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Improvement of Surface Evaporation by Reducing Heat Transfer to Fluid Bulk and Increasing Heat Absorption

A. Anjomrouz*

Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

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ABSTRACT

Surface evaporation is important in many natural phenomena and industrial applications; Therefore, improving this phenomenon is very useful. In this research, the water evaporation rate is increased by designing an innovative structure by inspiring from plant structures. This structure has two main effects, firstly, it reduces the amount of heat transferred to the fluid bulk through the surface and secondly, it increases the amount of heat absorption on the surface. This structure consists of three parts: an evaporation layer, insulation, and water-absorbing fibers. After many investigations on different materials to choose the best materials for these three parts, expanded polystyrene foam and cotton fibers showed the best performance. The structure after construction and testing was able to increase the mass of evaporated water during 24 hours by 28%. It also increased the temperature of the water surface in the evaporation process during 24 hours by 16%; This caused the water to evaporate at a high temperature. In addition, the mentioned structure increased the thermal efficiency up to 85% in the radiant flux of 0.6 kW/m^2. The proposed structure is scalable for any size and cost-effective.

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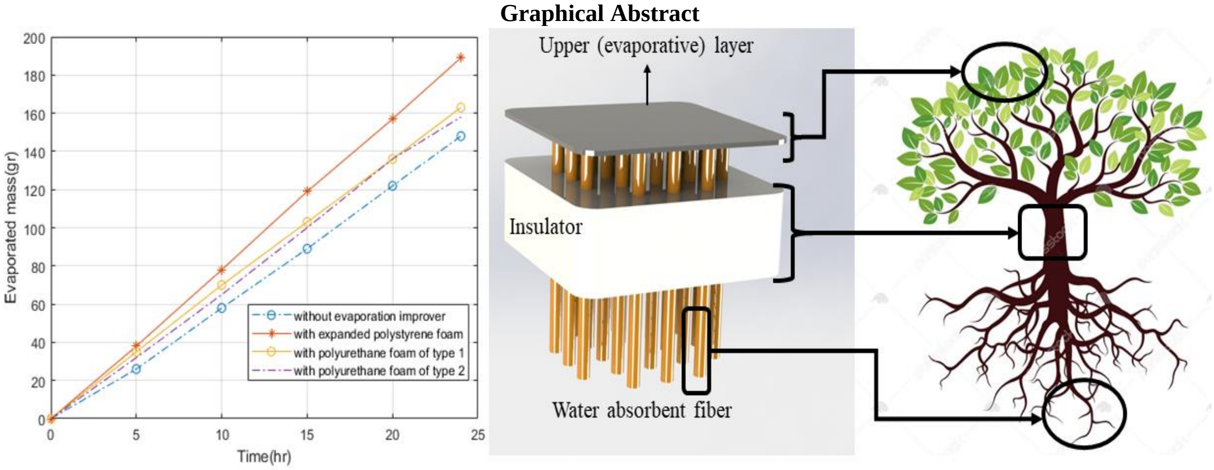
Graphical Abstract



NOMENCLATURE

A	Area	q''	Heat flux
h_{fg}	Enthalpy of vaporization	**Greek Symbols**	
$\dot{m}$	Mass flow rate	η_{th}	Thermal efficiency

*Corresponding Author Email: *amin.anjomrouz@mech.sharif.edu* (A. Anjomrouz)

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1. INTRODUCTION

Today, the process of fluid evaporation plays an important role in different industries and human life. From cooling towers in power plants to water desalination industries and even cooling a glass of hot tea, all of them are among the applications of the evaporation phenomenon. Given this widespread use of evaporation, the improvement of this process is also of particular importance. For example, one of the applications of this research is the evaporation of water by solar heat in water desalination which is important in many parts of the world. The main focus of the present study is on improving surface evaporation by reducing heat transfer to the fluid bulk and increasing heat absorption. This method of improving surface evaporation can improve the evaporation rate and efficiency of solar water purification.

According to the latest research, Ghasemi et al. (1) were able to achieve a thermal efficiency of more than 95% at a radiation intensity of 10 kW/m^2 by designing an innovative structure. This structure consists of two main parts: the upper part of the structure is an absorbent hydrophilic layer, and the lower part of it, is an insulating hydrophilic layer. Chen et al. (2), stated that in some applications such as solar water heaters, solar thermoelectric generators, etc.; there is a need for a type of solar absorber with high absorption and low radiation coefficients. They designed several colored absorber layers, on the TiN_xO_y base, which had an absorption coefficient of more than 95% and a radiation coefficient of less than 5%. Ni et al. (3) developed a floating absorber that was able to produce 100 °C vapor in ambient conditions under sunlight without the use of optical focusing methods. The idea used in this research was to use heat centralization and reduce the conduction and radiation heat transfer losses. Another feature of this structure is the low cost of construction and the ability to build on different scales. Li et al. (4) developed a graphene oxide-based evaporation-improving structure for desalination applications. This structure increased the thermal efficiency of the evaporation process by up to 80% and increased the desalination process's efficiency by four times. Zhu et al. (5) used black titania to create a nanocage structure to trap the light, increasing the rate of water evaporation to achieve a thermal efficiency of 70.9% at a flux of 1 kW/m^2. Zhou et al. (6) developed an evaporation-improving structure using aluminum nanoparticles embedded in a three-dimensional porous layer. This layer floats on the surface of the water, absorbs more than 96% of the sun's radiation, and concentrates it on the water's surface. With this structure, they were able to complete the water desalination process with 90% efficiency. Ouar et al. (7) examined the effect of three different coatings (bitumen, charcoal, and ink) to improve heat absorption and increase evaporation in a solar desalination plant and found that bitumen, charcoal, and ink coverages were approximately 25%, 18%, and 6% increase the efficiency of the desalination system respectively. Liu et al. (8) were able to improve the efficiency of a solar desalination plant by adding a suitable structure with a high absorption rate so that under one sun, the evaporation efficiency is 79% per day. To make this structure, they used active plasma filter paper as a photothermal material with a pleasant light absorption range of up to 92%. Huang et al. (9) used polypropylene coating on a polypropylene membrane to increase the efficiency of solar water vapor production by up to 72%. The reason for using polypropylene coating has a broad absorption spectrum that is almost consistent with the radiation spectrum of the sun, high efficiency in converting radiation into heat, and high stability of this material. Xu et al. (10) used a mushroom as a living organism that can improve the evaporation rate. They found that due to the structural properties of some mushrooms, they could be used as an evaporation-improving structure. In this study, they were able to achieve a thermal efficiency of 62% and 78% at a radiation intensity of 1 kW/m^2, using a natural mushroom and a carbonized mushroom, respectively. Ni et al. (11) were able to build a floating solar desalination plant that improved the rate of water evaporation and desalination efficiency by adding a floating structure on the water. Important features of this innovative structure were removing salt from the structure, increasing the absorption coefficient of solar energy, cost-effectiveness, etc. Li et al. (12) while stating that in general the rate of water evaporation is limited by radiant heat from the sun, designed a structure that, assumes a 100% efficiency of solar energy transfer for water evaporation. To make this structure, they used a linen core and several rods made of multilayer plant cellulose, which were deeply coated with ethyl alcohol-soluble carbon nanoparticles. The core was then placed on an insulating layer of polystyrene foam. Zhao et al. (13) developed a surface evaporation enhancer using a nanostructured gel based on polyvinyl alcohol and polypyrrole. Using this structure, they were able to achieve an evaporation rate of 2.3 $kg/h/m^2$ at a radiation intensity of 1 kW/m^2. They also increased the thermal efficiency of the evaporation process by 94%. Hu et al. (14) improved the surface evaporation rate in a desalination plant by designing a multilayer structure. This structure is composed of several materials including silicon oxide, cellulose nanofiber, and carbon nanotube. The bottom layer of this structure is hydrophilic to absorb and pump the water, and at the upper part where the evaporation process takes place, a hydrophobic layer is considered. Also, the special design and porosity of this structure prevent the separated salt from depositing on the upper layer of the structure and moving toward the lower part of the structure. Miao et al. (15) designed an innovative structure to increase heat transfer efficiency by 84.6%. In this structure, a layer of carbon nanotube was used as a solar absorber, a piece of aerogel as heat insulation, and a layer of filter paper to transfer water. In a review article, Wang et al. (16) investigated the methods and challenges of desalination of water with solar energy. A lot of research has been done in the field of improving evaporation efficiency. In this article, they reviewed the basic principles of optimal design of a solar desalination system which includes the development of suitable materials for this application and system development. Guo et al. (17) developed an evaporation-improving structure made of hydrophilic hydrogels with island-like fragments of hydrophobic material. This structure was able to increase the evaporation rate to about 4 $kg/h/m^2$ with an efficiency of 93% (at a radiant heat flux of 1 kW/m^2). They also examined the fabricated structure and the rate of water evaporation at the molecular level using molecular dynamics simulations, and a logical output consistent with the experimental results was obtained.

In lots of previous research, studied the evaporation efficiency specifically for the application of solar desalination and pure water generation.They proposed method improved evaporation in appropriate manor for this application (18-20); However, in this study, the surface evaporation has been improved for a general case and the proposed solution is not limited to a specific application.

In previous research, increasing the evaporation efficiency has been studied by methods such as using micro and nanostructures (21-23), using strong adsorbents (2, 7, 8), using hydrogel materials (24-26), etc. Many previous methods of evaporation improvement are so complex and expensive to use by everyone, but in the present study, the main emphasis is on improving the evaporation rate with a high thermal efficiency by using an innovative, economical, simple, and scalable structure inspired by the structure of plants is proposed for this purpose.

The idea of this study is to improve the evaporation rate, by reducing the heat transfer from the fluid surface to the fluid bulk and concentrating the heat in a thin layer of fluid on the fluid surface.

As can be seen in Figure 1 fluid heating occurs in three modes: bottom heating, bulk heating, and interfacial heating. In this research, the heating of the fluid volume should be prevented and the heat radiated to the fluid (for example, from the sun) should be concentrated on the surface. In this way, surface evaporation should be improved.

2. MATERIAL AND METHODS

In this section, the test device and measuring instruments used in this research are described and at the end, how the experiments are performed is explained.

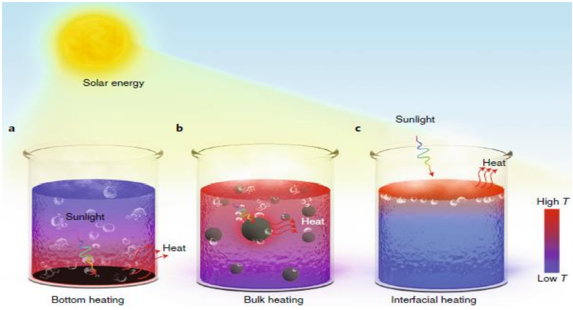

Figure 1. Three types of fluid heating (27)

2. 1. Setup Preparation In this study, since the purpose is to investigate surface evaporation, the heat transferred to the fluid must also be from the fluid surface, such as fluid evaporation using heat from sunlight. To keep the heating conditions constant during the test, a heat source with an output power of approximately 0.6 kW/m^2 is used. Also, a container with dimensions of 10*10*20 cm^3 is used to store the fluid. The main part of the test apparatus in this study (by which the test goal i.e., improving surface evaporation is achieved) is an innovative structure that improves evaporation. This structure consists of several parts. Figure 2 shows the test bed details.

2. 2. Materials The first part of the innovative structure is an insulator that aims to prevent heat transfer to the fluid volume; Which must be on the surface of the fluid and therefore need to have a lower density than the fluid. In this research, three types of foam with a thickness of 3.5 cm have been used as insulating material.

The second part of the structure is the fiber, which at this structure has the same function as plant vessels; The purpose of these fibers is fluid suction and according to this purpose, cotton has been selected as the material for these fibers. How to connect these two parts of the desired structure should be such that the water under the insulation layer is sucked by the fibers to the top of the structure.

The third part of the structure designed in this research is a type of hydrophilic layer that in addition to high wettability, must also have a high heat absorption coefficient. In this research, this layer is known as the evaporative layer. Many factors affect the high thermal absorption coefficient of this layer, which are the material, color of the layer, etc. The first feature considered in this study for the evaporative layer is that the effective surface of this layer is high relative to the geometric dimensions. This feature increases the rate at which fluid evaporates from the surface. To create this condition, a layer of cloth with regular villi in millimeter dimensions was used. The second feature of the evaporative layer used in this research is its color. Since black color has the highest heat absorption coefficient, it has been used as a suitable color for the evaporative layer.

The third feature of this layer is its material. The material of the evaporative layer should be selected from a hydrophilic material that has a good water absorption rate. For this purpose, cotton is used as the evaporative layer material.

As mentioned above, this structure has the same function as what happened in the plants and there is an analogy between them. More details on how plants work are explained by Bohr et al. (28). Figure 3 shows this analogy. According to this figure, the water-absorbing fibers are equivalent to the root and the vessels connected to it (which have the task of transferring water to different parts), the insulation part is equivalent to the stem (which is the place where the vessels pass), and the evaporation surface is equivalent to the leaf in a plant.

In this research, one type of expanded polystyrene foam and two types of polyurethane foam were used as insulation on the evaporation-improving structure. The expanded polystyrene foam is impermeable (closed cell) but polyurethane foams are permeable (open cell). The characteristics of these three types of foam are presented in Table 1.

2. 3. Measuring Instruments A digital scale and a digital thermometer are mainly used. The scale has a measurement resolution of 1 gram with a measurement error of ±1 gram. Also, the thermometer has a measurement resolution of 0.1 °C with an accuracy of 0.1 °C.

The characteristics of foams are measured. The density is obtained by measuring the mass and volume of a sample of each foam. The water absorption is measured by subtraction of the maximum mass of a wet foam and a dry one for each experimented foam. Contact angle measurement was performed according to ASTM D-7334-08 (29) with Jikan (30)CAG-20 SE device.

2. 4. Test Procedure The experiments performed in the present study are divided into two categories. To reduce the effect of errors in the experiment, in each category, if necessary, the experiments are repeated and averaging is used .

In the first group of experiments, the effect of reducing the fluid mass on the evaporation rate is investigated. In this section, no evaporation-improving structure is used and by reducing the mass of the initial water in the container from 1900 to 1700, 1500, and 1300 grams, its effect on the amount of water evaporation is checked.

In the second group, four experiments are done. This group aims to find the effect of the evaporation-improving structure. The mass of water in this group is 1900 grams. In the first experiment, there is no evaporation improver. In the second experiment, an evaporation improver with expanded polystyrene foam is used, in the third experiment evaporation improver with polyurethane foam of type 1 is used and in the fourth experiment evaporation improver with polyurethane foam of type 2 is used.

In this research, the tests were performed within 24 hours, and data collection was done at 0, 5, 10, 15, 20, and 24 hours after the start of the test. Data recorded in each experiment includes fluid mass and fluid surface temperature. In Table 2. the number of each experiment can be seen along with its specifications.

3. RESULTS AND DISCUSSION

For the first group of experiments, in Figures 4 and 5 the mass of evaporated water and Fluid surface temperature are presented in terms of the initial mass of water, respectively.

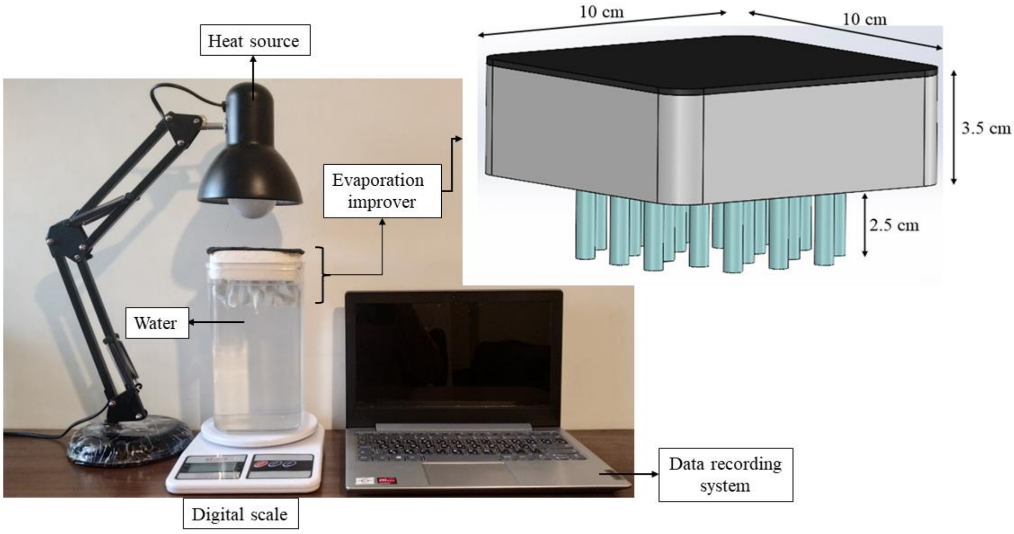

Figure 2. Test bed details

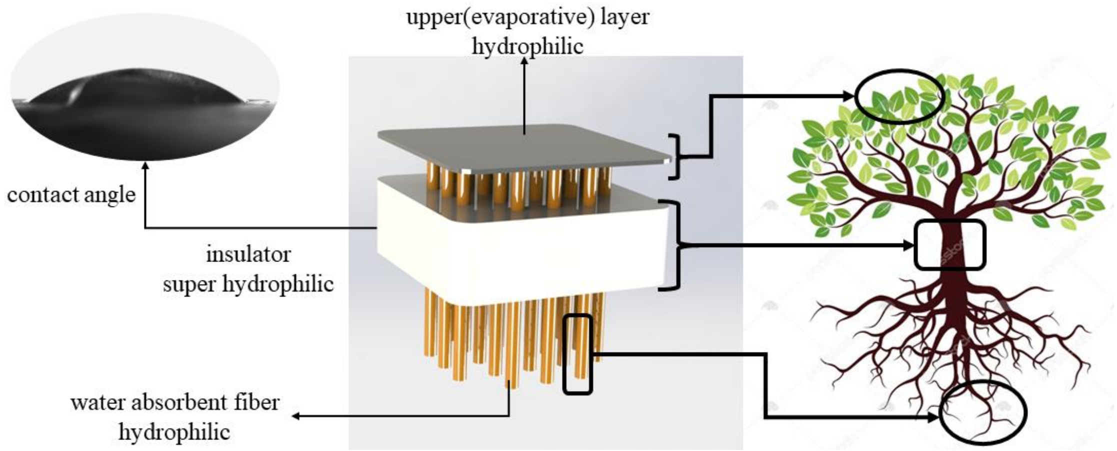

Figure 3. Details of the evaporation-improving structure and the analogy with the plants

TABLE 1. Characteristics of three types of foam used in this research

	Density ($\frac{kg}{m^3}$)	Water absorption (g)	Average contact angle (°)
Expanded polystyrene foam	27.5	0	under 10
Polyurethane foam of type 1	38.6	27	71.4
Polyurethane foam of type 2	13.6	70	78.3

TABLE 2. Specifications of experiments

Number of experiment		Specification
1st group	1	Without evaporation improver, initial water mass is 1900 gr.
	2	Without evaporation improver, initial water mass is 1700 gr.
	3	Without evaporation improver, initial water mass is 1500 gr.
	4	Without evaporation improver, initial water mass is 1300 gr.
2nd group	1	Without evaporation improver, initial water mass is 1900 gr.
	2	With evaporation improver by expanded polystyrene foam, initial water mass is 1900 gr.
	3	With evaporation improver by polyurethane foam of type 1, initial water mass is 1900 gr.
	4	With evaporation improver by polyurethane foam of type 2, initial water mass is 1900 gr.

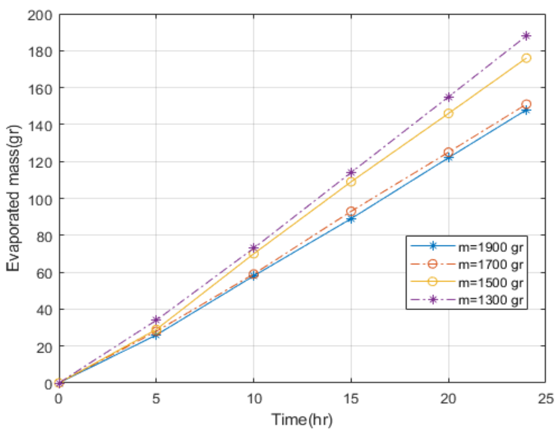

Figure 4. The mass of evaporated water in terms of initial water mass (without evaporation improver structure)

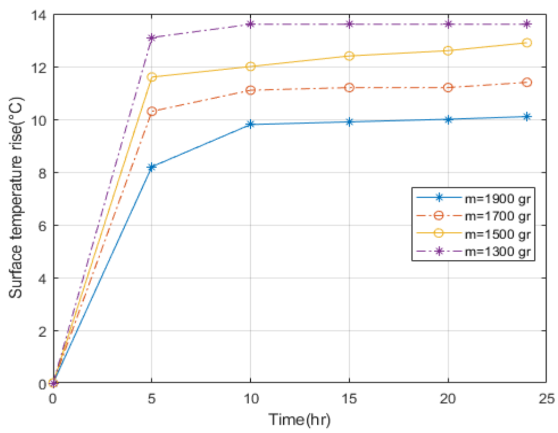

Figure 5. Fluid surface temperature rise in terms of initial water mass (without evaporation improver structure)

According to Figure 4 the amount of water evaporation increases with a decrease in the mass of the fluid bulk. Although this increase in evaporation is not the same for all experiments, on average, with each reduction of 200 grams of fluid mass, the amount of water evaporation increases by about 8%. To compare the temperature changes similarly, according to Figure 5 with the reduction of the fluid bulk mass, the changes in the water surface temperature increase. Although this increase is not the same for all experiments, on average, the water surface temperature gradient increases by about 8% with each 200g reduction of the fluid mass. According to the results of the first group of experiments, if the mass of the fluid bulk continues to decrease, it will lead to a thin film of fluid that is against the heat in the limiting case; In this case, the rate of evaporation will be higher than all the previous cases (with more fluid mass). With this idea, in the second group of experiments, a thin fluid film is tried to be exposed to heat.

For the second group of experiments, in Figure 6 the change in the fluid mass and temperature of the fluid surface in 24 hours for experiments 1 to 4 are presented, respectively. The initial surface temperature is about 27 °C in these experiments.

For a more detailed analysis, in Figure 7 a comparison between the mass of evaporated water in experiments 1 to 4 has been made. According to this figure, the evaporation-improving structure with expanded polystyrene foam, the evaporation-improving structure with polyurethane foam of type 1, and the

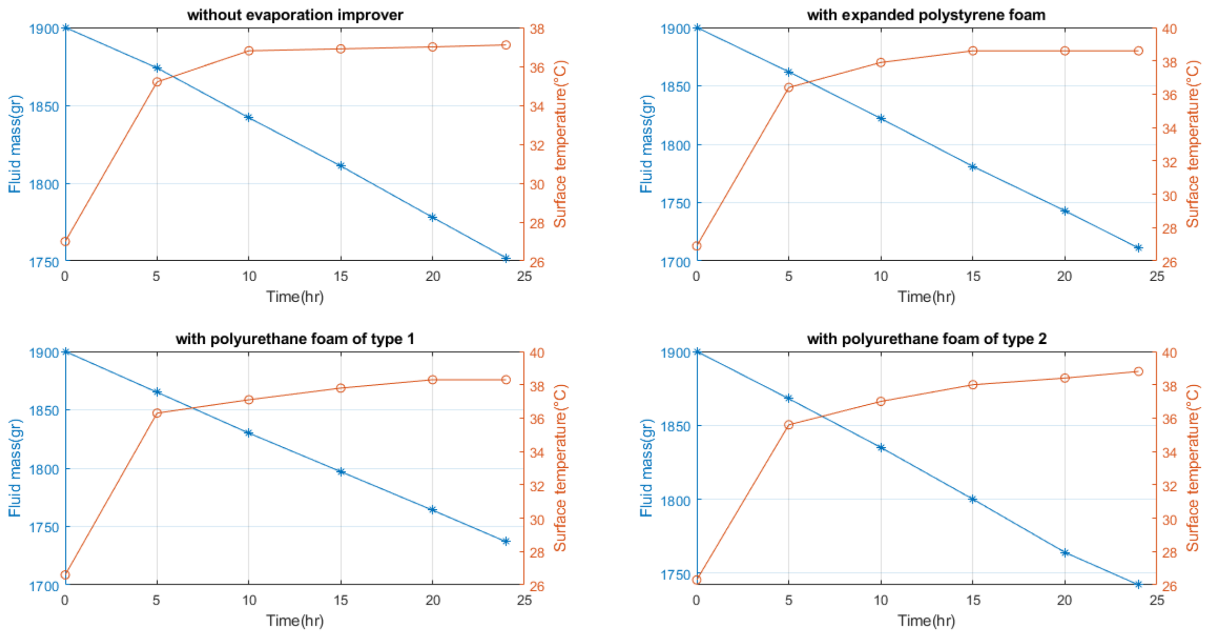

Figure 6. Fluid mass and temperature of the fluid surface with different evaporation improver structures

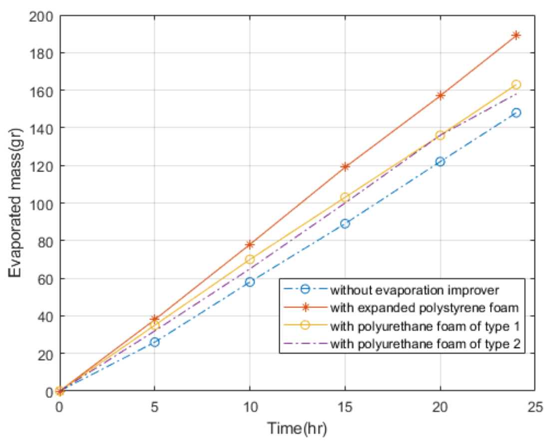

Figure 7. Comparison between the mass of evaporated water with different evaporation improver structures

evaporation-improving structure with polyurethane foam of type 2 respectively improved about 28, 10, and 7% in the amount of water evaporation in 24 hours.

In Figure 8, a comparison has been made between the temperature of the fluid surface in these four tests. According to this figure, the evaporation-improving structure with expanded polystyrene foam, the evaporation-improving structure with polyurethane foam of type 1, and the evaporation-improving structure with polyurethane foam of type 2 cause an increase of about 16, 13 and 20% in the temperature of the fluid surface, respectively. In this way, it is understood that the use of an evaporation-improving structure increases the steady-state surface temperature of water by about 2 degrees, which is an effective factor in the rate of water evaporation.

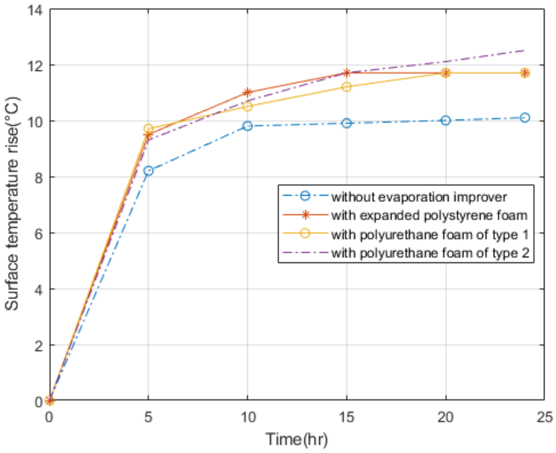

Figure 8. Comparison between fluid surface temperature rise with different evaporation improver structures

TABLE 3. Summary of the results for the second group of experiments

Specification	Increase in mass of evaporated water (%)	Increase in water surface temperature (%)
Evaporation emprover with expanded polystyrene foam	28	16
Evaporation improver with polyurethane foam of type 1	10	13
Evaporation improver with polyurethane foam of type 2	7	20

In the continuation of this section, the physical justification related to the cause of the difference between the results of the proposed structures in this research is discussed. It was observed above that in general the results of the structure made of expanded polystyrene foam are better than the results of the structure made of polyurethane foam of type 1. Also, the results of the structure made of polyurethane foam of type 1 are better than the results of the structure made of polyurethane foam of type 2. The reason for this issue can be attributed to the main difference between the two types of expanded polystyrene foam and polyurethane foam, which is water permeability. Expandable polystyrene foam does not allow water to pass through itself, and therefore all the insulation capacity is used to prevent heat transfer to the fluid volume. However, polyurethane foam passes water and gets wet after a while, and this makes the thermal conductivity of the wet foam to be higher than the thermal conductivity of the dry foam, and the performance of the insulation is problematic. This issue is also true for the two types of polyurethane foam used because one of the differences between the first and second type polyurethane foam is that the second type foam has a higher permeability than the first type foam, and as a result, after wetting will make the insulation weaker.

The main heat transfer mechanisms and energy balance between them are shown in Figure 9. According to Zhang et al. (31) and Zhuang et al. (32), thermal efficiency can be defined as Equation 1, where $\dot{m}$ is the evaporated mass flow rate, h_{fg} is the total enthalpy of liquid to vapor phase change, A is the cross-sectional area exposed to heat, and q'' is the heat flux radiated to the surface.

$$\eta_{th} = \frac{\dot{m}h_{fg}}{q'' A} \tag{1}$$

By using the above relationship, the thermal efficiency related to the evaporation process with the improving structure with expanded polystyrene foam is obtained at approximately 85% at a heat flux of 0.6 kW/m^2. In Table 4 a comparison of heat flux, efficiency and evaporation rate for some similar research is done.

One of the advantages of the method presented in this research is its economic efficiency. The majority of the cost spent on the construction of the evaporation-improving structure is related to the insulation and cotton fibers. Roughly, the cost spent for the construction of

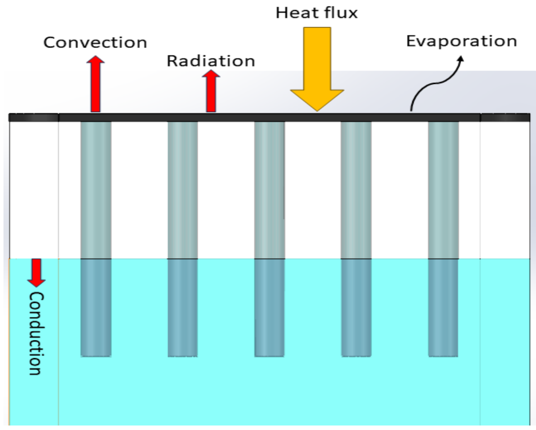

Figure 9. Energy balance and heat transfer diagram

TABLE 4. Comparison of heat flux, efficiency and evaporation rate for some similar research

Research	Heat flux (kW/m^2)	Efficiency (%)	Evaporation rate ($kg/h/m^2$)
Liu et al. (8)	0.9	79	0.97
Miao et al. (15)	1	84.6	1.31
Guo et al. (17)	1	93	4.0
Wang et al. (33)	1	54.6	0.87
Li et al. (34)	1	84	1.3
Lu et al. (35)	1	80	2.4
Present Study	0.6	85	0.79

each square meter of this structure is estimated at \$15. Also, according to the scalability of the designed structure and the linear growth of costs, the cost of building this structure can be calculated by the proportional method.

4. CONCLUSION

In summary, the cost-effective, innovative, simple, and scalable structure inspired by plant structure is proposed to improve the evaporation rate with a high efficiency.

In the present study, two groups of experiments are conducted. The first group of tests is performed to check the effect of fluid mass reduction on the rate of evaporation. The results of this group of experiments showed the upward trend of improving the evaporation rate with the reduction of the fluid mass so that with each reduction of 200 grams of the fluid mass, the fluid evaporation rate increased by about 8%; Also, the increase in water surface temperature also increased by about 8%. The results of this group of experiments inspired the fact that by gradually reducing the fluid mass until a thin film is reached, the evaporation rate can be continuously increased, which became the basis of the second group of experiments.

In the following, by designing and building an innovative structure and placing it on water, the rate of evaporation of water due to the heat radiating to its surface was increased. The main reason for this improvement in evaporation is two main things: the first reason is that the designed structure prevents the heat transfer from the surface to the depth of the water, and the heat radiated to the fluid is concentrated in a thin film; the second reason is that an increase in the heat absorption coefficient by the improving structure. The second group of experiments conducted in this research is dedicated to investigating the effects of the evaporation-improving structure on the rate of water evaporation.

The evaporation-improving structure designed in this research in the best case (use of expanded polystyrene foam) was able to increase the amount of water evaporation during 24 hours by 28%. This improving structure also increased the surface temperature of water in the evaporation process by 16%. It was also able to increase the thermal efficiency of the evaporation process to about 85% at a heat flux of 0.6 kW/m^2, which is at an optimal level compared to previous research.

To enhance future investigations, it is recommended to explore alternative absorbent materials for the top layer of the structure and conduct further experiments with varying heat fluxes to improve the efficiency and evaporation rate. Additionally, it would be beneficial to seek out a numerical simulation approach to eliminate the need for further experimentation.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Ghasemi H, Ni G, Marconnet AM, Loomis J, Yerci S, Miljkovic N, et al. Solar steam generation by heat localization. Nature Communications. 2014;5(1):4449. https://doi.org/10.1038/ncomms5449
2. Chen F, Wang S-W, Liu X, Ji R, Yu L, Chen X, et al. High performance colored selective absorbers for architecturally integrated solar applications. Journal of Materials Chemistry A. 2015;3(14):7353-60. https://doi.org/10.1039/C5TA00694E
3. Ni G, Li G, Boriskina SV, Li H, Yang W, Zhang T, et al. Steam generation under one sun enabled by a floating structure with thermal concentration. Nature Energy. 2016;1(9):1-7. https://doi.org/10.1038/nenergy.2016.126
4. Li X, Xu W, Tang M, Zhou L, Zhu B, Zhu S, et al. Graphene oxide-based efficient and scalable solar desalination under one sun with a confined 2D water path. Proceedings of the National Academy of Sciences. 2016;113(49):13953-8. https://doi.org/10.1073/pnas.1613031113
5. Zhu G, Xu J, Zhao W, Huang F. Constructing black titania with unique nanocage structure for solar desalination. ACS Applied Materials & Interfaces. 2016;8(46):31716-21. https://doi.org/10.1021/acsami.6b11466
6. Zhou L, Tan Y, Wang J, Xu W, Yuan Y, Cai W, et al. 3D self-assembly of aluminium nanoparticles for plasmon-enhanced solar desalination. Nature Photonics. 2016;10(6):393-8. https://doi.org/10.1038/nphoton.2016.75
7. Ouar MA, Sellami M, Meddour S, Touahir R, Guemari S, Loudiyi K. Experimental yield analysis of groundwater solar desalination system using absorbent materials. Groundwater for Sustainable Development. 2017;5:261-7. https://doi.org/10.1016/j.gsd.2017.08.001
8. Liu Z, Yang Z, Huang X, Xuan C, Xie J, Fu H, et al. High-absorption recyclable photothermal membranes used in a bionic system for high-efficiency solar desalination via enhanced localized heating. Journal of Materials Chemistry A. 2017;5(37):20044-52. https://doi.org/10.1039/C7TA06384A
9. Huang X, Yu Y-H, de Llergo OL, Marquez SM, Cheng Z. Facile polypyrrole thin film coating on polypropylene membrane for efficient solar-driven interfacial water evaporation. RSC Advances. 2017;7(16):9495-9. https://doi.org/10.1039/C6RA26286D
10. Xu N, Hu X, Xu W, Li X, Zhou L, Zhu S, et al. Mushrooms as efficient solar steam-generation devices. Advanced Materials. 2017;29(28):1606762. https://doi.org/10.1002/adma.201606762
11. Ni G, Zandavi SH, Javid SM, Boriskina SV, Cooper TA, Chen G. A salt-rejecting floating solar still for low-cost desalination. Energy & Environmental Science. 2018;11(6):1510-9. https://doi.org/10.1039/C8EE00220G
12. Li X, Li J, Lu J, Xu N, Chen C, Min X, et al. Enhancement of interfacial solar vapor generation by environmental energy. Joule. 2018;2(7):1331-8. https://doi.org/10.1016/j.joule.2018.04.004
13. Zhao F, Zhou X, Shi Y, Qian X, Alexander M, Zhao X, et al. Highly efficient solar vapour generation via hierarchically nanostructured gels. Nature Nanotechnology. 2018;13(6):489-95. https://doi.org/10.1038/s41565-018-0097-z

14. Hu R, Zhang J, Kuang Y, Wang K, Cai X, Fang Z, et al. A Janus evaporator with low tortuosity for long-term solar desalination. Journal of Materials Chemistry A. 2019;7(25):15333-40. https://doi.org/10.1039/C9TA01576K

15. Miao E-D, Ye M-Q, Guo C-L, Liang L, Liu Q, Rao Z-H. Enhanced solar steam generation using carbon nanotube membrane distillation device with heat localization. Applied Thermal Engineering. 2019;149:1255-64. https://doi.org/10.1016/j.applthermaleng.2018.12.123

16. Wang Z, Horseman T, Straub AP, Yip NY, Li D, Elimelech M, et al. Pathways and challenges for efficient solar-thermal desalination. Science Advances. 2019;5(7):eaax0763. https://doi.org/10.1126/sciadv.aax0763

17. Guo Y, Zhao X, Zhao F, Jiao Z, Zhou X, Yu G. Tailoring surface wetting states for ultrafast solar-driven water evaporation. Energy & Environmental Science. 2020;13(7):2087-95. https://doi.org/10.1039/D0EE00399A

18. Wang Z, Wu X, He F, Peng S, Li Y. Confinement capillarity of thin coating for boosting solar-driven water evaporation. Advanced Functional Materials. 2021;31(22):2011114. https://doi.org/10.1002/adfm.202011114

19. Wang Z, Wu X, Dong J, Yang X, He F, Peng S, et al. Porifera-inspired cost-effective and scalable "porous hydrogel sponge" for durable and highly efficient solar-driven desalination. Chemical Engineering Journal. 2022;427:130905. https://doi.org/10.1016/j.cej.2021.130905

20. Munasir N, Lutfianaa S, Nuhaab F, Evia S, Lydiaa R, Ezaac S, et al. Graphene Based Membrane Modified Silica Nanoparticles for Seawater Desalination and Wastewater Treatment: Salt Rejection and Dyes. International Journal of Engineering, Transactions A: Basics, 2023;36(4):698-708. https://doi.org/10.5829/ije.2023.36.04a.09

21. Chen J, Li B, Hu G, Aleisa R, Lei S, Yang F, et al. Integrated evaporator for efficient solar-driven interfacial steam generation. Nano Letters. 2020;20(8):6051-8. https://doi.org/10.1021/acs.nanolett.0c01999

22. Lu Q, Shi W, Yang H, Wang X. Nanoconfined water-molecule channels for high-yield solar vapor generation under weaker sunlight. Advanced Materials. 2020;32(42):2001544. https://doi.org/10.1002/adma.202001544

23. Liu H, Ye HG, Gao M, Li Q, Liu Z, Xie AQ, et al. Conformal Microfluidic-Blow-Spun 3D Photothermal Catalytic Spherical Evaporator for Omnidirectional Enhanced Solar Steam Generation and CO2 Reduction. Advanced Science. 2021;8(19):2101232. https://doi.org/10.1002/advs.202101232

24. Guo Y, Bae J, Fang Z, Li P, Zhao F, Yu G. Hydrogels and hydrogel-derived materials for energy and water sustainability. Chemical Reviews. 2020;120(15):7642-707. https://doi.org/10.1021/acs.chemrev.0c00345

25. Zhou X, Guo Y, Zhao F, Shi W, Yu G. Topology-controlled hydration of polymer network in hydrogels for solar-driven wastewater treatment. Advanced Materials. 2020;32(52):2007012. https://doi.org/10.1002/adma.202007012

26. Guo Y, Yu G. Engineering hydrogels for efficient solar desalination and water purification. Accounts of Materials Research. 2021;2(5):374-84. https://doi.org/10.1021/accountsmr.1c00057

27. Tao P, Ni G, Song C, Shang W, Wu J, Zhu J, et al. Solar-driven interfacial evaporation. Nature Energy. 2018;3(12):1031-41. https://doi.org/10.1038/s41560-018-0260-7

28. Bohr T, Rademaker H, Schulz A. Water Motion and Sugar Translocation in Leaves. Plant Biomechanics: From Structure to Function at Multiple Scales. 2018:351-74. https://doi.org/10.1007/978-3-319-79099-2_16

29. ASTM D. 7334-08; Standard Practice for Surface Wettability of Coatings, Substrates and Pigments by Advancing Contact Angle Measurement. ASTM International: West Conshohocken, PA, USA. 2008.

30. Jikan company 2023 [Available from: https://www.jikangroup.com/wp-content/uploads/2018/10/CAG-20-PE-Catalogue.pdf.

31. Zhang L, Tang B, Wu J, Li R, Wang P. Hydrophobic light-to-heat conversion membranes with self-healing ability for interfacial solar heating. Advanced Materials. 2015;27(33):4889-94. https://doi.org/10.1002/adma.201502362

32. Zhuang S, Zhou L, Xu W, Xu N, Hu X, Li X, et al. Tuning transpiration by interfacial solar absorber-leaf engineering. Advanced Science. 2018;5(2):1700497. https://doi.org/10.1002/advs.201700497

33. Wang X, He Y, Liu X, Zhu J. Enhanced direct steam generation via a bio-inspired solar heating method using carbon nanotube films. Powder Technology. 2017;321:276-85. https://doi.org/10.1016/j.powtec.2017.08.027

34. Li R, Zhang L, Shi L, Wang P. MXene Ti3C2: an effective 2D light-to-heat conversion material. ACS Nano. 2017;11(4):3752-9. https://doi.org/10.1021/acsnano.6b08415

35. Lu H, Shi W, Zhao F, Zhang W, Zhang P, Zhao C, et al. High-yield and low-cost solar water purification via hydrogel-based membrane distillation. Advanced Functional Materials. 2021;31(19):2101036. https://doi.org/10.1002/adfm.202101036

Persian Abstract

چکیده

تبخیر سطحی در بسیاری از پدیده‌های طبیعی و کاربردهای صنعتی مهم است؛ بنابراین بهبود این پدیده بسیار مفید است. در این پژوهش، نرخ تبخیر آب با طراحی یک ساختار ابتکاری الهام گرفته شده از ساختار گیاهان بهبود یافته است. این ساختار دو اثر اصلی دارد: اولا گرمای انتقال یافته به حجم سیال از طریق سطح را کاهش داده و ثانیا جذب سطحی حرارت را افزایش می‌دهد. این ساختار از سه بخش تشکیل شده است: لایه تبخیری، عایق و الیاف جاذب آب. پس از بررسی فراوان بر روی مواد مختلف برای انتخاب بهترین ماده برای این سه بخش، فوم پلی استایرن انبساطی و الیاف کتانی بهترین عملکرد را از خود نشان دادند. این ساختار پس از ساخت و آزمایش توانست جرم آب تبخیر شده در مدت ٢٤ ساعت را به اندازه ٢٨ درصد افزایش دهد؛ همچنین دمای سطح آب در فرآیند تبخیر در طول ٢٤ ساعت به اندازه ١٦ درصد افزایش یافت که باعث تبخیر آب در دمای بالاتر گردید. این ساختار همچنین بازده حرارتی را تا ٨٥ درصد در شار حرارتی ٠.٦ کیلووات بر متر مربع افزایش داد. سطح پیشنهاد شده دارای قابلیت مقیاس پذیری برای هر ابعادی و مقرون به صرفه است.