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Biomimicry of Fibrous Materials: The Thermal Conductivity and morphology of Man-Made and Natural Fibrous Materials ⋆

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Abstract

With the aim to gain an appreciation of how nature insulates animal bodies with furs, in this exploratory study we investigated the TC and morphology of natural and synthetic fibrous materials. Specifically, we present our experimental observations on coyote, wolverine, and synthetic furs, as well as Polyacrylonitrile (PAN) nanofibers and knitted fabric. The TC was measured at a temperature range of −10 °C to 65 °C. The natural furs consist of fibers with different diameters and cuticular scale patterns. They form core-shell fibers with complex cellular structures in the core. The natural furs have lower TC compared to that of the synthetic fibrous structures. The coyote furs have the lowest TC value of ∼ 0.046 W/mK at −10 °C. While the TC of all of the samples decreased with temperature, the TC of the natural furs decreased at a higher rate and showed a different behavior with temperature, compared to the synthetic fibrous materials.

Keywords: Thermal Conductivity; Natural Fur; HotDisc Method; Heat Transfer; Fibrous Materials

1 Introduction

Nature has inspired humans to develop novel materials and devices since the beginning of time. The idea of biomimicry has become even more attractive in the recent years as a result of advancement in scientific tools in revealing nature's designs for optimal performance. For example, by modulating the appropriate level of thermal conductivity (TC), breathability, self-cleaning, self-healing, energy conservation, hydrophobicity, and adhesion, many species have protected

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themselves and made life sustainable in harsh environments. Thermal conductivity is one of the important physical properties that influences many applications of fibrous structured materials.

It was shown that the thermal conductivity of polymer fibers along its axis direction is usually higher than that for the bulk material [1]. The thermal conductivity of polymer fibers depends on the crystalline grain orientation, molecular alignment, and crystallinity of the polymer. Several groups have studied the thermal conductivity of single fibers and they measured very high thermal conduction along the fibers [1-6]. For example the thermal conductivity of PEO NFs was improved by a factor of 150 times over bulk polymer due to increased molecular alignment and crystalline grain orientation [7].

Through evolution, many animals such as wolverine have developed furs that possess appropriate properties and protect them in different circumstances and environments [8]. Fibrous materials with low TC are extremely important in practical application, particularly for the fabrication of lightweight and efficient clothing and protective media. Nature would be a great source of inspiration for fibres designed for cold weather. We have recently studied the feasibility of measuring the TC of fur samples [9-11]. A one dimensional heat transfer model for wolverine hair was also reported by our group. Liwanag et al. have studied the thermal properties of natural furs of mammals, with a particular focus on comparing and analyzing the fur of marine and terrestrial organisms [12]. They showed that the ability to form an insulating layer of air between their fur plays an important role in decreasing the TC of marine animals in arctic water. Hes' group has conducted extensive studies on the thermal properties of artificial and natural furs and analyzed them in terms of their structures and materials [13]. They concluded that the applied pressure had a significant effect on the TC of the fur samples. At no applied pressure, the fur samples with fine fibers had a lower thermal conductance compared to the fur samples with thicker fibers i.e. larger diameters. They attributed this to the fact that thinner fibers were able to absorb more infrared radiation and lose less heat by conduction. On the other hand, under applied pressure, the furs with very thin fibers showed a higher TC compared to the furs with thicker fibers. They argued that the contact area of thin fibers greatly increased upon compression, resulted in an increase of the TC with pressure. Gibson et al. have shown that a major component of thermal conductivity in fibrous materials is a result of radiation heat transfer. It was shown that radiation heat transfer varies with the diameter of fibers and for each particular material there is an optimum fiber diameter where radiation heat transfer is minimum. In addition, the bulk density and porosity of the fibers was another factor that effected the TC of fibrous materials as well. They concluded that the effect of fiber diameter is much more significant on TC at lower bulk densities. At low bulk densities, TC decreases with fiber dimeter. Due to the large separation between fibers, the majority of heat transfer occurs through thermal radiation as opposed to conduction.

Fibrous materials with low fiber volume fraction have recently attracted a lot of interests, as they are light and efficient thermal insulation materials. Hence, they have the capability to minimize both thermal conductance, and weight. While there are several reports on the TC of fibrous materials, the variation of the TC of fibrous materials with temperature is still not well known. It is important to know the performance of insulation materials at different temperatures to be able to design appropriate clothing and protection media for different environments. In this preliminary study we present our experimental observations of the TC of natural and man-made furs at different temperatures, from -10 °C to 60 °C.

Several techniques have been developed for measuring the TC of materials that could be categorized in two main groups, steady state and non-steady state or transient techniques [14]. The