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Bionic Leaves Imitating the Transpiration and Solar Spectrum Reflection Characteristics of Natural Leaves

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Abstract

A novel thin film organic bionic leaf was prepared by a solution-casting method to simulate the thermal effect of transpiration and solar spectrum reflection characteristics of plant leaves. The main components of the bionic leaf are polyvinyl alcohol (PVA), lithium chloride (LiCl) and chromium sesquioxide (Cr_2O_3). The thin film was modified by chemical cross-linking, and its surface was modified by alkylsilane to prevent excessive swelling. The thin film can simulate the thermal effect of natural leaf transpiration because that the hygroscopic PVA and LiCl can absorb and desorb water due to the high and low humidity of the ambient air at night and day, respectively. The thin film has the similar solar spectrum reflection characteristics to those of plant leaves due to the Cr_2O_3 and the water content of the hygroscopic materials. The measured diurnal maximum radiation temperature difference between the organic bionic leaf and the *Osmanthus fragrans* leaf was only 0.55 ˚C. In addition, the solar spectrum reflection measurements revealed that the organic bionic leaf could precisely simulate the key solar spectrum reflection characteristics of plant leaves.

Keywords: thin film organic bionic leaf, thermal effect, transpiration, solar spectrum reflection

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1 Introduction

Many creations and inventions were inspired through understanding of the compositions, structures or special properties of plant leaves. Super-hydrophobic materials were prepared by UV-curable nanocasting[1], sol-gel[2] and alkylsilane modification[3], among other methods, inspired by the hydrophobicity of some plant leaves. The water and pigments of plant leaves significantly affect their spectral characteristics[4,5]; and the leaves' spectral characteristics are related to their photosynthesis and some biochemical information[6,7]. To describe the spectral characteristics and biochemical information of the plant leaves accurately, different physical models were developed to simulate the leaves' spectra, such as the radiative transfer model[8] and the prospect model[9]. Based on the composition of angiosperm leaves, Yang *et al.*[10] designed a bionic leaf composed of a chlorophyll/polyvinyl alcohol (PVA) film, a sealed bag of polyvinylidene chloride (PVDC) containing pure water and a piece of paper to simulate the solar spectrum reflection characteristics.

The reported work showed that introducing suitable pigments and moisture into materials or systems made it possible to simulate the solar spectrum reflection characteristics of plant leaves. However, the structure of the proposed bionic leaf was rather complex. In addition, the reported investigations on plant leaf bionics mostly involved the simulation of the structural features or compositions of the plant leaves and rarely involved the simulation of the physiological activities of the leaves. Transpiration is one of the basic physiological activities of plant leaves. In the 1960s, Gates[11] found that transpiration could decrease the temperature of a plant leaf. The transpiration rate of a plant leaf increases with the ambient temperature, thus increasing the cooling capacity of the leaf[12]. In our previous work, we found that the transpiration of a plant leaf could dissipate approximately 32.9% of absorbed solar radiation and could reduce the plant leaf temperature by 8.2 ˚C on a calm day[13]. Thus, to simulate the thermal infrared characteristics of a plant leaf, transpiration should obviously be

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taken into account. Hygroscopic materials can absorb water vapor from the air at high ambient humidity and desorb water at low ambient humidity. Usually, the ambient relative humidity is higher in the night and lower during the daytime. Therefore, hygroscopic materials can absorb water vapor at night and desorb water during the daytime, which can be used to simulate the thermal effect of leaf transpiration.

With recent developments in membrane technology, hygroscopic polymer membranes have been used in water vapor absorption. Various materials have been tested, such as polyvinyl alcohol[14,15], Nafion[16], polyimide[17], sulfonated polyimide[18] and polydimethylsiloxane[19]. The hygroscopic polymer membranes can absorb water vapor because that they have a large quantity of hydrophilic groups such as -SO_3H, -NH_2, -COOH and -OH. In this work, based on hygroscopic polymer membranes, we proposed a novel thin film organic bionic leaf that could simultaneously simulate the thermal effect of transpiration and the solar spectrum reflection characteristics of plant leaves. The main components of our organic bionic leaf are hygroscopic polyvinyl alcohol (PVA), lithium chloride (LiCl) and chromium sesquioxide (Cr_2O_3). The solar spectrum reflection characteristics and diurnal radiation temperature characteristics of the organic bionic leaves were measured and compared with those of natural leaves.

2 Experimental

2.1 Design and preparation of the thin film organic bionic leaf

To prepare the thin film organic bionic leaf, green pigments (Cr_2O_3) and the hygroscopic materials PVA and LiCl were selected as the main components. PVA has good membrane-forming and mechanical properties, and it can absorb water vapor because of its large quantities of -OH groups. PVA membranes can absorb 0.4 $g \cdot g^{-1}$ water vapor at 25 ˚C and 95% relative humidity[15]. However, it tends to swell and even dissolve after absorbing a certain amount of water vapor. Therefore, the PVA membrane must be modified through appropriate methods. A PVA membrane is usually modified by cross-linking to improve its stability in water and the usual methods are chemical cross-linking and radiation cross-linking[15,20–22]. In this work, chemical cross-linking was selected to modify the PVA membrane. L-malic acid was used as the cross-linking agent, and acetic acid was used as the catalyst agent. In this way, the PVA membrane could be cross-linked by an esterification of PVA and L-malic acid[15]. However, during the cross-linking, the hydrophilicity of PVA was sacrificed to a certain extent because that the number of -OH groups was reduced. On the other hand, LiCl is a highly hydrophilic salt that can absorb 7.9 $g \cdot g^{-1}$ water vapor at 25 ˚C and 95 % relative humidity[23]. When dispersed in a PVA membrane, LiCl can increase the membrane hydrophilicity. The Cr_2O_3 powder was selected because it has the similar spectral reflection characteristics in the range from 300 nm to 1300 nm with those of natural leaves. In addition, the organic bionic leaf can absorb moisture, which helps simulate the absorbing features of water from 1300 nm to 2500 nm. Thus, the organic bionic leaf would be able to simulate the key solar spectrum reflection characteristics of natural leaves. The hydrophobic surface of the organic bionic leaf was obtained by octadecyltrichlorosilane (OTS) modification to prevent the organic bionic leaf from being wetted by rainwater.

The organic bionic leaf was prepared by a solution-casting method. The preparation of the PVA casting solution is similar to that elucidated by Zhang *et al.*[15]. A certain amount of PVA 124 (GR) powder was dispersed in hot deionized water at 90 ˚C and subsequently stirred and heated for approximately 2 h until the PVA was completely dissolved. A certain amount of cross-linking agent (L-malic acid AR), catalyst agent (acetic acid AR), anhydrous LiCl (AR) and Cr_2O_3 powder were dispersed in the PVA solution to form the casting solution. It took approximately 0.5 h to make these different compositions completely dissolve to form a homogeneous solution by stirring at 70 ˚C. Then, the casting solution was vacuumed and placed still for debubbling. After that, the casting solution was placed into an electric thermostatic drying oven (DHG-9101-1SA) for cross-linking at 100 ˚C for 1 h. The cross-linked casting solution was then coated on a polytetrafluoroethylene (PTFE) plate and placed into a constant temperature and humidity test chamber (STIK CTHI-150B) to form the PVA membrane at 60 ˚C and 10% relative humidity for 6 h. A hydrophobic surface of the PVA membrane was obtained via immersion into hexane with 1 wt% OTS at room temperature for 30 min. The compositions of the casting solution are listed in Table 1. Four types of PVA membranes, *i.e.*, MP, M0, M1 and M2, representing pure PVA