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Guan, M., Psikuta, A., Camenzind, M., Li, J., Mandal, S., Rossi, R. M., & Annaheim, S. (2019). Effect of perspired moisture and material properties on evaporative cooling and thermal protection of the clothed human body exposed to radiant heat. Textile Research Journal, 89(18), 3663-3676.https://doi.org/10.1177/0040517518817067

Effect of perspired moisture and material properties on evaporative cooling and thermal protection of clothed human body exposed to radiant heat

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Abstract

Perspired moisture plays a crucial role in thermal physiology and protection of the human body wearing thermal protective clothing. Until now, the role of continuous sweating on heat transfer, when simultaneously considering internal and external heat sources, has not been well-investigated. To bridge this gap, a sweating torso manikin with twelve thermal protective fabric systems and a radiant heat panel were applied to mimic firefighting. Results demonstrated how the effect of radiant heat on heat dissipation interacted with amount of perspired moisture and material properties. A dual effect of perspired moisture was demonstrated. For hydrophilic materials, sweating induced evaporative cooling but also increased radiant heat gain. For hydrophilic station uniforms, the increment of radiant heat gain due to perspired moisture was about 11% of the increase of heat dissipation. On the other hand, perspired moisture can increase evaporative cooling and decrease radiant heat gain for hydrophobic materials. In addition to fabric thermal resistance (R_{ct}) and evaporative resistance (R_{et}), material hydrophilicity and hydrophobicity, emissivity and thickness are important when assessing metabolic heat dissipation and radiant heat gain with profuse sweating under radiant heat. The results provide experimental evidence that R_{ct} and R_{et}, the general indicators of the clothing thermo-physiological effect, have limitations in characterizing thermal comfort and heat strain during active liquid sweating in radiant heat. It offers a more complete insight into clothing thermal characteristics and human thermal behaviors under radiant heat, contributing to the accurate evaluation of thermal stress for occupational and general individuals.

Keywords

Sweating; thermal physiology; thermal protection; evaporative cooling; radiant heat gain; clothed human body.

1. Introduction

Firefighters and industrial workers wear thermal protective clothing for protection against environmental and work-related thermal hazards. However, the garment also impedes heat dissipation from the human body, causing heat strain (1, 2). It is thus generally accepted that thermo-physiological effect[1] (3) and thermal protective performance are the two crucial aspects of thermal protective clothing. The effective assessment of these two properties has therefore been extensively studied (4-8). In the development of evaluation methodologies, the combination and balancing of heat dissipation and thermal protection

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[1] The real thermo-physiological effect of clothing is complex and influenced by a variety of factors, e.g., clothing thermal characteristics, clothing weight and bulkiness. In this study, the definition of “thermo-physiological effect” refers to the heat and moisture transfer properties of clothing according to ISO 11092: 2014.

aspects of thermal protective clothing has become apparent (5, 7, 9). Standard measurements of clothing physiological effect were compared to the response of human subjects exercising in 250 W/m^2 radiant heat (5). The thermal protective performance as well as the physiological burden of protective materials were combinedly analyzed (7). However, the interaction between the environment, clothing, and the human body is complex. Due to this complexity, a convincing methodology enabling the combined investigation of heat strain and thermal protection has yet not been developed. There seem to be two main limitations in the existing assessment methods, firstly, the inaccurate simulation of human sweating with laboratory tests, and secondly, the independent investigation of thermal physiology and thermal protection.

First, the current evaluation methods do not consider liquid perspiration to its true extent, as encountered during intensive physical activities and in hot environments. When predicting the physiological impact of protective clothing, which is generally defined based on the reduction of heat dissipation from the human body due to the clothing, the thermal resistance (R_{ct}), the evaporative resistance (R_{et}) and the total heat loss (THL) are commonly investigated. These measures are obtained by the sweating hot plate (3, 10-12) and sweating manikins (13-15). However, in such tests, researchers typically use semi-permeable membranes or wet fabrics as the 'skin layer'. Thus, only sweat vapor transferred from the skin is considered and the influence of liquid sweat transfer on heat dissipation is not studied. On the other hand, in spite of the fact that a majority of burns are caused by steam condensation, thermal protective performance is usually evaluated with dry skin models according to thermal protection standards (e.g., ISO 13506, ASTM 1930 and ASTM 2700) (8, 16-20). To investigate the effect of perspired moisture on thermal protective performance, researchers have adapted these methods by using wet fabric systems (21-28) or a set-up with an adjustable microclimate relative humidity between the fabric specimen and the copper calorimeter (skin model) (29, 30). Within these studies, there is no clear conclusion about the effect of moisture on thermal protective performance. Some studies (7, 27, 28) showed that the internal moisture enhanced the thermal protective performance while other researchers (22, 31-33) demonstrated the opposing effect. Effect of moisture on thermal protection seemed to be influenced by moisture amount and material properties. The previous studies also indicate that it is crucial to realistically simulate the human perspiration, which may give a reasonable and accurate evaluation of perspired moisture effects on heat transfer (19, 28).

The second possible limitation of the existing evaluation approaches is that even though physiological impact and protective performance of clothing simultaneously affect the human body, they are usually addressed separately, and thus, only provide one-sided information on clothing thermal characteristics. Studies in the thermal protection field focus on the heat transfer from the environment to human body, paying less attention to the possible effect of metabolic heat production from human body on personal safety. On the other hand, the standard evaluations of clothing physiological effects (3, 10, 13-15) focus on the heat transfer from the human body to the environment without considering the effect of external heat source on the heat dissipation through clothing. The environmental conditions in these current standards usually require the mean radiant temperature not to be more than 1.0°C different from the mean air temperature, which may be inappropriate for thermal protective clothing which is specifically used for hot environment. Also, in the current heat stress assessment of radiant heat environment, the clothing thermal characteristics are estimated based on the above standards (3, 34). Some researchers (4) have recognized this disadvantage for heat stress assessments by using these standard measurements and pointed out that the clothing characteristics in radiant heat have not been considered appropriately. Thus, a series of manikin and modelling studies considering external radiant heat and heat production of the human body simultaneously were conducted to study the heat dissipation and heat gain in radiant heat in the frame of the European Union project THERMPROTECT (4, 35). The shortcoming of these studies is that the effect of sweating was simulated by only moistening the underwear and the moisture amount was not controlled. Following that, some researchers (6) quantified the effect of moisture on heat loss in radiant heat. However, only one type of turnout gear was used in their study and the effect of material properties cannot be explored.

The aim of this study is to comprehensively investigate thermal behaviors of a clothed (thermal protective clothing) human body in continuous sweating conditions under radiant heat exposure, and explore the factors influencing thermal characteristics of protective clothing, specifically, both the thermo-physiological impact in radiant heat and the thermal protective performance with internal heat production and sweating. For this, the thermo-physiological effect and thermal protective performance of clothing were evaluated under radiant heat. The effects of radiant heat, perspired moisture and material properties on the physiological and protective performance were thoroughly discussed. This study contributes to the understanding of clothing thermal characteristics and human thermal behaviors under radiant heat and help the improvement of the occupational and general health and safety.

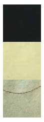
2. Methodology

2.1 Materials

Twelve common commercially-available thermal protective material systems with different physical properties were selected for the study, including seven single-layered station uniforms and five multi-layered turnout gears. As liquid sweating was investigated in our study, material hydrophilicity and hydrophobicity were identified by measuring the contact angle of the innermost side of the material systems. Pho-SU2, SU5, TG9 and TG10 are hydrophobic materials, while other samples are hydrophilic materials. Pho-SU2 and SU5 were treated with a fluorocarbon finish providing the hydrophobic property. No further information about the hydrophobic treatment of TG9 and TG10 is available. The radiation wavelength range of infrared lamps (SICCATHERM infra-red lamps, OSRAM Licht AG, Germany) used to simulate the external radiant heat in our study is 590-2,500 nm. Thus, material reflectivity (r), transmissivity (τ) and emissivity (ε) were also measured and averaged over this wavelength range. The main related physical properties of the material samples are presented in Table 1.

Table 1 Physical properties of material samples

Fabric Systems		Fiber Content	Physical Properties*						
			Color	Weight[a] (g/m^2)	Thickness[b] (mm)	Contact angle[c] (°)	R_{ct}[d] $(10^{-3}\cdot K\cdot m^2/W)$	R_{et}[e] $(m^2\cdot Pa/W)$	ε[f]
Station Uniform (single-layered fabric)	SU1	50% meta-aramid/50% fire retardant (FR) viscose		197	0.4	0	10.8	2.1	0.837
	phi-SU2	34% aramid/ 33% lyocell/ 31% modacrylic/ 2% anti-static fiber		241.6	0.6	0	13.4	2.7	0.648
	pho-SU2	34% aramid/ 33% lyocell/ 31% modacrylic/ 2% anti-static fiber		253.1	0.7	128.6	13.2	2.7	0.682
	SU3	93% meta-aramid/5% para-aramid/2% antistatic fiber		154.7	0.3	0	11.7	2	0.254
	SU4	93% meta-aramid/5% para-aramid/2% antistatic fiber		229.8	0.4	0	12.7	3.2	0.278
	SU5	55% FR Modacrylic/45% FR Cotton		367.3	0.7	130.7	16.6	3.4	0.247
	SU6	FR Cotton		366.8	0.8	0	14.5	4.4	0.421
Turnout Gear (multi-layered system)	TG7	99% aramid/1% beltron (OL) + PTFE coated meta-aramid (ML) + fleece (ML) + 50% meta-aramid/50% viscose (IL)		635.2	3.2	0	82.7	15.6	0.924
	TG8	Meta-aramid with thread on backside (OL) + PU		592.1	3.8	0	95.4	23.9	0.933

	liner on meta-aramid (ML) + aramid (IL)							
TG9	64% FR viscose/35% meta-aramid/1% antistatic (OL, yellow) + PU coated 50% meta-aramid/50% FR viscose (ML) + 65% FR viscose/35% meta-aramid (IL)		587.8	2	130.8	46.6	9.4	0.489
TG10	64% FR viscose/35% meta-aramid/1% antistatic (OL, blue) + PTFE coated 50% meta-aramid/50% FR viscose (ML) + 65% FR viscose/35% meta-aramid (IL)		599.8	2.2	130.2	49.3	10	0.834
TG11	Meta-aramid (OL) + PTFE coated 25% meta-aramid/25% para-aramid/50% basofil (ML) + non-woven meta-aramid quilted with 50% meta-aramid/50% FR viscose (IL)		493	2.3	0	71	16.8	0.901

For all Turnout Gears, the images from top to button are the materials from the outermost layer to the innermost layer. *Physical properties were measured according to [a]ISO 3801:1977 (by weighing balance of Mettler-Toledo, Switzerland), [b]ISO 5084:1996 (by thickness tester of Frank-PTI, Germany), [c]ASTM D7334 - 08(2013). If the contact angle of a material is 0°, it is categorized as hydrophilic. If the contact angle is greater than 90°, the material is categorized as hydrophobic, [d, e]ISO 11092:2014 (by hot plate tester of Hohenstein Institute, Germany) and [f]by extended FT-IR spectrometer VERTEX 80, Germany. (3, 36, 37). SU: station uniform; TG: turnout gear; OL: outer layer; ML: middle layer; IL: inner layer; PTFE: polytetrafluorethylene; PU: polyurethane.

2.2 Experimental design

Experiments were performed in a climatic chamber with air temperature of 20.0 ± 0.5 °C, relative humidity of 50 ± 2 % and air velocity of 0.65 ± 0.10 m/s. To accurately determine the heat transfer between the clothed human body and its surrounding environment, measurements were performed on a sweating torso manikin developed in our laboratory (**Fig. 1a**) (38, 39). The torso consists of a multi-layered main cylinder with the dimension of an adult human torso and two heated aluminum guards. The main cylinder can maintain a constant surface temperature by controlling heat input. The two guards are used to prevent heat losses in the upward and downward directions. Fifty-four sweating outlets are evenly distributed over the surface of the main cylinder and are connected to internal controlled valves for the accurate application of pre-set sweat rates. Test sample is wrapped around the main cylinder as clothing. More detailed information regarding the torso can be found in the literature (40, 41). **Fig. 1b** gives the heat and moisture transfer pathways between the clothed torso and the surrounding environment (42). The torso dissipated dry heat by conduction, radiation and convection. When sweating, the perspired moisture may (I) wick through the clothing, (II) evaporate or (III) drip from the clothed system. The evaporated sweat may then condense within the clothing layers. The heat from environment transfers to the torso by conduction, radiation and convection.

The experiment was designed to include three consecutive phases (**Fig. 1c**), with a constant surface temperature of 35 °C. In the first phase (P1), the torso was kept in the dry state for one hour. In phase two (P2), it began to sweat at a pre-set sweat rate for two hours. In the last phase (P3), a 96x188cm radiant heat panel filled with the infrared lamps was applied from the front side of the manikin for another two hours while the sweat rate was kept at its previous value. As the heat flux in the routine thermal environment for firefighters remains lower than 1.67 kW/m^2 (9) and for guaranteeing the normal working of the torso, the radiation intensity on the torso surface was determined as 1 kW/m^2 to simulate the work environment. Pre-tests with a thermal sensor (Schmidt-Boelter heat flux sensor, Medtherm Corporation, USA) were performed to identify a distance of 137 cm between the radiant heat panel and the torso, ensuring the set radiation intensity. Since the routine thermal environment was investigated, we considered that in this type of environmental condition, the human body is in a low to moderate level of sweating. Thus, three sweat rates of 100, 175 and 250 g/h, corresponding to the sweat rate of 400 - 1000 g/h of a firefighter with low to moderate sweating level (22) (assuming a body surface area of 1.8 m^2 (44)), were chosen. The test duration for each phase was determined according to the required time to reach the steady state of heat transfer. The three-phase experiment simulates the firefighting scenario: preparatory work without sweating followed by sweating and finally additional radiant heat exposure when entering the fire field.

Before the tests, thermal protective materials were preconditioned in the climatic chamber for at least 24 hours. Due to the complexity of moisture effect, we considered in this study that the material contacted the torso surface homogeneously without an air gap and, thus, we were able to investigate liquid sweat transfer and phase-change in the clothing-human body system. The real-time weight change of the clothed torso was measured by a weighing scale (Mettler-Toledo KCC150, Mettler-Toledo GmbH, Greifensee, Switzerland, accuracy: 0.001 g) to obtain the amount of water stored in fabrics. A thermographic camera (FLIR A40M, Flir Systems Inc., Wilsonville, Oregon, USA) was also used to record the thermal images of the clothed manikin, as to observe the sweat transport and evaporation.

For most fabrics, during the last 30 minutes of each phase, the coefficient of variation (CV) of the mean torso surface temperature was less than 0.7 % and the CV of torso heating power was less than 13.5 %. Compared to previous studies (42), we assumed that the heat transfer of the clothed torso during the period of time reaching a steady state. For each level of the sweat rates, at least three replications of the fabrics were tested on the sweating torso, guaranteeing the CV of torso heating power among repetition tests to be less than 8.5 %.

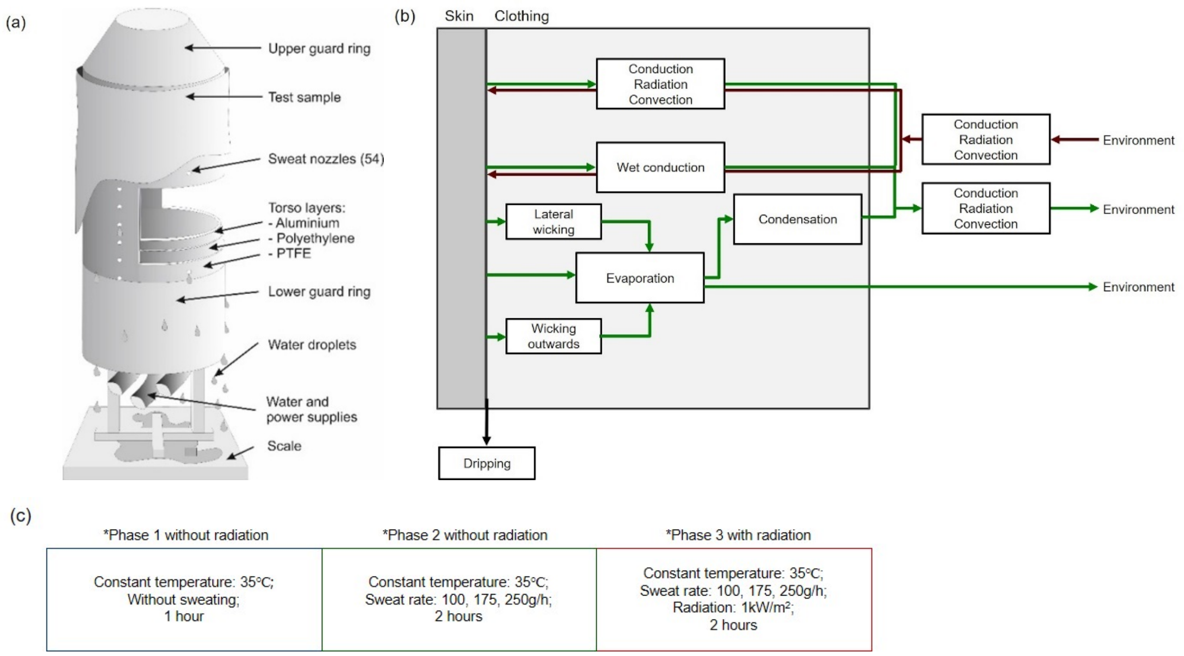


Fig. 1 (a) Schematic diagram of the sweating torso manikin. PTFE, polytetrafluoroethylene. (b) Schematic representation of heat and moisture transfer pathways when sweating. Modified from Ref. 18. (c)Schematic diagram of three-phase experimental design.

2.3 Calculations and dependent variables

In this study, instead of the total heat loss theoretically calculated according to ASTM F1868 (10), the total heat loss (THL), which was the heating power of the torso to maintain the surface temperature, was measured directly to characterize heat dissipation performance at each phase of the experiment. The THL in P1 (THL_{P1}) was obtained as dry heat loss. The THL in P2 (THL_{P2})was the combination of dry heat loss and heat loss caused by sweating. The THL in P3 (THL_{P3}) also included the effect of radiant heat.

To understand the effective cooling caused by sweating (EHL_{P2}) and effective heat gain caused by external radiant heat source (RHG_{P3}), the lumped and effective values were calculated as per eqn. (1) and (2). The heat pipe effect and wet conduction were not considered in detail, thus the effective cooling caused by sweating (EHL_{P2}), which is also named as the apparent evaporative heat loss (3), was assumed as evaporative heat loss*.

$$Evaporative\ heat\ loss * \ (EHL_{P2}) = THL_{P2} - THL_{P1} \quad (1)$$

$$Radiant\ heat\ gain\ (RHG_{P3}) \ = THL_{P2} - THL_{P3} \quad (2)$$

THL_{P2}, THL_{P3} and EHL_{P2} were chosen as indicators of thermo-physiological impact of protective clothing and RHG_{P3} chosen as the thermal protection indicator characterizing the thermal behaviors of the clothed manikin.

2.4 Statistical analyses

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 23.0 (IBM, Armonk, NY, USA). The combined effects of sweat rate and material properties on THL without and with radiant heat, EHL and RHG were investigated with multiple linear regression. The linear regression was chosen due to its effective interpretability and evaluability (46). The force enter method was chosen for predictor selection. The multicollinearity assessment, casewise diagnostics, assumptions of linearity and homoscedasticity and normality of residuals were also investigated for all the multiple linear regression models. The individual effect of sweat rate and radiant heat on the heat transfer indicators were analyzed by one-way analysis of variance (ANOVA) and followed by Tukey's honestly significant difference (HSD) or Tamhane's T2 post-hoc tests.

3. Results

3.1 Heat dissipation and heat gain at different sweat rates

Fig. 2 illustrates THL_{P2}, EHL_{P2}, THL_{P3} and RHG_{P3} at three sweat rates for all materials. Overall, THL_{P2}, EHL_{P2} and THL_{P3} of both SUs and TGs presented an increasing trend with sweat rates ($p<0.01$). RHG_{P3} variations with sweat rate exhibited different patterns among the materials.

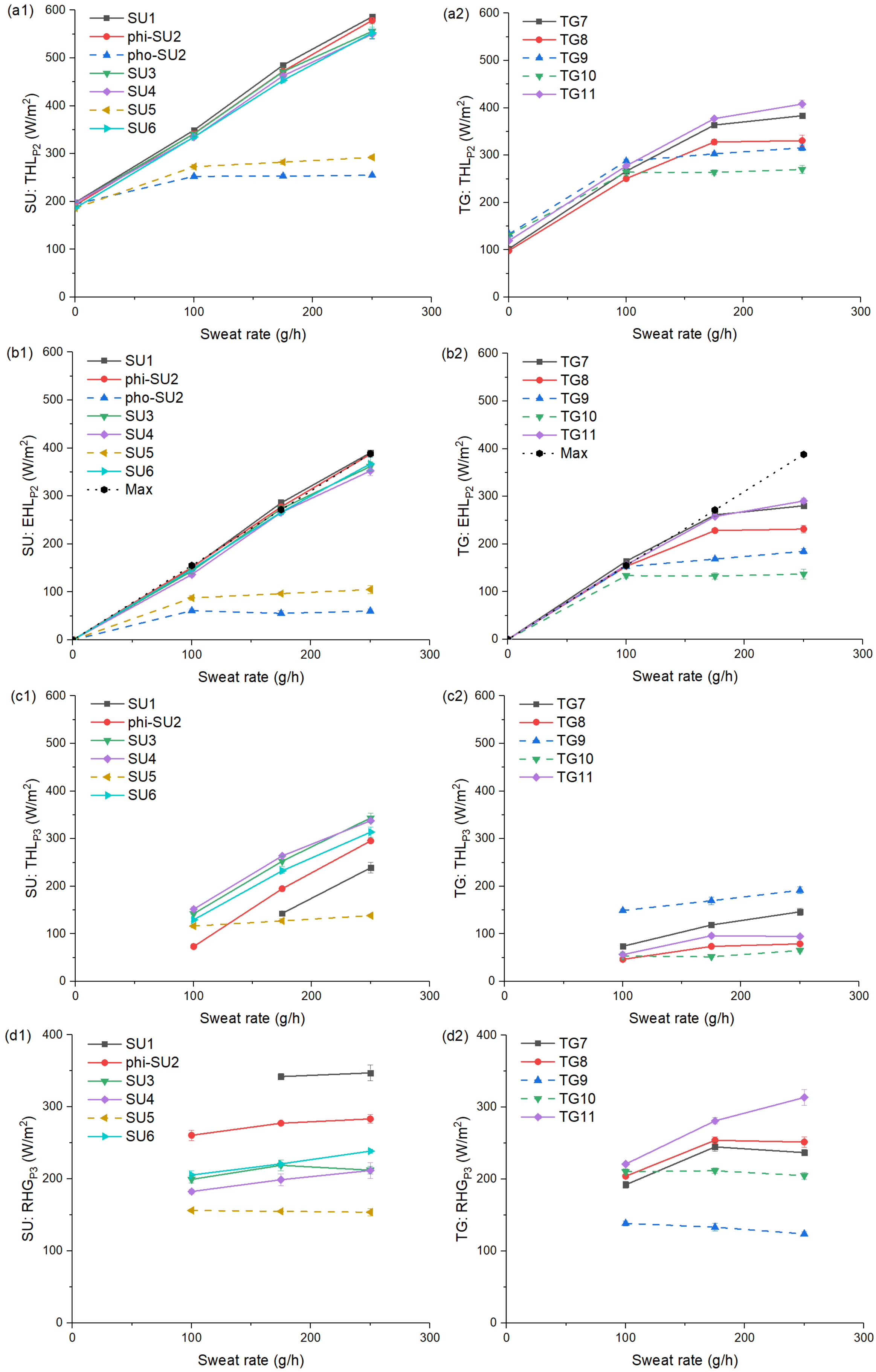


Fig. 2 Heat loss and heat gain at the three sweat rates. THL_{P2} of SU (a1) and TG (a2). EHL_{P2} of SU (b1) and TG (b2). Max: maximum evaporative power when assuming all the sweat evaporated. THL_{P3} of SU (c1) and TG (c2). RHG_{P3} of SU

(d1) and TG (d2). Note: SU1 at sweat rate 100g/h and pho-SU2 at three levels of sweat rates did not reach steady state in P3 with acceptable test duration and thus the corresponding data are excluded in (c1) and (d1). Hydrophilic materials: solid line, hydrophobic materials: dotted line.

3.2 Relationship between material properties and heat dissipation/heat gain

Fig. 2 demonstrates that material properties have effect on THL_{P2}, EHL_{P2}, $THL_{P3}$and RHG_{P3}. In most cases, hydrophilic and hydrophobic materials clearly behaved differently: (1) the hydrophobicity of SUs and TGs decreased THL_{P2}, EHL_{P2} and THL_{P3} noticeably by up to 330W/m^2 compared with hydrophilic materials; (2) the sweat effect on hydrophobic materials was less pronounced than hydrophilic materials. For hydrophilic materials, the results of multiple linear regression between material properties and THL_{P2}, EHL_{P2}, $THL_{P3}$and RHG_{P3} are shown in Table 2.

Table 2 Multiple regressions between material properties and heat dissipation/heat gain for hydrophilic SUs and TGs.

Material	R^2	Regression co-efficient	Unstandardized co-efficient (a1-a6, b)	Standardized coefficient[a]	Material	R^2	Regression co-efficient	Unstandardized co-efficient (a1-a6, b)	Standardized coefficient
			THL_{P2}					THL_{P2}	
	0.975	constant	196.63			0.859	constant	389.2	
		sweat rate**	1.49	0.99			sweat rate**	0.73	0.84
							weight*	-0.16	-0.18
							R_{et}**	-5.01	-0.34
			EHL_{P2}					EHL_{P2}	
	0.979	constant	0.33			0.847	constant	187.53	
		sweat rate**	1.51	0.99			sweat rate**	0.73	0.88
							R_{et}*	-3.89	-0.28
			THL_{P3}					THL_{P3}	
SU	0.986	constant	-97.57		TG	0.874	constant	-747.74	
		sweat rate**	1.32	0.96			sweat rate**	0.32	0.66
		R_{ct}*	15.70	0.24			R_{et}**	-6.69	-0.83
		emissivity**	-145.5	-0.37			emissivity**	984.19	0.45
			RHG_{P3}					RHG_{P3}	
	0.976	constant	357.12			0.815	constant	1829.42	
		sweat rate**	0.14	0.17			sweat rate**	0.41	0.71
		thickness*	127.16	0.4			R_{et}**	3.48	0.36
		R_{ct}**	-21.79	-0.53			emissivity**	-1873.16	-0.71
		emissivity**	178.7	0.74					

Note: The form of the regression equation is as follows: y=a_1*sweat rate+a_2*weight+a_3*thickness+a_4*R_{ct}+a_5*R_{et}+a_6*emissivity+b, y is the THL_{P2}, EHL_{P2}, $THL_{P3}$and RHG_{P3}, respectively. *p<0.05, **p<0.001. [a]Standardized coefficients are the estimates resulting from a regression analysis that have been standardized so that the variances of dependent and independent variables are 1.

3.3 Water amount stored in the clothed torso

As the accumulated water may have an influence on thermal conduction and heat capacity, the amount of water accumulated in materials during the steady state of P2 was measured as the water accumulation capacity of materials. For hydrophilic SUs (Fig. 3a), the accumulated water showed a positive relationship with fabric thickness. For hydrophilic TGs (Fig. 3b), the effect of thickness is less significant, which may be because of the multi-layer structure. TG 7 (thickness: 3.2 mm) with a four-layer structure showed a greater amount of accumulated water compared with the other two TGs (thickness: 2.3, 3.8 mm) with a three-layer structure.

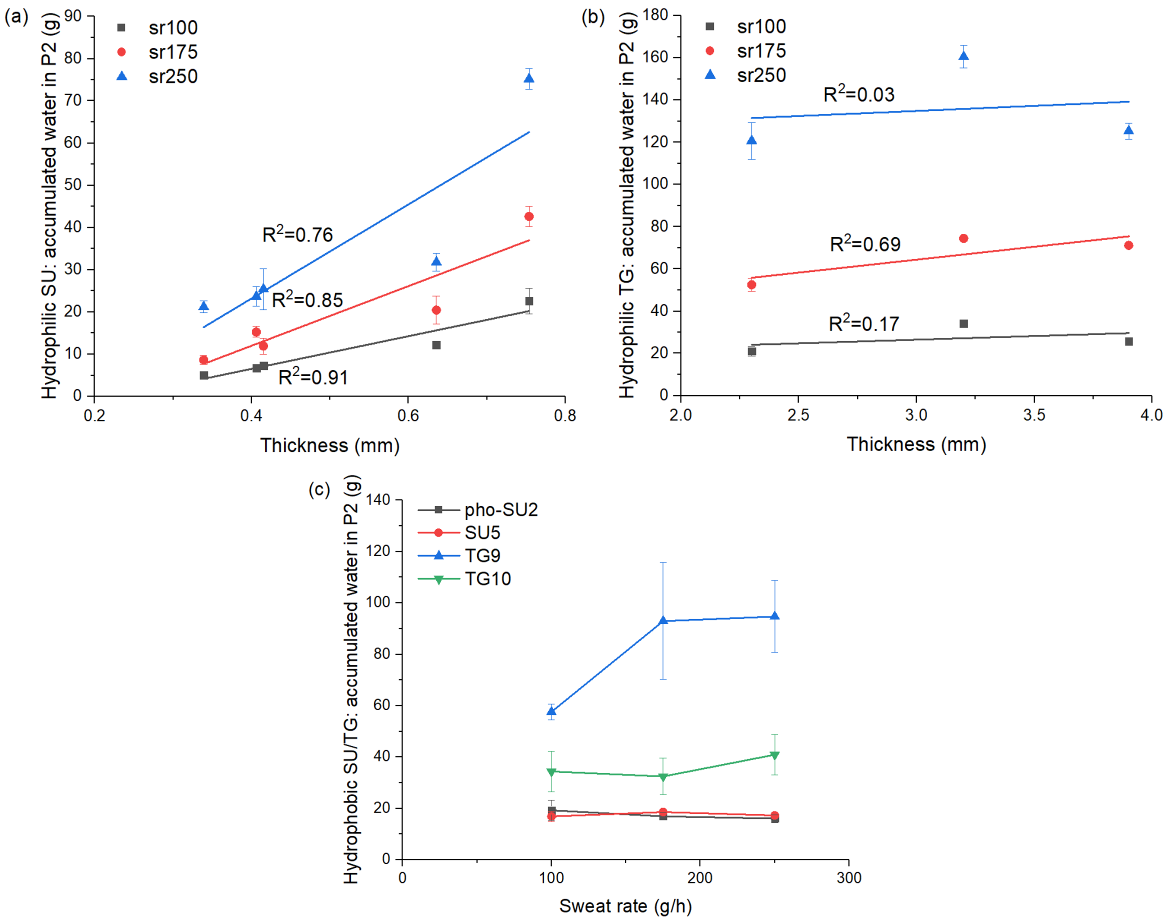


Fig. 3 Relationship between the thickness of hydrophilic materials and the water accumulated in materials in P2 at three sweat rates. (a) SU; (b) TG. (c) Amount of water accumulated in hydrophobic SUs and TGs in P2.

For hydrophobic materials, TGs showed a greater amount of accumulated water than SUs (Fig. 3c, $p<0.05$ at sweat rate 100 and 250g/h, $p>0.05$ at sweat rate 175g/h). This should be related to the multiple layer structure of TGs, which accumulated more water between the layers as observed after tests.

4. Discussion

4.1 THL comparison between environment without and with radiant heat

The comparison between THL_{P2} (without radiant heat) and THL_{P3} (with radiant heat) for all materials at three sweat rates (Fig. 4a) shows that the radiant heat significantly reduced THL (SU: 154-347 W/m^2, TG: 124-314 W/m^2, $p<0.001$). This is clearly indicated as no measurement crosses the reference line in Fig. 4a. And the THL reduction ($\Delta THL(RHG) = THL_{P2} - THL_{P3}$) positively related with the incident radiation intensity (Fig. 4b, $p<0.001$). ΔTHL also differed among materials. Table 3 presents the regression of THL_{P3} by using THL_{P2}, and further considering basic material properties (i.e., emissivity, hydrophilicity, thickness and weight). It shows that material emissivity is the most important material property that causes difference between THL_{P2} and THL_{P3}. This led to that a material with greater THL_{P2} than other materials may have a smaller THL_{P3} (e.g., at sweat rate 250 g/h, $THL_{TG11,P2}$ (408 W/m^2) > $THL_{TG9,P2}$ (316 W/m^2), $THL_{TG11,P3}$ (95 W/m^2) < $THL_{TG9,P3}$ (192 W/m^2), $p < 0.001$). This demonstrates that it may cause errors if the clothing physiological effect evaluated in the environment without radiant heat is applied in the environment with radiant heat.

Table 3 Regressions between THL_{P3} and THL_{P2}, further considering material properties (i.e., material emissivity (ε), hydrophilicity, hydrophobicity, thickness and weight)

Materials	Regression model	Coefficient of determination (R^2)	Significance

SU	$THL_{P3} = 0.653 * THL_{P2}(p < 0.001)$	0.728	p<0.001
	$THL_{P3} = 0.839 * THL_{P2}(p < 0.001) - 221.763 * \varepsilon(p < 0.001)$	0.979	p<0.001
TG	$THL_{P3} = 0.368 * THL_{P2}(p < 0.01)$	0.161	p<0.01
	$THL_{P3} = 0.513 * THL_{P2}(p < 0.001) - 226.651 * \varepsilon(p < 0.001)$	0.840	p<0.001
SU and TG	$THL_{P3} = 0.703 * THL_{P2}(p < 0.001)$	0.724	p<0.001
	$THL_{P3} = 0.630 * THL_{P2}(p < 0.001) - 136.791 * \varepsilon(p < 0.001)$	0.902	p<0.001

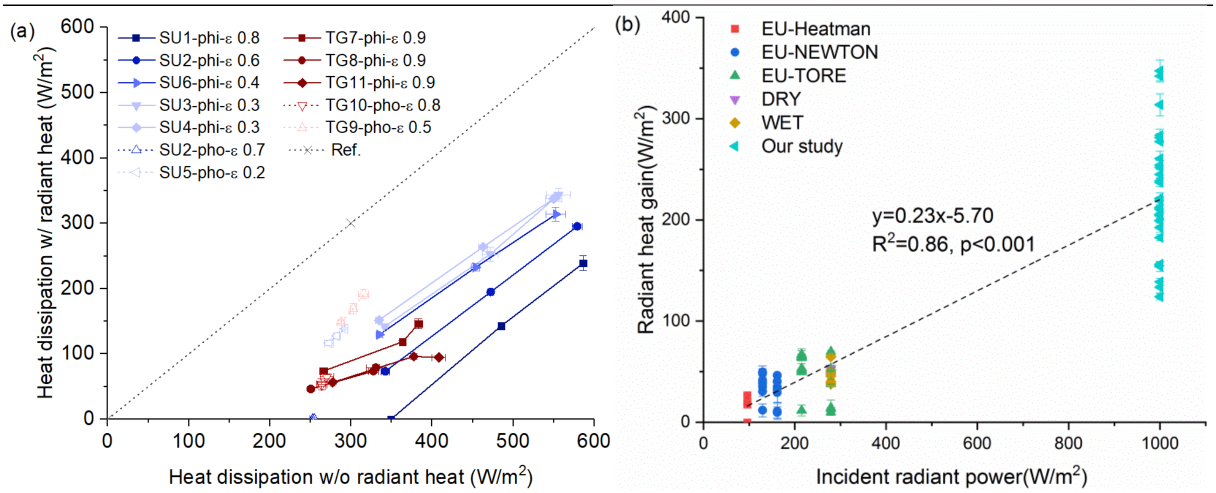


Fig. 4 (a) Comparison between the THL_{P2} and THL_{P3} for all materials at all sweat rate levels. SU: solid line, TG: dotted line. Ref: the reference line on which THL in P2 equals to that in P3. SU1 at sweat rate 100g/h and pho-SU2 at the three sweat rates did not reach steady state in P3 and THL_{P3} is zero during acceptable test duration. (b) Relationship between the incident radiant intensity and the radiant heat gain. The data are from EU project THERMPROTEC (internal reports), reference [3] and our study. Note: EU-Heatman, EU-NEWTON and EU-TORE are the data from different thermal manikins of the EU project without mentioning the dry and wet state of underwear. Ref [3] dry and Ref [3] wet are the data from Figure 5(a) and (b) of reference [3] with dry and wet underwear. The data from our study includes the results of all materials and all sweat rates.

4.2 Sweat behaviors in radiant heat

In our study, sweat behaviors on heat transfer in radiant heat can be divided into three types (Table 4). One, for hydrophilic SUs and TGs, with sweat rate increase, $\Delta THL_{P2} > \Delta THL_{P3} > 0$ ($p < 0.05$), that is, $\Delta RHG > 0$. This demonstrates the dual effect of perspired moisture on heat transfer for hydrophilic materials: more sweat can strengthen both the effective cooling and the radiant heat absorption of clothed human body. For hydrophilic SUs, ΔRHG due to perspired moisture (15.0 W/m^2) was about 11% of ΔTHL_{P3} (132.3 W/m^2). For hydrophilic TGs, ΔRHG was 41.1 W/m^2 while ΔTHL_{P3} was 31.9 W/m^2. It shows that, in our cases of hydrophilic SUs and TGs, perspired moisture can bring more physiological cooling benefit than radiant heat absorption. Two, for hydrophobic TG9, with sweat rate increase, $\Delta THL_{P3} > \Delta THL_{P2}$ ($p < 0.05$), that is, $\Delta RHG < 0$. Three, for hydrophobic SU 5 and TG 10, sweat rate only had very slight positive effect (SU5) or no significant effect (TG10) on THL_{P3} and there is no significant difference between ΔTHL_{P2} and ΔTHL_{P3} ($p>0.05$), that is, $\Delta RHG = 0$. $\Delta THL_{P2} > 0$ due to sweating is the increase of evaporation, wet conduction and possible evaporation-condensation process. For hydrophilic materials, the possible reason for $\Delta RHG > 0$ is that sweat increased the thermal conductivity and radiation absorptivity of materials largely, thus increasing the conductive and radiant heat transfer from environment to the torso. On the other hand, sweat did not change the thermal conductivity and radiation absorptivity largely for hydrophobic materials and added additional water layer, may acting as a small thermal insulation for radiant heat transfer, leading to $\Delta RHG < 0$. The different behavior between TG9 and SU5/TG10 is possibly due to the less water accumulation for SU 5/TG 10 (Fig. 3c), causing the thermal insulation effect of water insignificant.

Table 4 Sweat effect on heat dissipation and heat gain: ΔTHL_{P2}, ΔTHL_{P3}, ΔRHG for each 100 g/h sweat rate increment

Type of moisture effect	Materials	ΔTHL_{P2} (W/m^2)	ΔTHL_{P3} (W/m^2)	ΔRHG (W/m^2)
I	Hydrophilic SU	147.3**	132.3*	15.0**
	Hydrophilic TG	72.9*	31.9	41.1**
II	Hydrophobic TG9	18.6	28.4*	-9.8*
III	Hydrophobic SU5	13.0	14.6**	-1.5
	Hydrophobic TG10	4.1	7.8	-3.7

*p < 0.05, **p < 0.005

The results demonstrate that the continuous sweating has negative effect on thermal protective performance of hydrophilic materials, but positive effect for hydrophobic materials. The exact role of perspired moisture on thermal protective performance depends on material surface properties and water accumulation capacity. To our knowledge, it is the first time to quantify the effect of perspired moisture on radiant heat gain for hydrophilic and hydrophobic materials, exploring the role of continuous sweating on heat transfer of clothed human body (Fig. 5).

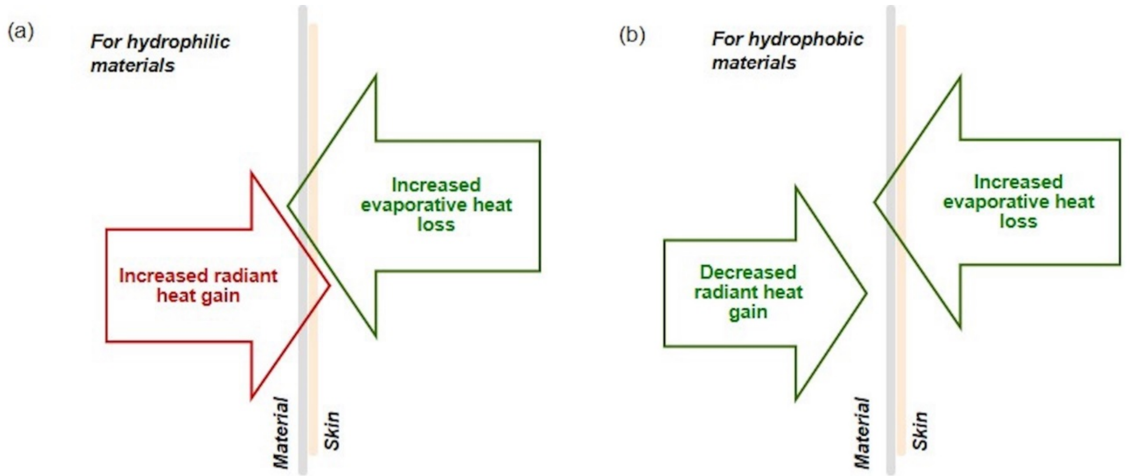


Fig. 5 Effect of perspired moisture on heat transfer. (a) Hydrophilic materials: perspired moisture increases both evaporative heat loss and radiant heat gain; (b) Hydrophobic materials: perspired moisture increases evaporative heat loss and decreases radiant heat gain. The start and end of the arrow "evaporative heat loss" is the human body and the environment, the start and end of the arrow "radiant heat gain" is the environment and the human body.

4.3 Characterizing the thermal comfort/heat stress of thermal protective clothing with liquid sweating and/or radiant heat - the limitations of standard R_{ct} and R_{et}

Firstly, fabric hydrophilicity and hydrophobicity play a crucial role in characterizing physiological burden in both environments without and with radiant heat (THL_{P2}, THL_{P3}). Human trials (44) showed that hydrophilic clothing exhibited more favorable thermal physiological performance than hydrophobic clothing. This is in agreement of most cases of our study: THL_{P2} and THL_{P3} of hydrophilic materials were higher than that of hydrophobic materials regardless of the relative magnitude of fabric R_{ct} and R_{et} (Fig. 2 (a1-2), (c1-2)). This could be due to the large amount of dripping water for hydrophobic materials that could not provide evaporation cooling, wet conduction and heat pipe effect. The exception of $THL_{TG9,P2}$ and $THL_{TG10,P2}$ at sweat rate 100 g/h demonstrated that at lower sweat rates, the negative effect of material hydrophobicity on physiological cooling was not obvious. The exception of $THL_{SU5,P3}$ at sweat rate 100g/h and $THL_{TG9,P3}$ at three sweat rates was due to the lower emissivity of SU5 and TG9.

For hydrophobic pho-SU2 and SU5, even though R_{ct} and R_{et} of SU5 are both higher than that of pho-SU2, SU5 showed a greater THL_{P2} and THL_{P3} than pho-SU2 at three sweat rates. In addition to the lower emissivity of SU5, another possible reason may be inferred from infrared images (Fig. 6). It is clear that SU5 has a larger evaporative area than pho-SU2 and we hypothesized that because SU5 has a better capacity to hold water between the material and the torso surface, more water can evaporate with SU5 and also more evaporative cooling. To confirm this point, the moisture management test (45) was conducted to compare the interaction behavior of pho-SU2 and SU5 with perspired moisture. The results (time for wetting top surface: pho-SU2: 10.8 ± 4.3 s, SU5: 8.2 ± 2.4 s) seemingly showed that SU5 did have a better moisture absorption capacity than pho-SU2.

In addition, it's worth noting that in our study, the sweat glands of the sweating torso manikin are a rough resolution as compared to human skin. Fifty-four sweat nozzles are distributed on the surface of the torso device (surface area: 0.4335 m^2) while the real human torso has about 100 sweat glands per cm^2. Thus, for hydrophobic materials the drip-off water in the torso test will be more than that in the human case because there will be less local moisture saturation for the human body. Therefore, for hydrophobic materials, the evaporation cooling may be more notable in the human body than the torso, in both environments without and with radiant. Caution needs to be taken when extending the results here on hydrophobic materials to actual clothed human body.

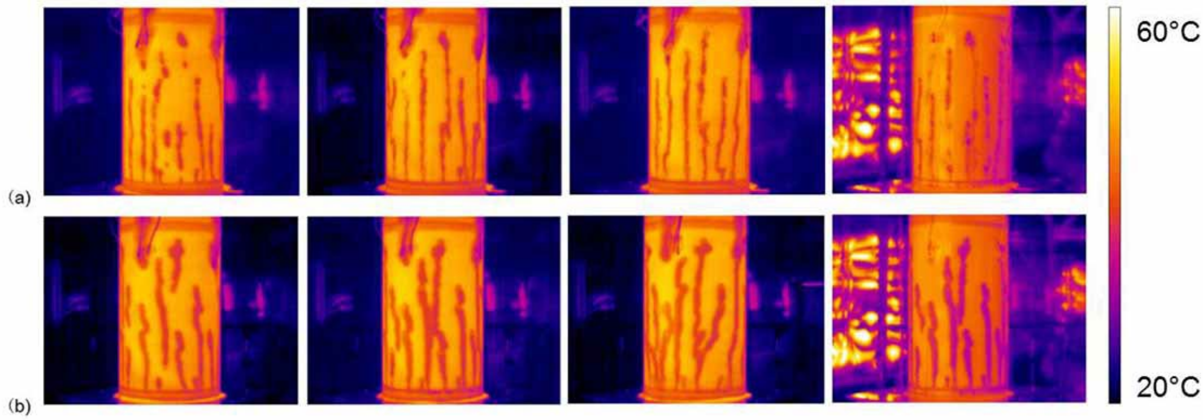


Fig. 6 Infrared images of pho-SU2 (a) and SU5 (b). From left to right: Sweat rate 100, 175, 250g/h in the steady state of P2, respectively, and sweat rate 175g/h immediately after taking off materials when tests end.

Secondly, our study showed the significant effect of fabric emissivity, R_{ct}, R_{et} and thickness on the heat transfer indicators, while the previous study (4) demonstrated a negligible influence of material properties except material reflectivity. The first possible reason is that the previous measurements were conducted using anatomically formed thermal manikin, which led to the formation of an air gap between the body and the clothing, making material effects less pronounced. In addition, previous experimental studies only considered pre-wetted underwear rather than continuous liquid sweating; and in the theoretical model (35) the evaporative heat transfer was neglected. However, for thicker hydrophilic SUs in our study, the clothed torso accumulated greater amount of water (Fig. 3a) and gained more radiant heat (Table 2). This indicates the importance of combine analyses of liquid sweat transport and its thermal effects in clothed system.

Thirdly, the two-way role of clothing/material R_{ct} in heat transfer may need further study. Generally, when a material has a greater R_{ct} and R_{et} and smaller THL than other materials, it is assumed that the material has worse thermal comfort (7, 10). In contrast, some researchers have pointed out that the higher R_{ct}, the more thermal protection can be provided to the wearers (4, 35). For hydrophilic SUs in our study, with 1×10^{-3} K·m^2/W R_{ct} increase, the human body dissipates 15.70 W/m^2 heat more and heat gain decreases by 21.79W/m^2 when other input parameters (i.e., sweat rate, fabric emissivity and thickness) are constant (Table 2). Besides, in P3, for SU1 of sweat rate 100 g/h and pho-SU2 at three sweat rates, the surface temperature of clothed torso kept above 35°C, not reaching steady state during the experiment. But for all TGs, the clothed torso reached steady state, i.e., the surface temperature decreased to 35°C and the heating power reached a certain value above zero for at least half an hour at the end of P3. That is, for SU1 and pho-SU2 with lower R_{ct} and R_{et} than all TGs, they cannot achieve heat balance in radiant heat while all TGs can. These results indicate the limitation of standard R_{ct} and R_{et} to characterize the clothing physiological effect and serve as an experimental evidence of the two-way role of R_{ct} in heat transfer.

Results in the present study is beneficial for understanding the heat transfer of contact area between clothing and human body, e.g., upper chest, upper back, upper arm and posterior pelvis in the standing posture and also lower arm and shin in exercising postures (46-48). For body regions which have lower contact area, further studies considering different sizes and distribution of the air gap are required (49).

5. Conclusions

In the present study, to understand thermal physiological impact and thermal protection of clothing simultaneously and investigate the effect of perspired moisture and material properties on these two clothing thermal characteristics, the external thermal hazard and internal heat production were combined, and perspired moisture and a range of common thermal protective clothing were applied. Results show how the effect of radiant heat on clothing thermal characteristics interacts with sweat rate and material properties. The dual role of perspired moisture in heat transfer for hydrophilic clothing was quantified: perspired moisture contributes to the evaporation cooling and also reduces protective performance. On the other hand, perspired moisture can increase evaporative cooling and decrease the radiant heat gain for hydrophobic materials. Standard fabric R_{ct} and R_{et} may be not sufficient for characterizing the heat stress in radiant heat. Material hydrophilicity and hydrophobicity, emissivity and thickness are also critical when assessing the thermal physiology and thermal protection with profuse sweating.

The results demonstrate that the fabric surface properties, the two-way effect of thermal resistance and the dual roles of perspired moisture are crucial factors that influencing thermal comfort and protection of thermal protective clothing. Further studies are required to investigate these factors within a larger range of materials and quantify the effect of material properties (e.g., thermal resistance, emissivity and thickness) and moisture in a variety of hot environment, including the extreme conditions with high intensity of radiant heat and flash fire. Such studies will finally contribute to the understanding of clothing thermal characteristics and human thermal behaviors in realistic conditions and guide the design and selection of materials for high performance thermal protective clothing, improving the occupational and public health and safety.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgements

The authors would like to thank DuPont, Switzerland and Trans–Textil, Germany for supplying the fabrics for this study and appreciate the technical support from Max Aeberhard, Ivo Rechsteiner and Shelley Kemp during the laboratory tests and the proofreading from Brit Maike Quandt. The authors would like to acknowledge the Fundamental Research Funds for the Central Universities (Grant NO. 2232018G-08), the financial support from the National Nature Science Foundation (Grant NO. 51576038), and Shanghai Municipal Natural Science Foundation (Grant NO. 17ZR1400500). The authors also gratefully acknowledge financial support from the China Scholarship Council.

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