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Design and optimization of a photo-thermal energy conversion model based on polar bear hair

Hao Jia, Jingjing Zhu, Zhaoling Li, Xiaomei Cheng, Jiansheng Guo*

Key Laboratory of Textile Science and Technology, Ministry of Education, College of Textiles, Donghua University, Shanghai 201620, China

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ABSTRACT

A design and optimization of photo-thermal energy conversion components using textile fiber is very important in solar thermal energy conversion technology. In this study, an innovative bionic photo-thermal energy conversion model based on polar bears hair (*Ursus maritimus*) energy conversion mechanism has been explored and optimized. Besides, a processing technology and wave guiding principle using this new model were investigated to enhance the solar-thermal energy utilization property. Specifically, the fluorescent property, reflectivity and photo-thermal conversion property of the selected fabricating materials were measured and demonstrated in detail. The experimental results showed that this proposed new model worked well to design high-efficiency photo-thermal energy conversion devices. Also the bionic materials exhibited a high photo-thermal converting efficiency as well as outstanding heat insulation properties.

1. Introduction

Solar energy has long been regarded as an essential and renewable resource of energy for relieving current energy crises. Regarding the thermal energy, plenty of relevant research work on exploring new and more effective solar thermal conversion devices have been done by many researchers [1]. The theory of solar energy conversion based on polar bear hair model was proposed several decades ago [2]. Polar bear hairs have been focused on mainly because of their significant structural mechanism and outstanding optical properties [3–6]. Observations of individual hairs under a light microscope indicate that they are hollow in structure along their length and nearly transparent with membrane structure [7]. Air can be captured not only in the hollow structure of each hair, but also among the hairs, which allows the heat radiation go through, however, the convection and conduction of the heat are blocked. It should be worth noting that the inner core is very rough with respect to the smooth outer surface. It has been demonstrated that the base of capillary has an ability to collect light energy, and the rough inner surface of hollow core can double the collection efficiency [8]. Specifically, the scattering process at the core of the capillary thus aids the coupling of light into the glass tube. Hence, a complex light collection mechanism begins in the hair core by two coupling processes, namely light scattering process and combined scattering-fluorescent process.

Besides, the polar bear hairs can also guide light transmission like optical fibers by trapping more sunlight, especially in the wavelengths of ultraviolet radiation [9]. This continuous process repeats all the time and then leads to the guiding of light toward the polar bear's black skin where it is absorbed and finally converted into heat. Combining the compelling properties of excellent photo-thermal conversion and heat insulation, polar bear fur plays vital role in energy harvesting and reserving, which serve and work like transparent thermal insulation materials. Therefore, these unique properties of polar bear contribute largely to the polar bears' survival in such an extreme environment on earth.

Inspired by the structures and function of polar bear hairs, considerable efforts have been committed in recent years to develop new kinds of fibers and thermal collectors to collect solar energy [10–12]. The main function of solar collector components are transforming the incident solar irradiation into heat and meanwhile suppressing heat losses caused by thermal radiation [13,14]. In addition, some scientific studies have tried using optical fiber bundle to transfer the concentrated solar energy to the load in high-temperature solar thermal applications [15]. And it has been demonstrated that PMMA fiber bundle has advantages in terms of high transmission efficiency compared to traditional heat exchangers.

Nowadays, textile based roofs, which consist of coated fabrics, are commonly used in the fields of football or tennis arenas, airport malls, and hangars [16]. Especially, solar collector tools are expected to be an innovative functionality of the textile roofs in the future [17,18]. Relevant research has enriched the prospect of technical textile products and such currently obtained progress

* Corresponding author.
E-mail address: jsguo@dhu.edu.cn (J. Guo).

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provides a good foundation for developing novel flexible textile solar collectors. It was demonstrated in previous [19] literature that modification of synthetic fiber by some treatment methods can lead to a higher photo-thermal conversion efficiency. To be specific, coupling of combined more scatter light and fluorescence effects contribute greatly to the sunlight utilization of fibers. Since most of the light is emitted at angles more grazing to the surface than the critical angle for total internal reflection, the light thus can be trapped in the collector and will propagate by successive reflections to the edges, where it can be coupled out [20,21]. As a consequence, it is an effective approach to modify the wave guiding fiber with fluorescent dyes in the aim of improving its photo-thermal conversion properties.

In this paper, a new photo-thermal conversion fiber structure based on polar bear hair was proposed and its characteristics have been investigated in detail. The innovative fiber structure has a relatively low transparency in the IR and a comparatively high thermal energy release due to Stokes shift. In addition, an advanced modification method of internal core coating for wave-guiding fiber was introduced. Specifically, the core part of wave-guide fiber is more close to the real polar bear hair after irregular internal coating. It has been proved that the expected solar harvesting performance was achieved by using polar bear hair fiber model with improved structure through experiments. This study has made some advance in the area of solar energy harvesting devices and could have possible positive impact on the future research.

2. Design of photo-thermal energy conversion fiber

In order to manufacture the described light trapping mechanism, fibers were required to be modified for better performance both in the direction of a luminescence gap and a broader fluorescent band. Referring to Tribusth's model of polar bear hair [8], three different geometry structures of photo-thermal conversion fiber models were designed by Bahners [22] and they were schematically illustrated in Fig. 1(a–c). It was demonstrated that the envisaged optical effect could be achieved by coating wave-guide fiber with an optically active thin layer in the form of fluorescent dyestuff dispersed into a coating matrix.

Nevertheless, only one proposed model (Fig. 1c) was analyzed for research among these models of technical fibers. The obtained previous research was only limited in the fibers' surface coating and the employed modification method was not fully comprehensive to mimic the structure of polar bear hairs. Moreover, the used methanol in some research groups [22] was not eco-friendly, especially considering that it was harmful to human beings' health. Hence, we proposed a new geometry model of photo-thermal conversion fiber (Fig. 1d) to mimic the polar bear hair.

The light collection efficiency of the fibers under this model can be improved by scattering scratches of the fiber core through combining both light scattering and fluorescent processes in the same time. Specifically, the rough inner surface is responsible for scattering phenomena of light and the wave-guiding property can guide them into absorption end where being converted into thermal energy. The total reflection principle of wave-guiding materials is related to its refractive index. According to Snell's law, all the photonic will be total reflected when the incident between material's interface and air is greater than the critical angle [14]. The critical angle is defined as

$$\theta_c = \sin^{-1}\left(\frac{1}{n}\right), \tag{1}$$

where n is the refractive index of waveguide materials. This means that approximate 75% of the photons will be total reflected by PMMA fibers as the refractive index of PMMA is 1.49. Besides, due to fluorescent process, the spectra of sunlight can be transferred from lower wavelength into higher wavelength by the introduced dyestuffs. Also it is widely known that the light of higher wavelength possesses stronger photo thermal effect, namely their light energy can more easily be absorbed by objects and converted into internal energy of lattices' thermal motions due to the lower penetrability [23,24]. Therefore, solar energy harvesting performance can be improved to a great extent, considering the fluorescent process is an exothermic reaction as well.

It should be noted that suitable absorption material can converse the light energy into thermal energy more effectively, as this kind of fibers can generate uniform radiance from the broad solar spectrum. The described experiments (Fig. 1) showed that the scattering processes and fluorescence processes exhibited the same order of magnitude in the area of coupling the initial light into the inside of fibers' conducting structures [8]. Moreover, the thermal insulation property can be drastically enhanced by its still air inside thanks to the host fibers' hollow structure. For the following experiments, fibers were prepared according to the model sketched in Fig. 1c and d, namely finished with an optically active coating and inner incompletely filling, and thus successfully mimicked the polar bear hair.

3. Experimental

3.1. Materials

According to the schemes shown in Fig. 1c and d, experiment fibers were selected to be used as commercial PMMA tubes supplied by GoodFellow GmbH, Germany. For Fig. 1c, the diameter of fibers (ME307902) was 2 mm. However, as the refractive index varies over the fiber diameter, two types of hollow tubes (ME30SH02&ME30SH03) have been selected to be used for Fig. 1d model, which the external diameters were 2 mm and 3 mm, respectively. Here, PMMA tubes were chosen in these experiments because of their good wave guide properties, high transmittance and easy fabrications. In addition, the relatively larger radius of fibers was employed to make experimental operation much more easily. Also, the modification effect can be remarkably enhanced by using this kind of PMMA tubes. Consequently, the mentioned materials were utilized, rather other optical fibers in the following experiments.

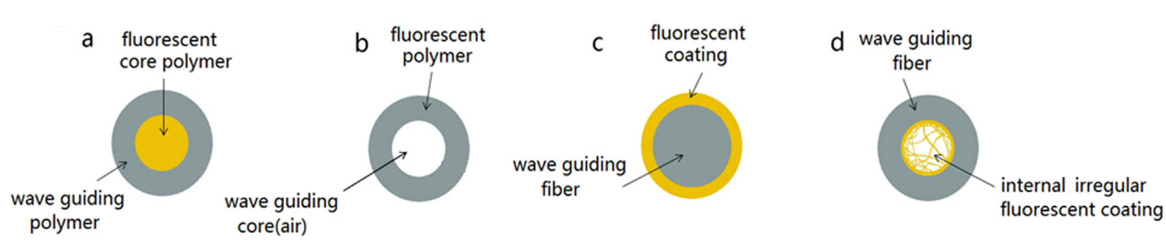

Fig. 1. Design concepts of optically active fibers: (a) Bi component fiber; (b) hollow fiber; (c) surface coated fiber; (d) internal coated hollow fiber.