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Comparison of air flow environmental effects on thermal fabrics

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Abstract

Smart thermal textiles are becoming increasingly popular and temperature precision is one of the important targets in their industrialization and commercialization. Some thermal products do not rely on temperature sensors but rather the input electric current pulse to achieve thermal control. In this situation, the surrounding environment, especially ventilation, can greatly affect the thermal control process.

Therefore, in this paper, a case study of an apparel system will be provided to study the effect of airflow on the heating process of thermal fabric. The relationship between temperature precision and ventilation is determined when the air flows at any angle to the surface of the thermal fabric. The results show that the thermal conductivity is proportional to the wind speed when the wind speed is high; in contrast, when the wind speed is near to zero, the thermal conductivity of the thermal fabric will not proportionally tend to zero as the result of self-generated heat transfer. This research also shows that the air inflow angle and the wind direction has little effect on the heat dissipation of thermal fabric. This research may generate the data archive and become a valuable reference for future soft thermal studies. It is expected that the developed system will span multidisciplinary gaps and contribute to a new form in a precise and controllable way within the textile industry.

Keywords
airflow, air inflow angle, functional design, temperature control, thermal conductivity

Recently, wearable textile electronics, especially those used in thermal garments, have drawn attention and better materials and technologies are rapidly being developed. The popularity of thermal garments in particular is on the rise in terms of both personal and professional use, especially in terms of the medical industry and the healthcare sector.[1–11] Thermal garments are well received because they can be applied to warm the body, used to assist physical therapy, and can also be used to resist extreme environments, assist with drug delivery, and so on.[12–18] Obviously, there is an increasingly large potential demand and market for thermal garments.

With a rapidly aging population, thermal treatment is more in demand and is becoming more important, as it is regarded as the most common type of physical therapy (Figure 1). Moreover, wearable electronics integrated into thermal garments help to optimize thermal treatment. Thermal garments with wearable electronics have many benefits. They are soft, light, and portable. Conductive fabrics, in which conductive yarns are embedded with other types of yarns during fabrication, are the most often used heating material for thermal garments, and their fabrication techniques and various properties have been fully explored.[19,20] In the previous research, the properties of conductive fabrics and the heating process were studied in detail. The effects of both the stretching by external forces and temperature changes on the resistance of conductive fabric have been extensively explored.[21,22] In addition, work was carried out to examine the thermal capacity and thermal conductivity of conductive fabrics, while some researchers have focused on the heating process of conductive fabrics.[23] With better insight gained on the various properties of conductive fabrics and the heating process, it is thus possible to achieve thermal control of thermal garments.

Figure 1. Garments in the current market for thermal treatment: (a) Ardica thermal jacket; (b) Burton thermal jacket; (c) WarmX thermal knitwear.

A number of factors are closely related to the temperature control of thermal fabrics. Selection of the type of conductive yarn, its fabrication structure, and the surrounding environment all greatly affect the temperature control of thermal fabric or its achieved temperature. Some efforts have already been made to investigate the various properties of thermal fabrics; however, environmental factors have not been taken into consideration in previous research work. There are some kinds of thermal products that do not rely on temperature sensors but rather the input electric current pulse to achieve thermal control. For them, environmental factors play an important role in temperature change. Therefore, a comprehensive research study of the effects of the environment on thermal fabrics has not been conducted. One of the most important environmental factors is the wind or airflow. It was found that the heating process of thermal fabrics/garments can be greatly affected by airflow. The work carried out will therefore be meaningful to future research, which can analyze airflow as an environmental parameter for garments. Obviously, better external ventilation is conducive to heat dissipation and results in a lower achieved temperature of the thermal fabric. Without taking into consideration the effect of external ventilation, the precision of thermal control would be seriously affected. Unlike applications for everyday use, the precision of thermal control is much more important in thermal treatment because some drugs require an optimal working point to function well. Therefore, there is a demand to investigate the effect of the wind or airflow on the heating process of thermal fabrics. The research results will not only complement the fundamental research on thermal textiles with wearable electronics, but also act as a reference for the design of electronic controls for thermal textiles. Furthermore, manufacturers of thermal textiles can provide more accurate temperature control to users in different environments – in the hospital, clinics, or at home, so as to improve comfort and treatment efficacy.

Theoretical details

The theories behind heat transfer, including heat conduction and heat convection, have been explored.[23–25] However, it is not feasible to apply previous theories to the analysis of the heating process of thermal fabrics in a ventilated environment, because they are overly complicated and it is not possible to use them in simulations. Thus, a simple method of analysis is required to address the heat transfer process of thermal textiles in a ventilated environment. Moreover, the situation can be greatly different for thermal fabrics in comparison with the use of theoretical analyses of thermal processes. The properties of thermal fabric may have a large impact on the airflow around the fabric. For instance, air transmission and air reflection may take place along with heat transmission and heat reflection, which complicates the process more than the process in theory. The extent of the influence of the airflow on the thermal process of thermal fabrics is still unknown. Thus, both theoretical analysis and experimental testing are carried out to explore the impact of airflow on heat dissipation in thermal garments.

Moreover, the angle at which the air flows through the fabric also needs to be taken into consideration. The different wind directions may affect heat dissipation greatly and lead to different results.

Heat transfer is a process of thermal energy exchange between physical systems and it is always driven by temperature differences. Heat transfer will not cease until all involved bodies and surroundings reach the same temperature and thermal equilibrium is attained. Heat conduction, convective heat transfer, and radiation are three fundamental modes of heat transfer. The processes of heat conduction and convective heat transfer are both found in thermal fabrics, and should therefore be taken into consideration. As fabric and air are both bad conductors of heat, convective heat transfer therefore plays a vital role in the heat transfer of thermal fabrics and sometimes its heat conduction becomes negligible.

The law of heat conduction states that the time rate of heat transfer through a material is proportional to the gradient in temperature. That is, for thermal fabrics, the heat flux from the fabric to the surrounding environment, which can be expressed as dQoutdtdQoutdt, is proportional to the difference between the temperature of fabric T and the temperature of its surroundings T_0[25]

$$\frac{\mathrm{dQ\ out}}{\mathrm{dt}} = \lambda * (T - T0) \tag{1}$$

where λ is the thermal conductivity under heat conduction, which measures the ability of a material to conduct heat. However, the thermal conductivities of fabric and air are both very low and can be neglected when there is convective heat transfer. As the mechanism of convective heat transfer is different from heat conduction, the heat flux form of convective heat transfer is more complicated. In the process of convective heat transfer, a hot or cold object, including its thermal energy, is moved from one place to another and consequently heat transfer is achieved by transferring particles of matter. The heat flux form can therefore be expressed as

$$\frac{\mathrm{dQ\ out}}{\mathrm{dt}} = A * v * \rho * c * (T - T0) \tag{2}$$

where dQdtdQdt is the heat flux density,A is the cross-section of the flow, v is the flow velocity of matter (matter refers to air in our testing), ρ is the density of matter, and c is its heat capacity. In our study, we assume that the air above the fabric is blown away at the rate of wind speed regardless of whatever angle the wind flows in. Therefore, the thermal conductivity under convective heat transfer is

$$\lambda' = A * v * \rho * c \tag{3}$$

For thermal fabrics, v denotes to the wind speed. As mentioned previously, the effect of thermal conduction is negligible. Therefore, it is highly possible that the total thermal conductivity of a fabric is proportional to the wind speed regardless of the wind direction

$$\lambda\mathrm{total} \sim v \tag{4}$$

The effect of both the wind speed and wind direction on the thermal conductivity of thermal fabric remains to be explored and determined.

Methodology and experimental design

Methodology

The aim of this study is to explore the relationship between the thermal conductivity of a thermal fabric and the external wind. Thus, the thermal conductivity of a thermal fabric will be measured under different wind speeds and different wind directions. The amount of heat dissipation from the thermal fabric to the surrounding environment equals the electrical power input when thermal equilibrium is achieved

$$\frac{\mathrm{dQ\ out}}{\mathrm{dt}} = P\mathrm{in} \tag{5}$$

By combining equation (1), we can obtain

$$P\text{in}=\lambda^*(T-T0) \tag{6}$$

Therefore, the thermal conductivity can be obtained by measuring the electrical power input and temperature difference. The fitting method is used to determine the thermal conductivity of the thermal fabric with different amounts of supplied electrical power. Then, under different wind directions, the relationship between thermal conductivity and wind speed can be determined.

Materials and setup

A woven structure was selected for testing, as woven fabric is more stable and uniform in resistance distribution. Yarns (100% cotton) with a density of 16/2 S ply were used as the primary material. Silver-coated conductive yarns were embedded into the woven fabric to provide the fabric with conductive properties. The conducting Yarn #1, which is a monofilament with resistance of 68.6 Ω per cm (22/1 dtex) and whose structure is nylon 6 fiber coated with silver on surface, forms the heating area (Figure 2). Another kind of conducting Yarn #2, which is a balanced two-plied yarn made from multifilament single yarns, with resistances of 1Ω per cm (235/34 dtex), was used to weave conductive paths to act as the electrodes of the electric power supply (Figure 2). The inner fibers of Yarn #1 and Yarn #2 are nylon 6 and nylon 66, respectively. The regular structure of weaving was adopted. The conductive woven fabric was fabricated by using a CCI Tech automatic dobby sampling loom. The finished fabric was 4.8 inches in width and 5.9 inches in length, while its weft and warp densities were 30 picks/inch and 40 ends/inch, respectively (Figure 3).

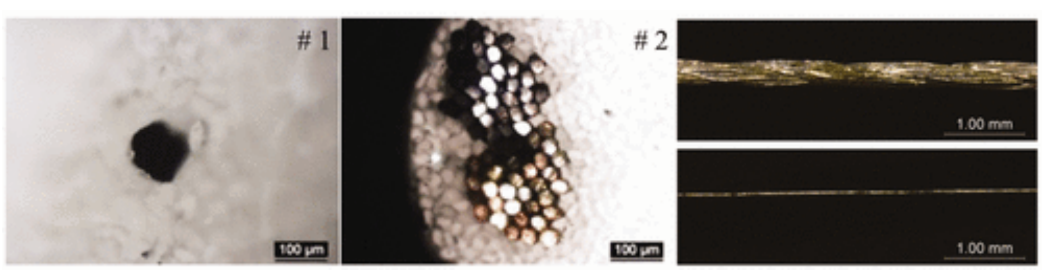

Figure 2. Cross-sectional and longitudinal views of conducting yarns selected for fabrication.

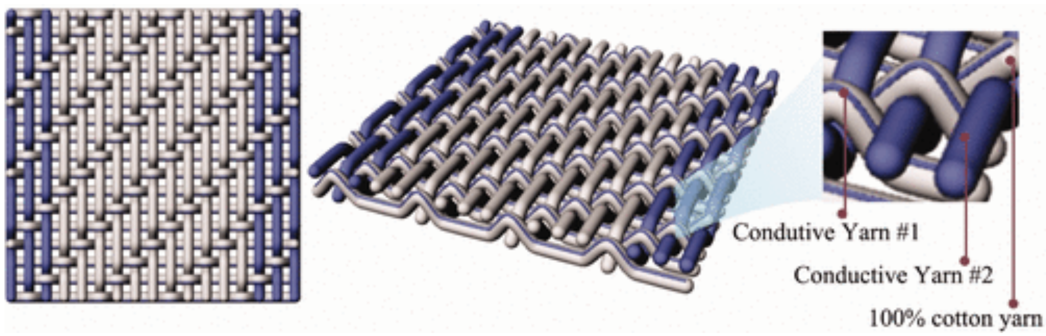

Figure 3. Three-dimensional model of the fabricated structure of conductive woven fabric and the arrangement of conductive yarns.

An adjustable power supply with different settings of output power was used to heat the samples. The power supply also provides electrical current monitoring. Thus, the output power could be obtained at all times. The woven fabric was not washed or ironed prior to the testing. Instead, the thermal fabric was dry relaxed and aligned on a rigid, non-conductive foam board for measurement purposes. An electronic thermometer was used to measure and record the temperature of the thermal fabric. The thermometer sensor was evenly placed at five locations on the thermal fabric to measure the temperature, and the average of the five temperatures was taken to represent the apparent temperature of the heated fabric.

An electrical fan with adjustable working wind speed was used to provide a good and stable ventilation environment. The fan is a Lileng-826 model from the Lileng Company and it offers free angle adjustment to ensure an accurate wind direction. A wind anemometer with an error of ±3%±3%was prepared to measure the surrounding wind speed of thermal fabric. The wind speed was measured five times around the thermal fabric in a test and was averaged to represent the average surrounding wind speed.

All of the tests were conducted under a standard atmosphere with an air pressure of 1 atm, temperature of 21.5 ± 0.5°C, and humidity of $60 \pm 2\%$ (Figure 4).

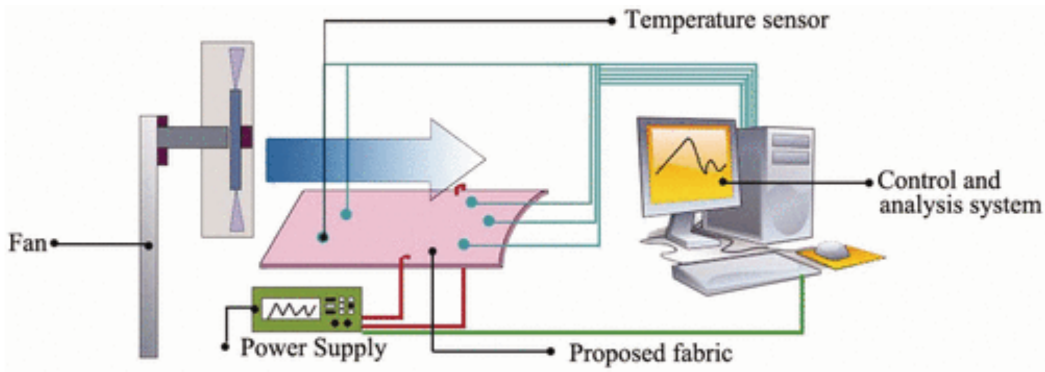

Figure 4. Testing equipment and control and analysis system.

Results and discussion

We used a direct current (DC) power supply to heat the fabric with increasing electrical power in the different tests. In each test, the thermal fabric was heated for 1800 seconds to achieve thermal equilibrium. It is found that the temperature is stable in 1800 seconds in all tests. Thus, it is guaranteed that thermal equilibrium is achieved in all tests. The achieved temperature of the thermal fabric and the applied power were both recorded. At the same time, the environmental wind speed was measured and recorded.

In the first step, the fan was turned off and the thermal fabric was heated without wind flow. As the testing was conducted in a poorly ventilated room, the wind speed reading was 0 (m/s) by the wind anemometer. Thus, it is guaranteed that the airflow in the testing environment can be neglected. The three available output powers were set to the DC power supply to heat the thermal fabric, and the corresponding obtained temperature was recorded. The temperature difference or increased temperature of the fabric was obtained by subtracting the initial temperature. Thus, variations in the electrical power with temperature difference were obtained, as shown in Figure 5. According to equation (6), the input amount of electrical power onto the thermal fabric is proportional to the temperature difference. A proportional function was therefore used to fit the relationship between the electrical power and temperature difference; the fitting result is presented in Figure 5. The fitting thermal conductivity λ is 0.30 (w/∘C∘C) and a regression coefficient of 0.992 is obtained, which indicates that a proportional relationship can be successfully applied between the power and temperature difference.

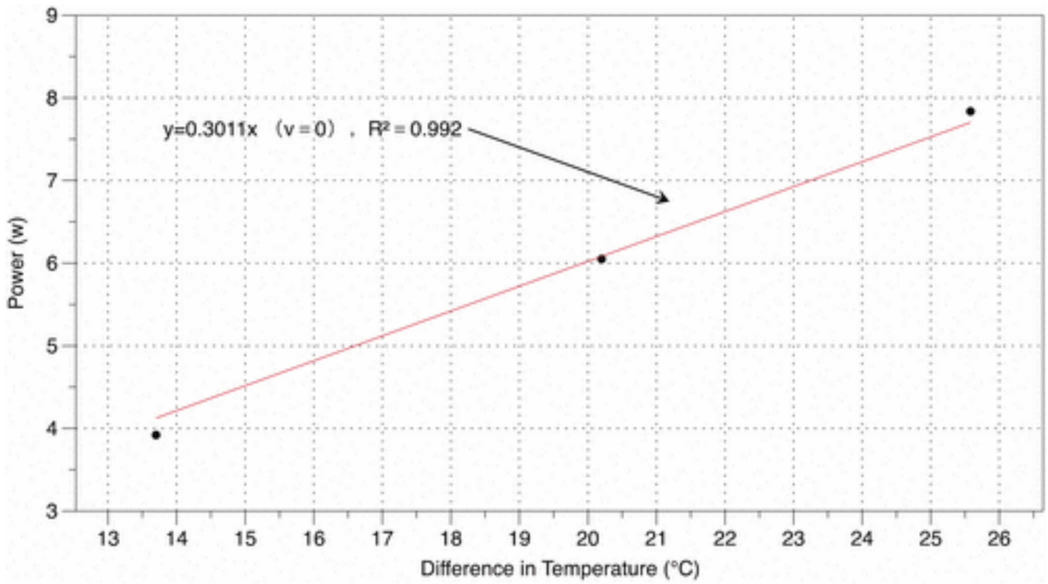

Figure 5. Variations in power with differences in temperature and the fitting curve (red line) without wind flow. (Color online only.)

Then the fan was turned on to provide a ventilated environment. Firstly, the fan was adjusted to provide a low wind speed and the board under the fabric was adjusted to change the air inflow angle. The test was conducted under air inflow angle θ=0∘,45∘,90∘. Under each air inflow angle, the obtained temperature of the thermal fabric was taken under four electrical power inputs. Then we adjusted the fan to increase the wind speed and the above process was repeated. Finally, the relationship between the power and temperature difference under different wind speeds and different air inflow angles (wind direction) was obtained. Figure 6 shows the relationship between the power input and temperature difference under different wind speeds when air inflow is parallel to the fabric (θ=0∘θ=0∘) and the good fitting results are achieved, which indicates that a proportional relationship between electrical power input and the increased temperature under different wind speeds is verified. In other words, the concept of thermal conductivity can be applied not only to examine heat conduction, but also convective heat transfer. The thermal conductivity values can be easily obtained from dividing the thermal dissipation by increases in the temperature, as shown below, which is actually the fitted slope in Figures 6(a)–(d)

$$\lambda = \frac{Pdiss}{T - T0} \tag{7}$$

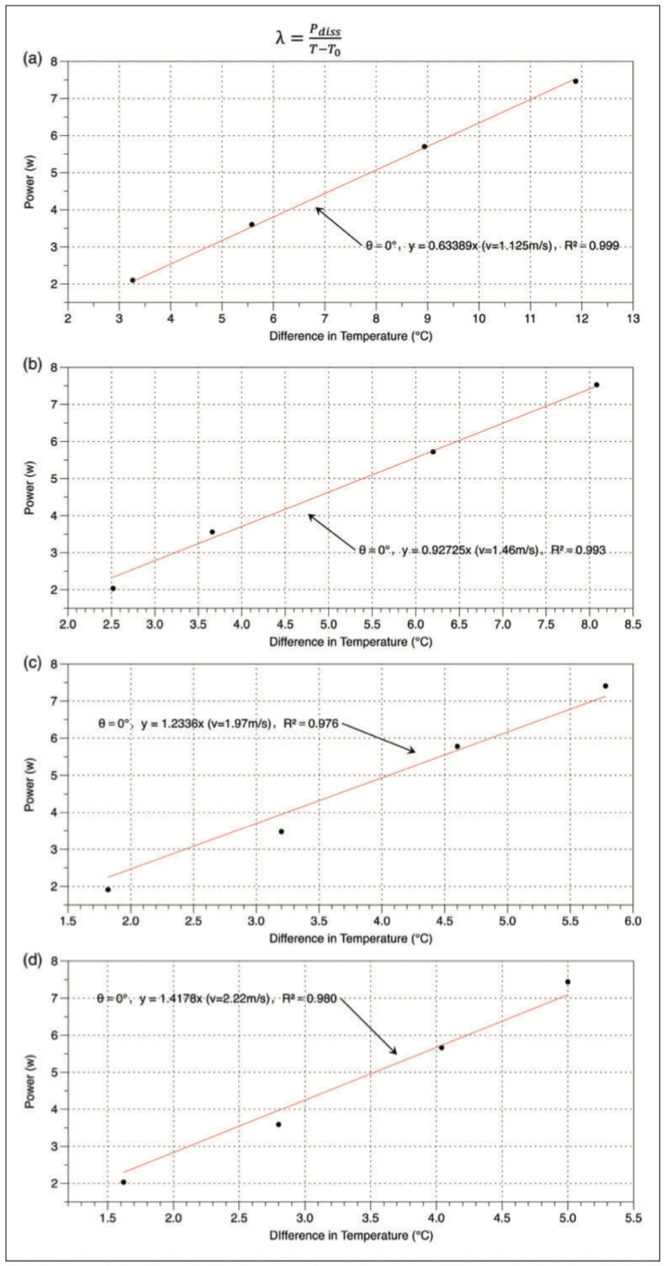

Figure 6. Relationship between the electrical power input and temperature difference of thermal fabric under different wind speeds (1.25, 1.46, 1.97, and 2.22 m/s), when

the air inflow angle is θ=0∘θ=0∘, and the fitting results (red line). It is clearly shown from (a) to (d) that with increasing wind speed the thermal conductivity increases continuously. (Color online only.)

After obtaining the relationship between power input and temperature difference of the thermal fabric under different wind speeds and different wind directions (air inflow angles), the relationship between thermal conductivity and wind speed under different air inflow angles remains to be examined. The fitted thermal conductivities with air inflow angle θ=0∘θ=0∘ from Figures 6(a)–(d) were integrated to find the relationship between thermal conductivity and wind speed. Line "θ=0∘,y=0.62627x″ in Figure 7 fits the relationship between thermal conductivity and wind speed under air inflow angle θ=0∘θ=0∘. In the same way, the fitted relationship is also obtained under air inflow angle θ=45∘,90∘, which is shown in Figure 7. Finally, we obtain the results in Figure 7, which shows the thermal conductivity of the thermal fabric under different wind speeds and air inflow angles as well as the environment without wind flow (v=0m/sv=0m/s). It can be seen in Figure 7 that a very good proportional relationship between thermal conductivity and wind speed (without v=0m/sv=0m/s) is obtained, which is consistent with the theory stated for equation (4); it is highly probable that the total thermal conductivity of a fabric is proportional to the wind speed. As the airflow carries thermal energy from the thermal fabric to the surrounding environment, airflow at higher speed would result in faster thermal dissipation. Therefore, thermal conductivity values proportionally vary with the wind speed. The airflow very simply affects the heat dissipation of thermal fabric in a simple way. However, it was found that the thermal conductivity of thermal fabric without wind flow shows inconsistencies compared with the regular pattern. This is because the airflow still exists even though there is no external wind provided. When the fabric undergoes a heating process, there exists a local temperature drop over the thermal fabric and, consequently, air starts moving at a small scale, which results in weak convective heat transfer. Although the convective heat transfer is not as strong as an external source of wind, it is still not negligible. In addition, there exists thermal conduction to a certain extent. These two modes of heat transfer both exist without external forces and form self-generated heat transfer of the thermal fabric. It is the self-generated heat transfer itself that contributes to the nonzero value of thermal conductivity with no wind flow. With increases in the wind speed and an approximate value exceeded (around 1.0 m/s in Figure 7), the convective heat transfer resulting from external airflow gradually dominates and covers both the self-generated convective heat transfer and the thermal conduction.

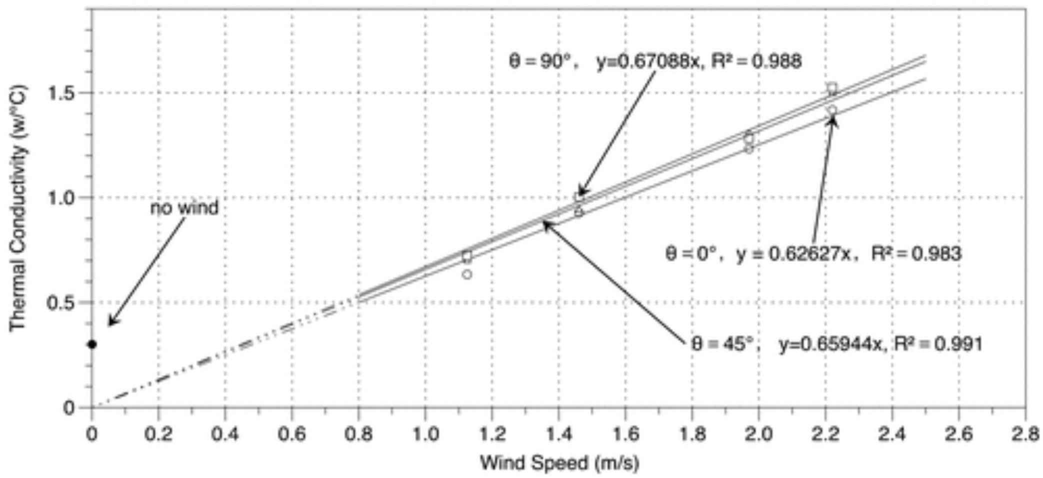

Figure 7. Thermal conductivity of thermal fabric versus wind speed with different inflow angles *θ*=0∘,45∘,90∘.

Another two fabric samples were also tested in the same process and the affect of wind speed and air inflow angles on their thermal conductivities are confirmed by their *k* values, which are shown in Table 1. Table 1 and Figure 7 together indicate that the air inflow angle (wind direction) has little effect on the thermal conductivity of the fabric. In other words, the wind direction does not affect temperature control of thermal fabric. The results verify our assumption in the *Theoretical details* section that air above the fabric is blown away at the rate of wind speed regardless of whatever angle the wind flows in.

Sample/θ	**k**$(\theta = 0^\circ)$	**k**$(\theta = 45^\circ)$	**k**$(\theta = 90^\circ)$
1	0.6263	0.6594	0.6709
2	0.5845	0.6108	0.6156
3	0.6455	0.6790	0.6931

Table 1. *k* value of fabric samples with air inflow angle *θ*=0∘,45∘,90∘θ=0∘,45∘,90∘.

Consequently, the thermal conductivity is proportional to the wind speed at the back of the λ−𝑣λ-vcurve. *k* is used as the proportionality factor

$$\lambda = k * v (v \text{ is high enough}) \quad (8)$$

Thus, the following formula is obtained

$$\lambda = \begin{cases} \lambda_0 & v \sim 0(m/s) \\ k * v & \text{v is high enough} \end{cases} \quad (9)$$

This formula indicates that the thermal conductivity changes with the change of wind speed and how the thermal conductivity can be obtained as expected. With the expected thermal conductivity with the help of equation (9), the temperature of the fabric is established with information of supplied power. This is the whole process of thermal control.

In conclusion, there are two types of heat transfer in the thermal fabrics – self-generated and convective, which is caused by the surrounding airflow. They compete with each other with increases in the wind speed. In the beginning, the self-generated heat transfer has a significant role, while the convective heat transfer caused by the surrounding airflow dominates the total heat transfer to further increase the wind speed and, consequently, the thermal conductivity becomes proportional to the wind speed. It was verified in the previous research work that the temperature that a thermal fabric can obtain is as follows[20]

$$Ts(U) = T0 + \frac{U2}{\lambda * Rs} \quad (10)$$

As the above formula does not take airflow into consideration, its applicability is limited. Thus, our research result complements the previous theory and applies the formula to the heating process in a ventilated environment, which is shown below. Thermal control in a ventilated environment is achieved and the results show extensive potential applications. For instance, a thermal garment that takes the ventilated condition into consideration can be designed based on the above theory by combining equation (8)

$$Ts(U) = T0 + \frac{U2}{k*v*Rs} \tag{11}$$

Application

A thermal garment with a heated panel on the waist is designed (Figure 8). The structure and its arrangement of conductive yarns on the heated area and the temperature control system are based on the heating theory and calculation in this paper. The temperature control system automatically adjusts in accordance with the ventilation of the surrounding environment. It is shown that the garment considering the airflow achieves more precise temperature because it provides more power to offset the heat dissipated by airflow. It has been demonstrated that temperature differences exist that cannot be neglected even if the effect of airflow in the surrounding environment is not taken into consideration. Precise temperature control is therefore successfully achieved in a ventilated environment with the improved thermal garment.

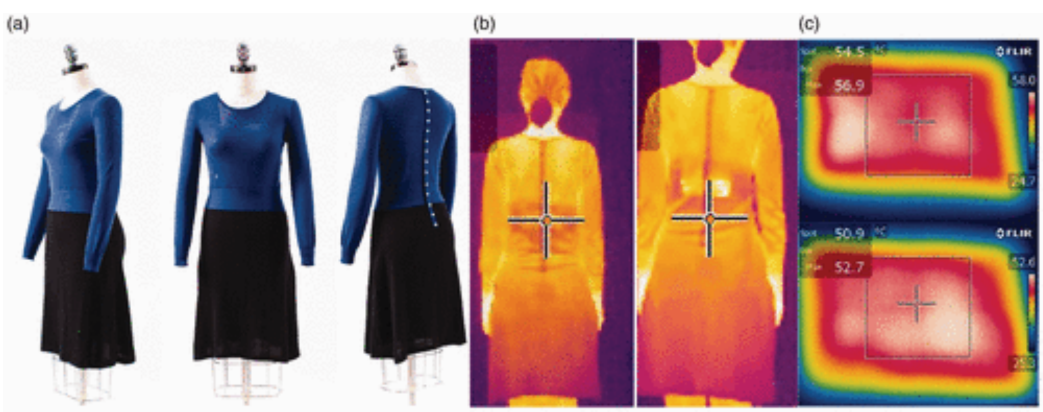

Figure 8. (a) Thermal garment with heated area near the waist area. (b) Infrared image of thermal garment when heated. The left-hand thermal garment takes into consideration airflow, versus the right-hand garment, which does not take airflow into consideration. (c) It is shown that the garment considering the airflow (upper image)

achieves a more precise temperature than the garment without considering airflow (lower image), because it provides more power to offset the heat dissipated by airflow

Conclusion

The effect of airflow on the heating process of thermal fabric has been explored and the relationship between the heat dissipation capacity (thermal conductivity) of thermal fabric and wind speed has been obtained. It is found that there is a good proportional relationship between thermal conductivity and wind speed when the wind speed is adequate. What is more, the wind direction has little effect on the heat dissipation rate of thermal fabric. However, when the wind speed is near zero, the thermal conductivity of the thermal fabric will not tend to zero, as the result of self-generated heat transfer. Previous research work in the literature has indicated that the temperature a thermal fabric can obtain is proportional to the applied electrical power and inversely proportional to its thermal conductivity. Our research shows that we can successfully obtain the thermal conductivity of thermal fabric under a ventilated environment with different wind speeds. Therefore, the relationship between the obtained temperature of a thermal textile and its various parameters is very clear; that is, we can amend the various parameters of the thermal fabrics and electrical power that is supplied to precisely control the temperature under a ventilated environment. The research results are applicable to thermal garments for outdoor use when there are strong and cold winds. In addition, as the thermal conductivity varies with wind speed, it is a promising way to use thermal textiles as a wind speed sensor, because an accurate relationship between temperature and the wind speed can be obtained. This research work is anticipated to complement other research on thermal textiles with wearable electronics and, moreover, increase the applicability of thermal fabrics to a broader range of uses with higher precision so that thermal garments with better performances can be found in daily life in the future.

Declaration of conflicting interests

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