Solar steam generation is regarded as one of the most sustainable techniques for desalination and wastewater treatment. However, there has been a lack of scalable material systems with high efficiency under 1 Sun. A solar steam generation device is designed utilizing crossplane water transport in wood via nanoscale channels and the preferred thermal transport direction is decoupled to reduce the conductive heat loss. A high steam generation efficiency of 80% under 1 Sun and 89% under 10 Suns is achieved. Surprisingly, the crossplanes perpendicular to the mesoporous wood can provide rapid water transport via the pits and spirals. The cellulose nanofibers are circularly oriented around the pits and highly aligned along spirals to draw water across lumens. Meanwhile, the anisotropic thermal conduction of mesoporous wood is utilized, which can provide better insulation than widely used super-thermal insulator Styrofoam ($\approx 0.03$ W m$^{-1}$ K$^{-1}$). The crossplane direction of wood exhibits a thermal conductivity of 0.11 W m$^{-1}$ K$^{-1}$. The anisotropic thermal conduction redirects the absorbed heat along the in-plane direction while impeding the conductive heat loss to the water. The solar steam generation device is promising for cost-effective and large-scale application under ambient solar irradiance.

1. Introduction

The shortage of fresh water is becoming a pressing challenge worldwide. The abundance of solar energy renders solar steam generation one of the most promising techniques for desalination and water purification.[1–10] In order to improve the performance of solar steam generation, three main factors have been considered including the efficiency of the solar energy receiver, thermal management capabilities, and the fluid transport and evaporation. Recently, there have been substantial improvements in performance via thermal management engineering by using bilayer foams,[11] plasmonic metal particles absorbers,[3,4,12] and heat confinement layers.[1,2,13–16] Previously demonstrated solar steam devices with high steam generation efficiency often entail complex fabrication processes and high material cost, which restrict the widespread application of these novel technologies. The search for a cost-effective solution continues for large-scale water treatment. In the meantime, high conversion efficiency typically can only be obtained under high concentration factors, which increases the system cost by requiring optical concentrators and entails additional manufacturing complications. Consequently, challenges remain to obtain a high conversion efficiency under ambient solar illumination. The requirements for 1 Sun high conversion efficiency include an efficient solar energy receiver, low thermal energy loss, as well as sufficient fluid supply. To satisfy these requirements simultaneously with a cost-effective solution is highly desirable.

Trees are the most abundant biomass on Earth that have been widely used in structural materials,[17] cellulose manufacturing,[18–21] energy management materials,[17,22–24] and water filtration.[25] Mesoporous natural wood has vertically aligned wood channels (lumens) that are connected via horizontal fluidic openings in the shape of nanoscale spirals and pits.[26] Due to the lumen alignment along growth direction, the thermal conductivity of wood is highly anisotropic ($0.35$ W m$^{-1}$ K$^{-1}$) and across its growth direction ($0.11$ W m$^{-1}$ K$^{-1}$). In this work, we report a simultaneously satisfied suppression of heat loss and an efficient water supply by decoupling the preferred heat transfer direction and the microfluidic channels in anisotropic mesoporous wood. The low crossplane (perpendicular to the lumen alignment) thermal conductivity prohibits heat loss to the surroundings while the much larger thermal conductivity along in-plane surface redirected the absorbed heat. The
crossplane microfluidic transport via the pits and spirals on the lumen walls can provide sufficient water supply for solar steam generation under ambient solar illumination. A layer of graphite was spray coated on wood with a weighted absorbance of >95% of the solar spectrum. The thin layer of graphite as well as the highly anisotropic thermal conduction of wood localizes the solar generated thermal energy within the thin water evaporation surface. A conversion efficiency of ≈80% was observed under ambient Sun conditions (1 kW m$^{-2}$), representing one of the highest value achieved so far.$^{[5–16]}$ Note that both the fluidic supply channels (vertical cut wood boards) and the top solar receiver (spray-coated graphite layer) are cost-effective materials with great abundance which can be readily applied to scalable clean water generation. There has been several recent work$^{[27,28]}$ on using horizontally cut wood for solar steam generation. The wood lumens were used for water uptake in the alignment direction. A detailed comparison of device performance between using horizontally cut wood and vertically cut wood can be found in Discussion S1 in the Supporting Information.

2. Results and Discussions

Figure 1a illustrates the simple and scalable process for making solar steam generation devices using natural wood. The wood board fabrication is compatible with industrial processes and, more specifically, cutting while rotating to make large-scale vertically oriented boards. In this work, we have used two cost-effective materials for the realization of a high efficiency solar steam generation device, namely graphite and vertically cut wood boards. The vertically cut wood boards exhibit a very low thermal conductivity (0.11 W m$^{-1}$ K$^{-1}$) which can help reduce thermal loss. In addition, we have spray coated a layer of high-emissivity graphite with a thickness of ≈50 µm on natural wood specimens with a typically thickness of 1.5 cm. As shown in Figure 1b, lumens are aligned along the growth direction while water transport is best directed across the lumens for efficient solar steam generation. The schematic of the device in Figure 1c has the following distinct features: (1) the crosstransport by the nanoscale pits on wood lumens facilitates rapid water flow, while yielding a low thermal conductivity; (2) the coated graphite layers exhibit close-to-unity broadband absorptivity and function as an efficient solar energy receiver; (3) thermal energy can be effectively confined within the volume of graphite layers due to the anisotropic thermal conductivity resulting from the large porosity of the aligned wood lumens. As a result, a high surface temperature of 38 °C under 1 Sun and 117 °C under 10 Suns were observed. The resulting high surface temperature is beneficial to achieving a high conversion efficiency.

American Basswood was used to create the solar steam fluidic channels in this work; however, all wood species are capable of fluidic transport for solar steam applications. The scanning electron microscope (SEM) images of the American Basswood channels are shown in Figure 2a–d. Natural basswood has an overall porosity of ≈70%.$^{[29]}$ In between the aligned microsized wood lumens (Figure 2a), there exist crossplane open pathways such as pits and horizontally grown spirals along the large wood lumens, as shown in Figure 2b. Interestingly, the nanofibers on
the lumen walls are oriented in a circular pattern around the pits (Figure 2c,d) and aligned along spirals to aid the fluidic transport in the crossplane direction. We cut a slice of wood of size 2 cm \( \times \) 2 cm \( \times \) 0.2 cm to demonstrate fluidic transport across the lumens (Figure 2e). The lumens are oriented along the thickness direction. The flow height was measured after the bottom of the wood slice was immersed in liquid. The liquid transport direction is thus perpendicular to the wood growth direction. As shown in the photographs in Figure 2e, the wood slice facilitates efficient microfluidic flow across the highly hydrophilic lumens. The flow rate is around 0.5 mm s\(^{-1}\) within the first 10 s, thereby confirming efficient fluidic transport in the crossplane direction of basswood. After the wood was fully infiltrated with water, the density increases from 0.45 to 1.12 g cm\(^{-3}\). The stabilized density of wood after floating on water increases to 0.69 g cm\(^{-3}\). The highly hydrophilic lumens and the high porosity ensure ample liquid loading of the wood.

The mesoporous microstructure of basswood consists of vessels (with average size \( d_v \approx 50 \) µm) that are surrounded by fiber tracheids (with average size \( d_t \approx 5–15 \) µm) and connected through pits (\( d_p \approx 2 \) µm). These pits are located extensively throughout the cell walls. To understand the water transport across a thin piece of basswood with repeated aforementioned structure, we conducted a computational fluid dynamics simulation based on SOLIDWORKS Flow Simulation. Surprisingly, we found that water transport is very efficient for such a thin piece of wood height whose top surface is 1 cm above the water surface. The evaporated water from the top of the wood surface can be replenished rapidly by capillary-driven water transport across the mesoporous wood microstructure. Under these conditions, in experiments a film of water can be always witnessed on the top surface of the wood and we can consider a steady-state water transport across the wood. We simulate this steady-state water transport using the continuity and Navier–Stokes equations

\[
\nabla \cdot \mathbf{u} = 0 \tag{1}
\]

\[
\rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla \cdot (\rho \mathbf{I}) + \nabla \cdot (\mu \nabla \mathbf{u}) \tag{2}
\]
Here \( \mathbf{u} \) is the flow velocity vector, \( p \) is the pressure, and \( \rho \) and \( \mu \) are the density and dynamic viscosity of water, respectively. We consider a boundary condition at the top of the wood surface that allows an evaporation rate of 10 kg m\(^{-2}\) h\(^{-1}\) under 8 Suns (see Figure 2f) and a no-slip boundary condition is set for the wood structure. A structured Cartesian immersed-body mesh approach is used for mesh generation with 145 600 fluid cells and 212 961 partial cells, and various adaptation criteria are used near complex solid–liquid interfaces (curvature, narrow channels, and small geometric features) along with the consideration of gradient in mid-term solutions. Water trajectories shown in Figure 2f illustrate the manner in which this flow occurs. We clearly see that the tiny pits present in the wood structure of diameter \( d_p \approx 2 \mu m \) (see Figure 2 in main text) regulate the flow. This is confirmed by the largest values of the velocity in the immediate vicinity of the pits.

Thermal management in solar steam generation devices is critical in increasing the overall conversion efficiency. The thermal properties of the basswood samples were evaluated. SEM observation indicates a graphite-coated thickness of \( \approx 50 \mu m \) (Figure 3a). A uniform layer of graphite flakes was formed after subsequent drying of sprayed-on graphite solution. Figure S3 in the Supporting Information shows the SEM images of the coated graphite layer on glass. The graphite flakes exhibit an average size of \( \approx 0.5 \mu m \). A photograph of a coated sample is shown in Figure 3b. In order to evaluate the attachment of graphite flakes to the wood mesoporous scaffold, we have tested the stability of a graphite-coated vertically cut wood slice in various harsh conditions such as high temperature (>70 °C in distilled), acidic, and alkaline environments. No notable changes were observed (Figure S6, Supporting Information). In order to achieve high photothermal conversion efficiency, the heat losses from the vapor-emitting surfaces to the surroundings (wood matric and air) need to be reduced. Owing to the anisotropic alignment of wood lumens, wood exhibits a 3 × higher thermal conductivity in the axial direction and a much lower thermal conductivity in the crossplane direction. The thermal conductivity in the crossplane direction of the wood lumens is as low as 0.11 W m\(^{-1}\) K\(^{-1}\) at 20 °C, which slowly rises to 0.14 W m\(^{-1}\) K\(^{-1}\) upon elevated temperatures up to 135 °C (Figure 3c). In contrast, the thermal conductivity along the lumen growth direction is 0.35 W m\(^{-1}\) K\(^{-1}\) under 20 °C. We also measured the thermal conductivity when the wood block is presoaked with water. The thermal conductivity

![Figure 3.](image-url)
across the lumens slightly increases to 0.14 W m$^{-1}$ K$^{-1}$ while the value along the lumen direction increases to 0.38 W m$^{-1}$ K$^{-1}$ under room temperature (22 °C) (Figure 3d). The observed high anisotropic factor of the thermal conductivity is due to the cellulose alignment in the natural wood. The thermal conductivity along the fluid pathways in our solar steam device is among the lowest values reported to date. As can be observed, the heat profile drops faster from the surface to the rear end of the wood block (Figure 3e). The results are summarized in Figure S2 in the Supporting Information shows the analysis of the anisotropic thermal conductivity of wood based on the porosity and alignment of wood mesostructures.

When exposed to the same solar irradiance, the converted thermal energy can thus be more confined in the wood piece by crossplane heat transport. The coated graphite layer exhibits an air mass 1.5 G weighted absorbance of >95% for 200–2500 nm, which functions as an efficient broadband solar energy receiver under illumination (Figure 3f). Interestingly, the absorbance is slightly higher than that of the pure graphite layer. As shown in Figure S5 in the Supporting Information, the graphite layer exhibits an absorbance of >92%. This might be due to the large roughness of the mesoporous wood surface which further reduces light reflection. Meanwhile, the coated graphite layer exhibits a small thickness with a low heat capacity = 0.7 J g$^{-1}$ K$^{-1}$ (Figure 3g). Thus, the fast temperature rise of the graphite layers can lead to a short response time in steam generation under sunlight exposure. In addition, due to the small volume of the solar receiver, upon receiving the same amount of solar energy, the converted thermal energy will be confined at the liquid–vapor generation interface. We used an IR camera to show the temperature profile along the side of the wood block. The surface temperature reaches 54 °C for the graphite coated wood while the temperature is only 32 °C for the uncoated wood (Figure 3h). Interestingly, the temperature at the bottom of the graphite-coated wood is even lower than that of the uncoated sample, indicating an effective confinement of thermal energy and reduced conduction loss. The graphite layer exhibits a much higher thermal conductivity.\textsuperscript{[30]} The incident radiative energy has been redirected in-plane on the top surface of the graphite coated sample.

To demonstrate the thermal insulation capabilities of the vertically cut wood, we evaluated the specimens under a conductive heat source and compared it against the widely used super thermal insulation material Styrofoam (isotropic, $k$ close to that of air =0.03 W m$^{-1}$ K$^{-1}$). The experimental setup scheme is shown in Figure 4a. The backside temperatures of the 2 mm thick specimens were measured when a conductive heat source (contact area 1 mm $\times$ 1 mm) was placed on top surface. The ambient temperature was 21 °C. The results are summarized in Figure 4b. When the heat source was 90, 120, and 160 °C, the stabilized backside temperature of vertically cut wood was 60, 87, and 98.1 °C, respectively, even lower than that of super-thermal insulation Styrofoam (65, 88.9, and 113 °C, respectively). The vertically cut wood exhibits an even better thermal insulation capability than super-thermal insulator Styrofoam. The anisotropic thermal conductivity of wood helps the heat confinement in the solar energy receiving layer by impeding the conductive heat transfer into the wood matrix.

The graphite-coated wood was then evaluated for solar steam generation performance. The device has a size of 2 cm $\times$ 2 cm $\times$ 1.7 cm. The water level is kept at 1 cm below the evaporation surface of wood (Figure 5a). A container of similar size was used to minimize the effect of pure water evaporation from the surroundings. An IR camera was used to monitor the temperature change of the water evaporation surface under 1 Sun conditions. The surface temperature of the graphite wood quickly rises to 38 °C after 10 min (Figure 5b). With only water in the same container, the stabilized evaporation rate is measured to be 0.3 kg m$^{-2}$ h$^{-1}$. In comparison, the evaporation rate with graphite coated wood rises to 1.2 kg m$^{-2}$ h$^{-1}$ quickly under 1 Sun conditions, representing a four times enhancement over pure water evaporation. The results are summarized in Figure 5c. Note that the evaporation rate rises to 1 kg m$^{-2}$ h$^{-1}$ already within 5 min of light exposure, indicating a fast response time for our solar steam generation device. Similarly, as shown in Figure 5d, the surface temperature of graphite
coated wood increased to 35 °C after 5 min and stabilized to 38 °C after 15 min. Typically, the steam-generation efficiency can be calculated based on the following equation \[\eta = \frac{m \cdot \dot{h}_L V}{C_{opt} P_0}\] 

where \(m\) refers to the mass flux (E.R.), \(h_L V\) to the total liquid–vapor phase change enthalpy including the sensible heat, \(P_0\) is the nominal solar irradiation value of 1 kW m\(^{-2}\) and \(C_{opt}\) represents the optical concentration. Accordingly, the stabilized steam generation efficiency was estimated to be 80%. The wood is stable in water. We have also performed the stability test for 50 cycles while the reading for each cycle was taken after 30 min (after the performance stabilized). The results are shown in Figure 5e. We observed excellent performance stability of graphite coated wood. The device’s performances under varied illuminations were also evaluated.

The evaporation rates under different illuminations of 1, 3, 5, 7, and 10 Suns are 1.15, 3.48, 5.98, 8.64, and 12.31 kg m\(^{-2}\) h\(^{-1}\), respectively (Figure 5f). The evaporation rate under 10 Suns exhibits more than ten times enhancement compared with that under 1 Sun potentially owing to an increase in the thermal-photocconversion efficiency under higher concentration factors. The temperature at the vapor surface increases to 117 °C under 10 Suns, indicating efficient thermal energy confinement at the graphite layers (Figure 5g). The corresponding steam generation efficiency slightly increases with the concentrator factor from 80% to 89% under 1 and 10 Suns, respectively, as shown in Figure 5h.

The observed high surface temperature upon solar irradiance from 1 Sun to 10 Suns serves as evidence of the effective thermal energy management in graphite coated anisotropic wood boards. The thin graphite layer effectively converts sunlight to heat while the heat is confined due to the low thermal conductivity of the natural wood. The 1 Sun steam generation efficiency of 80% is thus obtained, representing one of the highest values for all reported solar steam generation devices under 1 Sun conditions.\[1,3,7,11,28,31\]

A scalable solar steam system is highly desirable for the realization of clean water generation, ion purification, and...
seawater desalination. The wood matrix used in the demonstrated device is cut along the wood growth direction, which is compatible with large-scale wood cutting processes. The most common cutting procedure adapted by industry is to peel the wood block with desirable thickness and then press the boards flat. Figure 6a shows a typical wood board. The length direction is along the wood growth direction with aligned lumens. One side of the board is spray coated with graphite, as shown in Figure 6b. The resulting wood board can then be used for steam generation under solar irradiance (Figure 6c). Besides being scalable, the materials required are also cost effective. Vertically cut wood boards and graphite are both commercially available with a relatively low price. The estimated price for the demonstrated device with a dimension of 1 m × 1 m × 1.5 cm is below $3. The scalability, the cost-effectiveness together with the stable performance and high conversion efficiency renders our demonstrated solar steam generation device extremely attractive for realistic applications.

3. Conclusion

In summary, we have demonstrated an efficient and scalable solar steam generation device that is composed of spray-coated graphite on a natural untreated, vertically cut, mesoporous basswood block. Instead of using the intuitive water transport along the wood growth direction, for the first time we decouple the fluidic transport direction and the thermal transfer direction. The anisotropic thermal conductivity of mesoporous wood was utilized to further increase the temperature of the water evaporation interface and reduce conductive heat loss to bulk water. Surprisingly, the crosslumen pits serve as rapid fluidic supply channels, which provide sufficient water transport for steam generation under solar irradiance. Graphite layers exhibit a broadband absorbance of >95% from 300 to 2000 nm wavelength light, which can convert the full spectrum of sunlight to thermal energy at the vapor generation interface. The converted thermal energy was confined within the thin volume of graphite layers due to the low thermal conductivity of the wood matrix. The device exhibits a 1 Sun efficiency around 80% with an evaporation rate of 1.15 kg m⁻² h⁻¹ and a water–vapor interface temperature of 38 °C under ambient Sun conditions. The conversion efficiency is the highest among the biomaterial-based systems with scale-up capability. The demonstrated approach toward large-scale, high-efficiency solar steam generation under ambient solar irradiance is promising for the realistic application of cost-effective, easy-to-manufacture desalination and wastewater treatment.

4. Experimental Section

Sample Preparation: The basswood beam was purchased from Amazon. A wood block was cut along the wood growth direction, which was then placed with the lumen side faced upward. The commercially available graphite was subsequently spray coated on the surface until a uniform coating was formed. The wood block was then rested until the coating is dry. The resulting graphite layer was firmly attached to the mesoporous scaffold of wood, which can function as an efficient broadband light absorption layer.

Solar Steam Generation Efficiency Measurement: A standard solar simulator (Newport Oriel 69907) was used to test the steam generation efficiency. The graphite coated wood was cut into a similar size of the container to minimize the pure water evaporation when testing. The water level is kept 1 cm below the vapor generation surface. A k-type thermocouple was used to monitor the surface temperature under illumination. A calibrated electronic balance (Citizen CX301) was used to measure the mass change during evaporation.

Thermal Conductivity Measurement: Laser flash method represents a not-contact transient method to measure thermal diffusivity of materials, which is applied to test the vast majority of bulk materials. During the measurement, an instantaneous laser pulse was used to heat up one side of the sample, and the response of temperature on the other side was recorded by a detector. In this work, the Netzsch laser flash apparatus (LFA 457) was used for thermal diffusivity measurement. The thermal conductivity k (W m⁻¹ K⁻¹) of the samples was then calculated by the following equation
where \( \alpha (\text{mm}^2 \text{s}^{-1}) \) is the measured thermal diffusivity along a particular direction, \( C_p (\text{J g}^{-1} \text{K}^{-1}) \) is the heat capacity, and \( \rho (\text{g cm}^{-3}) \) is the density. The needed heat capacity, \( C_p \), can also be acquired by comparing with standard references Inconel 600 in parallel with thermal diffusivity measurement. The in-plane and crossplane samples were acquired by cutting the wood in different directions.

Optical Measurement: Optical measurements were carried out with a UV–vis Spectrometer Lambda 35 from 400 to 1500 nm (PerkinElmer, USA) that equipped with an integrated sphere. The absorbance \( \alpha \) and reflectance \( R \) measurement were calculated based on transmittance \( T \) and reflectance \( R \) measurement \( (A = 1 - R - T) \). The sample for the test was 3 cm × 3 cm × 0.5 cm [length × width × thickness]. An forward looking infrared (FLIR) camera (FLIR ONE) was used to monitor the change of temperature profile of the devices.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

Acknowledgements
T.L. and H.L. contributed equally to this work.

Conflict of Interest
The authors declare no conflict of interest.

Keywords
biodegradable devices, high-efficiency steam generation, mesoporous materials, microfluidics, solar steam

Received: December 7, 2017
Revised: January 12, 2018
Published online:

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