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BIOMASS-DERIVED 2D AND 3D PHOTOABSORBERS: INSIGHTS INTO HEAT PROLIFERATION FOR ENHANCED PHOTOTHERMAL INTERFACIAL SOLAR STEAM GENERATION (ISSG)

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1. ABSTRACT

The present work investigates the superior performance of 3D carbonized palm fiber photoabsorbers in interfacial solar steam generation (ISSG), surpassing 2D counterparts by 103.7% in solar-to-heat conversion efficiency. With 2D evaporation at 1.171 kg m^{-2} h^{-1} and 3D at 1.869 kg m^{-2} h^{-1}, our focus is on understanding heat proliferation within the photothermal zone. Utilizing heat transfer module in COMSOL, we unveil heat propagation mechanisms and losses, shedding light on novel biomass photoabsorbers' potential for efficient solar-driven steam generation and water purification systems.

2. INTRODUCTION

This study focuses on understanding and optimizing heat transfer processes in in, using biomass-derived carbonized palm fiber as a photoabsorber material. Primarily a pilot-scale exploration for water purification systems, this study compares the superiority of 3D biomass-derived photoabsorbers over their 2D counterparts. Experimentally, carbonized palm fiber functionalized with polydopamine (PDA) is analysed, generating time-series heat profiles and measuring energy conversion efficiencies of 2D and 3D photoabsorbers under 1 sun illumination. Notably, the 3D photoabsorber exhibits superior heat transfer characteristics with solar-to-thermal conversion efficiency of 103.7%, showcasing enhanced sensible heat transfer and heat recovery mechanisms compared to its 2D counterpart. The complex 3D morphologies, including protruding surfaces, play a crucial role in efficient heat recovery and retention. Additionally, simulation-based heat transfer analyses complement the experimental results, providing a comprehensive understanding of heat propagation and losses within the photothermal zone. These insights not only demonstrate the immediate potential of 3D photoabsorbers in water purification systems but also lay the groundwork for scaling up this technology in the future. This research advances our understanding of photothermal materials and emphasizes the importance of heat mechanisms and propagation mechanisms in achieving sustainable water solutions in real-world applications.

3. METHDOLOGY

Sample Preparation: Modified from our preceding works, raw palm fibers from empty fruit bunches were pretreated, compressed into thin sheets, and shaped into 3D structures using 3D-printed molds or cut into 2D disks [1]. These palm fiber structures were then carbonized and surface-functionalized with polydopamine (PDA).

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Characterization involved SEM, AFM, BJH analysis, WCA measurement, TGA, DSC, XPS, FTIR, and diffuse reflectance spectroscopy. Solar steam generation experiments utilized 2D and 3D photothermal evaporators, monitored using an electronic balance and solar simulator (1 sun) to capture time-dependent mass changes of water being evaporated. COMSOL Heat Transfer in Solids and Fluids module was chosen to perform temperature distribution simulation with initial temperature equals to 25°C, thermal conductivity of palm fiber is 10.58 W $m^{-1}K^{-1}$, heat capacity of water reservoir is 4200 J $kg^{-1}K^{-1}$, fluid density is 1000 kg m^{-3} and surface emissivity is 0.85.

4. RESULTS

The experimental results demonstrated that the 2D thin film, 3D cone, and 3D cup PDA c-fibers, with consistent projection areas, exhibited varying evaporation temperatures and rates under 1 sun illumination. The 2D thin film had the highest evaporation temperature at around 50 °C, while the 3D cup achieved the highest evaporation rate at 1.869 kg m^{-2} h^{-1}, with a remarkable solar-thermal conversion efficiency of 103.7%. The 3D cup morphology excelled due to its enhanced light absorption, multireflection capabilities, and efficient heat recovery properties, leading to superior water evaporation performance despite its lower surface temperature. Additionally, the superhydrophilic surface induced by PDA functionalization ensured continuous water transport for efficient evaporation [2].

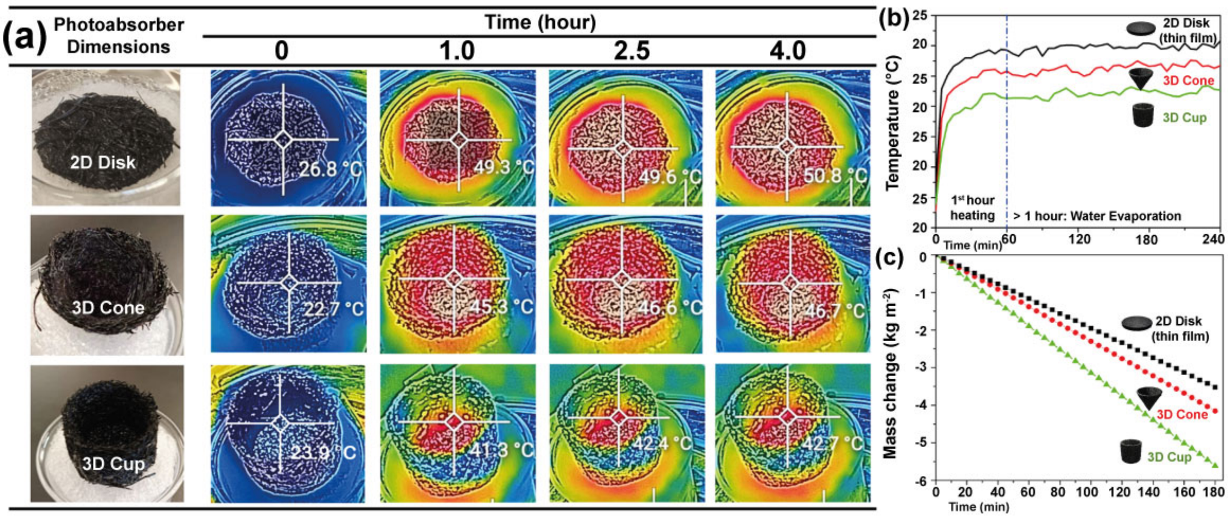

Fig. 1: (a) IR image of (Top to bottom): 2D thin film, 3D cone, and 3D cup PDA c-fibres. (b) Temperature profile plot obtained from the IR images. (c) Water mass change over time using 2D thin film, 3D cone, and 3D cup PDA c-fibre under 1 sun illumination.

Despite having a much lower evaporation surface temperature, 3D cup shape was able to outperform the other two morphologies. The reason lies within the thermal energy utilization of the morphology, where the thermal energy ($Q_{thermal}$) used are defined as follow:

$$Q_{thermal} = \Delta H_{latent} + \Delta H_{sensible} \quad (1)$$

$$\Delta H_{sensible} = c(T_{evap} - T_{amb}) \quad (2)$$

Where ΔH_{latent} is the latent heat taken at evaporation temperature (T_{evap}), $\Delta H_{sensible}$ is the sensible heat, c is the specific heat capacity of water, T_{amb} is the ambient temperature of water [3,4].

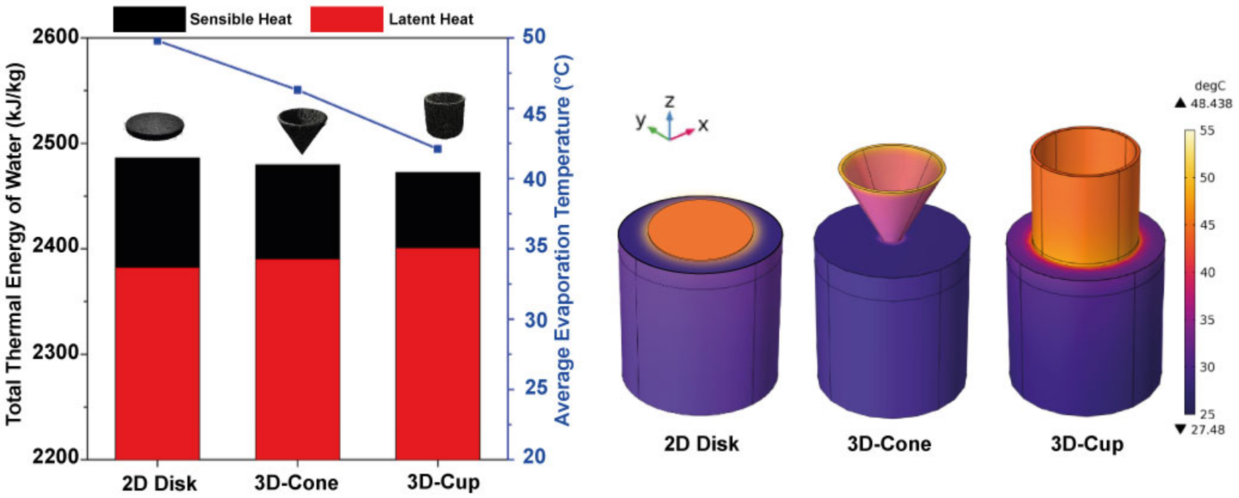

Fig. 2: (Left) Thermal energy used by 2D thin film, 3D cone, and 3D cup for water evaporation (separated into sensible, and latent heat) plotted together with the average evaporation temperature. It shows that 3D cup uses more energy for useful work of water evaporation (latent heat), and less energy for water heating (sensible heat). (Right) Heat transfer models and simulated temperature distribution over the photoabsorber of 2D disk thin film, 3D-cone, and 3D-cup geometries made of palm fiber under 1 sun irradiation during solar steam generation.

5. CONCLUSIONS

In summary, the current work enabled the performance comparison across three different morphologies through the construction of a consistent projection area. The heating profile of 2D thin film, 3D cone, and 3D cup PDA c-fibres were documented and studied. 3D cup PDA c-fibre, despite having a lower evaporation surface, were able to utilize thermal energy much more efficiently for water evaporation (latent heat). The 3D cone morphology despite having an inclined surface for enhanced light recovery, it does not have a thermal gradient to recapture heat loss. Therefore, 3D cup, which were able to form thermal gradient across two surfaces were able to recover both reflected lights and heat loss, making it the most energy efficient morphology. This study offers insights for scaling up to 3D photoabsorbers, suggesting potential optimizations particularly in heat localisation for enhanced interfacial solar steam generation with PDA carbonized-fiber.

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