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Investigation of the parameters influencing the evaporation rate of downward sprayed sea water in solar water desalination

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ABSTRACT

In this study, the evaporation of injected water droplets, as one of the most important parts of the solar desalination system, was investigated. Elevating the evaporation rate is considered as one of the important points in increasing the efficiency of solar water desalination systems. The effective parameters on evaporation rate and reduction of the droplets' diameter, which were sprayed in the chamber were investigated using the mathematical model. It should be noted that the effects of different factors mean environmental conditions inside the chamber, such as relative humidity and pressure, as well as the primary conditions of the droplet, including temperature, injection pressure, and initial diameter, were also considered. In this study, the information about a droplet inside the glass chamber in a downward direction at injection pressures of 1, 3 and 5 bar, inlet temperatures of 60°C, 65°C and 70°C and nozzle outlet diameters of 1.1, 1.0 and 0.9 mm was investigated by considering three types of long cone orifice, drilled steel orifice and sapphire orifice nozzle at different relative humidity and pressure values in a glass chamber to determine the favorable conditions for evaporation of saline water and freshwater production. Increasing the availability of freshwater by producing a high-flow rate of vapor is known as the most important achievement in solar water desalination systems. Finally, the best condition for producing freshwater was obtained at the injection pressure of 5 bar, the inlet temperature of 70°C, and the nozzle outlet diameter of 0.9 mm with a discharge coefficient of 0.9.

Keywords: Desalination system; Nozzle; Evaporation; Downward sprayed

1. Introduction

Water plays a very important role in all our daily activities, and it is noteworthy that, total water consumption is increasing due to the increasing the standards of human life. The need for freshwater is also increasing because of industrialization and population growth and the upgrading of living standards. According to the United Nations, about 1,800 million people will face water scarcity until 2025, and this problem will be resolved, if humans find other

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ways to produce freshwater. Desalination has been used in Arab countries of the Middle East region, as well as countries in North, south and Central American, Europe, Africa, and Australia due to the lack of fresh water and increasing demand for water [1]. 10,000 t of oil is needed annually in order to produce 1,000 m^3/d of freshwater [2]. The brine which has been discharged from desalination has created a very serious threat for aquatic fish [3]. Most desalination processes have been designed based on the multi-stage flash (MSF), multi-effect distillation (MED), vapor compression, reverse osmosis and electrical hydrolysis [4]. Darwish et al. [5] have studied about using wind and solar energy in desalination systems. Hanafi [6] conducted a test on an MSF desalination sample by producing about 15 m^3/d of freshwater, which has been designed by coupling 10 desalination units of 1 m^2 working area operating at a pressure of 9.0 bar with solar temperature of 70°C. Zhang et al. [7] conducted experimental studies on the horizontal evaporator pipes in solar-packed desalination with a solar collector in order to produce hot water inside the horizontal evaporator pipes. Ikegami et al. [8] have investigated the direction of spraying superheated liquid at temperatures of 24°C, 30°C, and 40°C including upward direction compared to downward one. Hou et al. [9] have studied about the influential parameters, such as flow rate of inlet water to the nozzle, the heated air temperature, the heated air-flow rate, the distilled water flow rate and the amount of vacuum created to test on parameters such as the water outlet and thermal efficiency. Mahmoud et al. [10] have conducted studies on the effects of climate changes on the performance of the solar desalination system (HD) using the EES software [10]. El-Bilay et al. [11] in a study analyzed the costs of desalination systems. El-Sebaii and El-Bialy [12] conducted studies on the advanced systems which are used in current desalination systems. Babinsky and Sojka [13] studied regarding the distribution of particle size based on mathematical equations. Joo and Kwak [14] in a study evaluated the performance of MED desalination in the optimized thermal desalination systems. Cai et al. [15] have done further studies about the governing equations, such as temperature, velocity, and reduction in the droplets' diameter which was sprayed downward and also effective factors on the evaporation. Sharqawy et al. [16] studied equations about saline water properties, including specific heat capacity and density. Balabel and Wilson [17] have done experimental and simulated studies about the reduction of droplets' diameter and compared the results obtained from these two studies.

2. Methods

2.1. System description

Evaporation rate is considered the most important factor in producing freshwater in the desalination system, which must be obtained according to the specific environmental and operational conditions. In this study, the amount of produced vapor was evaluated in a glass chamber at 35°C in the mode of spraying droplets downward by three types of a long-cone orifice, drilled steel orifice and sapphire orifice nozzles at a height of 90 cm from the bottom of the chamber. Orifice is one of the most commonly used instruments for measuring the flow rate of a stream based on the difference in pressure between the two sides of the nozzle because of an increase in fluid velocity. In addition, governing equations of it are well known in fluid mechanics.

The orifice discharge coefficient (C_d) is the product of the velocity coefficient (actual ratio to theoretical velocity) and contraction coefficient (spray ratio to orifice area). This coefficient which considers the friction losses and the effects of viscosity and turbulence of stream is known as an important factor in sprayed droplet evaporation and the vapor flow rate, so three types of orifice nozzles are studied with the discharge coefficients of 0.9 for long cone orifice, 0.7 for drilled steel orifice and 0.65 for sapphire orifice in mathematical modeling as constant parameters. Fig. 1 shows part of a droplet that has been injected by nozzle in the glass chamber which exits as vapor and the rest of it goes out as rejected saline water.

2.2. Mathematical modeling

Analyzing the force and energy balance on falling sprayed droplets gives the velocity and falling time which is used to calculate the vapor flow rate. Fig. 2 shows these forces like gravity, buoyancy, drag and additional mass forces.

The drag coefficient for calculating the drag force on the droplet obtained from Eq. (1) has been shown as follows [15]:

$$C_D = \begin{cases} \dfrac{24}{\mathrm{Re}_d} & \mathrm{Re}_d < 6.2 \\ 10\,\mathrm{Re}_d^{-\frac{1}{2}} & 6.2 \le \mathrm{Re}_d < 500 \\ \dfrac{24}{\mathrm{Re}_d}\left(1 + 0.12\,\mathrm{Re}_d^{0.687}\right) & 500 \le \mathrm{Re}_d < 800 \\ 0.44 & 800 \le \mathrm{Re}_d < 2\times10^5 \\ 0.1 & \mathrm{Re}_d < 2\times10^5 \end{cases} \quad (1)$$

The balance of forces which were applied to the droplet gives variation of droplet velocity during the falling time in the chamber as Eq. (2):

$$\frac{d\left(\mathrm{mu}_d\right)}{dt} = F_g - F_b - F_d - F_a \quad (2)$$

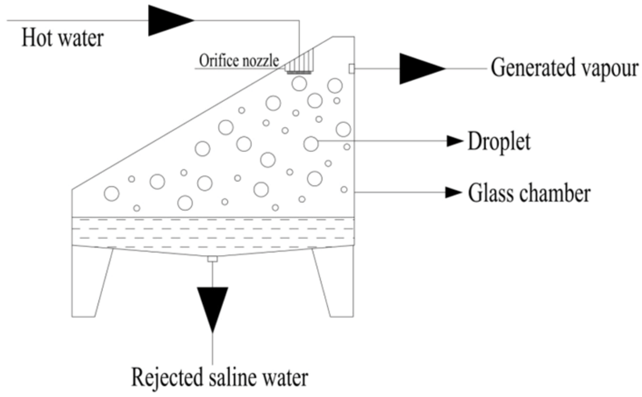

Fig. 1. Vapor production chamber in the system.

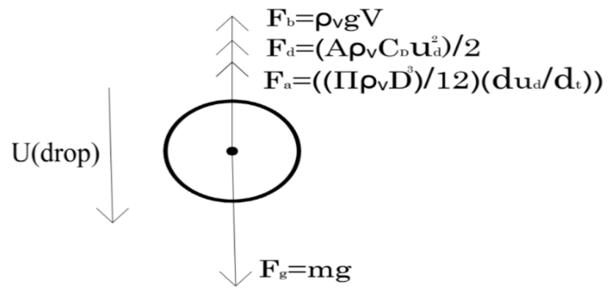

Fig. 2. Forces on a droplet in downward spraying system.

The mass reduction rate of the droplet is calculated by the following Eq. (3) because of evaporation:

$$\dot{m} = -2\pi D D_v \frac{M}{R}\left(\frac{P_d}{T_d} - \frac{P_\infty}{T_\infty}\right) \tag{3}$$

The diffusion coefficient (D_v) is calculated from the Chapman–Enskog theory by the following Eq. (4) [18]:

$$D_v = \frac{1.86.10^{-3} T_d^{\frac{3}{2}} \left(2/M\right)^{\frac{1}{2}}}{P_d \delta^2 \Omega} \tag{4}$$

Finally, the variation in the droplets' diameter during falling time is calculated by considering the relative humidity and the correction factor as follows [15]:

$$\frac{dD}{dt} = -\frac{4D_v\phi}{\rho_d D}\frac{M}{R}\left(\frac{P_d}{T_d} - \phi\frac{P_\infty^{\text{sat}}\left(T_\infty\right)}{T_\infty}\right) \tag{5}$$

$$\phi = \left(\frac{2\lambda + D}{D + 5.35\left(3.42\lambda + \frac{\lambda^2}{D}\right)}\right) \tag{6}$$

Eq. (7) shows the energy balance for a droplet. This equation considers conduction heat transfer in the droplet and also convection, radiation and latent heat of evaporation:

$$\frac{d\left(mc_pT_d\right)}{dt} = \pi D^2 k_{\text{eff}}\frac{dT}{dr} - \pi D^2 h\left(T_d - T_\infty\right) - \pi D^2 \varepsilon\sigma\left(T_d^4 - T_r^4\right) - \dot{m}h_{\text{fg}} \tag{7}$$

Abramzon and Sirigano [19] conducted a study into k_{eff} which considers the effect of convection and conduction heat transfer of the droplet, so energy balance is modified as follows:

$$\frac{d\left(mc_pT_d\right)}{dt} = \pi D^2 k_{\text{eff}}\frac{dT}{dr} - \pi D^2 \varepsilon\sigma\left(T_d^4 - T_r^4\right) - \dot{m}h_{\text{fg}} \tag{8}$$

k_{eff} is considered as an effective or modified thermal conductivity of the droplet regarding the conduction and convection heat transfer as Eq. (9):

$$K_{\text{eff}} = 1.86k + 0.86K\tanh\left[2.24\log 10\left(\frac{\text{Pe}_d}{30}\right)\right] \tag{9}$$

The pressure applied to the injected droplet is calculated according to Eq. (10), as suggested based on studies by Zhang et al. [20]:

$$P_d = \left(3.66\times10^{12} - 1.31\times10^{8}\times T_d - 3.38\times10^{6}\times T_d^2\right)\times\exp\left(\frac{-6150}{T_d}\right) \tag{10}$$

Eq. (11) gives flow rate of sprayed water through the nozzle [21]:

$$\dot{Q} = 11{,}126.92418\times C_d\times d_0^2\times P^{0.5} \tag{11}$$

The mean droplet diameter is a function of injection pressure and outlet diameter of nozzle which is used as the following Eq. (12) for water [17]:

$$d_m = a\cdot\frac{d_0^{1.5}}{P^{0.33}} \tag{12}$$

The density and specific heat capacity of the droplet are considered as important parameters in the governing equations. These parameters are a function of salt concentration and temperature of the droplet; and they vary during falling time. Sharqawy et al. [16] have investigated the equations used about the density and the specific heat capacity of saline water by considering the salt content and temperature. Therefore, the required properties of saline water are considered in the mathematical modeling based on study of Sharqawy.

2.3. Solution method

The outlet diameter of the nozzle, temperature, velocity and injection pressure have a significant effect on the evaporation rate of the droplet sprayed in the chamber therefore, Eqs. (1)–(12) were investigated by numerical methods for the droplet sprayed at the height of 90 cm to reach the bottom of the chamber. The algorithm of solving is shown in Fig. 3.

2.4. Verification

Wu et al. [22,23] have studied modeling the mass and heat transfer in the evaporation of water droplets. They compared the results of their model with experimental data. However, they didn't consider the effect of the injection pressure, discharge coefficient and type of nozzle and also outlet diameter of a nozzle in their study. In this study, the effect of the above parameters on initial droplet diameter, number of injected droplets or flow rate of inlet water and evaporation rate is considered. The parameters of nozzle and surrounding were adjusted to produce the same size of droplets and chamber conditions in order to verify the proposed model. The reduction of droplet's diameter and temperature were compared with experimental data which is given by Wu. Figs. 4 and 5 show these comparisons which have acceptable accuracy. However, this condition is not suitable definitely for the optimized performance of solar water desalination.

As it is shown in Figs. 4 and 5, the relative error on diameter reduction of droplet is less than 4.6% and the error on temperature change is less than 1%.

3. Results and discussion

3.1. Effect of outlet diameter of nozzle

Producing droplets with smaller diameter leads to increase evaporation rate due to the rapid reduction of droplets' diameter during the falling time of them in the chamber. Therefore, it influences the outlet flow rate of vapor and access to freshwater. In this study, the initial droplets' diameter and their reduction were investigated in various relative humidity by three nozzle outlet diameters of 0.9, 1, and 1.1 mm at a water temperature of 60°C. Fig. 6 and Table 1 show the results.

According to Table 1, the droplets' diameter sprayed from the nozzle was reduced by decreasing the outlet diameter of the nozzle; therefore, it results in raising the evaporation rate and the discharge vapor of the system. It should be noted that the low relative humidity in the glass chamber increases the evaporation rate of the droplets which were sprayed in the chamber.

3.2. Effect of the initial temperature of the droplet

Increasing the temperature of the droplets sprayed in the chamber is another important factor in the evaporation rate of solar systems. The injection pressure was considered 1 bar and relative humidity was assumed 60%.

As it is shown in Fig. 7, the temperature of inlet water was considered in three values of 60°C, 65°C and 70°C. A high temperature of the droplet sprayed into the chamber, increases the temperature of a vapor flow rate of vapor. The temperature of vapor can be effective in the pre-heating part of inlet water in desalination systems.

3.3. Effect of pressure inside the glass chamber

The pressure inside the glass chamber is another important factor in reducing the droplets' diameter. It should be

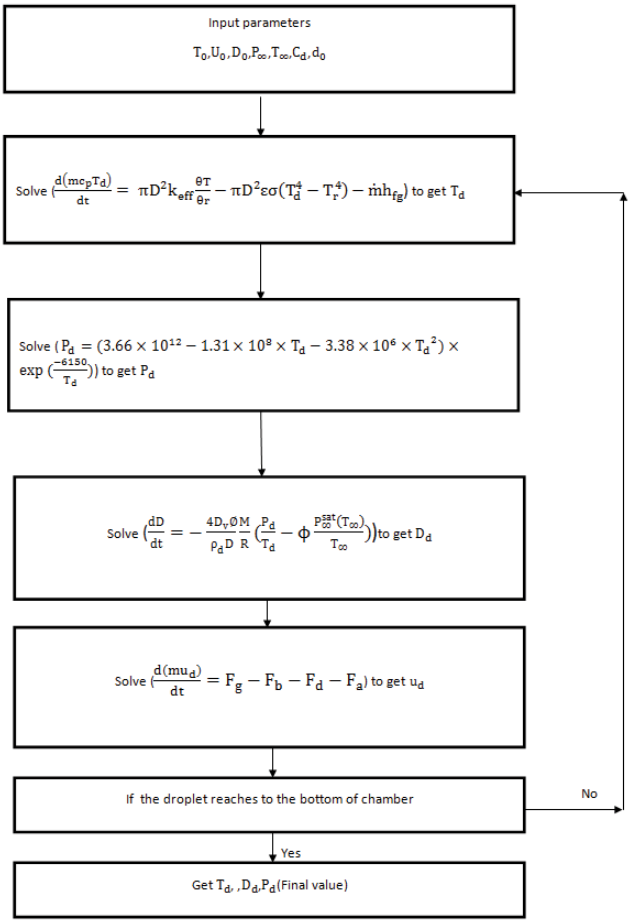

Fig. 3. Flowchart of model solution.

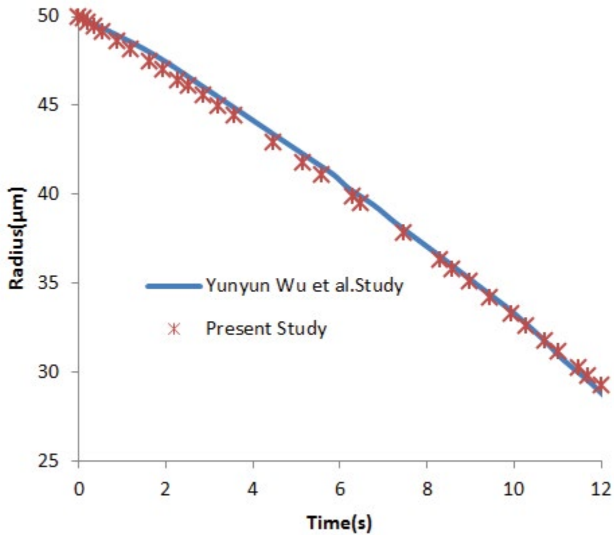

Fig. 4. Verification of the diameter reduction in relative humidity of 20% and surrounding temperature of 5°C.

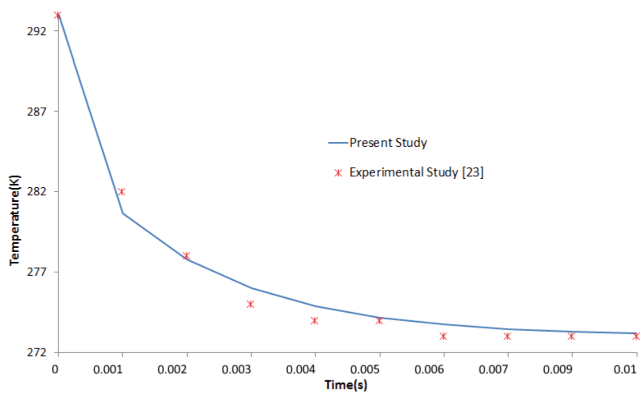

Fig. 5. Verification of droplet temperature changes in relative humidity of 80%, surrounding temperature of 0°C.

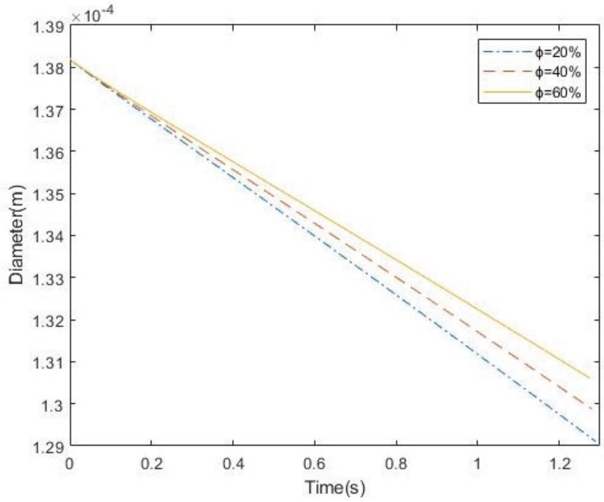

Fig. 6. Reduction of the droplets' diameter at nozzle outlet diameter of 0.9 mm.

Table 1
Values obtained from the outlet diameter of nozzle effect on reducing the droplets' diameter

d_0	D_0	D_n	ΔD	P	ϕ
0.9 mm	138.22 μm	129.10 μm	9.12 μm	5 bar	20%
1 mm	161.88 μm	156.37 μm	5.51 μm	5 bar	20%
1.1 mm	186.76 μm	183.12 μm	3.64 μm	5 bar	20%

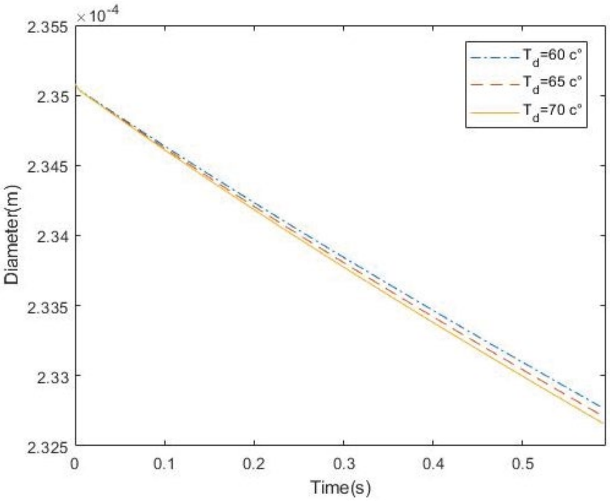

Fig. 7. Reduction of the droplets' diameter at the injection pressure of 1 bar.

noted that injection pressure was considered 5 bar and the temperature of inlet water was 60°C.

As it is shown in Fig. 8 and Table 2, the pressure inside the glass chamber was assumed at three values of 4,500; 5,500; and 6,500 Pa. High pressure inside the chamber causes the low evaporation rate in this system; therefore, the most favorable pressure inside the glass chamber was reached 4,500 Pa based on Table 2.

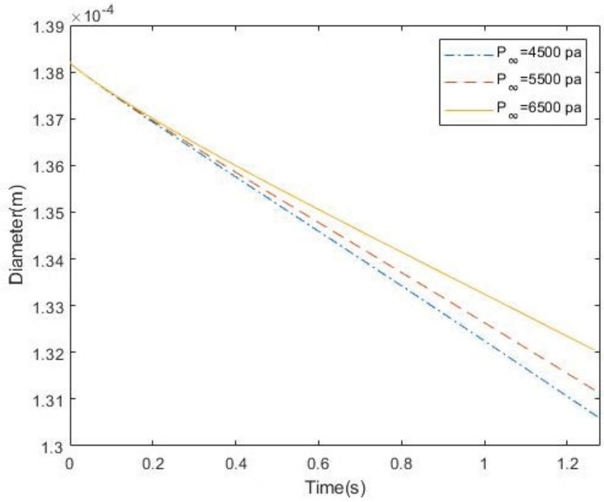

Fig. 8. Reduction of the droplets' diameter at the injection pressure of 5 bar.

Table 2
Values obtained regarding the effect of pressure inside the glass chamber on reducing the droplets' diameter

P∞	D_0	D_n	d_0	P	ϕ
4,500 Pa	138.22 μm	130.61 μm	0.9 mm	5 bar	60%
5,500 Pa	138.22 μm	131.17 μm	0.9 mm	5 bar	60%
6,500 Pa	138.22 μm	132.05 μm	0.9 mm	5 bar	60%

3.4. Effect of the initial velocity of the sprayed droplet

The velocity of the droplet sprayed from the nozzle is an effective parameter on the evaporation rate of the system. If a droplet is injected in the glass chamber with high speed, covered distance in the glass chamber will be occurred during a short period of time. Consequently, this leads to a decrease in the rate of evaporation in the system.

The droplet velocity at the nozzle exit depends on the discharge coefficient, outlet diameter of the nozzle and injection pressure. According to Table 3, in case of similar values for outlet diameter of nozzle and injection pressure, the smaller nozzle discharge coefficient has an effect on reduction of the droplet velocity at nozzle exit and, finally increases the evaporation rate of the sprayed droplet.

3.5. Effect of injection pressure in glass chamber

The inlet pressure of nozzle is another effective factor on droplet size and vapor production. According to Fig. 9, the initial droplets' diameter and their reduction were investigated in various relative humidity at an injection pressure of 3 bar.

As it is shown in Table 4, the injection pressure was considered of 1, 3 and 5 bar, relative humidity and temperature of inlet water were 20% and 60°C, respectively. Injection pressure affects evaporation rate and the reduction of the droplets' diameter during the time; therefore, according to Table 4, the most optimum value of injection pressure was obtained as 5 bar.

Table 3
Values obtained regarding the effect of the initial velocity of the sprayed droplet on reducing the droplets' diameter

C_d	P	d_0	u	D_0	D_n	ΔD
0.9	5 bar	0.9 mm	28.4514 m/s	138.22 μm	129.39 μm	8.83 μm
0.7	5 bar	0.9 mm	22.1637 m/s	138.22 μm	129.17 μm	9.05 μm
0.65	5 bar	0.9 mm	20.5918 m/s	138.22 μm	129.10 μm	9.12 μm

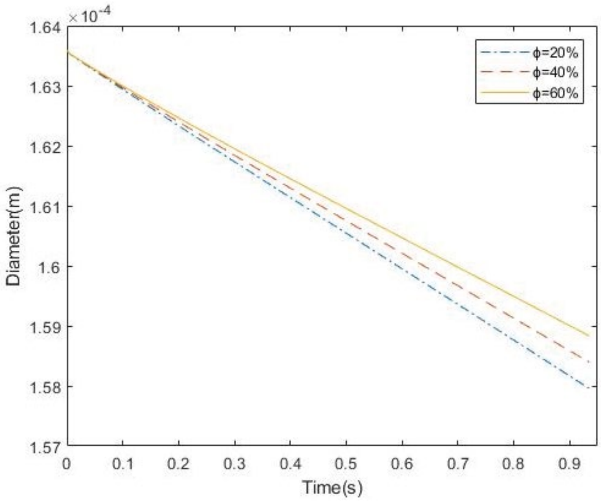

Fig. 9. Reduction of the droplets' diameter at the injection pressure of 3 bar.

3.6. Effect of nozzle discharge coefficient

The nozzle design based on the discharge coefficient and outlet diameter is an important part of the system which influences on increasing flow rate of vapor in the system. As it is shown in Fig. 10a, the flow rate of sprayed inlet water was increased by raising a nozzle outlet diameter. According to Fig. 10b, the flow rate of vapor by long cone orifice at an outlet diameter of 0.9 mm is higher than the other investigated diameters.

Table 4
Values obtained regarding the effect of the injection pressure on reducing the droplets' diameter

P	D_0	D_n	d_0	C_d	ϕ
1 bar	235.08 μm	232.46 μm	0.9 mm	0.65	20%
3 bar	163.59 μm	157.96 μm	0.9 mm	0.65	20%
5 bar	138.22 μm	129.10 μm	0.9 mm	0.65	20%

As it is shown in Fig. 11, the flow rate of vapor and inlet water sprayed into the glass chamber are affected by increasing in the discharge coefficient. Long cone orifice was found as a better type of orifice nozzle than drilled steel and sapphire for increasing the outlet vapor in this system. Generally, the nozzle outlet diameter of 0.9 mm and the discharge coefficient of 0.9 were reported as a better condition for designing the nozzle in comparison with other conditions which were investigated in this study.

4. Conclusion

There are some factors such as solar collector area, climate condition and rate of evaporation which affect efficiency of a solar water desalination system. Increasing the evaporation rate is one of the most important factors in solar water desalination systems to achieve more freshwater within a day. Therefore, in this study, the evaporation of water droplets was modeled and compared with experimental data which was investigated in other literatures.

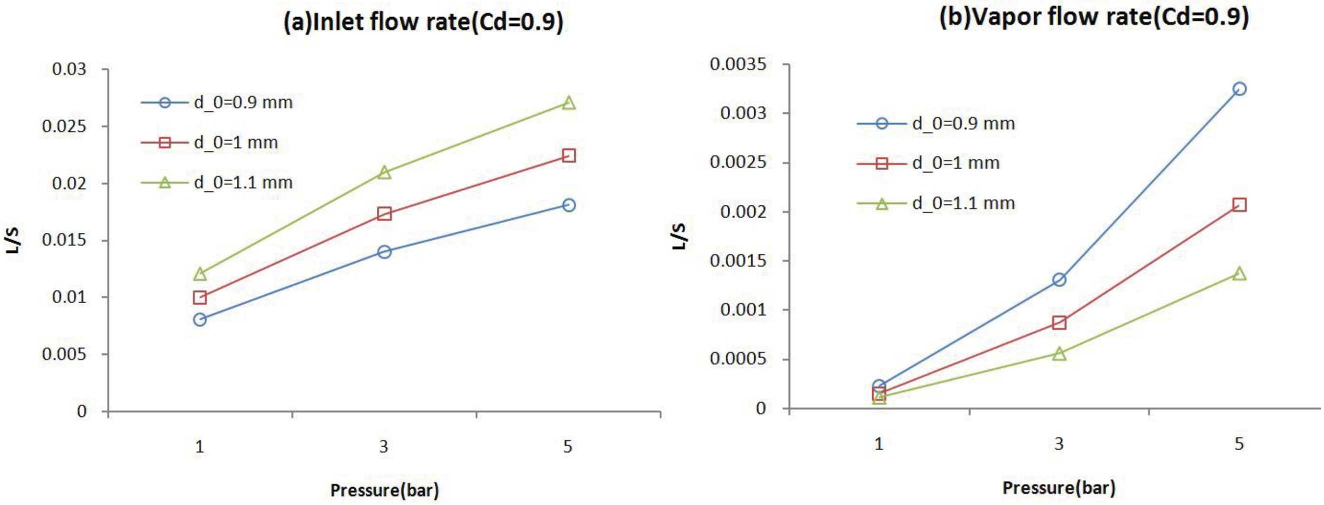

Fig. 10. Effect of outlet diameter of nozzle on flow rate of (a) sprayed inlet water and (b) produced vapor.

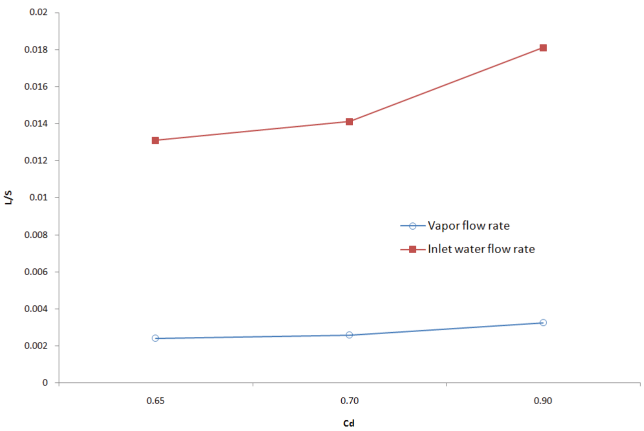

Fig. 11. Effect of nozzle type on flow rate of sprayed inlet water and produced vapor.

Then the effect of major parameters such as the injection pressure, the water temperature, the pressure and relative humidity inside the glass chamber, the discharge coefficient and the outlet diameter of the nozzle on vapor production was investigated with a mathematical model. The results showed that increasing the injection pressure of saline water from 1 up to 5 bar, results in more powdering outlet particles from the nozzle and increase the vapor flow rate to 90%. The effect of inlet saline water temperature was investigated in the interval between 60°C and 70°C. Increasing the temperature in this interval increases the evaporation to 4.5%. Three types of orifice nozzle with different discharge coefficients and outlet diameter were investigated and the results showed that changing C_d from 0.65 to 0.9 leads to raising flow rate of vapor to 25.4% and reducing the outlet orifice diameter from 1.1 to 0.9 mm increases the vapor flow rate to 57.6%. In addition, the above data is reported by considering other effective factors on the amount of output vapor, such as the pressure and relative humidity inside the glass chamber at 4,500 Pa and 20%, respectively. It should be noted that, investigating the factors, which were mentioned in this study, are useful in optimizing the operation of solar water desalination systems.

Symbols

F_g	—	Gravity force, N
F_b	—	Buoyancy force, N
F_d	—	Drag force, N
F_a	—	Additional force, N
m	—	Mass, kg
g	—	Gravity acceleration, N/kg
V	—	Volume, m^3
A	—	Area, m^2
C_D	—	Drag coefficient
u	—	Velocity, m/s
Re	—	Reynolds number
D	—	Diameter, m
D_v	—	Diffusion coefficient of vapor, m^2/s
M	—	Molecular weight, kg/mol
R	—	Universal gas constant, J/(mol K)
P_d	—	Droplet pressure, Pa
T	—	Temperature, K
C_p	—	Specific heat capacity, J/(kg K)
Q	—	Heat, W
k	—	Thermal conductivity, W/(m K)
$\dot{m}$	—	Mass evaporation rate of a droplet, kg/s
h_{fg}	—	Latent heat of vaporization, J/kg
Pe	—	Peclet number
R_d	—	Droplet radius, m
C_d	—	Discharge coefficient for nozzles
d_0	—	Nozzle diameter, m
d_m	—	Mean droplet diameter, m
D_0	—	Initial diameter, m
D_n	—	Final diameter, m
ρ	—	Density, kg/m^3
r	—	Radial distance in droplet coordinate,
P	—	Injection pressure, bar
$Q^\bullet$	—	Water flow rate, L/s
S	—	Salinity, g/kg

Greek letters

θ	—	Kinematic viscosity, m^2/s
π	—	Constant, 3.14
a	—	Constant, 8.70669362
δ	—	Collision diameter, m
Ω	—	Collision integral for mass diffusion
δ	—	Stefan-Bolzmann constant
∈	—	Emissivity
ϕ	—	Relative humidity
Ø	—	Correction factor
ƛ	—	Molecular mean free path, m

Subscripts

V	—	Vapor
d	—	Droplet
eff	—	Effective
Sat	—	Saturated
∞	—	Surrounding
0	—	Initial

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