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EVALUATING HEAT LOSS OF WET TEXTILE SAMPLES ON A SWEATING GUARDED HOTPLATE AT VARIOUS ENVIRONMENTAL CONDITIONS

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USARIEM TECHNICAL REPORT T22-08

EVALUATING HEAT LOSS OF WET TEXTILE SAMPLES ON A SWEATING GUARDED HOTPLATE AT VARIOUS ENVIRONMENTAL CONDITIONS

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14. ABSTRACT

This report details a new method to evaluate the heat transfer properties of wet textiles using a Sweating Guarded Hotplate (SGHP). The method is a controlled process of 1) submersing textile sample in water bath for 30 minutes, 2) hanging sample for 10 minutes, and 3) placing sample on heated and stable SGHP until dry. Initial mass ranged from 58.3–334.7 grams at 20°C and 74.4–345.0 grams at 10°C. Final mass ranged from 42.0–224.1 grams at 20°C and 54.0–254.6 grams at 10°C. Drying time ranged from 25-180 minutes at 20°C and 27-179 minutes at 10°C. Heat flux measured on SGHP during initial drying phase is an average 2.5 times the dry heat flux value. Environmental conditions may affect the mass absorbed and retained by a textile, while environmental conditions used in this study do not appear to have a large effect on drying times of textile samples. Heat flux versus time plots revealed a consistent profile.

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Sweating Guarded Hotplate; Insulation; Wet Clothing; Cold weather; Biophysics; Heat transfer

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EXECUTIVE SUMMARY

Introduction: This report details a new method to evaluate the heat transfer properties of wet textiles using a Sweating Guarded Hotplate (SGHP). The method quantifies water absorbed by textiles, measures drying time of wet textiles, and analyzes the accelerated heat loss of textiles saturated with water, providing a foundation for studying the effects of wet clothing on heat loss from the human body. **Methods:** Seven different materials were evaluated. The basic principles of the method include a controlled process of 1) submersing the textile sample in a water bath for 30 minutes, 2) hanging the sample for 10 minutes to allow excess water to drip off, and then 3) placing the sample on a heated and stable SGHP until the sample is dry. **Results**: Baseline thermal resistance (R_t) measurements of dry textile samples ranged from 0.08–0.131 $m^2 \cdot °C/W$. Initial mass of water absorbed by textile samples ($m_{water,i}$), immediately measured after the 30 minute water bath submersion, ranged from 58.3–334.7 grams at 20°C and 74.4–345.0 grams at 10°C. Final mass of water absorbed by textile samples ($m_{water,f}$), immediately measured after hanging the textile for 10 minutes, ranged from 42.0–224.1 grams at 20°C and 54.0–254.6 grams at 10°C. Drying time for textile samples ranged from 25-180 minutes at 20°C and 27-179 minutes at 10°C. The heat flux measured on the SGHP during the initial drying phase of the wet textile is an average 2.5 times the dry heat flux value. **Discussion:** Results from this study demonstrate the method to be quantifiable and repeatable. Drying times at both environmental conditions for a single textile were similar. There appears to be a consistent offset between the two environmental conditions throughout the duration of the experiment when examining the heat flux versus time for each material. Limitations of this method include subjectivity of determining drying times of the wet textile samples. Additionally, there are limitations that may be due in part to using an older model instrument that is designed for a specific test method. These limitations include unrealistically sharp increases in heat flux when the wet textile is placed on the SGHP and the SGHP not being able to maintain plate surface temperature at environmental air temperatures less than 10°C when a wet textile is on the plate surface. More research needs to be completed for a wider array of environmental conditions as well as for a greater variety of textile materials (e.g., heavy winter insulation) to confirm the trends observed in this study. **Conclusion:** Environmental conditions may affect the mass absorbed and retained by a textile, while environmental conditions used in this study do not appear to have a large effect on drying times of textile samples. Heat flux versus time plots showed a consistent profile for the textile samples used in this study.

INTRODUCTION

The Biophysics and Biomedical Modeling Division at the US Army Research Institute of Environmental Medicine (USARIEM) is a leader in performing biophysical evaluations (e.g. thermal manikin measurements) for clothing and individual equipment (CIE) and translating the results into meaningful human outcomes via thermoregulatory modeling [1, 2]. The biophysical testing and modeling methods used by USARIEM have been validated and used successfully for decades [3, 4]. Oftentimes, this work has been completed through collaborations with US and international military materiel developers as well as industry partners [5-7]. Collaborators, along with active military members, have shown significant interest to expand the biophysical evaluations to include wet clothing and textiles. The evaluation of materials saturated with water is important to improve understanding of heat transfer properties of textiles, to improve the analysis of new textile technologies that claim superior moisture management properties, and ultimately to increase accuracy of human thermoregulatory modeling.

Conventionally, the clothing input for thermoregulatory modeling is based on two clothing biophysics properties that are routinely collected, thermal resistance (R_t) and evaporative resistance (R_{et}), which are measured by following their respective ASTM International standards [8-10]. When strictly following these standards, R_t is performed with the clothing or textile in a dry state. While measuring R_{et}, the clothing becomes wet as a by-product of the test method. However, the clothing or textile may not be saturated with water entirely or uniformly. Additionally, the R_{et} test is typically completed in isothermal conditions, and therefore the intent is to examine heat loss from the body to the environment via the phase change of evaporation. There is a significant gap within the scientific community related to the effects of wet clothing, with a particular interest in evaluating how wet clothing affects the total heat loss. Specifically, the contributions of clothing wetness to the heat transfer modes (conduction, convection, and radiation), in addition to heat via phase change of evaporation. Additionally, wet clothing is of particular concern in cold environments, but not exclusively in extreme cold where hypothermia is expected. Although less evident, hypothermia may be lethal in environmental conditions where the air temperature is above the freezing point of water, particularly in scenarios where wet clothing may expedite the onset of hypothermia [11].

Quantifying the behavior of wet clothing is a complex process due to a number of factors. This report outlines a process for controlling a few of these factors. In the present work, all samples were saturated consistently with respect to time and method of submersion. However, in real situations clothing may have varying levels of saturation. Even when uniformly saturated, the amount of water absorbed will vary between different materials. Depending on the scenario, clothing may continually become drier if environmental conditions are favorable for evaporation, or may become increasingly wet due to precipitation or perspiration. This dependence on the environmental conditions further complicates the analysis of wet materials, especially with most outdoor environmental conditions subject to continuous fluctuations with respect to temperature, humidity, wind speed, and precipitation. Nonetheless, two of the first critical parameters that need to be examined are dry time (i.e., how long does a clothing material remain saturated with water) and the quantity of increased heat loss due to water saturation of textiles. The method outlined in this report details how to quantify these parameters, while controlling as many of the other factors as possible. The experiments were performed in two conditions to study the effects of environmental conditions on the heat loss through wet clothing.

Biophysical measurements performed on clothing with a thermal manikin (R_t and R_{et}) can also be performed on a sweating guarded hotplate (SGHP) [10]. Although the parameters collected on a thermal manikin and SGHP have the same name, they are not identical values. The measurements differ due to inevitable air gaps that will exist between the thermal manikin and the clothing, while the textile samples on a SGHP will lay flat with essentially no air gap [12]. Additionally, the SGHP produces data strictly on the textile material, while clothing on a thermal manikin takes into account design features such as fit (with the fit potentially changing when the clothing is wet, e.g., decreased air gap between clothing and body), closures (e.g., hook and loop, zippers), seams, and pockets. The ultimate goal of this effort studying wet clothing and textiles is to quantify the amount of water absorbed by clothing and textiles and the effect of wet clothing on heat loss of the human body in various environmental conditions. This report describes the pilot work to achieve these goals.

METHODS

MATERIALS

Various US Army clothing materials were selected as the textile samples for this study. Abbreviated names will be used to refer to each fabric to simplify presentation of results. Abbreviations and descriptions of each sample are shown in Table 1. Two samples were used for each material, except for the IHWCU and the FRACU, which each had only one sample available.

Table 1. Full description and abbreviated names of textile samples.

Description	Abbreviation
T-shirt - 100% Polyester	TS-P
T-shirt - 50% Cotton/50% Polyester	TS-CP
T-shirt - 58% FR Rayon/32% Wool/10% Nylon	TS-RWN
Improved Hot Weather Combat Uniform	IHWCU
Generation III ECWCS Level 1	ECWCS L1
Generation III ECWCS Level 2	ECWCS L2
Flame Resistant Army Combat Uniform	FRACU

BIOPHYSICAL ASSESSMENTS

Baseline Experiments

Before performing experiments with wet textiles, baseline experiments were performed on the SGHP in order to collect thermal resistance (R_t) and heat flux (Q) measurements of the completely dry samples. Baseline tests were completed according to ASTM F1868-17 Part A [10] and were necessary to determine when a wet textile on the SGHP could reasonably be considered “dry”. This is done by comparing the steady-state heat flux values at the end of a wet textile test with the baseline steady-state heat flux values of the same material.

USARIEM’s SGHP is manufactured by Thermetrics (Seattle, WA, USA) and has a 10.5 inch (26.7 cm) square measurement area, which is surrounded by a guard area that requires a 20 inch (50.8 cm) square textile sample. The environmental set points for the baseline experiments were an air temperature (T_a) of 20°C, relative humidity (RH) of 50%, and air velocity (v_a) of 1.0 m/s. Three trials of each sample were completed on the SGHP. The R_t and Q baseline measurements are the mean of a 30 minute steady-state period. An additional trial of each sample was completed at T_a of 10°C, 65% RH, and v_a of 1.0 m/s to collect baseline values for the lower air temperature used in the wet textile experiments.

Wet Textile Experiments

The SGHP wet textile experiment setup is shown in Figure 1. The basic principles of the method include 1) submersing the textile sample in a water bath for 30 minutes, 2) hanging the sample to allow excess water to drip off for 10 minutes, and then 3) placing the sample on a heated and stable SGHP until the sample is dry. There is greater nuance when performing the experiments and greater attention is required to account for finer details necessary to obtain repeatable measurements. For this purpose, a detailed step-by-step procedure is included in Appendix A.

Figure 1. Experimental setup for wet textile SGHP evaluations

The amount of water absorbed by each textile sample is of specific interest for the wet textile experiments. Prior to wetting the textiles, the mass of each dry sample was measured (m_{dry}). Mass of the samples were also measured after 30 minutes submerged in a water bath ($m_{wet,i}$) and then again after a 10 minute hang dry period ($m_{wet,f}$). Comparisons between textile materials based on the 3 mass measurements mentioned above can be difficult due the differences in material properties (e.g., dry mass, absorption properties). More appropriate comparisons across a variety of samples can be made by analyzing the amount of water initially absorbed and also the amount of water retained after the hang dry period. These two values are calculated by:

$$m_{water,i} = m_{wet,i} - m_{dry} \tag{1}$$

$$m_{water,f} = m_{wet,f} - m_{dry} \tag{2}$$

where $m_{water,i}$ is the mass of water in the textile sample immediately after the 30 minute submersion in the water bath, and $m_{water,f}$ is the mass of water in the textile sample immediately after the sample is suspended to air dry for 10 minutes.

After completing the wetting, hanging, and weighing process, each textile was placed on the SGHP until the heat flux measurements indicated that the sample returned to a dry state, i.e., until the heat flux versus time plot reached a steady-state approximately equal to the baseline heat flux of the completely dry sample (within ±10% difference). The wet textile SGHP experiments were performed at two separate environmental conditions, T_a = 20°C, 65% RH (vapor pressure 0.22 kPa), v_a = 1.0 m/s and T_a = 10°C, 65 %RH (vapor pressure 0.12 kPa), v_a = 1.0 m/s. The surface temperature (T_s) of the SGHP was set to 35°C for all experiments. The temperature of the water bath was not measured. However, the water bath was placed in the environmental chamber, and therefore the water temperature is assumed to be approximately the same as the air temperature. At both environmental conditions, 3 trials were completed for each material.

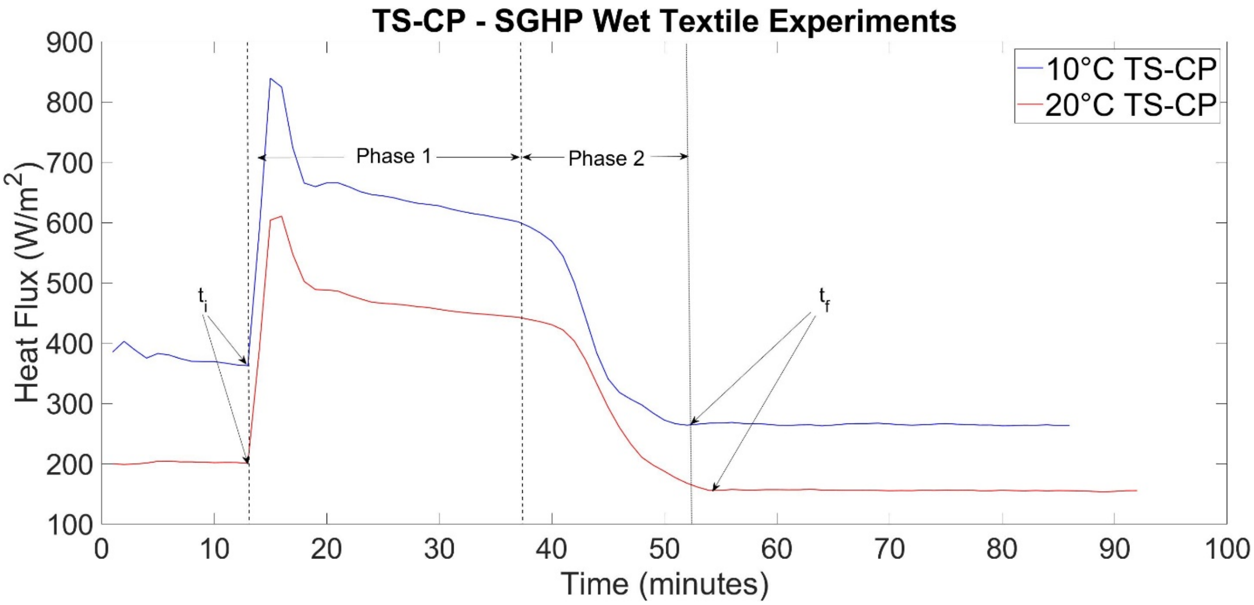
ANALYSIS

A MATLAB (Mathworks, Natick, MA, USA) script was created to import the necessary information from the raw SGHP experiment file. Heat flux versus time plots were then consistently examined using the plotting features in MATLAB, identifying the time, in minutes, when the wet textile sample was placed on the SGHP (t_i). From the same plot, the elapsed time when the textile sample becomes dry again (t_f) was determined, i.e., when the heat flux of the wet sample approximately equaled the baseline (dry) heat flux value and the heat flux began plateauing into a steady-state. The drying time of the wet textile sample was calculated by:

$$t_{drying} = t_f - t_i \tag{3}$$

where t_{drying} is in minutes. Detailed instructions for this method are in Appendix B and the MATLAB script is in Appendix C. An example is shown in Figure 2 that illustrates the points where t_i and t_f appear on plots for the TS-CP material.

Figure 2. Heat flux versus time plot for TS-CP material at 20°C and 10°C air temperature



Heat flux versus time plots are also useful to analyze the behavior of wet textiles over time. All the experiments in this study produced similar shaped curves, which are broken down into two phases illustrated in Figure 2. Phase 1 includes a 5-10 minute stabilization period when the wet textile sample is placed on the SGHP followed by a gradual linear decrease from the maximum heat flux value. Phase 2 contains a sharper decrease in heat flux.

One simple characterization of the wet textile behavior is to examine the mean heat flux during phase 1 (Q_{phase1}). Although the heat flux is not steady during phase 1, an approximation of the increased heat flux for the length of time of phase 1 (t_{phase1}) can be made. The calculation of Q_{phase1} should not include the initial destabilization period as this is likely a consequence of the technology of the SGHP used in this study (newer models with dynamic heat flux sensors may be able to account for large and sudden changes). However, since the wet textile is placed on the SGHP at the beginning of phase 1, the calculation of t_{phase1} will include the destabilization period.

RESULTS

The baseline R_t measurements of the dry textile samples are shown in Table 2 for the environmental conditions: T_a = 20°C, 50% RH and T_a = 10°C, 65% RH. Both environmental conditions maintain the same air velocity over the SGHP, v_a = 1 m/s. The R_t values are a standard measurement for textile samples. The heat flux values used to calculate the baseline R_t of dry textiles are used for comparison with wet textiles in Table 5.

Table 2. Baseline thermal resistance measurements

Sample	T_a = 20°C R_t (m^2·°C/W)	T_a = 10°C R_t (m^2·°C/W)	% error
TS-P	0.095	0.1023	7.9%
TS-CP	0.087	0.1008	14.2%
TS-RWN	0.095	0.0988	3.4%
IHWCU	0.092	0.0873	-4.8%
ECWCS L1	0.080	0.0784	-1.7%
ECWCS L2	0.131	0.1430	8.7%
FRACU	0.087	0.0875	0.9%

The mass of all dry textile samples are shown in Table 3. The standard deviation (SD) accounts for the differences between two textile samples of each material. The IHWCU and FRACU each only had one sample and therefore there is no SD.

Table 3. Mass of dry samples

	m_{dry} (g)	
Sample	Mean	SD
TS-P	49.69	1.04
TS-CP	39.08	0.76
TS-RWN	39.98	0.23
IHWCU	52.46	-
ECWCS L1	37.14	0.35
ECWCS L2	68.04	3.05
FRACU	58.79	-

The mass of the water absorbed and retained by each sample, calculated from equations 1 and 2, are shown in Figure 3. Each column is the mean of three trials and the error bars on the column chart are ± 1 standard deviation. The numerical values used to create the column chart are in Table 4 and includes the percent difference, which compares the two environmental conditions for each parameter ($m_{water,i}$ and $m_{water,f}$). The mass of water absorbed at 10°C is lower than mass of water absorbed at 20°C.

Figure 3. Mass of water absorbed by each sample after 30 minute submersion ($m_{water,i}$) and mass of water retained after samples hang dry for 10 minutes ($m_{water,f}$)

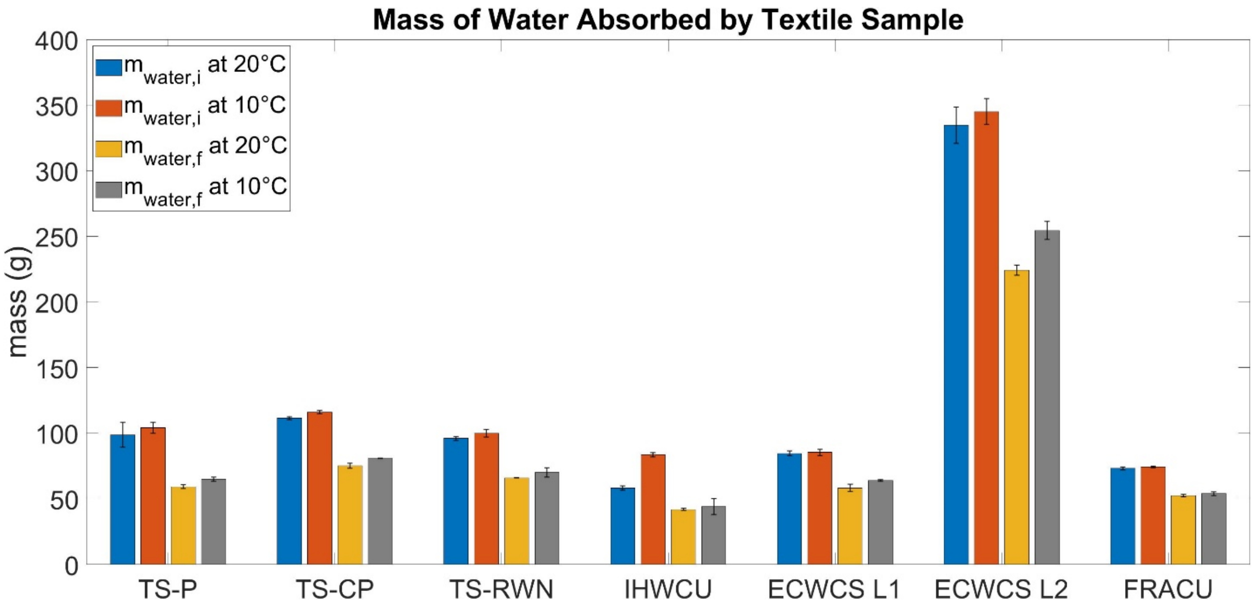


Table 4. Mass of water absorbed by each sample after 30 minute submersion ($m_{water,i}$) and mass of water retained after samples hang dry for 10 minutes ($m_{water,f}$)

	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	% diff.	% diff.
	20°C 65%RH		10°C 65%RH			
	$m_{water,i}$ (g)	$m_{water,f}$ (g)	$m_{water,i}$ (g)	$m_{water,f}$ (g)	$m_{water,i}$ (g)	$m_{water,f}$ (g)
TS-P	98.8 ± 9.4	59.4 ± 1.4	104.2 ± 4.1	64.9 ± 1.5	-5.2%	-9.0%
TS-CP	111.5 ± 1.2	75.4 ± 2.0	116.0 ± 1.2	80.9 ± 0.2	-4.0%	-7.0%
TS-RWN	96.1 ± 1.5	66.1 ± 0.2	100.0 ± 2.8	70.2 ± 3.4	-4.0%	-6.0%
IHWCU	58.3 ± 1.5	42.0 ± 0.9	83.7 ± 1.6	44.2 ± 6.0	-35.7%	-5.1%
ECWCS L1	84.7 ± 1.9	58.3 ± 2.7	85.4 ± 2.5	64.1 ± 0.6	-0.8%	-9.4%
ECWCS L2	334.7 ± 13.7	224.1 ± 3.9	345.0 ± 9.8	254.6 ± 6.9	-3.0%	-12.7%
FRACU	73.3 ± 1.0	52.5 ± 0.9	74.4 ± 0.6	54.0 ± 1.4	-1.6%	-2.9%

Heat flux (Q) measurements in Table 5 are from the dry baseline tests (ASTM F1868-17) and from after the wet textile test (labeled “Post Wet Textile”), with the 30-minute sample period beginning at the first recording interval (data recorded every 60 seconds) when the sample was determined to be dry. The results include experiments at both 20°C and 10°C environmental conditions. The comparison of baseline Q and post wet textile Q is useful to assess the criteria that was used to classify the wet textile as “dry”, which was examined in a previous paper [13], e.g., post wet textile Q within 10% of the baseline Q.

Table 5. Heat flux (Q) measurements from baseline experiments and the heat flux measurements for the 30 minute period beginning immediately after sample was determined to be dry

	20°C, 65% RH			10°C, 65% RH		
Sample	Dry Baseline Q (W/m^2)	Post Wet Textile Q (W/m^2)	% error	Dry Baseline Q (W/m^2)	Post Wet Textile Q (W/m^2)	% error
TS-P	154.9	144.0	7.0%	248.9	244.8	1.7%
TS-CP	168.3	156.4	7.1%	252.3	265.7	-5.3%
TS-RWN	160.7	163.5	-1.8%	257.3	267.3	-3.9%
IHWCU	160.7	170.5	-6.1%	291.0	284.0	2.4%
ECWCS L1	188.8	181.4	3.9%	324.3	305.6	5.8%
ECWCS L2	109.3	110.0	-0.6%	176.1	184.4	-4.7%
FRACU	165.3	170.9	-3.4%	289.1	289.5	-0.1%

The drying time (t_{drying}) of each sample, calculated from equation 3, is shown in Figure 4. Three trials of each sample were completed at environmental conditions of 20°C and 10°C. Each column is the mean of three trials and the error bars on the column chart are ± 1 standard deviation. The numerical values used to create the column chart are in Table 6 and include the percent difference of t_{drying} at two environmental conditions. The difference of t_{drying} at two environmental conditions are small, because evaporation is driven by the vapor pressure gradients and the vapor pressure gradients at the two conditions are very close. Assuming the textile temperature is 35°C, the vapor pressure at saturation on the SGHP surface is 0.82 kPa. The vapor pressure gradients between textile and environments are 0.6 kPa and 0.7 kPa for 20°C and 10°C conditions respectively.

Figure 4. Drying time on a Sweating Guarded Hotplate (SGHP) of each sample at air temperatures of 20°C and 10°C.

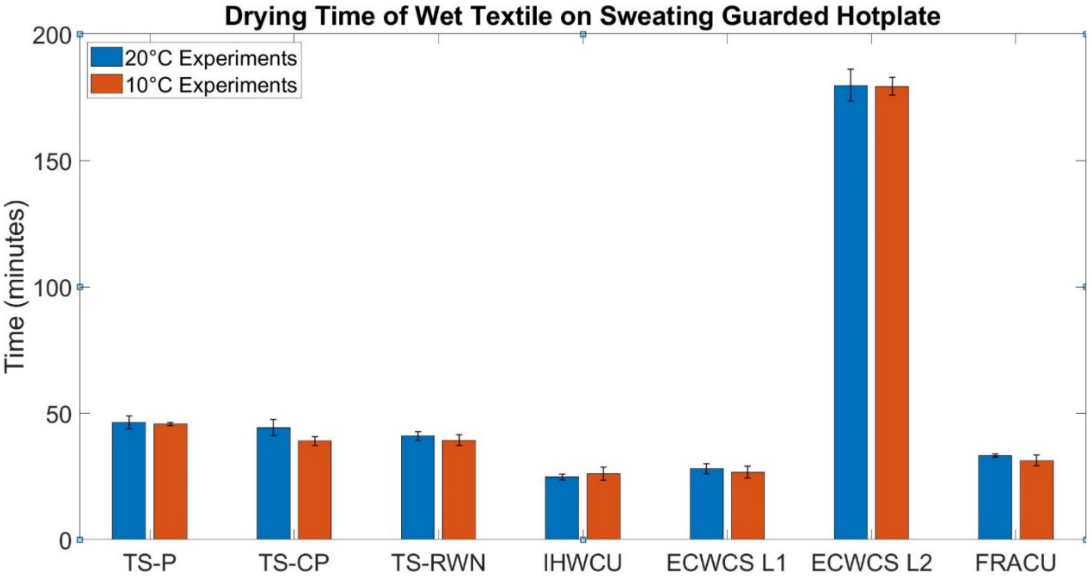


Table 6. Drying time on a Sweating Guarded Hotplate (SGHP) of each sample at air temperatures of 20°C and 10°C.

	20°C 65%RH		10°C 65%RH		
Sample	t_{drying} (minutes)	SD	t_{drying} (minutes)	SD	% diff
TS-P	46	2.5	46	0.6	1.4%
TS-CP	44	3.2	39	1.7	12.8%
TS-RWN	41	1.7	39	2.1	4.1%
IHWCU	25	1.2	26	2.6	-5.3%
ECWCS L1	28	2.0	27	2.3	4.9%
ECWCS L2	180	6.4	179	3.5	0.2%
FRACU	33	0.6	31	2.1	6.2%

Heat flux versus time plots for the SGHP wet textile experiments were created and are shown in Figure 5 through Figure 11. Each line in the plot represents the mean value of three trials at a single environmental condition. All trials were aligned to the time when the wet textile was placed on the SGHP (t_i).

Figure 5. Heat flux versus time plot for TS-P material at 20°C and 10°C air temperature

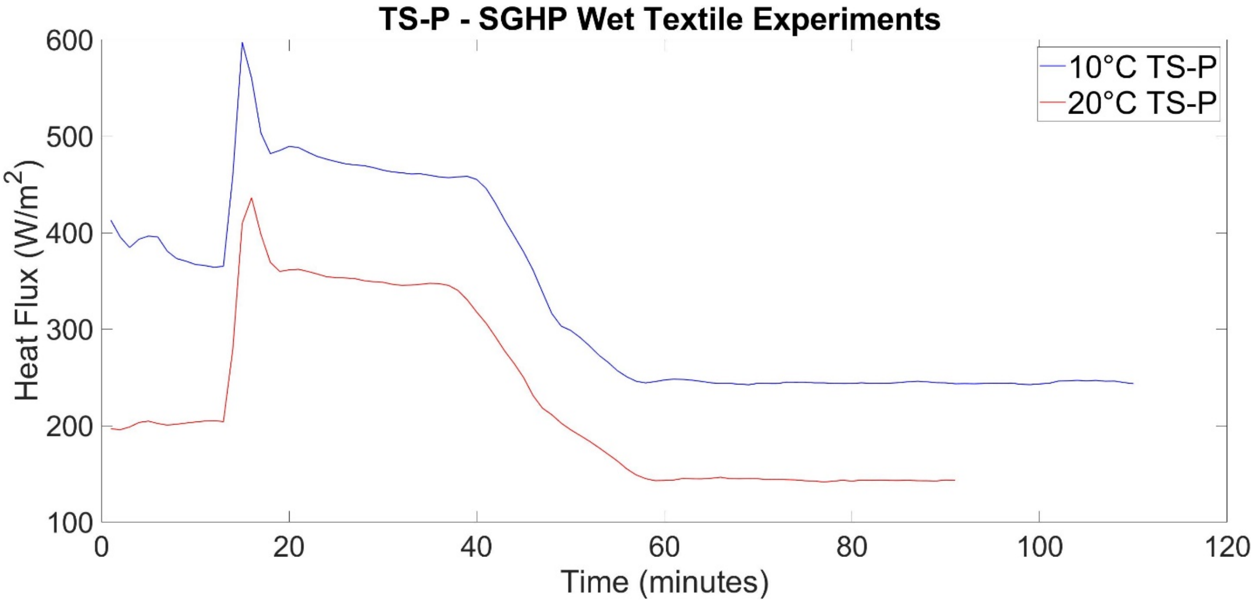


Figure 6. Heat flux versus time plot for TS-CP material at 20°C and 10°C air temperature

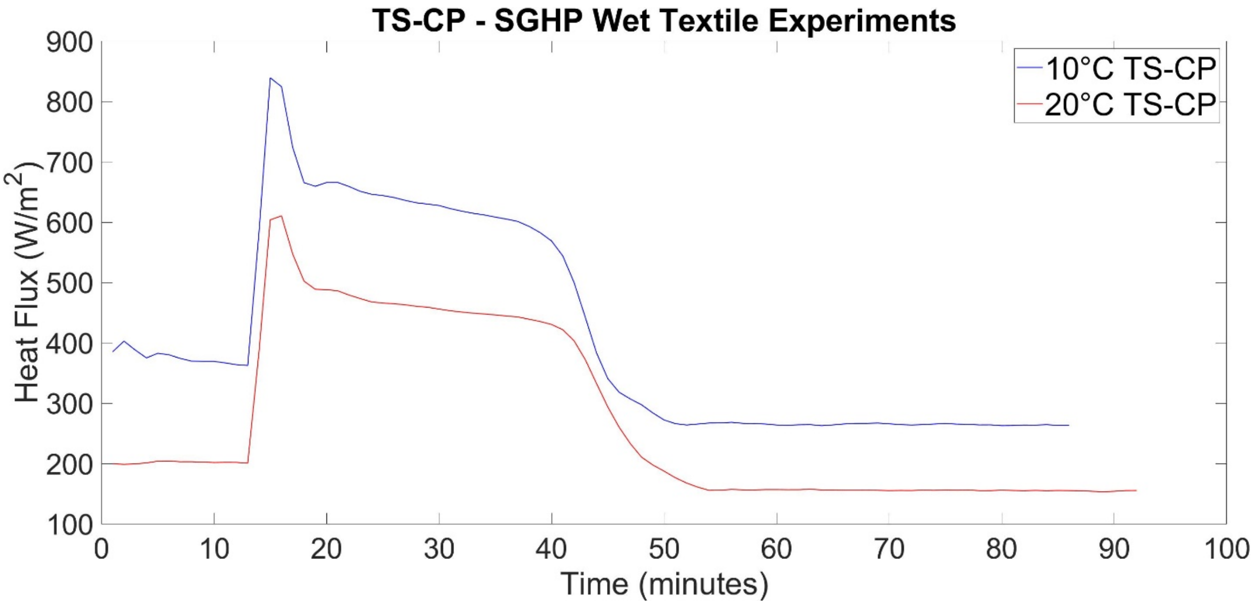


Figure 7. Heat flux versus time plot for TS-RWN material at 20°C and 10°C air temperature

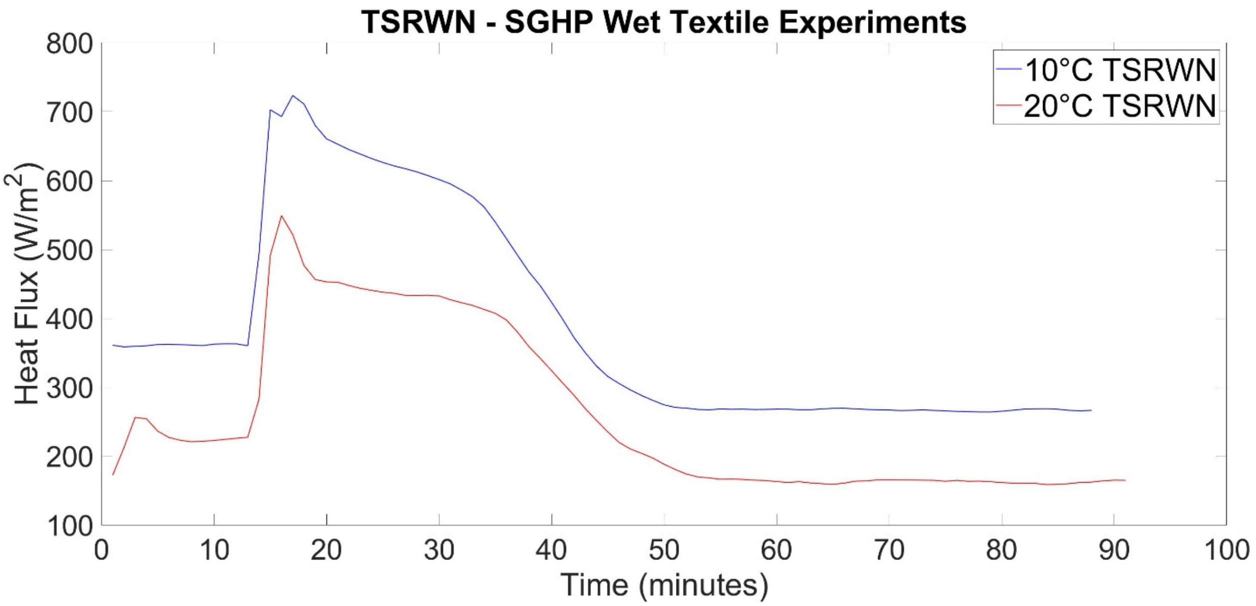


Figure 8. Heat flux versus time plot for IHWCU material at 20°C air temperature

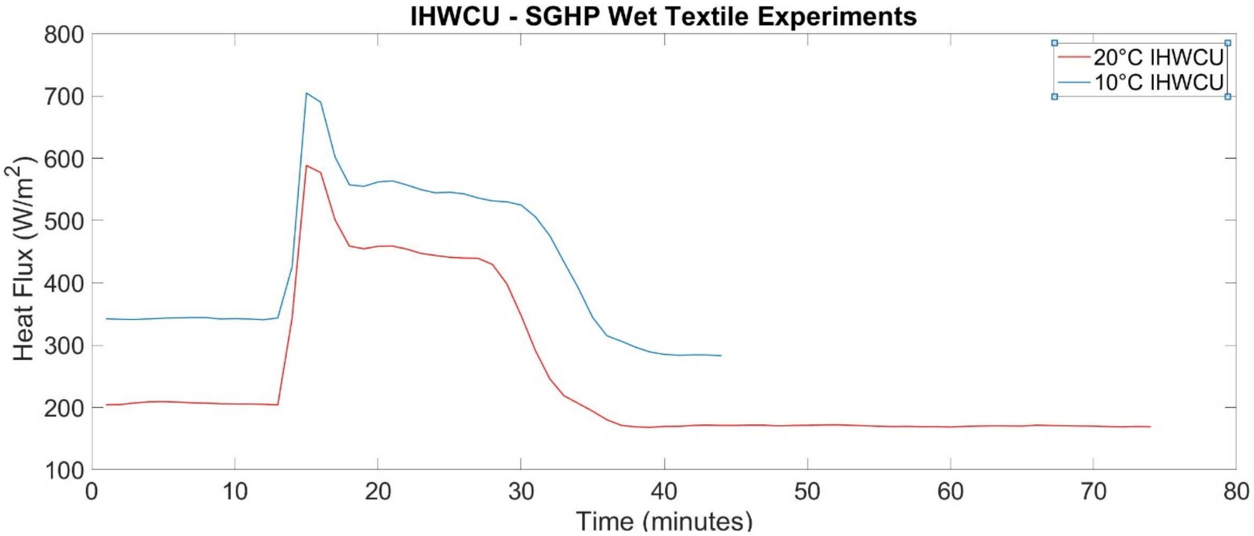


Figure 9. Heat flux versus time plot for ECWCS L1 material at 20°C and 10°C air temperature

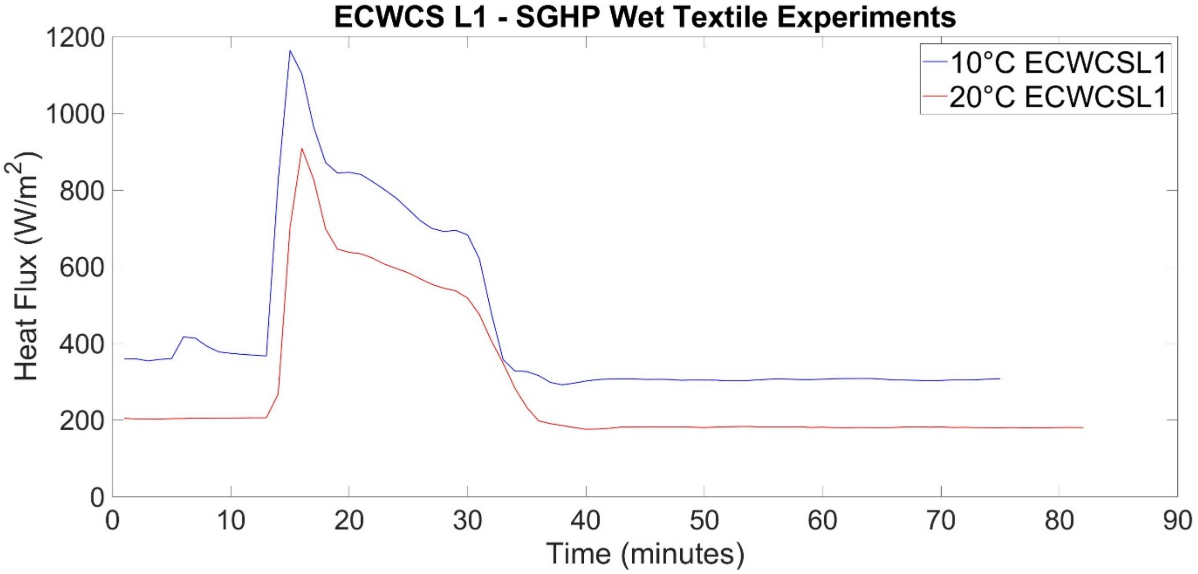


Figure 10. Heat flux versus time plot for ECWCS L2 material at 20°C and 10°C air temperature

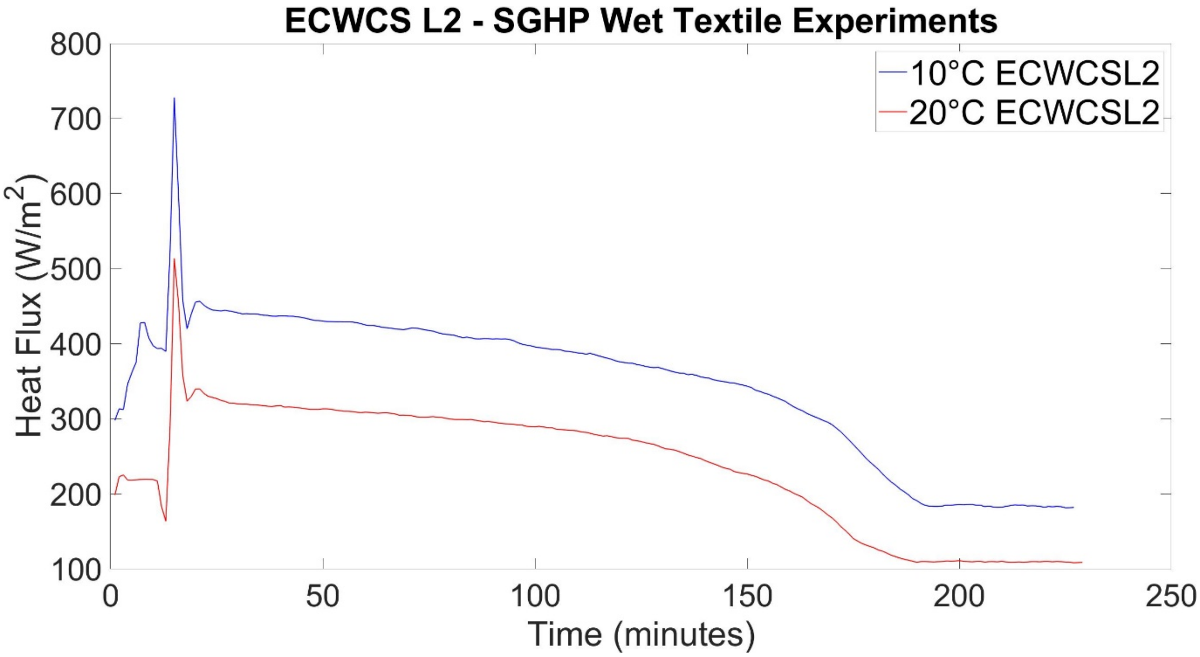
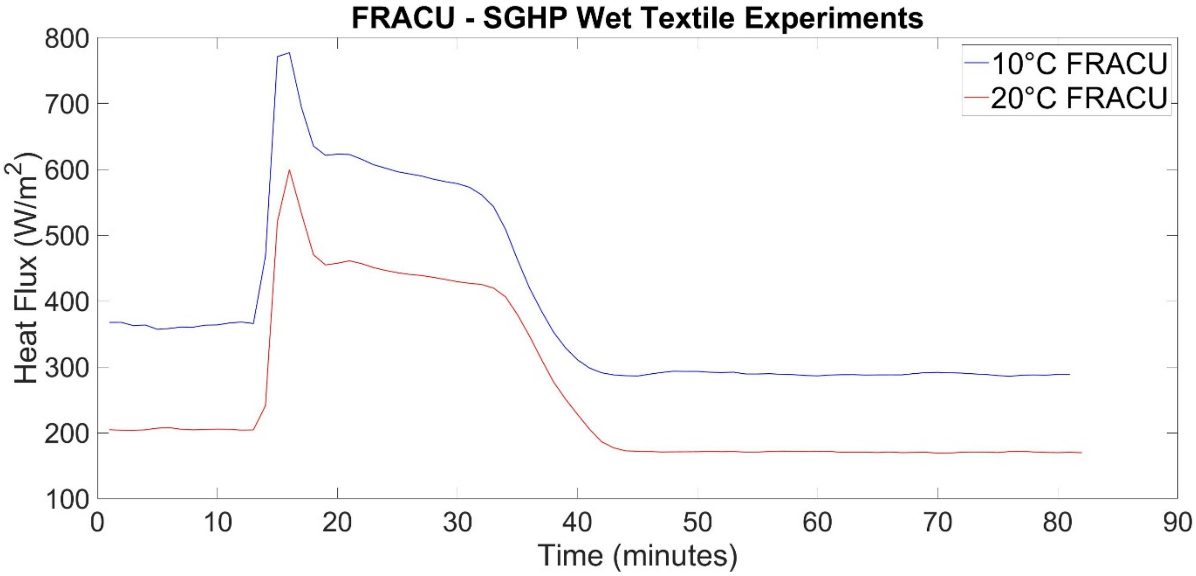


Figure 11. Heat flux versus time plot for FRACU material at 20°C and 10°C air temperature



The length of time of phase 1 and the percent of total drying time is shown in Table 7 for both environmental conditions. The mean heat flux during phase 1 (Q_{phase1}) and the standard deviation (SD) is shown in Table 8, as well as the number of times increase from baseline Q.

Table 7. Time period of phase 1 in minutes and the percentage of total drying time

	20°C 65%RH		10°C 65%RH	
Sample	t_{phase1}	% of t_{drying}	t_{phase1}	% of t_{drying}
TS-P	23	50%	26	43%
TS-CP	24	46%	24	38%
TS-RWN	17	59%	18	54%
IHWCU	15	39%	17	35%
ECWCS L1	16	43%	16	40%
ECWCS L2	113	37%	113	37%
FRACU	19	43%	18	43%

Table 8. Mean heat flux (Q_{phase1}) and SD during phase 1 and number of times increase of Q_{phase1} from baseline Q

	20°C 65%RH			10°C 65%RH		
Sample	Q_{phase1} (W/m^2)	SD	x increase from baseline Q	Q_{phase1}	SD	x increase from baseline Q
TS-P	352.3	5.72	2.3	470.0	10.7	1.9
TS-CP	462.9	14.88	2.8	635.6	21.40	2.5
TS-RWN	449.3	8.26	2.8	625.9	20.54	2.4
IHWCU	449.8	8.30	2.8	553.2	9.93	1.9
ECWCS L1	593.5	39.03	3.1	771.6	62.88	2.4
ECWCS L2	302.4	16.44	2.8	415.1	22.14	2.4
FRACU	443.0	12.05	2.7	599.2	17.62	2.1

DISCUSSION

A new method to quantify the heat transfer behavior of wet textiles has been developed, and this method was used to study the heat transfer behavior of seven textiles. The results from this study, i.e., mass of water absorbed in textiles, t_{drying}, and heat loss curves, are consistent. This indicates the method is appropriate and generates repeatable results. Drying times at both environmental conditions for a single textile were similar, indicating that the environmental temperatures in this study do not have a large effect on drying time, but the vapor pressure gradient may be a driving factor. Additionally, the same shape heat flux versus time curves were consistently produced, and there appears to be a consistent offset between the two environmental conditions throughout the duration of the experiment when examining the heat flux versus time plot for each material. Future work with additional environmental conditions needs to be completed to determine if this heat flux offset can be extrapolated to other conditions.

The method described in this report used an instrument (SGHP) specifically designed for a particular test method [10]. Therefore, there are limitations related to the instrumentation used, such as the initial heat flux surge for approximately 5-10 minutes after the wet textile was placed on the SGHP. This surge is likely an overcompensation by an instrument that is intended to be used in equilibrium states. An additional limitation based on preliminary experiments is that the SGHP may not have enough power to maintain the set point temperature of the SGHP surface (35°C) at air temperatures much lower than 10°C. One additional limitation to the work performed may be subjective by nature. For example, the selection of the end point of phase 1, beginning point of phase 2, and t_f may be open to interpretation. Subjectivity of these selections may add some fluctuation to the drying time and heat flux calculations.

The calculation of Q_{phase1} is a simple method for translating the wet textile SGHP experiments into useful data for analyzing heat loss from the human body while wearing wet clothing. The calculation of Q_{phase1} may be most appropriate for samples with a small delta between min and max Q of phase 1, such as the TS-P material. A different method may be required to analyze the results for samples such as ECWCS L2 where the separation between phase 1 and phase 2 are less straightforward. Eventually, equations to describe the change in heat flux over time for phases 1 and 2 may be useful, but while research is still ongoing, a simple approximation is appropriate.

A wider variety of textile samples may be used in future experiments with this method to confirm the trends seen in this study are reproducible and repeatable. Work is currently underway to translate this method to garments and clothing ensembles by using a thermal manikin.

CONCLUSIONS

The method outlined in this report provides an important step towards standardized evaluation of wetted textiles. Useful parameters that have come out of the development of this method are: 1) measurements of the mass of water absorbed and retained by a variety of textile materials for a specified water submersion time period and a hang drying time period, 2) measurements of drying time of wet textile samples placed on SGHP set to a surface temperature of 35°C, 3) heat flux versus time plots of the SGHP wet textile experiments displaying multiple phases of the experiment, and 4) quantification of accelerated heat loss from wet textiles.

The results from this study show environmental conditions may affect the mass of water absorbed and retained by the textile. Conversely, the environmental conditions used in this study do not appear have a large impact on drying time. Each material, with the exception of TS-CP, has drying times at both environmental conditions that are similar. The heat flux versus time plots have the same basic shape curve, regardless of the material or environmental condition used in this study—a sharp increase in heat flux when the wet textile is placed on the SGHP, followed by a period of slowly decreasing heat flux as the wet textile dries out, and ending with a rapid decrease in heat flux as drying accelerates. Additionally, there appears to be a consistent offset between the heat flux plots of the same textile material at the two environmental conditions of this study. Finally, for the materials and conditions used in this study, the mean heat flux of phase 1 is roughly 2.5 times the dry baseline heat flux value.

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APPENDIX A

STEP-BY-STEP INSTRUCTIONS EVALUATING WET TEXTILE SAMPLES ON THE SWEATING GUARDED HOTPLATE (SGHP)

1. Turn the voltage dial on the SGHP power supply to 10 (maximum value) in order for there to be enough power to maintain surface temperature (T_s) of 35°C with the wet textile.

2. Turn on the SGHP, begin a thermal resistance experiment and set all zones to T_s = 35 °C.

3. Allow test experiment to run for at least 30 minutes (can be done in parallel with steps 6 - 14).

4. Use a weighing container (e.g., bucket) to hold the textile sample. Place on top of the scale and press the tare button.

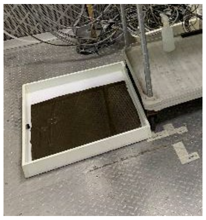
5. Measure the mass of the dry sample (m_{dry}).

   Note—Timing of this method is important and there are number of steps that should be performed in quick succession. In order to quickly and accurately record the mass measurements, a data acquisition system connected to the scale is ideal or another method, such as taking a picture of the scale at each weighing step and then recording the mass in a spreadsheet as soon as test setup is complete.

6. Place dry sample on SGHP. Check plate height and adjust distance between anemometer and top of sample if necessary.

7. Remove sample from SGHP and submerge sample in DI water for 30 minutes

   Note—Be sure to submerge when placing sample in the bath as some samples are hydrophobic and will remain on top of the surface for a period of time).

8. Remove sample from water bath and hold the sample over the water bath for 1 minute to allow excess water to drip off.

9. Measure the mass of the initial wet sample ($m_{wet,i}$).

10. After removing the sample, note the mass of any excess water remaining on scale/weighing container.

11. Wipe any excess water from the scale/weighing container.

12. Hang sample to dry for 10 minutes and undo any folds that may have occurred during process of hanging sample)

13. Measure mass of final wet sample ($m_{wet,f}$), i.e., after hang dry.

14. After removing the sample, note the mass of any excess water remaining on scale/weighing container.

15. Place sample on SGHP and smooth out any wrinkles by hand.

    Note—During the hang dry, the sample is hung vertically, which results in water collecting at the bottom of the sample. When placed on the SGHP, the bottom of the sample (more saturated edge) was oriented in the same position for every test, with the saturated edge being furthest away from the fans that generate the air flow over the SGHP.

16. Continue running the same thermal resistance experiment until sample is determined to be dry, i.e., 30 minute average of heat flux within 10% of dry baseline heat flux

17. Repeat 3 times for each sample.

APPENDIX B

INSTRUCTIONS FOR RUNNING MATLAB CODE

Determine drying time and heat flux (Q) for individual trials, using the MATLAB script provided in Appendix C (ExtractBiophysicsData.m)

1. Create a folder for the current project in “MATLAB” > "WET SGHP" > *Project Name*
2. Copy SGHP raw test data files (generated by ThermDAC—Thermetrics’s manikin and SGHP software) into *Project Name* folder
3. Open MATLAB, locate the "WET SGHP" folder in the Current Folder window, right click, and select Add to Path > Selected Folders and Subfolders
4. In the WET SGHP folder, open and run ExtractBiophysicsData.m
5. A dialog box will appear and prompt the user to select a file. Once a file is selected, the SGHP data should be loaded into vectors and appear in the Workspace.
6. In the command window, type: “plot(Time_minutes, Q);”
7. From the generated plot, determine the time when wet sample was placed on SGHP (t_i), i.e., when the heat flux increases sharply; and when the dry period begins (t_f), i.e., when heat flux begins to plateau. Enter times into a spreadsheet.
8. In the command window, type: "$t = t_i$;” in minutes (enter actual value for t_i determined from step 7)
9. To determine the heat flux through the textile for a 30 minute period immediately following the wet textile portion of the experiment, type “mean(Q(t:(t + 29)));” into the command window and record results into a spreadsheet.

Plotting multiple experiments on the same graph

1. Comment out “*clear; clc;*” at top of script in Appendix C.
2. Extract the data from a single experiment by following the directions in the above section.
3. Rename Q to be more descriptive of the particular experiment, e.g., *Q_SampleA_Trial1*
4. Clear all variables except Q (explicitly calling out each variable to be cleared so future Qs remain), by typing in the command line: *clear A_plate BlockData FileName FullPath I J Q Ta Time_minutes Time_seconds totrows Ts;*

5. Repeat steps 2 – 4 until all trials are in the Workspace and then save the Workspace.

6. Plot all trials on the same figure in order to find the Q vector with shortest elapsed time from experiment start until the wet textile sample was placed on the SGHP (t_i). Adjust all other Q vectors accordingly to align the time in minutes when the wet textile was placed on the SGHP. For example, if the vector Q_A has the shortest t_i of 15 minutes, and another vector Q_B has a t_i of 30 minutes, type "Q_B([1:15]) = [ ];" to remove the extraneous data in Q_B and align the t_i of the two vectors. Repeat the process for any additional vectors to be plotted on the same graph.

7. Once all vectors are in the Workspace, save the Workspace to preserve data for future use.

Creating an average matrix of multiple trials for plotting all materials on the same graph with error bars

1. Make all the vectors of the same material the same size by trimming excess data from the longer trials. Ex. If two trials have a vector length of 100 and the third trial has a vector length of 115 type the following in the command line: "Q_B_Trial3([101:115]) = [ ];"

2. When all the vectors for a single material are the same size, concatenate all trials into a matrix Ex. "Q_B = [Q_B_Trial1 Q_B_Trial2 Q_B_Trial3];"

3. Compute the mean of all trials for each timestamp Ex. "MeanQ_B = Mean(Q_B, 2);" Note: 2 is the dimension for calculating the mean across the row elements.

4. Compute the standard deviation for each timestamp Ex. "SD_Q_B = std(Q_B, 0, 2);"

5. Clear individual trials to clean Workspace

6. Repeat steps 1-5 for all materials

7. Save workspace and plot trials as desired.

APPENDIX C

MATLAB CODE

Script file name: ExtractBiophysicsData.m

```
%% This script imports data from raw ThermDAC files of biophysical tests
% for easier and automated plotting of data vs. time
% original script created by Tim Rioux 05/23/2017.
% Modified code section for SGHP 03/12/2021.

clear; clc;

%% open dialog box UI for user to select file
[FileName,FullPath,~] = uigetfile('*.csv', 'Please Select a ThermDAC Raw Data
File');

%import data from raw file
[~,~,BlockData] = xlsread([FullPath FileName]);
totrows=size(BlockData, 1);

%% Extracting data from sheet
%Extract Time
[I,J] = find(strcmp('Time', BlockData));
Time_seconds = cell2mat(BlockData(I+2:totrows,J));
Time_minutes = floor(Time_seconds/60);

%Extract Surface Temperature for Test plate
[I,J] = find(strcmp('Average Surface Temp', BlockData));
Ts=cell2mat(BlockData(I(1)+2:totrows,J(1)));

%Extract Heat Flux for Test Plate
[I,J] = find(strcmp('Heat Flux Generated', BlockData));
Q=cell2mat(BlockData(I(1)+2:totrows,J(1)));

%Extract Average Ambient Temperature
[I,J] = find(strcmp('Avg Amb Temp', BlockData));
Ta=cell2mat(BlockData(I+2:totrows, J));

%Extract Area of test plate
[I,J] = find(strcmp('m2', BlockData));
A_plate = cell2mat(BlockData(I, J+1));
```