Thermal and Wet Comfort of Fabrics Based on Fractal Dimension of Silicone Coating

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ABSTRACT

In this paper, thermal and wet comforts of silicone coated windbreaker shell jacket fabrics were studied. Both thermal insulation and evaporative resistance of fabric increased with an increase in coating area due to the barrier effect of the silicone coating layer. Moreover, the coated fabrics with self-similar structures showed different thermal insulation and evaporative resistance under the same total coating area. Fractal theory was used to explain this phenomenon. Optimal thermal-wet comfort properties were obtained when the fractal dimension (D=1.599) was close to the Golden Mean (1.618). When the fractal dimension of coating was lower than 1.599, fabric warmth retention was not high enough. In contrast, fabric evaporative resistance was beyond the value at which people would feel comfortable when the fractal dimension was greater than 1.599.

INTRODUCTION

A fractal is a mathematical set that exhibits a repeating pattern displayed at every scale [1]. If the replication is exactly the same at every scale, it is called a self-similar structure. Many natural materials in the world with self-similar structures have outstanding properties. The appearance of fractal theory opened a door for researchers to study the “structure-property” relationship of materials having self-similar structures using a mathematical method. He [2] implied a relationship exists between electrical resistance of the carbon nanotubes (CNTs) and their corresponding fractal structures. The electrical resistance of CNTs was predicted to increase exponentially with their length. Moreover, the exponent is equal to the fractal dimension (D=2.52) of the CNTs wall, agreeing with the experimental results. Fan et al [3] revealed that nature wool fiber had a hierarchical structure. They found that the fractal dimension (D=1.595) of natural wool fiber was close to the Golden Mean, 1.618. A lower fractal dimension value would cause the wool fiber to have good heat retention but poor heat dispersing ability. Otherwise, the fiber could not provide good heat insulating ability for sheep in cold weather. The hierarchical structure also provided a new way to explain the softness, elasticity and warmth retention of wool.

Recently, fractal theory was applied to analyze the properties of man-made materials. Chen et al [4] built a new fractal model for predicting the water permeability of satin fabrics. The predicted values agreed well with the experimental ones. Wang et al [5] made FeCrAl fibers having fractal porous structures. A greater porosity led to a higher fractal dimension.

Fan’s work [3] found that the fractal dimension (D=1.595) of nature wool fibers was close to the Golden Mean, 1.618. A lower fractal dimension would cause wool fiber to have good heat retention but bad heat dispersing ability. Thus, the fiber could not provide a good heat insulating ability for sheep alive in cold weather. This provided a new explanation of the softness, elasticity and warmth retention of wool fibers. The Golden Mean was first presented by Pythagoras (BC580-BC500) and considered as an optimal proportion in many fields in later years. It was applied in ancient buildings, classical arts and engineering. The design of the Parthenon at the Acropolis of Athens was based on the Golden Mean. Leonardo da Vinci represented the golden proportion of the human body in his Uomo vitruviano [6]. Han et al. [7] used a Golden Mean approach to prepare a ceramic brake lining with an optimal formulation and high cost/performance balance.

Human beings and apparel are inseparable because people wear clothes under most circumstances. Apparel is not only a part of the external environment, but also an extension of human body. Clothing can protect the human body and maintain the body’s thermal balance in order to adapt to external environmental change. The thermal insulation and evaporative resistance important parameters used to characterize the comfort of clothing [8-10]. To reduce the amount of heat dissipated into the external environment, a higher thermal insulation is required. However, a lower evaporative resistance is favorable to expel the perspiration vapor from human skin more easily and faster.

Previous studies showed that a silicone coating on a cotton fabric applied through a sol-gel process improved their flame retardant properties [11]. However, there are no studies on the effect of a silicone coating on the thermal insulation and evaporative resistance of fabrics. In this paper, silicone-coated fabrics were prepared and the effect of coating area on the fabrics comfort was studied. A fractal coating structure is created and the relationship with the thermal-wet comfort of the fabric is discussed.

EXERIMENTAL

Materials

Windbreaker shell jacket fabrics were supplied by Kuaibuzhe clothing company (Guangzhou, China). They had a sandwich-like structure in which a functional expanded poly-tetrafluoroethylene film was covered by two protective polyamide fabric layers. Liquid silicone was bought from Hongfeng silicone company (Dongguan, China). It contained two components, A and B, which corresponded to curing and pasting agents, respectively.

Coating

A mixture of components A and B with a weight ratio of 1: 1 was placed in a vacuum box to degas for 10 min. A mold with a thickness of 0.3 mm and different hollowed-out squares (*Figure 1 and Figure 2*) was mounted on fabric 32x32 cm in dimensions. Then the prepared silicones were coated on the molds using a roll and the coated fabric was left at the room temperature for three hours. Finally, the molds were removed and the coated fabric samples were heated in a vacuum oven for 30 minutes.

Fabric samples with different coating areas (0%, 25%, 50% and 75%) were prepared. Small coating squares (4x4 cm) were applied to each fabric sample, as shown in *Figure 1*. Fabric samples were also coated with same area (50%) but with different numbers of small coating squares, 2x2, 3x3, 4×4, 5x5 and 6x6 cm, respectively *(Figure 2*).

Measurement of Thermal Insulation and Evaporative Resistance

All samples were placed in an artificial climate room at a temperature of 20^{o}C and relative humidity of 65% for 24h before testing. The thermal insulation and evaporative resistance of samples were measured using a flat fabric heat retention tester (YG606G, Ningbo Textile Instrument Factory, China), following ISO 11092. A sample was placed on hot plate at 35^{o}C and then the chamber was closed. The thermal insulation of samples (R_{ct}) was measured in the chamber with an atmosphere temperature of 20^{o}C and relative humidity of 65 percent. To determine evaporative resistance (R_{et}), the atmosphere temperature and relative humidity of chamber were changed to 35^{o}C and 40%, respectively. Blank experiments were carried out to measure the thermal insulation (R_{ct0}) and the evaporative resistance (R_{et0}) of hot-plate and air gap, respectively.

The R_{ct} was calculated according to Eq. (1):

$$R_{ct} = \frac{A\times(T_m - T_a)}{H-\Delta H_c} - R_{ct0} \quad (1)$$

Where A is the total area of the fabric; T_m and T_a represent the hot-plate temperature and atmosphere temperature of the chamber, respectively; H stands for the power consumption during the tests and ΔH_c is the correction value of the testing instrument.

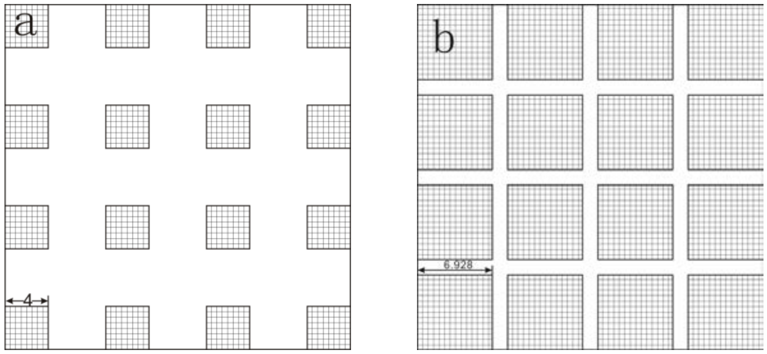

FIGURE 1. Illustration of fabrics coated with the same numbers of small silicone squares but different coating area (a) 25% coating area, (b) 75% coating area.(Shadow: silicone coating).

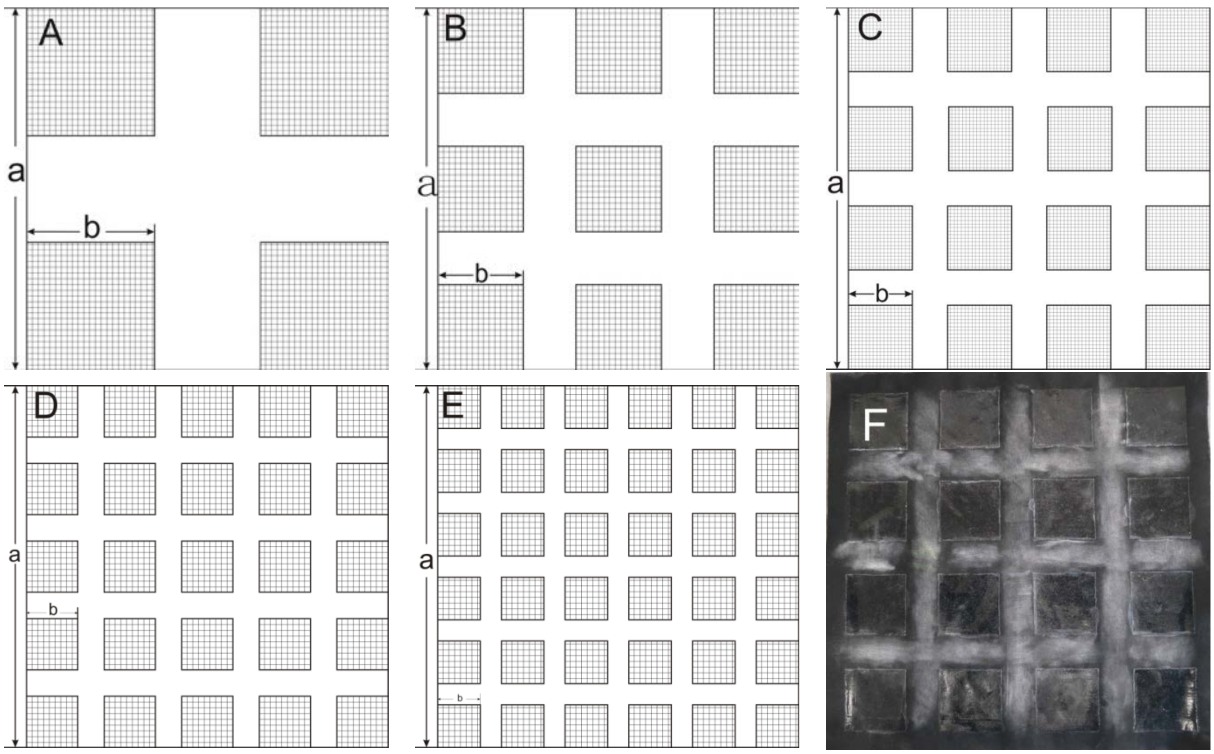

FIGURE 2. Illustration of fabrics coated with the same coating area but different numbers of small silicone squares (A)2x2,(B)3x3,(C)4x4,(D)5x5,(E)6x6,(F)The photo of fabric coated with 4x4 small silicone square.

The R_{et} was determined by Eq. (2):

$$R_{et} = \frac{A \times (P_m - P_a)}{H - \Delta H_e} - R_{et0} \tag{2}$$

Where, P_m and P_a mean the saturated vapor pressure at 35^{o}C and vapor pressure in the testing chamber, respectively, and ΔH_e is the correction value of the testing instrument.

RESULTS AND DISCUSSION

The thermal insulation and evaporative resistance of fabrics with different coating areas are shown in *Figure 3*. Both thermal insulation and vapor resistance increased with increasing coating area. That is because the silicone layer as a physical barrier prevented the heat and vapor transferring through the fabrics. To improve thermal and wet comfort, the fabric should have a higher thermal insulation and a lower evaporative resistance.

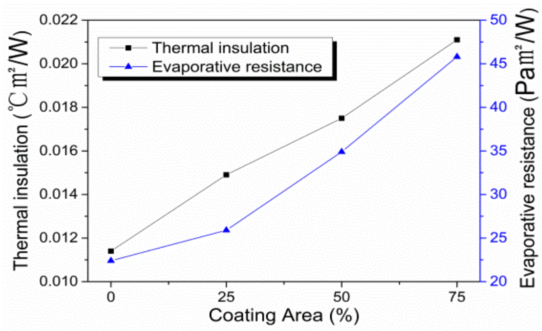

FIGURE 3. R_{ct} and R_{et} of samples with different coating areas.

Fabric samples coated the same amount (50%) but with different arrangements silicone squares were prepared following the illustration shown in *Figure 2*. Their measured thermal insulation and evaporative resistance are shown in *Table I*.

TABLE I. R_{ct} and R_{et} of the samples coated with different silicone squares.

Square number	Length of square(cm)	Fractal dimension	R_{ct} ($^{o}Cm^2/W$)	R_{et} (Pam^2/W)
2x2	11.314	1.335	0.0135	30.4
3x3	7.542	1.519	0.016	34
4x4	5.657	1.599	0.0185	35.4
5x5	4.525	1.647	0.0201	43.4
6x6	3.771	1.675	0.0392	57.8

As the number of silicone blocks increased, the coating distribution on the fabrics became more uniform, causing higher thermal insulation and greater evaporative resistance. The increase in thermal insulation improved the warmth of fabric, while higher evaporative resistance reduced the wet comfort of the fabrics. In order to make a shell jacket with good warm and wet comfort, the coating should provide the fabric with sufficient evaporative resistance that meets the wet comfort requirement of human bodies, with the highest possible thermal insulation. The evaporative resistance of outdoor clothing is required to be less than 40 Pam^2/W according to ISO 9920-2007 [9]. If the evaporative resistance is higher than this value, perspiration is not able transfer to the atmosphere efficiently, making people feel stuffy. In this study, the 4×4 cm coating proved optimal, resulting in the best thermal-wet comfort. The fabrics with the same coating area had self-similar structures produced by different molds. The difference in thermal insulation and evaporative resistance among the samples was possibly due to different fractal dimensions of self-similar coatings. The fractal dimension is defined as [12].

$$D_f = Log\,M/LogN \tag{3}$$

Where M is the number of new units having a new dimension within the original unit and N is the ratio of the original dimension to the new dimension.

For the fabric illustrated in *Figure 2a*, the length proportion between the small coating square and the fabric is

$$N_1 = \frac{a}{b} = \frac{32}{11.314} = 2.828, \qquad M_1 = 4$$

Where a and b stand for the length of a side of fabric and silicone square, respectively.

The fractal dimension D_1 can be calculated as follows:

$$D_1 = LogM_1/LogN_1 = \frac{log4}{log2.828} = 1.335$$

In a similar way, D_2, D_3, D_4 and D_5 for the corresponding sample shown in *Figure 2b-2e* are calculated as following:

$$N_2 = \frac{a}{b} = \frac{32}{7.542} = 4.243, \qquad M_2 = 9$$

$$D_2 = LogM_2/LogN_2 = \frac{log9}{log4.243} = 1.519$$

$$N_3 = \frac{a}{b} = \frac{32}{5.567} = 5.567, \qquad M_3 = 16$$

$$D_3 = LogM_3/LogN_3 = \frac{log16}{log5.567} = 1.599$$

$$N_4 = \frac{a}{b} = \frac{32}{4.525} = 7.072, \qquad M_4 = 25$$

$$D_4 = LogM_4/LogN_4 = \frac{log25}{log7.072} = 1.647$$

$$N_5 = \frac{a}{b} = \frac{32}{3.771} = 8.486, \qquad M_5 = 36$$

$$D_5 = LogM_5/LogN_5 = \frac{log36}{log8.486} = 1.675$$

As the side length of square unit decreases, the number of square units increases. Therefore, the number of square units can be limitless. Also, the corresponding fractal dimension will increase. The 4×4 cm coating that had a fractal dimension of 1.599 resulted in a fabric with the best balance of thermal-wet comfort. The fractal dimension was very close to the Golden Mean. It is well known that golden mean plays a significant role in many natural phenomena [13-16]. In this work, the possible range of fractal dimension values of the coating structures is between 0 and 2. Therefore, the two boundary conditions will be: (1) D=0, which means the fabric coating does not have a fractal structure and the thermal retention remains at a relatively low value, resulting in poor thermal comfort; (2) D=2, indicating infinite squares coating the fabric, causing the thermal insulation and evaporative resistance of the fabric tend to reach very high values. The fabrics cannot provide a good wet comfort when people wear them. This suggests that the thermal-wet comfort of fabrics is related to the fractal dimension of coating structures.

CONCLUSION

In this study, thermal insulation and evaporative resistance of wind breaker shell jacket fabrics coated with different areas of silicone (25%, 50%, 75%) were investigated. Their values increased with an increase in coating area. Moreover, self-similar coating structures were designed by coating different numbers of silicone blocks on the fabrics with the same total coating area (50%). A relationship between the fractal dimensions of coating structures and thermal-wet comfort was found. The 4×4 cm coating had a fractal dimension of 1.599, which was close to the Golden Mean (1.618), leading to the best combination of thermal-wet comfort. When the fractal dimension of coating was lower than 1.599, the warmth retention of fabrics were not high enough. In contrast, evaporative resistance of fabrics was beyond the value at which people would feel comfortable when the fractal dimension was greater than 1.599. Thus the idea of fractal theory and Golden Mean value can be applied to design clothes with good comfort properties.

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