



Research Article



Numerical Analysis of a Solar Desalination System With Porous Separator Blades

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Abstract

Today, the scarcity of freshwater resources worldwide and the increasing human demand for water have prompted experts to explore various ways to meet their water needs. One of these methods is the production of water by desalination. On the other hand, the existence of the oil crisis and fossil fuels in the world requires other methods to supply energy to conventional desalination devices that receive energy from fossil fuels. One of the most efficient methods for studying and developing large-scale desalination systems is the use of renewable energies. Therefore, improving their performance can be considered. For this purpose, by placing the blades in the chamber, it directs and controls the vortices created by natural convection and the distillation rate increases. In the present paper, a solar desalination system with porous separator blades was studied using computational fluid dynamics in a porous medium, and the output water production, porosity percentage, and effective thermos-physical parameters were considered. The results showed that the increase in porosity of the blades generally decreases the Nusselt number and water production.

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1. Introduction

After air, water is the most important substance needed by living organisms and one of the most important environmental resources. The life and health of all living creatures, including humans, plants, and animals, depend on their existence. More than three-quarters of the earth is covered by water, but most of these waters contain salt, and only one percent of the total available water is fresh and usable. All the needs of humans, plants, and animals living on earth and 90% of human drinking water are provided from this amount. The increase in the population of the earth has caused an increase in the consumption of water resources, and at the same time, due to the increase in the temperature of the earth (due to air pollution), the precipitation of snow and rain has also decreased drastically. Although the amount of usable water (freshwater) on the earth is very limited, this amount is not used properly. Humans, with their carelessness, not only consume water unnecessarily and more than they need but also cause pollution with their incorrect behavior. Drought is a reality in the region and the first complication of this drought is dehydration. According to the available statistics, 28% of water is wasted in the water supply network of cities. In some cities, such as Tehran, this amount reaches 31%. According to official statistics and experts, Iran is on the brink of a water crisis, and in the coming years, water supply will become one of the country's biggest challenges in many provinces, cities, and regions. Geographically, Iran is located in the semi-arid and arid part of the world in such a way that the average rainfall in Iran is about 250 mm, while the global average is about 850 mm, which is more than three times the amount of rainfall in Iran. One of the ways to access fresh water is to desalinate the salt water of the seas and oceans, and how much better the required energy is provided by renewable energies, especially solar energy.

Solar water desalination systems have been used for many years. These devices have been working for hundreds of years using simple technology and can be used anywhere. The desalination mechanism is based on heat transfer and natural mass transfer inside the container depending on the buoyancy force caused by the difference in temperature and density created in the fluid. The solar distiller is simply composed of a water basin and a glass cover facing completely the sun's radiation. At the bottom

of the pond, there is a black plate to absorb more sunlight, which causes the water temperature to rise. The water starts to evaporate, and during evaporation, only water vapor is separated from the basin, and salt and other solutes remain. There is no leakage from the device, in this way, the water vapor generated turns into a liquid on the glass cover. The glass cover has a relatively small slope and thus the evaporated water enters the storage tank (Malik et al., 1982).

In general, the solar distillation process is carried out in two models, active and passive, as reported by (Malik et al., 1982). (Soliman, 1979) has studied the catchment area performance of an active solar still associated with a flat plate collector. (Kiatsiriroat et al., 1987) analyzed the multi-effect performance of a solar still with a flat plate collector. (Zaki et al., 1992) has experimentally investigated the active external distillation system of a conventional single-slope solar still with a flat plate collector that operates in a special thermosiphon mode. (Tiwari et al., 2003) in 2003 have developed computer analysis to evaluate the performance of active and passive solar desalination. In another research, Tripathi and Twairi (Tripathi and Tiwari, 2005) experimentally studied the effect of water depth on internal heat and volume transfer for an active system. In the field of desalination, many scientists have reported that active solar distillation is a slow process for purifying and desalination of salt water. Some mechanisms can be employed to improve heat transfer rate from the base into the basin water such as: using nanofluids (Javadpour and Dehghani, 2021) and porous fins (Liu et al., 2024).

The most common model used to calculate the heat transfer coefficient in solar desalination water is presented. (Omri et al., 2005) researched a type of triangular desalination plant and showed that the fluid flow and the amount of heat transfer significantly depended on the shape of the desalination plant and the Rayleigh number, and at an angle of 35 degrees, the maximum amount of heat transfer and the highest efficiency is obtained for desalination. (Islam et al., 2004) investigated the mass transfer inside the desalination water and showed that the constant of the Dunkel model is not always constant and depends on temperature changes and increases with increasing water temperature. In another research, Islam and Fukuhara (ISLAM & Fukuhara, 2007) presented

theoretical equations with mass and energy balance and using experimental results. They obtained convection heat and mass transfer coefficients for desalination. They also presented models based on the temperature difference between the hot and cold surface to calculate the heat transfer coefficients, convection and mass.

(Yu et al., 2010) also numerically analyzed the slow natural convection heat transfer inside a circular chamber combined with a triangular box inside in order to investigate the effect of the Prandtl number on the flow and heat transfer structure. They developed models to calculate average the heat transfer rate inside the chamber according to Prandtl and Rayleigh number for both aspect ratios. In another research, (Omri, 2007) numerically investigated the optimization of the dimensions of the solar desalination system and the effect of the dimensions of the inclined surfaces on the temperature and velocity fields for a natural flow in an asymmetric triangular chamber. (Setoodeh et al., 2011) investigated and compared the convective and evaporation heat transfer coefficients obtained from experimental results and computational fluid dynamics in a two-phase three-dimensional model. Also, in another research, he has investigated the effects of the angle of the inclined distillation surface on the operation of the solar desalination system using computational fluid dynamics. In another research, (Papanicolaou et al., 2002) and his colleagues numerically investigated the natural convection heat transfer in the available air in an asymmetric industrial water desalination still. A combination of PCM and stepped solar desalination has been done by (Grewal & Kumar, 2022a). They studied the effect of three different PCM masses on the concentration of sugarcane juice in a stepped solar desalination plant. They showed that the highest PCM mass causes the highest water production, thermal and exergy efficiency and CO₂ reduction. They also experimentally investigated the effect of different masses of energy storage materials (ESM) in a continuous stepped solar desalination system along with thermal, economic and environmental analysis (Grewal & Kumar, 2022b).

In this research, solar desalination with porous blades has been investigated. The presence of porous blades lead to more eddies due to the presence of more contact surface of the fluid with the blade, which will increase the productivity in some percentages of porosities and decrease the

productivity of fresh water in others. In this research, in addition to the numerical analysis and theory of solar desalination with porous separating blades, the effort will be to investigate the effective parameters on the amount of water production, such as porosity percentage and blade height.

2-Material and Method

Fig. 1 represents the geometry studied in this research. This figure represents a single wall desalination system with length L and two heights H_l and H_r . In order to examine and analyze the device, the bottom surface and the top surface of the device are assumed to have constant temperature T_w and T_g respectively, and the side and bottom walls are insulated. The fluid flow inside the two-dimensional chamber is assumed to be a wet, incompressible and ideal. Fluid properties (mixture of air and water vapor) are also considered constant. So that the density and viscosity of air are 1.225 kg/m^3 and $1.78 \times 10^{-5} \text{ Pa.s}$, and the density and viscosity of saturated steam are 0.025 kg/m^3 and $1.2 \times 10^{-5} \text{ Pa.s}$, respectively. In order to validate the results of Rahbar et al. (Rahbar & Esfahani, 2012), the assumptions of the problem are presented in Table 1.

Table 1. Problem assumption

parameter	value	unit
T_g	321	K
T_w	336	K
L	0.483	m
H_r	0.187	m
H_l	0.075	m
θ	14.35	degree

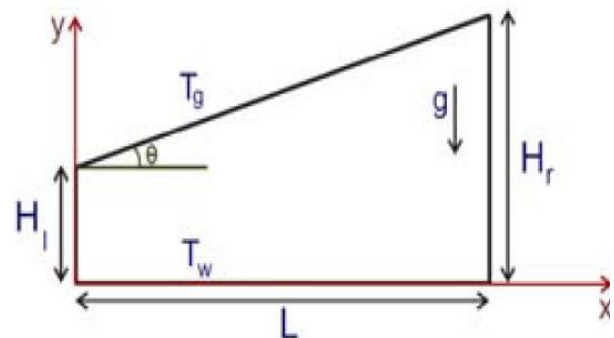


Figure 1. Schematic and geometry studied in this research

The geometry and boundary conditions are exactly the same as the research of (Rahbar &

Esfahani, 2012). So that it is possible to compare and validate the results. Also, the height of the blade in different situations is equal to 11, 31, 65 and 86 mm and its location is considered in $x=2L/3$ of the chamber. In the studied model, the blades are considered in four solid and porous states with 20, 50 and 80 percent porosities.

3- Governing equations and solution method

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\vartheta}{C_p} \left(\frac{\partial u}{\partial y} \right)^2 + \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)$$

$$u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\vartheta}{C_p} \left(\frac{\partial u}{\partial y} \right)^2 + \alpha \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)$$

In the above relationship, u and v are the x and y direction velocity of the fluid, T is the fluid temperature, α is the thermal diffusivity coefficient, β is the compressibility coefficient and ϑ is kinematic viscosity. After the above equations were dimensionless, the dimensionless Rayleigh and Prandtl numbers also appeared in the above equations. Considering the blades as a porous medium, the equation of momentum in a porous medium in one dimension can be written as follows (Jiang & Lu, 2006):

$$-\frac{dP}{dx} = \frac{\mu}{K} u + \frac{F}{\sqrt{K}} \rho u^2 \quad (2)$$

In the above relationship, μ is fluid viscosity, ρ is fluid density, and P is flow pressure. Also, in this relationship, F and K are defined according to the porosity coefficient of the medium (ε) as follows (Jiang & Lu, 2006):

$$F = \frac{1.75}{\sqrt{150}(\varepsilon)^2} \quad (3)$$

$$K = \frac{d_p^2 \varepsilon^3}{150(1-\varepsilon)^2}$$

In the above relationships, d_p is the average diameter of the holes of the porous medium. All the numerical analysis of the above problem has been done with the help of Ansys-Fluent 18 software. In solving the above equations numerically, the 2nd-order central discretization method has been used to

The governing equations of momentum and energy in free convection are obtained from the relevant conservation principles. Inertia and viscous forces as well as energy transfer by fluid mass transfer and thermal diffusion are also important here. The main principle of the natural convection flow is that the buoyancy forces play an important role in free convection. The set of governing equations including continuity, momentum, and energy equations in two dimensional are in the following form (Jiang & Lu, 2006):

(1)

discretize the governing equations. Also, SimpleC algorithm is used to calculate the pressure from the velocity. Because the temperature difference is small and the Rayleigh number is in the laminar region in all cases of the above problem, therefore, the laminar flow regime is considered. Productivity refers to the volume of water production per unit of time. The Nusselt number and the productivity of the device can be calculated from the following relations with the help of a numerical solution:

$$\overline{Nu} = \frac{-H}{L(T_w - T_g)} \int_0^l \frac{\partial T}{\partial y} \Big|_{wall} dx \quad (4)$$

$$\dot{m}_{hourly} = \frac{-3600 \times D_{AB}}{L} \int_0^l \frac{\partial c}{\partial y} \Big|_{wall} dx \quad (5)$$

In these relationships, H is the average height of the chamber, C is the water vapor concentration, and D_{AB} is the vapor mass distribution.

4. Results and discussion

4-1. Validation and mesh independence

To check the mesh independence of the solution and to eliminate the errors caused by the coarseness of the created grid network, the number of 100 vertical and 200 horizontal grid have been selected (Rahbar & Esfahani, 2012). The validity of the upcoming research, in terms of computer modeling, has been compared with the simulation results in the reference (Rahbar & Esfahani, 2012) for the case without blades. After producing the same geometry

and creating the same boundary conditions, the Nusselt number is calculated 10.22 which in the reference article is equal to 11.5. It gives an error percentage of 11.1%. Also, the productivity is 14.9% in the reference work and 15.14% in the present work, which indicates an error of 3.25%.

4.2. Statement of results

In this article, by numerically simulating the heat transfer inside the solar desalination system, considering the wet air conditions inside the desalination reservoir, the effect of the porous separator blades on the rotating vortices and Nusselt number has been investigated. Considering that the Nusselt number determines the heat transfer process at the fluid-solid boundary, and on the other hand, it is the ratio of the convection heat transfer to the conduction heat transfer in the fluid, an increase in the Nusselt number will lead to an increase in the convection heat transfer. Therefore, this dimensionless number is one of the important parameters that is studied. Due to the large volume of the results, the contours and distribution of temperature and velocity are shown only for the 31 mm and 65 mm blades. However, in final conclusion, to compare the Nusselt number and productivity of solar desalination system, the results of 11 mm and 86 mm blades are also presented.

Fig. 2 shows the temperature contour inside the solar still in the case of a 31 mm blade. As can be seen from this figure, at this height of the blade, there is not much difference in the temperature

contour for different porosities. Fig. 3 compares the temperature and velocity distribution in the vertical direction in the middle of the chamber for different places. As it can be seen, in the graphs of velocity and temperature, for the zero percentage of porosity (solid blade), 20% and 50% porosities, the distribution of temperature and velocity exactly coincide. But in the porosity percentage of 80%, in the middle areas between 2 and 10 cm, the speeds are higher and the temperatures are lower in comparison with other porosities for a 31 cm blade. Above this height, the temperatures are higher. Also, by increasing the percentage of porosity to 80%, the maximum speed inside the desalination water increases.

Fig. 4 shows the temperature contour inside the chamber in the case of a 65 mm blade. This figure shows that at a higher height of the blade, different porosities have a great effect on changing the rotating vortices and the temperature distribution inside the chamber. In Fig. 5, the distribution of temperature and velocity in the vertical direction in the middle of the solar still with a 65 mm blade is compared for different states of its porosity. As you can see in the velocity and temperature graphs, unlike the 31 mm blade, in the case of the 65 mm blade with low percentage of porosity, the deviation of temperature and speed distribution is observed compared to the state of the solid blade. Also, based on Fig. 5, it is estimated that the average velocity and temperature inside the chamber decreased by increasing the percentage of porosity up to 80%.

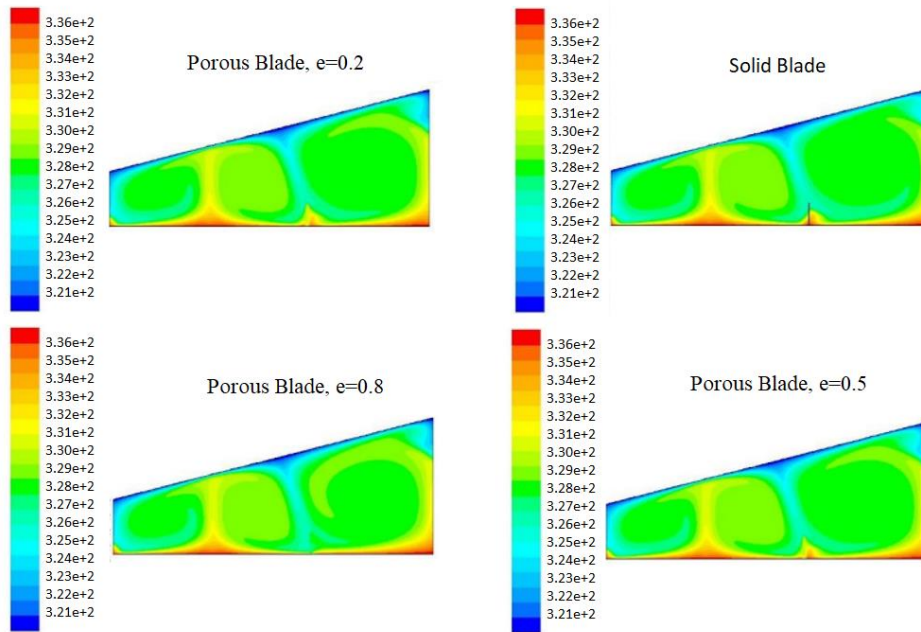
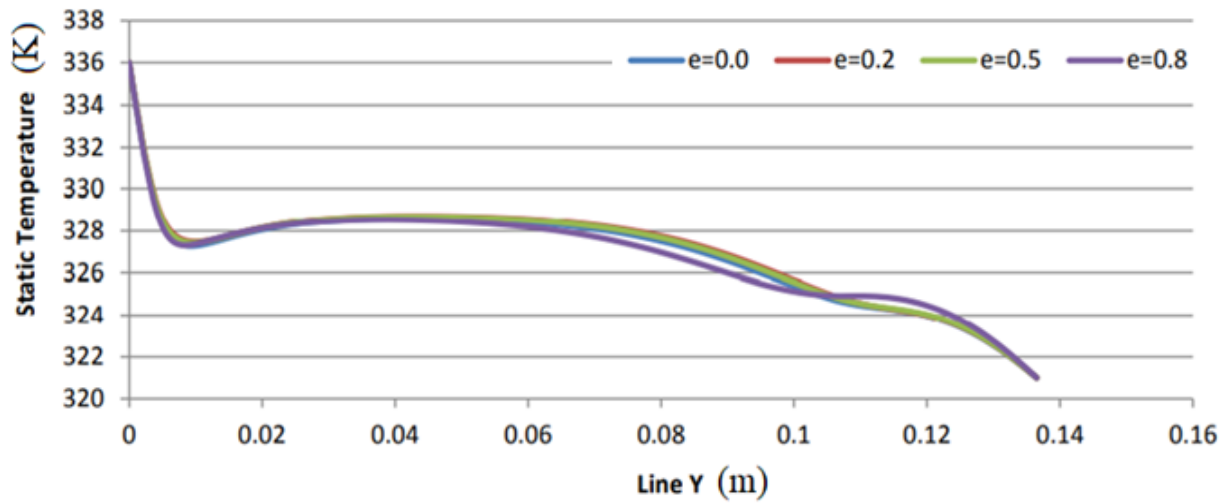


Figure 2. Temperature contour inside the solar still in the case of a 31 mm blade with different porosities

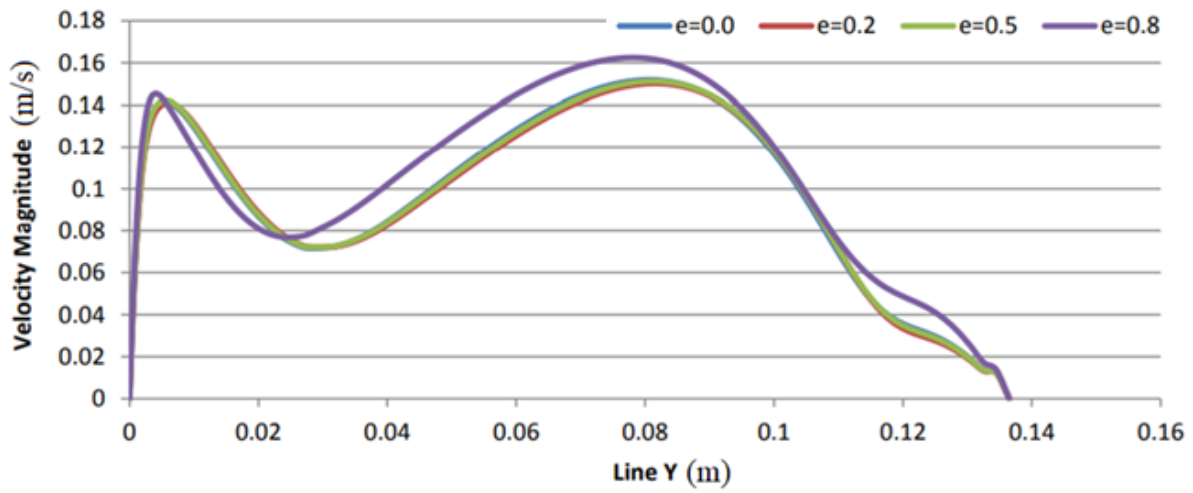
The rotating vortex on the right side of the chamber is larger and its direction of rotation is counterclockwise. That is, its direction of rotation is from the side of the hot wall to the side of the cold wall, which causes heat exchange and natural convection in the chamber. Therefore, this rotating cell has the most important role in heat transfer and mass transfer and finally in the production of fresh water. In the central area of this rotating cell, temperature and concentration changes are very small and even the observed isotherm reduces the heat transfer rate. The largeness of this vortex creates excessive heat exchange time between hot and cold surfaces. On the other hand, if there are smaller vortices, the heat exchange time between the hot and cold surfaces is less than the desired level, and as a result, it reduces the heat and mass transfer. One of the suitable techniques to increase heat transfer is to place the blade in the desalination system. So that the large vortex is split and more vortices are created inside the desalination water. With this method, mass and heat transfer can be increased. Using the blade will increase the power

of the rotating vortexes. Table 2 shows the changes in the Nusselt number and, accordingly, the changes in water production in different porosities.

What is known is that the use of blades may increase the Nusselt number and the amount of water production due to the change in the shape and type of eddies. Another thing that exists in the meantime is that changing the height of the blade affects the amount of Nusselt number and water production in such a way that there will always be an optimal height to maximize each of the Nusselt number and water production cases. The same is true for porosity. It is necessary to explain that the maximum Nusselt is equal to 12.405 for an 11 mm blade with a porosity of 20% and the maximum percentage of water production is equal to 19.35% for an 86 mm blade without porosity (solid), and the minimum of these two values is respectively equal to 10.09 and 15.02% for a 65 mm blade at a porosity of 80%. According to these data, the optimization can be improved further with Taguchi and ANFIS methods (Goharimanesh et al., 2022).



(a)



(b)

Figure 3. Distribution of temperature (a) and velocity (b) in the vertical direction in the middle of the desalination plant with a 31 mm blade for different porosity conditions.

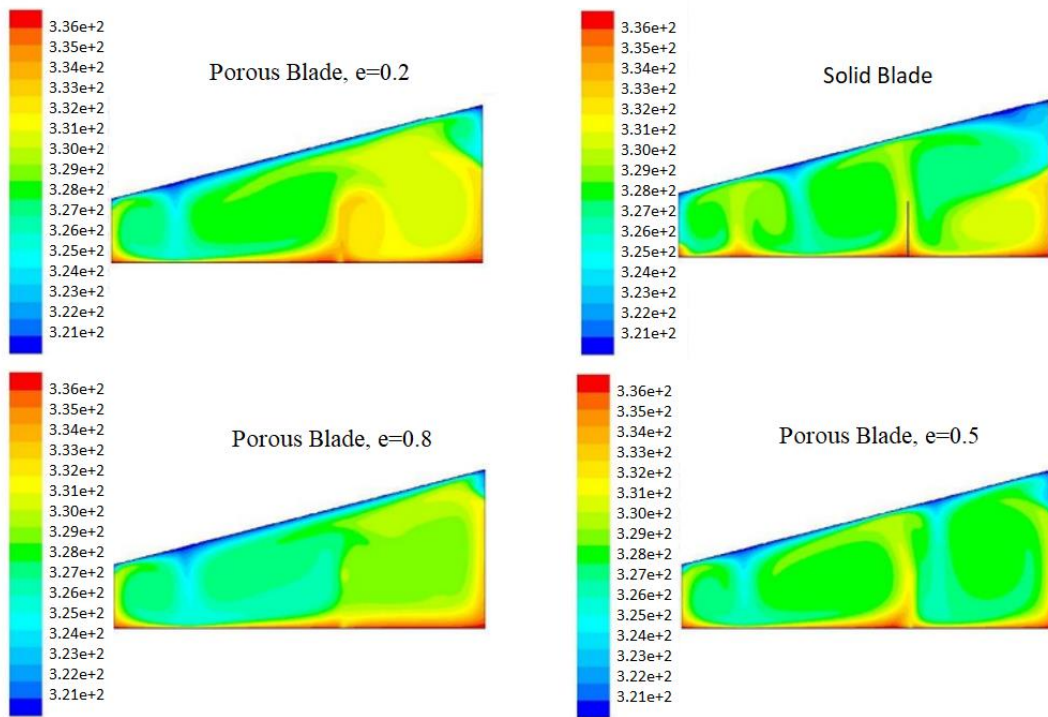
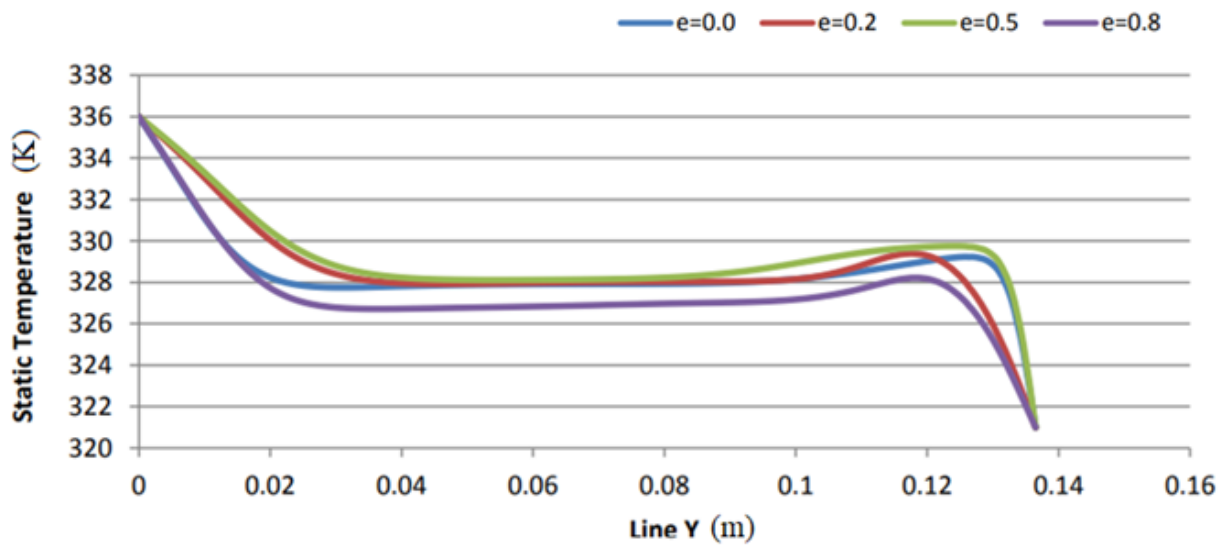
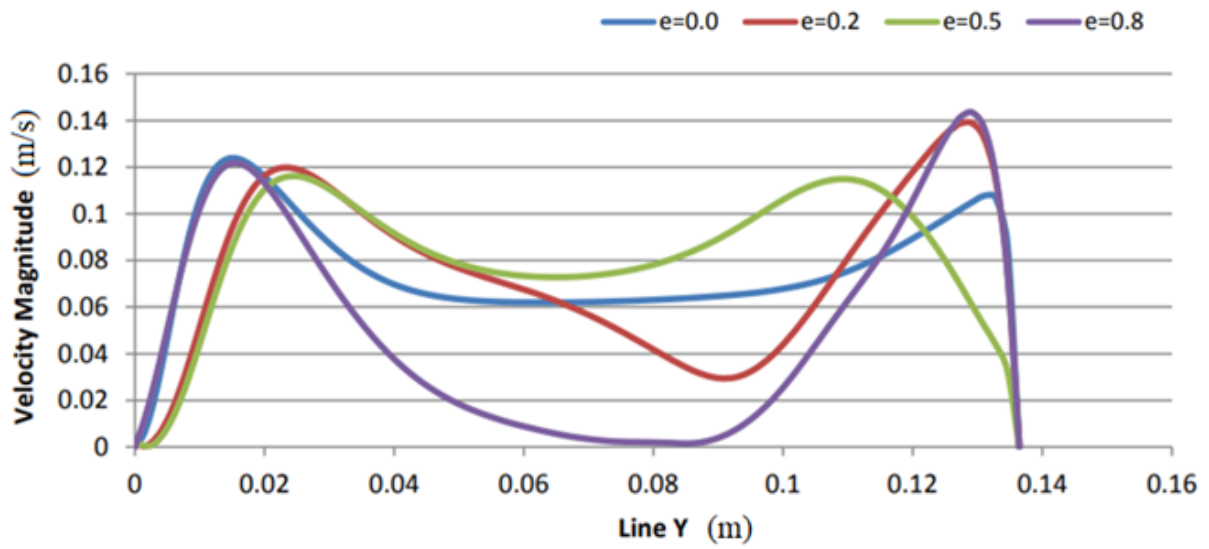


Figure 4. Temperature contour inside the solar still in the case of a 65 mm blade with different porosities



(a)



(b)

Figure 5. Distribution of temperature (a) and velocity (b) in the vertical direction in the middle of the desalination plant with a 65 mm blade for different porosity conditions.

Table 2. Changes in the Nusselt number and the productivity of the desalination system at different heights and porosity percentages

Nusselt number			Productivity		
Without blade	10.22		Without blade	15.14%	
11 mm blade	$\varepsilon=0$	12.32	11 mm blade	$\varepsilon=0$	19.02%
	$\varepsilon=0.2$	12.41		$\varepsilon=0.2$	18.64%
	$\varepsilon=0.5$	12.41		$\varepsilon=0.5$	18.63%
	$\varepsilon=0.8$	12.35		$\varepsilon=0.8$	18.51%
31 mm blade	$\varepsilon=0$	11.64	31 mm blade	$\varepsilon=0$	18.67%
	$\varepsilon=0.2$	11.51		$\varepsilon=0.2$	18.27%
	$\varepsilon=0.5$	11.96		$\varepsilon=0.5$	18.26%
	$\varepsilon=0.8$	12.03		$\varepsilon=0.8$	18.23%
65 mm blade	$\varepsilon=0$	11.47	65 mm blade	$\varepsilon=0$	18.16%
	$\varepsilon=0.2$	10.46		$\varepsilon=0.2$	15.99%
	$\varepsilon=0.5$	12.07		$\varepsilon=0.5$	18.21%
	$\varepsilon=0.8$	10.09		$\varepsilon=0.8$	15.02%
86 mm blade	$\varepsilon=0$	12.18	86 mm blade	$\varepsilon=0$	19.35%
	$\varepsilon=0.2$	12.31		$\varepsilon=0.2$	18.22%
	$\varepsilon=0.5$	11.36		$\varepsilon=0.5$	17.42%
	$\varepsilon=0.8$	11.22		$\varepsilon=0.8$	16.31%

5- Conclusion

Compared with solar still without the blade, the flow field and heat transfer in blade solar have special characteristics. The results of this study show that installing the blade in the right position with suitable height, changes the main vortex, which plays the most important role in heat and mass transfer and ultimately in the production of a desalination system. This leads to full rotation flows on both sides of the blade, allowing heat exchange between hot and cold surfaces. In other words, changing the height of the blade changes the strength of the rotating cells, which causes significant changes in the Nusselt number. Some of the significant results of this research are as follows:

- Numerical analysis using computational fluid dynamics can accurately predict the amount of heat transfer inside the desalination water.
- The presence of 11 mm and 86 mm blades increases the mass and heat transfer from the surface of salt water to the cold surface of the cover glass and also obtains the highest Nusselt number.
- In the central region of the eddies, the change in temperature and concentration is insignificant.
- An increase in porosity generally causes a decrease in water production except 65 mm blade.
- For the 11 mm and 86 mm blades, the highest Nusselt number corresponds to 20% porosity, and for the 31 mm blade, the highest Nusselt number corresponds to 80% porosity. For the 65 mm blade, the highest Nusselt number relates to the 50% porosity.

- The presence of porosity causes maximum water production at a lower height of the blade.

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Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution

All research was done by the author of the article.

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