Advanced Film Thermal Protectors for Electronic Devices

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ABSTRACT

We proposed a novel design of thin film thermal diode based on Patent (U.C. Case No. 2012-130) by utilizing the fundamental of two-phase phenomena in heterogeneours porous media. In this study, we test MWCNT buckypaper as a potential proposed thermal diode. We found that the thermal conductivity of a dry sample is low in the through-plane direction, about 0.25 W/m K. Adding water signifantly increases the thermal conductivity by over 10 times. Carbon paper's diodicity is also presented for comparison, which shows 1.5-2.5 in diodicity. Thus, by controlling dry/wet media one could design a thin film to alter the thermal conductivity in two opposite directions, and achieve thermal protection for eletronic devices which require heat dissipation in operation and heat protection when temporarily subject to a hot enviroment.

Keywords: thin film, diode, heat transfer, buckypaper, MWCNT

1 INTRODUCTION

There are various applications in which it would be desirable to control the direction of heat transfer. For example, in the case of firefighter clothing and protective gear, it would be desirable to enable heat from within the clothing/gear to escape without enabling heat from the environment to enter. While such control would be useful in various applications, there are few devices that enable it.

We recently filed a Patent (U.C. Case No. 2012-130) to control the direction of heat transfer through thermal diode design. More particularly, the thermal diodes can be used to enable heat transfer flow in a first direction but inhibit heat transfer flow in a second direction opposite to the first direction. In this way, the thin film can be installed over an electronic device to prevent heat inflow when subject to high temperature enviroment (e.g. fires or hot conditions) and permit heat outflow to dissipate the heat generation by the electronic device to avoid heat accumulation. The fundamental of the proposed diode design is two-phase flow in thin porous media. This is different with those designs based on phonon rectification [2-4], which is usually solid and unable to be fabricated flexible. The proposed patent is based on either rigid or flexible porous media, enabling a wide application for thermal management and thermal protection.

For electronic devices, heat is produced during their function/operation, which can be dissipated via a wet diode. The water injection can be realized by putting liquid water in touch with the sample (the capillary action will absorb the water rapidly). When the electronic device is subject to hot enviroments, e.g. fire condition, the water will be vaporized automatically/rapidly, slowing down the heat inflow to the electronic device. This advanced function is imporant to several devices sensitive to temperature or military devices that may be used in battle fields, including those used in airforces.

In this study, we tested a simple idea of this patent design by measuring the thermal conductivities of carbon papers and MWCNT bulkypapers. Experimental follows our previous design on thin film thermal codncitivity measurement [5]. Both dry media and wet media of various water contrent were measured. Compression impacts were investigated as well. The focus is placed on the difference between a dry and wet medium. In practice, the thin film protector will be dry when subject to fire or high-temeprature enviroment; and be wet when heat dissipation is required.

2 EXPERIMENTAL

To investigate the dry/wet sample conductivity under compression, a special experimental setup was designed, following our previous work [12] as shown in Figure 1. The device consists of a sample housing that prevents liquid loss due to leakage or evaporation, a load cell that measures the compression force over the sample, a cooling plate for heat removal, an electric heater for heat addition, two metal end plates for holding the sample, and insulation enclosure to prevent heat loss. The heat flow rate through a sample was obtained through the temperature measurement by thermal couples. The thermal conductivity was then determined through Fourier's law. In experiment, each measurement took about one hour to reach operation steady state, after which the temperatures were measured.

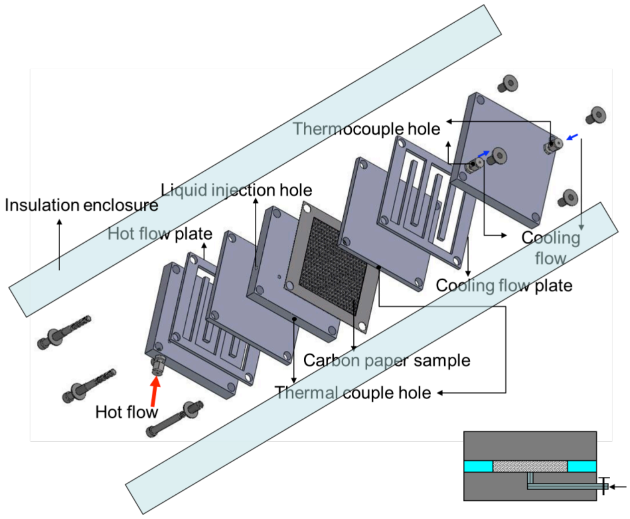

Fig. 1. Experimental set up to measure the thermal conductivity of dry/wet thin film [5].

The MWCNT buckypapers were purchased from NanoLab (NanoLab Inc.) The buckypaper fabrication follows the standard papermaking method: MWCNTs are first suspended in water using a surfactant Nanosperse AQ with adequate sonication. The sonicated solution yields a stable nanotube suspension and is then filtered using a filter under pressure. The MWCNT layer forms and is peeled from the filter. Due to the papermaking method, most MWCNTs in the buckypapers are randomly aligned in the lateral direction, see Figure 2. The buckypaper sample was used with the dry sample thickness of 140 µm and density of 733 kg/m^3. This kind of the solid matrix usually yields a highly tortuous structure for heat flow, in which the through-plane heat flow relies on the contact points among CNTs. Thus, the thermal contacts play an important role in the overall heat flow [6]. Toray carbon papers follow a similar structure with the solid matrix's tortuosity reported as high as 13 [7], see Fig. 3.

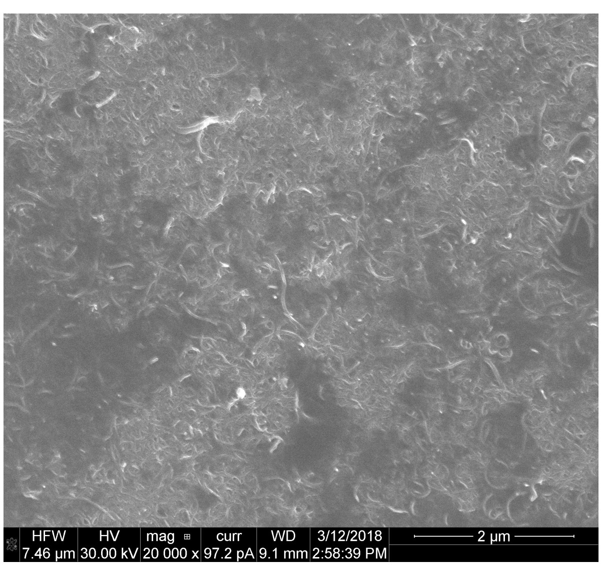

Fig. 2. SEM of MWCNT buckypaper.

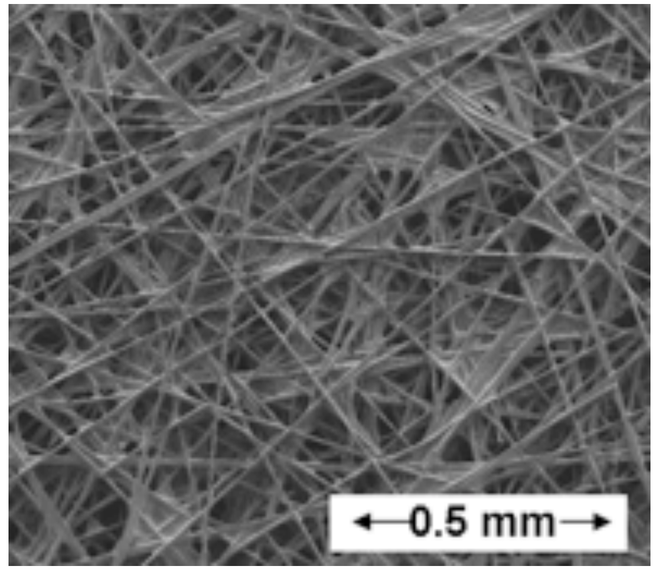

Fig. 3. SEM of Toray carbon paper.

3 RESULTS AND DISUSSION

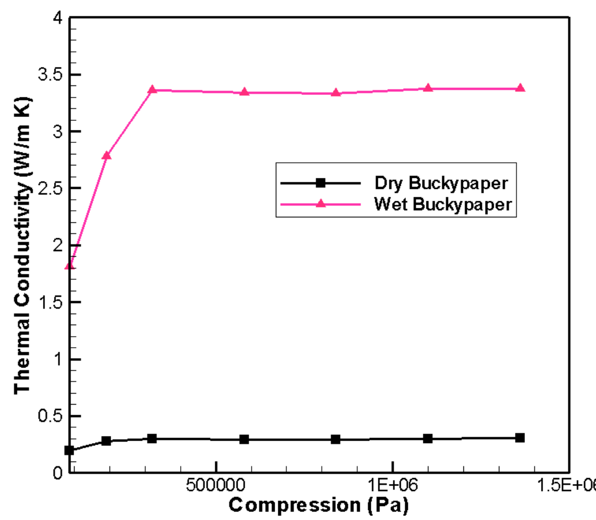

Fig. 4. Thermal conductivies of dry/wet buckypaper under various compression.

Fig. 4 presents the sample thermal conductivity under varying compression, showing that the conductivity increases rapidly upon initial compression for wet buckypaper. Two major mechanisms may be responsible for the observed increase, including the increased number of the CNT-CNT contacts and enhancement in thermal contact. For the former, a portion of neighboring CNTs may not directly touch each other, especially in presence of interstitial liquid which may lead to swelling. External compression brings them close, leading to physical contact. For the latter, the contact area between CNTs is small due to the cylindrical shape, see Fig. 5. External force will improve physical contact by increasing the contact area. In addition, it is seen that the compression's impact slows down as pressure increases until no evident change is observed. This is likely due to the MWCNT super stiffness with its Young's modulus as high as 1.8 TPa [8], resisting nanotube physical deformation and hence further thermal contact enhancement. For the dry buckypaper, it is evident that the thermal conductivity changes little within the range of compression.

Fig. 5 shows the schematic of heat flow near the CNT-CNT thermal contact. It is seen that the contact is physically very small, a point, for the dry case. Thus, the contact becomes a bottleneck that limits heat flow. This may also explain the low thermal conductivity as shown in Fig. 4, in comparison with single MWCNT. Note that the dry thermal conductivity is only about 0.25 W/m K, which is even much smaller than liquid water (about 0.6 W/m K). When liquid water is added to the sample, the liquid will rapidly spread to the contact point area and increase the heat flow path. This increase can be significant, given that the CNT-CNT contact is a point for a perfect rigit tube. The liquid water will bridge a heat flow with an area of 100-1000 larger than the CNT-CNT contact alone.

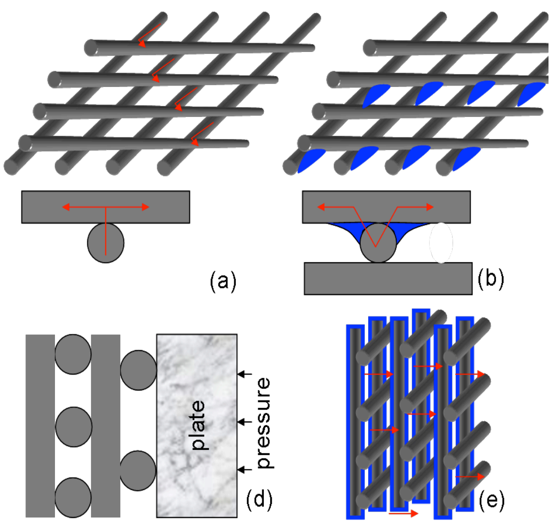

Fig. 5. Schematic of heat transfer at the thermal contact in dry (a, d) and wet (b,e) samples. Structured arrangment of CNTs is used for illustration purpose only.

Fig. 6 presents the thermal conductivity of a wet buckypaper as a function of water content. It is seen that the thermal conductivity increases rapidly when the liquid is initially added. This is likely due to the fact that initial addition yields rapid filling of the interfacial gap driven by the capillary force, and hence a considerable increase in the thermal contact. The interfacial space between two cylindrical CNTs is shaped by a small gap near the contact point which increases rapidly with the distance away from the point, see Fig. 5. The initial liquid addition mostly fills the very small gap near the contact point, yielding a large enhancement in heat transfer. As the liquid content increases, the thermal conductivity enhancement slows down. This may be due to the fact that the gap space becomes larger, thus the enhancement becomes smaller.

In addition, for the thermal diodicity of dry/wet thin film, the thermal conductivity is about 0.25 W/m K at dry state, and becomes as high as about 3 W/m K at wet state. Thus, totally more than 10 times difference in thermal conductivity. For electronic devices, heat is produced during their function/operation, which can be dissipated via a wet diode. The water injection can be realized by putting liquid water in touch with the sample (the capillary action will absorb the water rapidly). When the electronic device is subject to hot enviroments, e.g. fire condition, the water will be vaporized automatically/rapidly, slowing down the heat inflow to the electronic device. This advanced function is imporant to several devices sensative to temperature or military devices that may be used in battle fields, including those used in airforces.

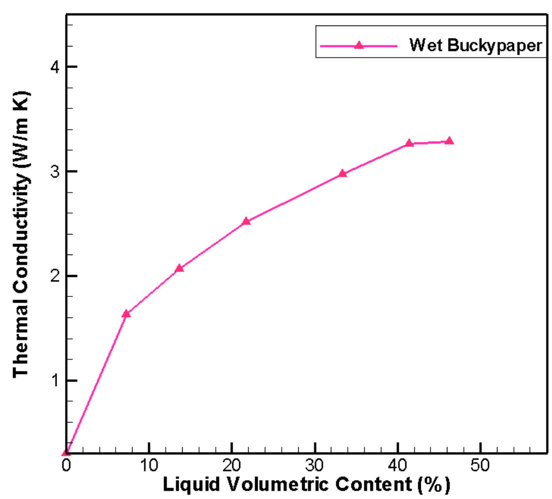

Fig. 6. Thermal conductivity of wet sample of various water contents.

The diodicity can be adjusted and is determined by many factors, including the porous layer structure, temperature, and working fluid. Fig. 7 presents the thermal conductivity of carbon paper under different water content (i.e. the water saturation s), and temperature. It is clearly seen that water addition increases the overall thermal conductivity. However, under low temperature, e.g. 30-50 degree C, the increase is small, yielding a diodicity around 1.5. As tempeature increases, the diodicity can reach about 2.5 at ~85 degree C. The increased value was also partly attributed to heat pipe effect.

While a diodicity of 10 is already very high at current, it is desirable to fabricate materials for a much large diodicity, which may benefit a large range of application. The research is ongoing in the lab, and we are fabricating buckypapers, graphene layers, and others, and exploring new fabrication techniques including surface property modification.

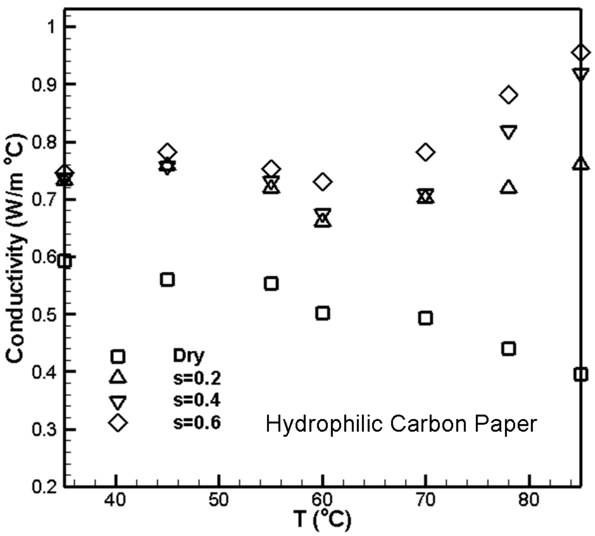

Fig. 7. Thermal conductivies of carbon paper under different water saturation s and temperatures [5].

4 CONCLUSIONS

This study presented an experimental study on the thermal conductivity of dry/wet buckypaper under various compression and water contents for thermal protection purpose. The thermal conductivity of dry buckypaper was found to be about 0.25 W/m K. The conductivity was found to increase significantly by adding liquid water. The wet sample's conductivity reaches ~3.2 W/m K for a liquid water volume fraction of 35% or higher, more than 10 times higher than the dry sample. The increasing rate slows down as the water volume fraction increases. For a ~10% water addition, the thermal conductivity increases by about 4 times. Beyond the volume fraction of 35%, liquid addition has little impact on the conductivity. We indicated that the thermal contact limits the heat flow through the sample, and illustrated that liquid water significantly increases thermal contact. The diodocity was found to be over 10 for the studied paper, which is much larger than that of carbon paper (~2.5).

For electronic devices, heat is produced during their function/operation, which can be dissipated via a wet diode. The water injection can be realized by putting liquid water in touch with the sample (the capillary action will absorb the water rapidly). When the electronic device is subject to hot enviroments, e.g. fire condition, the water will be vaporized automatically/rapidly, slowing down the heat inflow to the electronic device. This advanced function is imporant to several devices sensitive to temperature or military devices that may be used in battle fields, including those used in airforces.

In Wang's lab at UCI, we are fabricating buckypapers, graphene layers, and others, and exploring new fabrication techniques including surface property modification with a ultimate goal of significantly increasing the thermal diodicity (i.e. >100).

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