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Journal of Technomaterial Physics
Journal homepage: https://talenta.usu.ac.id/JoTP

Effect of Activated Carbon on Cellulose Nanofiber Aerogels for Enhanced Solar Steam Generation

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ARTICLE INFO

Article history:
Received 12 June 2023
Revised 17 August 2024
Accepted 24 August 2024
Available online 30 August 2024

E-ISSN: 2656-0755
P-ISSN: 2656-0747

How to cite:
D. A. Barus and K. Nainggolan, "Effect of Activated Carbon on Cellulose Nanofiber Aerogels for Enhanced Solar Steam Generation," Journal of Technomaterial Physics, vol. 06, no. 02, pp. 84-88, Aug. 2024, doi: 10.32734/jotp.v6i2.12329.

ABSTRACT

The development of efficient and environmentally friendly clean water production systems is becoming increasingly important. This study focuses on an innovative evaporator for a Solar Steam Generator (SSG) system designed to produce clean water using accessible materials. The SSG evaporator is constructed from cellulose bonded with Polyvinyl Alcohol (PVA) and incorporates a freeze-drying method to enhance porosity, which improves water delivery within the SSG system. To further boost the efficiency of the evaporator, activated carbon (AC) is added due to its effective absorption of visible to infrared radiation. Evaporation rate testing demonstrates that the addition of 3 wt% AC yields an evaporation rate of 1.39 kg/m²/h and an efficiency of 58.56%. Fourier-transform infrared (FTIR) spectroscopy was employed to analyze changes in the sample after AC addition and to examine infrared absorption characteristics.

Keywords: Activated Carbon, Aerogel, Cellulose nanofiber, Freeze drying, Photothermal

ABSTRAK

Pengembangan sistem produksi air bersih yang efisien dan ramah lingkungan semakin penting. Penelitian ini berfokus pada evaporator inovatif untuk sistem Solar Steam Generator (SSG) yang dirancang untuk menghasilkan air bersih menggunakan bahan-bahan yang mudah diakses. Evaporator SSG dibuat dari selulosa yang terikat dengan Polyvinyl Alcohol (PVA) dan menggunakan metode pengeringan beku untuk meningkatkan porositas, yang membantu pengantaran air dalam sistem SSG. Untuk lebih meningkatkan efisiensi evaporator, karbon aktif (KA) ditambahkan karena kemampuannya dalam menyerap radiasi dari cahaya tampak hingga inframerah. Pengujian laju evaporasi menunjukkan bahwa penambahan 3 wt% KA menghasilkan laju evaporasi sebesar 1,39 kg/m²/h dan efisiensi sebesar 58,56%. Spektroskopi Fourier-transform inframerah (FTIR) digunakan untuk menganalisis perubahan pada sampel setelah penambahan KA dan untuk memeriksa karakteristik penyerapan inframerah.

Kata kunci: Aerogel, Fototermal, Karbon Aktif, Nanofiber Selulosa, Pengeringan Beku

1. Introduction

The need for clean water is one of the main challenges in this modern era. Currently, nearly one-fifth of the world's population lives in water-stressed areas. In some underdeveloped countries, 1 in 10 people cannot access clean water. Global warming is also causing more frequent droughts in some places. It is predicted that the number of people affected by drought will increase to reach 3.9 billion in 2030 [1].

Several systems for cleaning water, such as Reverse Osmosis (RO) [2] and distillation [3], require considerable energy for the filtration system, and RO requires media replacement or renewal. Therefore, there is a great need for a more efficient, low-cost, sustainable system with easily accessible technology and devices to produce clean water.

The sun is the most abundant energy resource on earth; utilizing solar energy for water purification is a promising technology for producing clean water from various non-potable water resources such as seawater [4], rivers, lakes, water contaminated with oil [5] and wastewater with heavy metals [6]. Solar steam generator or solar steam generation (SSG) is a tool that utilizes solar power. SSG works by capturing energy from the sun in the form of light and converting the light energy into thermal energy to heat and evaporate the water in the system; the conversion of energy from the form of light to thermal energy is also known as photothermal conversion [7].

To increase the efficiency of solar steam generation, the three most essential parts that can be improved are the growing absorption of sunlight, improving thermal control, and accelerating water evaporation [7]. Various materials have been used to increase sun absorption, such as graphene, MXene, activated carbon (AC), and metal nanoparticles [8]. However, among these materials, Activated Carbon is the most accessible, has the lowest price, is relatively stable [9], and is easily dispersed [10].

Aerogel is a lightweight material with a porous structure. This large porosity provides a capillary force for the liquid to flow through the Aerogel [11]. This high porosity makes aerogel have good absorption properties, able to absorb up to 200 times the mass of the aerogel. Aerogel can be made from various materials, from silica, metals, metal oxides, carbon, and graphene to those derived from biomass such as alginate, starch, and cellulose [12]. The mechanical properties of Cellulose Nanofiber (NS) aerogels are better than silica aerogels; they are not brittle and can be used repeatedly [13] and are easy to obtain and manufacture, which are more environmentally friendly [14].

Activated carbon is a material formed from carbon components with good photothermal properties and good absorption capacity for electromagnetic waves, thus enabling activated carbon to be applied in various fields, such as solar steam generators and biomedicine [15].

Cellulose nanofiber Aerogel filled with Activated Carbon, which has water absorption and photothermal properties for converting solar energy into thermal energy, has good potential in manufacturing solar steam generation aerogels. So, in this study, aerogels consisting of cellulose nanofibers with activated carbon fillers will be made as SSG materials.

2. Material and Methods

2.1. Material

The materials used in this research include palm oil trunk sourced from USU Medan, Indonesia, 99.97% H_2SO_4, 37% hydrochloric acid solution from Merck, 30% hydrogen peroxide, sodium hydroxide from Smart Lab, polyvinyl alcohol (PVA) from Merck, cellulose from Nitra Kimia, and activated carbon (AC) from a commercial source.

2.2. Synthesis of Cellulose Nanofibers

A solution of 135 ml H_2SO_4 was dissolved in 500 mL of distilled water and mixed with 10 grams of cellulose. The mixture was stirred at 400 rpm at 40°C for 2 hours. After stirring, the mixture was filtered and washed until a neutral pH was achieved. The filtered product was then dissolved in 1000 mL of distilled water and homogenized using an ultrasonic homogenizer for 10 minutes.

2.3. Synthesis of Cellulose Nanofiber Aerogel

A mixture of 0.6 grams of PVA and varying amounts of AC (0 wt%, 1 wt%, 2 wt%, and 3 wt%) was combined with a 13.4 grams of 1.5% CNF dispersion. The mixture was heated on a hotplate at 90°C for 2 hours; then distilled water was added to reach a total mass of 20 grams. The resulting mixture was poured into a silicone mold and subjected to freeze-drying for 48 hours.

3. Results and Discussion

3.1. Evaporation Rate

The Solar Steam Generator's (SSG) performance is evaluated by measuring the change in water mass per unit area of the evaporator over time. The evaporation rate is typically determined from the slope of the mass change over time (dm/dt) once the system has reached a steady state, where dm/dt remains nearly constant.

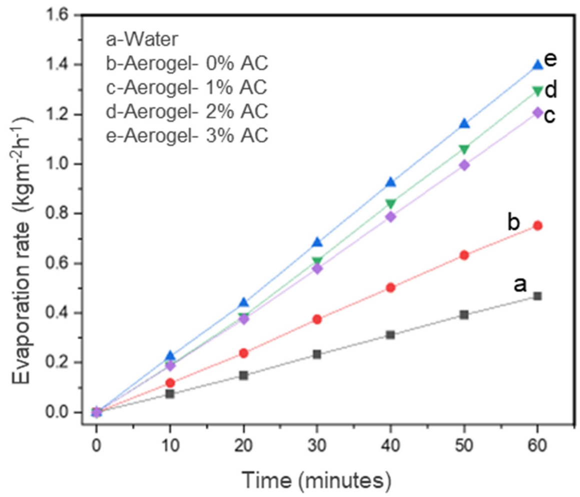

Figure 1. Evaporation rate of aerogels with various concentrations of activated carbon (AC).

The tests show that the highest evaporation rate, 1.39 kg/m²/h, was achieved in the sample containing 3 wt% activated carbon. This was followed by samples with 2 wt%, 1 wt%, and 0 wt% activated carbon, with evaporation rates of 1.29 kg/m²/h, 1.2 kg/m²/h, and 0.75 kg/m²/h, respectively.

The efficiency of the Solar Steam Generator (SSG) is directly correlated with the evaporation rate, increasing alongside the concentration of activated carbon in the sample. The sample with 3 wt% activated carbon achieved the highest efficiency of 58.56%, followed by samples with 2 wt%, 1 wt%, and 0 wt% activated carbon, which recorded efficiencies of 54.37%, 50.6%, and 31.52%, respectively.

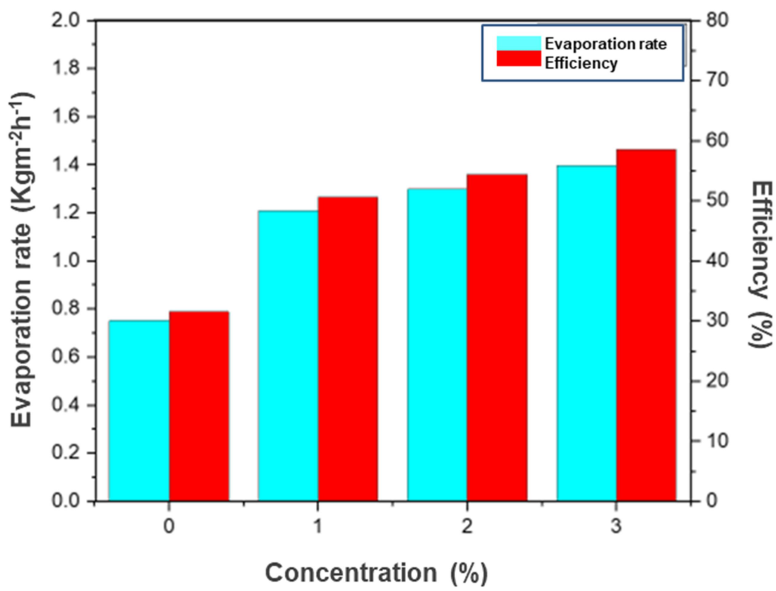

Figure 2. Evaporation rate and solar thermal efficiency.

3.2. Characterization

The cellulose nanofiber aerogel samples were analyzed to determine their morphology and observe the activated carbon's distribution and structure. A comparative analysis of the surface morphology between the 3 wt% AC (KA3 wt%) and 0 wt% AC (KA0 wt%) samples was conducted.

The magnified images reveal that the cellulose nanofiber aerogels possess a porous structure, as indicated by numerous cavities within the samples. Additionally, a rough surface texture is visible, which suggests the integration of cellulose nanofibers with PVA in the aerogels. This characteristic is evident in both samples, regardless of the presence of activated carbon filler.

The results align with previous research by Liu et al. (2021), which described a structure with irregular porosity resembling wood. This structure enhances water transfer and contributes to the improved efficiency of aerogels as evaporators in Solar Steam Generators (SSGs) [16].

FT-IR analysis revealed the presence of OH and C=O groups in the first sample, confirming the presence of PVA and cellulose. In the second sample, a significant decrease in transmittance at wavenumbers 985 and 1160 cm⁻¹ was observed. This decrease indicates the presence of activated carbon, which is rich in C=C and C-O bonds. The overall reduction in transmittance suggests an increase in infrared absorption due to the presence of activated carbon in the sample.

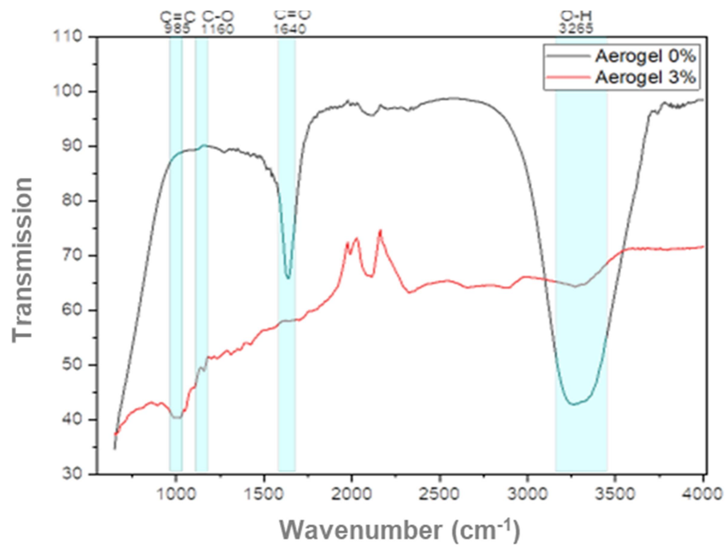

Figure 3. FT-IR of aerogel with 0 wt% (a) and 3 wt% (b) activated carbon.

4. Conclusion

Aerogels filled with commercially available activated carbon (AC) were successfully used for efficient solar steam generation under one sun illumination. The study achieved an evaporation rate of up to 1.39 kg/m²/h and an efficiency of 58.56%. FTIR analysis confirmed the beneficial impact of AC on the aerogel, particularly in enhancing infrared absorption. The improved evaporation efficiency of the aerogel-based Solar Steam Generator (SSG) is attributed to the strong absorption of visible, IR, and UV light by the materials used, the well-developed porous structure that enables better water supply and steam escape, and the low thermal conductivity that minimizes the temperature increase of bulk water. This study contributes to developing future solar steam generation systems using commercially available and long-term stable water evaporators that are also more affordable.

Acknowledgments

The author would like to thank the Basic Science Laboratory, Universitas Sumatera Utara (LIDA USU), for providing the research facilities.

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