C and relative humidity at 65 ± 5%) for one hour to evaluate the degree of water loss within a predetermined period. WER in terms of % water evaporated is commonly defined as:

WER (%) = (water evaporated from fabric/water applied to fabric) x 100 % (3.1)

In this study, an auto-pipette was used to apply water onto a plastic card, which the plastic card was placed on an electronic balance (Mettler Toledo, ME403E; resolution 1 mg, repeatability 0.7 mg). Sample fabric was put on the water droplet, so the water droplet was in contact with centre back of the fabric. Then the fabric was dried naturally in the standard atmospheric condition. The wind shields of balance at left and right were opened completely during the whole drying process. Wind speed near sample surface was measured by anemometer (Digitron, AF210). It was less than 0.1 m/s with occasional gust reaching 0.15 m/s. The weight change of fabric was recorded by computer so that the WER can be calculated by Equation (3.1).

All 28 fabrics were tested with the conventional drying rate test. The WER at 30th and 60th minute are shown in Figure 3.2. WC1, WC2, P3M, SIL, PET1 and PET3 have 100 % WER indicate that they are completely dried after 60 minutes drying time. Therefore, WER saturates to affect analysis of this conventional drying test method. The WER result will be compared with the new drying rate testers in this study.

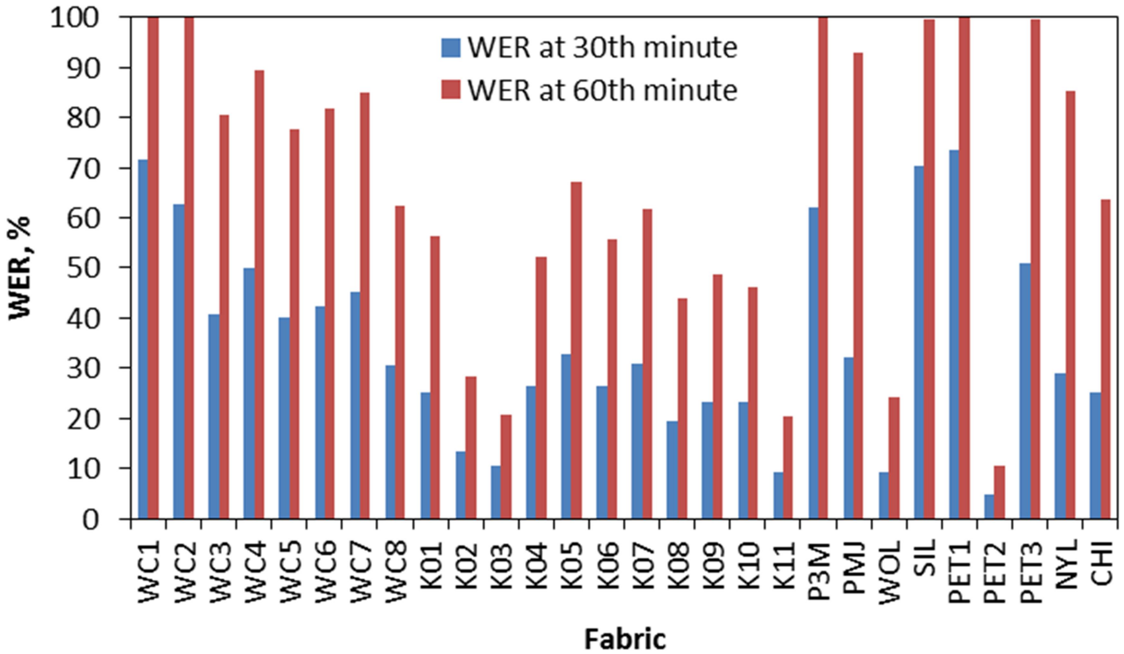


Figure 3.2 Drying rate of tested samples by conventional method, WER % at 30th and 60th minutes

3.4 Frictional Properties by Conventional Method

Table 3.2 shows frictional properties of fabric measured by Kawabata automatic surface tester (KESFB4-AUTO-A), MIU refers to the mean value of the coefficient of friction between fabric and testing probe, SMD refers the mean deviation of fabric surface roughness. The Kawabata measurement results in Table 3.3 will be compared with new friction tester developed in this study.

Table 3.3 Frictional properties of fabric measured by KES-FB4 Kawabata automatic surface tester

Fabric	Warp MIU	Weft MIU	Warp SMD (µm)	Weft SMD (µm)
K01	0.190	0.191	1.66	1.69
K02	0.215	0.206	2.48	2.04
K03	0.186	0.196	3.60	4.03
K04	0.190	0.190	1.67	1.95
K05	0.223	0.302	1.96	6.73
K06	0.246	0.246	10.99	3.78
K07	0.178	0.171	1.04	1.25
K08	0.225	0.223	7.75	3.68
K09	0.329	0.235	4.63	4.69
K10	0.230	0.305	1.84	6.54
K11	0.196	0.333	3.82	12.98
WC1	0.180	0.173	3.24	3.64
WC2	0.170	0.155	2.71	3.24
WC3	0.181	0.180	3.28	2.49
WC4	0.155	0.149	2.42	2.42
WC5	0.187	0.187	3.69	4.54
WC6	0.154	0.212	2.75	2.33
WC7	0.180	0.177	3.36	3.89
WC8	0.196	0.196	6.16	5.19
PMJ	0.147	0.202	4.47	19.79
P3M	0.205	0.214	2.36	2.35
WOL	0.163	0.189	2.30	5.29
SIL	0.123	0.155	1.26	2.52
PET1	0.126	0.127	0.13	0.13
PET2	0.134	0.130	1.91	1.45
PET3	0.171	0.137	3.24	2.25
NYL	0.109	0.108	4.19	3.88
CHI	0.128	0.136	3.07	4.23

Chapter 4 Development of Constant Power Drying Rate Tester (CPDRT) for Fabrics

4.1 Introduction

Drying rate of fabric represents evaporation of sweat from skin surface. Evaporation of sweat can effectively cool down human body (Kofler et al., 2015; Smith and Johnson, 2016). A garment with good drying properties can help to keep user cool and dry (Holmér, 2006; Mokhtari Yazdi and Sheikhzadeh, 2014; Revel and Arnesano, 2014). Therefore, high quality garment should offer good absorption, spreading and evaporation against sweat or water. This can maintain comfort sensation to wearer (Stämpfli et al., 2013) and prevent undesirable post-exercise evaporative cooling (Gavin, 2003; Kim and Na, 2016). There are huge numbers of quick dry fabrics emerged every day, so there is a need to develop an efficient and simple fabric materials drying tester.

Constant Power Drying Rate Tester (CPDRT) gives constant and same thermal energy (per unit time per unit area) input to all samples, so the power output is irrespective of sample's materials, structure, geometry etc. This is an equal materials comparison of drying rate of fabric. Additionally, such materials comparison test is not yet available in the literature. Against this research background, the newly developed CPDRT is introduced. It can dry fabric on a heated plate with constant power applied. The whole drying process can be monitored continuously in terms of weight change of fabric and this provides comprehensive information throughout the entire drying process.

The CPDRT takes 15 to 25 minutes for each measurement, which is much faster than conventional drying methods, and similar to other methods with heat. In addition, a negative pressure gradient system is deployed to keep air temperature and humidity constant all the time, with no wind passes through or along fabric surface that may affect drying result of fabric sample. Syringe pump is employed to deliver water to the back side of sample. Its pump rate is adjustable to demonstrate required sweat rate. So CPDRT is useful in manufacturing state for an early comparison between materials, finishing and structures of fabric in terms of drying rate.

4.2 Limitation of Conventional Methods

Current fabric drying measurements and standard methods are listed in Table 2.1 and 2.2 respectively. Many researchers did not fix the amount of applied water for drying test, the applied amount depended on fabric weight (Fangueiro et al., 2010; Yanılmaz and Kalaoğlu, 2012; Saricam and Kalaoglu, 2014; Yu et al., 2015) or absorptive capacity (Coplan, 1953; Crow and Osczevski, 1998; Laing et al., 2007; Beskisiz et al., 2009; Japanese Industrial Standard, 2010; American Association of Textile Chemists and Colorists, 2013; Duru and Candan, 2013; American Association of Textile Chemists and Colorists, 2015). However, this is not the case for human response. For example, people wear heavy cotton shirt in winter sweat less than wear light polyester shirt in summer. This is because people will choose suitable clothing depend on weather and activity. The apply water amount according to fabric weight or capacity does not fit with actual wearing condition. This issue can also be discussed in the view of materials. For example, little amount of water should apply to low absorption capacity fabrics, or large variation in applied water amount due to material's density of fabric (unit: g/cm^3; Also known as specific gravity: cotton: 1.54, nylon: 1.14) (Collier et al., 2009). These can also cause drying rate result largely depends on fabric weight or absorptive capacity. In this study, it is decided to apply fix amount of water onto sample fabrics. Therefore, the drying rate result of CPDRT do not dominated by fabric weight and absorptive capacity, in addition, the result also depends on fabrics materials, structure etc.

There are two major ways to dry fabric, dry fabric at room temperature and on a heated plate. Dry fabric at room temperature (Coplan, 1953; Laing et al., 2007; Beskisiz et al., 2009; Fangueiro et al., 2010; Petrulyte and Velickiene, 2011; Yanılmaz and Kalaoğlu, 2012; Duru and Candan, 2013; Saricam and Kalaoglu, 2014; American Association of Textile Chemists and Colorists, 2015; Yu et al., 2015) is simple and able to monitor intermediate drying process, however, it does not follow actual wearing temperature, and has long testing time. On the other hand, the heated plate method (American Association of Textile Chemists and Colorists, 2014b) simulates skin temperature, but technically, researchers cannot measure weight of sample during experiment. Some researchers (Crow and Osczevski, 1998; Laing et al., 2007) proposed to use guarded hot plate to conduct drying measurement. This method monitored heat flux away from hot plate, but it did not give good resolution in result. In this research, a novel setup is introduced to dry fabric on a heated plate and continuously measure weight change of the fabric.

There is no consensus about the best air speed/flow for drying measurement. Some researchers (Laing et al., 2007) may enclose sample to prevent air flow, but this may cause accumulation of moist air. On the other hand, some applied air flow (Laing et al., 2007; American Association of Textile Chemists and Colorists, 2014b; American

Association of Textile Chemists and Colorists, 2015) to simulate some kinds of environment or movement. However, the drying rate of fabric is largely depends on wind speed (Wang et al., 2014; Yin et al., 2014), which can be more depending than fabric's intrinsic properties. Also, it is difficult to maintain and measure air speed at high accuracy, so zero wind speed is selected for CPDRT to easy control of the system and compare between samples. While air flow is removed, ventilation problem may become severe and introduce accumulation of moist air. The ventilation problem is then solved in this study by applying gentle negative air pressure to bring away moist air. According to Bernard et al., negative air gradient pressure suppresses turbulence (Bernard et al., 2016), so moist air can be exhausted directly away from sample surface without unwanted air movement.

4.3 Experimental

4.3.1 Setup of Tester

Figure 4.1 shows the schematic experimental setup of Constant Power Drying Rate Tester (CPDRT). In order to maintain stable environmental condition for testing, all components of the measuring system placed on a base platform and enclosed within a wind shield (W: 37 cm, D: 37 cm, H: 37 cm). In this setup, only water supply system, sample and sample holder were put onto an electronic balance (Shimadzu, UW4200H; resolution 0.01 g, repeatability ≤ 0.01 g). In another word, only water loss from the test sample was recorded by the electronic balance. The heater does not have direct contact with electronic balance. The heater transfers heat to sample holder in terms of radiation (infrared) and convection, without physical contact. This configuration has solved previous research problem that the weight change of the sample in the heated system is hard to measure accurately. Details of experimental setup are expressed below.

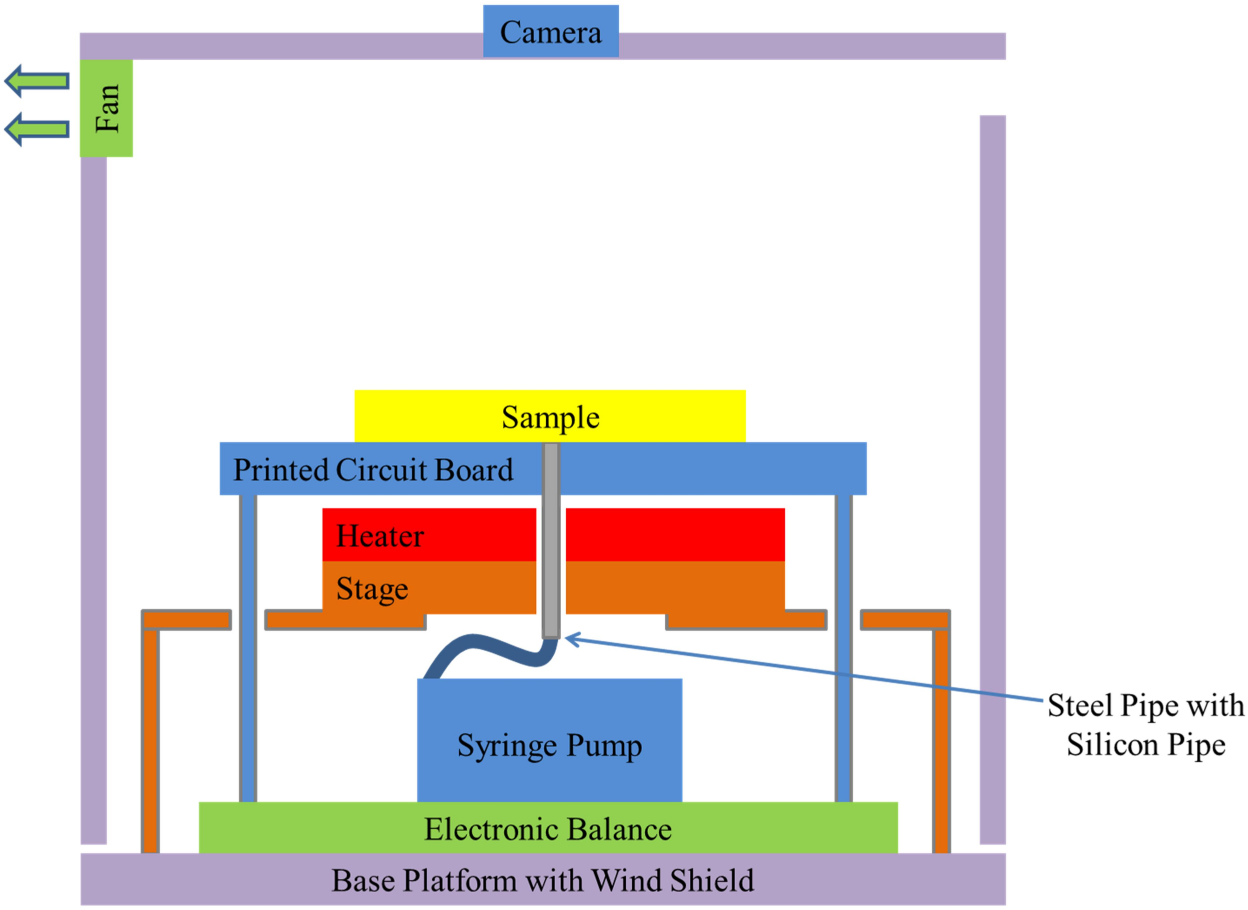


Figure 4.1 Schematic diagram of CPDRT in cross-section view

The syringe pump (SK Medical, SK-500I, accuracy ± 3 %) was equipped with built-in battery, so it did not need to connect with the socket with power cable. The pump was under 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 platform, a printed circuit board (PCB). The top opening of stainless steel pipe was at the same level as the PCB. While syringe pump was operated, water was delivered to the back side of sample, the measured weight from electronic balance did not change unless water evaporated from testing fabric sample. An unpatterned PCB was used as the sample platform because it offered good thermal conductivity and rigid physical dimension. In addition, the contact angle of water-PCB was found as 89° (measured by ramé-hart, model 200 Standard Contact Angle Goniometer), which is similar to unwashed skin interface (Schott, 1971; Mavon et al., 1997).

Heater mat at 20 x 20 cm^2 was placed on a wooden stage. The wooden stage stood on the base platform and had no contact with any other components of CPDRT. A circular hole at 5 mm diameter was drilled through centre of the wooden stage. This allowed stainless steel pipe passing through the wooden stage and supply water to the centre back of the sample. Finally, a fan was installed at the top of wind shield to maintain steady air flow with negative pressure ventilation.

A camera (1080p web-cam) was installed at the top of the wind shield, it was used to capture the water spreading area. The correlation of the water transport parameter against the drying rate of sample is investigated in the discussion section.

4.3.1.1 System Parameters of the Tester

The ventilation system of the CPDRT helps to control air temperature and relative humidity within the tester. The fan exhausted air from inside to outside of wind shield at air speed of 2.7 m/s. Air speed at sample surface and all ventilation openings (located at top and bottom of wind shield) was found to be smaller than 0.1 m/s by using an anemometer (Digitron, AF210). Therefore, while negative pressure gradient was introduced to prevent accumulation of moist air, the slow and steady air flow did not cause wind chilling effect to sample or sample platform.

The temperature of bare sample platform (PCB without placing sample on it) was set at 37 °C, this parameter was according to the literature review of skin temperature (Section 2.5.1). The upper limit of skin temperature under exercise was found as 38 °C and the majority highest skin temperature of taking exercise were reported as 37 °C. In addition, upper limit of skin temperature was preferred in this study, so that testing time can be as short as possible. In order to achieve selected bare sample platform temperature (37 °C), the 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 platform temperature can be found in Section 4.6, calibration of CPDRT. The test of CPDRT was performed in standard condition where ambient temperature and relative humidity was maintained at 20 ± 1 °C and 65 ± 5 %, respectively.

For setting of syringe pump, pump rate was set at 10 ml/hr simulating the sweating rate at high level of work, for example high speed running, and it refers to our previous study (Tang et al., 2015a) The amount of water delivered is 0.2 ml, which is the same as our previous investigation that 0.6 ml of water was applied on three layers of materials.

4.3.2 Specimens

28 fabric samples in knitted and woven structure with various fibre contents were tested by CPDRT, and their specifications are listed in Section 3.1. These specimens were in size of 12 x 12 cm^2, they were gently ironed to achieve a flat surface, and then conditioned in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for at

least 12 hours before test, the CPDRT tests were conducted at the same environmental condition.

4.3.3 Operation of CPDRT

Table 4.1 shows operating procedures of CPDRT. Steps 1 to 5 correspond to start-up of the system, they take less than 30 minutes to stabilise CPDRT, which is reasonably good for heat related instruments. Steps 6 to 12 indicate general measuring procedure of CPDRT. These steps take 15 to 25 minutes for each measurement, depending on materials and structure of fabric samples.

Table 4.1 Operating procedures of CPDRT

Step	Procedure
CPDRT start-up procedure	
1	Fill water at 20 °C into syringe pump, and pre-set its pumping rate and target volume (10 ml/hr and 0.2 ml)
2	Turn on fan and balance
3	Set applied voltage and current to 12.0 V and 3.22 A (input power = 38.64 W) respectively for 6 minutes
4	Set applied voltage and current to 6.5 V and 1.74 A (input power = 11.31 W) respectively
5	Wait 20 minutes for environment to stabilise, inside the wind shield
CPDRT measuring procedure	
6	Place sample fabric onto the sample platform
7	Tare (zero) the balance and switch on the syringe pump
8	Acquire reading from electronic balance every 3 seconds
9	Capture photos of the wetted fabric sample at: (i) The time when syringe pump has just stopped (ii) 60 seconds after syringe pump stopped
10	Stop the experiment when weight loss of fabric larger than applied water amount (0.2 ml, i.e. 0.2 gram)

11	Remove the tested fabric sample and wait for 5 minutes until the next experiment begins
12	Start from Step 6 for next measurement

4.3.4 Measurement Parameters

The key measurement parameter of CPDRT is drying rate (DR_{CP}) calculates from the plot of weight change of fabric against time. Figure 4.2 shows a typical drying curve demonstrating the calculation of DR_{CP}. According to Step 10 from Table 4.1, the weight loss measurement of fabric can be terminated when measured weight loss (WL_{CP}) is larger than weight of applied water. However, the measurements were continued until there was no change in fabric weight in this study. This aims at acquiring the most information for the instrument development.

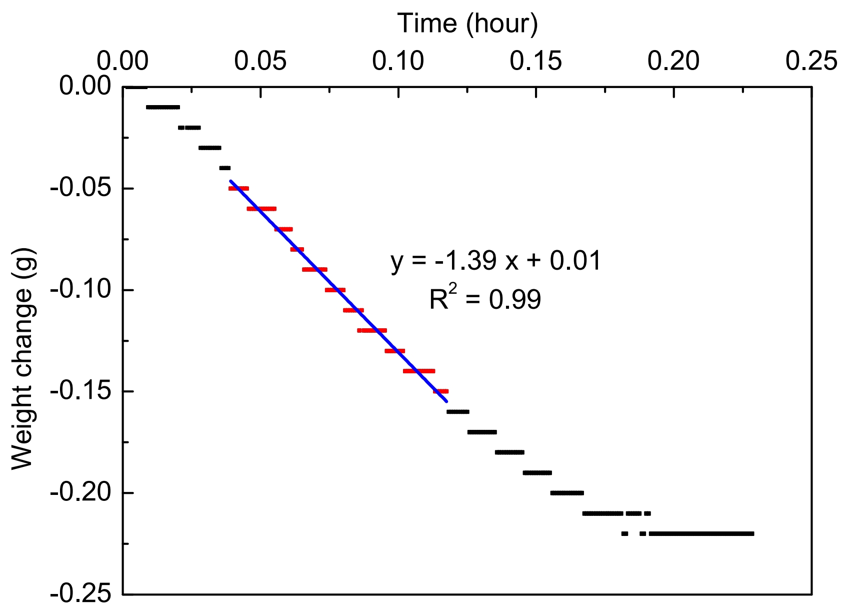


Figure 4.2 Drying curve: Weight change of woven cotton fabric WC1 against time, data selected for calculating drying rate is highlighted in red.

Figure 4.2 shows the weight change of WC1 against time. It shows that weight loss

(WL_{CP}) from the system was 0.22 g. The discrepancy between water lost and water applied was induced by the intrinsic moisture content (IMC). It is a part of moisture regain, since fabric's temperature is 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 is used for calculation. Therefore, only data of WL_{CP} between 0.05 g to 0.15 g are selected to calculate DR_{CP}. DR_{CP} is defined as:

Drying rate, DR_{CP} = (-1) x Slope of weight change against time $(0.05\ g \leq WL_{CP} \leq 0.15\ g)$ (4.1)

by using linear regression, the slope at $(0.05\ g \leq WL_{CP} \leq 0.15\ g)$ can be found. The example in Figure 4.2 shows DR_{CP} of the woven cotton fabric WC1 is found to be 1.39 ml/hr. For the ease of calculation, it is assumed that density of water is 1 g/cm^3 (density of water at 20 °C is 0.998 g/cm^3 (Cohen et al., 2003)). R^2 value of the linear fitting is 0.99, so the relationship between WL_{CP} and time is linear at selected region $(0.05\ g \leq WL_{CP} \leq 0.15\ g)$. This implies fabric dried at constant rate during the specified region. The effect of moisture regain to the drying experiment is further discussed in Section 4.4.3.

Area of water spot on fabric at (i) syringe pump has just stopped (A_{CP0}), and (ii) 60 seconds after syringe pump stopped (A_{CP60}) are additionally recorded by CPDRT. These two parameters were obtained from photos of water spot from the fabric's face side (Figure 4.3; Step 9 of Table 4.1) at corresponding time, and then pixel-counting. It is generally believed that fabric will dry faster if water spread wider on it. Therefore, wetted area is expected to be positively correlated with drying rate of fabric. When the syringe pump is switched off, water spreading is still ongoing. In order to obtain more stable and reliable picture, A_{CP60} is considered instead of A_{CP0}. A_{CP60} is regarded as stable reading for water-absorbing fabrics, and it is assumed to be the maximum area throughout each experiment.

Figure 4.3 Photos of water spot on fabric surface of WC3 (left) syringe pump has just stopped, and (right) 60 seconds after syringe pump stopped

4.4 CPDRT Result and Discussion

Figure 4.4 shows CPDRT result of the 28 fabrics, the drying rate (DR_{CP}) ranges from 0.32 to 1.69 ml/hr. Error bar on the plot indicates one standard deviation (SD) of each drying rate. Regarding DR_{CP}, the coefficients of variation (CV) of most fabrics are smaller than 3 %, so the variation or dispersion of DR_{CP} are low. In other words, DR_{CP} is reproducible. The CVs of some fabrics are higher than 3 %, including PET1, PET2, PET3 and NYL. CVs large than 3% are caused by slow water absorption, and these cases are discussed in Section 4.7.

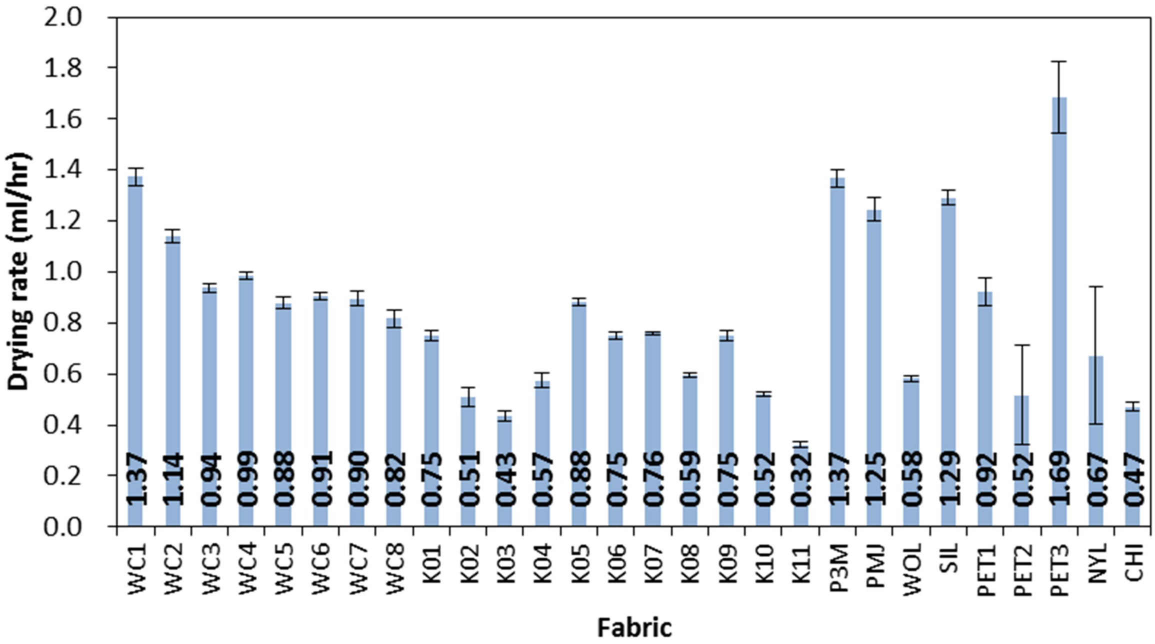


Figure 4.4 Drying rate (DR_{CP}) of fabric, error bar represents one SD of uncertainty

4.4.1 Validity of DR_{CP}

One-way analysis of variance (ANOVA) is conducted to validate DR_{CP}. Cotton woven fabrics WC1 to WC8 have the same materials but different yarn count and density. The null hypothesis of one-way ANOVA is DR_{CP} of all WC fabrics is the same. ANOVA result (Table 4.2(a)) suggests that hypothesis is rejected, so that the effect of WC fabrics to DR_{CP} is significant ($p = 0.000 < 0.050$). Pairwise comparison is further performed to check if there is significant difference in DR_{CP} between various fabrics. The result, as shown in Table 4.2(b), suggests that three-fourths of the WC fabrics have significant difference in terms of DR_{CP} (I-J) at 0.05-level which is relatively high. Figure 4.4 also shows that the drying rate between 28 tested fabrics is significant.

Table 4.2(a) One-way ANOVA of drying rate (DR_{CP}) of woven cotton fabric, WC1 to WC8

ANOVA

DR_{CP}

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	.890	7	.127	220.211	.000
Within Groups	.014	24	.001		
Total	.904	31			

Table 4.2(b) Pairwise comparison of drying rate (DR_{CP}) of woven cotton fabric, WC1 to WC8

Multiple Comparisons

Dependent Variable: DR_{CP}

Bonferroni

(I) Fabric	(J) Fabric	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
WC1	WC2	.236*	.017	.000	.176	.295
	WC3	.436*	.016	.000	.379	.492
	WC4	.388*	.017	.000	.328	.447
	WC5	.494*	.017	.000	.435	.554
	WC6	.468*	.017	.000	.408	.527
	WC7	.477*	.017	.000	.417	.537
	WC8	.557*	.018	.000	.492	.621
WC2	WC1	-.236*	.017	.000	-.295	-.176
	WC3	.200*	.016	.000	.143	.256
	WC4	.152*	.017	.000	.092	.212
	WC5	.258*	.017	.000	.199	.318
	WC6	.232*	.017	.000	.172	.291
	WC7	.241*	.017	.000	.181	.301
	WC8	.321*	.018	.000	.256	.385
WC3	WC1	-.436*	.016	.000	-.492	-.379
	WC2	-.200*	.016	.000	-.256	-.143
	WC4	-.048	.016	.184	-.105	.009

	WC5	.059*	.016	.037	.002	.115
	WC6	.032	.016	1.000	-.025	.089
	WC7	.041	.016	.485	-.015	.098
	WC8	.121*	.018	.000	.059	.183
WC4	WC1	-.388*	.017	.000	-.447	-.328
	WC2	-.152*	.017	.000	-.212	-.092
	WC3	.048	.016	.184	-.009	.105
	WC5	.107*	.017	.000	.047	.166
	WC6	.080*	.017	.002	.020	.140
	WC7	.089*	.017	.001	.029	.149
	WC8	.169*	.018	.000	.105	.233
WC5	WC1	-.494*	.017	.000	-.554	-.435
	WC2	-.258*	.017	.000	-.318	-.199
	WC3	-.059*	.016	.037	-.115	-.002
	WC4	-.107*	.017	.000	-.166	-.047
	WC6	-.027	.017	1.000	-.086	.033
	WC7	-.017	.017	1.000	-.077	.042
	WC8	.062	.018	.066	-.002	.127
WC6	WC1	-.468*	.017	.000	-.527	-.408
	WC2	-.232*	.017	.000	-.291	-.172
	WC3	-.032	.016	1.000	-.089	.025
	WC4	-.080*	.017	.002	-.140	-.020
	WC5	.027	.017	1.000	-.033	.086
	WC7	.009	.017	1.000	-.050	.069
	WC8	.089*	.018	.002	.025	.154
WC7	WC1	-.477*	.017	.000	-.537	-.417
	WC2	-.241*	.017	.000	-.301	-.181
	WC3	-.041	.016	.485	-.098	.015
	WC4	-.089*	.017	.001	-.149	-.029
	WC5	.017	.017	1.000	-.042	.077
	WC6	-.009	.017	1.000	-.069	.050
	WC8	.080*	.018	.006	.015	.144
WC8	WC1	-.557*	.018	.000	-.621	-.492
	WC2	-.321*	.018	.000	-.385	-.256
	WC3	-.121*	.018	.000	-.183	-.059
	WC4	-.169*	.018	.000	-.233	-.105

WC5	-.062	.018	.066	-.127	.002
WC6	-.089*	.018	.002	-.154	-.025
WC7	-.080*	.018	.006	-.144	-.015

*. The mean difference is significant at the 0.05 level.

Table 4.3 shows the Pearson correlation coefficient between DR_{CP}, fabric weight and thickness of cotton woven fabrics WC1 to WC8. It is found that DR_{CP} has significant correlation with fabric weight ($p = 0.004 < 0.050$) and thickness ($p = 0.038 < 0.050$). DR_{CP} depends on fabric weight and thickness for these simple structured woven cotton fabrics, therefore, the validity of CPDRT is again confirmed. Moreover, it suggests that thicker and heavier fabrics have smaller drying rate (DR_{CP}), this observation match the common understanding about drying fabric.

Table 4.3 Pearson coefficient between DR_{CP}, fabric weight and thickness of cotton woven fabrics WC1 to WC8

Correlations

		DR_{CP}	Fabric Weight	Fabric Thickness
DR_{CP}	Pearson Correlation	1	-0.881**	-0.734*
	Sig. (2-tailed)		0.004	0.038
	N	8	8	8

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

4.4.2 Comparison of CPDRT Result with Fabric's Basic Properties

In addition to Table 4.3, Figures 4.5 and 4.6 show the correlation between CPDRT drying rate (DR_{CP}) result and fabric thickness and fabric weight respectively. The points in these two plots are scattered and the R^2 value 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 construction. For example, synthetic materials commonly dry faster than natural fibre.

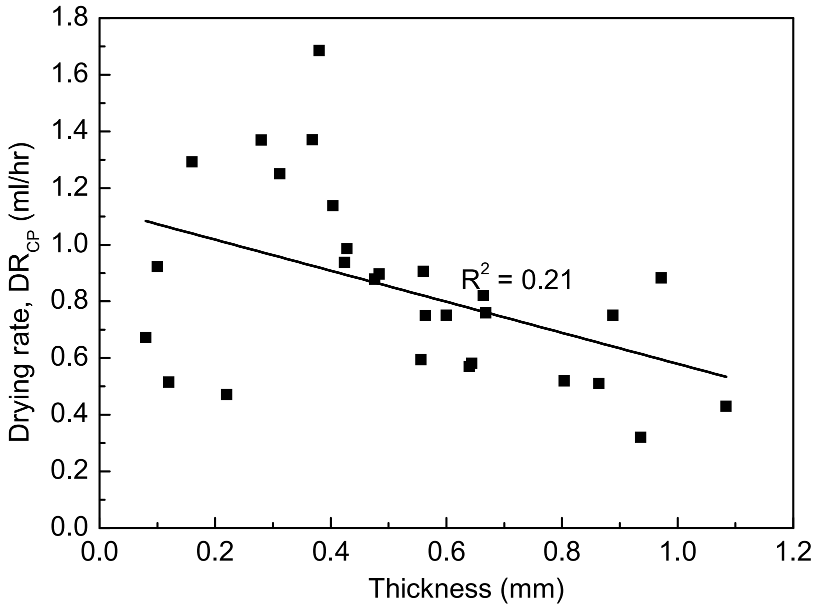


Figure 4.5 Drying rate (DR_{CP}) against fabric thickness of all tested fabrics

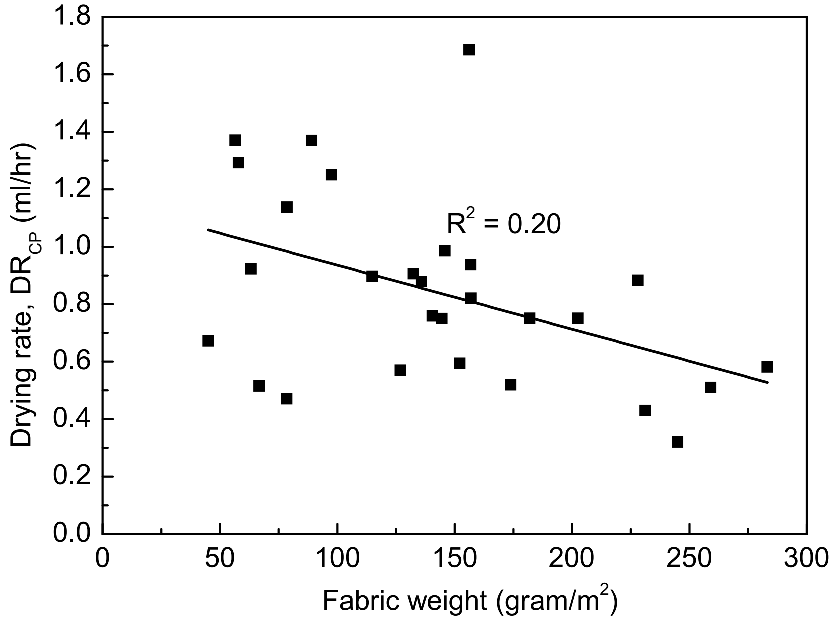


Figure 4.6 Drying rate (DR_{CP}) against fabric weight of all tested fabrics

Figure 4.7 shows DR_{CP} against wetted area of fabric measures at pump off (A_{CP0}) and 60 seconds after (A_{CP60}). It shows that DR_{CP} correlated better with A_{CP60} (R^2 = 0.6) than with A_{CP0} (R^2 = 0.47). This is because the wetted area is still increasing when syringe pump is 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 4.7 agrees with general understanding that fabrics with larger wetted area dry faster, as given that applied water amount are the same.

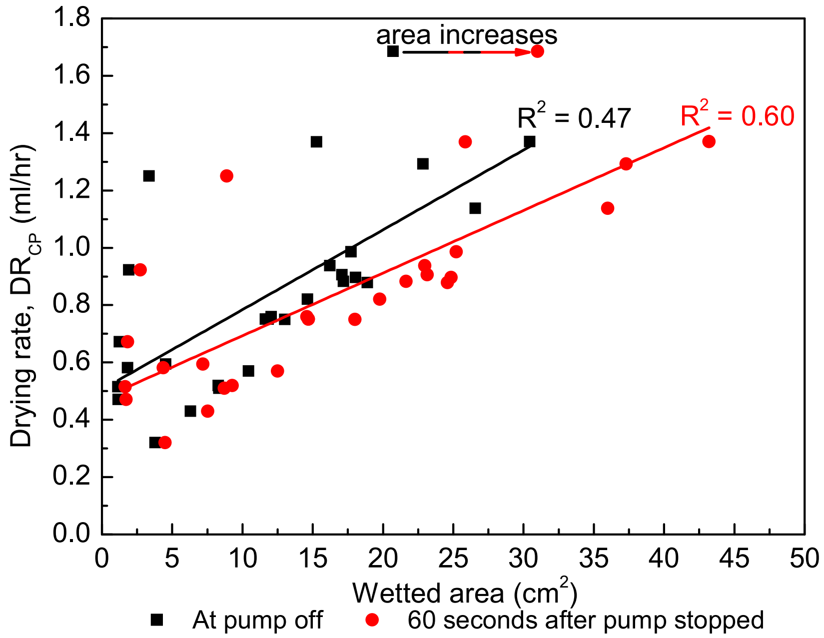


Figure 4.7 Drying rate (DR_{CP}) against wetted area of fabric at pump just stop (A_{CP0}) and 60 seconds after pump stopped (A_{CP60})

In summary, Section 4.4.1 and 4.4.2 suggests that drying rate of fabrics is a complicated phenomenon. A single factor, such as fabric weight and thickness, cannot be used to predict drying property of fabrics. Instead, many factors interact with each other and so it poses the need to have a drying instrument like CPDRT.

4.4.3 Evaporation of Moisture from Fabric

This section aims at presenting different drying curves measured by CPDRT. In Figures 4.8 to 4.11, fabrics with various amount of moisture regain (K02 > WC3 > WC1 > P3M) are presented to show typical drying curves. These curves present characteristics that observed in the whole CPDRT experiments. WC1, WC3, K02 and P3M have various fabric specifications, e.g. fabric weight, construction, material and water absorbance. The evaporated moisture on drying curves is composed of water supplied from syringe pump and moisture regain from fabric itself. Figures 4.8 to 4.11 show raw data taken from the electronic balance during CPDRT measurements. Therefore, these figures are able to indicate the effect of moisture regain to CPDRT measurement. The criteria for modifying WL_{CP} range for calculating DR_{CP} is also discussed with the moisture regain.

WC1 and WC3 are plain structure cotton fabric, but different in yarn count and fabric density (fabric's specification see Table 3.1), so they have similar drying curves (Figures 4.8 and 4.9). The major difference of drying curves between WC1 and WC3 is (i) slope and (ii) water loss (WL_{CP}) at the end of drying curves. For (i) different in slope of drying curve, WC1 has steeper slope than WC3. This is because WC1 is thinner, lighter and dries faster than WC3. For (ii) different in final WL_{CP}, it is contributed by moisture regain. This is not exactly equivalent to moisture regain because fabric is not heated to higher than 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 4.8 and 4.9 represent CPDRT drying curve of WC1 and WC3 without applying water. These "without apply water" trials indicate IMC evaporates from tested 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 sample, considered data of water loss (WL_P) from 0.05 g to 0.15 g can also help to eliminate the effect of moisture regain.

When CPDRT measurement comes near the end, fabric's wetted area decreases, rate of change of WL_{CP} decreases. While all applied water evaporates from fabric, weight change measured by balance becomes constant.

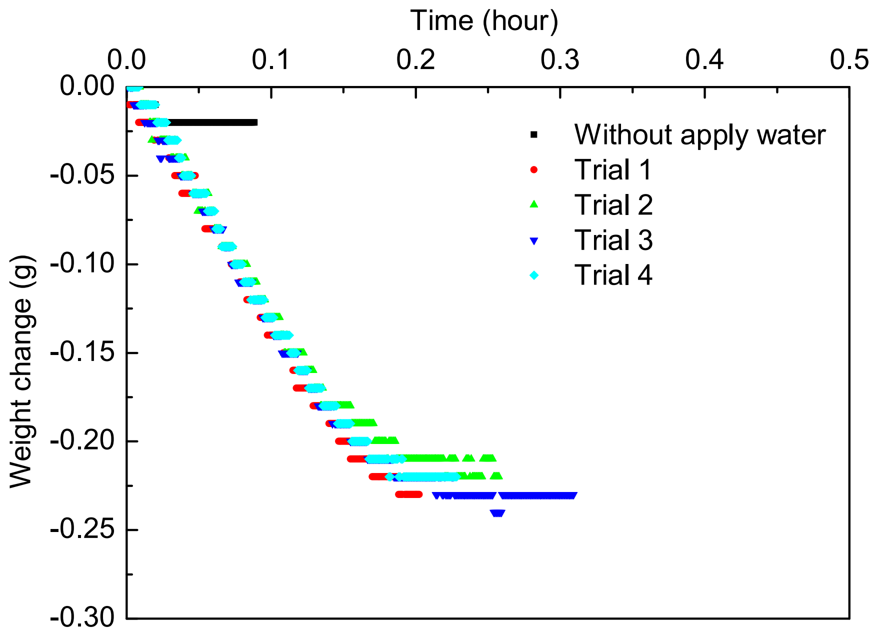


Figure 4.8 Weight change of woven cotton fabric WC1 against time.

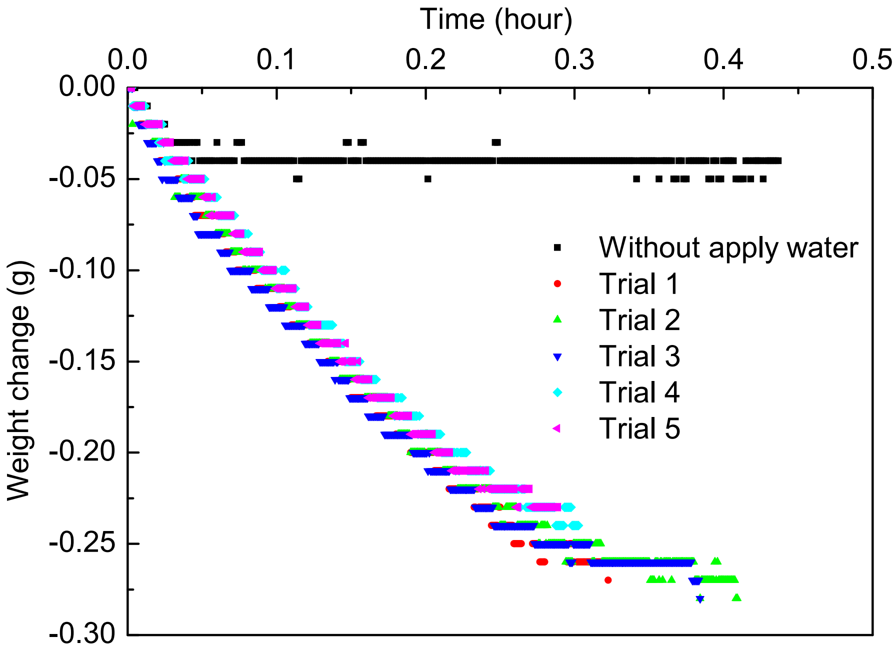


Figure 4.9 Weight change of woven cotton fabric WC3 against time.

As compares with WC1 and WC3, 95 % rayon and 5 % spandex knit fabric K02 has larger amount of weight loss on "without apply water" trial, which is around 0.09 g as represents by black signs of Figure 4.10. This is because the moisture carried on rayon (13.0 % at 21 °C and 65 % RH) is larger than cotton (7 to 11 %) (Tortora and Collier, 1997), and fabric weight of K02 is heavier than WC1 and WC3. Because of the large IMC of K02 and linear region of drying curve, 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 based on linear region of the drying curve, so that is easy to compare and analyse against fabrics. The length of linear region of all tested fabrics in terms of weight change are longer than 0.10 grams, therefore the range selected to calculate DR_{CP} is representative.

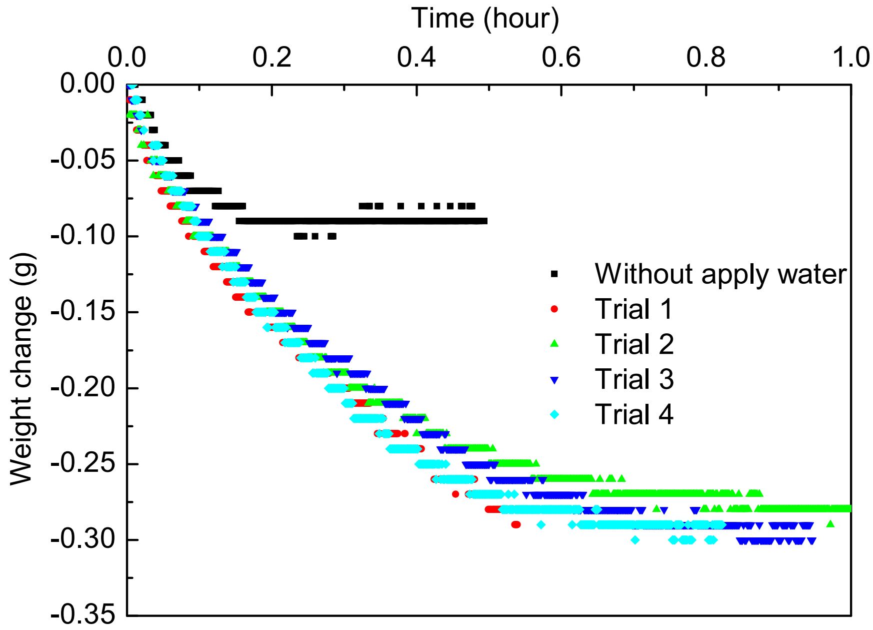


Figure 4.10 Weight change of knitted rayon fabric K02 against time.

Finally, drying curve of 96 % polyester, 4 % spandex (sport dry fit, 3M) woven fabric P3M is shown in Figure 4.11. Different from the above discussed cases, evaporation rate of moisture is zero in the first 2 minutes of experiment. This is because the moisture regain of polyester is relatively low which is only 0.4 to 0.8 % (at 21 °C and 65 % RH) (Tortora and Collier, 1997). In other words, IMC contributes almost zero on weight loss (WL_{CP}). No change in weight of "without apply water" trial also indicates CPDRT drying curves of P3M is independent with moisture regain. Also, all other synthetic samples present the same phenomena at the "without apply water" trial as P3M. Until temperature of applied water raised and water spread through fabric, WL_{CP} of sample increases obviously to achieve large DR_{CP}.

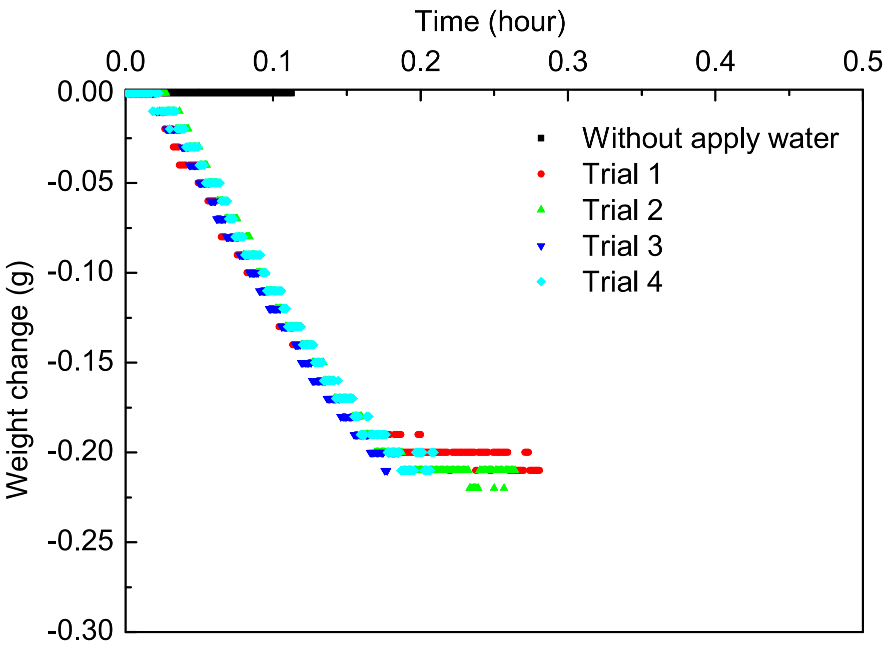


Figure 4.11 Weight change of woven polyester fabric P3M against time.

In fact, there are many other features can be found in a drying curves. These include "time to dry", "turning points", "length of linear region" etc. These provide much information to offers high flexibility for researcher and product developer to study drying phenomenon of fabric comprehensively.

4.4.4 Repeatability of CPDRT Result

As shown in Figure 4.4, coefficient of variation of DR_{CP} is smaller than 3 % in most fabric. This is evidence to prove that DR_{CP} has good repeatability. Figures 4.8 to 4.11 show raw data of all repetitions taken from electronic balance of fabric WC1, WC3, K02 and P3M during CPDRT measurement respectively. These measurements repeat well among each trial, and they overlap with each other. This verified that CPDRT offers good repeatable drying curves, and drying rate (DR_{CP}).

4.5 Correlation between CPDRT Result and Conventional Test

In order to compare CPDRT with conventional drying test, Water Evaporating Rate (WER), the results of conventional drying test, are plotted against DR_{CP} in Figure 4.12. It shows that these two parameters are positively correlated. This finding is rational because both DR_{CP} and WER represent rate of fabric dries. WER at 30^{th} minutes and 60^{th} minutes correlate moderately well with DR_{CP} with R^2 value equal to 0.65 and 0.71 respectively. This is because DR_{CP} and WER have similar function. However, they involve different parameter, such as heat up of fabric, air flow control, and fixed applied water amount are newly introduced for CPDRT. Finally, several fabrics are completely dried before WER test end, i.e. WER become 100% at 60^{th} minute. Drying rate of such completely dried fabrics cannot be distinguished by WER, so this is a disadvantage of WER test.

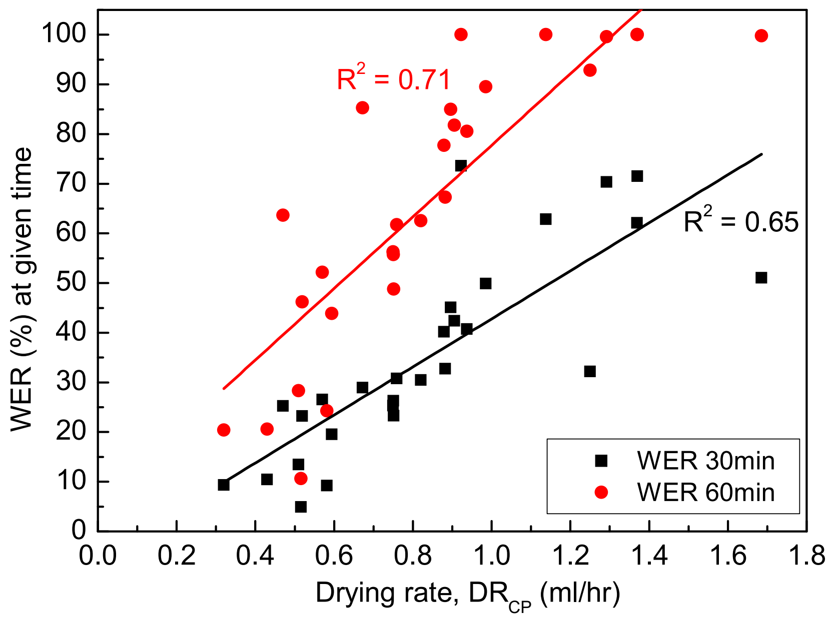


Figure 4.12 Drying rate result of fabrics: Conventional test against CPDRT, WER at 30th and 60th min vs DR_{CP}.

4.6 Calibration of CPDRT and Uncertainty of DR_{CP}

Calibration of CPDRT includes calibration of electronic balance, syringe pump, air speed and temperature of bare sample platform. Shimadzu UW4200H electronic balance has built-in calibration weight, so it can conduct internal calibration for the measurement of weight change on fabric. Internal timer of software LabVIEW is used as the system time of CPDRT. Therefore, the timing of CPDRT is based on computer's clock. The LabVIEW gives commands to electronic balance in every 3 seconds for acquiring data to computer. This is a common practice in research laboratories and the uncertainty is assumed to be negligible. Water delivered by syringe pump is calibrated by measuring weight of water delivered to fabric. Air speed at sample surface and all ventilation opening are confirmed to be lower than 0.1 m/s by an anemometer. The calibration of input power is conducted by attaching a thin film Pt100 platinum resistance thermometer (accuracy: ± 0.35 °C with data logger) at the centre of sample platform. The input power is tuned to maintain sample platform temperature within 37 ± 0.5 °C. Table 4.4 summarises the calibration and uncertainty of instruments and system parameters of CPDRT.

Table 4.4 Calibration and uncertainty of instruments used and system parameters of CPDRT

Instrument	Parameter	Calibration	Uncertainty (given by manufacturer)
Electronic balance	Weight change on fabric	Execute the built-in calibration function	± 0.01 g
Syringe pump	Water delivered	Confirm the weight of water delivered	± 3 %
/	Air speed at sample surface and all ventilation opening	Confirm air speed is smaller than 0.1 m/s by using the anemometer	± 0.1 m/s
/	Temperature of bare sample platform	Specified in Section 2.1.1	± 0.35 °C
Timer	Time	Use internal timer of software LabVIEW to facilitate regular data acquisition from electronic balance	Assumed to be negligible

According to Equation (4.1), the measurement of DR_{CP} depends on WL_{CP} and time. Uncertainty of DR_{CP} (i.e. δDR_{CP}) can be found as below calculations:

$$\delta DR_{CP} / DR_{CP} = (\delta WL_{CP} / WL_{CP}) + (\delta time / time) \quad (4.2)$$

while error of internal timer of the LabVIEW was assumed to be negligible. Therefore

$$\delta DR_{CP} / DR_{CP} = (\delta WL_{CP} / WL_{CP}) + 0 \quad (4.3)$$

and given that uncertainty of electronic balance is 0.01 g, 0.10 g is the range selected for calculating DR_{CP}

$$\delta DR_{CP} / DR_{CP} = (0.01 \text{ g} / 0.10 \text{ g}) \quad (4.4)$$

$$\delta DR_{CP} / DR_{CP} = 0.10 = 10 \% \quad (4.5)$$

so that δDR_{CP} is at 10 % of DR_{CP}.

4.7 Limitations of CPDRT

As shown in Figure 4.4, some samples demonstrated large CVs in drying rate DR_{CP} (PET1, PET2, PET3 and NYL). These samples are slow water absorbing samples (absorbing time larger than 60 seconds by modified AATCC 79 standard test, Section 3.2). There is prerequisite that a sample absorbs water before it can be dried, and so measuring slow absorbing or non-absorbing would be out of the scope of fabric drying rate. Besides, only the face side of fabrics are recorded while measuring the maximum wetted area. However, wetted area is optional measurement parameter and does not affect accuracy of DR_{CP}.

4.8 Summary

Constant Power Drying Rate Tester (CPDRT) is capable of measuring the weight change of fabrics throughout the experiment. This was accomplished by equipping with non-contact heating component and so comprehensive information can be obtained. The power input to the sample platform is set at constant level. Compared with the drying instrument where constant skin temperature is maintained, this set up provides fair comparison for fabrics made of different materials and with different fabric structure. For the ease of comparison, zero air speed is used. 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 temperature and humidity within the setup.

CPDRT testing time of each sample is around 15 to 25 minutes. The validity of CPDRT is confirmed by comparing fabric with different yarn count and density. Drying rate (DR_{CP}) is the key parameter obtained from CPDRT, which measures evaporation rate of moisture from fabric on a heated sample platform. DR_{CP} results of 28 fabrics are repeatable with a range between 0.32 and 1.69 ml/hr. Wetted area of fabric at syringe pump just stops (A_{CP0}), and 60 seconds after syringe pump stopped (A_{CP60}) were measured. The DR_{CP} is found to have moderate correlation with A_{CP60} and conventional test. This shows CPDRT's result is reasonable, and CPDRT has a uniqueness to evaluate drying rate with constant power applied to materials under real time data acquisition.

Chapter 5 Development of Constant Temperature Drying Rate Tester (CTDRT) for Fabrics

5.1 Introduction

Drying rate of fabric largely affects thermal-wet comfort of wearer. This is dominated by materials, structures and finishing of fabric used. Drying rate of fabric depends on evaporation of sweat and this depends on absorption and spreading of sweat (Figure 1.1). When people sweat, garment with good water absorption and drying properties can capture sweat drops. Then the sweat spreads along fabric wide and evaporates to cool down the body (Casa, 1999b; Filingeri et al., 2015; Zhong et al., 2017) to prevent over sweating (Casa, 1999a) and unflavoured post-exercise chill sensation (Splendore et al., 2011; Kim and Na, 2016). Therefore, Constant Temperature Drying Rate Tester (CTDRT) is built to evaluate drying rate of fabric at skin temperature.

CTDRT is developed to offer a test for simulating evaporation of water on the fabric-skin interface at a target skin temperature, which provides comprehensive information throughout the entire drying process. Constant temperature implies that energy input (per unit time per unit area) to samples is different. The input energy depends on sample's materials, structure, geometry and finishing etc. The target constant skin temperature can be altered by a simple system parameter input, so that CTDRT is able to dry fabric at any temperature depends on end use of textile materials. The end uses are varied with activity level, environment and body site, a summary of the conditions with skin temperature are shown in Section 2.5.1. The CTDRT is newly designed to continuously measure weight change of test fabric. This setup can monitor the whole process of drying, and samples are dried at desired constant temperature.

The CTDRT takes 15 to 40 minutes for each measurement, which is similar to other drying methods with heat, but shorter time than conventional methods. In addition, CTDRT equipped with a negative pressure gradient system to keep air temperature and humidity constant all the time. This system allows no wind pass through or along fabric to give stable drying rate result and enable comparison between fabrics.

5.2 Limitation of Conventional Methods

The CTDRT shares the same conventional methods with CPDRT, detail discussion of the limitation of conventional methods can be find in Section 4.2. Current fabric drying measurements and standard methods are listed in Table 2.1 and 2.2 respectively. Below is a brief summary of limitation of conventional methods.

In previous researches, many did not fix the amount of applied water for the drying test, allowing the applied amount to depend upon fabric weight or absorptive capacity. However, this did not simulate the case for common use of clothing. In this research, a fixed amount of water was applied to avoid distortion of drying rate results in case of special fabrics, such as less water absorption capacity, very heavy or light fabrics.

Drying fabric at room temperature is simple; however, it does not simulate actual wearing temperature, and the testing time is long. On the other hand, the heated plate method simulates skin temperature, but technically, researchers cannot measure the weight of sample during the heated plate experiment. In this research, a novel setup will be introduced to dry fabric on a heated plate with continuous measuring of weight change of the fabric.

Some researchers did not apply air flow onto sample, and some applied air flow. In addition, fabric drying rate highly depends on air speed, and the dependency can be stronger than fabric's properties. In order to offer an equal comparison among fabrics, air flow was not applied onto sample. While air flow is removed, ventilation problem is then solved by applying gentle negative air pressure gradient to steadily remove moist air from fabric.

5.3 Experimental

5.3.1 Setup of Tester

Figure 5.1 shows the schematic experimental setup of CTDRT. In order to maintain stable environmental condition, all testing components of the measuring system were placed on a base platform and were enclosed with a wind shield (W: 30 cm, D: 44 cm, H: 45 cm). In this setup, only temperature sensor system, sample and sample platform were put onto the electronic balance (Mettler Toledo, MS1003S; resolution 1 mg, repeatability 0.7 mg). In other words, temperature sensor system, sample and sample platform were isolated from other components, so that only water loss from test sample was measured and recorded. As shown in Figure 5.1, the heater had no contact with electronic balance and the sample platform, the heater was transferred heat to sample platform (printed circuit board) in terms of radiation (infrared) and convection, without physical contact. This configuration has solved previous research problem that it is difficult to measure weight of sample in a heated plate system. Details of experimental setup are expressed below.

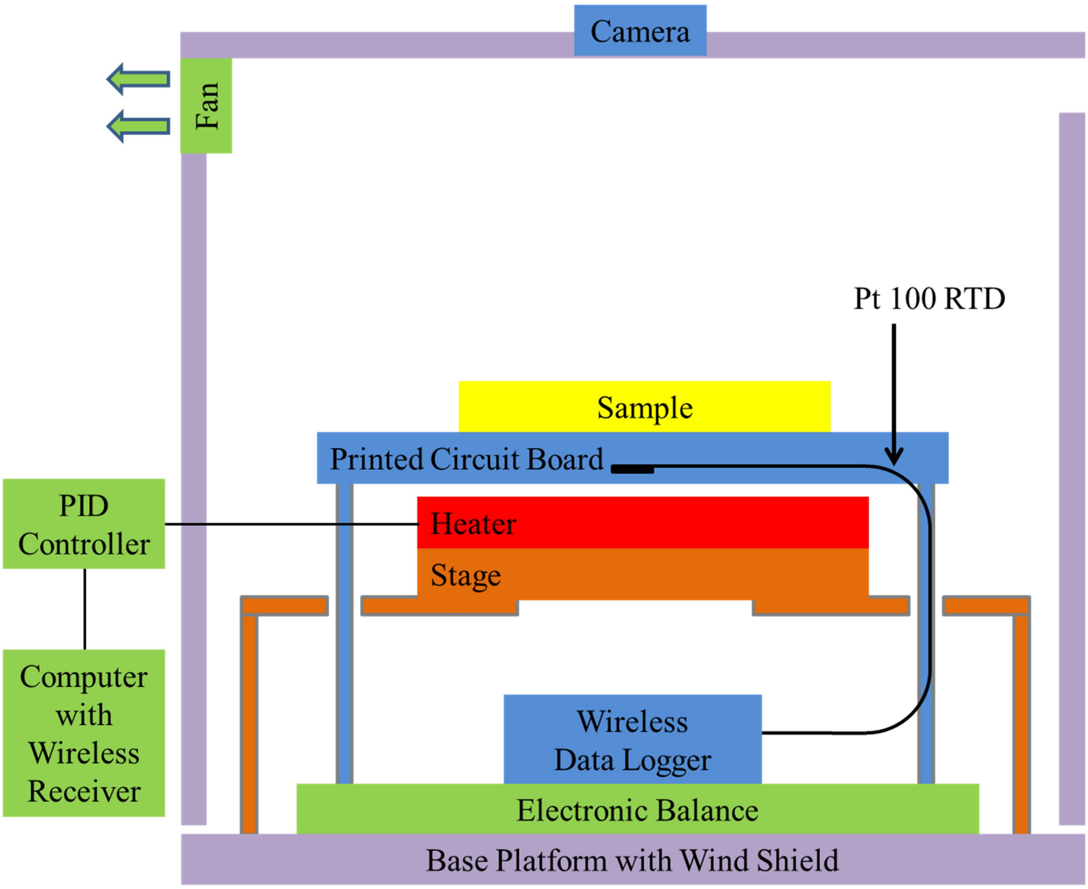


Figure 5.1 Schematic diagram of CTDRT in cross-section view

The thin film Pt100 resistance temperature detector (RTD, stability: ± 0.05 %) was embedded inside the centre back of the sample platform, and it was connected to a wireless data logger (accuracy: ± 0.2 °C). The temperature of sample platform was then sent to computer and Proportional-Integral-Derivative (PID) controller (Omega, CNi 3223) for temperature control with heater. Auto-pipette (Finnpipette F2, 20 – 200 µl) was used to deliver distilled water onto the surface of sample platform. An unpatterned printed circuit board was used as sample platform, since its surface has a water contact angle of 89° (measured by ramé-hart, model 200 Standard Contact Angle Goniometer), which is similar to the contact angle at water-unwashed skin interface

(Schott, 1971; Mavon et al., 1997). PCB also offers good thermal conductivity and rigid physical dimensions.

Heater mat at 15 x 15 cm^2 was placed on a wooden stage. The wooden stage was stood on base platform, and it had no contact with any other components of CTDRT. A fan was installed on the side (near the top) of wind shield to maintain steady ventilation, but air speed within wind shield is negligible.

Finally, a camera (1080p web-cam) was installed at the top of wind shield, it was used to capture water spreading area. The correlation of the water transport parameter against the drying rate of sample is investigated.

5.3.1.1 System Parameters of the Tester

It is important to prevent accumulation of moist air and to maintain constant air temperature and relative humidity within the CTDRT, so it is essential to have the ventilation system. The fan exhausts air from inside to outside of wind shield at air speed 2.7 m/s, so that a negative pressure gradient was built to pull away moist air steadily without turbulence generated. Air speed at sample surface and all ventilation opening (located at top and bottom of wind shield) were lower than the detection limit 0.1 m/s of an anemometer (Digitron, AF210). Selected fan speed was gentle to keep steady air flow, and did not cause wind chilling effect to sample or sample platform.

Temperature of sample platform (print circuit board) was set at 37 °C, this parameter was set according to the literature review of skin temperature (Section 2.5.1). The upper limit of skin temperature under exercise was found as 38 °C and the majority highest skin temperature of taking exercise were reported as 37 °C. Therefore, 37 °C was chosen as sample platform temperature of CTDRT to simulate skin temperature during exercising. This temperature level was maintained by using PID system with heater and Pt100 RTD. The temperature of sample platform can be altered to fit the aim of experiments or end use of fabrics. Only 37 °C was applied to demonstrate the functions and uses of CTDRT in this study. In each CTDRT experiment, 0.2 ml of water was delivered onto the sample platform by using auto-pipette. This matched with 0.6 ml of water for three layers of materials in previous study (Tang et al., 2015a). The sample platform may drop 1 °C or less after applying water on it, but it can return to 37 °C and stabilises within one minute. The temperature of sample platform was well controlled at 37 ± 0.5 °C during entire experiment. It was given that ambient temperature at 20 ± 1 °C and relative humidity at 65 ± 5%.

5.3.2 Specimens

Total 28 fabric samples of knitted and woven structure with various fibre contents were tested by CTDRT, and their specifications were listed in Section 3.1. These specimens were in size of 12 x 12 cm^2, they were gently ironed to achieve a flat surface, and then conditioned in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for at least 12 hours before test. The CTDRT tests were conducted at the same standard atmospheric condition.

5.3.3 Operation of CTDRT

Operating procedures of CTDRT are shown in Table 5.1. Steps 1 to 3 correspond to start-up of the system, they spend less than 20 minutes to stabilise sample platform's temperature at 37 °C, which is very fast for thermal related instruments (compared with thermal resistance and water vapour resistance). Steps 4 to 11 are standard measuring procedures of CTDRT, these steps take 15 to 40 minutes in general for each measurement, depends on materials, structure and construction of samples.

Table 5.1 Operating procedures of CTDRT

Step	**Procedure**
CTDRT start-up procedures	
1	Turn on fan and balance
2	Turn on PID controller
3	Wait for 20 minutes to stabilise the environmental conditions inside the wind shield
CTDRT measuring procedures	
4	Place sample fabric on sample platform, and wait for temperature of sample platform stabilised at 37 °C; this step takes around 5 minutes
5	Tare balance; and acquire data from electronic balance every second
6	Lift half of the sample, and apply 0.2 ml of distilled water at 37 °C to the centre of the sample platform by using auto-pipette
7	Lay the fabric down on the sample platform so that its centre back is in contact with the water drop
8	Capture photo of the wetted fabric 60 seconds after water is applied
9	Stop the experiment when weight change (ΔW) returns to zero
10	Remove the tested fabric and wait for 5 minutes until next experiment begins
11	Start from Step 4 for next measurement

5.3.4 Measurement Parameters

CTDRT offers two major measurement parameters, those are drying rate (DR_{CT}) and area of water spot on fabric 60 seconds after water is applied (A_{CT60}). The key measurement parameter of CTDRT is DR_{CT}. It is calculated from the slope of "weight change (ΔW) of fabric against time" (Figure 5.2), Figure 5.2 shows a typical drying curve obtained by CTDRT. As shown in Step 9 of Table 5.1, the measurement can be terminated when weight change of fabric returns to zero.

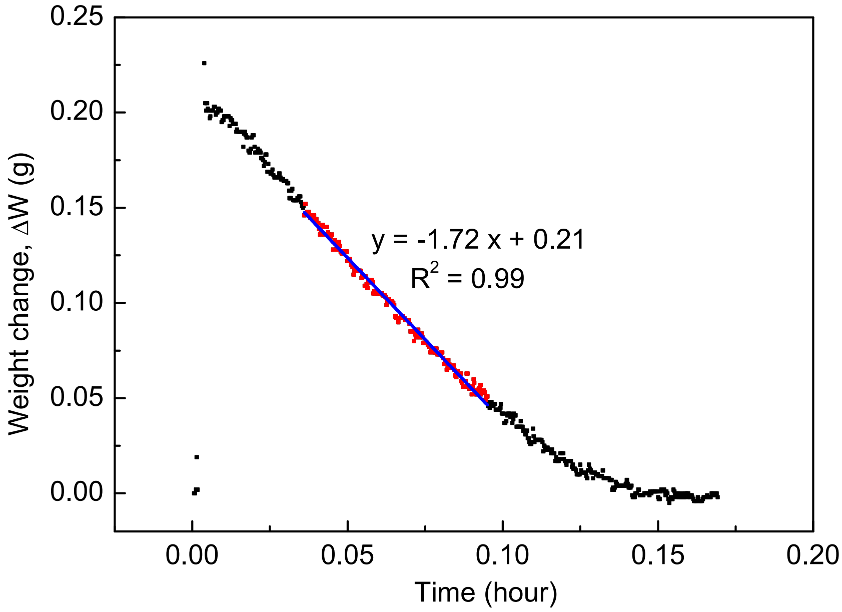


Figure 5.2 Drying curve: Weight change of woven cotton fabric WC1 against time, data selected for calculating drying rate is highlighted in red.

In Figure 5.2, it is found that weight change (ΔW) measured decreases from 0.20 g to 0.00 g in around 0.15 hours. The rate of ΔW (slope of Figure 5.2) is low near the beginning and end of measurement, and it is the highest and constant at the middle of measurement. In order to compare fabrics at the most stable, linear and representative region during drying, the region between ΔW at 0.15 g and ΔW at 0.05 g (red data points in Figure 5.2) are selected for mathematic calculation and comparison. DR_{CT} is defined as:

Drying rate, DR_{CT} = (-1) x Slope of weight change against time (0.15 g ≥ ΔW ≥ 0.05 g) (5.1) the slope at (0.15 g $\geq \Delta W \geq$ 0.05 g) can be found by using linear regression. Figure 5.2 indicates DR_{CT} of a woven cotton fabric WC1 is found to be 1.72 ml/hr. For the ease of calculation, this assumes that density of water is 1 g/cm^3 (the actual density of water at 37 °C is equal to 0.993 g/cm^3 (Lide et al., 2013)). The linear region of drying curve at 0.15 g $\geq \Delta W \geq$ 0.05 g had R^2 value 0.99. This suggests that the relationship between ΔW and time is almost perfectly linear. Also, this indicates WC1 dried at constant rate during the specified region.

In addition to DR_{CT}, CTDRT also measures the water spreading area of fabric at 60th seconds after water applied (A_{CT60}). This parameter is recorded by capturing image and counting the pixels of water spot (Figure 5.3; Step 8 of Table 5.1) at 60th second. When water is absorbed and spread widely within the fabric, it is believed that it can dry fast. In order to verify this belief, the correlation between wetted area and drying rate of fabric is studied. At the zeroth second of CTDRT experiment, water drop comes in contact with fabric, water keeps spreading from centre to edge of fabric. The area at zeroth second is not representative for analysis and A_{CT60} is recorded for stable and reliable reading. For water-absorbing fabric, A_{CT60} is steady and this is assumed as the maximum area throughout each experiment.

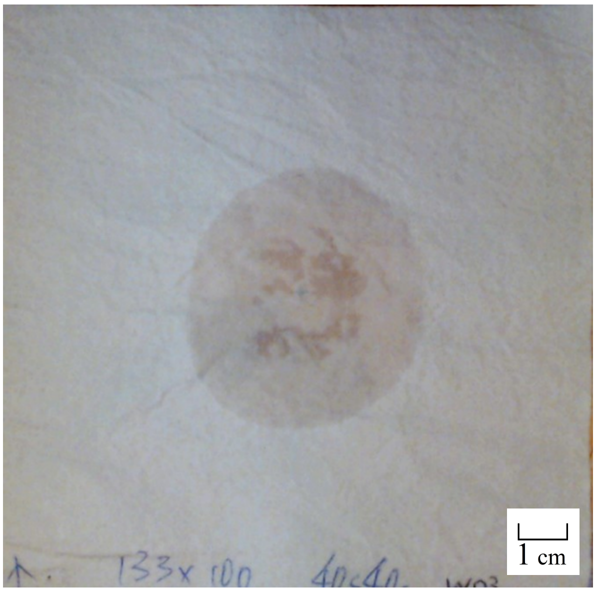


Figure 5.3 Photo of water spot on fabric surface of WC3 at 60 seconds after putting fabric on water bead.

5.4 CTDRT Result and Discussion

Figure 5.4 shows the CTDRT result with error bar of positive and negative one standard deviation (SD). The drying rate (DR_{CT}) of the 28 fabrics is found to be between 0.36 (K11) to 2.56 (PET3) ml/hr. The DR_{CT} of PET3 is larger than K11 for more than seven times. This shows that DR_{CT} gives high discrimination to drying rate of sample. The coefficient of variation (CV) of DR_{CT} are smaller than 3 %, so measurements of CTDRT are stable with just small amount of variation or dispersion of data for most tested fabric. Some of the results have CV larger than 3%, they are slow water absorbing fabrics PET1, PET2, PET3, NYL and CHI (Table 3.2). Their CVs fall between 3 and 10 %. The small CVs indicate the dispersion of DR_{CT} within-fabric measurements is small. Therefore, the repeatability of DR_{CT} among various types of fabric is good.

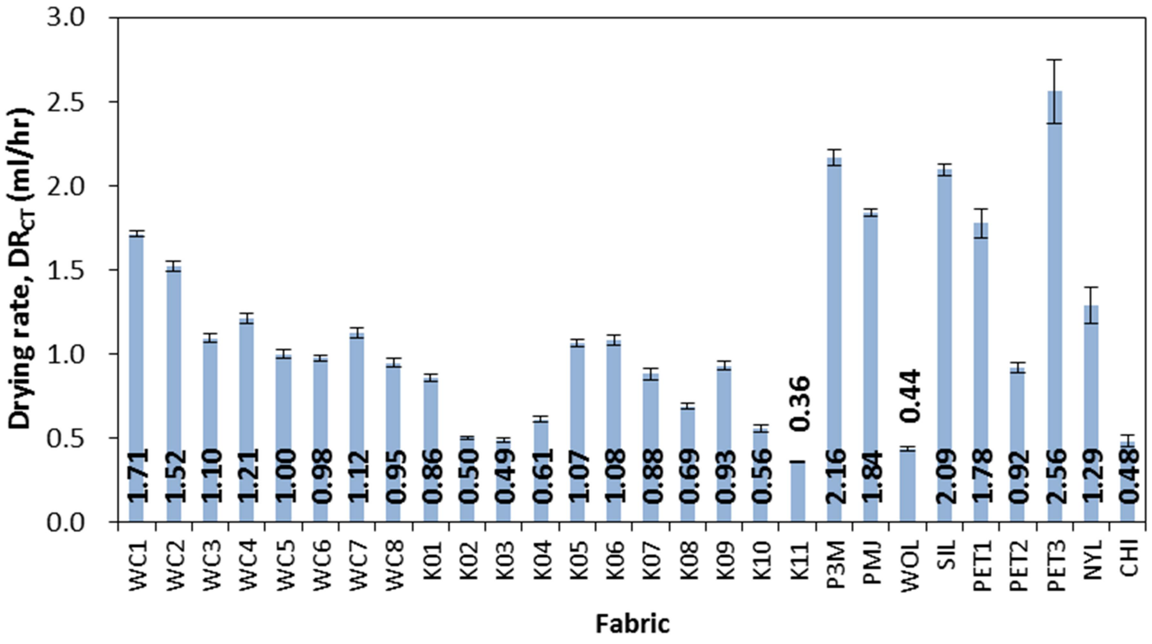


Figure 5.4 Drying rate (DR_{CT}) of fabric, error bar represents one SD of uncertainty

5.4.1 Validity of DR_{CT}

A systematically proof to validate the DR_{CT} is conducted by one-way analysis of variance (ANOVA). Cotton woven fabrics WC1 to WC8 have the same materials but different yarn count and density. ANOVA result shows that null hypothesis (DR_{CT} of WC fabrics is the same) is rejected (Table 5.2(a)), so that the effect of WC fabrics to DR_{CT} is significant ($p = 0.000 < 0.050$). Table 5.2(b) presents pairwise comparison to cotton woven fabrics WC1 to WC8. Under significance level of 0.05, six-sevenths of the DR_{CT} (I-J) are significantly different with each other. This shows good validity of DR_{CT} against fabrics. In addition, all 28 tested fabrics shown in Figure 5.4 are made from wide range of materials, structures and finishing, the difference in DR_{CT} among fabrics further confirmed CTDRT is able to distinguish drying property of fabrics.

Table 5.2(a) One-way ANOVA of drying rate (DR_{CT}) of woven cotton fabric, WC1 to WC8

ANOVA

DR_{CT}

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.751	7	.250	375.030	.000
Within Groups	.013	19	.001		
Total	1.764	26			

Table 5.2(b) Pairwise comparison of drying rate (DR_{CT}) of woven cotton fabric, WC1 to WC8

Multiple Comparisons

Dependent Variable: DR_{CT}

Bonferroni

(I) Fabric	(J) Fabric	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
WC1	WC2	.190*	.021	.000	.113	.266
	WC3	.619*	.021	.000	.542	.695
	WC4	.504*	.021	.000	.427	.580
	WC5	.714*	.020	.000	.642	.785
	WC6	.737*	.020	.000	.665	.808
	WC7	.590*	.021	.000	.514	.667
	WC8	.765*	.020	.000	.693	.837
WC2	WC1	-.190*	.021	.000	-.266	-.113
	WC3	.429*	.021	.000	.353	.506
	WC4	.314*	.021	.000	.237	.390
	WC5	.524*	.020	.000	.452	.595
	WC6	.547*	.020	.000	.476	.619
	WC7	.400*	.021	.000	.324	.477
	WC8	.575*	.020	.000	.504	.647
WC3	WC1	-.619*	.021	.000	-.695	-.542
	WC2	-.429*	.021	.000	-.506	-.353
	WC4	-.115*	.021	.001	-.192	-.039

	WC5	.095*	.020	.004	.023	.166
	WC6	.118*	.020	.000	.046	.190
	WC7	-.029	.021	1.000	-.105	.048
	WC8	.146*	.020	.000	.075	.218
WC4	WC1	-.504*	.021	.000	-.580	-.427
	WC2	-.314*	.021	.000	-.390	-.237
	WC3	.115*	.021	.001	.039	.192
	WC5	.210*	.020	.000	.138	.282
	WC6	.233*	.020	.000	.162	.305
	WC7	.087*	.021	.017	.010	.163
	WC8	.262*	.020	.000	.190	.333
WC5	WC1	-.714*	.020	.000	-.785	-.642
	WC2	-.524*	.020	.000	-.595	-.452
	WC3	-.095*	.020	.004	-.166	-.023
	WC4	-.210*	.020	.000	-.282	-.138
	WC6	.023	.018	1.000	-.043	.090
	WC7	-.123*	.020	.000	-.195	-.052
	WC8	.052	.018	.304	-.015	.118
WC6	WC1	-.737*	.020	.000	-.808	-.665
	WC2	-.547*	.020	.000	-.619	-.476
	WC3	-.118*	.020	.000	-.190	-.046
	WC4	-.233*	.020	.000	-.305	-.162
	WC5	-.023	.018	1.000	-.090	.043
	WC7	-.147*	.020	.000	-.218	-.075
	WC8	.028	.018	1.000	-.038	.095
WC7	WC1	-.590*	.021	.000	-.667	-.514
	WC2	-.400*	.021	.000	-.477	-.324
	WC3	.029	.021	1.000	-.048	.105
	WC4	-.087*	.021	.017	-.163	-.010
	WC5	.123*	.020	.000	.052	.195
	WC6	.147*	.020	.000	.075	.218
	WC8	.175*	.020	.000	.103	.247
WC8	WC1	-.765*	.020	.000	-.837	-.693
	WC2	-.575*	.020	.000	-.647	-.504
	WC3	-.146*	.020	.000	-.218	-.075
	WC4	-.262*	.020	.000	-.333	-.190

WC5	-.052	.018	.304	-.118	.015
WC6	-.028	.018	1.000	-.095	.038
WC7	-.175*	.020	.000	-.247	-.103

*. The mean difference is significant at the 0.05 level.

Cotton woven fabrics WC1 to WC8 are selected to further confirm the validity of DR_{CT}. Pearson correlation is analysed on WC fabrics to study the relationship between DR_{CT}, fabric weight and fabric thickness. As shown in Table 5.3, the DR_{CT} has very high correlation with fabric weight at 0.01-level, and DR_{CT} has a strong relation with fabric thickness at 0.05-level. Since DR_{CT} highly followed fabric weight and thickness, this is a strong evidence for the validity of DR_{CT}, while the materials and finishing of those fabrics are fixed in these 8 cotton fabrics. Once materials and finishing is varied, the strong correlation of DR_{CT} against fabric weight and thickness are reduced, this phenomena is discussed in the next paragraph.

Table 5.3 Pearson coefficient between DR_{CT}, fabric weight and thickness of cotton woven fabrics WC1 to WC8

Correlations

		DR_{CT}	Fabric Weight	Fabric Thickness
DR_{CT}	Pearson Correlation	1	-.899**	-.754*
	Sig. (2-tailed)		.002	.031
	N	8	8	8

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

5.4.2 Comparison of CTDRT Result with Fabric's Basic Properties

All results comparison of CTDRT drying rate (DR_{CT}) against fabric thickness and fabric weight are shown in Figure 5.5 and 5.6 respectively. The correlations are found to be weak. The R^2 value of linear regression in the plots is just larger than 0.3, but a negative trend can still be observed. It can be observed that the thicker fabrics and heavier fabrics have smaller drying rate (DR_{CT}). Finishing on fabric can increase absorption and spreading rate of water along fabric to enhance drying rate, and synthetic materials normally dry faster than natural fibre. Therefore, drying rate of fabric is subjected to the change of materials, finishing and construction, but not just limits to fabric weight and fabric thickness.

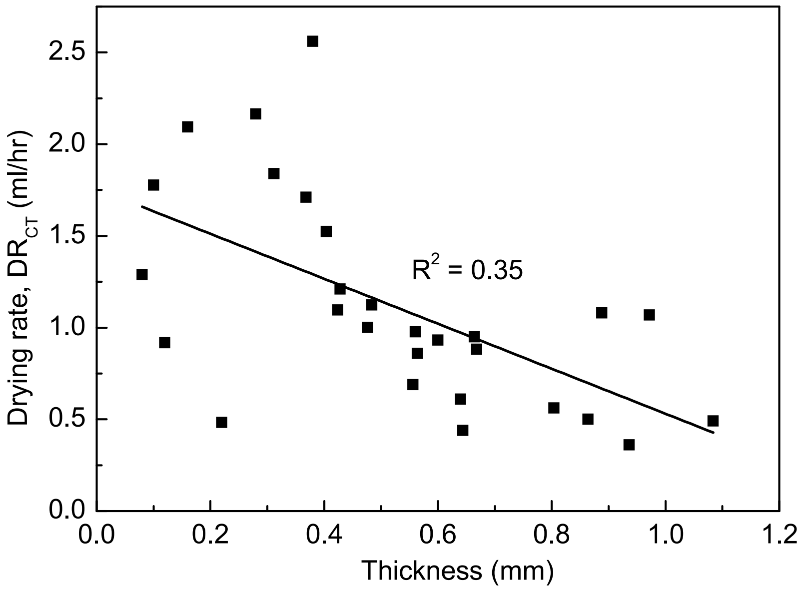


Figure 5.5 Drying rate (DR_{CT}) against fabric thickness of all tested fabrics

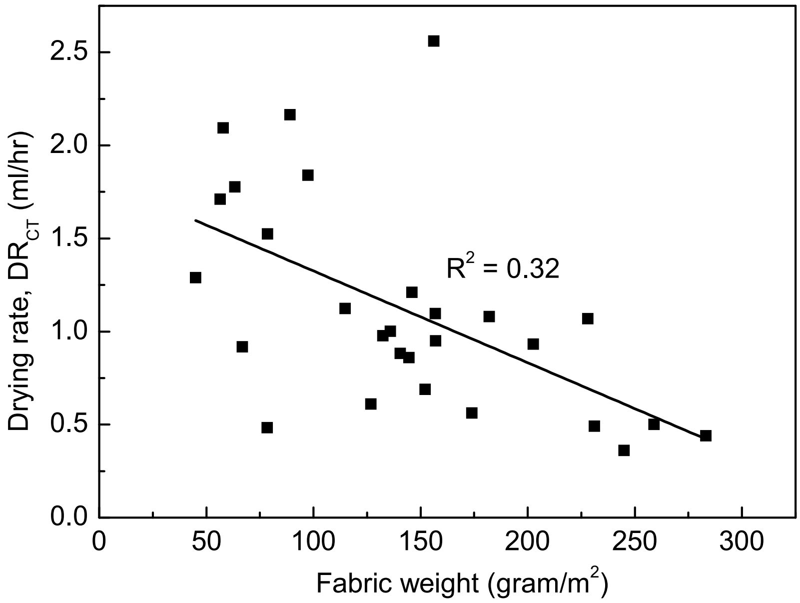


Figure 5.6 Drying rate (DR_{CT}) against fabric weight of all tested fabrics

Other than fabric weight and thickness, the plot of DR_{CT} against wetted area of fabric at 60 seconds after water applied (A_{CT60}) is shown in Figure 5.7, R^2 values of its linear regression is found as 0.26. This indicates the correlation between fabric wetted area and drying rate is weak. The weak correlation is scattered by some discrete result, those scattered fabrics are P3M, PMJ, SIL, PET1, PET3 and NYL (circled in red in Figure 5.7). This is because of wetted area of all these fabrics are still increasing at 60^{th} second. The linear regression without these six fabrics gives R^2 value 0.83 and this shows A_{CT60} correlates well with DR_{CT} for most cases. This good fit agrees with general understanding that fabrics with larger wetted area dry faster, as given that applied water amount are the same. On the other hand, those scatter result presents in Figure 5.7 implies that DR_{CT} cannot be easily replaced by wetted area of fabric.

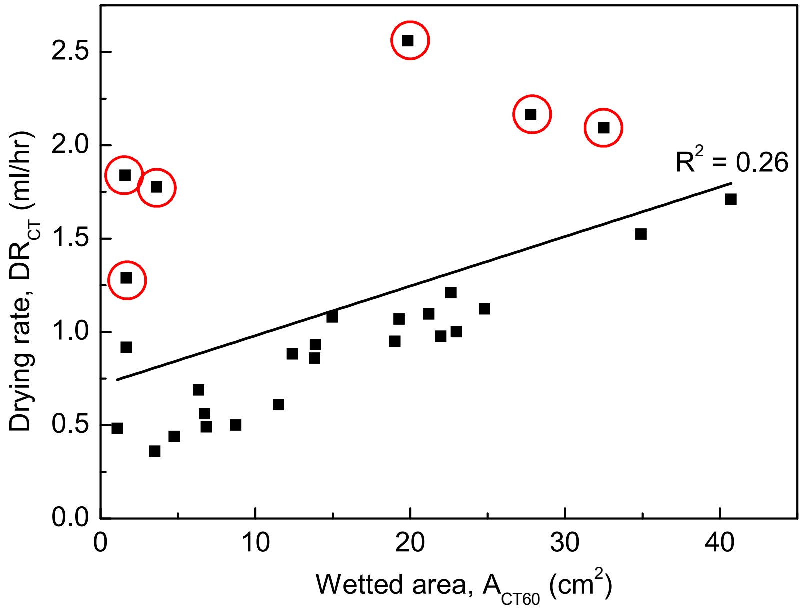


Figure 5.7 Drying rate (DR_{CT}) against wetted area of fabric at 60 seconds after putting fabric on water bead (A_{CT60}), scattered data are circled in red.

According to the discussion in this Section (5.4.2), fabric basic properties e.g. weight, thickness, materials and finishing affect the value of DR_{CT}. Moreover, wetted area of fabric (A_{CT60}) relates to DR_{CT}. There are moderately high correlation between drying rate and above-mentioned properties in some situation, but not all. For example, correlation between DR_{CT} and fabric weight is high while materials and construction is fixed (Table 5.3), however, the correlation becomes low for all 28 tested fabrics (Figure 5.6). This implies that such basic properties can only preliminarily predict drying rate of fabric in certain cases. However, the actual value of fabric's drying rate shall be measured by a drying rate tester, for example, CTDRT.

5.4.3 Evaporation of Moisture

The drying curve of evaporation of moisture from fabric includes full information about drying of fabric. This involves water supplied by auto-pipette, absorbs and spreads by fabric, then evaporates from fabric. Figures 5.8 to 5.11 are selected examples to investigate the phenomena and parameters commonly found throughout CTDRT experiments. These 4 figures show real-time data acquired from electronic balance of fabric WC1, WC3, K02 and PMJ during CTDRT measurement. These four examples cover the range of fabric absorption property. Absorbency time of K02 is shorter than 1 sec and PMJ is longer than 60 sec (Table 3.2; K02 < WC3 < WC1 < PMJ). Therefore, various absorption and spreading properties can be found in Figures 5.8 to 5.11. In each individual measurement, balance is tared before applying water on it (Step 5 of Table 5.1). So the amount of water applied by auto-pipette is recorded additionally, this enhances the traceability of CTDRT's operation.

WC1 and WC3 are different in yarn count and fabric density (Table 3.1). They are both plain structure cotton fabric (Table 3.1), so they have similar drying curves (Figure 5.8 and 5.9). There are some scattered data at the very beginning of tests. These data are induced by the delivery of water to the fabric, however these noise signal do not affect the measurement. Drying curves of WC1 and WC3 are slightly bent at the first 0.025 hr (90 seconds), the bends are because of the time required to stabilise wetted area. The stabilisation of wetted area includes absorption and spreading of water by specimen. The length of bends in time matches with the absorption time of fabric, i.e. modified AATCC 79: WC1 = 32 sec, WC3 = 13 sec (section 3.2). Another bend is found near the end of each drying curves, this is because of the decrease in wetted area. The decrease in wetted area means that effective area contributes to evaporation reduces gradually. This causes rate change of ΔW reduces near the end of drying curve, and the curve goes back to zero at the end. The major difference of the drying curves for WC1 and WC3 is the slope of drying curves, the lower fabric thickness and fabric weight

WC1 dry faster than WC3 (DR_{CT}: WC1: 1.71 ml/hr; WC3: 1.10 ml/hr).

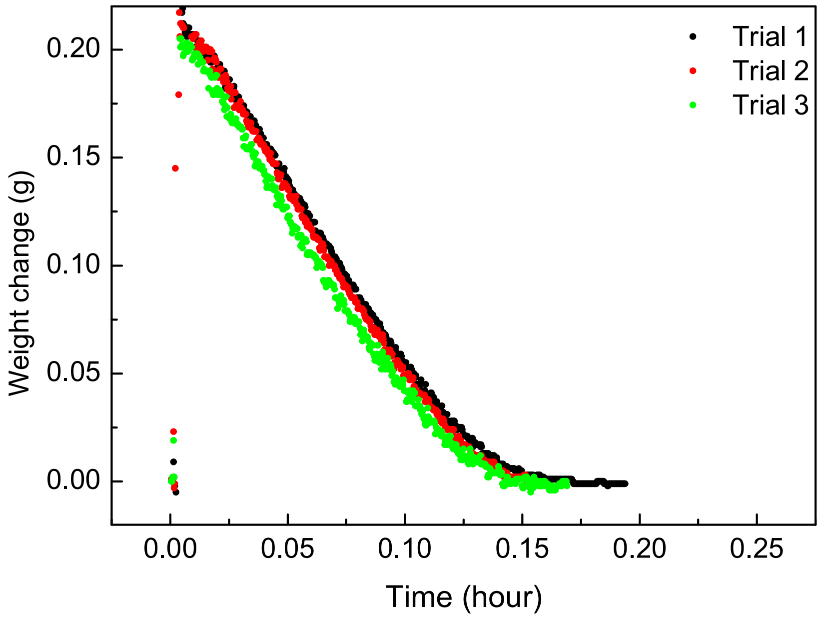


Figure 5.8 Weight change of woven cotton fabric WC1 against time.

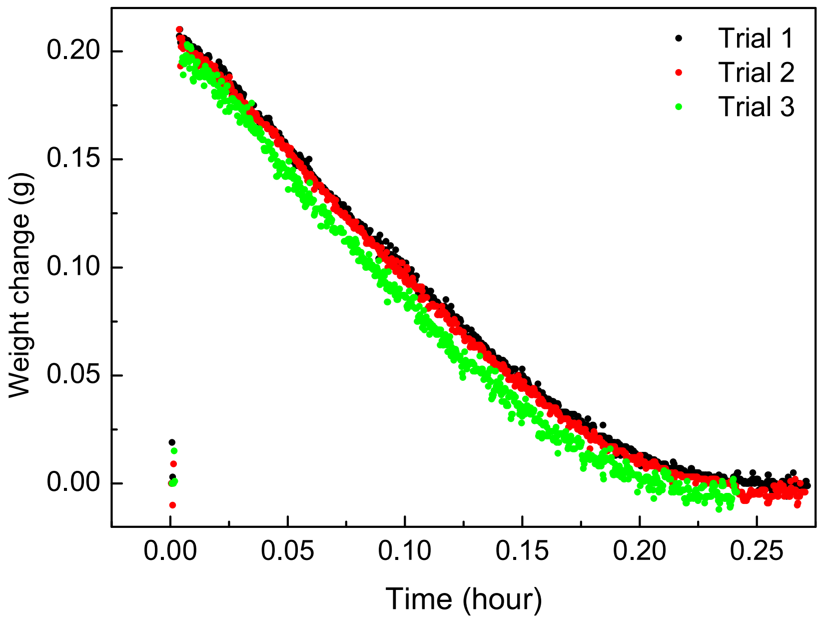


Figure 5.9 Weight change of woven cotton fabric WC3 against time.

As compare with WC1 and WC3, 95 % rayon and 5 % spandex knit fabric K02 takes around double time to completely dry (Figure 5.10). Since they have not undergone any special finishing, the difference among them is mainly due to materials and structures of fabrics. K02 has much smaller DR_{CT} (0.50 ml/hr) than WC1 and WC3. The shape of drying curves of WC1, WC3 and K02 are similar, except K02 does not bend at the beginning of drying curve. This is because K02 absorbs water in very short time, modified AATCC 79 test recorded result of K02 is less than one second (Section 3.2). The wetted area reaches its maximum within seconds, so no obvious bend can be found from the drying curves of K02.

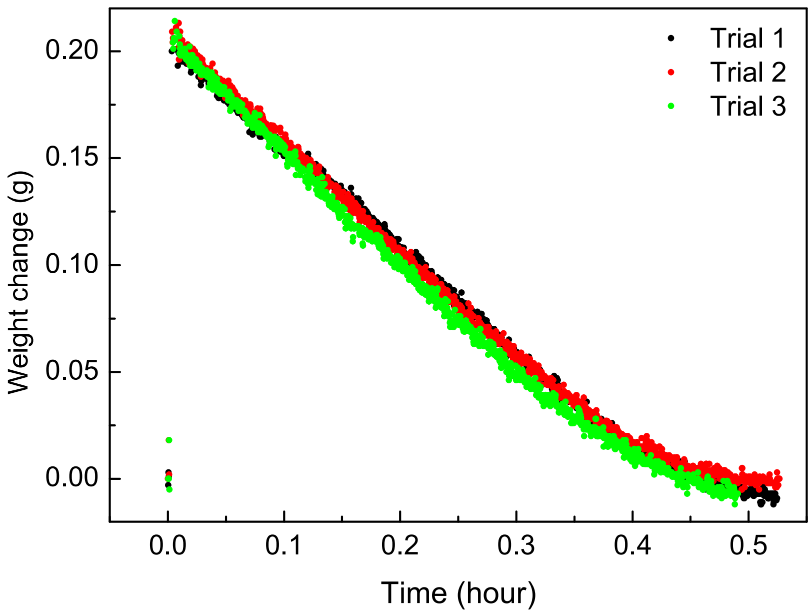


Figure 5.10 Weight change of knitted rayon fabric K02 against time.

Finally, Figure 5.11 shows drying curve of polyester micro jacquard woven fabric PMJ. PMJ has similar drying rate with WC1 (PMJ: 1.84 ml/hr; WC1: 1.71 ml/hr). Compared with WC1, PMJ has longer nonlinear region 0.05 hr, i.e. 3 minutes, at the beginning of PMJ's drying curve. This is because PMJ absorbs (section 3.2, modified AATCC 79 test: PMJ > 60 sec) and spreads water much slower than WC1. In other words, small wetted area on fabric causes smaller drying rate. Once wetted area becomes stable, the slope of Figure 5.11 becomes constant. The linear regions of all 28 tested fabrics are wider than the 0.15 g ≥ ΔW ≥ 0.05 g range. Therefore, the linear region is the main section of drying curve, so it is used to calculate the key parameter DR_{CT}. At the same time, the special drying properties at the beginning of experiment reflect absorption and spreading properties of fabric. This shows the advantage of CTDRT to analyse any atypical fabric drying properties at skin temperature. This function has not been achieved by previous studies with heater used.

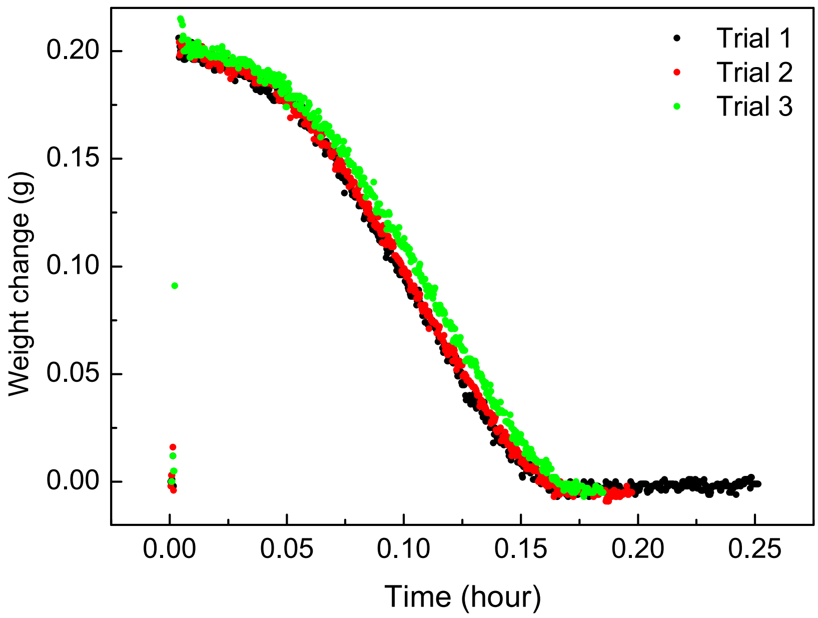


Figure 5.11 Weight change of woven polyester fabric PMJ against time.

5.4.4 Repeatability of CTDRT Result

Figure 5.4 shows the coefficient of variation of all water absorbing fabrics are smaller than 3 %, and slow water absorbing fabrics are smaller than 10 %. These confirm that the key parameter of CTDRT, drying rate DR_{CT}, has high repeatability. Figures 5.8 to

5.11 show raw data taken by electronic balance against time. Three repeats are performed on each fabric and are shown in the graph. It can be clearly seen that the whole drying curves are overlapping with each other, suggesting good repeatability. The good repeatability of drying curves provided informative trace during the whole drying process.

5.5 Correlation between CTDRT Result and Conventional Test

Figure 5.12 shows the conventional test, Water Evaporating Rate (WER) at 30th minutes and 60th minutes plot against DR_{CT}. It is not surprising that DR_{CT} and WER are roughly directly proportional to each other. This is because both methods show the evaporation of water from fabric. DR_{CT} has moderately good correlation with WER. The R^2 value between DR_{CT} and WER at 30th minute is 0.64, the R^2 of DR_{CT} and WER at 60th minute is 0.67. However, there are some completely dried fabrics recorded in the WER at 60th minute experiment. This saturation of result (100 % WER) is a disadvantage of WER to study broad range of fabrics. In comparisons, heating up of fabric, controlling air flow, and applying fixed amount of water to the fabric are used in CTDRT. These features can simulate skin temperature, provide stable result and is easier for comparison. In general, the differences in DR_{CT} and WER are due to fabric properties, e.g. materials, structure and finishing.

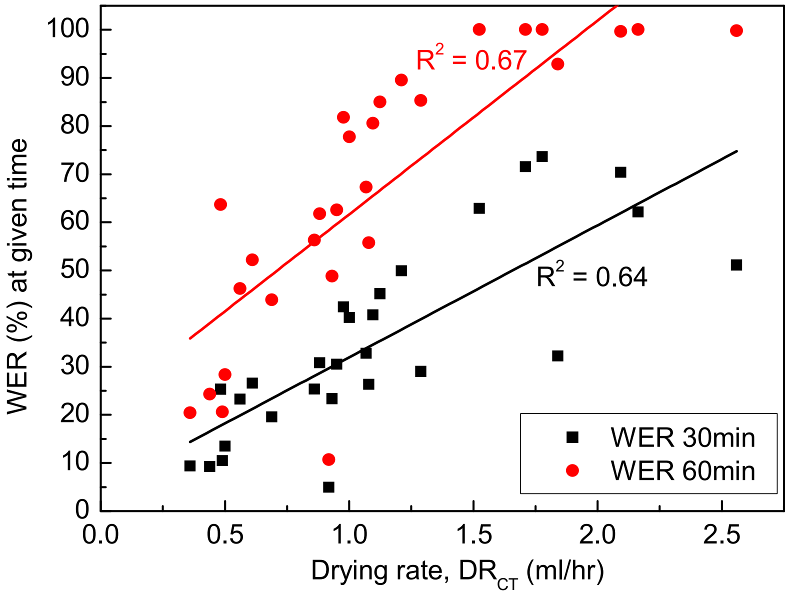


Figure 5.12 Drying rate result of fabrics: Conventional test against CTDRT, WER at 30^{th} and 60^{th} minute vs DR_{CT}.

5.6 Calibration of CTDRT and Uncertainty of DR_{CT}

Calibration procedures of CTDRT are simple, these involve calibration of electronic balance, auto-pipette and air speed. Mettler Toledo MS1003S electronic balance has a built-in calibration weight, so it can be calibrated internally to ensure readings for CTDRT are correct. Water transfer by auto-pipette is calibrated by measuring weight of water delivered. Air speed at sample surface and all ventilation opening are confirmed to be lower than 0.1 m/s by the anemometer. The calibration of auto-pipette and wind speed aims at verifying the system parameter. CTDRT employs internal timer of LabVIEW software to manipulate the system time, so that timing of CTDRT is offered by computer's clock. The LabVIEW sends commands to electronic balance every second for returning weight change (ΔW) back to computer. The uncertainty of computer's clock can be neglected in research laboratories. Calibration and uncertainty issues about CTDRT are summarised in Table 5.4.

Table 5.4 Calibration and uncertainty of instruments used and system parameters of CTDRT

Instrument	**Parameter**	**Calibration**	**Uncertainty (given by manufacturer)**
Electronic balance	Water evaporates from fabric	Use built-in calibration function of balance	± 0.001 g
Auto-pipette	Water delivered	Measure the weight of water delivered	± 0.6 %
/	Air speed at sample surface and all ventilation opening	Air speed lower than 0.1 m/s, is checked by an anemometer	± 0.1 m/s
Timer	Time	Use internal timer of software LabVIEW to facilitate regular data acquisition from electronic balance	Negligible

According to Equation (5.1), the key parameter DR_{CT} depends on two parameters, weight change (ΔW) and time. Uncertainty of DR_{CT} (i.e. δDR_{CT}) can be found as below calculations:

$$\delta DR_{CT} / DR_{CT} = (\delta\Delta W / \Delta W) + (\delta time / time) \quad (5.2)$$

while uncertainty of internal timer of the LabVIEW can be neglected, so that

$$\delta DR_{CT} / DR_{CT} = (\delta\Delta W / \Delta W) + 0 \quad (5.3)$$

the uncertainty of electronic balance is 0.001 g and the range for DR_{CT} calculation is 0.100 g

$$\delta DR_{CT} / DR_{CT} = (0.001\ g / 0.100\ g) \quad (5.4)$$

$$\delta DR_{CT} / DR_{CT} = 0.01 = 1\ \% \quad (5.5)$$

so that δDR_{CT} is at 1 % of DR_{CT}.

5.7 Limitations of CTDRT

As shown in Figure 5.4, there are CVs larger than 3 % for drying rate DR_{CT} on some of the slow absorbing samples (absorbing time larger than 60 seconds by modified AATCC 79 standard test). However, it should be noticed that water shall be absorbed by fabric before water evaporated/dried from the fabric. Rolling off of sweat commonly occurs on slow water absorbing sample during in vitro use, however, this is out of the scope of studying drying rate. Another limitation would be pictures taken from the face side of fabrics are assumed as the maximum wetted area of fabric. This assumption allows quick capture of the wetted area, and it does not affect the accuracy of DR_{CT} measurement.

5.8 Summary

Constant Temperature Drying Rate Tester (CTDRT) equipped with a non-contact heating component. CTDRT offers a test method to measure weight change (ΔW) of fabric throughout the whole experiment. This helps to provide valuable information for analysis and comparison. Therefore, drying properties of fabric can be known with the effect of absorption and spreading of water on fabric. This helps to figure out fabrics with special drying profiles while other fabric drying rate methods with heat (AATCC 199, AATCC 201) cannot provide such information.

CTDRT's sample platform can be selected at different target constant temperature to simulate different skin temperature to dry wetted fabric, and 37 °C was chosen. The PID controlling algorithm helps to maintain very stable temperature, ± 0.5 °C, at the sample platform. Fabric drying rate highly depends on air speed, and the dependency can be stronger than fabric's properties. Therefore, this study used zero air speed for the ease of comparison. The wind shield offers very good protection to the CTDRT measuring system against wind or any disturbances from the outer side. A fan installed at wind shield generates a negative air pressure gradient to exhaust moist air inside of the wind shield. This negative pressure gradient system is able to keep a constant atmospheric condition, but it maintains zero wind speed at and near test sample.

CTDRT testing time of each sample is around 15 to 40 minutes. Drying rate (DR_{CT}) is the most representative parameter for fabric's drying phenomena. One-way ANOVA of eight simple structured woven cotton fabrics has confirmed the validity of DR_{CT} at 0.05-level significance. In addition, DR_{CT} has a wide range, 0.36 to 2.56 ml/hr, for all 28 fabrics tested. The wide range shows that DR_{CT} is able to discriminate drying property of samples. The coefficient of variations of DR_{CT} of water absorbing fabrics are smaller than 3 %, and poor water absorbing samples are smaller than 10 %. From the plot of weight change against time, overlapping the drying curves of the same fabric measures at different time confirms that the tests are repeatable. The drying curves also give comprehensive full picture of fabrics drying profile. The DR_{CT} is found to have good and moderate correlation with A_{CT60} and conventional WER test respectively. This shows CTDRT's result has a uniqueness to evaluate drying rate at constant temperature.

Chapter 6 Assessing the Subjective Wet Sensation of Fabrics with Different Drying Time

6.1 Introduction

Drying of fabric refers evaporation of water from wetted fabric, and the fabric is commonly wetted by sweating. For example, a shirt is wetted by sweat when a wearer walks under sunshine or hot weather. Then, the wearer goes indoor area for meeting or dining but he/she may have no chance to change the clothes. This can induce unflavoured post-exercise chill sensation (Gavin, 2003; Splendore et al., 2011; Kim and Na, 2016). The shirt gives a wet sensation to wearer for an extended period before it turns dry. Therefore, the wet sensation against drying fabrics is worth to be investigated. The condition of this subjective wet sensation assessment is set to demonstrate wearer in recovery period after light activities, and no further sweat secretion.

There was some wearing subjective wetness assessments with recovery/rest period investigated in previous research (Bakkevig and Nielsen, 1995; Chung and Cho, 2004; Yoo and Barker, 2005; Ahn et al., 2011). Time-consuming would be major limitation of wearing tests. This is because subjective assessments involve hiring subjects for extended testing period and preparation of batches of garments. These complicated procedures would limit the number of assessors and variety of specimens. Further, wearing test cannot be conducted at the beginning of project, for example, fabric manufacturing and fabric screening stages. Therefore, there are needs to hold fabric based subjective test, so as to quickly select and compare fabric in various stages of research and business works. While wetted fabric dries on the skin, the wet sensation will change from time to time. The wet perception drops when water in fabric reduces due to evaporation. There was no fabric based subjective wetness assessment against time studied in the literature. This Chapter aims at investigating wet sensation of human against drying fabrics over time, from wet fabrics to dry fabrics.

A wetness rating given by a subject represents an actual sense against wetted fabric. On the other hand, the time dependence of wetness rating reflects the resultant effect of water transport within fabric and water evaporation from fabric over time. This study acquires the wetness rating at fixed intervals for an extended duration, and then investigates the time dependence of wetness rating. Since sensory fatigue of subjects can be a concern in subjective assessments (Ennis and Jesionka, 2011; Tang et al., 2015c), the maximum fabric dry time is limited at 64 minutes for acquiring wetness rating. Then, the wetness rating is projected to the whole time span of drying process. The rolled off of non-absorbed sweat under body movement is considered in the assessment by using “stamping” method for applying water to specimens. Furthermore, a 2-arm fabrics driver was built to simulate human’s daily movement.

During the wetness assessment, wetness rating against specimens is always rated by comparing with wetted reference simultaneously by both forearms. The subjects are not required to memorise the perception against the reference fabric, the possibility of drift in reference value can be avoided. Therefore, subjects can focus on comparing the difference in wetness between specimen and reference. This helps in enhancing reliability of the assessment. All subjective assessments were conducted in a single day for each subject. This prevents within subject drift and contributed to reliability as well.

Ratio scale is used as wetness rating scale in this study. This experimental design gives no boundary to subject's rating, allows subjects to compare level of wetness in ratio. Subjects also not required to deal with the meaning of verbal terms (e.g. slightly wet, barely wet, etc. lists in Table 2.3). Therefore misunderstandings of verbal terms are prevented.

6.2 Experimental

6.2.1 Setup of Fabrics Driver

In order to provide repeatable fabrics movements against assessor's forearms, a 2-arm fabrics driver (Figure 6.1) was built to drive fabrics to and fro on assessor's forearms. The design of the driver referenced to the experimental setup of (Tang et al., 2015c). However, the driver built for this study moved two fabrics in-phase on forearms of assessor. This allowed comparison of wet sensation between reference fabric and sample fabric simultaneously. The motion of fabrics was actuated by rotation of two motor-driven paddles. The paddles pulled fabrics via inelastic strings at the first-half cycle and sent back fabrics by springs at the second-half cycle. Clips were used to hold fabric at around 0.5 cm at both ends. This allowed quick reload of test and reference specimens in every trial. The specimens were moved along the length of fabrics. This prevented large elongation of knitted fabric during tests. One of the forearms was presented with reference fabric, another forearm was presented with testing fabric. The left-right arrangement of reference specimen was randomly drawn at the beginning of the assessment. The left-right hand arrangement was fixed for each subject to avoid confusing subjects and operators during test.

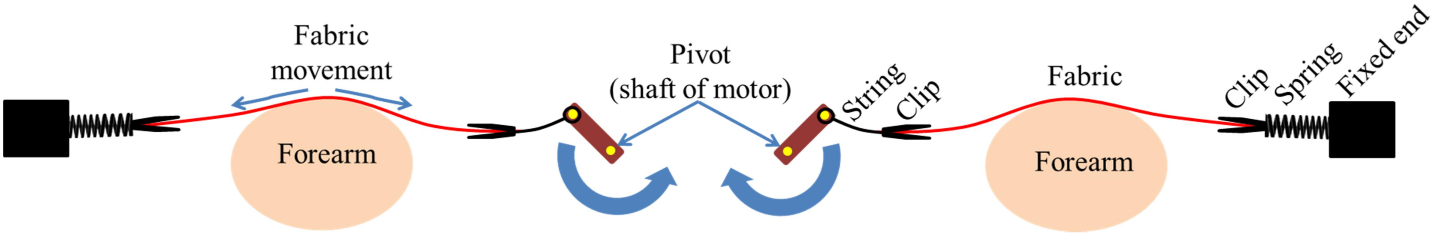


Figure 6.1 Schematic diagram of 2-arm fabrics driver for subjective wetness assessment (cross-section)

6.2.2 Assessors, Specimens, Reference Fabric and Environmental

Condition

21 subjects were invited for wet sensation assessment, and one of them failed to pass a screening test (screening test and its rejection criterion specified in Section 6.2.3.1). Therefore, 7 male and 13 female subjects participated in the assessment. The age range of subjects was from 23 to 38, average value was 28 years old. These subjects had no knowledge about specimens and reference fabric.

Eight samples were selected for the subjective wet sensation assessment. They were K01, K02, WC1, WC3, P3M, WOL, SIL and PET2. These samples include knitted and woven fabrics with various fibre content, their specifications are listed in Section 3.1. These specimens in size of 12 x 12 cm^2 were gently ironed for a flat surface, and then conditioned in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for at least 12 hours. The subjective tests were conducted at the same condition. WC3 carried 0.8 gram of water was selected as reference fabric, the amount of water was defined empirically. The WC3 for reference was wetted but not yet saturated for comparing with specimens.

All testing fabrics, including reference fabrics, were wetted by spraying water on a plastic card in the size of 12 x 12 cm^2. Then, each fabric was put on the wetted plastic card, and the stack was pressed by a pressure of 2.5 g/cm^2 for 5 seconds. The pressure referenced to Gravimetric Absorbency Testing System (GATS) (McConnell, 1982) to achieve good contact between fabric and wetted plastic card. As mentioned in last paragraph, reference fabric was WC3 which carried 0.8 gram of water. The same spraying and wetting procedures were done for all specimens, however, 1.4 gram of water sprayed on the plastic card. The wetted specimens were then put on a bench and wait for 0, 16, 32, 48 or 64 minutes. Once the pre-set time was up, the sample was delivered to subject's forearm for assessment. This is named as the "drying time of fabric".

For the ease of communication, K01-00 is nominated to represents waiting time of 0 minute and K01-16 represents the waiting time of 16 minutes, etc. 1.4 gram of water on 12 x 12 cm^2 area (around 10 mg/cm^2) corresponded to sweat amount for around 23 to 61 minutes of light activity, the time depended on sweat rate listed in Section 2.5.2.

6.2.3 Procedure of the Subjective Assessment

The subjects were asked to confirm that they were at normal physical condition. Then, their age and sex were recorded. After that, subjects were asked to wash their forearm with water and then acclimatised in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for 30 minutes. During this acclimatisation time, detail instructions of the wetness assessment were given to the subjects.

When training session began, subjects were invited to sit on a chair and putting both arms on a table. Subjects can decide a comfortable posture. A curtain was set in front of subjects to ensure blind tests were conducted. Ten training fabrics were presented to each subject. They were K01-32, K02-32, WC1-32, WC3-32, P3M-32, WOL-32, SIL-32, PET2-00, PET2-32 and PET2-64. These ten fabrics were presented to subjects randomly for adopting wet sensation rating scale. The subject should give wetness rating for all training fabrics. The wet sensation rating scale was in ratio and based on comparing wet sensation between reference fabric and specimen. While reference and specimen were the same in wet sensation, wetness rating 100 (percent) should be rated by subject. If subject sensed that specimen was less wet than the reference in half, wetness 50 (percent) should be given. In contrast, if subject sensed specimen was much wetter than reference, he/she can rate 1000 (percent) for a specimen that 10 times wetter than reference fabric. The wetness rating can be any non-zero positive number, and not limited to integer. As discussed in Section 6.1, sensory fatigue of subjects can be a concern in subjective assessment (Ennis and Jesionka, 2011; Tang et al., 2015c). In order to prevent drop in skin sensitivity by prolonged exposure under stimulants, subjects had a 15 seconds limit to rate each sample. If time was over, the corresponding wetness rating should leave blank. One specimen fabric with one reference fabric were presented to subject every minute. There was at least 45 seconds rest time between assessments. After each test, subjects should get soft tissues to gently absorb residual water on the skin. However, rubbing was prohibited to prevent skin irritation. Above procedures were applied to whole subjective wetness assessment, test samples were K01, K02, WC1, WC3, P3M, WOL, SIL and PET2 wetted, then waited for 0, 16, 32, 48 and 64 minutes before presented to subject. The total number of test specimens was 40 pieces, plus 10 pieces of training fabrics for each subject. Since assessing wetness sensation of dried fabric is contradictory, the design of experiment not intended to measure wetness sensation at the end point, i.e. at fabric completely dried.

6.2.3.1 Screening Test and Rejection of Subjects

The three PET2 training fabrics mentioned in the last paragraph (PET2-00, PET2-32 and PET2-64) also acted as screening fabric of subjects. If a subject cannot give wetness rating of 0^{th}, 32^{nd} and 64^{th} minute at descending (≥) sequence, the subject was rejected in the whole experiment. Finally, one subject was rejected under this selection criterion.

In addition to screening, rejecting criterion was set to further reject subjects based on wetness rating result in data analysis stage. Linear regressions were conducted on wetness rating with corresponding drying time (i.e. 0, 16, 32, 48 or 64 minutes after water applied to fabrics). The linear regressions were executed on each set of data, i.e. each subject and each fabric individually. If the regression result gave positive slope (i.e. wetter perception for drier fabric) with $R^2 \geq 0.50$, corresponding results shall be rejected. This reflected that subject may be unstable for wetness assessment. Therefore, all assessment result given by that subject should be disregarded. No rejection of subject was recorded under data analysis stage, this may be benefited from conducting screening tests at the beginning of sensation assessments.

6.3 Result and Discussion

Fabric wetness rating is evaluated by subjects at various “time”. The “time” referred to how long that specimens are dried naturally at standard atmospheric condition (20 ± 1

°C and 65 ± 5 % RH) after they are wetted. Given that fixed amount of water is sprayed, the wetness rating against "time" of drying can be found. The wetness rating is an actual sense of wetted fabric. The time dependence of wetness rating reflected the resultant effect of water transport and water evaporation of fabric over time. The amount of water carried by fabrics is weighted just before the fabrics were presented to subjects for wetness evaluations. Based on the experimental results, within-subject reliability, between-subject consistency and sensitivity of the subjective wetness assessment are discussed later in this section.

Figure 6.2 is a box-and-whisker plot of subjective wetness rating of all result. The fabrics and "time" are labelled on the x-axis. In this plot, a small square indicates the mean of wetness rating. The bottom and top of the box show 25 percentile and 75 percentile of data respectively. The band inside the box is the median of result. Maximum and minimum of data are marked with crosses. Lastly, the whiskers represent one standard deviation apart from the average value. The wetness rating is a comparison between test specimen and reference fabric, rating 100 means specimen and reference fabric give the same wetness sensation. Rating 200 indicates specimen is wetter than the reference in double (detail rules see Section 6.2.3). Overall, the wetness rating recorded from 20 subjects consistent with the general understanding that wet sensation decreased with the increases of drying time. The drop in wetness rating against drying time changes obviously at relatively thin specimens (WC1, SIL and PET2). This also agrees with the common perception that thin fabric dries faster than thick fabric. Wetness rating of WC1-00 and SIL-00 is rated higher than 500 by some subjects. This is because these specimens are saturated with water during wetness assessment, and water is in contact with subject's forearm intimately. Such results are still considered in this study since they are actually sensed by the subjects.

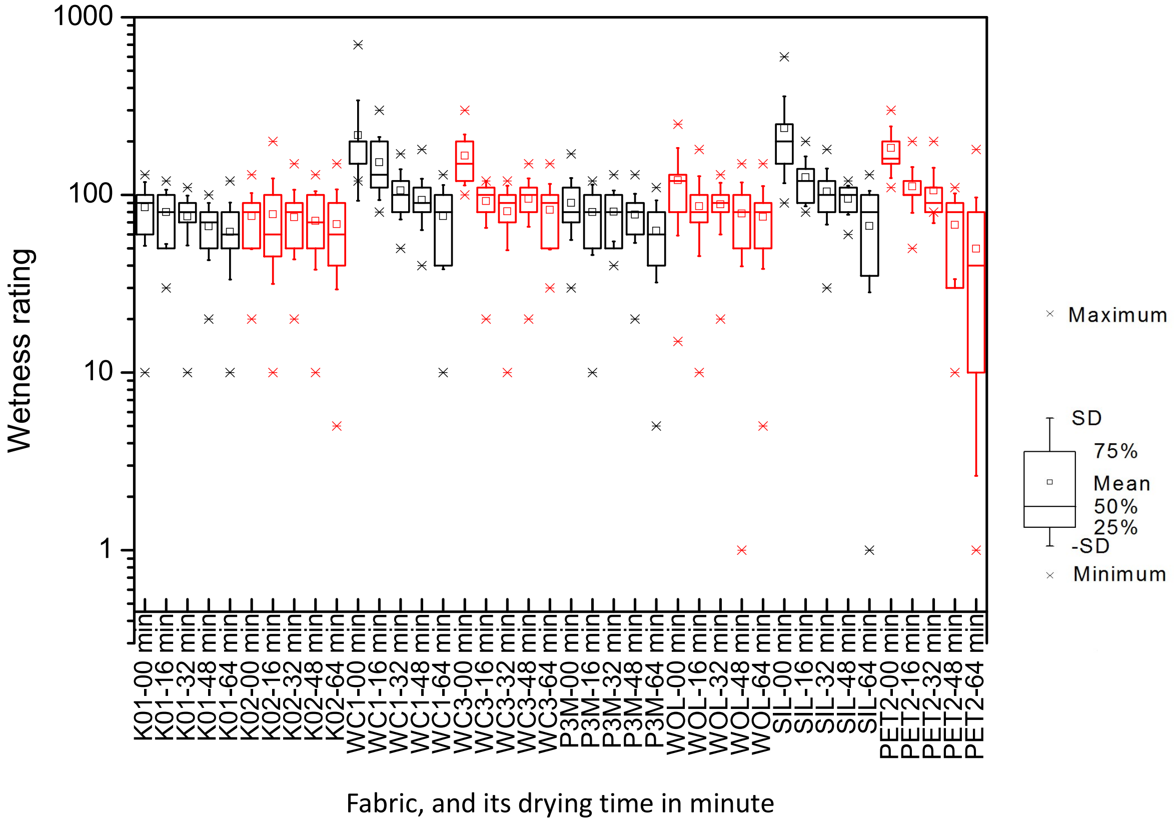
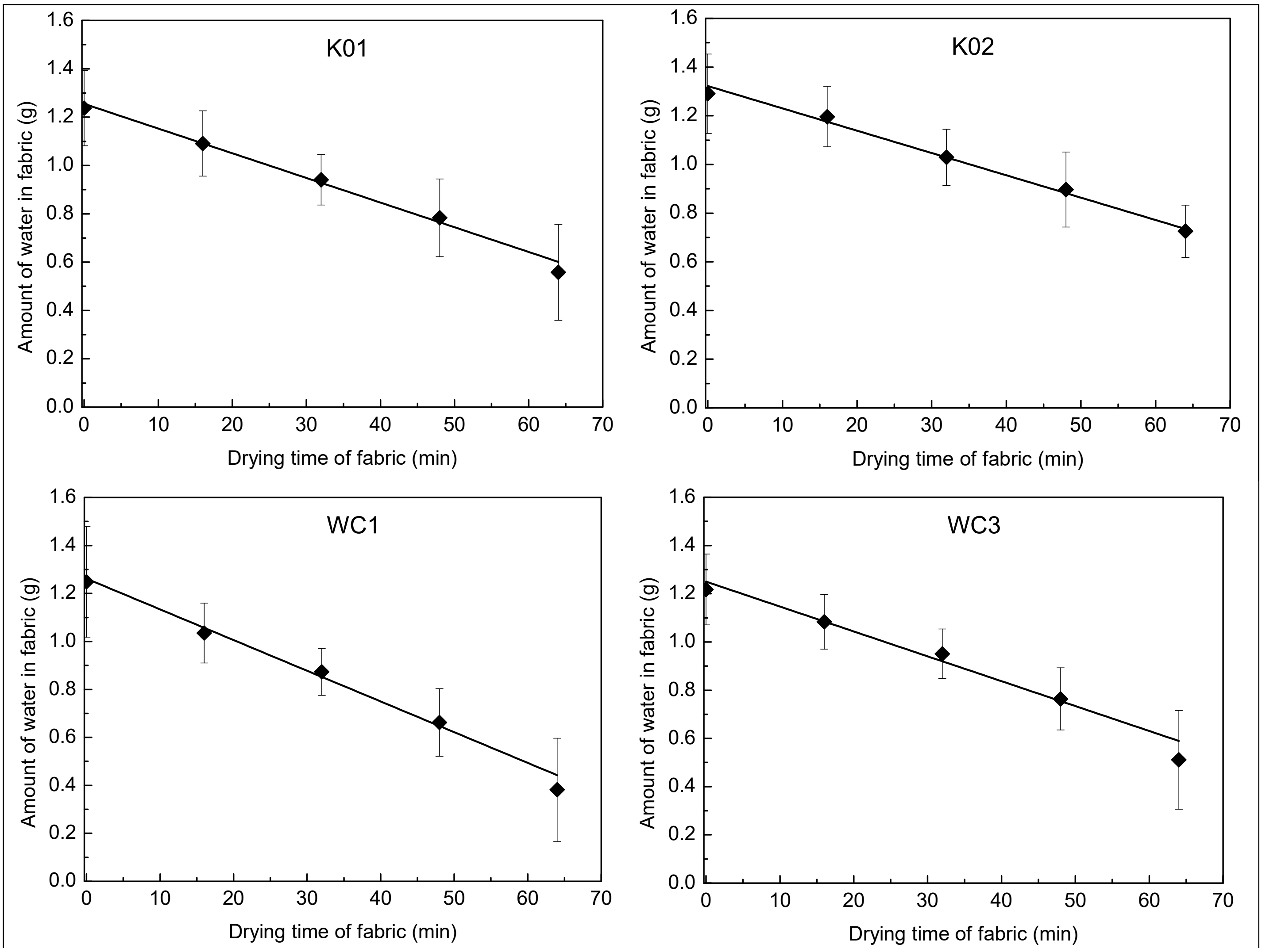


Figure 6.2 Wetness rating of all assessed fabrics at various drying time (20 subjects).

In Figure 6.3, the y-axis of plots represents water carried by fabric before it is delivered onto subject's forearm. X-axis is the time of fabric wetted then dried naturally at standard atmospheric condition. Linear regressions are conducted on each of the plots, the slope, intercepts and R^2 value of plots shown in Figure 6.3 are listed in Table 6.1. The R^2 value of all these eight plots are at least 0.97. This implies water amount on fabrics decreases constantly under a natural drying process. The slope of plots represents the drying rate of fabrics at standard atmospheric condition. The x-intercept is an extrapolated value, it represents the projected time for fabric completely dried. The parameters shown in Table 6.1 help in later analysis of this study. As specified in Section 6.2.2, 1.4 gram of water is sprayed on a plastic card, then fabric is placed and pressed to absorb water. It is found that part of water remains on the plastic card. This phenomenon becomes obvious for SIL and PET2. Data point 0 min of "water amount against time" (Figure 6.3) indicates that SIL and PET2 carry less than 1.0 gram of water after pressing. The residual water on plastic card is disregarded, as this consisted with actual wearing situation that sweat may roll off if it is not absorbed. The "water amount against time" plots (Figure 6.3) shows fabrics dried in different rates, PET2-64 almost completely dried at 64th minute. On the other hand, K02-64 and WOL-64 evaporates roughly half of absorbed water.



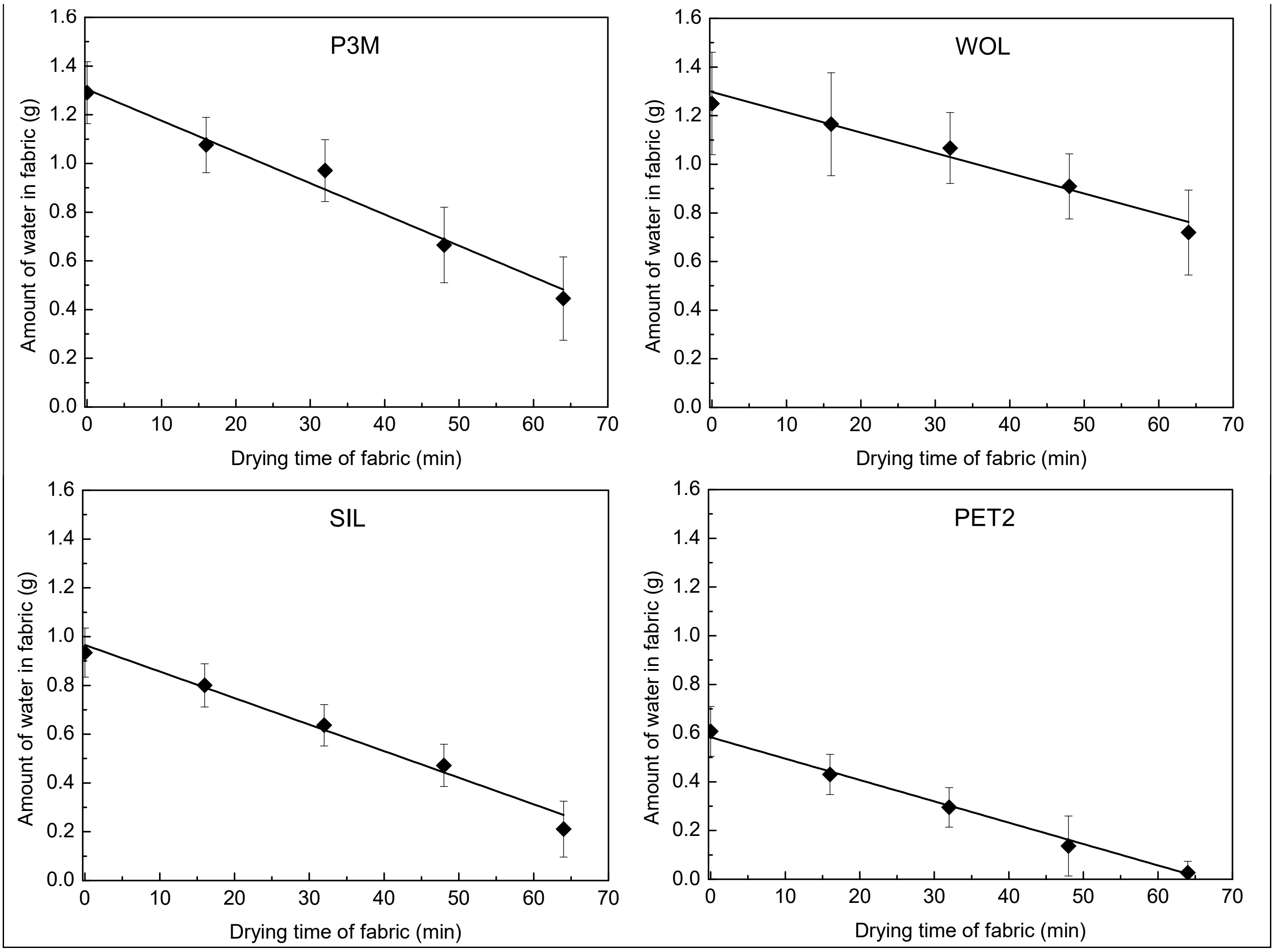


Figure 6.3 Plots of water amount on fabric at corresponding drying time (20 subjects), error bars show one SD of uncertainty

Table 6.1 Slope, intercepts and R^2 value of plots shown in Figure 6.3 (amount of water against drying time)

Fabric	Slope (drying rate, ml/min)	Y-intercept (water carried at 0th minute, ml)	R^2	X-intercept (expected time for fabric dried out, minute)
K01	-0.0104	1.26	0.99	120
K02	-0.00894	1.31	0.99	147
WC1	-0.0132	1.26	0.99	95.8
WC3	-0.0108	1.25	0.98	116
P3M	-0.0131	1.31	0.98	99.7
WOL	-0.00823	1.29	0.97	156

SIL	-0.0111	0.966	0.98	87.0
PET2	-0.00909	0.590	0.99	64.9

6.3.1 Categorisation of wetness rating results

Figure 6.4 and 6.5 present three sets of data of K01 from three individual subjects. These examples help to introduce the rules of categorising each set of data. Two categories show (i) subject senses drop in wetness when that fabric drying out, and (ii) subject does not sense change in wetness when that fabric drying out.

The first set of data of K01 (Figure 6.4) shows an assessor sensed lower wetness when drier fabrics (waited longer time after sprayed) were presented. When linear regression of a set of data gave $R^2 \geq 0.50$ and negative slope, this set of data is defined as category (i) subject senses drop in wetness when that fabric drying out. Some fluctuations in data are accepted in subjective sensation test, e.g. 32nd minute shown in Figure 6.4. The number of count of category (i) fabrics is listed in Table 6.2. Table 6.2 also lists the average value of slope and the average of y-intercept of "wetness rating against drying time of fabric". Detail regarding Table 6.2 is discussed after introducing the definition of category (ii) response of subjects. It should be reminded that data set with $R^2 \geq 0.50$ and positive slope shall be rejected. Such response from subject is not found in this research (Section 6.2.3.1).

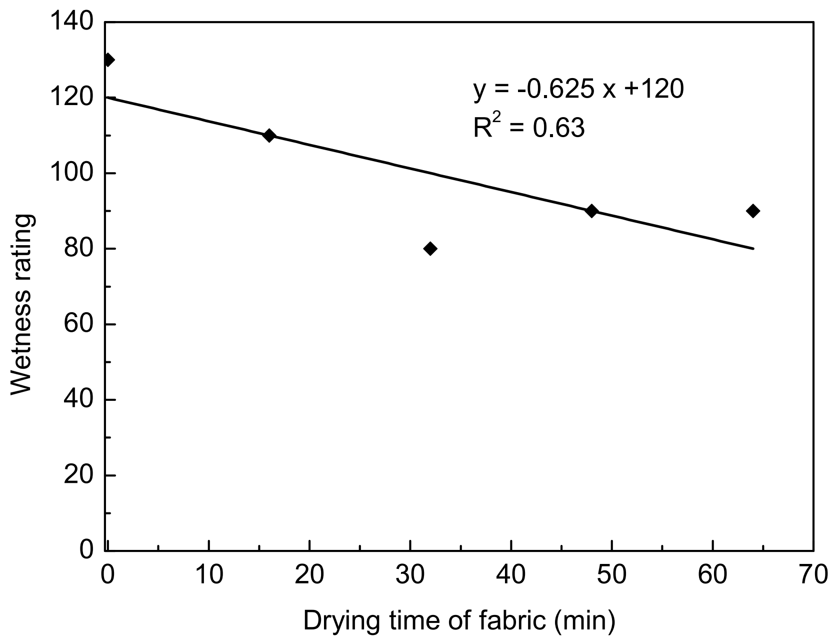


Figure 6.4 Wetness rating against drying time of K01 of subject A, subject A senses drop in wetness.

Table 6.2 Data sets that fall into category (i), subject senses drop in wetness when that fabric drying out

Fabric	**Number of data set (subject) falls into category (i)**	**Average**	**Standard deviation**	**Coefficient of variation**	**Average**	**Standard deviation**	**Coefficient of variation**
		of slope of "wetness rating against time dried"			**of y-intercept of "wetness rating against time dried"**		
K01	10	-0.644	0.236	0.37	98.8	13.0	0.13
K02	1	-0.438	/	/	104	/	/
WC1	14	-2.57	1.81	0.70	213	99	0.46
WC3	11	-1.22	0.71	0.58	138	30	0.22
P3M	6	-0.828	0.349	0.42	121	17	0.14
WOL	8	-1.21	0.69	0.57	128	23	0.18
SIL	19	-2.45	1.57	0.64	206	71	0.34
PET2	18	-2.02	1.06	0.52	165	46	0.28

When linear regression gave $R^2 < 0.50$, such set of data is regarded as category (ii) subject does not sense change in wetness when that fabric drying out. This implies no significance trend in wetness sensation when fabrics with different drying time are assessed. Result within a set of category (ii) data is similar and random, so both positive and negative slope in linear regression are included in category (ii), examples can be found in two sets of data of K01 (Figure 6.5). No sense on change in wetness is a reasonable response. This can be due to fabric's properties or subject's sensitivity. In such cases, subject still gives certain wetness rating, and the rating does not have an obvious change against drying time. Therefore, data falls in category (ii) are kept for analysis. However, they are analysed separately from category (i) result. This is because the characteristic of data sets in category (i) and (ii) are different, they should be processed in different ways.

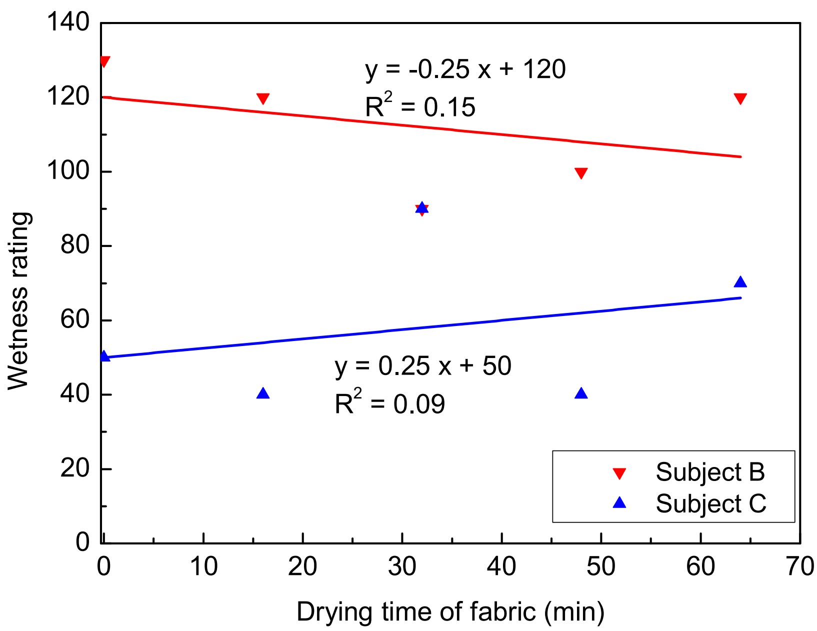


Figure 6.5 Wetness rating against drying time of K01 of subject B and C, subject B and C do not sense change in wetness.

Table 6.3 summarises number of data sets fall into category (ii), and average wetness rating at various drying time of fabric. Subject's responses for K01, K02, P3M and

WOL mainly fall into category (ii). Their averaged wetness ratings are rather constant with respect to drying time (Table 6.3). This is coherent with the definition of category (ii) response "no sense in change". Average wetness rating of category (ii) data sets can be applied as additional information in the wetness sensation study. This parameter is able to figure out the wetness sensation rating of time independent sets of results. The wetness rating listed in Table 6.3 reflects that the accessors feel that K01, K02 and P3M are drier than WOL. The constant wetness response is mainly due to fabric properties, but not poor sensitivity of subjects. This is because screening test and some other fabric's results (e.g. SIL and PET2) prove that subjects are sensitive to wetness of fabric. In contrast with K01, K02, P3M and WOL, averaged category (ii) wetness ratings of WC1, WC3, SIL and PET2 are not constant with respect to drying time of fabric. The discussion on category (ii) sense pause at here, and following contents go back to category (i) wetness response.

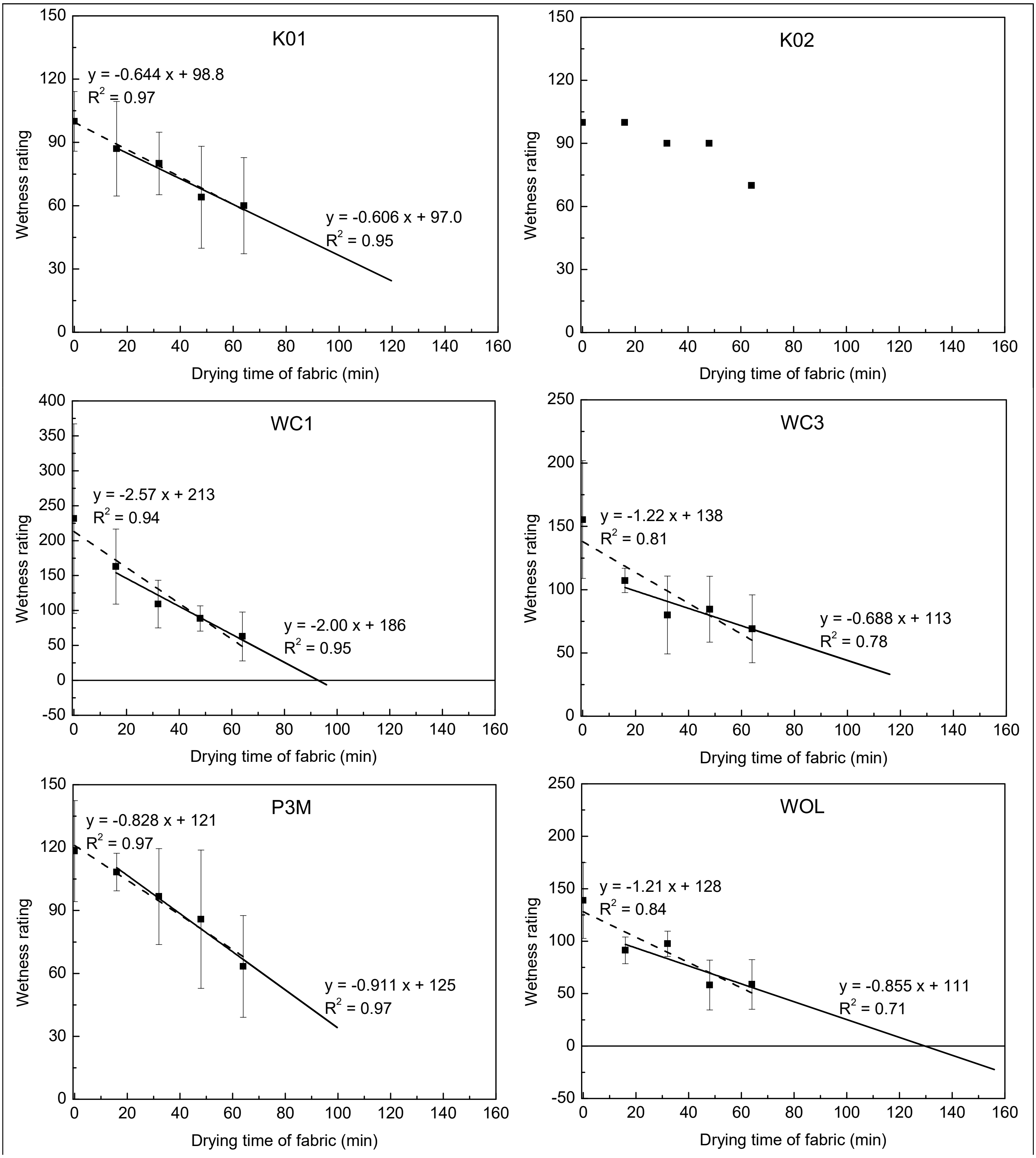
Table 6.3 Data sets that fall into category (ii), subject did not sense change in wetness when that fabric drying out

Fabric	**Number of data set (subject) falls into category (ii)**	**Average wetness rating at "xx" minutes drying time (Standard deviation)**				
		0^{th} min	**16^{th} min**	**32^{nd} min**	**48^{th} min**	**64^{th} min**
K01	10	70 (38)	73 (28)	71 (28)	69 (21)	64 (32)
K02	19	75 (26)	77 (46)	74 (32)	71 (33)	68 (39)
WC1	6	182 (62)	130 (60)	98 (27)	105 (43)	107 (18)
WC3	9	178 (54)	74 (29)	82 (31)	108 (25)	99 (31)
P3M	14	78 (29)	68 (32)	74 (23)	74 (16)	63 (32)
WOL	12	110 (70)	83 (51)	83 (33)	92 (40)	86 (39)
SIL	1	90 (/)	80 (/)	100 (/)	100 (/)	80 (/)
PET2	2	215 (/)	105 (/)	155 (/)	65 (/)	130 (/)

6.3.2 Analysis of wetness rating results

Based on data sets fall into category (i) (Column 2 of Table 6.2), the analysis is further conducted to compare result between fabrics and to project wetness rating result in the whole drying process. As mentioned in Section 6.1, the first reason to conduct projection is to limit the total testing time. This is important to prevent subjects fatigue during the assessment. Another reason for wetness projection is because it is not reasonable to give a wetness sensation rating at a completely dried fabric. Line fitting and then projection are done for wetness rating from fabric freshly wetted (0^{th} min) until it is dried. The time of fabric dried out is obtained from the x-intercept shown in "water amount on fabric at corresponding drying time" (Figure 6.3, also listed in the last Column of Table 6.1). Plots "Wetness rating against drying time of fabric" according to category (i) are shown in Figure 6.6 for linear plots and Figure 6.7 for semi-log plots. The reasons to use both scales are explained in next paragraph.

As shown in Figure 6.6, for example, ten data (from ten trials assessed by ten subjects) of K01-00 are averaged and shown as the first data. The error bar shows one SD of uncertainty. As indicates by Figure 6.3, water evaporates from wet to dry at a constant rate. Water carried by fabric is in a linear relationship with the drying time. This linear relationship are consistent with previous water evaporating rate (WER) study (Saricam and Kalaoglu, 2014). Therefore, linear scale is employed in Figure 6.6 for line fitting and projection of wetness rating against drying time of fabric. For semi-log graphs shown in Figure 6.7, the y-axes are transformed to base-10 logarithmic scales. This is because the range of wetness rating is not limited, and a wide range of wetness rating (from 1 to 700) is given by the 20 subjects. The plots shown in Figure 6.6 and 6.7 help to study the relationship between wetness rating and drying time of fabric. This is the wetness sensation against wetted fabrics while fabrics are drying.



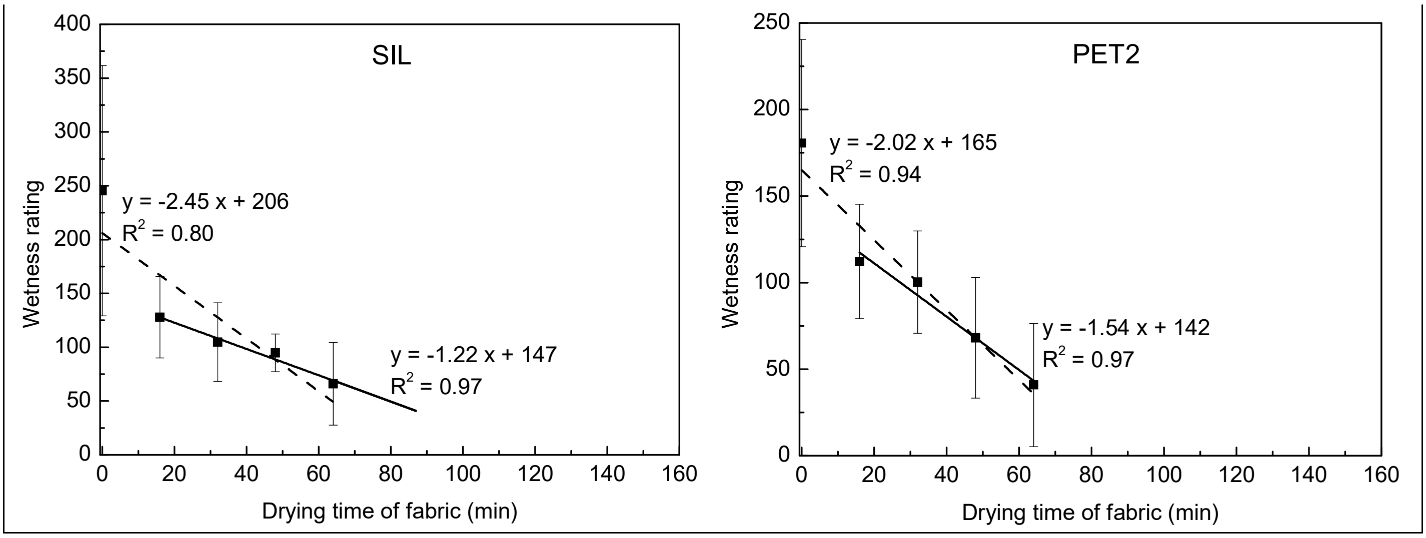
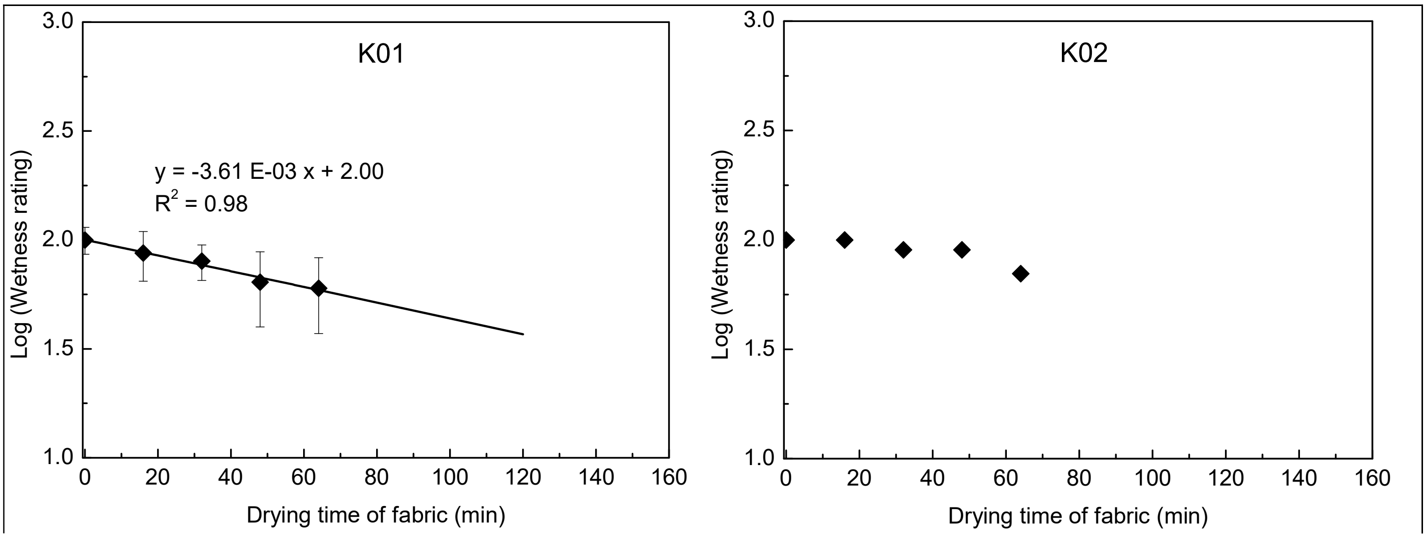


Figure 6.6 Wetness rating against drying time of fabric, dotted line and solid line represent the best linear fit of all data points and last 4 data points respectively. Error bars show one SD of uncertainty.



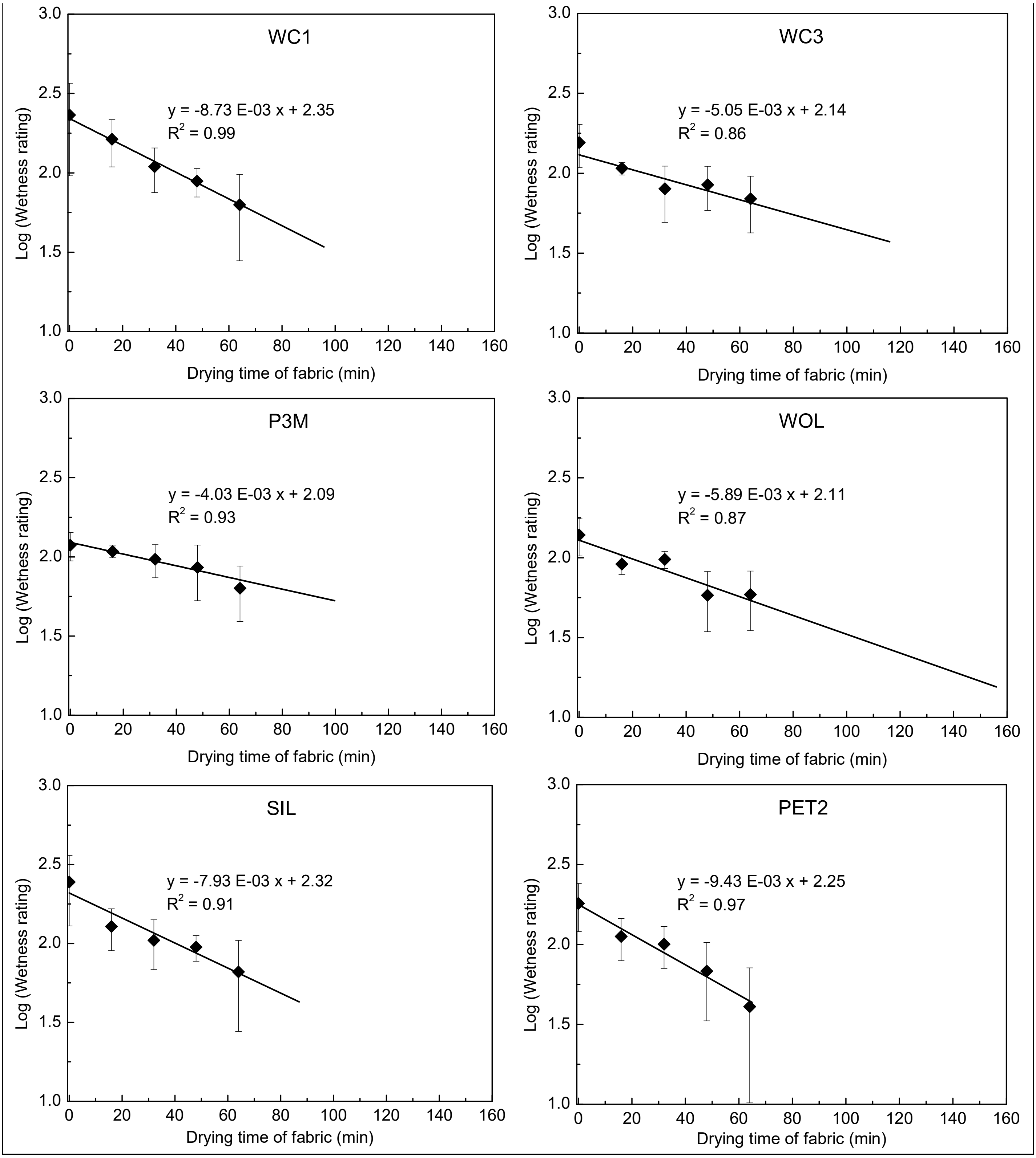


Figure 6.7 Semi-Log plots of wetness rating against drying time of fabric, error bars show one SD of uncertainty.

As shown in the table of "Data sets that fall into category (i)" (Table 6.2), K02 has only one set of data falls into category (i) response. Therefore, only data is presented and no line-fitting is shown in the plots of "wetness rating against time". In general, in both linear and semi-log scale, all other seven tested fabrics (K01, WC1, WC3, P3M, WOL, SIL and PET2) have good linear fit between wetness rating/log (wetness rating) and drying time of fabric. Dotted lines shown in linear-wetness rating plot (Figure 6.6) indicate the linear fit of data, equations and R^2 values are located at the top-left corner of the plot. High R^2 values (≥ 0.80) confirm the highly linear relationship between wetness rating and drying time of fabric. Similarly, solid lines shown in linear plot (Figure 6.6) do the same as dotted lines, except that data point of 0^{th} second is excluded. The 0^{th} second data deviates high from the linear best-fit for thin fabrics, including WC1, WC3, SIL and PET2. This is because water saturated at the back-side surface of these thin fabrics, and then subjects sensed a large amount of water on skin. Therefore, excludes 0^{th} second data gives better correlation, higher R^2, in linear regression, so that better projection can be achieved in the extrapolations. However, linear-wetness rating plots shown in Figure 6.6 have a problem that extrapolated "negative" wetness rating for some fabrics (WC1 and WOL). The negative value violates the definition of wetness rating. This is the major issue encountered by considering a linear relationship between wetness sensation and drying time of fabric. Table 6.4 summarises important parameters shown in "wetness rating against drying time" (Figure 6.6 and 6.7). On the other hand, semi-log plots shown in Figure 6.7 apply base-10 logarithmic to wetness rating. In this semi-log plot, correlates log (wetness rating) and drying time of fabric with linear regression. This gives very high R^2 value (≥ 0.86) among seven fabrics (summarised in Table 6.4), and "negative" wetness does not present in the extrapolation. Furthermore, the semi-log plots are able to fit all data points in the prediction of all fabrics. Therefore, the semi-log plot is better than the linear plot to present good fits for representing wetness sensation in the whole drying process. In other words, wetness sensation is found to have a logarithmic relationship with drying time of fabric.

Table 6.4 Comparison of best fit lines obtained from Figure 6.6 and 6.7 (wetness rating and log(wetness rating) against time)

Best linear fit line	Linear plot (Figure 6.6, dotted line)	Linear plot, excluded 0^{th} sec data (Figure 6.6, solid line)	Semi-log plot (Figure 6.7, solid line)
R^2 range among fabrics	0.80 (SIL) to 0.97 (K01, P3M)	0.71 (WOL) to 0.97 (P3M, SIL, PET2)	0.86 (WC3) to 0.99 (WC1)
0^{th} second data (first data, fabric just wetted)	WC1, WC3, SIL and PET2 deviates high when fitted with a linear relationship.		Deviation to linear best fit does not exist.
"Negative" wetness when extrapolated	Not extrapolated	WC1 and WOL	The problem does not exist

Since the semi-log relationship is the best to represent interaction between wetness rating and drying time of fabric, it is used to compare fabric wetness performance. Equations of semi-log relationship (shown in Figure 6.7) are employed for analysis, and Table 6.5 lists key parameters of fabric's wetness performance. The analysis begins from substituting the "time for fabric dried out" (Table 6.1) into equations of semi-log relationship (Figure 6.7). The results give the range of projected wetness rating in category (i) response. The ranges are listed in Column 2 of Table 6.5. It is found that projected wetness rating of fabrics converged into a similar level of wetness (33 to 49) when fabric dried out. By integrating Equation (6.3) with respect to time (x), with limit from 0 to "time for fabric dried out", an area under curve can be found. The area under curve represents the combined effect of user suffered in wet sensation due to the fabric, together with the time span of wet sensation. This total suffering from wet and time is named as Wetness Factor (WF) with a dimension of wetness x time. The smaller WF indicates that the user suffers less against wetness. The calculation of WF of fabric K01 is shown below as an example:

from Figure 6.7, $y = -0.00361\,x + 2.00$ (6.1)

where $y = log_{10}(s)$, s is wetness rating, x is drying time of fabric, therefore

$$\log_{10}(s) = -0.00361\,x + 2 \quad (6.2)$$

$$s = 10^{-0.00361\,x + 2} \quad (6.3)$$

integrates equation (6.3) with respect to time (x), with limit from 0 to 120 minutes (from wet to dry) gives WF

$$WF = \int_0^{\text{time for fabric dried out}} s\,dx = \int_0^{120} 10^{-0.00361\,x + 2}\,dx \quad (6.4)$$

$$= 10^2 \int_0^{120} 10^{-0.00361\,x}\,dx \quad (6.5)$$

let $u = -0.00361\,x$, then $\frac{du}{dx} = -0.00361$

therefore,

$$WF = 10^2 \int_0^{-0.00361 \times 120} 10^u \frac{du}{-0.00361} \quad (6.6)$$

$$= \frac{10^2}{-0.00361} \int_0^{-0.00361 \times 120} 10^u\,du \quad (6.7)$$

by looking up integral table (Sullivan and Miranda, 2014) $\int a^z dx = \frac{a^z}{\ln(a)} + C,\ a > 0,$ $a \neq 1$, and apply it to equation (6.7) gives equation (6.8)

$$WF = \frac{10^2}{-0.00361} \left[\frac{10^u}{\ln(10)}\right]_0^{-0.00361 \times 120} \quad (6.8)$$

$WF = 7.59 \times 10^3$

WF of K01 is found to be 7590, and WF of other six fabrics with Category (i) sensation is also shown in Column 4 of Table 6.5. WF of the seven fabrics falls between 6190 and 9510. COT1 and P3M show a good example of the use of WF results. WC1 and P3M have almost the same time for fabric to dry out (WC1: 96 min, P3M: 100 min; from Table 6.5, Column 3). On the other hand, WC1 has high wetness rating when it is just wetted and drops quickly from 224 to 33 (Table 6.5, Column 2). P3M has lower wetness rating than WC1 at just wetted, but higher wetness rating near dries out (wetness rating of P3M from 123 to 49). Therefore, the performance of wet sensation of WC1 and P3M cannot be distinguished by drying time and the range of wetness rating. However, the WF represents resultant effects of total suffering against wetness by using the area under curve. P3M has WF of 8000, better than WC1 that has WF of 9510. In addition, some of the fabrics show there would be a compromise between "dries fast" and "offers dry sensation". For example, WC3 and SIL have similar WF values, 8790 and 9110 respectively. WC3 offers dry sensation and water evaporates slowly, but SIL gives wet sensation and evaporates fast (Table 6.5, Column 2 and 3). This shows a good fabric for keeping thermal-wet comfort sense should get dried fast and offer dry sensation. PET2 has the smallest WF, 6190. This is because PET2 has the advantage that it picks up only around half of water amount compared to other fabrics during the wetting process. This is because of the low water absorption capacity of PET2 (Table 3.2; 1.05 g for 144 cm^2 of fabric. 1.05 g lower than the sprayed amount 1.4 g in this wetness assessment). PET2 takes the least time to dry out, so it gives the shortest wet sensation to subjects.

Table 6.5 Key parameters obtained against fabric's wetness performance

	Category (i) response			**Range of wetness rating in category (ii) response, from 0^{th} to 64^{th} minutes**
	Range of projected wetness rating from just wetted to dried out	**Expected time for fabric dried out (minute)**	**Wetness factor (WF) (dimension: wetness x time)**	
Source / Fabric	**Calculates from equations given in semi-log plot of wetness rating against "time" (Figure 6.7)**	**X-intercept of water amount on fabric against "time" (Table 6.1)**	**Calculates from equations given in semi-log plot of wetness rating against "time" (Figure 6.7)**	**Summary table of category (ii) wetness rating (Table 6.3)**
K01	[100, 37) Feel: wet → dry	120	7590	[64, 73]
K02	/	147	/	[68, 77]
WC1	[224, 33) Feel: very wet → dry	95.8	9510	/
WC3	[138, 36) Feel: wet → dry	116	8790	/
P3M	[123, 49) Feel: wet → dry	99.7	8000	[63, 78]
WOL	[129, 16) Feel: wet → dry	156	8350	[83, 110]
SIL	[209, 43) Feel: very wet → dry	87.0	9110	/
PET2	[178, 43) Feel: very wet → dry	64.9	6190	/

Notes: [inclusive value, exclusive value)

Notes: Column 2 shows category (i) sensation response of whole drying process, and Column 5 lists category (ii) response of first 64 minutes. So the values in these two Columns should not be compared directly, but Column 5 can be regarded as addition information to Column 2.

Column 5 of the summary table of fabric's wetness performance (Table 6.5) shows the range of wetness rating under category (ii) response (subject did not sense change in wetness when fabric drying out). The range given in category (ii) only represented the wet perception in first 64 minutes period. Only 4 fabrics (K01, K02, P3M and WOL) mainly fall into category (ii). As discussed in last paragraph, wet sense and its time span are both important. While the category (ii) wetness rating of K01, K02 and P3M are almost the same. The shorter expected time for fabric dried out (Column 3 of Table 6.5) indicates P3M is the best fabric among these 3. Lastly, although K02 does not have a WF to evaluate its wetness performance directly, the category (ii) response can help to indicate its performance. K02 has similar category (ii) response with K01 (last Column of Table 6.5) and longer time to dry up (3rd Column of Table 6.5); K02 has similar time to dry with WOL and better category (ii) response than WOL. So the wetness performance can be stated as K01 (best) > K02 > WOL.

6.3.3 Within-Subject Reliability

For the 20 subjects that passed the screening test, they are invited to conduct full wetness sensation test. By applying rejection criterion mentioned in Section 6.2.3.1, none of these 20 subjects was rejected. Therefore, all these subjects give consistent result in each set of data. “Each set” is referring to five wetness rating data at various waiting time (drying time) of the same fabric. Since subjects give consistent result, they are reliable for the subjective assessment.

6.3.4 Between-Subject Consistency

For the data sets defined as category (i), refers that subject sensed drop in wetness when that fabric drying out. Each set of data gave slope and y-intercept. Average value of slope and y-intercept of each fabric gave CVs (Table 6.2). CVs of the slope of fabric are range from 0.37 to 0.70, and CVs of y-intercept of fabrics are between 0.13 and 0.46. The CVs are within acceptable range. The variation depends on sensitivity of subjects. This is because a more sensitive subject gives result with larger slope and y-intercept. Therefore, the between-subject consistency is reasonable in this study.

6.3.5 Sensitivity of Wetness Assessment

Nonparametric statistics tests are applied against wetness rating to evaluate the sensitivity of wetness assessment method. The sensitivity of "drying time of fabric before assessed by subject" to "wetness rating", and "fabric type" to "wetness rating" are investigated. Since there would have no nonparametric statistics test can test the two independent variables in a single test (Pett, 2016). i.e. the nonparametric equivalent of 2-way ANOVA would not available. Therefore, the effects of "drying time of fabric before assessed by subject" to "wetness rating" and "fabric type" to "wetness rating" are tested separately by Friedman tests and Kruskal-Wallis tests. IBM SPSS Statistic 22 is used to conduct these statistical tests.

Friedman test is a nonparametric statistical rank test to compare multiple related samples (Corder and Foreman, 2009; Kemp et al., 2009). As summarised in Table 6.6, there are seven individual Friedman tests conducted on seven fabrics (K01, WC1, WC3, P3M, WOL, SIL and PET2). The null hypotheses of Friedman tests are ranks of wetness rating at all drying time of fabric are the same. The mean ranks of wetness rating at "0^{th} min" are the largest (Table 6.6(a)). This represents that the wetness rating at "0^{th} min" is the highest in terms of "time". All of the seven null hypotheses are rejected at 0.050 significant level. Therefore, the difference in wetness sensation between various "time" is sensitive.

Table 6.6(a) Seven individual sets of wetness rating by ranks for Friedman tests against drying time of fabric. Fabric sample is the fixed factor.

Ranks

	Mean Rank of Wetness Rating						
Fabric / Drying Time	K01	WC1	WC3	P3M	WOL	SIL	PET2
64th min	1.70	1.39	1.68	1.08	1.81	1.24	1.31
48th min	2.15	2.14	2.55	2.42	1.38	2.42	2.11
32nd min	2.90	2.82	2.27	3.33	3.63	2.84	3.11
16th min	3.70	3.79	3.73	3.67	3.44	3.61	3.61
0th min	4.55	4.86	4.77	4.50	4.75	4.89	4.86

Table 6.6(b) Test statistics of Friedman tests of seven fabrics

Test Statistics[a]

Fabric	K01	WC1	WC3	P3M	WOL	SIL	PET2
N	10	14	11	6	8	19	18
Chi-Square	22.984	43.227	29.889	18.018	26.093	59.567	57.940
df	4	4	4	4	4	4	4
Asymp. Sig.	.000	.000	.000	.001	.000	.000	.000

a. Friedman Test

Kruskal-Wallis test is a nonparametric statistical rank test to comparing multiple unrelated samples (Corder and Foreman, 2009; Kemp et al., 2009). There are five Kruskal-Wallis tests conducted with the drying time of fabric (0^{th} min, 16^{th} min, 32^{nd} min, 48^{th} min and 64^{th} min) as fixed parameter in each test. The null hypotheses of each test are all fabrics give equal rank in wetness rating. The mean rank of wetness rating (Table 6.7(a)) indicates the wetness sensation against various fabrics by given number of subjects with category (i) response. It is found that at 0^{th} min, 16^{th} min and 48^{th} min, the null hypotheses are rejected at 0.050 significance level (Table 6.7(b)).

Therefore, the wetness rating is sensitive to fabrics at 0th min, 16th min and 48th min. On the other hand, the null hypotheses are accepted at 32nd min and 64th min. This is because the wetness sensations are similar when fabric dried out, and the wetness rating converges into a small range. The trend of convergence in wetness rating can be observed in Figure 6.8, which is a summary of wetness rating against time (Figure 6.6). Therefore, the subjective wetness assessment is sensitive to fabrics.

Table 6.7(a) Five individual sets of wetness rating by ranks for Kruskal-Wallis tests against fabric. Drying time of fabric is the fixed factor.

Ranks

		Mean Rank of Wetness Rating				
Fabric	Time / N	0^{th} min	16^{th} min	32^{nd} min	48^{th} min	64^{th} min
K01	10	9.70	22.20	25.95	27.90	43.60
WC1	14	59.07	67.29	54.04	50.21	46.32
WC3	11	38.86	39.59	33.73	49.73	50.77
P3M	6	19.08	40.75	44.33	49.75	47.17
WOL	8	31.69	21.56	45.56	21.63	42.75
SIL	19	61.82	51.58	50.39	56.32	48.26
PET2	18	47.06	41.36	42.56	37.25	30.89
Total	86					

Time: Drying time of fabric

N: Number of subject

Table 6.7(b) Test statistics of Kruskal-Wallis tests of the five drying time of fabric

Test Statistics[a,b]

	Wetness Rating				
	0^{th} min	16^{th} min	32^{nd} min	48^{th} min	64^{th} min
Chi-Square	43.399	29.298	10.842	18.565	6.592
df	6	6	6	6	6
Asymp. Sig.	.000	.000	.093	.005	.360

a. Kruskal-Wallis Test

b. Grouping Variable: Fabric

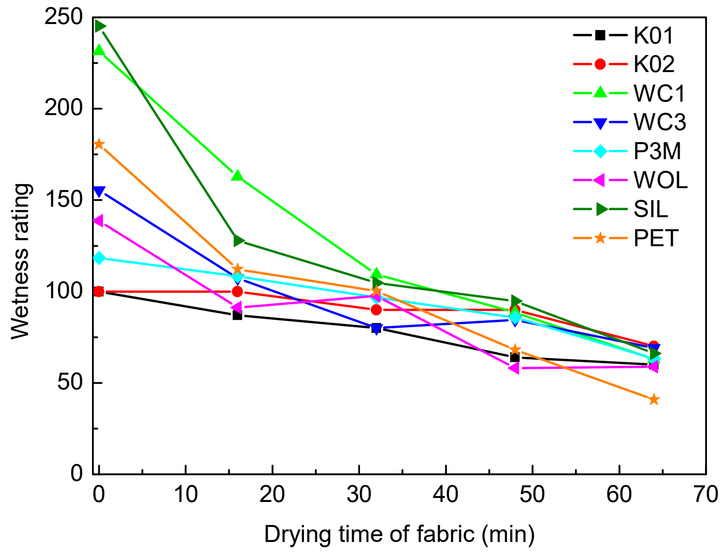


Figure 6.8 Wetness rating against drying time of fabric

6.4 Limitation of Subjective Wetness Assessment

The major limitation of this subjective test is the whole fabric drying process does not conduct on subject's forearm. However, if wetted fabric specimen is put on forearm during the whole drying process, the duration will be at least 10 minutes for each test. This extended exposure to stimulants prone to fatigue subject, and then affects the reliability of results. This is the reason that five identical specimens with different drying time (0, 16, 32, 48 and 64 minutes) are presented to subjects separately to give breaks and shorten the accumulated test time.

The drying mechanism of subjective wetness assessment is the same as conventional objective drying test method, Water Evaporating Rate (WER) (Section 3.3). The "time" predicted for fabric completely dried is based on room temperature (standard atmospheric condition: 20 ± 1 °C and 65 ± 5 % RH). The subjective wetness assessment will be more versatile than current experimental design by varying drying temperature of specimens to simulate any actual use of fabrics. This can be achieved by using multiple of heating systems used in Constant Temperature Drying Rate Tester (CTDRT) (section 5.3.1). The CTDRT's heating system can be adjusted to fit a target skin temperature, so that fabrics can be dried at desired temperature.

6.5 Summary

The wet sensation assessment is aim at investigating the profile of wet sensation while a wetted fabric is drying. 21 subjects were invited for wet sensation assessment, and one of them failed to pass a screening test. A 2-arm fabrics driver was built to offer repeatable movements to two fabrics in-phase on forearms of assessors. The driver allowed comparison of wet sensation between reference fabric and sample fabric simultaneously. Wetness rating of each specimen was given by subjects in ratio scale. K01, K02, WC1, WC3, P3M, WOL, SIL and PET2 were selected as samples for the subjective wet sensation assessment. All fabrics were wetted by putting them on a water sprayed plastic card, with a pressure of 2.5 g/cm^2 applied on them. After pressed, fabrics were put on a table and waited for 0, 16, 32, 48 and 64 minutes drying time. This procedure demonstrated fabrics drying at room temperature.

The wetness rating is the highest at 0th minute and the magnitude is especially high for some water saturated fabrics. The wetness rating decreases when drying time (waiting time) increases, and it has a trend of convergence in wetness rating among fabrics. Data sets are classified into category (i) subject senses drop in wetness when that fabric drying out, and (ii) subject does not sense change in wetness when that fabric drying out. For category (i) response, with help of the measurement of the amount of water on fabric, wetness rating of fabric can be predicted beyond 64^{th} minutes, until fabric dried. A good linear relationship between $\log_{10}$ (wetness rating) and drying time of fabric is found. Wetness Factor (WF) is introduced to include level of wet sensation and duration suffered from wet. A larger WF indicates that subject (or end user) suffered deeper in wet sensation due to the fabric. PET2 has the smallest WF (6190), and WC1 has the highest WF (9510) among all tested fabrics. The analysis of WF indicates that, both “dries fast” and “offers dry sensation” are important criteria for a good thermal-wet comfort fabric. Category (ii) result is addition information to category (i) result. Category (ii) response refers some subjects may not be able to detect change of wetness against time of particular fabric. This is mainly because of the properties of that particular fabric, and those subjects still can discriminate in other situations. The key results of tested fabrics fell into both categories are summarised in Table 6.5.

Within-subject reliability of the wetness assessment is confirmed by all of the 20 subjects gave consistent result in individual sets of data. Each “set” of data refers to five data points at various waiting time (drying time) of the same fabric. On the other hand, each “set” of data gives slope and y-intercept. The CV of slope and y-intercept of fabrics (given by different subjects) are in acceptable range. This confirms between-subject consistency. Friedman test is used to show wetness sensation is sensitive to drying time of fabric. Kruskal-Wallis test is applied to indicate wetness rating is sensitive to fabrics.

Chapter 7 Development of Fabric Drag Force Measurement System (FDFMS) on wet surface

7.1 Introduction

As discussed in Section 1.1, interaction between human skin and garment involves absorbing, spreading, adhering and evaporating. Among these interactions, adhesion is the last component to be investigated in this study. Stickiness is a general term to describe wet adhesion between textile and skin. Upon daily activities and exercise, sweated garments are dragged against our skin to evoke discomfort (Wang et al., 2012). Applying cyclic drag force for extended duration can cause skin injuries, such as irritation, abrasion and blister (Gerhardt et al., 2008; Derler and Gerhardt, 2012; Falloon, 2014; Jayawardana et al., 2017). A subjective test can realistically reflect human perception against stickiness. However, a large sample size should be tested in order to reduce uncertainties. This can be a time-consuming and costly task. In this Chapter, Fabric Drag Force Measurement System (FDFMS) was built to offer an efficient alternative for subjective stickiness test. This instrumental measurement can evaluate fabric stickiness, for objective and reproducible results.

FDFMS drags specimen through a wetted surface. The surface is selected as simulated skin, Lorica Soft, to simulate human skin. FDFMS equips with a force gauge to measure the drag force against fabric during the whole experiment. Since specimen fabric is dragged through a pre-wetted simulated skin, the amount of water supplied to sample keeps increasing throughout the experiment. As a result of water accumulation, drag force of sample against broad range of applied water amount can be investigated by using FDFMS. A “drag force curve” of FDFMS presents the drag force against water amount applied to fabric. The curve is a full drag force profile of fabric. Therefore, drag force as a function of fabric wetness can be found in a single drag force curve.

Intimate contact is achieved at the fabric-simulated skin interface of FDFMS. The good contact comes from the adhesion force of water in between fabric and simulated skin. This is the actual case that stickiness is sensed by a wearer. A drag type sample holder design enables measurement of the intimated wet contact. This is done by mounting the front edge of specimen on the sample holder, and lefts other portion of specimen free and flat on the simulated skin. The specimen can be elongated by the drag force (from sample holder) and adhesion force (of water). This elongation simulates wearer’s daily activities. It depends on fabric’s properties and fabric-simulated skin interaction. Such elongation cannot be observed, if there is external pressure applied to the fabric during drag force experiment. It is a novel sample holding technique to use free-end dragging with no external pressure applies to fabric simulates the actual wear condition of clothing.

A subjective stickiness sensation assessment was conducted for acquiring real stickiness sense of human against fabrics. The correlation between subjective assessment and instrumental experiment is studied in this Chapter, so as to investigate the possibility of using instrument as an alternative of subjective sensation assessment. A multiple linear regression is setup to predict subjective sensation by objective test results.

7.2 Limitation of Conventional Methods

According to the literature review in Section 2.3, there is a trade-off between using in vivo measurement (skin) and alternative contact materials (metal, polymer) for fabric friction measurement. Therefore, either representative result or reproducible result would be sacrificed. The simulated skin, Lorica Soft made of polyamide microfleece and coated with polyurethane has natural texture of human skin. Lorica Soft has been shown to realistically simulate human skin friction against textiles under dry condition. Lorica Soft also demonstrated surface properties of human skin, such as roughness, topography, water contact angle (Dąbrowska et al., 2016). Because of the versatile properties of Lorica Soft, it is selected as the contact materials of the drag force measurement system.

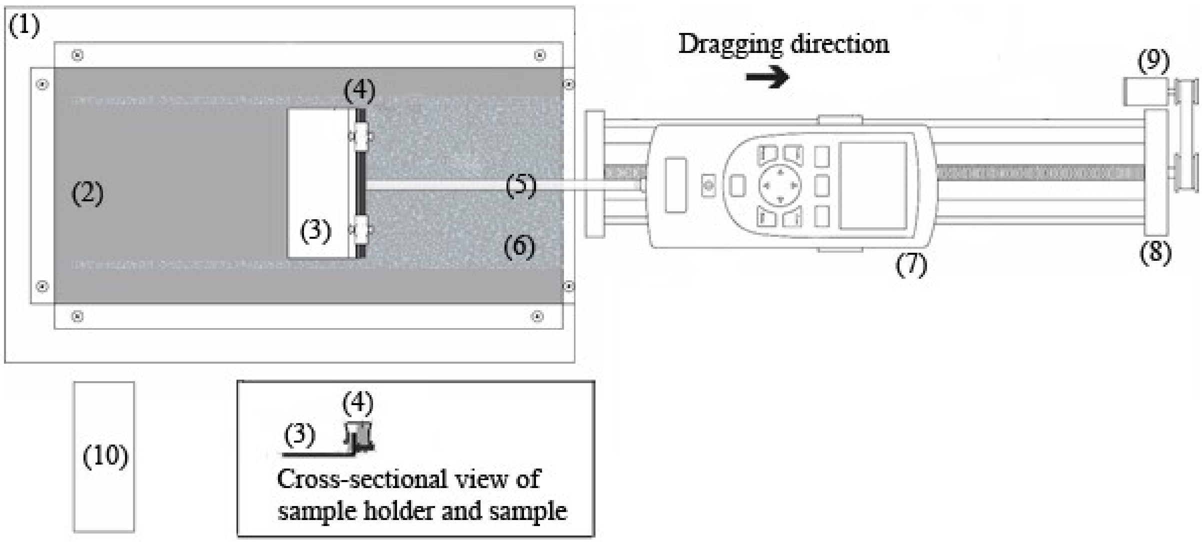
Level of wetting to garment induced by sweat varies at all the times, the drag force measurement at different wetting level is important. However, the previous studies were focused on dry fabric and single level wetted fabric. Except one of the previous research conducted friction measurement at several discrete water levels on sample fabrics (Wang et al., 2012). In this research, investigation is pushed to a full scan among all water levels. So drag force between Lorica Soft and fabric at all water levels, until fabric is saturated with water, can be found in one to two tests.

The adhesion force between skin and fabric becomes obvious when people are sweated. When wearer is in motion, drag forces present at the skin-fabric interface. Then the pair of adhesion force and drag forces stretch the garment to cause deformation. However, most of the previous studies had fixed the fabric during friction test (Ajayi, 1992; Ramkumar et al., 2003; Hermann et al., 2004; Lima et al., 2005; Amber et al., 2015). The reason for fixing the dimensions was to maintain a flat surface for the skin-fabric (sample platform-fabric) interaction. These studies mainly conducted dry tests, so the magnitude of drag force does not cause much of stretching to fabric. However, the stretching will become significant for wetted fabric. Therefore, limiting fabric's stretching does not simulate wet skin-fabric interaction. In order to consider stretching and flat fabric when dragging on skin (sample platform) surface, a new free-end dragging method is introduced. The new method uses a sample holder to clip the front end of fabric, and pull the fabric over a wetted platform. Surface tension of water holds sample fabric at good contact with platform, so the fabric is flat during drag force measurement. Because of the good contact, vertical pressure is not required to apply on fabric. The sample is just pulled by the sample holder at the front end with no pressure or mounting on it. Therefore, free fabrics movement and deformation under pulling force are allowed. This is much closed to demonstrate actual wearing condition that wet garments stick on people's skin than previous studies.

7.3 Experimental

7.3.1 Setup of FDFMS

Schematic diagram of FDFMS is shown in Figure 7.1. FDFMS equipped with a precision digital force gauge (Chatillon, DFS2-002). It is an important component to obtain drag force against fabric at 1 mN (Millinewton) resolution with maximum reading 10 N. Sampling rate of the force gauge was set at ten samples per second to capture rapid changes of fabric's drag force. Motion of the force gauge was linear and horizontal, and driven by a motorised translation stage. Travelling length of translation stage with force gauge was 24 cm, and the translation stage stopped automatically by activating a photoelectric sensor. The motion of translation stage was driven by a DC motor. The force gauge was connected with a sample holder for pulling specimen along a sample platform. The sample holder included an acrylic tube, two pieces of 12 x 1 x 0.1 cm^3 (width x height x thickness) aluminium plates and two foldback clips. Front edge of sample, i.e. 12 x 1 cm^2 (dimension of sample, warp x weft: 6 x 12 cm^2) was mounted between aluminium plates by using foldback clips. In the other words, 5 x 12 cm^2 of fabric contacted with the sample platform and contributed to drag force measurement. The acrylic tube was used as connection between force gauge and aluminium plates.



(1) Grooved stage
(2) Sample platform with simulated skin
(3) Sample
(4) Sample holder
(5) Acrylic tube
(6) Water droplets
(7) Force gauge
(8) Translation stage
(9) DC motor
(10) External pressure plate

Figure 7.1 Schematic diagram of FDFMS.

A grooved stage was made to fix the position of a sample platform (Figure 7.1). The sample platform of FDFMS was made of Lorica Soft (simulated skin), and which was firmly adhered on an acrylic board. The Lorica Soft simulates human skin and the acrylic board offered rigid support. Lorica Soft's surface had a water contact angle of 90° (measured by ramé-hart, model 200 Standard Contact Angle Goniometer) which is similar with the contact angle at water-unwashed skin interface (Schott, 1971; Mavon et al., 1997). A spray was used for delivering water onto the sample platform, with a frame to confine spraying area (Dragging direction x width: 30 cm × 14.5 cm). The sample platform was placed onto electronic balance (Sartorius, ENTRIS 623-1S), so that weight of water applied can be monitored while spraying was in progress. The weight and area of wetted section were known, so that the water amount on simulated skin in terms of mg/cm^2 was controlled. An external pressure (2.5 g/cm^2 for 5 seconds) was accompanied with sample platform to ensure the fabric laid flat and have sufficient contact with the simulated skin. The external pressure was removed from sample before fabric drag measurement.

7.3.1.1 System Parameters of the Tester

Total amount of water applied to fabric shall be larger than the water absorption capacity of fabric. For example, fabric K03, it has the highest capacity among all fabrics in this study (Table 3.2). Its capacity is 71.0 mg/cm^2, so the total amount of applied water can be chosen as 80 mg/cm^2 to observe all drag force features. There are around half of fabrics have capacity smaller than 30 mg/cm^2. It is necessary to choose a small total amount of water, for example, 35 mg/cm^2. The small total amount of water can enhance the resolution of drag force curve. Similarly, travelling length of sample was set at 24 cm. This is the upper limit of the equipment, so that the drag force curve can achieve maximum resolution.

The water sprayed on simulated skin was determined by parameters mentioned in last paragraph and fabric contact area (5 x 12 cm^2). When the sample was dragged against the simulated skin, accumulated amount of water applied onto the sample increased. The length of fabric contact area was 5 cm, plus fabric's travelling length 24 cm. The total length of water supplied by simulated skin was 29 cm. Taking 80 mg/cm^2 of total water amount for calculation. 80 mg/cm^2 x 5 cm x 12 cm = 4800 mg of water was required for the sample. 4800 mg divided by (29 cm x 12 cm) = 13.79 mg/cm^2 ≈ 14 mg/cm^2 of water shall be applied on simulated skin. Therefore, the applied water to fabric was scanned from 14 mg/cm^2 to 81.2 (≈ 80) mg/cm^2 in a single trial. Similarly, 6 mg/cm^2 was applied to simulated skin for supplying total 34.8 mg/cm^2 of water to sample. Therefore, the applied water to fabric scanned from 6 mg/cm^2 to 34.8 (≈ 35) mg/cm^2. All sample conducted 6 to 34.8 mg/cm^2 scan, this was because of the need of comparing static friction at the same amount of applied water. For those samples with high absorption capacity, 14 mg/cm^2 to 81.2 mg/cm^2 drag force curve was also studied.

The dragging speed is set at 0.2 cm/s in this study to maintain testing stability and efficiency. The duration of a drag force scan is 120 seconds. If the speed is set to be slower than 0.2 cm/s, the testing time would be too long. In contrast, if the speed is too high, fabrics have not enough time to absorb water. Also, the resolution of drag force curve will be decreased due to a high-speed scanning.

7.3.2 Specimens

28 samples were tested by FDFMS, they are knit and woven fabrics with various fibre contents, and their specifications are listed in Section 3.1. These specimens in size of 6 x 12 cm^2 were gently ironed for flat surface, and then conditioned in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for at least 12 hours before test.

The FDFMS tests were conducted at the same condition. The dragging direction of fabric was along the warp direction of fabric. This prevented large stretching if fabric was dragged along weft direction. Current dragging direction is easy for comparison between knitted and woven fabric.

7.3.3 Operation of FDFMS

Table 7.1 shows operating procedures of FDFMS.

Table 7.1 Operating procedures of FDFMS

Step	Procedure
1	Spray water onto simulated-skin-sample-platform, with aid of frame and balance to confine sprayed area and weight respectively. (e.g. 30 × 14.5 cm^2 and 2610 mg for the 6 mg/cm^2 scan)
2	Mount sample onto sample holder
3	Insert sprayed sample platform underneath of mounted sample
4	Apply an external pressure (2.5 g/cm^2) onto the sample for 5 seconds to ensure the fabric laid flat and have sufficient contact with the simulated skin
5	Acquire data from force gauge for every 0.1 second
6	Start translation stage to moving force gauge at 0.2 cm/sec
7	Stop translation stage at 24^{th} cm travel distance (Automatically done by hardware)
8	Stop data logging from force gauge
9	Dismount tested sample
10	Send force gauge back to origin
11	Dry the residual water on simulated skin, and start from Step 1 for next measurement

7.3.4 Measurement Parameters

Figure 7.2 shows typical drag force curves obtained by FDFMS. Drag force curve is the raw data that indicates drag force of fabric against the accumulated amount of water applied to fabric. The amount of water applied to fabric is in terms of weight of water applied per unit area. Three examples of drag force curves are shown in Figure 7.2, they are PET1, SIL and K08. These three fabrics are able to clearly demonstrate key features of drag force curve which present among all tested fabrics. PET1 shows the simplest drag force curve that drag force is the maximum at the beginning of experiment. The initial peak data is named as static drag force (F_S) of a fabric. While the applied drag force on fabric is larger than the F_S, the fabric start move along simulated skin. Since water applied to PET1 at the beginning of test (6 mg/cm^2) is larger than fabric's absorption capacity (3.51 mg/cm^2), the drag force curve decreases to a minimum as applied water increases. The decreases in drag force can be explained by hydrodynamic lubrication (Adams et al., 2007; Derler et al., 2009; Derler and Gerhardt, 2012). The relationship between drag force and absorption capacity is further discussed in Section 7.4.1.1.

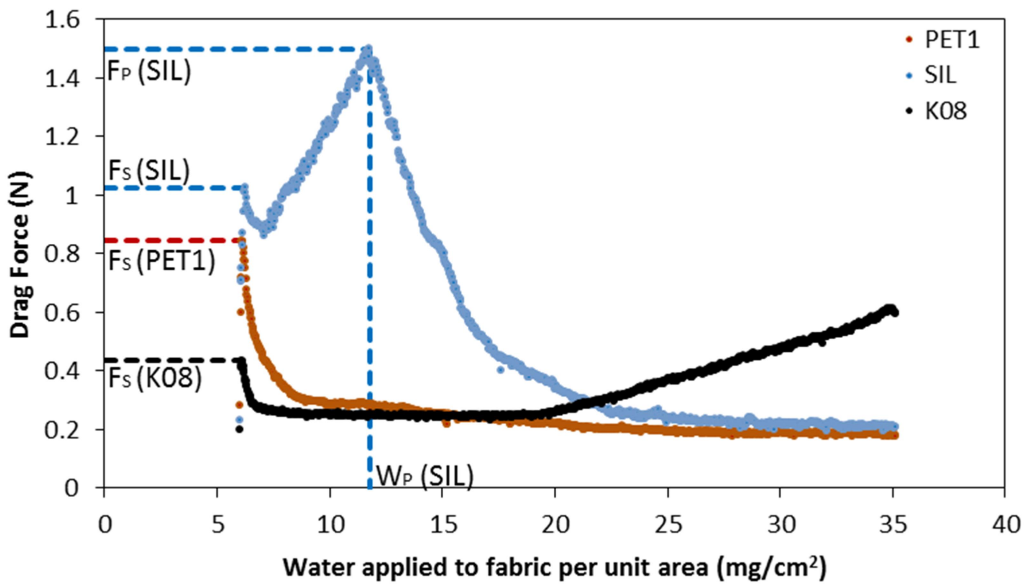


Figure 7.2 Drag force curve: The change of drag force while fabrics (SIL, PET1 and K08) are dragged along the simulated skin wetted at 6 mg/cm^2.

The second measurement parameter of FDFMS is peak drag force (F_P). Once applied drag force to fabric overcomes F_S, the drag force curve goes to dynamic drag force section. The dynamic drag force is smaller than F_S. This is the same as dynamic friction of a dry interface (Benenson et al., 2002). However, the specimen on sample platform experiences accumulating of applied water, the drag force rises and reaches the F_P. The F_P can be higher or lower than F_S, and this depends on the initial amount of applied water. Figure 7.2 shows the drag force curve of SIL, SIL presents F_P (1.5 N) at corresponding water supplied to fabric (Amount of Water Supplied to Fabric at F_P, W_P). W_P of SIL is found to be around 12 mg/cm^2. Figure 7.2 also shows the drag force curve of K08, however, the F_P does not present. This is because the curve ends at 34.8 mg/cm^2, which is smaller than the absorption capacity of K08 (41.1 mg/cm^2; Table 3.2). Figure 7.3 shows drag force curve of K08 with simulated skin wetness at 14 mg/cm^2. The F_P can be clearly observed, this is because the range of applied water covers absorption capacity of K08. After passing through the F_P, the drag force curve of SIL and K08 drop to minimum value. This trend is the same as PET1. Finally, individual F_S are found in both curve of K08 (Figure 7.2 and 7.3). They represent F_S at different water applied to fabric. Therefore, the F_S at different water amount cannot be compared or interchanged directly.

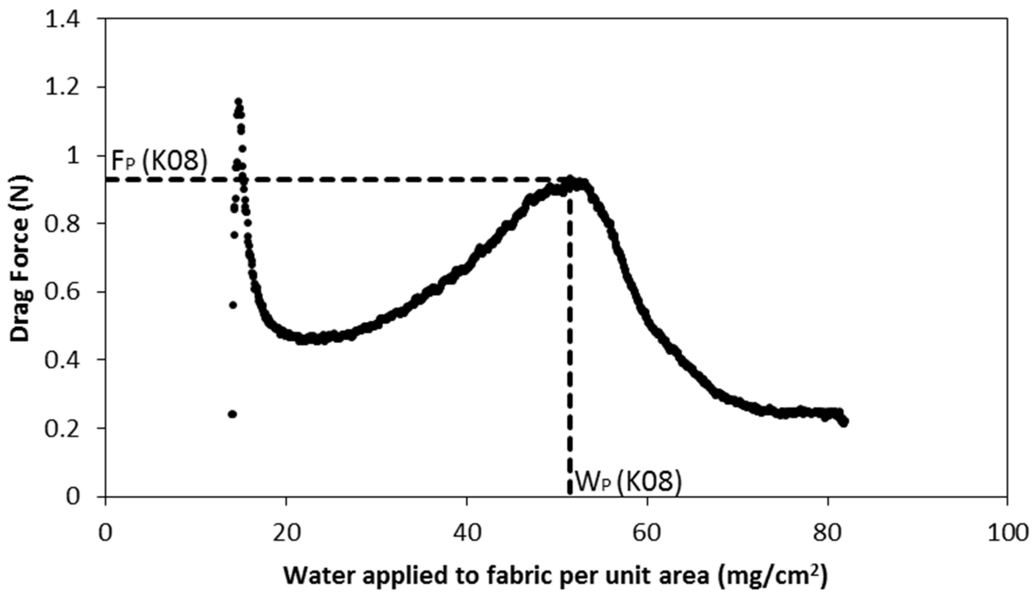


Figure 7.3 Drag force curve: The change of drag force while fabric K08 is dragged along the simulated skin wetted at 14 mg/cm^2.

7.3.5 Subjective Stickiness Sensation Assessment

7.3.5.1 Fabrics Driver, Assessors, Specimens, Reference Fabric and Environmental Condition

The 2-arm fabrics driver used in subjective stickiness sensation assessment was the same as the subjective wet sensation assessment (Section 6.2.1). The 20 subjects participated in the wet sensation assessment were invited for the stickiness sensation assessment. Therefore, 7 male and 13 female subjects participated in the stickiness assessment. The age range of subjects was from 23 to 38, average value was 28 years old. These subjects had no knowledge about specimens and reference fabric.

27 out of 28 fabrics listed in Table 3.1 were selected as specimens of the subjective test.

WC4 has very similar properties with WC3, so it was not included as specimen. WC3 was chosen as reference fabric of the subjective assessment. The size of specimen and reference were 12 x 12 cm^2, and they were gently ironed to achieve a flat surface. The specimen and reference fabrics were conditioned 12 hours in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH). The standard atmospheric condition was applied for the entire subjective assessment. Before presenting fabrics to subjects, 1.4 gram (9.7 mg/cm^2) of water was sprayed onto tilted sample and reference fabrics. The tilting was at 60 degree from horizontal. This allowed rolling off of residual amount of sprayed water.

7.3.5.2 Procedure of the Subjective Stickiness Assessment

The subjects were asked to confirm that they were at normal physical condition. Then, their age and sex were recorded. After that, subjects were asked to wash their forearm with water and then acclimatised in a standard atmospheric condition (20 ± 1 °C and 65 ± 5 % RH) for 30 minutes. During this acclimation time, detail instructions of the stickiness assessment were given to the subjects.

When training session began, subjects were invited to sit on a chair and putting both arms on a table. Subjects can decide a comfortable posture. A curtain was set in front of subjects to ensure blind tests were conducted. Eight training fabrics, K01, K02, WC1, WC3, P3M, WOL, SIL, PET2 were presented randomly to subjects in pair with reference fabric. This allowed subjects to adopt fabrics with different texture and also the stickiness rating scale. Stickiness rating of the assessment was in ratio scale. By comparing stickiness sensation of specimen with reference, if specimen and stickiness were the same, the subject should rate 100 for stickiness rating. If the subject sensed that specimen fabric is sticker than reference in double, 200 should be given to the specimen. The stickiness rating shall be any positive and non-zero number. Left-right hand arrangement of specimen and reference fabrics for each subject was randomly decided. The arrangement will not be changed during assessment to prevent confusion.

The training session was followed by the full fabrics set of stickiness sensation assessment. All 27 samples were presented to subjects once, plus two addition replicates for K01, P3M, SIL and WC3. Therefore, 35 specimens were assessed by each subject. The replicates were used for confirming within-subject reliability. During the assessment, pair of sample and reference fabric were delivered to subjects forearms every minute. The subjects had a limit of 15 seconds to give the stickiness rating. If subject cannot give rating in 15 seconds, the result of that fabric should leave blank. After rating of each specimen, there was at least 45 seconds recovery time given to subject. During recovery period, soft tissues were given to subjects for gently absorbing residual water on their forearms. However, rubbing was not allowed to prevent skin irritation. The limit of 15 seconds test time and recovery period were used to prevent sensory fatigue.

7.4 Result and Discussion

7.4.1 FDFMS

Figure 7.4 shows the static drag force (F_S) of fabrics. The blue and the yellow columns indicate 6 mg/cm^2 and 14 mg/cm^2 of water applied on simulated skin respectively. F_S represents the minimum required drag force to overcome the adhesion force between fabric and simulated skin. In the real skin-fabric case, a large F_S implies large stickiness between fabric and skin. This is because there is no relative motion between skin and fabric. Therefore, the drag force deforms skin and muscle to evoke stickiness perception. This is the reason that F_S simulates the static stickiness interaction between fabric and skin. As shown in bar chart of F_S, F_S ranges from 0.29 N (K09) to 2.37 N (PET2) among 6 mg/cm^2 result. This indicates that F_S gives high resolution to the measurement system. As comparing 6 mg/cm^2 result, fabrics made with synthetic materials have larger F_S than natural fibres. Synthetic fabrics have high F_S, since the initial applied water amount (6 mg/cm^2) is closed to their absorption capacity.

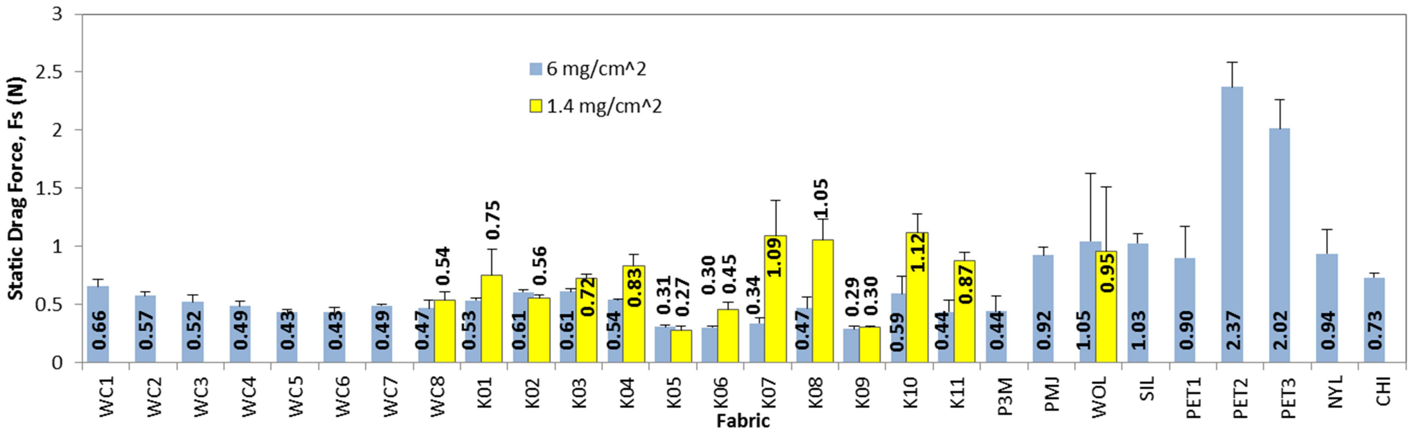


Figure 7.4 Static drag force (F_S) of 28 tested fabrics, blue columns and yellow columns represent 6 and 14 mg/cm^2 of water applied on simulated skin respectively, error bar represents one SD of uncertainty.

Figure 7.5 shows peak drag force F_P of fabrics. F_P represents the highest point (excluding F_S) of the drag force curve. Blue columns shown in Figure 7.5 means those result were obtained from 6 mg/cm^2 of simulated skin wetness, and yellow columns correspond to 14 mg/cm^2. If the F_P of a fabric can be found clearly in 6 mg/cm^2 trial, F_P is given in terms of 6 mg/cm^2. Otherwise, if the applied water is not enough to show F_P in 6 mg/cm^2 trial, F_P is given in terms of 14 mg/cm^2. PET1, PET2, NYL and CHI have no F_P. This is because their water absorption capacity (Section 3.2) is very closed or smaller than 6 mg/cm^2. The F_P of remaining 24 fabrics is found to be between 0.51 N (K05) and 1.98 N (P3M). This shows that F_P gives high discrimination to FDFMS. F_P has high correlation with water absorption capacity of fabric and detail is given in Section 7.4.1.1. As compared fibre types, structure and finishing of all tested fabrics, no obvious trend is found against F_P. So F_P depends on sets of parameter, and it is not easy to be predicted by other parameters. In general, F_P has smaller coefficient of variation (CV) than F_S. This is because in every measurement, the F_S just appears in a very short moment. The sampling rate of force gauge, ten samples per second, would be just enough for capturing the phenomena. CVs of F_P given by 28 samples are around 5 %, and they are all below 10 %. The CVs of F_S are around 10 %, except that WOL has a 58 % CV. The large CV of WOL is because of uneven absorption of water on sample surface.

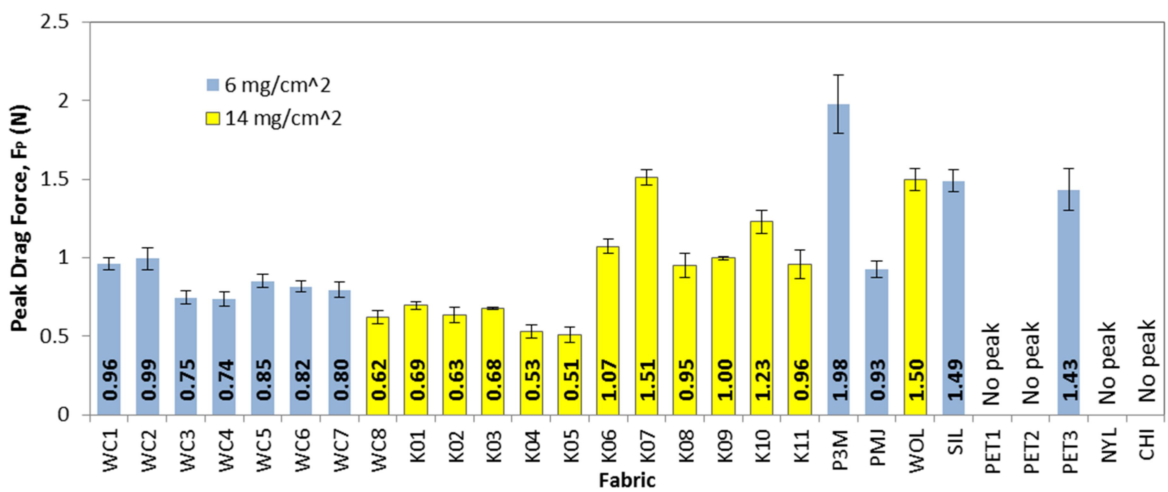


Figure 7.5 Peak drag force (F_P) of 28 tested fabrics, blue columns and yellow columns represent 6 and 14 mg/cm^2 of water applied on simulated skin respectively, error bar represents one SD of uncertainty.

The amount of water supplied to fabric at F_P (W_P) of fabrics is shown in Figure 7.6. W_P always comes in pair with F_P to show the amount of water that peak force presents.

The W_P is closely related with fabric water absorption capacity. The details are discussed in the next Section (Section 7.4.1.1).

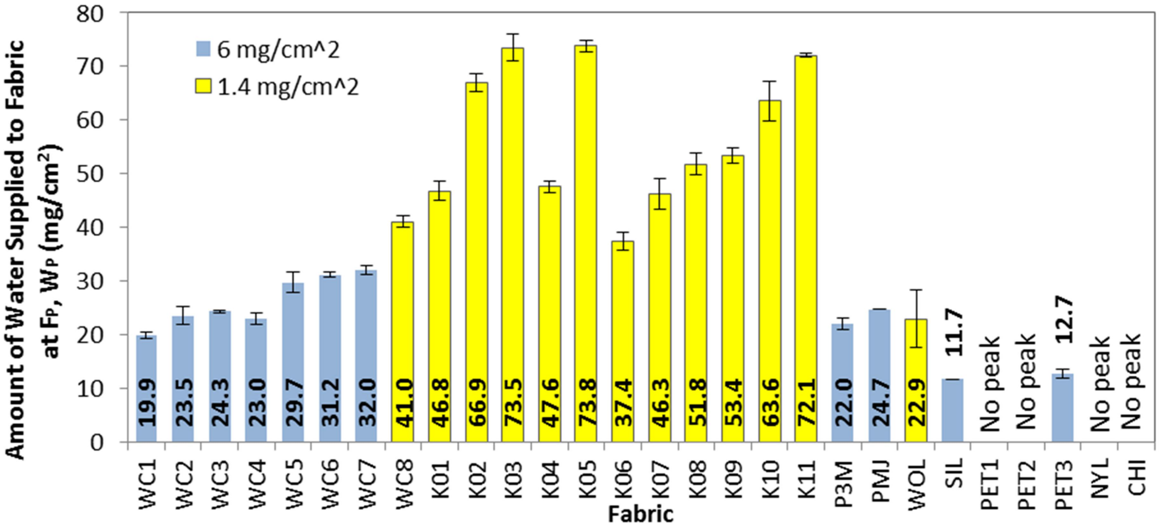


Figure 7.6 The amount of water supplied to fabric at F_P (W_P), blue columns and yellow columns represent 6 and 14 mg/cm^2 of water applied on simulated skin respectively, error bar represents one SD of uncertainty.

7.4.1.1 Correlation of FDFMS Result and Fabric's Absorption Properties – Validity of FDFMS

Figure 7.7 shows the correlation between W_P and absorption capacity of fabrics. The W_P is found to be direct proportional to absorption capacity of fabric with a small offset. The factor between W_P and absorption capacity is 1.06 with R^2 value 0.94. This means drag force of fabric reach its peak when water applied to fabric at 1.06 times of absorption capacity. In the other words, slightly exceeds of absorption capacity of fabric induces peak drag force at fabric-simulated skin interface. When fabric is dragged along the wetted simulated skin, the amount of water at the fabric-simulated skin interface increases. Surface tension of water enhances the adhesion force at the interface. This adhesion force is named as stickiness and it is frequently experienced at wetted skin-textile interface. While excessive water is carried by fabric, water lubricates the interface, so that the adhesion between fabric and simulated skin decreases. This explains why drag force curve drops after it reached F_P. The relationship between F_P, W_P and fabric's absorption capacity explains the critical feature of drag force curve. This explanation confirms the validity of FDFMS.

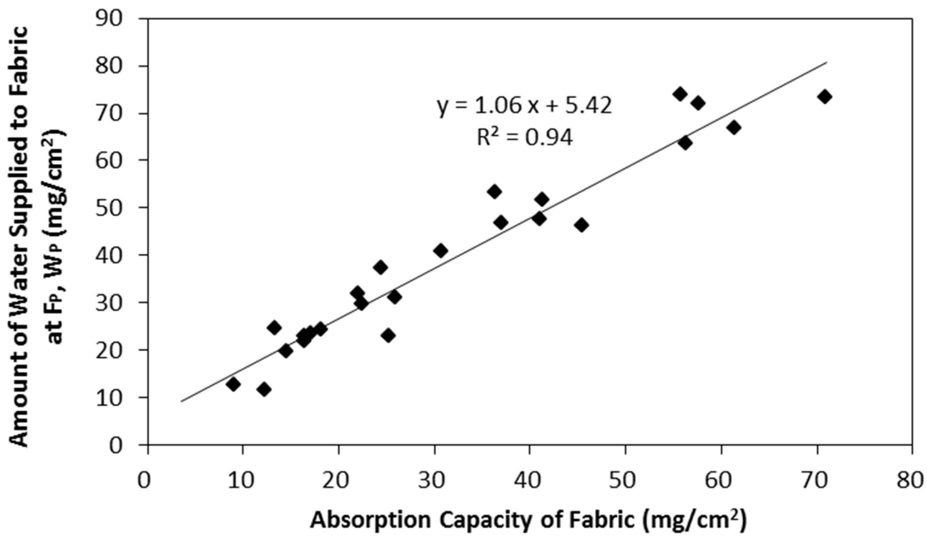


Figure 7.7 Correlation between water supplied to fabric at F_P (W_P) of FDFMS and absorption capacity of fabric

7.4.1.2 Repeatability of FDFMS Result

As mentioned in Section 7.4.1, the CVs of F_P and F_S are around 5 % and 10 % respectively. This proves that FDFMS results have good repeatability.

7.4.2 Subjective Stickiness Sensation Assessment

Stickiness rate result of all subjects and samples are shown in a box-and-whisker plot

(Figure 7.8). In this plot, a small square indicates the average of stickiness rating. The band inside the box is the median. The bottom and top of the box show 25 percentile and 75 percentile of data respectively. The whiskers represent one standard deviation apart from the average value. Lastly, maximum and minimum of data are marked with crosses.

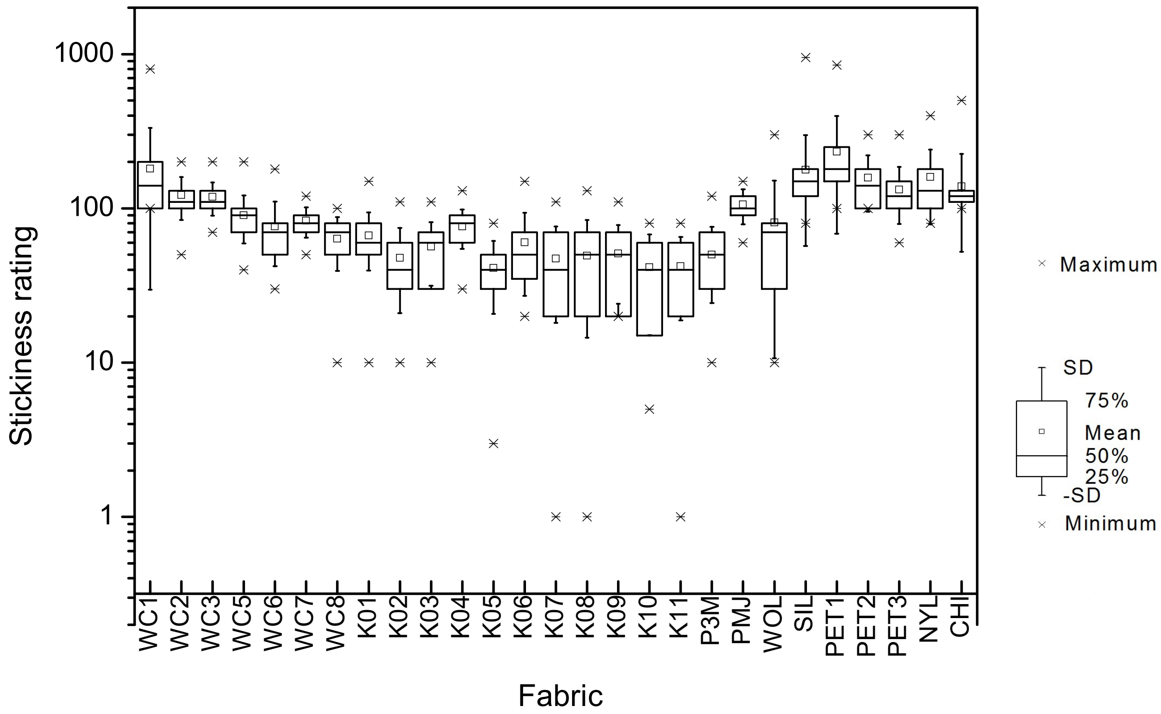


Figure 7.8 Stickiness rating of all assessed fabrics (20 subjects).

Most of the stickiness ratings fall between 30 and 300 (Figure 7.8). The smallest stickiness rating is 1 (K07, K08 and K11), and the largest stickiness is 950 (SIL). It has a trend that the knitted fabrics (K01 to K11) have smaller stickiness rating than the woven fabric. This is because of the short modified AATCC 79 absorbency time and large absorption capacity of knitted fabrics (Section 3.2). The evidence for the effect of absorption properties to stickiness sensation is shown in Table 7.2. In comparing the simple structure woven cotton fabrics (WC1 to WC8), absorbency time and absorption capacity are correlated with stickiness rating. Comparing these fabrics can eliminate the effect of materials and finishing. The stickiness rating is found to be highly correlated with water absorbency time of modified AATCC 79 ($p = 0.000 < 0.050$). This means the longer absorption time gives stronger stickiness perception. On the other hand, stickiness rating is negatively correlated with absorption capacity ($p = 0.006 < 0.050$). This implies that fabric with higher absorption capacity gives lesser stickiness feel. The high correlations are because of the absorbency time and absorption capacity determine the amount of water presents at the skin-fabric interface. This gives important proof that absorption properties affect stickiness very well.

Table 7.2 Pearson coefficient between stickiness rating, water absorbency time of modified AATCC 79 and absorption capacity of cotton woven fabrics WC1, WC2, WC3, WC5, WC6, WC7 and WC8.

Correlations

		Stickiness Rating	Absorbency Time	Absorption Capacity
Stickiness Rating	Pearson Correlation	1	.967**	-.896**
	Sig. (2-tailed)		.000	.006
	N	7	7	7

**. Correlation is significant at the 0.01 level (2-tailed).

There is 1.4 gram of water sprayed on each fabric in the size of 12 x 12 cm^2. The corresponding amount of sprayed in terms of density is 9.7 mg/cm^2. Figure 7.9 shows water carried by sample when presented to subject against absorption capacity of sample. Majority of water amount carried by fabric is around 9.0 mg/cm^2, this level is shown with dotted line in Figure 7.9. The difference between water sprayed and amount of water carried by fabric is because of the fabric is sprayed at tilted position. The non-absorbed amount of water rolls away. It is because of the small absorption capacity, some fabrics carry much less than 9.0 mg/cm^2 of water. Since most of the fabrics carry around 9.0 mg/cm^2 of water during subjective assessment, this water level is selected to compare with the result of the objective instrument FDFMS (Section 7.5).

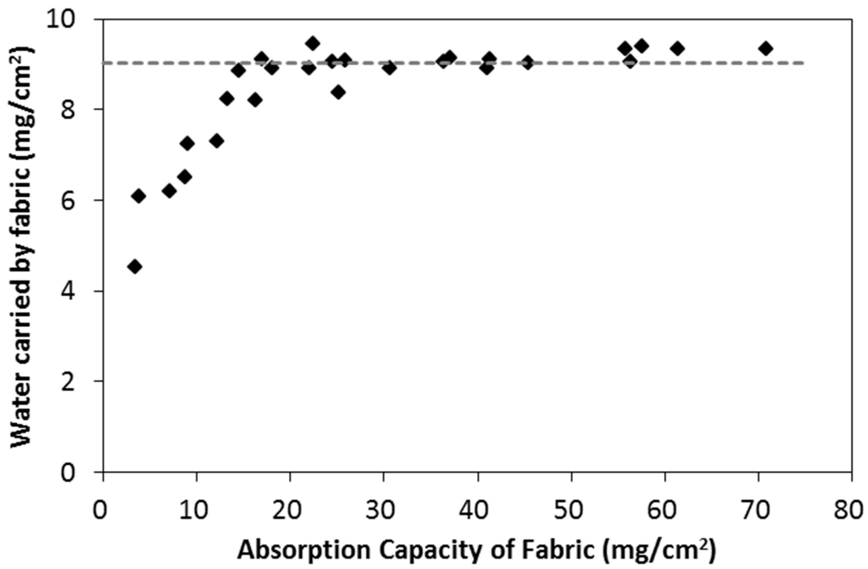


Figure 7.9 Water carried by fabric in subjective stickiness assessment against absorption capacity of fabric.

7.4.2.1 Within-Subject Reliability

K01, P3M, SIL and WC3 have three replicates in the subjective stickiness assessment. Their coefficient of variation (CV) of stickiness rating of each subject is shown in Table 7.3(a). The 80 CV values, come from 20 subjects and 4 samples, have a median of 0.19. This small CV value for a subjective test indicates subjects are reliable. A one-sample T-test is applied to further confirm within-subject reliability. Since WC3 was chosen as reference fabric, the subjects were expected to give 100 as stickiness rating to specimen WC3. Therefore, in the one-sample T-test, null hypothesis is stickiness rating of WC3 is 100. The null hypothesis of 18 out of 20 subjects is accepted, so these subjects are reliable for the stickiness assessment. For the two subjects that null hypothesis is rejected at significance level of 0.050, they are confirmed to give reliable result in another statistical test (one-way ANOVA), so his/her stickiness ratings are still regarded as valid in this study. One-way analysis of variance (ANOVA) is conducted against each subject. K01, P3M, SIL and WC3 of a subject gives the same mean is the null hypothesis of one-way ANOVA test. 17 out of 20 subjects have been rejected against the null hypothesis at significance level of 0.050 (Table 7.3(a)). Table 7.3(b) also lists the one-way ANOVA result of the 20 subjects. Therefore, these subjects are able to distinguish those 4 samples. According to statistical analysis discusses in this paragraph, overall within-subject reliability is high.

Table 7.3(a) CV of stickiness rating of K01, P3M, SIL and WC3; significance (2-tailed) by one-sample T-test of WC3 (against mean value 100); significance by one-way ANOVA of stickiness rating of the 4 samples.

Subject	**Coefficient of variation (CV)**				**Significance (2-tailed) by one-sample T-test of WC3**	**Significance by one-way ANOVA**
	K01	**P3M**	**SIL**	**WC3**		
01	0.14	0.19	0.57	0.06	.742	.181
02	0.32	0.00	0.14	0.21	.444	.011*
03	0.18	0.22	0.10	0.05	.423	.000*
04	0.43	0.37	0.22	0.16	1.000	.002*
05	0.23	0.20	0.07	0.09	.423	.011*
06	0.06	0.00	0.10	0.09	.667	.000*
07	0.57	0.99	0.11	0.28	.268	.006*
08	0.09	0.06	0.03	0.09	.038*	.000*
09	0.79	0.46	0.21	0.16	.208	.004*
10	0.53	0.47	0.18	0.23	.235	.002*
11	0.16	0.53	0.15	0.25	.754	.001*
12	0.20	0.64	0.27	0.20	.368	.005*
13	0.11	0.20	0.18	0.10	.580	.053

14	0.34	0.81	0.13	0.18	.184	.000*
15	0.30	0.27	0.06	0.10	.423	.000*
16	0.23	0.29	0.74	0.17	.250	.130
17	0.00	0.35	0.19	0.10	.423	.004*
18	0.09	0.22	0.21	0.20	.113	.001*
19	0.10	0.23	0.00	0.04	.020*	.000*
20	0.20	0.20	0.12	0.21	.317	.014*

*. The statistic test is significant at the 0.05 level.

Table 7.3(b) One-way ANOVA result of stickiness rating of K01, P3M, SIL and WC3.

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Sub01	Between Groups	21456.250	3	7152.083	2.084	.181
	Within Groups	27450.000	8	3431.250		
	Total	48906.250	11			
Sub02	Between Groups	11466.667	3	3822.222	7.280	.011
	Within Groups	4200.000	8	525.000		
	Total	15666.667	11			
Sub03	Between Groups	17666.667	3	5888.889	39.259	.000
	Within Groups	1200.000	8	150.000		
	Total	18866.667	11			
Sub04	Between Groups	35558.333	3	11852.778	13.676	.002
	Within Groups	6933.333	8	866.667		
	Total	42491.667	11			
Sub05	Between Groups	4966.667	3	1655.556	7.358	.011
	Within Groups	1800.000	8	225.000		
	Total	6766.667	11			
Sub06	Between Groups	9533.333	3	3177.778	27.238	.000
	Within Groups	933.333	8	116.667		
	Total	10466.667	11			
Sub07	Between Groups	56225.000	3	18741.667	9.105	.006
	Within Groups	16466.667	8	2058.333		
	Total	72691.667	11			
Sub08	Between Groups	17758.333	3	5919.444	50.738	.000

	Within Groups	933.333	8	116.667		
	Total	18691.667	11			
Sub09	Between Groups	24333.333	3	8111.111	10.355	.004
	Within Groups	6266.667	8	783.333		
	Total	30600.000	11			
Sub10	Between Groups	38825.000	3	12941.667	13.274	.002
	Within Groups	7800.000	8	975.000		
	Total	46625.000	11			
Sub11	Between Groups	25266.667	3	8422.222	16.301	.001
	Within Groups	4133.333	8	516.667		
	Total	29400.000	11			
Sub12	Between Groups	31491.667	3	10497.222	9.616	.005
	Within Groups	8733.333	8	1091.667		
	Total	40225.000	11			
Sub13	Between Groups	5556.250	3	1852.083	3.951	.053
	Within Groups	3750.000	8	468.750		
	Total	9306.250	11			
Sub14	Between Groups	227133.333	3	75711.111	61.387	.000
	Within Groups	9866.667	8	1233.333		
	Total	237000.000	11			
Sub15	Between Groups	16091.667	3	5363.889	23.840	.000
	Within Groups	1800.000	8	225.000		
	Total	17891.667	11			
Sub16	Between Groups	346200.000	3	115400.000	2.534	.130
	Within Groups	364266.667	8	45533.333		
	Total	710466.667	11			
Sub17	Between Groups	7939.583	3	2646.528	10.163	.004
	Within Groups	2083.333	8	260.417		
	Total	10022.917	11			
Sub18	Between Groups	37625.000	3	12541.667	14.612	.001
	Within Groups	6866.667	8	858.333		
	Total	44491.667	11			
Sub19	Between Groups	16833.333	3	5611.111	61.212	.000
	Within Groups	733.333	8	91.667		
	Total	17566.667	11			
Sub20	Between Groups	13922.917	3	4640.972	6.690	.014

Within Groups	5550.000	8	693.750		
Total	19472.917	11			

7.4.2.2 Between-Subject Consistency

Kendall's Coefficient of Concordance is used to examine between-subject consistency of the subjective assessment. The coefficient ranging from 0 to 1, 0 refers no agreement between subjects and 1 means complete agreement. Kendall's Coefficient of Concordance is found to be 0.733. Therefore, the between-subject consistency of the subjective stickiness assessment is good.

7.4.2.3 Sensitivity of Stickiness Assessment

Kruskal-Wallis test is a nonparametric statistic test. It compares more than two independent samples. Kruskal-Wallis test combines all samples and gives ranks to sample together. The mean rank of stickiness rating of all fabrics is listed in Table 7.4. Since K01, P3M, SIL and WC3 are assessed three times for each subject, they have 60 samples. The null hypothesis of Kruskal-Wallis test of the stickiness assessment is all fabrics gives the same rank for stickiness rating. The null hypothesis is rejected at a significance level of 0.050 ($p = 0.00 < 0.050$). Therefore, the stickiness rating of fabrics is not the same. This proves that the subjective stickiness assessment is sensitive against fabrics, so the assessment is able to distinguish stickiness of fabrics.

Table 7.4 Mean rank of stickiness rating against fabric for Kruskal-Wallis test

Ranks

	Fabric	N	Mean Rank
Stickiness	CHI	20	526.98
	K01	60	258.44
	K02	20	168.23
	K03	20	208.98
	K04	20	307.08
	K05	20	135.40
	K06	20	222.13
	K07	20	169.85
	K08	20	181.55
	K09	20	183.28
	K10	20	143.53
	K11	20	143.40
	NYL	20	550.53
	P3M	60	180.27
	PET1	20	627.18
	PET2	20	568.05
	PET3	20	513.75
	PMJ	20	446.03
	SIL	60	587.93
	WC1	20	574.13
	WC2	20	498.68
	WC3	60	496.43
	WC5	20	369.00
	WC6	20	298.75
	WC7	20	343.95
	WC8	20	244.33
	WOL	20	273.60
	Total	700	

N: Number of sample

7.5 Correlation between FDFMS and Subjective Stickiness Assessment

Most of the samples carry around 9.0 mg/cm^2 of water during subjective assessment (Figure 7.9). Therefore, the drag force at 9.0 mg/cm^2 of water applied from the FDFMS is compared with stickiness rating. The drag force at required water level can be easily located from the drag force curve (Figure 7.2 and 7.3). The stickiness rating and drag force at 9.0 mg/cm^2 is in a direct proportion relationship, and its R^2 value is 0.67 (Figure 7.10). The correlation shows that FDFMS is able to predict stickiness sensation against fabrics at given water level.

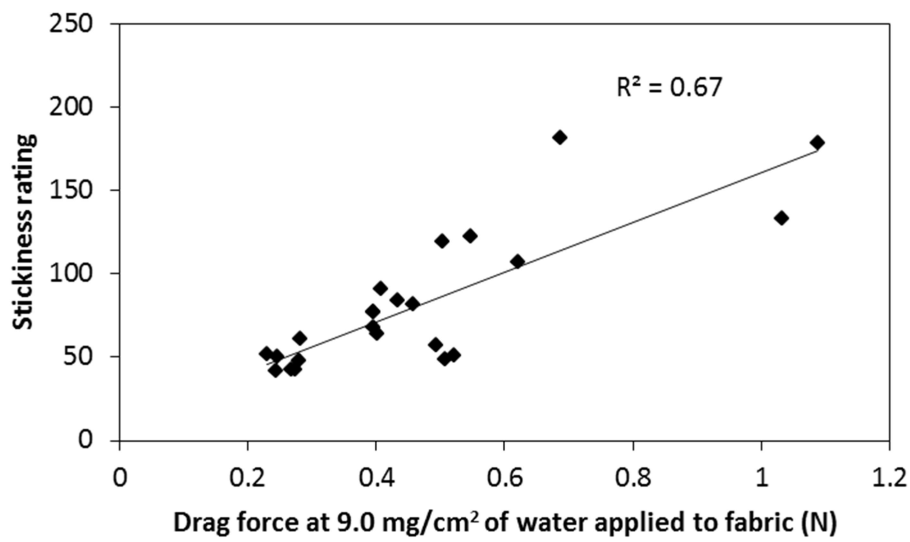


Figure 7.10 Relationship between stickiness rating from subjective assessment and drag force at 9.0 mg/cm^2 of water applied to fabric in FDFMS measurement.

The stickiness is compared with another FDFMS's result, W_P (Figure 7.11). In the linear plot of stickiness rating against W_P (Figure 7.11(a)), a trend of exponential decay of stickiness rating is observed. This means if a fabric capable to absorb more water at peak drag force, that fabric gives less stickiness sensation. This is consistent with the Pearson coefficient between stickiness rating and absorption capacity shows in Table 7.2. On the other hand, the base-10 logarithmic (stickiness rating) shows linear relationship with W_P with R^2 value of 0.67 (Figure 7.11(b)). Therefore, W_P and drag force at 9.0 mg/cm^2 of water applied to fabric in FDFMS gives the same degree of prediction to stickiness rating. A multiple linear regression is conducted to predict stickiness rating by W_P and drag force at 9.0 mg/cm^2 in next paragraph.

(a) (b)

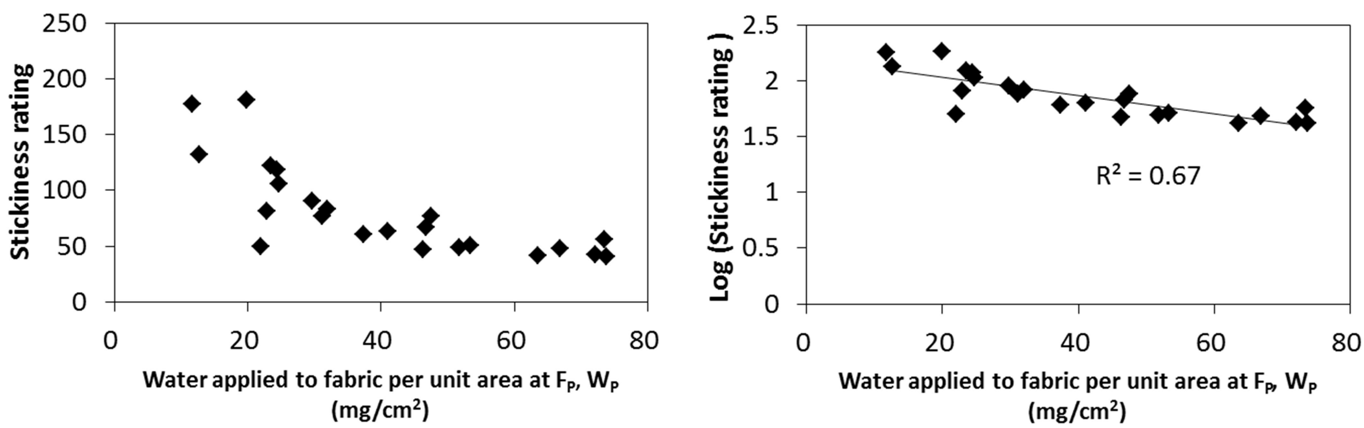


Figure 7.11 (a) Stickiness rating of subjective test against water applied to fabric at peak force of FDFMS measurement. (b) Semi-log plot of (a).

The log (stickiness rating) is the dependent variable of the multiple linear regression. Using log scale is for the easy of manipulation. This is because log (stickiness rating) correlated with W_P. W_P is the one of the two independent variables of linear regression. Another independent variable is log (drag force at 9.0 mg/cm^2), the log scale is used because dependent variable is log (stickiness rating). Table 7.5(a) shows the model summary of the multiple linear regression, and R^2 value of the regression is found to be 0.79. The "goodness of fit" of linear regression is good and around 80 % of variability can be explained by Equation 7.1. Table of coefficients (Table 7.5(b)) lists all necessary information of the linear regression. The coefficients in Equation 7.1 is according to B weight given in Table 7.5(b).

$$\text{Log (Stickiness rating)} = 2.250 + 0.512 \log(\text{drag force at } 9.0 \text{ mg/cm}^2) - 4.88 \times 10^{-3} W_P \quad (7.1)$$

Table 7.5(a) Model summary of linear regression that log (stickiness rating) is dependent variable, W_P and log (drag force at 9.0 mg/cm^2) are independent variable.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.890[a]	.792	.772	.09447

a. Predictors: (Constant), W_P, Log (drag force at 9.0 mg/cm^2)

Table 7.5(b) Table of coefficients of linear regression that log (stickiness rating) is dependent variable, W_P and log (drag force at 9.0 mg/cm^2) are independent variable.

Coefficients[a]

Model		Unstandardised Coefficients		Standardised Coefficients			Correlations		
		B	Std. Error	Beta	t	Sig.	Zero-order	Partial	Part
1	(Constant)	2.250	.049		46.365	.000			
	Log (drag force at 9.0 mg/cm^2)	.512	.151	.479	3.389	.003	.818	.604	.345
	W_P	-4.88×10^{-3}	.001	-.488	-3.450	.003	-.820	-.611	-.352

a. Dependent Variable: Log (Stickiness rating)

7.6 Comparison of FDFMS Result with Conventional Test

Kawabata automatic surface tester's (KESFB4-AUTO-A) result was selected to compare with F_S and F_P. F_S and F_P in this study are obtained by the warp dragging direction of FDFMS. Therefore, mean value of the coefficient of friction (MIU) in warp scanning direction is correlated with F_S and F_P (Figure 7.12 (a) and (b)). Kawabata warp MIU is found to have weak correlation (R^2 = 0.23) with F_S. At the same time, Kawabata warp MIU is independent with F_P. The weak correlations are because Kawabata surface tester measures the dry friction at fabric-metal interface. However, FDFMS studies the wet stickiness at fabric-simulated skin interface, so this confirms the need of a FDFMS to simulate wet skin-fabric interaction.

(a) (b)

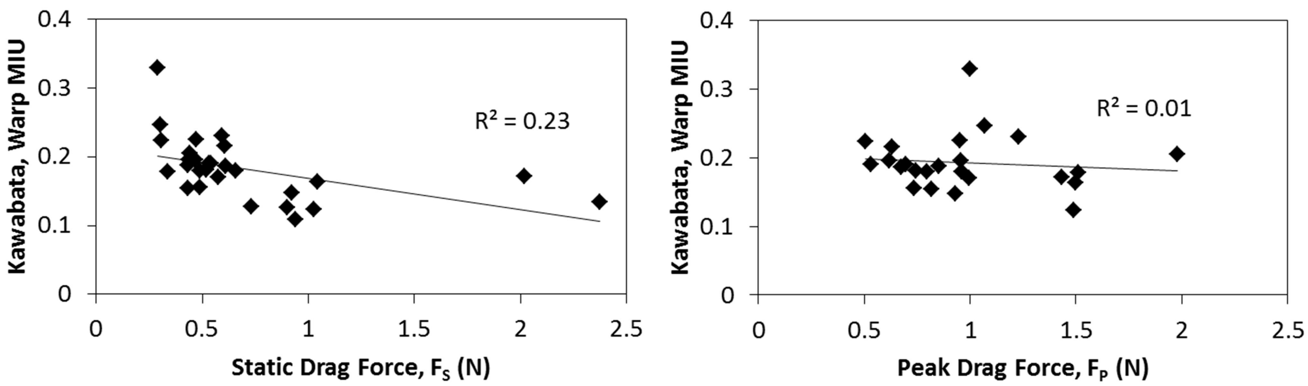


Figure 7.12 (a) Kawabata warp MIU against F_S (b) Kawabata warp MIU against F_P

7.7 Calibration of FDFMS and Uncertainty of FDFMS

The force gauge is a key instrument to obtain drag force result. Its calibration shall be conducted by manufacturer annually to ensure reliable reading. The uncertainty of F_S and F_P are the same as force gauge's reading, which is ± 1 mN. The typical value of F_S and F_P are in the order of magnitude 1 N, so the uncertainty of F_S and F_P are small.

Calibration of FDFMS also includes calibration of electronic balance and dragging speed of the system. The electronic balance is calibrated by a reference weight. The uncertainty of the balance is ± 1 mg. Tolerance for delivering water to simulated skin is ± 100 mg. Therefore, the uncertainty of water delivered for 6 mg/cm^2 trial is ± 3.8 % (100 mg/2610 mg). Similarly, 14 mg/cm^2 trial has ± 1.6 % (100 mg/6090 mg) of uncertainty of water delivered. Lastly, the calibration of fabric's dragging speed is conducted by using a stopwatch. The stopwatch is used to count the travelling time 120 ± 0.3 second of translation stage with sample holder. The sample dragging speed is set at 0.2 cm/sec in the 24 cm travelling distance. The tolerances of water delivery and dragging speed are defined with considering the accuracy of measurement and the ease of operation. Calibration and uncertainty of instruments used and system parameters of FDFMS is summarised in Table 7.6.

Table 7.6 Calibration and uncertainty of instruments used and system parameters of FDFMS

Instrument	Parameter	Calibration	Uncertainty
Force gauge	Drag force	Conducts by the manufacturer	± 1 mN (given by manufacturer)
Electronic balance	Water delivered	Measures the weight of water delivered	Equipment: ± 1 mg (given by manufacturer)
			The tolerance is ± 100 mg, for the total amount of 2610 mg and 6090 mg of water delivered onto simulated skin for 6 mg/cm^2 and 14 mg/cm^2 trials respectively. The tolerance is defined with considering the accuracy of measurement and the ease of operation
Motor	Dragging speed of fabric	Use a stopwatch to count the travelling time of translation stage for 24 cm in 120 ± 0.3 second	The tolerance ± 0.3 second is defined with considering the accuracy of measurement and the ease of operation. Uncertainty is ± 0.25 % (0.3 s/120 s)

7.8 Limitation of FDFMS

FDFMS measures the drag force to move fabric. It is an indirect measurement of the static adhesion force between fabric and simulated skin. The configuration of FDFMS only allows horizontal drag force measurement and only one dragging direction in each measurement. However, measurement in all fabric directions can be done separately. FDFMS is not applicable for measuring friction at dry interface.

7.9 Summary

FDFMS drags specimen through a wetted simulated skin, Lorica Soft. The amount of water applied to fabric accumulated when fabric was dragged along the simulated skin. Drag force curve was then acquired to show a plot of "drag force against water applied to fabric". The drag force curve shows a full profile of fabric-simulated skin interaction. There is no external pressure applied to the fabric during test. This simulates the natural elongation of fabric on skin in actual wear condition.

As observes from the drag force curve, the sample experiences static drag force (F_S) at the beginning of experiment. This is the force required to set fabric moves along simulated skin. This simulates the skin-fabric interaction with a given amount of applied water. The F_S has a range of 0.29 N to 2.37 N among all of the 28 tested fabrics. The contact area of fabric-simulated skin is 60 cm^2 and water applied to each fabric is 6 mg/cm^2. When the amount of applied water accumulates to around 1.06 times of fabric's absorption capacity, a peak drag force (F_P) can be found on the drag force curve. The F_P is an optimal point between water adhesion and lubrication at the wetted fabric-simulated skin interface. The F_P of 24 tested fabrics is found to be between 0.51 N and 1.98 N. Four of the 28 fabrics have no F_P. This is because the experiments were begun nearby the absorption capacity of those fabrics.

There is a linear relationship between W_P and absorption capacity of fabrics. R^2 value of the relationship is 0.94. This explains the critical feature of F_P and proves the validity of FDFMS. The repeatability of FDFMS results are confirmed by the CVs of F_P and F_S. The CV of F_P and F_S are around 5 % and 10 % respectively.

A subjective stickiness assessment had been conducted by 20 subjects. Specimen and reference fabrics were put and driven by a 2-arm fabrics driver on subject's forearms. Under repeatable fabric movements, subjects rate stickiness rating in ration scale. 27

samples were assessed in this subjective assessment. It is found that the water absorption properties highly affect the stickiness rating. The shorter absorption time (modified AATCC 79) and the larger absorption capacity give lesser stickiness sensation. It is a trend that stickiness rating of woven fabrics is larger than knitted fabrics. This is because, in general, knitted fabrics have larger absorption capacity than woven fabrics.

Objective test results obtained from FDFMS are compared with subjective stickiness rating. It is found that FDFMS results, the drag force at 9.0 mg/cm^2 of applied water (the same water amount carried by subjective test samples) is directly proportional to stickiness rating (R^2 = 0.67). Secondly, water applied (W_P) to fabric at the peak of drag force curve is in linear relationship with log (stickiness rating) (R^2 = 0.67). Finally, a multiple linear regression is conducted to predict stickiness rating by objective measurement result. The log (stickiness rating) is set as dependent variable, W_P and log (drag force at 9.0 mg/cm^2) are independent variables. The "goodness of fit" of linear regression is good, and the R^2 value is 0.79.

Conventional instrument, Kawabata automatic surface tester's (KESFB4-AUTO-A) result is compared with F_S and F_P. Kawabata warp MIU is found to have weak correlation (R^2 = 0.23) with F_S and F_P(R^2 = 0.01). This is because FDFMS studies the wet stickiness at fabric-simulated skin interface, but Kawabata surface tester measures the dry friction at fabric-metal interface. This confirms the need of a FDFMS to simulate wet skin-fabric interaction.

Chapter 8 Conclusions and Recommendations

8.1 Conclusions

8.1.1 Drying Rate Instruments, CPDRT and CTDRT

Constant Power Drying Rate Tester (CPDRT) and Constant Temperature Drying Rate Tester (CTDRT) were constructed to measure fabric drying rate. CPDRT applied constant power to sample platform to heat up fabric. It compares the drying properties of fabric materials. CTDRT maintains constant temperature to sample platform. It simulates fabric dries on skin.

The drying rate testers demonstrate non-contact heated plate method. The non-contact methods provide comprehensive information throughout the entire drying process. The drying rate testers equipped with ventilation system to maintain negative air pressure gradient within the tester chambers. This is an important design to steadily remove moist air from the chamber, and to maintain air temperature and humidity within the setup. CPDRT and CTDRT have moderately good correlation with Water Evaporating Rate (WER). However, there are some completely dried fabrics recorded in the WER at 60^{th} minute experiment. This saturation of result (100 % WER) is a disadvantage of WER to discriminate drying rate of fabrics.

The CPDRT takes 15 to 25 minutes for each measurement, Drying rate (DR_{CP}) results are found to be reproducible with range between 0.32 and 1.69 ml/hr among 28 measured samples. CTDRT testing time of each sample is around 15 to 40 minutes. Drying rate (DR_{CT}) has a wide range, 0.36 to 2.56 ml/hr, for all 28 fabrics tested.

CTDRT is able to eliminate the contribution of moisture regain of fabric during measurement. However, CPDRT captures evaporation of moisture regain in drying curve. Without the effect of moisture regain, CTDRT gives better observation on water absorption and spreading properties of fabric than CPDRT. In comparing CV of DR_{CT} and DR_{CP}, DR_{CT} has better repeatability than DR_{CP}. The difference between CV would be because of the method of delivering water.

8.1.2 Subjective Wet Sensation of Drying Fabrics over Time

Subjects assessed wet sensation against fabrics at various drying time. Wetness rating is the wet sensation given by subject. The wetness rating is especially high when fabric is saturated with water. The wetness rating is the highest for 0^{th} minute (just after wet) fabric. The wetness rating decreases when drying time (waiting time) increases. The wetness rating of all fabrics is similar when fabrics are almost dry.

Data sets of the subjective wetness assessment are classified into category (i) subject senses drop in wetness when that fabric drying out, and (ii) subject does not sense change in wetness when that fabric drying out. For data sets with category (i) response, wetness rating of fabric can be predicted beyond 64^{th} minutes, until fabric is dry. There is a linear relationship between $\log_{10}$ (wetness rating) and drying time of fabric. Wetness Factor (WF) is developed to quantify the level of wet sensation and the time span of suffered from wet fabric. A larger WF indicates that subject (or end user) suffers deeper in wet sensation due to the fabric. In compared with “offers dry feel”, “dries fast” was much easier to be measured by objective measurement. It is fast to use drying rate for estimating wet sense against fabric. Although the estimation may not be highly representative, it is widely adopted in the commercial market. Category (ii) data sets give addition wetness sensation information to category (i) result. Category (ii) data set reveals that subject is not able to sense the change of wetness against time of particular fabric. This is mainly because of the properties of that particular fabric, and that subject is able to rate category (i) data sets for other fabrics.

8.1.3 Stickiness Instrument, FDFMS

Fabric Drag Force Measurement System (FDFMS) was built for studying adhesion force at fabric-simulated skin interface. The adhesion force is studied by measuring drag force between wetted fabric and simulated skin. Drag force curve is acquired by the FDFMS to show a plot of "drag force against water applied to fabric". The drag force curve is a full profile of fabric-simulated skin interaction. The newly developed drag-type sample holder requires no external pressure applies to the fabric during measurement. This allows FDFMS simulates actual wear condition that fabric is elongated by body movements.

At the beginning of each experiment, the sample experiences static drag force (F_S). The F_S has a range of 0.29 N to 2.37 N among all of the 28 tested fabrics. When the amount of applied water accumulates to around 1.06 times of fabric absorption capacity, a peak drag force (F_P) is observed on the drag force curve. The F_P is an optimal point between water's adhesion and lubrication at the wetted fabric-simulated skin interface. F_P do not present from four of the 28 tested fabrics. This is because the applied water amount at the beginning of test closes to the absorption capacity of those fabrics. The F_P of remaining 24 tested fabrics is found to be between 0.51 N and 1.98 N.

A subjective stickiness assessment was conducted, and its results are compared with

FDFMS's results. It is found that FDFMS results, the drag force at 9.0 mg/cm^2 of water applied to fabric (the same water amount carried by subjective test samples) is directly proportional to subjective stickiness rating (R^2 = 0.67). Secondly, water applied (W_P) to fabric at the peak of drag force curve is linearly correlated to log (stickiness rating) (R^2 = 0.67). A multiple linear regression is conducted to predict stickiness rating by FDFMS's results. Dependent variable of the regression is the log (stickiness rating), W_P and log (drag force at 9.0 mg/cm^2) are independent variables. R^2 value of the linear regression is 0.79, so that the "goodness of fit" is good.

8.1.4 Use of the Drying Rate and Stickiness Instruments

Figure 8.1 shows results of CTDRT and FDFMS. Since some fabrics (PET1, PET2, NYL and CHI) do not have peak in the drag force curves, 24 fabrics are included in Figure 8.1. This Figure presents DR_{CT} as drying rate result on y-axis. The x-axis is the stickiness rating predicted by FDFMS, which is the multiple linear regression (Equation 7.1) of W_P and drag force at 9.0 mg/cm^2. As discussed previously, large DR_{CT} refers fast evaporating fabric and small stickiness rating represents less stickiness sensation is evoked by fabric. Therefore, fabric falls into the top-left corner of the plot gives the best performance among drying and stickiness properties. Figure 8.2 enlarges information shown in "DR_{CT} against stickiness rating predicted by Equation 7.1.". It shows all knitted fabrics results. K05 falls into the top-left corner of the plot. This shows K05 is the best knitted fabric. K05 is polyester fabric, so water could spread wider in K05 than natural fibre fabrics to provide higher drying rate. K05 has mesh structure that is able to reduce skin-fabric contact as well as high water absorption capacity (Table 3.2; 55.9 mg/cm^2). Therefore, it evokes less stickiness sensation than other fabrics.

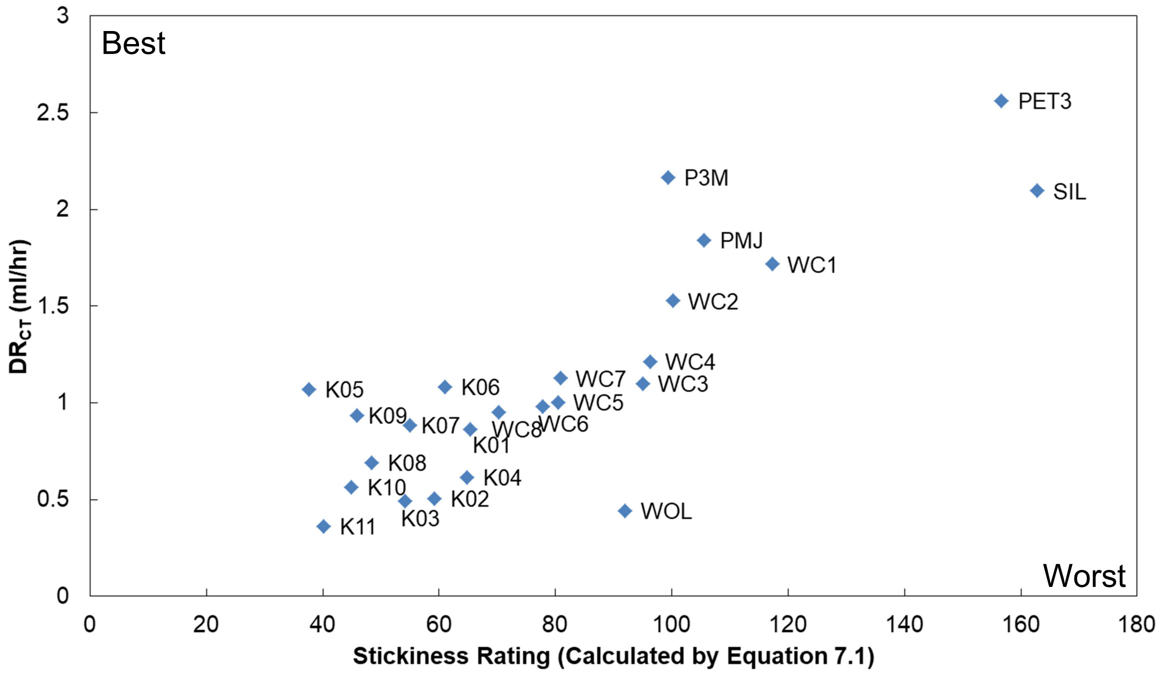


Figure 8.1 CTDRT and FDFMS results; DR_{CT} against stickiness rating predicted by Equation 7.1.

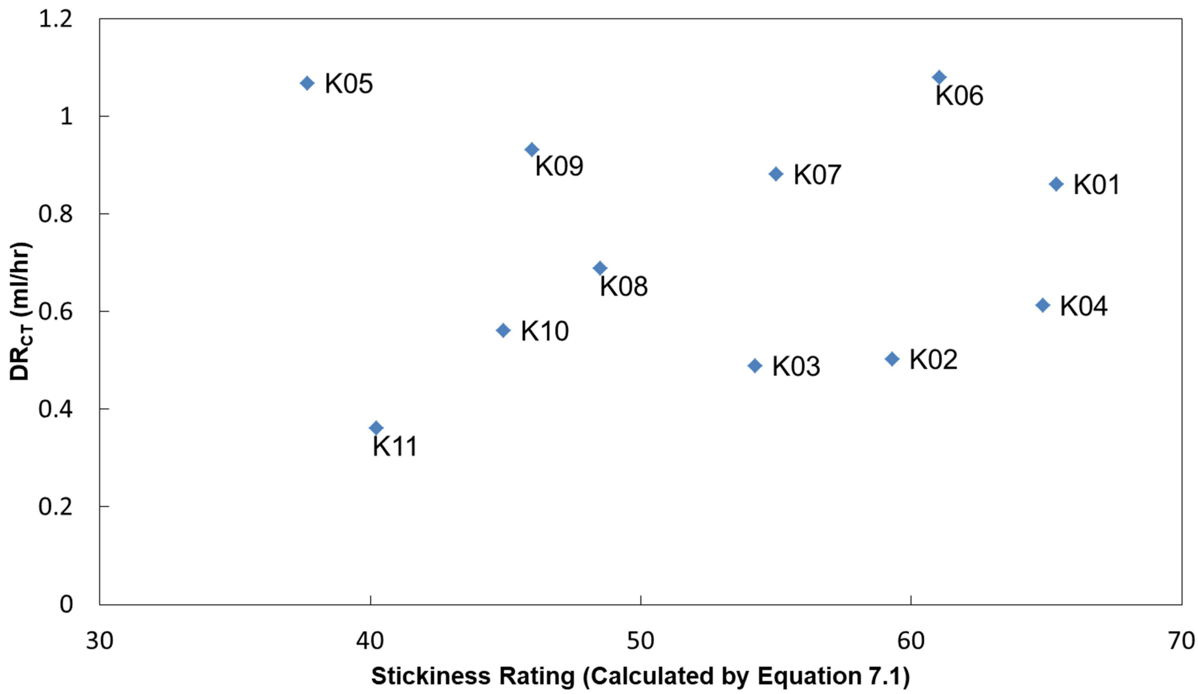


Figure 8.2 Enlarged plot of "DR_{CT} against stickiness rating predicted by Equation 7.1" for comparing performance of knitted fabrics.

8.2 Recommendations

As found in this study, the absorption properties of fabric affect drying and stickiness properties of fabric. Therefore, fabrics treated with different finishing agents can be employed for further investigation. The finishing agents could provide various water wettability to fabrics. The relationship between fabric wettability, drying rate, wetness and stickiness can be further studied by the developed testers and methods.

8.2.1 Drying Rate Instruments, CPDRT and CTDRT

The resolution of electronic balance used in CPDRT is 0.01 g, and the uncertainty of DR_{CP} is 10 %. If electronic balance is replaced by another one with 1 mg resolution, the uncertainty will greatly reduce to 1 %. However, it would be expensive to purchase a balance with high resolution and high weighting capacity.

The wetting and drying mechanism can be further studied by using developed testers. The time dependence of fabric wetted area can be investigated. The drying rate tester may be modified to observe wetted area of fabric back side directly. Therefore, the relationship between wetting and drying phenomena may be studied.

8.2.2 Subjective Wet Sensation of Drying Fabrics over Time

Water is sprayed onto fabric, and it is operated manually. This involves training to achieve repeatable amount of water to fabric. An automatic sprayer can be used to maintain stable water delivery.

Current subjective wet sensation dries fabric at room temperature. The fabric is suggested to dry at skin temperature. A multiple of constant temperature heating systems of CTDRT can be used to provide stable temperature control to fabrics.

8.2.3 Stickiness Instrument, FDFMS

The length of sample platform of FDFMS can be increased, so that dragging distance can be increased. Therefore, the amount of water per unit area delivers to simulated skin is reduced to meet the same total amount of applied water to fabric. This can enhance resolution of the measurement.

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