COMPARATIVE ANALYSIS OF THERMAL AND WET COMFORT BETWEEN NOVEL PHASE-CHANGE PROTECTIVE FIREFIGHTING SUIT AND ITS COMMON COUNTERPART

by

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The superb firefighting garment is the critical guarantee to protect firefighters from burn harm. Despite intensive effort has been devoted to the inflammability of firefighting suit prepared with the novel PCM, its comfort satisfaction is rarely studied. Thus, the thermal and wet comfortability of PCM-firefighting suit and its common counterpart were contrastively analyzed to clarify the effects of PCM on the wear comfort. Results of correlation analysis and partial correlation analysis through SPSS showed that PCM-firefighting suit was more suitable for the harsh environment of high temperature and humidity due to the improved over-all performance than its common counterpart. The paper sheds a promising light on the future design and construction of high performance firefighting garment integrated with excellent inflammability and wear comfort.

Key words: *comfort, firefighting suit, PCM, wet comfort, thermal resistance and insulation*

Introduction

Firefighting suit is the crucial protective product for firefighters when they are exposed in harsh temperature and heat strains [1]. An ideal firefighting suit not only protects firefighters from skin burn injuries, but also provides wear comfort. For thermal protective property, one of the most promising strategy is to integrate the efficient PCM into firefighting suits [2]. As an excellent latent heat-storage materials, PCM can automatically adjust the storing or releasing heat property as they undergo phase change reactions [3]. Thus, extensive fruits have been achieved on the flame resistance of protective suit, especially for selection criteria, dosage, anchor location and application method of PCM [1, 4].

As for wear comfort, it is a key factor that should be considered for work efficiency and personal safety of wearers to inhibit the hyperthermia accompanied with irreversible body damage [5, 6]. As a second skin, the clothing plays a decisive role on the body safety of wearers, which directly determines the clothing comfort beyond body temperature and wet regulation. Generally speaking, a low thermal resistance and water vapor resistance of clothing mean the high thermo-physiological comfort that is preferred in making firefighting suit [7]. Currently, the effects of human activity, suit layers, body posture and environmental conditions on the wear comfort of common firefighting suits were systematically studied in previous reports [8, 9]. Although PCM-firefighting suit exhibited a better heat insulation perfor-

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mance than common ones, its thermal and wet comfortability was neglected during the fire exposure phase. An effective suit is usually composed of three essential layers involved flame retardant outer layer, waterproof breathable interlayer and comfortable inner layer [1, 10]. Obviously, the comfortable inner layer with good thermal and perspiration property can prevent itching sensation caused by the direct contact between outer fabric layer and human body, thus optimizing wear comfort.

Based on these analysis, PCM are firstly introduced to treat inner clothing of firefighting suit. To optimize the wear comfort for firefighters, two critical parameters of thermal comfort and wet comfort were regulated. And these two properties of PCM-firefighting suit and common counterpart were contrastively analyzed to clarify the improvement function of PCM on the wear comfort of firefighting suit.

Experimental

Materials

The firefighting suit is generally composed of the outer layer (80% aramid and 20% viscose), inter layer (PTFE) and inner layer (aramid fabric). The thermal energy storage microcapsule PCM with the size of 1-50 μm were purchased from Jiangsu HANOS Chemicals Co. Ltd.

Preparation of PCM-firefighting suit

The 40 g of PCM was firstly added into a clean beaker with 760 mL distilled water under the stirring condition to obtain a uniform finishing solution. After that, the inner fabric with the size of 50×50 cm was dipped for 20 minutes, then taken out and dehydrated. Subsequently, this fabric was re-immersed for another 10 minutes, then fetched out and dried at 80 °C. Finally, the flame retardant outer layer, waterproof breathable interlayer and this PCM comfortable inner layer was stitched together, as shown in fig. 1. For comparison, common fire suit was prepared with flame retardant outer layer, waterproof breathable interlayer, and common inner layer.

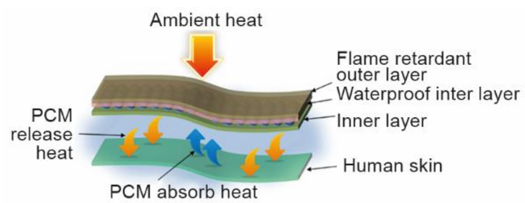

Figure 1. Schematic diagram of PCM firefighting suit with three typical layers

Experimental procedures for thermal resistance and wet resistance

Thermal resistance was tested according to ISO 11092-2014[S] (Textiles-physiological effects-measurement of thermal and evaporative resistance under steady-state conditions (sweating guarded-hotplate test). The wet resistance was tested according to ISO 11092-2014[S] (Textiles-physiological effects-measurement of thermal and evaporative resistance under steady-state conditions (sweating guarded-hotplate test). Firstly, the blank experiment was carried out. Then, the control experiments of common and PCM-firefighting suit were both tested in same conditions, respectively. To thoroughly study the effects of ambient temperature and humidity on the thermal resistance, the ambient temperature was adjusted, respectively, as 20 °C, 22 °C, 25 °C, 28 °C, or 30 °C, and the humidity was controlled at, respectively, 40%, 50%, 55%, 60%, or 65% RH. to conduct above experiments. For wet resistance, the ambient temperature was adjusted as 25 °C, 28 °C, 30 °C, or 32 °C, and the ambient humidity was controlled as 40%, 45%, 50%, 55%, or 60 RH., respectively.

Results and discussion

The effects of ambient temperature and humidity on thermal comfort

As we all know, thermal comfort is an important and typical character of the clothing comfort to ensure human body in a comfortable environment due to timely sweat transfer from body to outside. Herein, the thermal resistance, R_{ct}, *clo* (a unit unique to the textiles industry for representing the thermal resistance of a textile or textile product) and thermal conductivity, K, are three critical factors to evaluate thermal comfort. The R_{ct} represents the dry heat flow through a specified area of textiles under stable temperature gradient conditions. The *clo* is a representation unit of R_{ct}, while K is the reciprocal of R_{ct} per thickness. Clearly, the greater R_{ct} and *clo* of firefighting suit, the better thermal insulation property [11]. Although these three parameters are inherent features of firefight suit, their measured values are subjected to the test environment because of the interaction of radiation heat transfer and other factors of surrounding environment. Therefore, it is important to clarify the effect of ambient temperature and humidity on the thermal comfort.

From fig. 2, PCM-firefighting suit showed the higher R_{ct} and *clo* than those of common counterpart even at different ambient temperature and humidity. However, a vice versa result was observed on the thermal conductivity where common firefighting suit presented a slightly higher value. The R_{ct} and *clo* for PCM firefighting suit and common counterpart both decreased as the environment temperature and humidity increased, while their thermal conductivity all increased. Compared these effects, it was easy to conclude that the ambient temperature played a decisive role on the thermal comfort because of 10-fold difference significant change in thermal resistance, *clo* and thermal conductivity when the ambient temperature rose from 20 °C to 30 °C, where the thermal comfort change caused by ambient humidity was slight. Also, the difference on these three factors of R_{ct}, *clo*, and K between PCM-firefighting suit and common counterpart increased with the increase of ambient temperature. At the highest temperature of 30 °C, R_{ct}, *clo*, and K of PCM-firefighting suit were measured as 0.0051 m^2K/W, 0.033 W/mK and 967.80 W/mK, while those of common counterpart were 0.0003 m^2K/W, 0.002 W/mK and 976.96 W/mK, respectively. Thus, PCM-firefighting suit was more suitable for high temperature scene to provide an optimal thermal comfort for firefighters due to the self-adaptability of PCM.

The effects of ambient temperature and humidity on wet comfort

The wet comfort is another important property to keep the human body within a required perspiration limited at a higher temperature. Wet resistance, R_{et}, water vapour permeability index W_d, and water vapour transmission rate, *WVT*, are three crucial parameters to evaluate wet comfort. The R_{et} is the heat flow of evaporation through a specified area of textiles under stable water vapor pressure gradient conditions. The W_d is the ratio of thermal resistance to wet resistance, and its value is between 0 and 1. When its value is 0, it means the test piece is impermeable [12]. The *WVT* is determined by wet resistance and ambient temperature. With these indicators, it is equally important to explore the effects of ambient temperature and humidity on wet comfort.

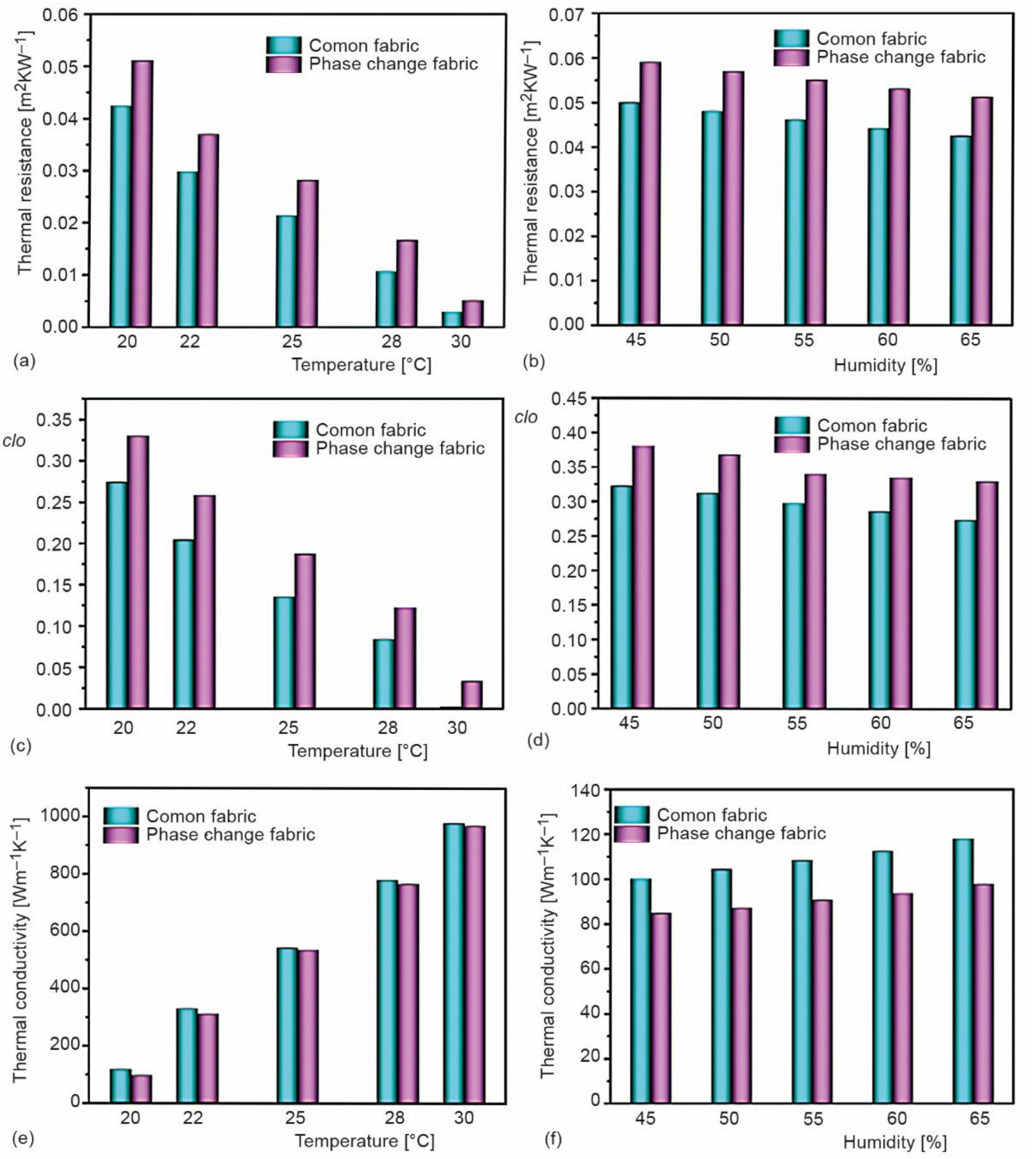

Figure 2. Effects of ambient temperature and humidity on the R_{ct}, *clo* and *K*

From fig. 3, PCM firefighting suit exhibited a higher R_{et} than common one at different ambient temperature and humidity. The vice versa results were detected on W_d and *WVT* where PCM firefighting suit exhibited a lower value. It was easily inferred that common firefighting suit was of a slightly better wet comfort than that of PCM-firefighting suit due to the relatively poor air permeability of PCM coating. Their R_{et} values both increased as ambient temperature went up, while they both decreased as ambient humidity rising. Clearly, PCM firefighting suit might be more suitable for high temperature to guarantee wet comfort for firefighters in comparison with high humidity due to the slight wet resistance difference between their two.

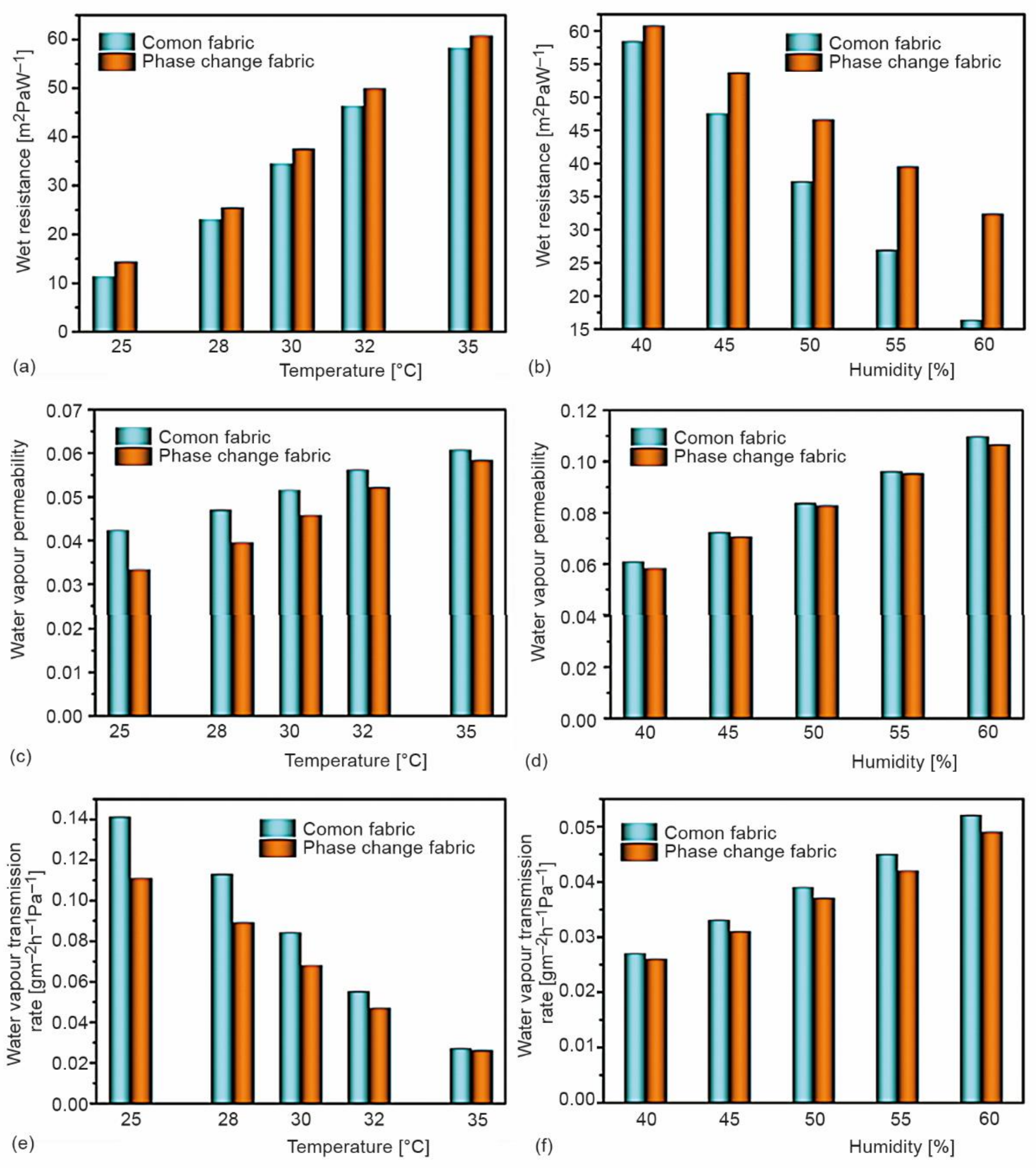

Figure 3. The effects of temperature and humidity on R_{et}, W_d, and *WVT*

From figs. 3(c) and 3(d), both PCM firefighting suit and common counterpart showed a synchronously growing trend as ambient temperature and humidity rising. When temperature rose from 25 °C to 35 °C, the increment of W_d was lower than that when humidity rose from 40-60% RH. It meant that ambient humidity played a significant effect on W_d. The PCM firefighting suit showed a slightly lower W_d at different temperature and humidity than that of common one, suggesting PCM finishing had a tiny adverse effect on the air permeability.

From fig. 3(e), *WVT* of PCM firefighting suit and common one reduced as the temperature increased, along with a gradually declining trend on water vapour transmission rate difference between their two. When the temperature increased to 35 °C, *WVT* values of these two suits were basically same. While their *WVT* value increased with the humidity increased, along with a nearly unchanged difference between their two. It was easy to found that the ambient temperature showed an obvious effect on *WVT* due to a higher difference when the temperature increased from 25 °C to 35 °C, where its change difference was slight during the process of increasing ambient humidity. Notably, all the water vapour transmission rate of PCM firefighting suit was lower than that of common counterpart at different temperature and humidity, suggesting PCM coating did not cause obvious damage to wet comfort.

Correlation analysis of thermal and wet influence factors for PCM-firefighting suits

The PCM firefighting suit was demonstrated a super clothing comfort at high temperature and humidity. To clarify its applicability, it is imperative to explore the correlation between any two of these important fabric properties like thermal resistance-thermal conductivity and so on. Therefore, statistical analysis of Pearson correlation and Partial correlation analysis were introduced to determine their correlation form and degree.

Pearson correlation analysis

Pearson correlation coefficient is generally employed to analyze the degree and direction of linear correlation between any two factors of R_{ct}, *clo*, and K under different temperatures. From tab. 1, obviously, the positive correlation between R_{ct} and *clo* value was verified by the positive Person correlation coefficient of 0.998. While the relationship between R_{ct} and K was negative correlation. Also, a negative correlation between *clo* value and K was determined due to a negative Person correlation coefficient of –1.000. Namely, the higher thermal resistance or *clo* value, the lower thermal conductivity. All these results were consist with those of fig. 2. Similarly, the relationship between R_{ct} and *clo* value was confirmed as positive at different humidity, tab. 2, while that between K and R_{ct} or *clo* value was negative.

Table 1. Correlation analysis of various factors under different temperature

		Mean of R_{ct} [m^{2}kW^{-1}]	*clo*	Mean of K [Wm^{-1}K^{-1}]
Mean of R_{ct} [m^{2}kW^{-1}]	Pearson correlation	1	0.998**	–0.998**
	Sig. (2-tailed)		0	0
	N	5	5	5
Clo	Pearson correlation	1.000**	1	–1.000**
	Sig. (2-tailed)	0		0
	N	5	5	5
Mean of K [Wm^{-1}K^{-1}]	Pearson correlation	–0.998**	–1.000**	1
	Sig. (2-tailed)	0	0	
	N	5	5	5

** Statistically significant correlation at 0.01 level (bilateral)

Table 2. Correlation analysis of various factors under different humidity

		Mean of R_{ct} [m^{2}kW^{-1}]	*clo*	Mean of *K* [Wm^{-1}K^{-1}]
Mean of R_{ct} [m^{2}kW^{-1}]	Pearson correlation	1	0.999**	–0.996**
	Sig. (2-tailed)		0.000	0.000
	N	5	5	5
Clo	Pearson correlation	0.999**	1	–0.994**
	Sig. (2-tailed)	0.000		0.001
	N	5	5	5
Mean of *K* [Wm^{-1}K^{-1}]	Pearson correlation	–0.996**	–0.994**	1
	Sig. (2-tailed)	0.000	0.001	
	N	5	5	5

Similarly, for temperature variable, R_{ct} and W_d positively correlated, which was verified by the positive Person correlation coefficient in tab. 3. While the negative relationship between *WVT* and R_{et} or W_d was confirmed by negative Person correlation coefficient. For humidity variable in tab. 4, the relationship between R_{et} and W_d or *WVT* was negative at different humidity, while that between R_{et} and *WVT* was positive.

Table 3. Correlation analysis of various indicators under different temperature

		Mean of R_{et} [m^{2}PaW^{-1}]	W_d	Mean of *WVT* [gm^{-2}h^{-1}Pa^{-1}]
Mean of R_{et} [m^{2}PaW^{-1}]	Pearson correlation	1	1.000**	–1.000**
	Sig. (2-tailed)		0.000	0.000
	N	5	5	5
W_d	Pearson correlation	1.000**	1	–1.000**
	Sig. (2-tailed)	0.000		0.000
	N	5	5	5
Mean of *WVT* [gm^{-2}h^{-1}Pa^{-1}]	Pearson correlation	–1.000**	–1.000**	1
	Sig. (2-tailed)	0.000	0.000	
	N	5	5	5

Wet resistance: R_{et}, water vapor permeability index: W_d, water vapour transmission rate: *WVT*

Partial correlation analysis

Different from Pearson correlation coefficient, partial correlation coefficient of *r* can avoid the inevitable influence of other variables on the correlation between any of two variables if there are many influencing variables at the same time [13]. The partial correlation coefficient value of *r* is between 1 and –1. The closer the absolute value of *r* gets to 1, the greater the linear correlation between these two variables. If *r* value is greater than 0, the correlation between these two variables is positive, and vice versa. The 0 of *r* value means non-linear correlation.

Table 4. Correlation analysis of various indicators under different humidity

		Mean of R_{et} [m^{2}PaW^{-1}]	W_d	Mean of *WVT* [gm^{-2}h^{-1}Pa^{-1}]
Mean of R_{et} [m^{2}PaW^{-1}]	Pearson correlation	1	–0.398**	–0.998**
	Sig. (2-tailed)		0.057	0.000
	N	5	5	5
W_d	Pearson correlation	–0.398**	1	–0.355**
	Sig. (2-tailed)	0.057		0.558
	N	5	5	5
Mean of WVT [gm^{-2}h^{-1}Pa^{-1}]	Pearson correlation	–0.998**	0.355**	1
	Sig. (2-tailed)	0.000	0.558	
	N	5	5	5

From tab. 5, *r* absolute values of R_{ct}, *clo*, *K*, R_{et}, W_d ,and WVT were all greater than 0.99, indicating that temperature was significantly correlated with these factors. Clearly, the ambient temperature was negatively correlated with R_{ct} and *clo*, and positively correlated with other four indicators. Except for W_d, all *r* absolute values of above five indicators were greater than 0.995. Namely, the humidity was negatively correlated with R_{ct}, R_{et} and *clo*, and positively correlated with other three indexes, as shown in tab. 6. Except for insignificant correlation with W_d, the humidity was highly correlated with other five indexes. Comparing *r* values of W_d in tabs. 5 and 6, the temperature was significantly correlated with W_d due to a higher *r* value of 0.997, where the humidity was not significantly correlated with W_d due to a lower *r* value of 0.398. All these results were consistent with those of Pearson correlation analysis.

Table 5. Partial correlation analysis of various indicators under different temperature

Control variable		Mean of R_{ct} [m^{2}kW^{-1}]	*clo*	*K* [Wm^{-1}k]	Mean of R_{et} [m^{-2}PaW^{-1}]	W_d	*WVT* [gm^{-2}h^{-1}Pa^{-1}]
Temperature	r	–0.991	–0.996	0.999	0.999	0.997	0.997
	p	0.001	0.000	0.000	0.000	0.000	0.000
	df	2	2	2	2	2	2

Table 6. Partial correlation analysis of various indicators under different humidity

Control variable		Mean of R_{ct} [m^{2}kW^{-1}]	*clo*	*K* [Wm^{-1}k]	Mean of R_{et} [m^{2}PaW^{-1}]	W_d	*WVT* [gm^{-2}h^{-1}Pa^{-1}]
Humidity	r	–1.000	-0.999	0.996	-1.000	0.398	0.998
	p	0.000	0.000	0.000	0.507	0.507	0.000
	df	2	2	2	2	2	2

Discussion and conclusion

Textiles and textile product manufacturers have looked to physical tests to quantify thermal performance of their products, *e.g.*, the thermo-physiological comfort property [14], and new theories for thermodynamics for porous media have been appeared, especially the two-scale fractal thermodynamics [15-17]. In this study, the thermal comfort and wet comfort of PCM firefighting suit and common counterpart were profoundly compared. Under the same ambient temperature and humidity, the comfort differences between their two were ascribed to heat storage and temperature regulation characters of PCM. With correlation analysis and partial correlation analysis, the effects of ambient temperature and humidity on these indicators of R_{ct}, *clo*, K, R_{et}, W_d, and *WVT* were analyzed. Herein, the temperature was negatively correlated with R_{ct}, *clo* and *WVT*, and positively correlated with K, R_{et}, and W_d when the external humidity remains constant. The humidity was negatively correlated with R_{ct}, *clo*, and R_{et}, and positively correlated with K, W_d, and *WVT* when the external temperature unchanged. Except for the insignificant correlation with *WVT*, the humidity had a significant correlation with other five indexes. When the temperature was same, R_e changed most dramatically as the humidity changed. While humidity was same, R_{ct} changed most dramatically as the temperature changed. With these results, PCM firefighting suit exhibited a superiority in harsh environment of high temperature and humidity.

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