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Measuring the Thermal Conductivity of Bulk Fibres

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Abstract—Polymers are generally known to be poor conductors of heat but few researches have had contradicting results on the thermal conductivity of spider silk. The disparity and controversy of the results obtained for similar spider silk by different authors is suspected to be due to varying test methods. Thus the aim of this research to create a new, uniform and varying means of testing thin fibres as well as validating the ability of the apparatus to measure the thermal performance of the fibres. A novel method of enclosing bulk fibres in Lego block sample holders was also developed. Polymer fibres such as *Bombyx mori*, Kevlar, LDPE, E-glass and carbon fibre were enclosed longitudinally in Lego blocks while the K-type thermocouples were used to sense the temperature change when the fibres were exposed to a cold metal rod enclosed in an ice bucket within a 10s time frame. Copper wire which has a more consistent thermal conductivity was used as the reference sample. The signals were sent to the computer through the LabVIEW software acting as an interface. The obtained data were analysed and used to generate curves that showed the gradual response of the fibres to the change in temperature. The thermal conductivity curves obtained were compared to already existing literature and the pattern gotten showed that the setup is suitable for measuring quantitatively the conductivity of various fibres.

Index Terms—Bulk fibres, Conductivity, LabVIEW, Polymers, Thermal performance, Thermocouples

1 Introduction

THE knowledge of the thermal properties of materials is essential in determining the status of a material as a conductor, semi-conductor or an insulator "[5], [15]". This property is dependent on environmental factors as well as the inherent properties such as temperature, crystallinity and orientation of the material considered [5]. Fibres are mostly poor conductors of heat and electricity at room temperature while a few others tend to show an increasing conductivity with temperature. No single instrument or method can measure accurately the thermal performance of the wide range of materials in existence and few but different techniques have attempted to thermally analyse fibres with the difficulties faced being that of handling and aligning as a result of their small diameter (usually between 5-12 microns) and anisotropic properties "[4], [7], [8], [10], [14], [17]". Individual fibres are more widely considered for thermal characterisation than the bulk due to the ease in which the samples are prepared though there is likelihood for the heat losses by convection and radiation to be more significant than the thermal conductance [8]. For bulk fibres though, apart from the challenges faced in sample preparation, there is also the possibility of air occupying a large space in the bulk as well as strong phonon scattering due to different interfaces and defects, thus lowering the conductivity "[5], [8].Earlier researches have characterised fibres as very poor thermal conductors with conductivity ranging from 0.1W/mK to 20W/mK "[2], [4], [5], [10]" but in recent times though, three different publications had contradicting values for the thermal conductivity and diffusivity of a particular natural fibre – the spider silk from the *Nephilla clavipes* spider, where thermal conductivity ranged from 0.2W/mK to 384W/mK "[2], [13], [18]". The wide variation in their measurements signifies a gap in knowledge and is a call for concern to further investigate newer methods that could be more consistent and reliable in measuring the thermal performance of fibres, thus aid in correcting this anomaly. The idea of testing various fibres with known thermal characteristics in a similar sample holder and with the same method will help to validate the instrument as well as uniformly account for heat losses by convection and radiation of the various samples. Literature have few details of measured thermal conductivity values of both artificial and natural fibres, thus some of the thermal conductivity values for the sample fibres were extracted from the CES Edupack software literature [2]. Table 1 below shows the measured thermal conductivity of various fibres from existing literature.

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Table 1: Thermal conductivity of fibres from literature

Fibres	Conductivity at room temp (W/mK)
Copper wire	401[19]
Carbon fibre	21 – 125 [2]

E-glass	1.2 – 1.35 [2]
LDPE	0.30 [2,7]
Bombyx mori silk	0.35 - 0.39 [2]
Kevlar	0.04 [2]

2 MATERIALS AND METHODS

2.1 Experimental methods

The test apparatus consist of seven sample holders for the various fibres investigated, an amplifier, resistors (two), thermocouples (two), supporting Lego blocks, metal rod, plastic separator and the Data Acquisition (DAQ) National Instrument. The electronic components which include the resistors, thermocouples and amplifiers were enclosed in transparent box as shown in Figure 1, with one end of the thermocouple attached to the amplifier to improve the signal generated before transferring it to the DAQ while the other end makes contact with the sample surface enclosed in a sample holder as shown in Figure 2. The fibres were stimulated by a cold rod and the response rate acquired by a DAQ instrument using a frequency and time to acquire data as 5 KHz and 10s respectively. Amplifiers were used to magnify the thermocouple signals so that it could be differentiated from electrical and environmental noise and each experiment generated 50000 data points that were analysed using Microsoft Excel and Origin Pro 8 software.

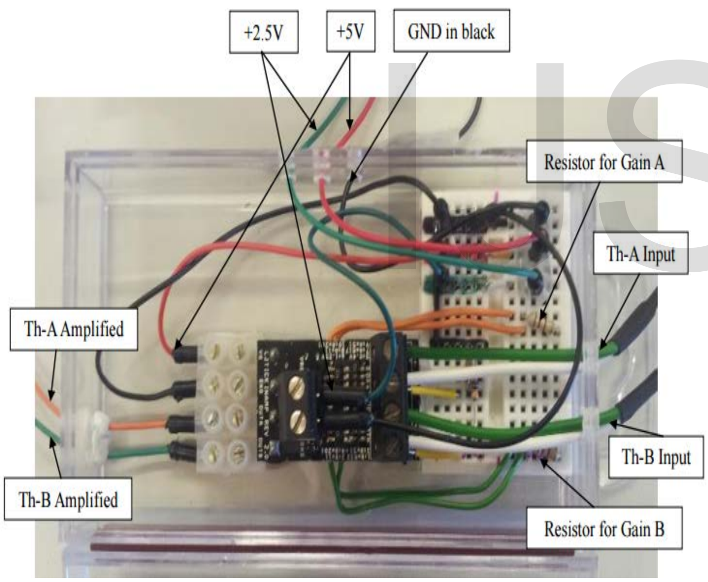

Figure 2: Electronic box

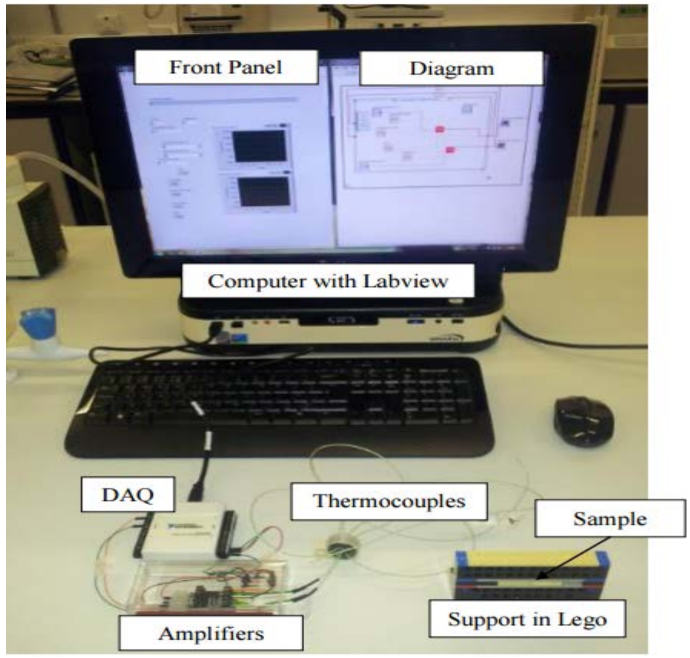

Figure 1: Experimental set-up

2.2 Sample Preparation

Kevlar, LDPE, E-glass, carbon and *Bombyx mori* fibres were all obtained from the composite laboratory and the Natural Materials Group (NMG) Laboratory both from the University of Sheffield. Each sample holder was made of two Lego blocks of equal length and width of 15.8mm and 4.3mm respectively and havin0g a 1.5mm cylindrical hole drilled through its centre (Fig 3a). The fibres were then tactically enclosed in the blocks by reeling them onto the semi-cylindrical groove of the drilled blocks when placed in opposite direction in order to successfully fill each half of the tube with fibres (Fig 3b). For the *Bombyx mori*, the unravelling was done as described by [1] and the reeling was performed with the aid of an electric motor while the artificial fibres were hand reeled due to their short discontinuous length. After successfully close-packing the semi-cylindrical tube with fibres (Fig 3c), the blocks were then reversed to their initial cylindrical form by holding the fibres in place with the aid of a twine while separating the fibre links (Fig 3d), thus forming a tube of 1.5mm enclosed with fibres (Fig 3e). Sharp laboratory blades were then used to level the fibres to the height of the tube and thus, a bulk fibre sample with a diameter of 1.5mm and a tube length of 15.8mm (Fig 3f) was prepared. With these fibres securely enclosed in the Lego blocks, a more rigid body was formed round the sample holder using other Lego blocks so that the weight of the metal rod could be contained (Fig 3g). The length of fibres required to fill this cylindrical tube is dependent on the diameter of the individual fibres and considering the *Bombyx mori* fibre with a diameter of 12microns, the total length needed to completely fill the drilled hole was 1745m using the equation 1 below, and this took approximately 3hrs to reel from the cocoon.

$$Length\ of\ silk = \frac{Tube\ area}{Filament\ area} X\ Tube\ Length \quad \text{...} (1)$$

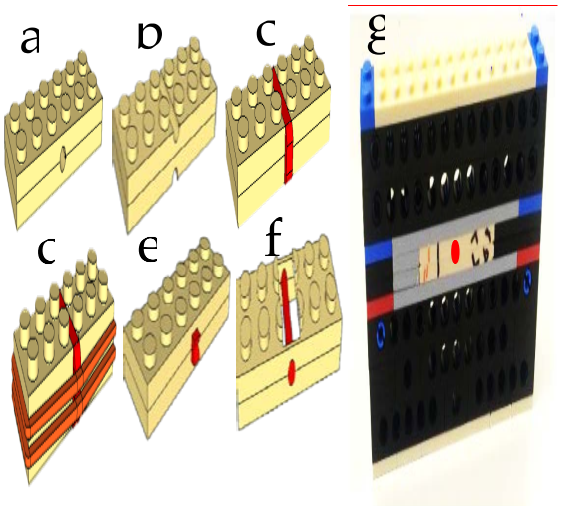

Figure 3: Sample preparation procedure: (a) 1.5mm drilled Lego block (b) Reversed Lego block (c) Fibres reeled unto the reverse block (d) Fibres held firm with the aid of a thread (e) Lego blocks reversed to the initial state after cutting the sides of the fibres (f) Sample holder with fibres levelled to the length of the block (g) The rigid block with test samples enclosed

2.3 Thermal characterization

The test sample was stimulated by a cold metal rod and the response rate determined using a K-type thermocouple which measures the change in potential difference at both ends of the fibres. They were held fixed to one surface of the fibres using an adhesive tack and other minute Lego block assemblies fixed to the supporting rigid block to give a good contact of the thermocouples with the fibres. The sensitivity of the fibres to the applied heat was also increased by using a silver paste thermal compound on the surface of the bulk. A metal rod maintained at a constant temperature of -23^{O}C in an ice bucket acted as the stimulant. This rod was attached to a retort stand which had the rigid sample holder fixed on its base and polystyrene material was fixed to the clamps of the stand to act as a passage for the rod as well as an insulator thus reducing heat loss from the cold rod during the experiment. Each experimental set-up had two sample holders containing the sample fibre to be tested and a reference copper wire fixed in the rigid structure. This reference sample was used as a correcting factor for the various samples with respect to uncontrollable environmental changes of the laboratory with the amplifiers having the function of magnifying the signals obtained from the thermocouples and as such differentiating noise from significant signals. The DAQ on the other hand had the function of acquiring the analogue signal from the thermocouples, converting it to a digital signal and storing it using the LabVIEW interface. The frequency and time to acquire each data for every test was 5 KHz and 10s respectively.

3 EXPERIMENTAL RESULTS

After repeated test being carried out, data were gotten and extrapolated to give the following figures below. Fig 4 shows the response rate of the various fibres to the cold source in a period of 10s. The Fig 5 below shows the response rate of the reference copper samples with the various fibres. Due to a slight deviation in their mode of response, the reference copper samples were normalized and the difference added to their corresponding test samples, thus accounting for the latency time and other uncontrollable factors. The viability of this set-up was determined by quantitatively analysing the response rate of the various fibres to the reference material – copper. This rate was then compared with the literature trend of decreasing/increasing conductivity for the various samples and this trend showed a high similarity with that obtained from literature thus validating the set-up.

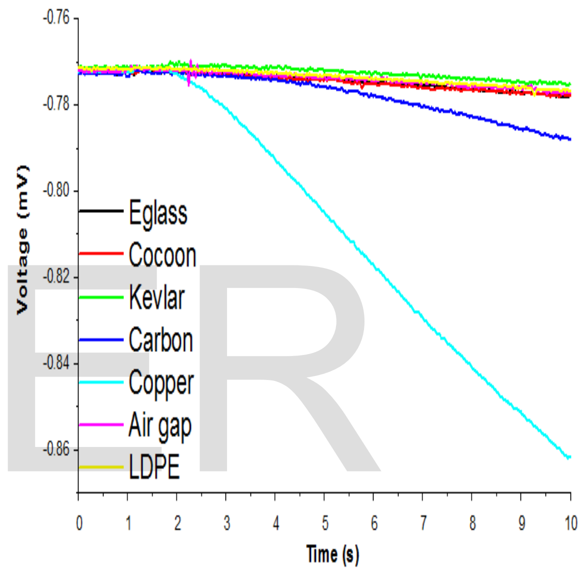

Figure 4 : Graph of Voltage against time for various fibres and their corresponding reference copper wire.:

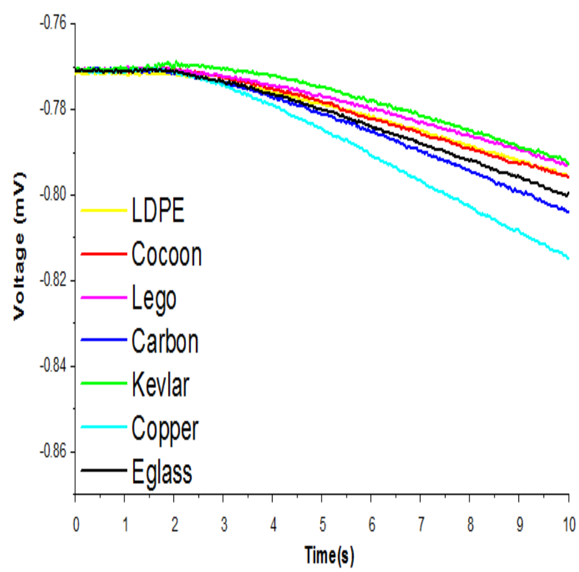

Figure 5: Reference copper samples: colours corresponds to the fibre samples

4 DISCUSSION

A temperature difference between the reference junction and the measured junction of a thermocouple creates a voltage and a change in voltage is a function of the Seebeck coefficient ($\Delta V = S\Delta T$) "[11], [12]". This is usually a non-linear which is negligible when dealing with small temperature changes [12]. This experiment was carried out in the laboratory at a temperature of approximately 23^{o}C and in addition, the K-type thermocouple which was used exhibits a fairly constant value of Seebeck coefficient over this temperature range, thus allowing the assumption of a linear relationship between the change in voltage and temperature to be valid [11]. Two test were run concurrently i.e., every sample with a reference copper wire and the results obtained were presented in an excel sheet and extracted to give Figure 4 showing a graph of voltage against time. The conductivity of a material from Fourier's law of heat conduction is dependent on the area, change in temperature and time. In this case, the time for collecting the data is the same and the area of the material was assumed to be the same, though it is not possible to get a bulk fibre without air trapped within it but this assumption is allowable since care was taken during sample preparation to fill the sample holders with the required length of fibres. Thus, the conductivity of a material here is a measure of the response rate of the material to the application of heat source and from quantitative analysis of the graph. The graph shows the copper wire having the greatest response rate which shows its superior conductivity. The carbon fibre also showed a distinct response rate different from other fibres which followed a very close trend showing their very low cooducivities as reported in literature.

In an attempt to take into consideration the effect of changing environmental factors on the results obtained, the data of the copper reference material from the seven different tests carried out were compared with each other and it was observed that they varied slightly amongst themselves (Fig 5). Considering the fact that the reference sample, copper will have the same curve under uniform operating temperature and condition, a correction factor was established to account for this deviation with respect to their corresponding sample fibres. This correction factor is an input to determine the latency time which in this context, is the time taken for the fibres to show a significant change in voltage when the heat source is applied to it. Due to the massive data points obtained from the experiment, it was difficult to obtain the latency time by visual inspection of the voltage-time curve and it was even more difficult for fibres without significant variations. Thus after a trial and error method, an ideal percentage increase of 2% from the initial voltages was used to obtain the latency time as shown in Table 2. The shorter the latency time, the more conductive a fibre will be and vice versa. The table shows that the latency for copper was 0.96s which means that the copper sample took approximately 0.96s to respond to the change in voltage at the opposite end which depicts its superior conductivity. This was closely followed by carbon fibre, LDPE, E-glass, Kevlar, cocoon and finally the air gap.

Table 2: Increasing thermal conductivity of fibres using latency time

Fibre	Latency time (s) (Fibres)	Latency time (s) Cu Ref	Normalised Time (s)	Calculated Latency time (s)	Actual latency time (s)
Lego	3.16	2.45	0.90	4.12	2.12
Coc	2.45	2.45	0.96	3.41	1.41
Kev	3.22	3.41	0.00	3.22	1.22
E-Gls	1.82	2.21	1.20	3.02	1.02
LDPE	2.06	2.45	0.96	3.02	1.02
Carb	1.82	2.21	1.20	3.02	1.02
Cu	2.00	2.45	0.96	2.96	0.96

5 CONCLUSION

In summary, the thermal conductivity apparatus that was designed for this experiment was efficient in obtaining data and though specific values for this property was not obtained for this experiment, by quantitative analysis, it is visible that the data obtained from the set-up conformed to the values of existing literature. The uniqueness of this test method is the uniform test environment for all samples which would account for the losses by convection and radiation. The difficulty encountered in this set-up is the preparation of the sample bulk fibres and this is understandable because of the delicate nature of handling fibres. From the results obtained above, this apparatus would be best suitable for comparative analysis on the thermal performance of fibres to determine the status of a material as a conductor, semi-conductor and an insulator. The major drive behind developing a new set of experiment which arose as a result of the disparities arising from the conductivity of the spider silk can also be validated through this method, though the major difficulty will be getting the spider silk in bulk to fill the test sample holder. It will be best to test materials with a wide difference in the conductivity. If the spider silk is a good conductor as proposed by some researchers, it will follow closely the trend of the copper wire but if it is not a very good conductor, it would follow the trend of the carbon fibre and if an insulator, it would follow the trend of the other insulating fibres tha were shown in the graphs.

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