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Development of a cooling fabric from conducting polymer coated fibres: proof of concept

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Abstract

It is supposed that there should be a thermal electric effect if a DC current is applied across two dissimilar conducting polymers, similar to so called “Peltier Effect” in metals or semiconductors. However, this hypothesis has not been tested on conducting polymers and using these materials to make cooling fabrics has never been attempted before. Polypyrrole coated fabrics were used to test the hypothesis in this preliminary study. Seebeck and the Peltier effects were proven to exist. However, thermoelectricity effect between two conducting polymer coated fabric samples was only about 10 (μV/°C). Cooling effect by conductive polymer powder was achieved but performance was unsteady due to electrical degradation of the conducting polymer. Nevertheless, the concept was demonstrated and the development of a cooling fabric is possible.

Keywords: Cooling effect; Peltier effect; Conducting polymers; textiles

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1. Introduction

The clothing industry has been involved in research on textile materials that offered greater comfort and functionality. A cooling effect would be one of the most desired attributes of clothing. New fabric technologies have recently introduced garments that provide a cooling effect without relying on external cooling sources. A portable cooling system is often incorporated into a garment and includes a heat transfer medium to absorb heat from the body. Typically, these materials can be grouped into three general categories: Granular materials, Phase change materials and Water-retaining fibre-based materials. These systems can be further classified as circulating or passive [1]. The former includes a fluid circulating through tubes stitched into the garment and upon contact the fluid removes the body heat. This set up requires a power supply, a pump, and a heat sink to absorb the heat from the circulating liquid. The latter use special materials incorporated into the garment to absorb heat from the body through contact and do not require interaction of the wearer. Both of these systems are generally bulky and not suitable for lightweight applications. Moreover, additional weight causes additional metabolic heat generation due to extra work done by the wearer.

Conducting polymers have attracted a great deal of research interest due to wide-ranging modulation of their electrical properties and responsiveness to external stimuli such as temperature and chemicals [2-4]. But chemically or electrochemically synthesized conducting polymer films have poor mechanical properties, which hinder their practical applications. This limitation is overcome by allowing the polymerisation to take place on textile surfaces to produce conductive fabrics with excellent mechanical properties [5-7]. Potential of such fabrics in heating applications have been reported [8-10]. Furthermore, novel fibres that act as a semiconductor (n- type or p type material) [11-12] could be produced by coating the surface of fibres with conducting polymers. Using these conductive fibres, new fabric could be produced, that will demonstrate the so called “Peltier Effect” and achieve the cooling effect like the traditional semiconductor cooler. This paper presents the preliminary investigations on the proposed cooling fabric by working on the Peltier Effect.
2. Experimental and Results

2.1 The Seebeck Effect

In the world of thermoelectric technology, there are three thermoelectric effects, the Seebeck Effect, Peltier Effect and Thomson Effect. The Seebeck effect occurs between junctions of any two members of the thermoelectric series. In the presence of a temperature difference between the junctions a small current flows around the circuit. The Peltier effect occurs whenever electrical current flows through two dissimilar conductors; depending on the direction of current flow, the junction of the two conductors will either absorb or release heat. The Peltier effect is the reverse of the Seebeck effect and a typical junction phenomenon.

Experimentally, it is easier to prove the Seebeck effect than Peltier effect as the applied temperature is controlled in the former and the resulting potential difference is measured. If the Seebeck effect exists in the conductive fabric, the Peltier effect should also be observed. So, experiments to prove the existence of the Seebeck effect on conductive fabrics were followed by the Peltier effect tests.

In order to prove the existence of Seebeck effect in conducting polymer coated fabrics, a simple experimental bench rig was set up. Two different fabrics (A and B) were connected as shown in Fig. 1. Conductive fabric A was prepared by immersing the textile in an aqueous solution containing 2.4 mg/ml pyrrole and 14 mg/ml Ferric chloride. The reaction was conducted at 4°C for 4 hours. Then, the conductive fabric is rinsed with water and dried at 80°C for 6 hours. Conductive fabric B was prepared by oxidizing the fabric by immersing into a 10 g/l ferric chloride solution followed by exposure to monomer (pyrrole) vapour to obtain a semiconducting coating of polypyrrole on the fabric. A temperature difference is applied to the two junctions of conductive fabrics A and B. The potential difference was measured by a Fluke 189/FVF multimeter.
The low temperature plate (ice water, about 5°C) was connected to the positive and the high temperature (hot water) to the negative terminal of the voltmeter (Fig. 1). The thermoelectricity was observed and the result is shown in Table 1. If the cold and the hot sides are reversed, thermoelectricity will be negative.

Table 1. Results showing the existence of Seebeck effect

The thermoelectricity was also observed in conductive polymer fabric (part A) in contact with aluminium as part B. The result is shown in Fig. 2.

Fig.2. Thermoelectricity effect between conducting polymer coated fabric (A) and Aluminium (B).

Table 2. Thermoelectricity Comparison
2.2 Peltier Effect

Results demonstrate that the Seebeck effect exists between two conductive polymer fabrics. However, Peltier effect is the key for the cooling effect. A rig was built (Fig.3) to test the Peltier effect. A fan blew air through top side and kept the heat exchange equilibrium between both sides. An electrical potential (12 V) was applied between the metal plates causing an electrical current to flow between the plates through the conducting polymer layer. In this process the charge carriers overcome the potential difference between metal and conductive polymer to achieve the cooling effect (Peltier effect) on the bottom side in Fig. 3. Bulk polymerised polypyrrole (p-doped) particles were used as the conducting polymer material in this experiment as the layers required to be well separated to minimise heat transfer effects between the metal plates. The bulk polymerised particles compress to yield a highly conductive layer and also enable a good separation between the layers. In the experimental set-up, shown in Figure 3, the heat should be absorbed from the downside and released to topside; the polymer has higher potential than the metal. A thermocouple and a thermal camera were both used to measure temperatures on both sides to prove the cooling effect.

Fig.3. Experimental set-up for proving the Peltier effect

Polypyrrole (PPy) (p-Doped) conducting polymer particles were prepared from 10% Ferric Chloride 6H₂O₂, 2% Anthraquinone Sulphuric Acid and 5% Pyrrole [7]. Anthraquinone sulphuric acid, pyrrole and ferric chloride were slowly added into a beaker. Polymerisation takes place in the solution and often referred to as Bulk Polymerisation. The solution was continuously stirred for about three hours before filtering to get the black conducting polypyrrole powder (Fig. 4a). The nodular morphology of polypyrrole particles can be seen in the scanning electron microscopy image in Fig. 4b. The conductivity of the powder was about 100 S/cm.
Results from the Peltier test rig (Fig. 5a) indicate that a slightly lower temperature was observed in the lower plate, which proved the existence of the Peltier effect in the material. However, the temperature difference between two sides gradually diminished during the experiment while the electrical resistance across the polymer increased with time. This may be attributed to the accelerated rate of degradation of the conducting polymer due to the applied potential between the plates. The increased resistance resulted in reduction of the current as the conducting polymer degraded (Fig. 5b). Another factor that contributed to the smaller temperature difference was the poor thermal insulation between the two sides so that heat from the hot side heated up the cold side.

Fig. 4a. Polypyrrole powder

Fig. 4b. Scanning electron microscopy image of polypyrrole powder

Theoretically, the magnitude of the cooling effect in the Peltier rig depends on the electrical potential difference between the conducting polymer and metal. When a charge carrier (i.e. positive electron, the “hole”) moves from metal (lower electrical potential) to the polymer (higher potential), the amount of heat absorbed depends on the potential difference between the polymer and metal layer. This mechanism is shown in Fig. 6. At the same time, the passage of charge carriers through the polymer layer (with electrical resistance) creates ohmic heat, which is conducted to the other side (i.e. low temperature side). In other words, two opposite heat flows exist between polymer and metal in this experimental setting, one is from metal to polymer due to the passage of “holes” that results in the lower (than polymer) temperature of metal i.e. the cooling effect, the other is heat conduction from polymer to metal due to the temperature difference between them. To improve the cooling effect, theoretically, the first heat flow must be increased
by increasing the potential difference between the two materials used and the second must be reduced by better insulation. In our case, the potential difference between metal and polypyrrole (p-doped) powder was not large enough to produce a significant cooling effect (i.e. the first heat flow). The potential of metal is between that of p and n type semiconductors (or polymers). A junction formed between an n-doped and the p-doped polypyrrole would be ideal for this test, if an n-doped polymer sample could be made. Better insulation can be achieved by improving design of the experimental settings.

Fig. 5a. Peltier effect experiments. Temperature and current vs. time.

Fig. 5b. Resistance and current vs. time for polypyrrole

Figure 6. Peltier effect between a P type semiconductor and a metal

3. Conclusion

This preliminary study demonstrated that both the Seebeck and Peltier effects can be achieved by using conducting polymer materials, so that it is possible to make a cooling fabric from conducting polymer coated fibres. However, a practically useful cooling effect has not been achieved yet by using the current conducting polypyrrole fibres due to their electrical instability, insufficient dissimilarity in electrical properties and the unideal set up of testing rig. The current polymers used are more like a P type semiconductor materials. Therefore further research should focus on the development of N-type conducting polymer fibres and on rendering the conducting polymers more electrically stable especially under high temperatures. Future work will focus on
synthesising conducting polymers, which will overcome problems encountered in achieving a satisfactory temperature difference and to achieve a more significant and practically useful cooling effect.
Acknowledgements

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References

Figure and Table Captions

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Table3 . Results showing the existence of Seebeck effect

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Table 5. Results showing the existence of Seebeck effect

<table>
<thead>
<tr>
<th>Sample</th>
<th>ΔT (°C)</th>
<th>ΔV (mV)</th>
<th>R (Ω)</th>
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<tbody>
<tr>
<td>1</td>
<td>55</td>
<td>0.022</td>
<td>5300</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>0.058</td>
<td>587</td>
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</tbody>
</table>

ΔT: the temperature difference between hot and cold side
ΔV: the thermoelectricity produced at ΔT
R: the resistance of fabric
Table 6. Thermoelectricity Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermoelectricity (µV/°C)</th>
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<tbody>
<tr>
<td>Metal</td>
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</tr>
<tr>
<td>Semiconductor</td>
<td>100–1000</td>
</tr>
<tr>
<td>Conductive polymer fabric</td>
<td>~10</td>
</tr>
<tr>
<td>Fabric and metal</td>
<td>~150</td>
</tr>
</tbody>
</table>