Curvature Change Analysis of SMART Fibers used for Temperature Adaptive Insulation

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ABSTRACT

A thermally adaptive insulation has previously been developed by the US Army. The insulation is designed to expand at lower temperatures and shrink at higher temperatures. This is accomplished using multi-component polymer fibers that are spun in a side-by-side configuration that change curvature in response to a temperature change. The concept is based on Timoshenko's bi-metallic beam bending theory. In this work, a method for measuring curvature change of individual fibers over a range of temperatures was developed. Determining the curvature change of fibers is a necessary step in optimizing performance of the insulation as a whole. Curvature change is induced by suspending fibers on the surface of a cooling bath and changing the temperature. Taking digital images at discrete temperature intervals using a microscope and then extracting fiber curvature from the images provides a consistent method for determining curvature change.

Keywords: smart, fiber, curvature, polymer, cte

1 INTRODUCTION

In the past decade, a new concept was put forward by the US Army Combat Capabilities Development Command - Soldier Center (CCDC-SC), which utilizes multi-component fibers that deform in response to an environmental temperature change [1]. The fiber cross-section is composed of two or more polymers arranged in a side-by-side configuration. The polymers are selected so that there is a large mismatch between their coefficients of linear thermal expansion (CLTE), so that when exposed to a temperature change, internal thermal stresses are induced, leading to a change in curvature along the length of the fiber. This concept is based on the principle of bi-metallic strips which have traditionally been used in thermostats to detect temperature. One potential application for these fibers are thermally adaptive clothing battings. Battings are generally found in winter clothing as an insulative layer, traditionally their thickness and thermal resistance remain constant. When temperature responsive fibers are formed into a batting, the batting's thickness changes proportionally with temperature. This results from fibers interacting with each other as their curvature changes in response to temperature change. An increase in batting thickness leads to an increase in thermal resistance [2]. Designing battings to significantly increase thickness as the ambient temperature is decreased would allow clothing to be functional and comfortable over a greater range of conditions than is currently feasible with traditional clothing. The concept has already been qualitatively proven by observing an increase in batting thickness when temperature is decreased. However, until now, there was no way to quantitatively measure the curvature change of individual fibers, which is a crucial parameter in further developing and optimizing this technology. In this work, a method was developed to characterize the curvature of individual fiber filaments over a range of temperatures.

2 METHODS

Any change in temperature will induce a change in fiber curvature, which can be visually observed. However, due to the random three-dimensional orientations of these fibers along their full length, quantifying curvature change of a long fiber would be exceedingly difficult and complex. One way to minimize this complexity is to ensure that the fiber remains in a two-dimensional plane, without exerting any significant unbalanced external forces that can interfere with results. When these fibers are cut into short enough segments, they tend to conform to a two-dimensional plane. This makes curvature analysis much simpler since digital images of the fibers can be captured and analyzed. Fiber samples are suspended on the surface of a miniature variable temperature bath. The fiber remains at the surface of the liquid due to surface tension. This technique keeps fibers confined to a two-dimensional plane while introducing a uniform temperature to the entire fiber segment. One end of the fiber is attached to a glass slide held at surface level of the liquid to prevent translational motion around the bath. The fiber remains attached to the glass slide without any need for adhesive as shown in Fig. 1(a).

2.1 Temperature Control

Suspending the fiber in a liquid greatly improves heat transfer to the fiber compared with air as a surrounding medium. The liquid used in the bath is composed of a 50:50 (vol. %) mixture of DI water and ethylene glycol based anti-freeze to prevent freezing when the temperature drops below 0 °C. The bath temperature is lowered using a thermoelectric cooler controlled by a PID temperature controller. Temperature is sensed with a thermocouple positioned in close proximity to the fiber. Excess heat is removed from the hot side of the thermoelectric cooler by a heat exchanger connected with an isothermal heat rejection bath.

Temperature was varied from 20 °C down to -20 °C with images taken at every 5 °C interval. A cooling rate of approximately 7.5 °C/min was selected. This cooling rate was observed to be low enough to allow fibers to fully reach a steady-state curvature at each measurement interval.

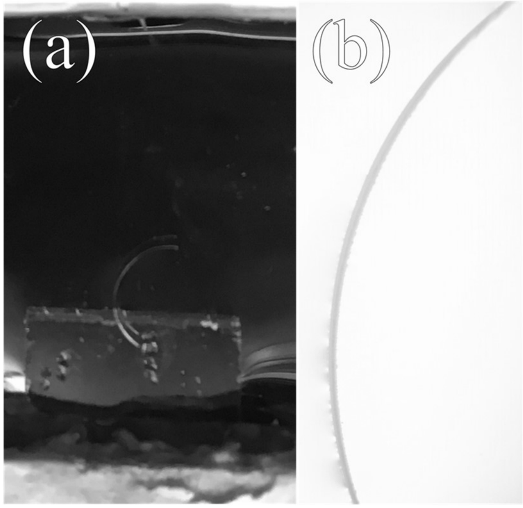

Figure 1: (a) Fiber suspended on liquid bath, fixed on glass slide; (b) fiber under microscope.

2.2 Image Capture and Curvature Determination

Images of the fibers were captured using an optical microscope configured with a digital camera (Fisher Micromaster 12-561; Amscope MU500). Fig. 2(b) shows an image of a sample fiber taken with this microscope setup. A section of Silicon wafer was added to the bottom of the fiber reservoir, creating a reflective background to prevent shadowing on images. A schematic diagram of the testing setup is shown in Fig. 2.

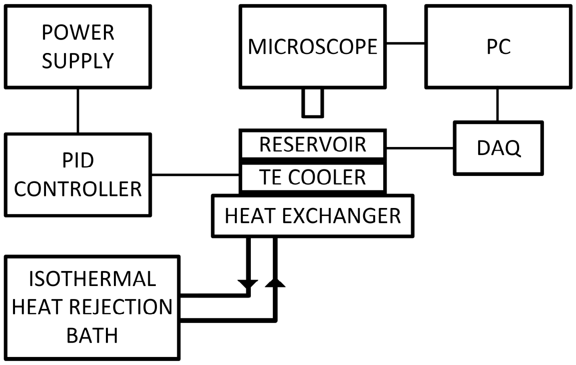

Figure 2: Schematic diagram of test setup.

After images of the fiber are taken, they are processed by finding the edge of the fiber and converting this to X-Y positional data. This data is scaled to size using a scale factor determined through calibration. Uniform curvature can be accurately approximated with as few as three discrete points that lie coincident to a curve [3]. The formula used to determine curvature (κ) is shown in Eqn. (1).

$$\kappa = \frac{1}{r} = \frac{4 \cdot A_{tri}}{L_{AB} \cdot L_{BC} \cdot L_{AC}} \tag{1}$$

Curvature is defined as the inverse of the radius of curvature, r. L_{AB}, L_{BC} and L_{AC} refer to length between respective points and A_{tri} is the area within the triangle shown in Fig. 3.

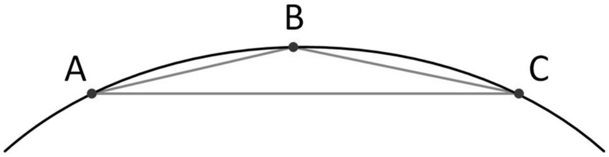

Figure 3: Points used for determination of fiber curvature.

Most fibers have a non-uniform curvature along their length; to account for this, the average value of curvature is recorded for each sample. This is accomplished by using an automated script to determine one thousand distinct values for curvature by using different points in Eqn. (1). These values are then averaged together to obtain the final value of curvature for a sample. This method is beneficial since it helps suppress error caused by local defects in the image or on the fiber surface.

2.3 Fibers

Four different fibers were provided by the US Army CCDC-SC. Two of the fibers are bi-component with a linear low density polyethylene (LLDPE) layer and an isotactic polypropylene (i-PP) layer. In these fibers, the LLDPE has a high CLTE while the i-PP has a very low CLTE. The other two fibers are tri-component, consisting of i-PP, syndiotactic polypropylene (s-PP) and an ethylene-propylene copolymer (co-EP). In these fibers, the s-PP functions as the high CLTE material and the co-EP layer is added to reduce interfacial stress. All fibers have a triangular cross-section, with the top layer defined as the top of the triangle, or section with a singular vertex. The bottom layer is the base of the triangle, with two vertices. Fibers ranged in diameters from 20-50 μm. The cross-sectional material proportions of the fibers are detailed in Table 1.

Fiber	Top Layer	Middle Layer	Bottom Layer
1	0.4 s-PP	0.2 co-EP	0.4 i-PP
2	0.4 i-PP	0.2 co-EP	0.4 s-PP
3	0.7 LLDPE	N/A	0.3 i-PP
4	0.5 LLDPE	N/A	0.5 i-PP

Table 1: Composition of fiber samples showing area fraction of each layer.

For each fiber, three different samples were selected. Samples with a highly uniform curvature, that appeared to be constrained in the two-dimensional plane were chosen. Each of the three samples were then subject to three experimental trials. This totaled nine trials for each fiber. Curvature measurements at each temperature were then averaged out of the three trials for each fiber sample.

3 RESULTS AND DISCUSSION

When curvature is plotted against temperature, there is insight into how a fiber will perform over a range of temperatures. The curvature results for fibers 1 and 2 over a temperature range of 20 °C to -20 °C are displayed in Fig. 4.

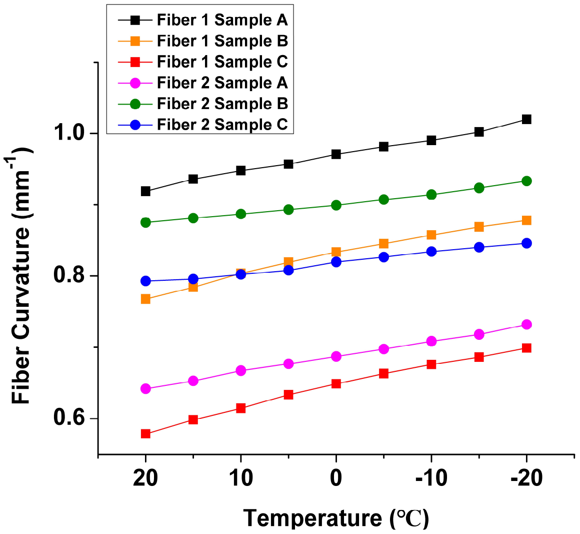

Figure 4: Curvature vs. Temperature for Fibers 1 & 2 (Tri-Component PP).

The data in Fig. 4 indicates that both fibers 1 and 2 experience a positive change in curvature over the temperature interval. In other words, as the temperature decreases, these fibers curl more. The curvature change is also linear for both fibers over the entire temperature interval. While the fibers behave in a similar manner, the slope for curvature vs. temperature seems to be steeper for the fiber 1, than fiber 2. It also appears that the total change in curvature for fiber 1 is higher than fiber 2 over the temperature range. From this data, it can be predicted that when fibers 1 & 2 are formed into an insulation structure, the battings would experience a linear thickness change over the entire temperature range.

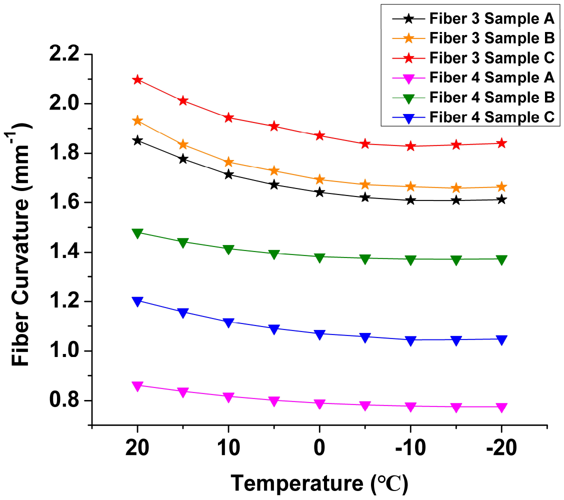

Figure 5: Curvature vs. Temperature for Fibers 3 & 4 (Bi-Component LLDPE/PP).

The data in Fig. 5 shows opposite behavior between fibers 1 & 2 and fibers 3 & 4. As the temperature decreases, fibers 3 and 4 are experiencing a decrease in curvature, or "straightening out" phenomena. In addition to this, the curvature vs. temperature slopes for these fibers are negative and steep in the 20 °C to 0 °C region, and approach zero after -10°C. Furthermore, the slopes for fiber 3 appear to become positive after -15°C, thus indicating that these fibers are beginning to curl in the opposite direction. These results suggest that there could be a cross-over in CLTE between the two components below -15°C. This means that the high and low CLTE components could be behaving opposite to their intended purpose at lower temperatures. CLTE is a temperature dependent property that can vary greatly over a range of temperatures in polymers, especially above and below their glass transition temperatures. These results predict that batting insulation made from fibers 3 & 4 would have a greater thickness change in the 20 °C to 0 °C range than they would below 0 °C. Below -10 °C, battings made from fiber 3 may even begin to reverse their thickness change direction.

To examine the overall performance of each fiber over the entire temperature range, curvature change/°C was determined for each fiber sample. This value is expressed as a percentage of the sample's initial curvature, in order to make an equal performance comparison between samples. Equation 2 shows how percent curvature change/°C was calculated over the entire temperature range.

$$P = \frac{\kappa_{Final}-\kappa_{initial}}{\Delta Temp} \cdot \frac{100\%}{\kappa_{Initial}} \qquad (2)$$

Fig. 6 depicts the overall curvature change for each sample between 20 °C and -20 °C.

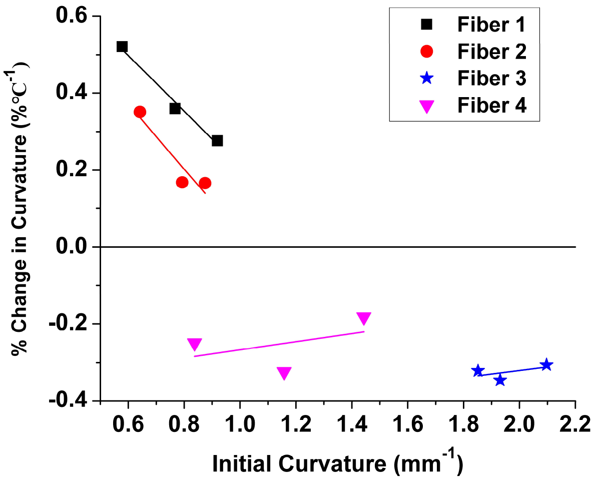

Figure 6: Overall change in curvature per degree as a percent of initial curvature.

Fiber 1 exhibited the highest overall curvature change over the temperature range. This fiber contained the crystalline, isotactic polypropylene on the bottom of its triangular cross-section, and the amorphous, syndiotactic polypropylene on the top of its triangular cross-section. Prior theoretical calculations performed by CCDC-SC concluded that this configuration would lead to the greatest ratio of moduli between the two components. This explains why it out performed its counterpart, fiber 2, which was formed with the opposite configuration. Additionally, there appears to be a trend between the initial curvature of fibers and their overall performance within the temperature range. This trend is stronger for fibers 1 and 2 than in fibers 3 and 4. It is unclear whether this is a geometrical effect occurring in each fiber, or a change in the molecular structure which is facilitated by the stress relaxation mismatch, leading to this initial curvature. Minimizing the stress relaxation mismatch and crimping phenomenon in the side-by-side bi-component fibers may be a way to combat this effect in future fibers.

4 CONCLUSION

An experimental setup has been developed to measure curvature change of temperature adaptive fibers used in thermally adpative insulation. Curvature change of fibers works on the same principle as beam bending of a bi-metallic strip consisting of a high CLTE material and a low CLTE material attached in a side-by-side configuration. In the new method, curvature measurements of individual fibers are made using comparision of digital images. Fibers float in an antifreeze/DI water bath and are subject to a change in temperature. Images are taken at 5 °C intervals and processed using an automated script to calculate average fiber curvature. Understanding how these individual fibers are behaving on the microscale provides insight as to how batting structures created from them will perform within a given temperture range on the meso-scale. Curvature change in individual fibers can be complicated to predict because of their complex processing and temperature dependent properties. Predicting batting growth becomes even more difficult due to the complexity of a non-woven batting structure. The experimental method presented is able to obtain consistent, accurate curvature change data of individual fibers to characterize and predict batting growth.

REFERENCES

[1] B. S. DeCristofano, S. A. Fossey, E. A. Welsh, J. Perry and D. Archambault, Temperature-adaptive Insulation Based on Multicomponent Fibers of Various Cross-sections, MRS Proceedings, 1312, 2011

[2] I. M. Stuart and B. V. Holcombe, Heat Transfer Through Fiber Beds by Radiation with Shading and Conduction, Textile Research Journal, 54, 149-157, 1984

[3] A. G. Belyaev, A Note on Invariant Three-Point Curvature Approximations, Surikaisekikenkyusho Kokyuroku, 1111, 157-164, 1999