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Experimental investigation of the effects of delignification of common woods in Iran on the performance of interfacial solar steam generators

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Abstract

Although the use of wood absorbers has been introduced as an effective method for the direct production of solar steam, only highly processed wood is a suitable candidate for these systems. Therefore, in this study, the impact of delignification on the performance of wooden absorbents is experimentally investigated in interfacial solar steam generators, so that a wider range of wood can be used as surface adsorbents. Six wood samples sourced from Iran were treated with a solution that contained 2.5 M NaOH and 0.4 M Na2SO3. After delignification, the porosity of all the samples increased to approximately 0.76, providing larger microchannels in the wood tissues. For an interfacial solar steam generator equipped with a carbonized natural poplar wood absorber, an evaporation rate of 3.63 kg/m^2hr was achieved, which was a 101% improvement compared with a volumetric solar steam generator. The delignification process had a significant impact on wood with naturally low evaporation rates, with the highest increase in evaporation rate observed in red poplar wood (25 %), reaching a rate of 3.35 kg/m^2hr. Furthermore, no salt deposition was observed on any of the samples after delignification, which is a significant issue for interfacial solar steam generators.

Keywords: Interfacial solar steam generator; Wooden absorbent; Delignification; Evaporation rate.

1. Introduction

Today, the challenging problem of drinking water shortage has affected a significant part of the world, for which water purification and desalination are known as basic solutions. Several methods have been proposed for water desalination, such as evaporation-distillation, electrodialysis, and reverse osmosis. However, these methods are expensive and result in environmental problems. In this situation, using a solar water softener can be very effective in reducing the production of greenhouse gases, in addition to meeting the human need for water desalination. The steam generator is an essential part of the solar water softener. There are two types of steam generators: volume and surface. In volumetric steam generators, solar radiation heats the entire volume of water in the steam generator tank. This issue is associated with considerable heat loss from the body of the device. However, in surface steam generators, by adding a floating substance to the water surface, solar radiation is absorbed and converted into heat only at the water-air interface.

The complexities of producing efficient artificial absorbents and their high cost are obstacles to the commercialization of surface steam generators. For this reason, many researchers have drawn attention to using natural materials as absorbent materials. Among natural materials, wood is cheap, non-toxic, and biodegradable, which makes it suitable as a solar absorber. The wood surface absorbs solar radiation and converts it to heat. However, it has low thermal conductivity and acts as a thermal insulator. Wood vessels act as natural microchannels, causing water to transfer from the reservoir to the absorbent surface.

Li et al. [1] investigated the performance of different types of wood as absorbent material. The wood surface was carbonized using a hot plate at 500 °C. Poplar wood exhibited the highest evaporation efficiency (86.7%) at a radiation intensity of 10 kW/m^2. The evaporation efficiency was further improved by 89% by sprinkling graphite onto the surface of the. Wood consists of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose are hydrophilic, while lignin is hydrophobic. Therefore, the water transport capacity of wood increases with lignin removal [2]. Delignification can also increase the number of voids in wood, thus reducing its thermal conductivity [3]. Ge-Zhang et al. [4] used delignified poplar wood, whose surface was coated with multi-walled carbon nanotubes, to make a steam-generating absorber. They showed that the use delignified wood without surface coating reduced the evaporation efficiency. With ultraviolet radiation in a 24h period, the evaporation efficiencies of natural wood and delignified wood were reported to be 21.9% and 20.4%, respectively. Meanwhile, the evaporation efficiency of the coated absorbents was 51.1%. Using a deep eutectic solvent, Chen et al. [5] delignified basswood and carbonized its surface using a flame. With the help of this absorber, the surface steam generator achieved an evaporation efficiency of 89% and an evaporation rate of 1.3 kg/m^{2}h at a radiation intensity of 1 kW/m^2.

Ghafurian et al. [6] made a surface steam generator using delignified poplar wood absorbent coated with iron/palladium nanoparticles. The evaporation efficiency of this device at a radiation intensity of 3 kW/m^2 was 103% higher than that of a similar volumetric steam generator. They showed that the evaporation efficiency could be increased up to 167% by using a two-layer absorber, in which the upper layer was similar to the previous one, and the lower layer was made of polystyrene foam.

A review of the available articles shows that removing lignin from the wood structure improves the evaporative performance of surface solar steam generators. However, it should be noted that the percentage of lignin and its chemical composition are different in different woods [7]. Based on the best knowledge of the authors, in this study, a common type of wood in each region was selected as an absorbent, and the effects of parameters such as coating, delignification, and the use of nanofluids on the evaporative efficiency of the steam generator were studied. The review of the articles shows that there is no significant information on the effect of delignification of different wood types on evaporation efficiency. Therefore, in this study, for the first time, six common woods in Iran were selected as surface solar steam-generating absorbents, and the effect of delignification on wood characteristics and evaporation efficiency was investigated experimentally.

2. Materials and methods

Based on the variety of climates in Iran, with priority given to abundance and economic efficiency, mulberry, pine, poplar, ash, white poplar, and red poplar trees were selected for study. Sodium hydroxide and sodium sulfite solutions were used for the delignification. To perform the tests, samples were prepared in the form of circular cylinders with diameters and heights of 36 and 10 mm, respectively. There are different methods for delignification that affect the quality of extracted lignin. In this study, the goal was to remove lignin from wood tissue, and the extracted lignin was not used. For delignification, wood samples were placed in a solution of 2.5M sodium hydroxide and 0.4M sodium sulfite and waved in an ultrasonic bath for 1h. This set was then left at room temperature for 24h to dissolve the lignin in the wood to a large extent in the solution. Subsequently, to wash and remove the solution and lignin remaining in the wood, the samples were placed in deionized water and waved in an ultrasonic bath for 1 h. Finally, by placing the samples in an oven, they were dried and ready for testing.

To increase light absorption, it is better to improve the radiant absorption coefficient of the wood surface. Owing to the simplicity and low cost of the process, as well as its significant effect on the light absorption property, a hot surface carbonization method was used in this research. In the heat treatment method, a plate of galvanized iron at a temperature of 500 °C was placed on the surface of natural wood for 60 s. This process causes the surface of the wood to be well carbonized, and its light absorption coefficient increases. The experimental setup included a sunlight simulator equipped with a 1600 W xenon lamp with a radiation temperature of 6000 K, manufactured by the Nano Shargh Tos Tool Company. In addition, a glass beaker with a height and diameter of 70 and 38 mm, respectively, was used as the light receiver, which contained water and a wooden absorber float on its surface. All tests were performed in 40 s at 3.3 kW/m^2 radiation intensity.

3. Results and discussions

During the delignification process, most of the resin on the wood surface was removed, and larger channels appeared. Owing to the hydrophobicity of lignin, this process improves the hydrophilic properties of wood. By eliminating lignin from the interstitial space and reducing the strength of the wood, its volume decreases, particularly in the direction perpendicular to the vessels (diameter of the samples). The deformations of the samples were not isotropic; therefore, the final shape of the samples deviated from the perfect circular shape. As a result of the reduction in wood mass, its density is reduced and its buoyancy is improved. Considering the importance of the buoyancy parameter in the selection of absorbent materials in surface solar steam generators, delignification makes wood a better candidate for this purpose. The results showed that after delignification, mulberry wood (23%) and poplar wood (2.5%) experienced the highest and lowest density reductions, respectively. Wood porosity was obtained from (1) [3].

$$\varphi = (m_b - m_a)/V\rho_w \qquad (1)$$

where m_a, m_b and V are the dry mass, wet mass, and volume of the sample, respectively. $\rho_w = 998\ \mathrm{kg/m^3}$ is the water density. The porosities of the samples before and after delignification are shown in Figure 1. According to this figure, the lower the porosity of the samples before delignification, the more they are affected by this operation. In such a way that regardless of wood porosity in its natural state, after delignification, the porosities of all samples were close to each other. Ignoring pine wood, which showed a different behavior, the average porosity of the samples after delignification was approximately 0.76. Poplar wood had the highest porosity after delignification (0.79).

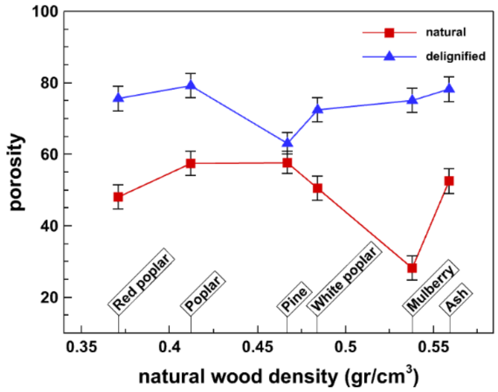

Figure 1. Wood porosity before and after delignification

In the absence of wood as an absorber, the received radiant heat was distributed throughout the volume, increasing the bulk temperature by 16°C. With the addition of wood, the heat received from the sun is localized on the surface, which increases the evaporation rate. Consequently, the bulk temperature decreased (16°C). The percentage of temperature reduction owing to the use of different woods in the two natural and delignified states is shown in Figure 2. For pine wood, the water bulk temperature increases by 15.6°C, which only shows a decrease of 2.6% compared to the volumetric evaporation state. However, for poplar wood, the increase in water bulk temperature is 13.4 °C, which is equivalent to a 16.1% reduction compared to volume evaporation. The reason for this behavior is the difference in thermal conductivity owing to the difference in wood porosity and the amount of lignin in its structure. Delignification, in addition to reducing thermal conductivity, improves the hydrophilicity of wood and simultaneously increases the diameter of the microchannels in its structure. As a result, the water transport ability of wood increased. Under these conditions, the increase in the bulk temperature in most samples was approximately 13°C.

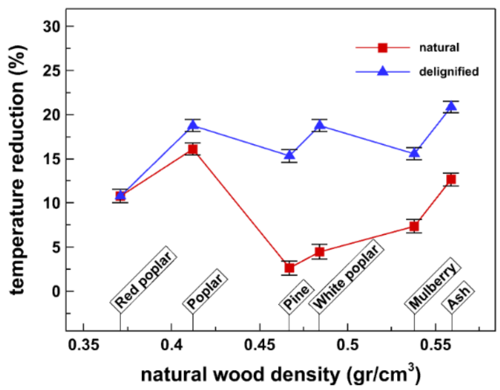

Figure 2. The effect of wood on reduction of water bulk temperature

The specific evaporation rate of the steam generator was defined by dividing the mass of evaporated water by the evaporation time per surface area of the sample. Figure 3 shows the evaporation rates of different samples before and after delignification. Without a wooden absorber (volumetric solar steam generator), the evaporation rate was equal to 1.81 kg/m^{2}h. By adding wood to the system, the rate of evaporation increased significantly, reaching 2.68 kg/m^{2}h with an increase of 48.4% for red poplar wood. This parameter for poplar wood was 3.63 kg/m^{2}h with a 101.3% increase.

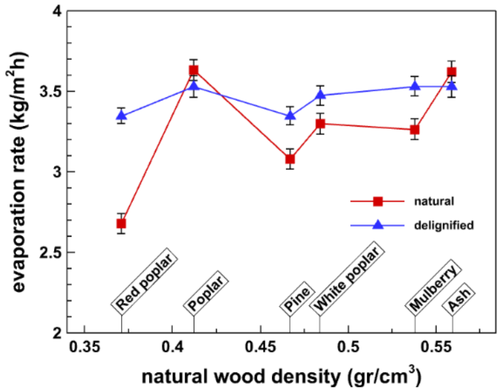

Figure 3. Effect of delignification on evaporation rate

Woods with a low natural evaporation rate experienced a significant increase in evaporation rate after delignification. For example, in red poplar wood, delignification increased the evaporation rate by 25%, reaching 3.35 kg/m^{2}h. This trend has been confirmed by other studies. Ghafurian et al.'s [6], showed that the evaporation rate of walnut and beech wood increased by 25% and 42%, respectively, as a result of delignification. Evaporation efficiency is an important parameter in determining the performance of steam generators, and is defined according to (2) [8].

$$\eta = (\dot{m} h_{fg})/IA \tag{2}$$

where, $\dot{m}$, h_{fg}, I and A are the evaporation mass, enthalpy, light intensity, and evaporation surface, respectively. The enthalpy of evaporation of pure water at atmospheric pressure is 2257 kJ/kg, and the light intensity is 3.3 kW/m^2.

The evaporation efficiencies of natural and delignified samples are listed in Table 1. In addition, the evaporation efficiency of steam generator which is equal to 34.3%, is reported in the table. The highest evaporation efficiency was related to natural poplar wood (69%), which is consistent with the results of Chen et al. [5]. This amount decreased to 67.1% after delignification. This behavior was also reported by Ge-Zhang et al. [4]. Interestingly, after delignification, the evaporation efficiency of all wood species was in the same range, at 65.7% on average for the tested samples. Therefore, it seems that as a result of delignification, the performance of the surface steam generator is largely independent of the type of wood used as absorbent material, and a similar conclusion has been made in the study of Ghafurian et al. [6].

Table 1. Evaporation efficiency before and after delignification (%)

	natural		delignified	
	η	%	η	%
No wood	34.3	-	-	-
Red poplar	50.9	48.4	63.3	85.5
Pine	58.5	70.7	63.6	85.5
Mulberry	62.0	80.9	67.1	95.6
White poplar	62.7	82.8	66.0	92.5
Ash	68.8	100.6	67.1	95.6
Poplar	69.0	101.3	67.1	95.6

One of the requirements of a solar steam generator is its stable performance over time. As seawater evaporates from the surface of the absorbent, its salt remains on wood. Salt deposition closes wood microchannels and reduces their ability to deliver water. However, by depositing salt, the solar absorption coefficient of the surface decreases, and less heat is released for evaporation. A very important result of this study is that after delignification, salt deposition was not observed in any of the samples. This is one of the most important effects of delignification, which guarantees the stable operation of the solar steam generator.

4. Conclusions

In this study, the effect of lignin removal from wood absorbents on the performance of a surface solar steam generator was investigated experimentally. Wood samples were prepared from six common trees in Iran. The most important results obtained in this study are as follows:

1) The porosity of the samples increased owing to the delignification. Except for pine wood, whose porosity changed by only 9% after delignification, the porosities of the other samples increased significantly. Mulberry wood received the most impact from the delignification process, with a 165% increase in porosity. Poplars with a porosity of 0.79 obtained the highest porosity after delignification.
2) The lower the porosity of the samples before delignification, the more they are affected by this process. On average, the porosities of the samples after delignification were almost equal (approximately 0.76)
3) Woods with a low initial evaporation rate, such as red poplar and pine, showed a significant increase in evaporation rate after delignification. The highest increase in evaporation rate was observed in red poplar wood, which increased by 25%, reaching 3.35 kg/m^{2}h.
4) After delignification of the absorbent wood, salt deposition was not observed in any sample. Therefore, delignification ensures continuous operation of the surface steam generator.

5. References

[1] Li T, Liu H, Zhao X, Chen G, Dai J, Pastel G, Jia C, Chen C, Hitz E, Siddhartha D, Yang R, Hu L (2018) Scalable and Highly Efficient Mesoporous Wood-Based Solar Steam Generation Device: Localized Heat, Rapid Water Transport. *Adv. Funct. Mater.* 28(16): 1707134.

[2] Mredha MTI, Pathak SK, Cui J, Jeon I (2019) Hydrogels with Superior Mechanical Properties from the Synergistic Effect in Hydrophobic–Hydrophilic Copolymers. *Chem. Eng. J.* 362(15): 325-338.

[3] Li Y, Fu Q, Yu S, Ya M, Berglund L (2016) Optically Transparent Wood from a Nanoporous Cellulosic Template: Combining Functional and Structural Performance. *Biomacromolecules* 17: 1358-1364.

[4] Ge-Zhang S, Yang H, Mu H (2023) Interfacial solar steam generator by MWCNTs/carbon black nanoparticles coated wood. *Alexandria Eng. J.* 63: 1-10.

[5] Chen Z, Dang B, Luo X, Li W, Li J, Yu H, Liu S, Li S (2019) Deep Eutectic Solvent-Assisted in Situ Wood Delignification: A Promising Strategy to Enhance the Efficiency of Wood-Based Solar Steam Generation Devices. *ACS Appl. Mater. Interfaces* 11(29): 26032–26037.

[6] Ghafurian MM, Niazmand H, Goharshadi EK, Bakhsh Zahmatkesh B, Moallemi AE, Mehrkhah R, Mahian O (2020) Enhanced solar desalination by delignified wood coated with bimetallic Fe/Pd nanoparticles. *Desalination* 493: 114657.

[7] Li J, Chen C, Zhu JY, Ragauskas AJ, Hu L (2021) In Situ Wood Delignification Toward Sustainable Applications. *Acc. Mater. Res.* 2(8): 606-620.

[8] He Y, Li H, Guo X, Zheng R (2019) Delignified wood-based highly efficient solar steam generation device via promoting both water transportation and evaporation. *BioResources* 14(2): 3758-3767.