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Water mist system application in solar collector system to increase clean water production

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ABSTRACT

This research is motivated by the problem of lack of clean water in remote areas such as coastal/sea and riverside/estuary areas. Apart from wells, some people also use river water for bathing and washing toilets. Water's low level of hygiene is almost ignored as long as it can still be used to meet daily needs. To overcome this problem, this research proposes a method to convert feed water or brackish water into clean water. The purpose of this study is to investigate an evaporation method to increase clean water production by adding a water mist system to the solar collector. With the discovery of a method to increase clean water production from the purification of feed water, this research makes a small contribution to improving public health, especially communities around the sea coast. This research was carried out using an experimental method referred to as factorial design method. From the experiment, the ratio of clean water production to the feed water flow rate is 7.9%. The maximum clean water production is 5.78 ml/minute or 1.25% of the feed water flow rate when using 4 nozzles in the chamber.

Key words: clean water production, collector plate, mist nozzle, solar collector system, water mist system

HIGHLIGHT

- A new evaporation method by water mist system in solar collector system was proposed to increase clean water production.

INTRODUCTION

The shortage of clean fresh water in remote areas such as coastal/sea and riverside/estuary areas is still faced by the majority of people living in these areas. The community needs fresh water for bathing, washing toilets, and drinking every day. To meet the need for freshwater, some coastal communities build wells and apply pumps to drain the water. The taste of freshwater around the coast is generally typical of brackish water. Apart from wells, some people also use river water for bathing and washing toilets. Water with a low level of hygiene is almost ignored as long as it can still be used to meet daily needs.

To overcome this problem, this research proposes a method to convert feed water or brackish water into clean fresh water. Some inexpensive technology-based tools such as solar collectors can be used to convert feed water into clean water even at low production rates. Although this tool has been proven to be able to produce clean water, due to its low production rate, it is not suitable to be applied to marine coastal communities. For this reason, further research on solar collectors is needed to increase their productivity. Modification is by adding a water mist system in the solar collector chamber. Fine water droplets in the form of a mist are sprayed on the hot surface of the solar collector so that more evaporation occurs. A higher evaporation rate is expected to produce more freshwater production. The water purification method through evaporation carried out on the solar collector combined with a water mist system may improve the evaporation rate. Clean water production, in this case, is correlated with the number of mist nozzles and feedwater flow rate, which will be studied further.

The purpose of this study is to investigate an evaporation method to increase clean water production by adding a water mist system to the solar collector. This research is distinguished by the evaporation method, which employs a water mist system in the solar collector. In addition, this research will produce a mathematical equation that relates the clean water production with number of nozzles and feed water flow rate. With the

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discovery of a method to increase clean water production from the purification of feed water, this research has a small contribution to improving public health, especially communities around the sea coast.

Studies on evaporation in solar collector systems have been carried out by many researchers. In this section, a description of previous research will describe research and patents on solar collector systems and their performance. A parameter study on the comprehensive characteristics and performance of a parabolic solar collector system was carried out by Cheng *et al.* (2014). In his research, Cheng describes the results of a theoretical analysis of the relationship between the reflector geometry parameters of a parabolic solar collector system and the focal shape formed by the defocusing phenomenon of non-parallel sunlight. Then the effect of the designed parameters and the obscuration phenomenon focused on the comprehensive characteristics and performance of the whole photo-thermal conversion process in the PTC system was studied and numerically optimized.

Not only Cheng, but research on parabolic solar collector systems was also carried out by Wang *et al.* (2014) and Wu *et al.* (2015). Wang *et al.* (2014) carried out a three-dimensional simulation of a parabolic solar collector system using molten salt as a heat transfer fluid. In his research, Wang describes three-dimensional simulations based on the finite element method to solve complex problems related to radiation, heat conduction, and convection in parabolic solar collector systems. The performance of the solar system using molten salt as the heat transfer fluid was numerically studied, and the influence of the main operating parameters on the solar collector system was investigated. Another time, Wu *et al.* (2015) conducted an experimental study on the heat transfer characteristics of low melting point salts in parabolic solar collector systems. The melting point of the new salt is 86 °C and the upper limit of the working temperature is about 550 °C. Experiments were carried out to obtain the heat loss of the heat collecting element, the total heat transfer coefficient from the water to the salt heat exchanger, and the convective heat transfer coefficient for molten salt in a circular tube.

The investigation of the solar collector system by Chen & Zhang (2014) was experimentally carried out with the natural convection of supercritical CO_2. This study deals with the thermal conversion of solar and water heating systems achieved by the natural circulation of supercritical CO_2. The experimental system was created and tested in Zhejiang Province (approximately. N 30.0°, east 120.6°) in southeastern China. The system is designed to operate in the supercritical region so that the system can be compactly fabricated and achieve high levels of natural convective flow. Another solar collector system in the form of a flat plate was studied by Zhou *et al.* (2019). In his research, Zhou proposed a flat plate solar collector system with antifreeze characteristics that use PCM material to store a certain amount of heat energy during the day and release energy at night. The daytime and nighttime antifreeze performance of the system was evaluated. The results showed that the conventional flat plate solar collector system will freeze when the daily average temperature is less than 5 °C. The system can work if the daily average temperature is in the range of 0–5 °C.

The use of hybrid solar collector systems in medical plant drying technology was investigated by Čiplienė *et al.* (2015). In the temperature under natural conditions, obtaining dried medicinal plants to a moisture content of 8–12% and the preparation of quality medicinal plant raw materials is a complex task. In many cases, the drying process of medicinal plant raw materials, especially those rich in volatile compounds, requires an optimal drying temperature of 30–45 °C and relative humidity of not more than 50–60%.

Other research on solar collector systems was carried out by Dikmen *et al.* (2014). The research was conducted to estimate and optimize the thermal performance of the evacuated tube solar collector system. In this research, an artificial neural network (ANN) and adaptive neuro-fuzzy inference system (ANFIS) have been used to predict the thermal performance of the evacuation tube solar collector system. ANN results were compared with ANFIS using the same data set. The value of R^2 for the collector thermal performance value of 0.81 can be considered satisfactory.

Furthermore, Owolabi *et al.* (2017) investigated the performance of an integrated thermal energy storage solar collector system using nanofluids. The effect of Fe nanofluid on improving the performance of a solar water heater integrated with a thermal energy storage system was experimentally investigated. The nanoparticle fraction of 0.5% Fe (Wt) was synthesized with a mixture of water/propylene-glycol base liquid. Experimental implementation using 40 nm Fe nanoparticles, 15° collector tilt angle, and circulating heat transfer fluid with a mass flow rate of 1.5 kg/min.

Through an experiment, Shehata *et al.* (2019) also studied the conversion of saltwater to freshwater. The proposed desalination system uses solar radiation, hot water spray, and a humid-dehumidification system in a channel, as opposed to the evaporation and condensation methods developed in this study. As part of their

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research, Shehata *et al.* utilized an ultrasonic fogger to increase the humidity of the channel's air, allowing for the production of more pure water.

In addition to submitting research reports, several researchers have also patented solar collector systems, including Robertson (1976), Mills (2000), Natter (1981), and Nydahl & Carlson (2002). Robertson (1976) reported a patent on a solar collector system. From this invention, a solar collector system comprises a multi-element collector coupled with an optical radiation concentrator system, the system of which is designed to enable optimization of the energy collection process by a precise sequential flow of the heat transfer fluid through the multi-element.

Natter (1981) reports another patent describing a solar energy collector system having an array of solar concentrators mounted at intervals along with a network of channels through which the heat transfer fluid is circulated. The concentrator includes an arcuate duct that provides a heat absorption surface and a saddle member for attaching the duct section to the duct. An insulating sheath surrounds the conduit and conduit members. An elongated lens panel can be positioned above the absorption surface to focus on incident solar radiation. The angle of inclination of the lens panel can be varied by the manual rotation of the solar concentrator around the longitudinal axis of the channel.

Mills (2000) published a patent describing a solar collector system consisting of several reflectors and a receiver system representing a surface that absorbs solar radiation reflected by the reflector. The receiving system is raised relative to the reflector and the reflector is pivotally mounted to support the structure in such a way that it can be positioned at an angle to reflect radiation against one of the receiving systems. Later in 2002, Nydahl & Carlson (2002) also reported a patent on a solar collector system. The solar collector system consists of a frame member and a top plate supported by a frame member with a top plate transparent to solar energy.

RESEARCH METHODOLOGY

The water purifier begins the water purification process using untreated water from rivers, lakes, and wells. Feed water may contain solid particles or other dissolved substances, thus it must be filtered beforehand. Other solid particles that are very small and dissolved in contaminated water will be removed by the purifier after undergoing a purification process. Consequently, the water purifier will create solid particle deposits in addition to clean water. Figure 1 depicts the process diagram of producing clean water from feed water. Figure 2 provides additional information on how a diaphragm pump is utilized to convey filtered feed water through a filter. Figure 2 also demonstrates that the water purifier system or the modified solar collector comprises a solar collector containing a water mist system.

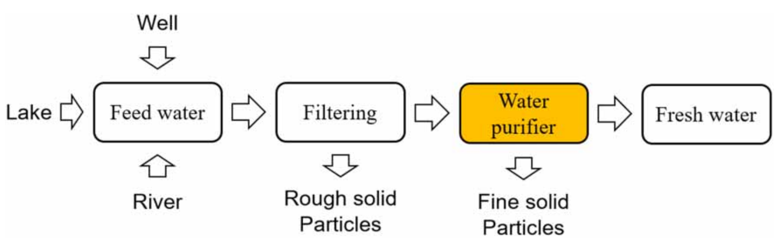

Figure 1 | Schematic diagram of clean water production system.

The experimental method was applied in this research. The experimental setup of the modified solar collector is shown in Figure 2. The term 'modified' referred to the addition of a water mist system to the conventional solar collector, as shown in Figure 3. A water mist system is a mist distributor system consisting of single or multiple mist nozzles located inside of solar collector chamber. Water mist is a water spray product supplied by a pressure of 2 bar-g diaphragm water pump. As an evaporation product, water vapor is then condensed by a condenser pipe and collected by measuring glass.

The experiment was started by heating the collector plate inside the solar collector chamber. Heating the plate with an electric heater is an analogy of the plate being heated by the sun because in this experiment the collector plate does not receive direct heat from the sun. The collector plate temperature is monitored by a K-type thermocouple with MAX 6675 module. This module works at 12-bit and 0.25 °C resolution. The end of the thermocouple

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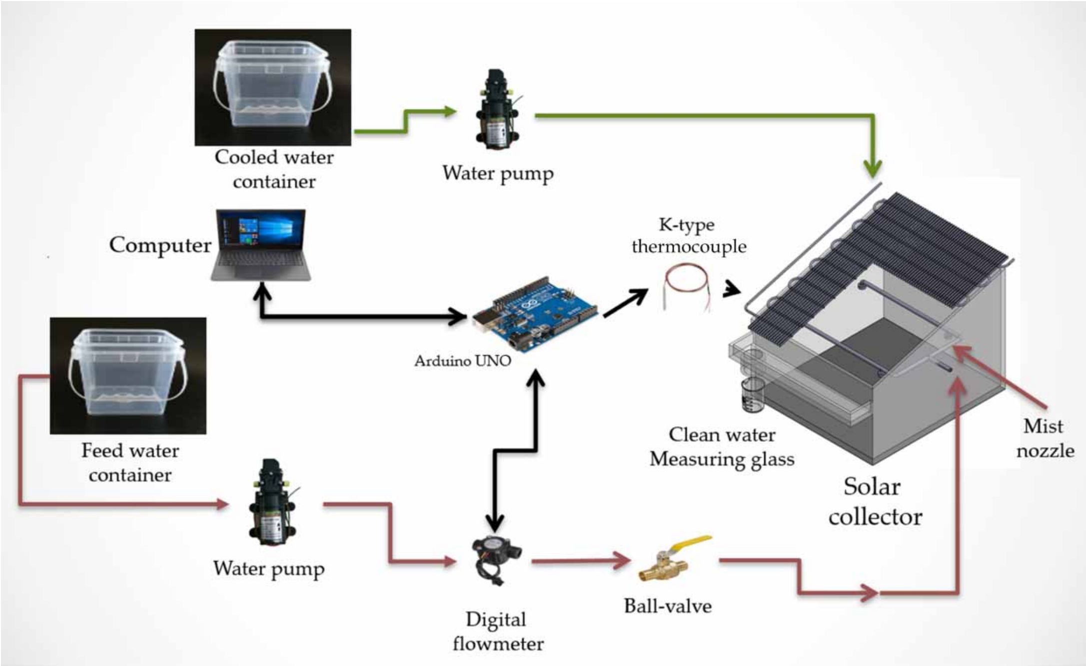

Figure 2 | Experimental setup of modified solar collector.

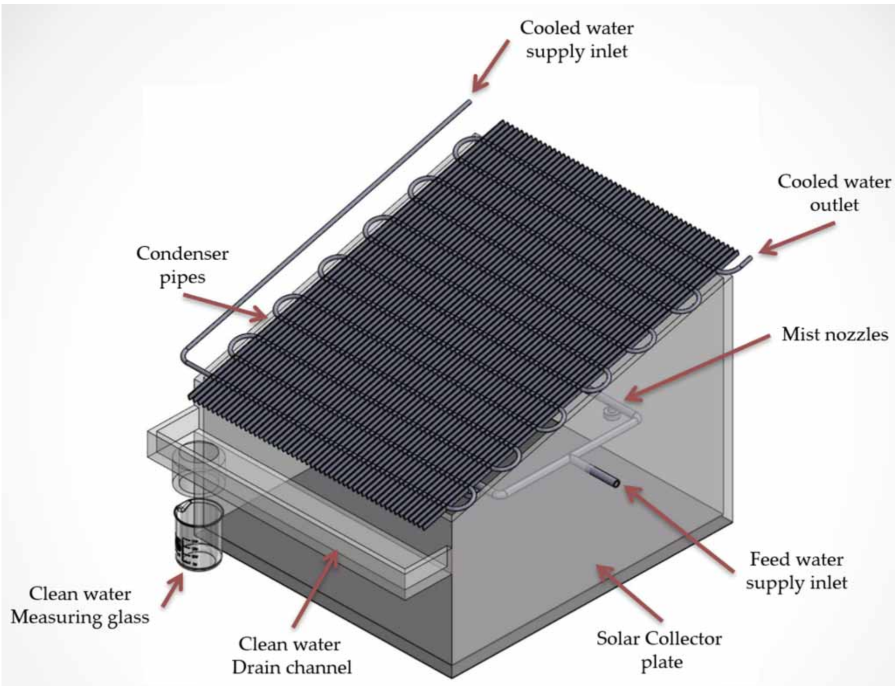

Figure 3 | Modified solar collector design.

wire is sticked at collector plate surface with aluminum foil tape. The collector plate as a vaporizer component receives a feed water supply in the form of water mist from the nozzle and evaporates it into the solar collector chamber so that water vapor fills the chamber with a certain density. The feed water flow starts from the water container and is directed to the nozzle by a water pump with a certain pressure where the feed water pressure is not specifically varied. Feed water flow measured by a YF-S201 digital sensor, which has flow range from 1 to 30 l/min. The performance of the evaporation process in the solar collector chamber was studied by varying

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the use of single and multiple nozzles and varying the feed water flow rate through the ball valve adjustment. Finally, the water vapor drifts in the solar collector are condensed in the condenser pipes to produce clean water. The volume of clean water is accommodated in the measuring cup after one experimental batch is completed. As described, the tested variables in this experiment are the number of mist nozzles, feed water flow rate and pressure, and solar collector plate temperature as input variables, and clean water production as output variable.

RESULT AND DISCUSSION

The experiment was carried out by following the experimental design in Tables 1 and 2. The whole experimental results are displayed in graphical form as presented in Figures 4–7. The measurement results with microcontroller-based data acquisition produce the history of measuring the feed water flow rate and the temperature of the solar collector plate.

Table 1 | Feed water flow rate at various valve openings

	Feed water flow rate [ml/min]		
Nozzle number	**100%-open**	**75%-open**	**50%-open**
1	144.75 ± 11.52	132.29 ± 03.84	123.75 ± 06.40
2	340.01 ± 08.96	325.68 ± 08.96	302.31 ± 12.80
3	393.66 ± 23.04	360.23 ± 26.88	325.94 ± 15.36
4	462.75 ± 23.04	425.51 ± 26.88	352.98 ± 23.04
	Uncertainty percentage of feed water flow rate [%]		
Nozzle number	**100%-open**	**75%-open**	**50%-open**
1	7.96	2.90	5.17
2	2.63	2.75	4.23
3	5.85	7.46	4.71
4	4.98	6.32	6.53

Table 2 | Clean water production at various valve openings

	Clean water production [ml/min]		
Nozzle number	**100%-open**	**75%-open**	**50%-open**
1	3.30	2.97	2.81
2	4.79	4.63	3.97
3	5.14	4.97	4.64
4	5.78	4.96	4.79
Nozzle Number	**Increase of clean water production [%]**		
1	17.44		
2	20.65		
3	10.78		
4	17.13		
Mean value	16.50		

From Figures 4–7 for the various numbers of nozzles, feed water flow rate at steady state is summarized in Table 1, while the measured clean water production for each experimental batch is presented in Table 2. The presented data in Tables 1 and 2 are the mean values and their uncertainties. The uncertainty value of the measurement results is calculated from the difference between the maximum value and the minimum value divided by two.

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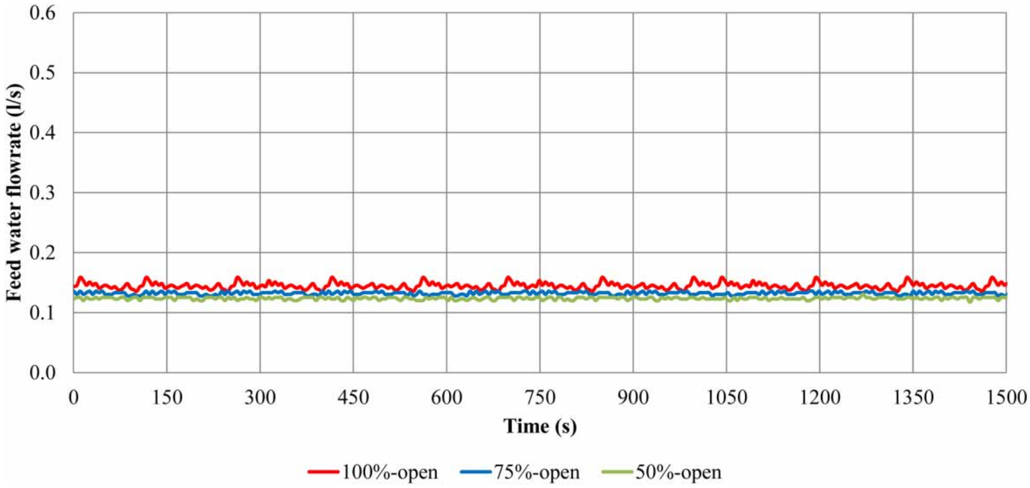

Figure 4 | History of feed water flow rate measurement when applying 1 nozzle.

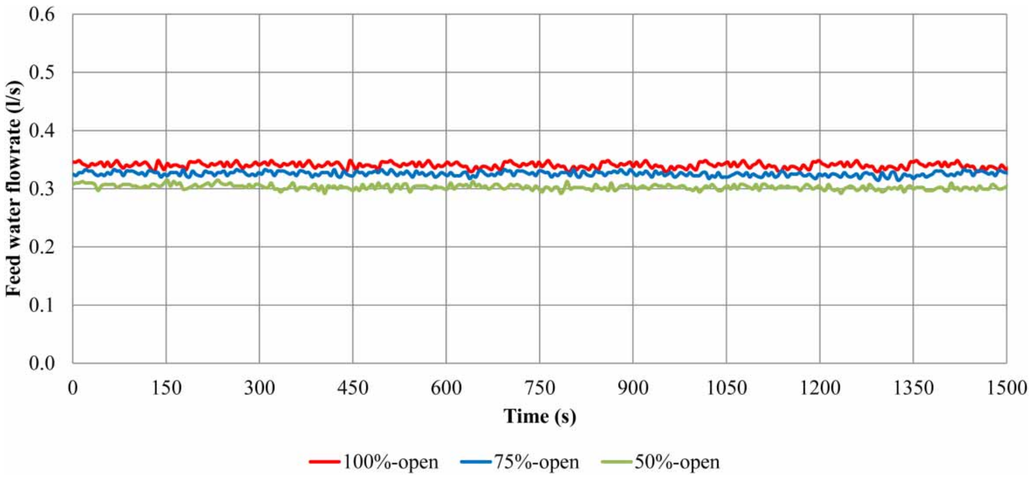

Figure 5 | History of feed water flow rate measurement when applying 2 nozzles.

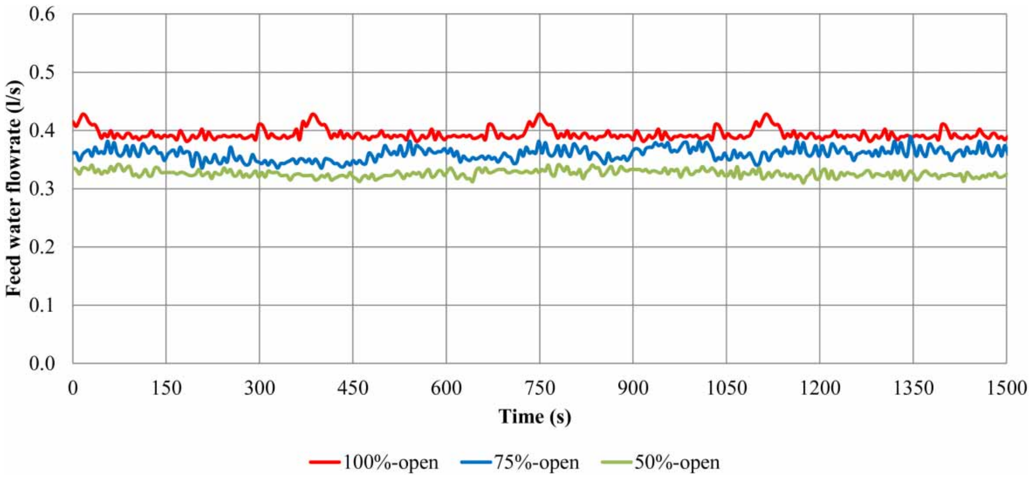

Figure 6 | History of feed water flow rate measurement when applying 3 nozzles.

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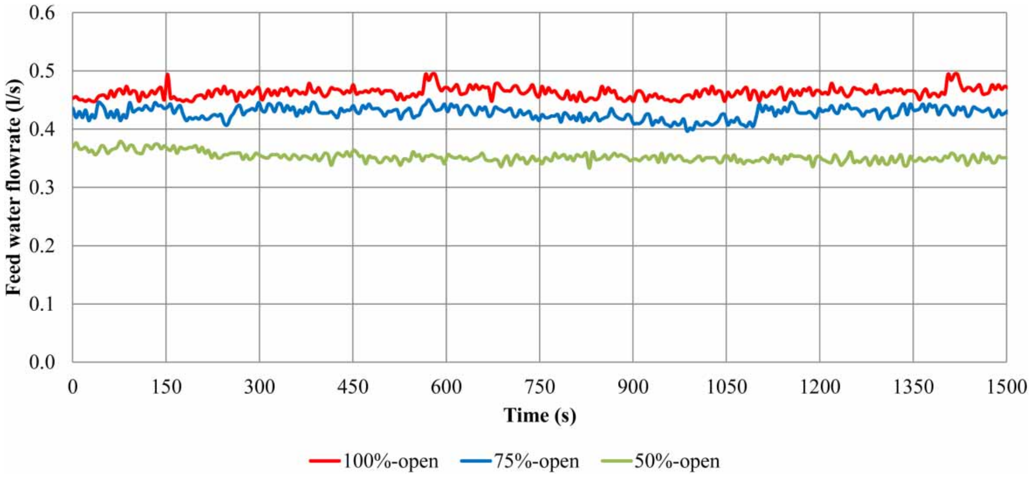

Figure 7 | History of feed water flow rate measurement when applying 4 nozzles.

The uncertainty value may express the fluctuation of the flow rate measurement results relative to the mean value. The use of single and multiple nozzles in the water mist system shows that the feed water flow rate tolerance is quite varied. However, the entire percentage of uncertainty is still below 10%, which means that the fluctuation of the measured flow rate is still within reasonable limits.

The clean water production presented in Table 2 is the product of evaporation that occurs in the modified solar collector. Evaporation occurs when the mist water touches the collector plate. As soon as the mist water touches the collector plate, the fine droplets enter the boiling phase and then evaporate. The tendency of evaporation is further enlarged after the mist water touches the hot collector plate at a temperature of 100 °C.

To investigate the magnitude of the evaporation rate, the feed water flow rate that is sprayed onto the collector plate surface is also varied by adjusting the ball valve opening and the nozzle number. The curves shown in Figures 8 and 9 show the increase in feed water flow rate varied by the number of nozzles and ball valve openings.

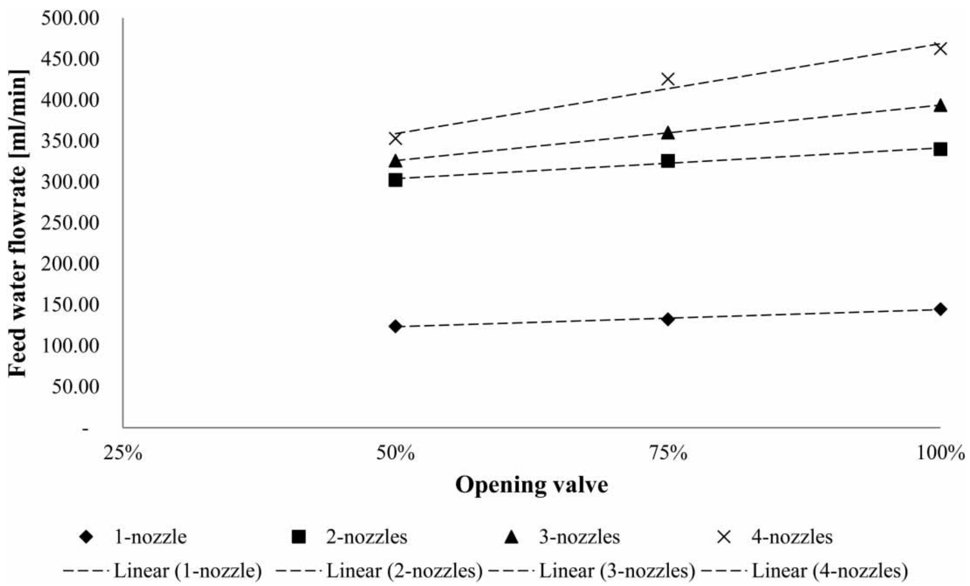

Figure 8 | Profile of changes in feed water flow rate concerning valve opening and number of nozzles.

An increase in clean water production or evaporation rate is proportional to the number of nozzles. The increase in clean water production was around 16.50% compared to the 20.33% increase in feed water. However, the use of multiple nozzles is not always proportional to the production of clean water, which means that there is

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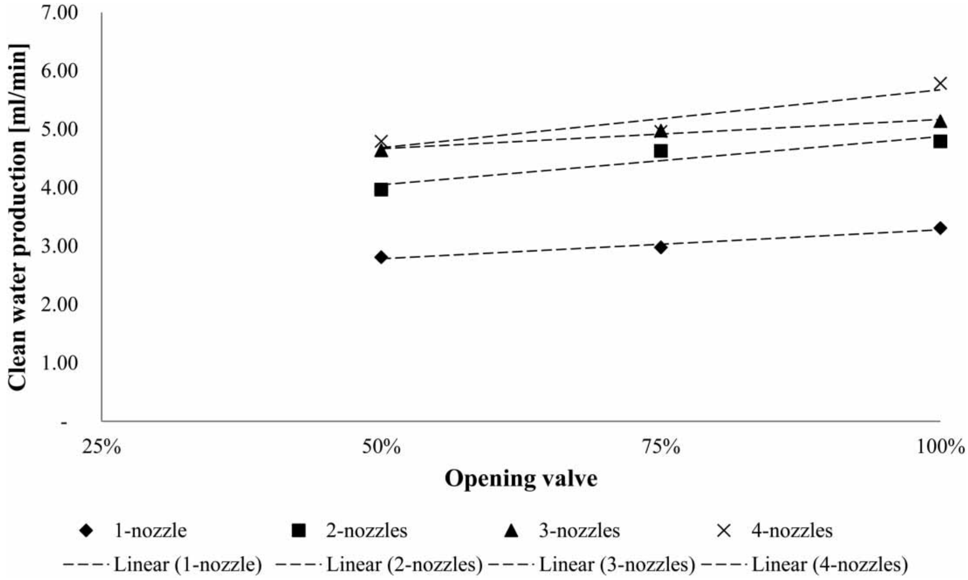

Figure 9 | Clean water production profile on valve opening and number of nozzles.

optimal clean water production when using multiple nozzles. From Figures 10 and 11, there is a tendency for clean water production to reach its optimum at the use of a certain number of nozzles.

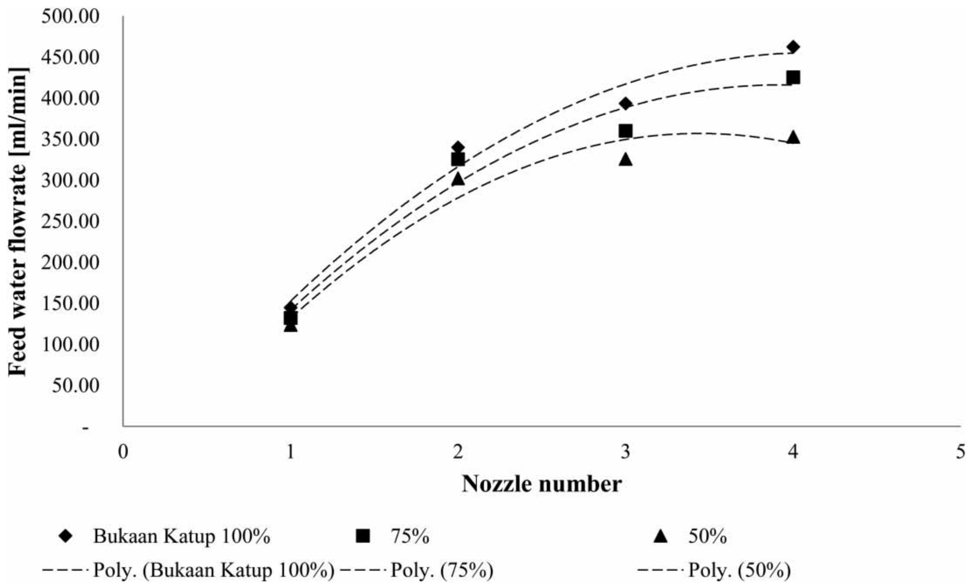

Figure 10 | Profile of changes in feed water flow rate concerning valve opening and number of nozzles.

The nozzle in the water mist system is added to the solar collector system role as a distributor of mist water in the solar collector chamber. Once being sprayed by the nozzle, the mist water will fulfill the solar collector chamber. The more nozzles are used, the more the density of the mist water in the chamber. Theoretically, the density of mist water in a chamber causes a higher tendency for collisions between the droplets and a decreased evaporation rate. The water volume on the collector plate surface increase and inhibit the water evaporation by the collector plate. A decreased evaporation rate which is indicated by a decrease in clean water production is the main effect. Under certain conditions, the optimum clean water production may be obtained from a certain number of nozzles. From Figure 12, to produce optimum clean water production, 3 or 4 nozzles may be applied in a modified solar collector system. Using more than 4 nozzles, a decrease in clean water production due to a decrease of evaporation on the collector plate surface may be attained.

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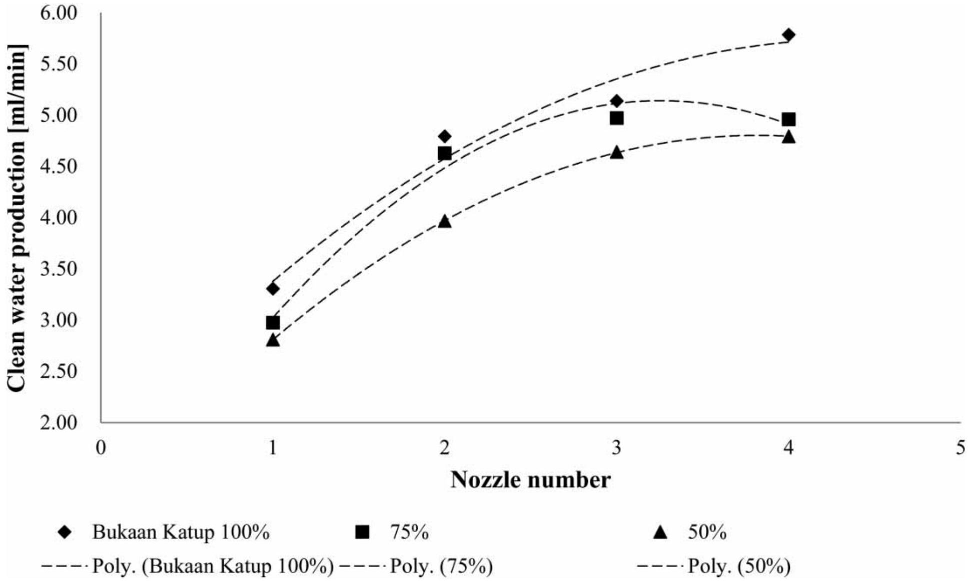

Figure 11 | Clean water production profile on valve opening and number of nozzles.

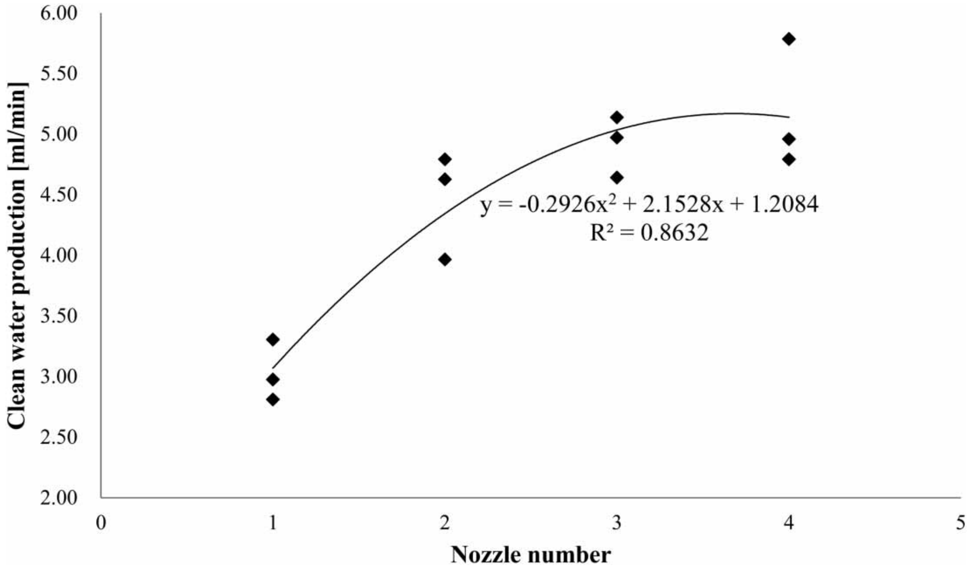

Figure 12 | Optimum clean water production is achieved by using 3–4 nozzles.

When using less than 3 nozzles, the density of mist water in the chamber is still less than the maximum density level.

From the four graphs in Figures 8–11, the relationship between clean water production and feed water flow rate can be connected by the number of nozzles and valve openings. By combining all the data for the use of single and multiple nozzles (up to 4 nozzles) a new curve is obtained as shown in Figure 13. By using the least square method, the correlation between clean water production and the number of nozzles can be expressed by Equation (1).

$$\dot{m}_{clean-water} = 0.0079\,\dot{m}_{feedwater} + 1.9538 \quad (1)$$

with a determination coefficient R^2 of 0.9536.

From this correlation, it can be seen that the clean water production was very small compared to the supplied feed water through the nozzle, which is indicated by the gradient value of the curve of 0.0079. In other meaning,

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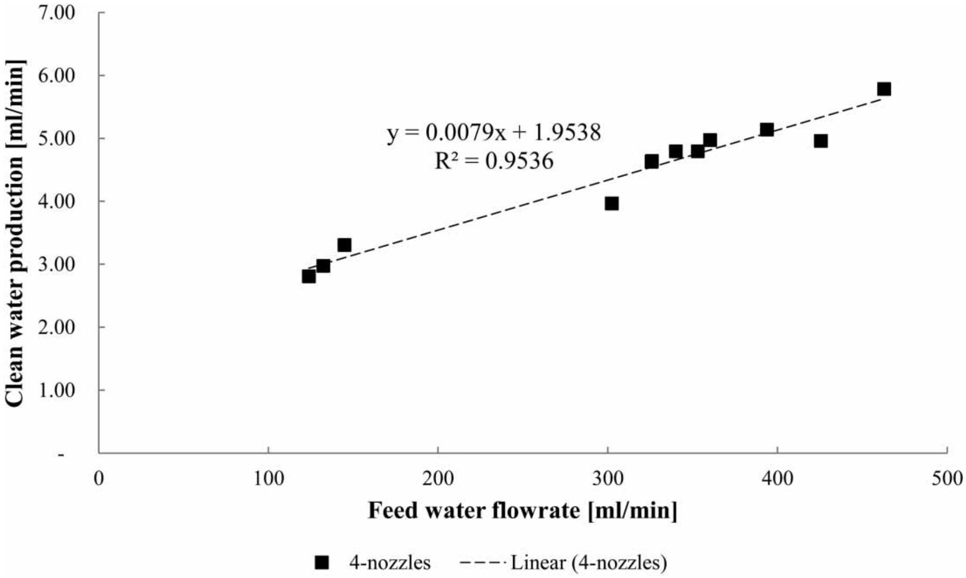

Figure 13 | Clean water production as a function of feed water flow rate for 1–4 nozzles.

the ratio of clean water production to feed water flow rate is 7.9%. Some of the contributing factors include the nozzle hole size, the feed water pressure, and the condenser geometry. The nozzle used in this experiment has a hole diameter of 0.3 mm but can be replaced by a diameter of 0.5 mm to increase the flow rate. Likewise, the feed water pressure can be increased from 2 bar.g to refine the mist water sprayed by the nozzle. The finer the mist water, the easier it to evaporate when it touches the collector plate surface.

The third factor that affects clean water production is the condenser geometry. The condenser has a large enough gap between the pipes that allows water vapor to escape from the chamber, thereby reducing the condensation rate or the clean water production.

From the results of this experiment, the evaporation method that applies a water mist system to the solar collector system has been proven to be able to produce clean water even though the percentage is relatively small. However, when compared to the traditional evaporation method, which evaporates water directly from the collector plate surface, as done by Khan & Mustafa (2019), the production of clean water from this method is still higher. The maximum clean water produced by Khan's research is 230 g/hour or 3.83 ml/minute, while the method using a water mist system can reach a maximum of 5.78 ml/minute.

Then research conducted by Puja *et al.* (2016) distillation of solar energy water with energy recovery using the capillarity method, produces distilled water of 4.38 l/m^2.day or equivalent to 3.04 ml/minute for a collector cross-sectional area of 1 m^2. From the comparison of the two other research products, it has been proved that the water purification method that applies the water mist system can produce higher clean water. Compared to the research of Shehata *et al.* (2019), they produce 11 times more clean water, which is approximately 45 kg per day or 62.5 ml per minute. Based on the findings of this study, there is still an opportunity to increase the production rate of clean water, such as by replacing a nozzle with one that has a diameter between 0.5 and 0.8 mm.

CONCLUSION

From the research, the evaporation method that applies a water mist system has been proven to be able to produce clean water from feed water sources. Clean water production is correlated with feedwater flowrate for a nozzle diameter of 0.3 mm and the number of nozzles of 1–4 pcs through the following equation:

$$\dot{m}_{clean-water} = 0.0079\ \dot{m}_{feedwater} + 1.9538$$

with a determination coefficient R^2 of 0.9536. The optimum clean water production is obtained when using 3–4 nozzles, which are connected through the following equation:

$$\dot{m}_{clean-water} = -0.2926\ N^2 + 2.1528\ N + 1.2084$$

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with a determination coefficient R^2 of 0.8632. The maximum clean water production is 5.78 ml/minute or 1.25% of the feedwater flow rate when using four nozzles in the chamber.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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