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Improving the performance of a forced-flow desalination unit using a vortex generator

Dan Mugisidi[1*], Oktarina Heriyani[1]

1. Mechanical Engineering, Engineering Faculty, Universitas Muhammadiyah Prof. Dr HAMKA, Indonesia

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Water is a primary need for living creatures, and water scarcity can trigger a crisis. Water scarcity is becoming an issue in Indonesia, especially in coastal village areas, including in salt-producing areas. Salt production involves evaporating large amounts of seawater in concentration ponds. Using evaporated seawater as a source of clean water would reduce the risk of water scarcity. Therefore, this study aims to obtain fresh water by condensing water vapour that has been evaporated in a desalination unit. More specifically, the study uses a vortex generator to increase the rate and efficiency of evaporation in a forced-flow desalination unit. This research was conducted indoors to reduce uncontrollable variables. An evaporation container with a volume of 0.35 m^3 was filled with sea water. The rate of evaporation in the desalination unit with a vortex generator was compared to that in a unit without a vortex generator. The results show that the vortex generator leads to faster evaporation. The rate of evaporation with a vortex generator was 1.13 times higher than that without a vortex generator, and evaporation efficiency was also increased 1.14 times with the vortex generator. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

Keywords: Desalination; evaporation; solar still; condenser; vortex generator

1. Introduction

Humans and other living creatures need water to live. As the global population increases, the need for water will increase as well; a global population increase of 15% will reduce the amount of available fresh water by 40% [1]. Without changes to the use and treatment of water, this will lead to water scarcity [2], which is predicted to impact half of the world's population by 2025 [3]. Water is so important that it can raise issues related to human rights, politics and even racism [4]. Since physical water scarcity is often associated with agricultural production, growing human populations and state sovereignty, it is almost certain that water scarcity will trigger various crises [5]. In addition to being a global threat, water scarcity has become an urgent issue in specific parts of the world, including Indonesia.

Indonesia, an archipelagic country, has the longest coastline in the world, so many people live in coastal areas. Unfortunately, coastal village communities often experience severe water scarcity. There are 12,827 coastal villages throughout Indonesia, and only 66.54% of these have regular access to clean water. Thus, coastal villagers use turbid and salty water for daily needs, such as washing and bathing, and buy drinking water [6]; many members of these coastal village communities are salt farmers.

There is a high demand for salt in Indonesia. The Indonesian salt industry still uses traditional mining methods, which involves injecting seawater into ponds and evaporating it. Evaporation of sea water in concentration ponds is very dependent on water surface pressure and temperature [7]. Therefore, if the sun's heat is blocked or the wind is still, the rate of evaporation is slowed. However, making salt requires evaporating large amounts of water.

The water evaporated in the concentrating pool is not collected; it evaporates into the environment and rejoins seawater, which has a salinity of 30–45‰ or 3–4.5 °Be [8]. To concentrate 1,000 litres of seawater to 30–45 °Be, about 900 litres of seawater must be evaporated. A concentration pool for salt mining can contain up to 10,000 litres of seawater, which undergoes a concentration process lasting four to five days [8]. Collecting and condensing this evaporated seawater could provide 9,000 litres of clean water. A large amount of this water could then be used by villagers. Thus, the ability to collect and use the water that evaporates from the salt fields would significantly benefit Indonesia's coastal villages. However, recovering moisture from the salt fields without reducing salt production is a challenge. Little research has been done on the use of desalination to produce fresh water and salt [9]. A simpler solution would be to evaporate the seawater in evaporation chambers similar to solar stills.

A solar still is a simple device that uses the greenhouse effect [10] to convert salt water or waste water into clean water by evaporating and recondensing it [11]. A solar still can produce up to 200 m^3 of fresh water per day [12], and various studies have explored ways to increase the productivity of solar stills [13]. Methods for increasing the production of a solar still fall into four categories: hybrid solar stills, stills with added reflectors and concentrators, stills with added condensers, and stills with added absorbers. Several types of absorbers can increase the productivity of solar stills. These approaches include changing the type of heat absorber [14], [15], using a wick [16]–[19], using fins [20]–[22], adding reflectors [23]–[25] and adding a heat collector. Furthermore, according to Nasri [26], solar still heat absorbers can use materials such as gravel, sand or polyurethane, and it is easy to add such materials to speed the evaporation process. The expansion of the absorber increases the water temperature, while the addition of a condenser increases the heat absorption capabilities of the water vapour. Increasing the rate of air flow over the surface of the water also increases the rate of evaporation. The air flow causes the pressure above the water surface to decrease, resulting in evaporation [27]. Some studies have used increased air flow in solar stills to increase the rate of evaporation [28], [29] but so far, no solar still has used a vortex generator to increase the rate of evaporation.

A vortex generator reduces air pressure, thereby increasing the pressure difference between the surface of the water and the air above it. This pressure difference is the driving force for evaporation [30]. A vortex generator also increases heat transfer [31] by creating turbulence and vortices [32]. Vortex generators can increase heat transfer in cooling tower ducts [33] by increasing the speed of air flow around the tip of the vortex generator [34]. An increase in flow velocity creates vortices, lowering the surface pressure of the water and increasing the rate of evaporation. Thus, the present study aims to explore the impact of air flow on evaporation and condensation in salt field desalination units using vortex generator. Therefore, various amounts of air flow were tested with a constant water temperature. Each variation in air flow underwent two treatments, one without a vortex generator (NVG) and one with a vortex generator (VG). In addition, a condenser is used to condense water vapor since in previous studies prove that the addition of internal and external condensers has been shown to increase the efficiency of solar stills [35]–[43]. Solar still efficiency can also be increased by expanding the condensation surface [44]; increasing the condensation surface by 7.5 times increases fresh water production by more than 50% [45]. Specifically, this paper examines the impact of a vortex generator on the rate of evaporation in a forced-flow desalination unit.

2. Methods

A. Experimental Setup

This research was conducted indoors to reduce uncontrolled variables [46], as shown in Fig. 1. Three lamp units with a total power of 3,000 watts were used to maintain solar radiance at 500 watts/m^2. As shown in the research scheme (Fig. 1.), water was pumped from the water reservoir to the water level

Fig. 1. Forced-flow desalination experimental rig

control, which was connected to the evaporation chamber. Thus, the water level in the evaporation chamber remained the same as that in the water level control. The evaporation chamber holds 350 litres of water. The water level control has an overflow channel, and the water level is determined by the height of the overflow. The water emerging from the overflow flows back into the seawater reservoir. When evaporation occurs in the evaporation chamber, water from the water level control flows into the evaporation chamber to equalize the level. Because the water level is maintained by the overflow, the reduction in water volume or weight in the seawater reservoir is proportional to the volume of the water that evaporates in the evaporation chamber. In addition to water circulation, the system also includes air flow. The direction of air flow is shown by the arrow in Figure 1. The air flow, at a rate of 1 m/s, is caused by fan suction. Air flow was tested in a desalination unit with (D-VG) and without (D-NVG) a vortex generator. The vortex generator was attached to the top cover of the evaporation container so that it could be removed and replaced with a cover that did not include a vortex generator. The vortex generator is 9.4 mm high and was mounted on the inside of the glass cover. The ratio of the height vortex generator to that of the glass cover is 0.47 [47]; the width of the vortex generator is the same as that of the glass cover. The first vortex generator was placed 286 mm from the air inlet, and the second vortex generator was placed 286 mm from the first. Thus, the longitudinal pitch ratio of the distance between the vortex generators to the length of the cover was 0.2 [48]. Four vortex generators were used, all placed 286 mm apart. Data were collected every five minutes. A simulation of the system was also conducted using computational fluid dynamics (CFD).

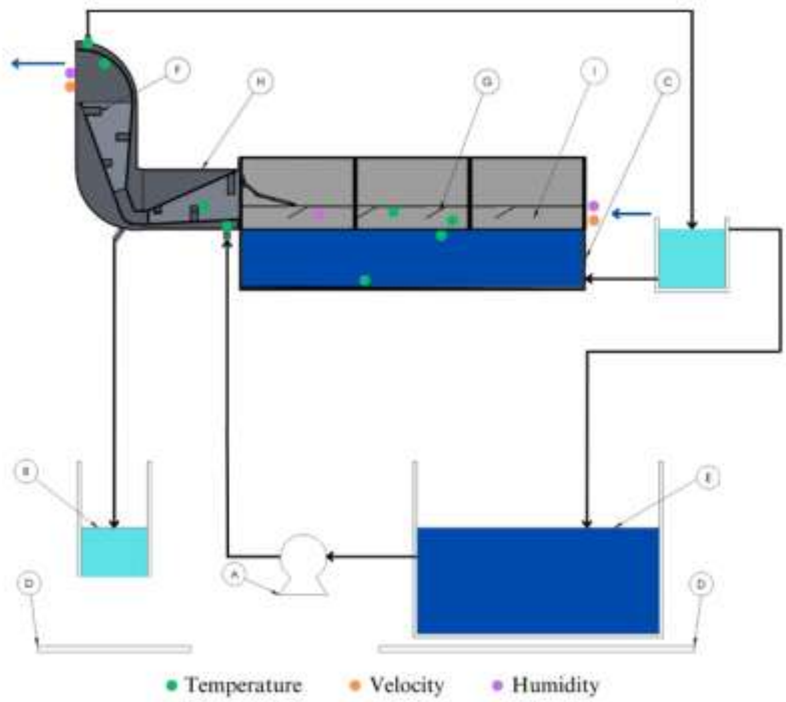
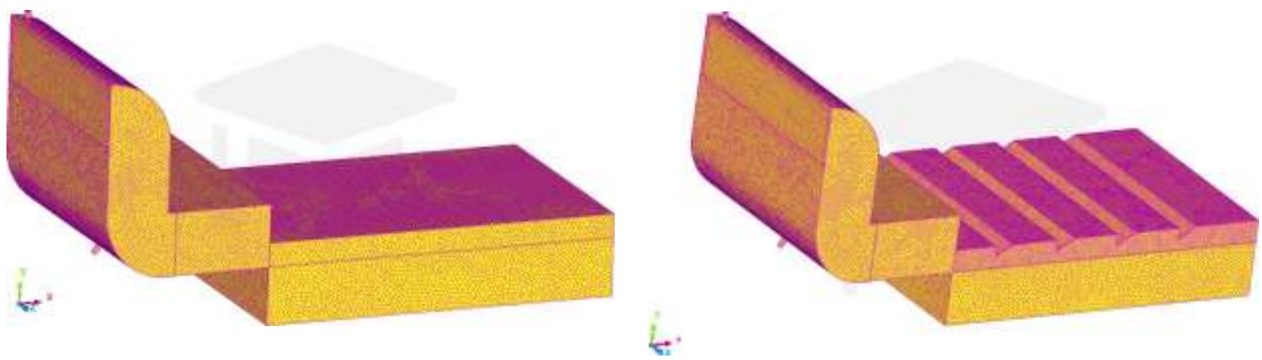


Fig. 2. Schematic of the forced-flow desalination experimental rig
(A) Circulation pump, (B) Freshwater reservoir, (C) Sea water, (D) Scale, (E) Condenser cooling water reservoir, (F) Vortex generator in condenser, (G) Vortex generator, (H) Condenser, (I) Evaporation chamber. The coloured dots show the locations of the sensors; the arrow shows the direction of air flow.

Many previous studies have included CFD simulations [49]–[52]. In the present study, a simulation was created using Cradle CFD software by Hexagon. In CFD, meshing or discretization is used to convert a continuous fluid domain into a discrete computational domain. This approach allows fluid equations to be solved using numerical methods. An efficient mesh is very important in multiphase simulations because it impacts the accuracy of the simulation [53]. A hexahedron mesh was used here; this mesh has good resolution and high computational efficiency. For more detailed analyses, a polyhedral mesh was used in the present study used, which can simulate the movements of objects along a high curvature (Figure 3). When creating a CFD simulation, it is also necessary to conduct a grid independence test [54], [55] as shown in Table 1.



(A) (B)

Fig. 3. A CFD hexahedron mesh without vortex generator (A) and using vortex generator (B)

Table 1
Grid independence test

No. of element	Water level
169851	1.007815
276986	0.976572
350756	0.885430
494312	0.799841
509258	0.799853

Data were collected using the tools listed in Table 2.

Table 2
Tools used in the study

No.	Factor	Tools	Specification
1	Temperature	Thermometer	40–400 °C, 0.09%
2	Solar radiance	Solar meter	0–2000 W/m^2
3	Wind velocity	Wind meter	0–30 m/s
4	Relative humidity	Hygrometer	10%–99%
5	Weight	Digital balance	0–20 kg ± 0,1

3. Results

The temperature of the water and of the air flowing over the water significantly impact the rate of evaporation, while the condenser temperature determines the amount of water vapour that can be condensed, as shown in Fig. 4.

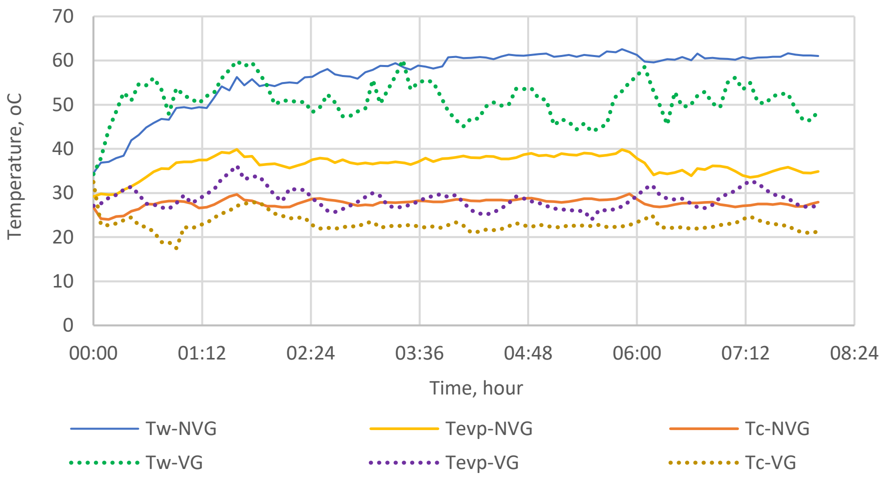
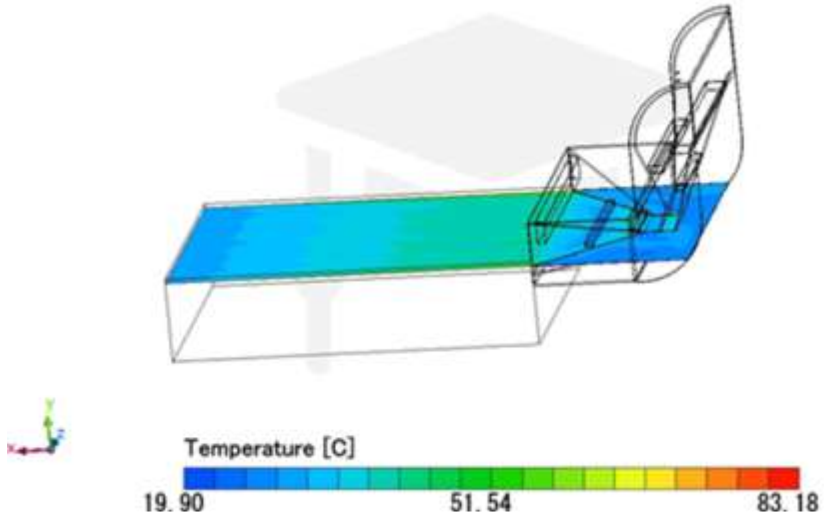
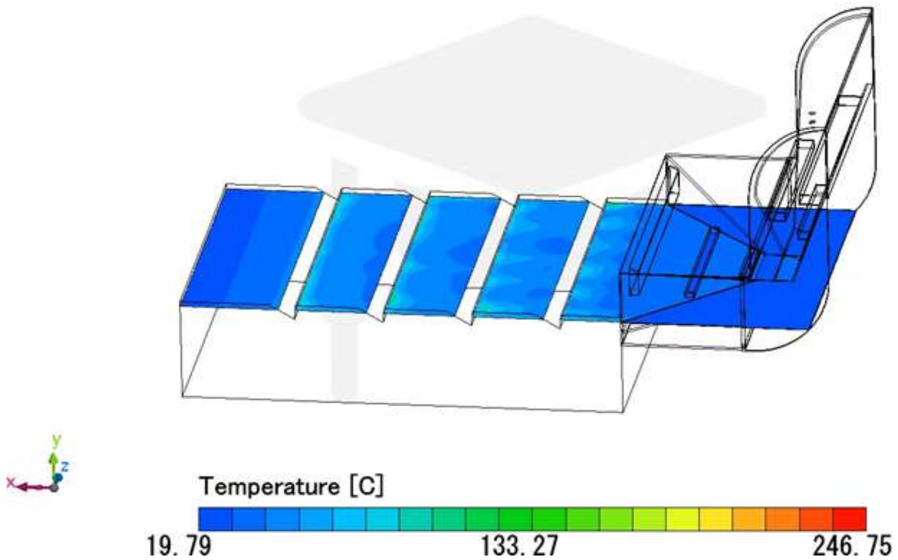


Fig. 4. Water temperature (Tw), air flow temperature (Tev) and condenser temperature (Tc) in the desalination units with (Tw-VG, Tev-VG and Tc-VG) and without a vortex generator (Tw-NVG, Tev-VG and Tc-VG)

As shown in Fig. 4, the water temperature was lower with a vortex generator (Tw-VG) than without it (Tw-NVG). The average Tw-VG and TW-NVG were 51.42 °C and 58.06 °C, respectively. The air flow temperature is a mix of the temperature of the air entering from outside and the temperature of the evaporated water vapour. The temperature of air flow was generally lower with the vortex generator (Tev-VG) than without it (Tev-NVG). Although Tev-VG was lower than Tev-NVG, the difference between the temperature of the water and that of the vapour in the desalination unit with the vortex generator was greater than the difference between the temperature of the water and the vapour in that without the vortex generator; these differences are 25.72 °C and 21.18°C, respectively. This temperature difference is proportional to the pressure difference [30] and promotes evaporation. Tc-VG was lower than Tc-NVG, the average difference between these temperatures was 2.36 °C, because Tev-VG entering the condenser is lower than Tev-NVG. The temperature during evaporation predicted by the simulation does not differ much from the temperature recorded in the experiment, as shown in Fig. 5.



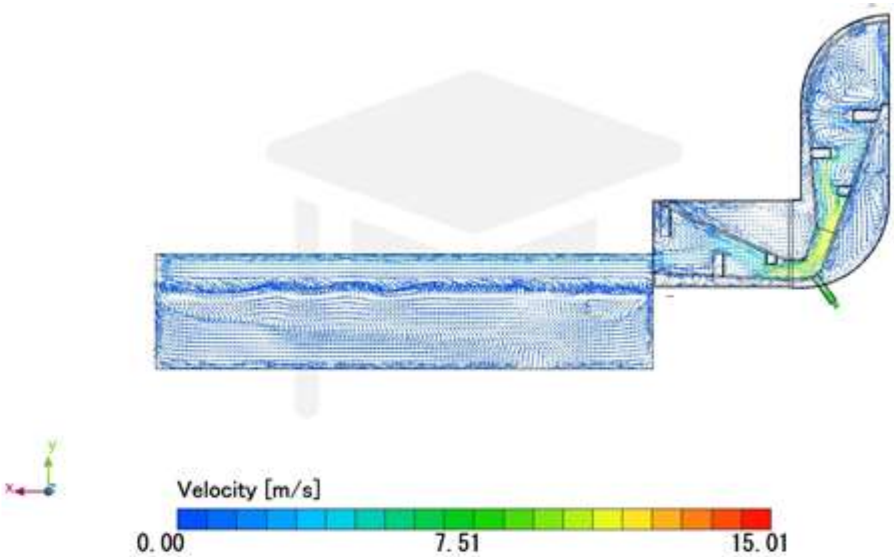
(A)



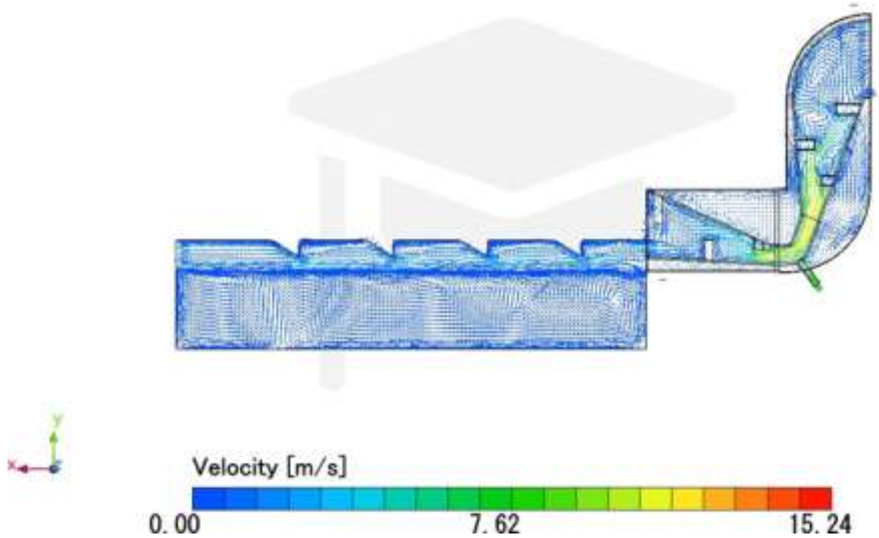
(B)

Fig. 5. Temperature distribution without (A) and with a vortex generator (B)

As shown in Figure 5, the temperature of the water surface with a vortex generator is about 50 °C; it is about 55 °C without the vortex generator. The speed of air flow increases around the tip of the vortex generator, reducing the water temperature. This increase in air flow speed can be seen in Fig. 6.



(A)



(B)

Fig. 6. Air flow velocity without (A) and with a vortex generator (B)

As shown in Fig. 6, the rate of air flow without the vortex generator was about 2.28 m/s; without the vortex generator, air speed tends to remain constant throughout the evaporation chamber. With a vortex generator, air flow speed increases around the tip of the vortex generator. This increase in speed causes a drop in air pressure at the tip of the vortex generator; this drop does not occur without the vortex generator [56]. This shift increases the difference in air pressure, encouraging faster evaporation, as shown in Figure 7.

Figure 7 illustrates evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-VG) the vortex generator. Evap-VG was consistently greater than Evap-NVG; on average, the difference was 1.13 times greater. Condensation was also greater with the vortex generator; the average relative humidity after evaporation was 56.5% without the vortex generator and 67.6% with it. With the vortex generator, 91% of the condensation evaporated; without it, only 86% of the condensation evaporated. Thus, the desalination unit with the vortex generator created more water vapour than the one without a vortex generator. The Reynolds number (Re) was also higher with a vortex generator than without it. Without a vortex generator, Re was 5.236.37; with it, Re was

11,259.23, 1.15 times greater. A higher Reynolds number indicates more counter-rotating vortices at various distances [57], which leads to faster evaporation.

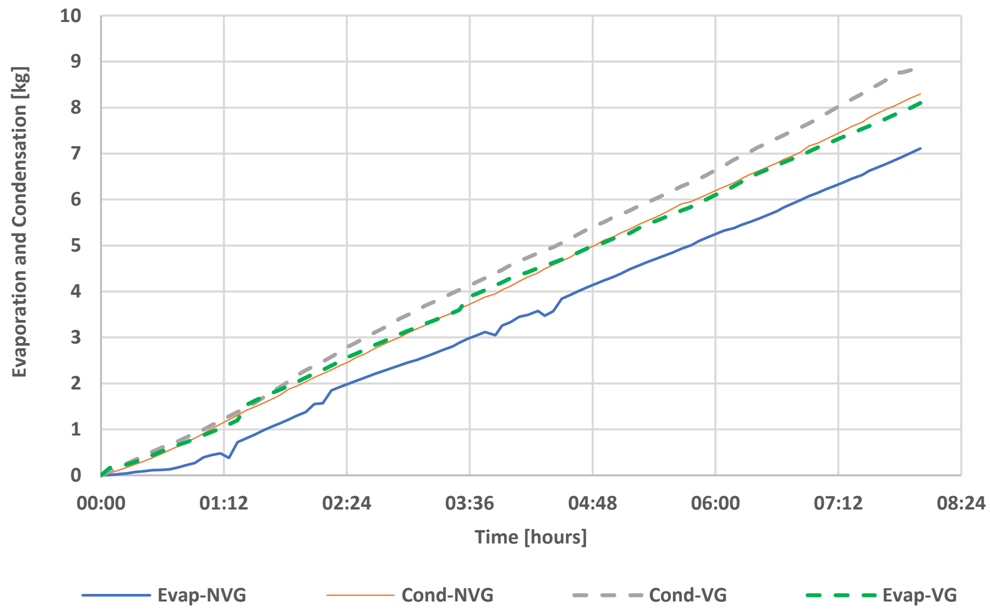


Fig. 7. Evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-NVG) a vortex generator

As mentioned above, more condensation leads to faster evaporation. This finding also aligned with the simulation. Since the yield of water vapour is higher with the vortex generator than without it, the desalination unit with the vortex generator is more efficient than the one without (Table 3).

Table 3
System efficiency

	VG	NVG
Efficiency	76.1%	66.4%

As shown in Table 3, the desalination unit with the vortex generator is 1.14 times more efficient than the unit without the vortex generator. Therefore, a vortex generator is very useful for increasing the rate of evaporation.

4. Conclusions

The results of this study show that a vortex generator increases the rate of evaporation. In the unit with a vortex generator, evaporation occurred 1.13 times faster than without a vortex generator. This means that more fresh water was produced. Thus, a vortex generator can increase the efficiency of a desalination unit. In this study, efficiency increased from 66.4% in a unit without a vortex generator to 76.1% with one. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

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BUKTI KONFIRMASI REVIEW
DAN HASIL REVIEW

Dan Mugisidi <dan.mugisidi@uhamka.ac.id>

[CFD Lett.] Editor Decision

2 messages

Wan Arif <journal2017cfdl@gmail.com> Sat, Dec 16, 2023 at 9:00 PM
To: Dan Mugisidi <dan.mugisidi@uhamka.ac.id>, Oktarina Heriyani <oktarina@uhamka.ac.id>

Dear Dan Mugisidi, Oktarina Heriyani:

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Submission URL: https://semarakilmu.com.my/journals/index.php/CFD_Letters/authorDashboard/submission/5385
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We have reached a decision regarding your submission to CFD Letters, "Improving the performance of a forced-flow desalination unit using a vortex generator".

Our decision is: Revisions Required

Please revise your manuscript as requested in the following comments **AND PLEASE FILL IN THE "RESPONSE TO REVIEWER" FORM**. Please send the revised manuscript together with the form **WITHIN TWO WEEKS.**

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Collaboration with intl co-author is recommended.

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3. Please provide all email of the co-author at the last page of manuscript after the reference list.
4. In the abstract section, it should have a **short introduction of the background study**, **problem statement**, **objective** of the paper, **briefing about the used method** and **main finding**.
5. At the **last paragraph of the introduction section,** it should **have** the **gap** and **significant of study** before write the **objective** of the study.
6. Nomenclature list should not be written in manuscript. Please write in a **full sentence of abbreviations** for the first time used.
7. Please refer to the CFD Letters Template about how to **present** equations, figures and tables in a manuscript. Besides that, please check on how to **mention** to those equations (**Eq. (X)**), figure (**Figure X**) and table (**Table X**) in a body paragraph.
8. PLEASE CHECK THE CITATION NUMBER. **All citation numbers must be in ascending order without skipped numbers, for the first time cited**. **PLEASE REARRANGE ALL THE CITATIONS.**
9. Please provide a clear, readable, and high-resolution Figure for all figures. Besides that, the font size of **LEGEND, AXIS** and **LABEL** in all the Figures should be **10pt**. Please increase the font size in its original software. **DO NOT SIMPLY INCREASE THE SIZE OF THE EXISTING FIGURES. Please use the correct aspect ratio for all figures. PLEASE DO NOT STRETCH THE FIGURES. THE LOW-RESOLUTION FIGURES ARE UNACCEPTABLE FOR PUBLICATION.**
10. Citation in the body paragraph, the **"et al"**must be written as "*et al.,*".
11. Citation cannot stand alone as subject or object. It just as a support to a statement. For example, " .... are taken **from [17, 21-23]**......", should be written as " .... are taken **from the previous study [17, 21-23]**...... ". Please CHECK.
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Reviewers' Comments:

Reviewer A:

Paper Review for CFD Letters

Paper Ref.: 27452

Paper Title: Improving the performance of a forced-flow desalination unit using a vortex generator.

This paper deals with experimental work aiming to improve the distillation yield of a forced-flow desalination unit using air vortex generators. The paper is of technological interest, and its publication is recommended after considering the following suggestions/comments:

1. English needs improvement throughout the text.
2. In the Abstract, try to use percentages for a better illustration of the obtained results.
3. Kindly use "The rate of distillation" instead of "The rate of evaporation"; use "condensing it [11]" instead of "recondensing it [11]"; use "stills with reflectors" instead of "stills with added reflectors"; the same observation for concentrators, condensers, and absorbers.; use "few solar stills have used a vortex generator" instead of "no solar still has used a vortex generator".
4. Solar still operates under natural convection, and there is no need for vortex generators. Concerning the convection air generation inside stills, there are some works using air motion like that given in: https://doi.org/10.1016/0196-8904(91)90144-8 and https://doi.org/10.1016/0196-8904(93)90009-Y
5. This declaration must be verified "A solar still can produce up to 200 m3".
6. When using a light source, the heating process is by a constant (imposed) heat flux (not by constant temperature).
7. Why air-flow is not recirculated for the recovering energy and moisture, leaving the condenser (reducing heat/mass losses)?
8. Y-label in Fig. 7 must be corrected, and Fig. 2 must be highlighted.
9. Based on the experimental data, compare the heat transfer coefficients (by evaporation, convective, and radiation) with and without vortex generation.
10. Limitations associated with the work done and future works may be stated at the end of the conclusion section.

Recommendation: Revisions Required

Reviewer B:

The researchers carried out simulation and experimental investigations on the solar still intended for seawater desalination, comparing the performance of the solar still equipped with a vortex generator versus that of the solar still not equipped with one. This object of investigation in the manuscript is highly relevant for solving water scarcity and the work of the paper is fulfilling. However, there are some issues with the structure and content presentation of the current manuscript that make it unsuitable for immediate publication. The authors need to complete the following important revisions:

1. The 3 page of the manuscript describes the basics of the experimental system, but it does not give the working conditions of the experimental tests, the solar energy input and the environment, please add this part.

2. The description of CFD modelling on page 4 is not detailed enough. Figure 3b in the manuscript clearly uses local encryption while Figure 3a does not, please add the reason why.
3. Also, for the vortex generator, this part causes air to be mixed into the still. does the CFD simulation consider two-phase flow, and how do CFD's continuity, energy and momentum equations describe this complex process? The authors need to add the mathematical model of the CFD simulation and list the UDF used, if it exists.
4. The grid independence analyses in Table 1 only list comparisons of water levels, which is clearly insufficient. The most important parameters for desalination are temperature and evaporation rate, which should also be compared to ensure that the grid is sufficiently accurate.
5. Two Table 1 have appeared on page 5, please correct them.
6. Comparative analyses of experiments and simulations need to be added to the paper in order to enhance persuasiveness.
7. The temperature bar in Figure 5b actually reaches a maximum temperature of 246.75°C, which is clearly incorrect. Please check if this is because the CFD simulation results have not converged?
8. For desalination systems, GOR is an important indicator for evaluating the system's excellent energy efficiency, so please add a discussion of solar still's GOR situation.
9. The performance of only two test units is compared in Table 3, and the authors need to add comparisons with the various types of new desalination systems available.
10. Authors can refer to the following literature when revising their papers：
https://doi.org/10.1016/j.desal.2019.04.001
https://doi.org/10.1016/j.ijheatmasstransfer.2019.118621
https://doi.org/10.1016/j.isci.2021.103565
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https://doi.org/10.1016/j.desal.2023.116559;
According to the current manuscript, the topic of the paper is very meaningful and the workload is detailed. However, There are still many problems with this paper that need to be addressed. Therefore, I suggest that the author should make the Major Revision to this manuscript.

Recommendation: Revisions Required

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Dan Mugisidi <dan.mugisidi@uhamka.ac.id> Mon, Jan 22, 2024 at 12:26 PM
To: Wan Arif <journal2017cfdl@gmail.com>, azwadi@semarakilmu.com.my
Cc: Oktarina Heriyani <oktarina@uhamka.ac.id>

Dear sirs,
Hopefully this email finds you well. I would like to ask about the status of my article "Improving the performance of a forced-flow desalination unit using a vortex generator". I have sent the revision since December 30, 2023. Please be informed since I have to provide a report to my Institution.
I do apologize for this. Thank you for your information.

Best Regards
Dan Mugisidi
[Quoted text hidden]

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Round 1

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3	In the abstract section, it should have a **short introduction of the background study**, **problem statement**, **objective** of the paper, **briefing about the used method** and **main finding**.	V

4	At the **last paragraph of the introduction section,** it should **have** the **gap** and **significant of study** before write the **objective** of the study.	V
5	Nomenclature list should not be written in manuscript. Please write in a **full sentence of abbreviations** for the first time used.	V
6	Please refer to the CFD Letters Template about how to **present** equations, figures and tables in a manuscript. Besides that, please check on how to **mention** to those equations (**Eq. (X)**), figure (**Figure X**) and table (**Table X**) in a body paragraph.	V
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8	Please provide a clear, readable, and high-resolution Figure for all figures. Besides that, the font size of **LEGEND, AXIS** and **LABEL** in all the Figures should be **10pt**. Please increase the font size in its original software. **DO NOT SIMPLY INCREASE THE SIZE OF THE EXISTING FIGURES. Please use the correct aspect ratio for all figures. PLEASE DO NOT STRETCH THE FIGURES. THE LOW-RESOLUTION FIGURES ARE UNACCEPTABLE FOR PUBLICATION.**	V
9	Citation in the body paragraph, the **"et al"**must be written as "*et al.,*".	V
10	Citation cannot stand alone as subject or object. It just as a support to a statement. For example, " .... are taken **from [17, 21-23]**......", should be written as " .... are taken **from the previous study [17, 21-23]**...... ". Please CHECK.	V
11	**PLEASE CHECK GRAMMAR MISTAKES IN THE MANUSCRIPT BEFORE YOU SUBMIT THE REVISION FILE. NO CHANGES CAN BE MADE AFTER SUBMISSION FOR GRAMMAR ISSUE.**	V
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No.	Reviewer 1	Respond
1	English needs improvement throughout the text	The article has been revised and proofread on Scribendi (https://www.scribendi.com/)
2	In the Abstract, try to use percentages for a better illustration of the obtained results	Percentages have been used to illustrate research results in the abstract
3	Kindly use "The rate of distillation" instead of "The rate of evaporation"; use "condensing it [11]" instead of "recondensing it [11]"; use "stills with reflectors" instead of "stills with added reflectors"; the same observation for concentrators, condensers, and absorbers.; use "few solar stills have used a vortex generator" instead of "no solar still has used a vortex generator".	Thank you for the advice. The sentences in the introduction have been corrected accordingly

4	Solar still operates under natural convection, and there is no need for vortex generators. Concerning the convection air generation inside stills, there are some works using air motion like that given in: https://doi.org/10.1016/0196-8904(91)90144-8 and https://doi.org/10.1016/0196-8904(93)90009-Y	Thank you for the advice. Suggested references have been studied and used to enrich the discussion in the article. Additions were made to the introduction and discussion sections
5	This declaration must be verified “A solar still can produce up to 200 m3”.	This statement has been removed from the article
6	When using a light source, the heating process is by a constant (imposed) heat flux (not by constant temperature).	Thank you for the advice. Improvements have been made to the experimental setup according to the research conditions
7	Why air-flow is not recirculated for the recovering energy and moisture, leaving the condenser (reducing heat/mass losses)?	Because the air coming from the environment is more humid than that coming out of the condenser, so if you use air from the environment we will get higher condensate.
8	Y-label in Fig. 7 must be corrected, and Fig. 2 must be highlighted.	Y-label in Fig 8 already corrected. Figure 2 already highlight in experimental setup.
9	Based on the experimental data, compare the heat transfer coefficients (by evaporation, convective, and radiation) with and without vortex generation.	Base on experimental data, Reynolt number, evaporation coefficient and convective coefficient calculared and compared in Table 2.
10	Limitations associated with the work done and future works may be stated at the end of the conclusion section.	Future research will use heat from solar already added in conclusion

No	Reviewer 2	Respond
1	The 3 page of the manuscript describes the basics of the experimental system, but it does not give the working conditions of the experimental tests, the solar energy input and the environment, please add this part.	This research was conducted indoors. The heat source uses several spotlight units and already stated in experimental setup section.
2	The description of CFD modelling on page 4 is not detailed enough.	CFD modelling description already added to complete existing information
3	The authors need to add the mathematical model of the CFD simulation and list the UDF used, if it exists.	Mathematical model of CFD simulation already added in fourth pages
4	The grid independence analyses in Table 1 only list comparisons of water levels, which is clearly insufficient. The most important parameters for desalination are temperature and evaporation rate, which should also be compared to ensure that the grid is sufficiently accurate	Thank you for the advice. Grid independence is reset using temperature as a parameter

5	Two Table 1 have appeared on page 5, please correct them	Table 1 on page 5 already corrected
6	Comparative analyses of experiments and simulations need to be added to the paper in order to enhance persuasiveness	The explanation in the results section has been corrected
7	The temperature bar in Figure 5b actually reaches a maximum temperature of 246.75°C, which is clearly incorrect. Please check if this is because the CFD simulation results have not converged?	Thank you for your advice, I miss this part. I missed this part. Previously the scale of both images had not been set. Currently the scale of the two images is equalized using the smallest scale to make it easier to compare them
8	For desalination systems, *GOR* is an important indicator for evaluating the system's excellent energy efficiency, so please add a discussion of solar still's *GOR* situation.	Performance of the system also can be expressed with efficiency as well as GOR. I put both expression in result discussion.
9	The performance of only two test units is compared in Table 3, and the authors need to add comparisons with the various types of new desalination systems available	Table 3 already added for comparison with other researcher

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Improving the performance of a forced-flow desalination unit using a vortex generator

Dan Mugisidi[1*], Oktarina Heriyani[1]

[1] Mechanical Engineering, Faculty of Industrial Technology and Informatics, Universitas Muhammadiyah Prof. Dr HAMKA, Jakarta, Indonesia

ARTICLE INFO

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Received 29 October XXXX
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ABSTRACT

Water is a primary need for living creatures, and water scarcity can trigger a crisis. Water scarcity is becoming an issue in Indonesia, especially in coastal village areas, including salt-producing areas. Salt production involves evaporating large amounts of seawater in concentration ponds. Using evaporated seawater as a source of clean water would reduce the risk of water scarcity. Therefore, this study aims to obtain fresh water by condensing water vapour that evaporates in a desalination unit. More specifically, the study uses a vortex generator to increase the rate and efficiency of evaporation in a forced-flow desalination unit. This research was conducted indoors to reduce uncontrollable variables. An evaporation container with a volume of 0.35 m^3 was filled with seawater. The rate of evaporation in the desalination unit with a vortex generator was compared to that in a unit without a vortex generator. The results show that the vortex generator leads to faster evaporation. The rate of evaporation with a vortex generator was 13% higher than that without a vortex generator, and the gained output ratio increased 14% with the vortex generator. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

Keywords:
Desalination; solar still; evaporation; vortex generator; condenser

1. Introduction

Humans and other living creatures need water to live. As the global population increases, the need for water will increase as well; a global population increase of 15% will reduce the amount of available fresh water by 40% [1]. Without changes to the use and treatment of water, this will lead to water scarcity [2], which is predicted to impact half of the world's population by 2025 [3]. Water is so important that it can raise issues related to human rights, politics and even racism [4]. Since physical water scarcity is often associated with agricultural production, growing human populations and state sovereignty, it is almost certain that water scarcity will trigger various crises [5]. In addition

* *Corresponding author.*
E-mail address: dan.mugisidi@uhamka.ac.id (Dan Mugisidi)

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to being a global threat, water scarcity has become an urgent issue in specific parts of the world, including Indonesia.

Indonesia, an archipelagic country, has the longest coastline in the world, so many people live in coastal areas. Unfortunately, coastal village communities often experience severe water scarcity.

There are 12,827 coastal villages throughout Indonesia, and only 66.54% of these villages have regular access to clean water. Thus, coastal villagers use turbid and salty water for daily needs, such as washing and bathing, and buy drinking water; many members of these coastal village communities are salt farmers.

There is a high demand for salt in Indonesia. The Indonesian salt industry still uses traditional mining methods, which involve injecting seawater into ponds and evaporating it. The evaporation of seawater in concentration ponds is very dependent on water surface pressure and temperature [6]. Therefore, if the sun's heat is blocked or the wind is still, the rate of evaporation slows. However, making salt requires evaporating large amounts of water.

Sea water in the concentration pond, with a salinity of 30–45‰ or 3–4.5 °Be [7], is allowed to evaporate into the environment. To concentrate 1,000 litres of seawater to 30–45 °Be, about 900 litres of seawater must be evaporated. A concentration pool for salt mining can contain up to 10,000 litres of seawater, which undergoes a concentration process lasting four to five days [7]. Collecting and condensing this evaporated seawater could provide 9,000 litres of clean water. A large amount of this water could then be used by villagers. Thus, the ability to collect and use water that evaporates from salt fields would significantly benefit Indonesia's coastal villages. However, recovering moisture from salt fields without reducing salt production is a challenge. Little research has been done on the use of desalination to produce fresh water and salt [8]. A simpler solution would be to evaporate the seawater in evaporation chambers similar to solar stills.

Solar still is a simple device that uses the greenhouse effect [9] to convert salt water or wastewater into clean water by evaporating and condensing it [10]. Even though its productivity is low, because its operation is easy and economical, various studies have explored ways to increase the productivity of solar distillation equipment [11]. Methods for increasing the production of solar still fall into four categories: hybrid solar stills, stills with reflectors and concentrators, stills with condensers and stills with absorbers. Several types of absorbers can increase the productivity of solar stills. These approaches include changing the type of heat absorber [12], [13], using a wick [14]–[17], using fins [18]–[20], adding reflectors [21]–[23] and adding a heat collector. Furthermore, according to Nasri [24], solar still heat absorbers can use materials such as gravel, sand or polyurethane, and it is easy to add such materials to speed the evaporation process. The expansion of the absorber increases the water temperature, while the addition of a condenser increases the heat absorption capabilities of the water vapour. Increasing the rate of air flow over the surface of the water also increases the rate of evaporation. The air flow causes the pressure above the water surface to decrease, resulting in evaporation [25]. Some studies have used increased air flow in solar stills to increase the rate of evaporation [26], [27], but so far, few solar stills have used vortex generators to increase the rate of evaporation.

A vortex generator reduces air pressure, thereby increasing the difference in pressure between the surface of the water and the air above it. This pressure difference is the driving force for evaporation [28]. A vortex generator also increases heat transfer [29] by creating turbulence and vortices [30]. Vortex generators can increase heat transfer in cooling tower ducts [31] by increasing the speed of air flow around the tip of the vortex generator [32]. An increase in flow velocity creates vortices, lowering the surface pressure of the water and increasing the rate of evaporation. Thus, the present study aims to explore the impact of air flow on evaporation and condensation in salt field desalination units using a vortex generator. Therefore, various amounts of air flow were tested with constant heat. Each variation in air flow underwent two treatments: one without a vortex generator and one with a vortex generator. In addition, a condenser is used to condense water vapour; previous studies have proven that the addition of internal and external condensers has been shown to increase the efficiency of solar stills [33]–[40]. Solar still efficiency can also be increased by expanding the condensation surface [41]; increasing the condensation surface by 7.5 times increases freshwater production by more than 50% [42]. Specifically, this paper examines the impact of a vortex generator on the rate of evaporation in a forced-flow desalination unit.

2. Methodology

2.1 Experimental Setup

This research was conducted indoors to reduce uncontrolled variables [43], as shown in Fig. 1. Three lamp units with a total power of 3,000 watts were used to maintain a constant solar radiance at 500 watts/m^2. As shown in the research scheme (Fig. 2.), water was pumped from the water

Fig. 1. Forced-flow desalination experimental rig

reservoir to the water level control, which was connected to the evaporation chamber. Thus, the water level in the evaporation chamber remained the same as that in the water level control. The evaporation chamber holds 350 litres of water. Water level control has an overflow channel, and the water level is determined by the height of the overflow. The water emerging from the overflow flows back into the seawater reservoir. When evaporation occurs in the evaporation chamber, water from the water level control flows into the evaporation chamber to equalize the level. Because the water level is maintained by the overflow, the reduction in water volume or weight in the seawater reservoir is proportional to the volume of water that evaporates in the evaporation chamber. In addition to water circulation, the system also includes air flow. The direction of the air flow is shown by the arrow in Fig. 1. The air flow at a rate of 2 m/s is caused by fan suction. Air flow was tested in a desalination unit with (D-VG) and without a vortex generator (D-NVG). The vortex generator was attached to the top cover of the evaporation container so that it could be removed and replaced with a cover that did not include a vortex generator. The vortex generator was 9.4 mm high and mounted on the inside of the glass cover. The ratio of the height vortex generator to that of the glass cover is 0.47 [44]; the width of the vortex generator is the same as that of the glass cover. The first vortex generator was placed 286 mm from the air inlet, and the second vortex generator was placed 286 mm from the first. Thus, the longitudinal pitch ratio of the distance between the vortex generators and the length of the cover was 0.2 [45]. Four vortex generators were used, all placed 286 mm apart. A schematic of forced-flow desalination is shown in Fig. 2. Data were collected every five minutes. A simulation of the system was also conducted using computational fluid dynamics (CFD).

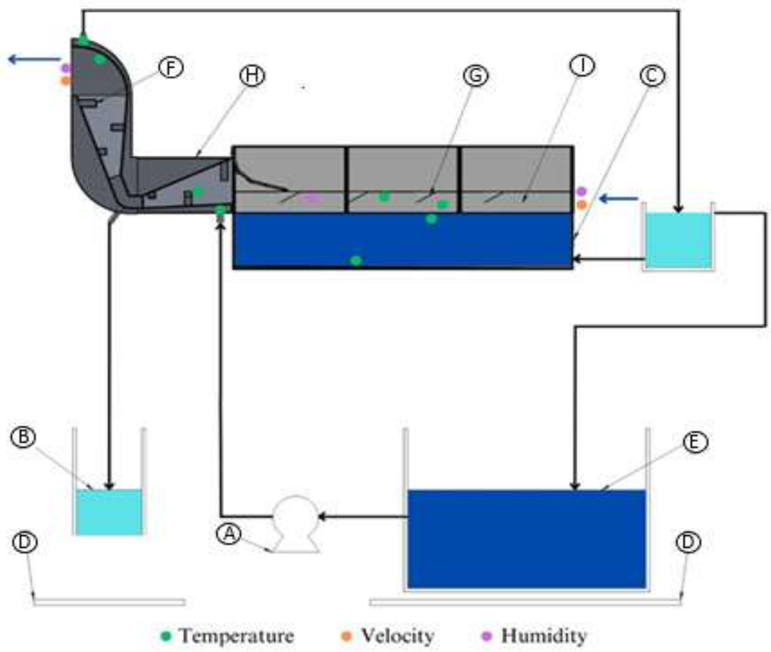


Fig. 2. Schematic of the forced-flow desalination experimental rig.
(A) Circulation pump, (B) Freshwater reservoir, (C) Sea water, (D) Scale, (E) Condenser cooling water reservoir, (F) Vortex generator in condenser, (G) Vortex generator, (H) Condenser, (I) Evaporation chamber. The coloured dots show the locations of the sensors; the arrows show the direction of air flow.

Many previous studies have included CFD simulations [46]–[49]. In the present study, a simulation was created using Cradle CFD software by Hexagon. There are three governing equations in fluid dynamics: the continuity equation, the momentum equation and the energy equation.

Integral form continuity equation:

$$\frac{\partial}{\partial t}\iiint_{V}\rho dV + \iint_{A}\rho\vec{V}\cdot d\vec{A} = 0 \quad (1)$$

Differential form continuity equation:

$$\frac{\partial\rho}{\partial t} + \rho\vec{\nabla}\cdot\vec{V} = 0 \quad (2)$$

Momentum equation in the x-axis direction:

$$\frac{\partial(\rho u)}{\partial t} + \vec{\nabla}\cdot\left(\rho u\vec{V}\right) = -\frac{\partial p}{\partial x} + \frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{yx}}{\partial y} + \frac{\partial\tau_{zx}}{\partial z} + \rho f_x \quad (3)$$

The momentum equation in the y-axis direction:

$$\frac{\partial(\rho v)}{\partial t} + \vec{\nabla} \cdot \left(\rho v \vec{V}\right) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad (4)$$

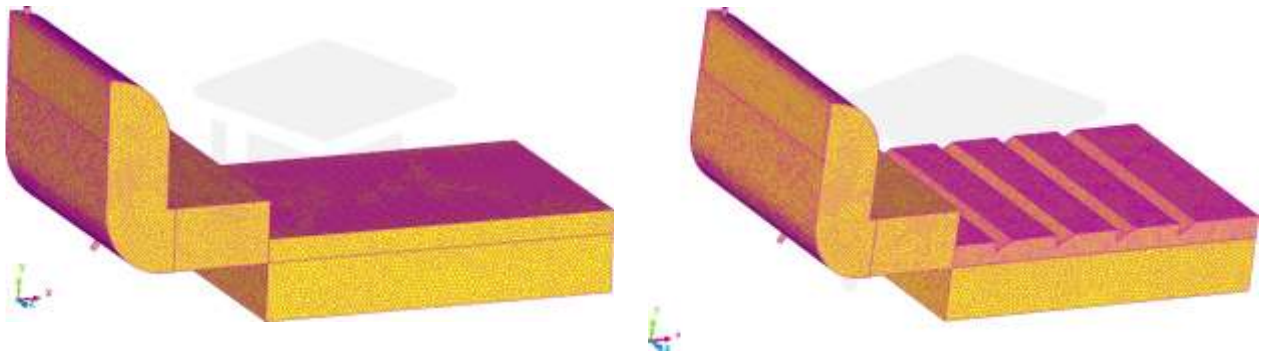
The momentum equation in the z-axis direction:

$$\frac{\partial(\rho w)}{\partial t} + \vec{\nabla} \cdot \left(\rho w \vec{V}\right) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad (5)$$

The energy equation is written in the form of internal energy:

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \vec{\nabla} \cdot \left[\rho\left(e + \frac{V^2}{2}\right)\vec{V}\right] = \rho\dot{q} - \frac{\partial(\rho p)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \rho\vec{f} \cdot \vec{V} \quad (6)$$

In CFD, meshing or discretization is used to convert a continuous fluid domain into a discrete computational domain. This approach allows fluid equations to be solved using numerical methods. An efficient mesh is very important in multiphase simulations because it impacts the accuracy of the simulation [50]. A hexahedron mesh was used here; this mesh has good resolution and high computational efficiency. For more detailed analyses, a polyhedral mesh was used in the present study, which can simulate the movements of objects along a high curvature (Fig. 3). When creating a CFD simulation, it is also necessary to conduct a grid independence test [51], [52] as shown in Fig. 4.



(A) (B)

Fig. 3. A CFD hexahedron mesh without vortex generator (A) and using vortex generator (B)

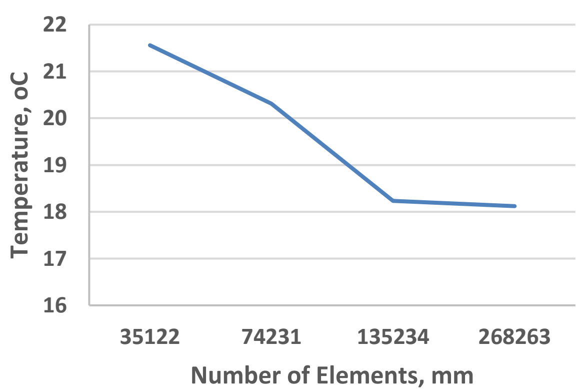


Fig. 4. Grid independence test

Data were collected using the tools listed in Table 1.

Table 1
Tools used in the study

No.	Factor	Tools	Specification
1	Temperature	Thermometer	40–400 °C, 0.09%
2	Solar radiance	Solar meter	0–2000 W/m^2
3	Wind velocity	Wind meter	0–30 m/s
4	Relative humidity	Hygrometer	10%–99%
5	Weight	Digital balance	0–20 kg ± 0,1

3. Results

The temperature of the water and the air flowing over the water significantly impact the rate of evaporation, while the condenser temperature determines the amount of water vapour that can be condensed, as shown in Fig. 5.

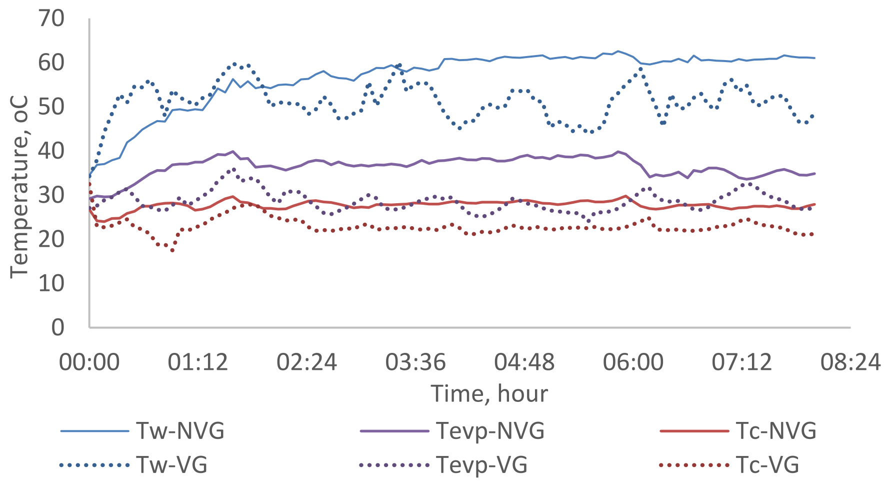


Fig. 5. Water temperature (Tw), air flow temperature (Tev) and condenser temperature (Tc) in the desalination units with (Tw-VG, Tev-VG and Tc-VG) and without a vortex generator (Tw-NVG, Tev-VG and Tc-VG)

As shown in Fig. 5, the water temperature was lower with a vortex generator (Tw-VG) than without it (Tw-NVG). The average Tw-VG and TW-NVG were 51.42 °C and 58.06 °C, respectively. The air flow temperature is a mix of the temperature of the air entering from outside and the temperature of the evaporated water vapour. The air flow temperature was generally lower with the vortex generator (Tev-VG) than without it (Tev-NVG). Although Tev-VG was lower than Tev-NVG, the difference between the temperature of the water and that of the vapour in the D-VG was greater than the difference between the temperature of the water and the vapour in the D-NVG; these differences were 25.72 °C and 21.18 °C, respectively. This temperature difference is proportional to the pressure difference [28] and promotes evaporation. Tc-VG was lower than Tc-NVG; the average difference between these temperatures was 2.36 °C because Tev-VG entering the condenser is lower than Tev-NVG. The temperature during evaporation predicted by the simulation did not differ much from the temperature recorded in the experiment, as shown in Fig. 6.

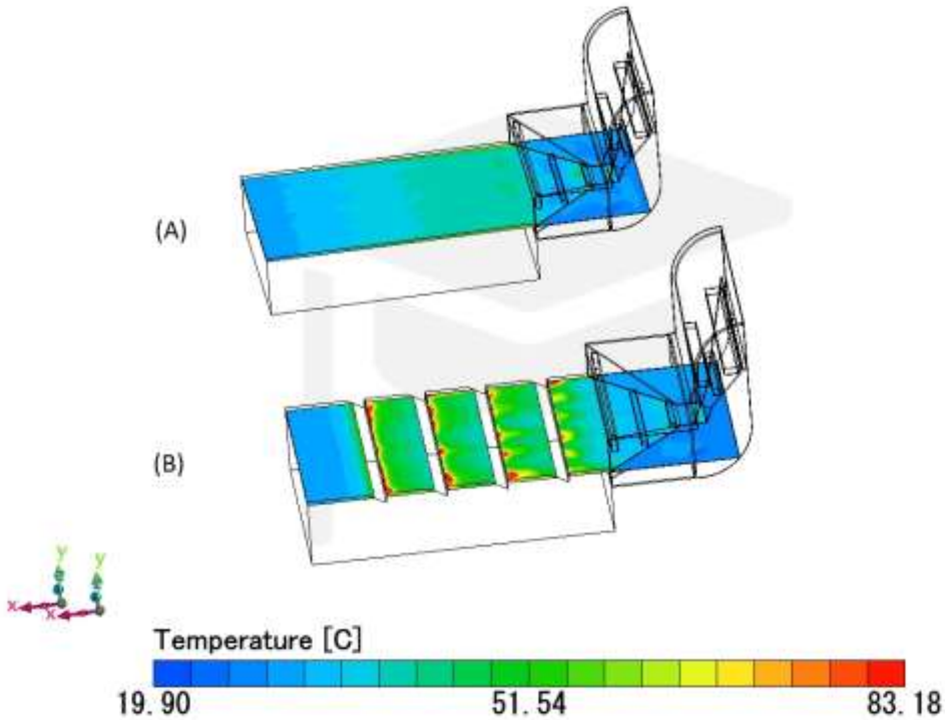
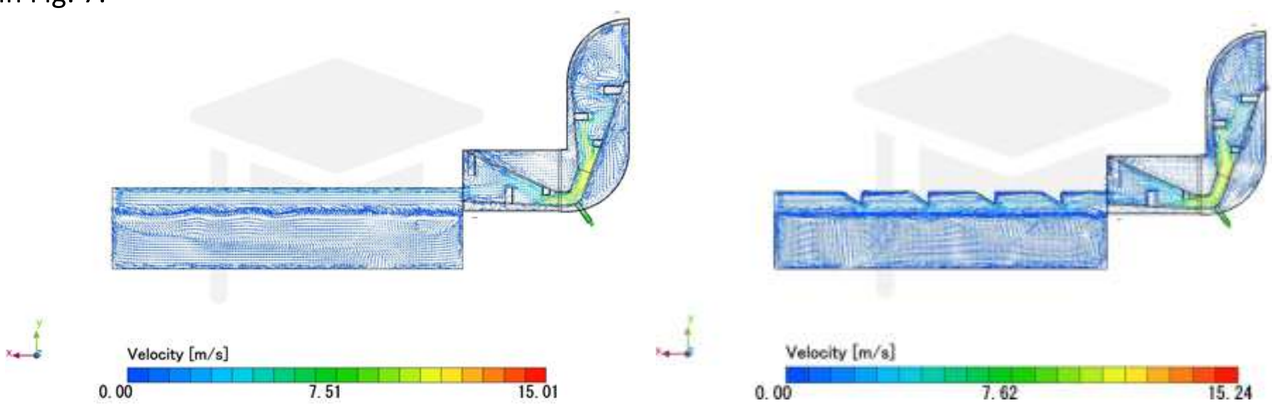


Fig. 6. Temperature distribution without (A) and with a vortex generator (B)

As shown in Fig. 6, the temperature of the water surface with a vortex generator is about 50 °C; it is about 55 °C without the vortex generator. The speed of air flow increases around the tip of the vortex generator, thus reducing the water temperature. This increase in air flow speed can be seen in Fig. 7.



(A) (B)

Fig. 7. Air flow velocity without (A) and with a vortex generator (B)

As shown in Fig. 7, the rate of air flow without the vortex generator was about 2.28 m/s; without the vortex generator, the air speed tends to remain constant throughout the evaporation chamber. With a vortex generator, the air flow speed increases around the tip of the vortex generator. This increase in speed causes a drop in air pressure at the tip of the vortex generator; this drop does not occur without the vortex generator [53]. This shift increases the difference in air pressure, encouraging faster evaporation, as shown in Figure 8.

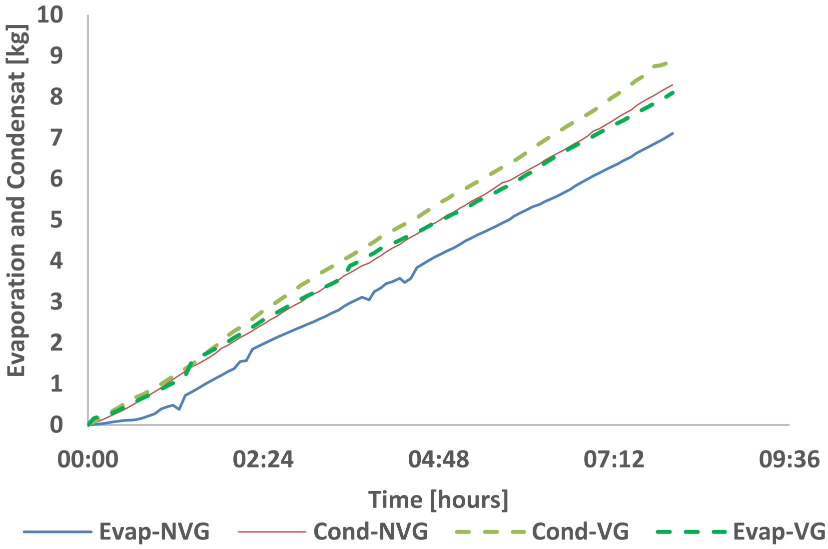


Fig. 8. Evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-NVG) a vortex generator

Figure 8 illustrates evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-VG) vortex generators. Evap-VG was consistently greater than Evap-NVG; on average, the difference was 1.13 times greater. Condensation was also greater with the vortex generator; the average relative humidity after evaporation was 56.5% without the vortex generator and 67.6% with it. With the vortex generator, 91% of the condensation evaporated; without it, only 86% of the condensation evaporated. Thus, the D-VG created more water vapour than the D-NVG. The Reynolds number (Re) was also higher with a vortex generator than without it. The Reynolds number is calculated as follows:

$$Re = \frac{\rho V x}{\mu}, \tag{7}$$

where the dynamic viscosity μ, density of air ρ and length x were taken as 1.954 × 10^{-5} kg/ms, 1.09 kg/m^3 and 0.025 m, respectively. The evaporation coefficient (h_{ew}) and convection coefficient (h_{cw}) can be calculated based on evaporation [54]; the results of evaporation per hour (m_w) for a solar still are [55] as follows:

$$m_w = \frac{h_{ew}\,(T_w - T_{evp})}{h_{fg}}\; x\; 3600, \tag{8}$$

where the latent heat of evaporation (h_{fg}) were taken as 2.372.099. The convection coefficient was obtained from the following equation:

$$h_{e,w-gi} = 0{,}0163\;\; x\;\; h_{cw}\left[\frac{P_w - P_{evp}}{T_w - T_{ev}}\right], \tag{9}$$

Where P_w and P_{evp} are partial vapour pressure at the water surface temperature and partial vapour pressure at the evaporation chamber, respectively. The results can be seen in Table 2.

Table 2
Reynolds Number (Re), evaporation coefficient (h_{ew}) and convection coefficient (h_{cw})

	Re	h_{ew}	h_{cw}
Without Vortex Generator	6,626.29	1,148.92	124.76
With Vortex Generator	7,729.21	3,543.10	560.74

Without a vortex generator, Re was 6.626.29; with it, Re was 7,731.12, 1.15 times greater. A higher Reynolds number indicates more counter-rotating vortices [56] and also leads to an increase in the mass transfer coefficient [57], hence increasing the convection and evaporation rate, which is indicated by increasing the convection coefficient (h_{cw}) and evaporation (h_{ew}).

As mentioned above, greater evaporation leads to higher condensation. This finding also aligns with the simulation. Since the yield of water vapour was higher with the vortex generator than without it, the D-VG was more efficient than the D-NVG (Table 3).

The efficiency of the system is measured by the gained output ratio (GOR), which can be expressed as [58]:

$$GOR = \frac{\sum m_w \cdot h_{fg}}{Q_{in}} \tag{10}$$

Table 3
System efficiency and comparison

	GOR	η	
Flat Plate evaporator	4.49		[59]
Thermal collector–evaporator	3.99		[60]
With Vortex Generator	1.53	76.1%	
Without Vortex Generator	1.34	66.4%	
Air Heating Counter flow	0.62		[61]
Air motion in solar still		55.6%	[62]
Natural circulation loop		45.15%	[63]

As shown in Table 3, efficiency or can be measured as GOR [64], [65]; the D-VG is 1.14 times more efficient than the D-NVG. Although several studies show higher GOR values, the system used is different and can be used in further research. However, when compared with solar desalination, the efficiency of using a vortex generator is higher. Therefore, a vortex generator is very useful for increasing the rate of evaporation.

4. Conclusions

The results of this study show that a vortex generator increases the rate of evaporation. In the unit with a vortex generator, evaporation occurred 1.13 times faster than without a vortex generator. This means that more fresh water was produced. Thus, a vortex generator can increase the efficiency of a desalination unit. In this study, GOR or efficiency increased from 1.53 in a unit without a vortex generator to 1.34 in a unit with a vortex generator. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

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Respectfully, I would like to inquire about the anticipated publication date of the article "Improving the performance of a forced-flow desalination unit using a vortex generator" in CFD Letters. Thank you for your attention to this matter.

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Improving the Performance of a Forced-flow Desalination Unit using a Vortex Generator

Dan Mugisidi
Mechanical Engineering, Faculty of Industrial Technology and Informatics, Universitas Muhammadiyah Prof. Dr HAMKA, Jakarta, Indonesia

Oktarina Heriyani
Mechanical Engineering, Faculty of Industrial Technology and Informatics,

THE PUBLISHER

Universitas Muhammadiyah Prof. Dr HAMKA, Jakarta, Indonesia

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ABSTRACT

Water is a primary need for living creatures, and water scarcity can trigger a crisis. Water scarcity is becoming an issue in Indonesia, especially in coastal village areas, including salt-producing areas. Salt production involves evaporating large amounts of seawater in concentration ponds. Using evaporated seawater as a source of clean water would reduce the risk of water scarcity. Therefore, this study aims to obtain fresh water by condensing water vapour that evaporates in a desalination unit. More specifically, the study uses a vortex generator to increase the rate and efficiency of evaporation in a forced-flow desalination unit. This research was conducted indoors to reduce uncontrollable variables. An evaporation container with a volume of 0.35 m3 was filled with seawater. The rate of evaporation in the desalination unit with a vortex generator was compared to that in a unit without a vortex generator. The results

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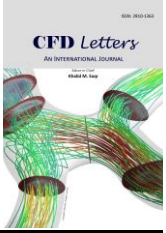

Improving the Performance of a Forced-flow Desalination Unit using a Vortex Generator

Dan Mugisidi[1,*], Oktarina Heriyani[1]

[1] Mechanical Engineering, Faculty of Industrial Technology and Informatics, Universitas Muhammadiyah Prof. Dr HAMKA, Jakarta, Indonesia

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Water is a primary need for living creatures, and water scarcity can trigger a crisis. Water scarcity is becoming an issue in Indonesia, especially in coastal village areas, including salt-producing areas. Salt production involves evaporating large amounts of seawater in concentration ponds. Using evaporated seawater as a source of clean water would reduce the risk of water scarcity. Therefore, this study aims to obtain fresh water by condensing water vapour that evaporates in a desalination unit. More specifically, the study uses a vortex generator to increase the rate and efficiency of evaporation in a forced-flow desalination unit. This research was conducted indoors to reduce uncontrollable variables. An evaporation container with a volume of 0.35 m^3 was filled with seawater. The rate of evaporation in the desalination unit with a vortex generator was compared to that in a unit without a vortex generator. The results show that the vortex generator leads to faster evaporation. The rate of evaporation with a vortex generator was 13% higher than that without a vortex generator, and the gained output ratio increased 14% with the vortex generator. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

1. Introduction

Humans and other living creatures need water to live. As the global population increases, the need for water will increase as well; a global population increase of 15% will reduce the amount of available fresh water by 40% [1]. Without changes to the use and treatment of water, this will lead to water scarcity [2], which is predicted to impact half of the world's population by 2025 [3]. Water is so important that it can raise issues related to human rights, politics and even racism [4]. Since physical water scarcity is often associated with agricultural production, growing human populations and state sovereignty, it is almost certain that water scarcity will trigger various crises [5]. In addition to being a global threat, water scarcity has become an urgent issue in specific parts of the world, including Indonesia.

Indonesia, an archipelagic country, has the longest coastline in the world, so many people live in coastal areas. Unfortunately, coastal village communities often experience severe water scarcity.

* *Corresponding author.*
E-mail address: dan.mugisidi@uhamka.ac.id (Dan Mugisidi)

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There are 12,827 coastal villages throughout Indonesia, and only 66.54% of these villages have regular access to clean water. Thus, coastal villagers use turbid and salty water for daily needs, such as washing and bathing, and buy drinking water; many members of these coastal village communities are salt farmers.

There is a high demand for salt in Indonesia. The Indonesian salt industry still uses traditional mining methods, which involve injecting seawater into ponds and evaporating it. The evaporation of seawater in concentration ponds is very dependent on water surface pressure and temperature [6]. Therefore, if the sun's heat is blocked or the wind is still, the rate of evaporation slows. However, making salt requires evaporating large amounts of water.

Sea water in the concentration pond, with a salinity of 30–45‰ or 3–4.5 °Be [7], is allowed to evaporate into the environment. To concentrate 1,000 litres of seawater to 30–45 °Be, about 900 litres of seawater must be evaporated. A concentration pool for salt mining can contain up to 10,000 litres of seawater, which undergoes a concentration process lasting four to five days [7]. Collecting and condensing this evaporated seawater could provide 9,000 litres of clean water. A large amount of this water could then be used by villagers. Thus, the ability to collect and use water that evaporates from salt fields would significantly benefit Indonesia's coastal villages. However, recovering moisture from salt fields without reducing salt production is a challenge. Little research has been done on the use of desalination to produce fresh water and salt [8]. A simpler solution would be to evaporate the seawater in evaporation chambers similar to solar stills.

Solar still is a simple device that uses the greenhouse effect [9] to convert salt water or wastewater into clean water by evaporating and condensing it [10]. Even though its productivity is low, because its operation is easy and economical, various studies have explored ways to increase the productivity of solar distillation equipment [11]. Methods for increasing the production of solar still fall into four categories: hybrid solar stills, stills with reflectors and concentrators, stills with condensers and stills with absorbers. Several types of absorbers can increase the productivity of solar stills. These approaches include changing the type of heat absorber [12, 13] using a wick [14-17], using fins [18-20], adding reflectors [21-23] and adding a heat collector. Furthermore, according to Nasri [24], solar still heat absorbers can use materials such as gravel, sand or polyurethane, and it is easy to add such materials to speed the evaporation process. The expansion of the absorber increases the water temperature, while the addition of a condenser increases the heat absorption capabilities of the water vapour. Increasing the rate of air flow over the surface of the water also increases the rate of evaporation. The air flow causes the pressure above the water surface to decrease, resulting in evaporation [25]. Some studies have used increased air flow in solar stills to increase the rate of evaporation [26, 27] but so far, few solar stills have used vortex generators to increase the rate of evaporation.

A vortex generator reduces air pressure, thereby increasing the difference in pressure between the surface of the water and the air above it. This pressure difference is the driving force for evaporation [28]. A vortex generator also increases heat transfer [29] by creating turbulence and vortices [30]. Vortex generators can increase heat transfer in cooling tower ducts [31] by increasing the speed of air flow around the tip of the vortex generator [32]. An increase in flow velocity creates vortices, lowering the surface pressure of the water and increasing the rate of evaporation. Thus, the present study aims to explore the impact of air flow on evaporation and condensation in salt field desalination units using a vortex generator. Therefore, various amounts of air flow were tested with constant heat. Each variation in air flow underwent two treatments: one without a vortex generator and one with a vortex generator. In addition, a condenser is used to condense water vapour; previous studies have proven that the addition of internal and external condensers has been shown to increase the efficiency of solar stills [33-40]. Solar still efficiency can also be increased by expanding the condensation surface [41]; increasing the condensation surface by 7.5 times increases freshwater production by more than 50% [42]. Specifically, this paper examines the impact of a vortex generator on the rate of evaporation in a forced-flow desalination unit.

2. Methodology

2.1 Experimental Setup

This research was conducted indoors to reduce uncontrolled variables [43], as shown in Figure 1. Three lamp units with a total power of 3,000 watts were used to maintain a constant solar radiance at 500 watts/m^2.

Fig. 1. Forced-flow desalination experimental rig

As shown in the research scheme in Figure 2, water was pumped from the water reservoir to the water level control, which was connected to the evaporation chamber. Thus, the water level in the evaporation chamber remained the same as that in the water level control. The evaporation chamber holds 350 litres of water. Water level control has an overflow channel, and the water level is determined by the height of the overflow. The water emerging from the overflow flows back into the seawater reservoir. When evaporation occurs in the evaporation chamber, water from the water level control flows into the evaporation chamber to equalize the level. Because the water level is maintained by the overflow, the reduction in water volume or weight in the seawater reservoir is proportional to the volume of water that evaporates in the evaporation chamber. In addition to water circulation, the system also includes air flow. The direction of the air flow is shown by the arrow in Figure 1. The air flow at a rate of 2 m/s is caused by fan suction. Air flow was tested in a desalination unit with (D-VG) and without a vortex generator (D-NVG). The vortex generator was attached to the top cover of the evaporation container so that it could be removed and replaced with a cover that did not include a vortex generator. The vortex generator was 9.4 mm high and mounted on the inside of the glass cover. The ratio of the height vortex generator to that of the glass cover is 0.47 [44]; the width of the vortex generator is the same as that of the glass cover. The first vortex generator was placed 286 mm from the air inlet, and the second vortex generator was placed 286 mm from the first. Thus, the longitudinal pitch ratio of the distance between the vortex generators and the length of the cover was 0.2 [45]. Four vortex generators were used, all placed 286 mm apart. A schematic of forced-flow desalination is shown in Figure 2. Data were collected every five minutes. A simulation of the system was also conducted using computational fluid dynamics (CFD).

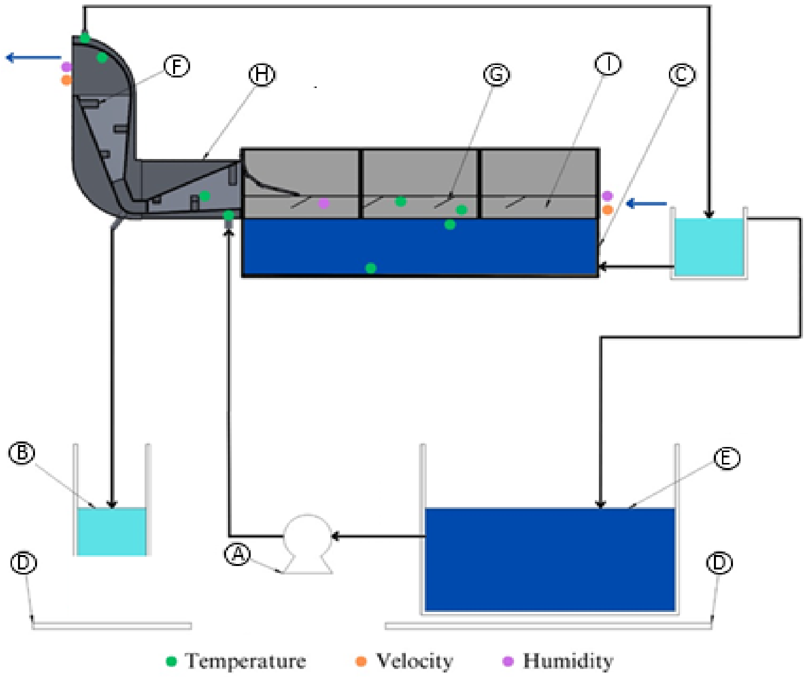


Fig. 2. Schematic of the forced-flow desalination experimental rig. (A) Circulation pump, (B) Freshwater reservoir, (C) Sea water, (D) Scale, (E) Condenser cooling water reservoir, (F) Vortex generator in condenser, (G) Vortex generator, (H) Condenser, (I) Evaporation chamber. The coloured dots show the locations of the sensors; the arrows show the direction of air flow

Many previous studies have included CFD simulations [46-49]. In the present study, a simulation was created using Cradle CFD software by Hexagon. There are three governing equations in fluid dynamics: the continuity equation, the momentum equation and the energy equation.

Integral form continuity equation:

$$\frac{\partial}{\partial t}\iiint_{V} \rho dV + \iint_{A} \rho\vec{V} \cdot d\vec{A} = 0 \qquad (1)$$

Differential form continuity equation:

$$\frac{\partial \rho}{\partial t} + \rho\vec{\nabla} \cdot \vec{V} = 0 \qquad (2)$$

Momentum equation in the x-axis direction:

$$\frac{\partial(\rho u)}{\partial t} + \vec{\nabla} \cdot \left(\rho u\vec{V}\right) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + \rho f_x \qquad (3)$$

The momentum equation in the y-axis direction:

$$\frac{\partial(\rho v)}{\partial t} + \vec{\nabla} \cdot \left(\rho v \vec{V}\right) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + \rho f_y \quad (4)$$

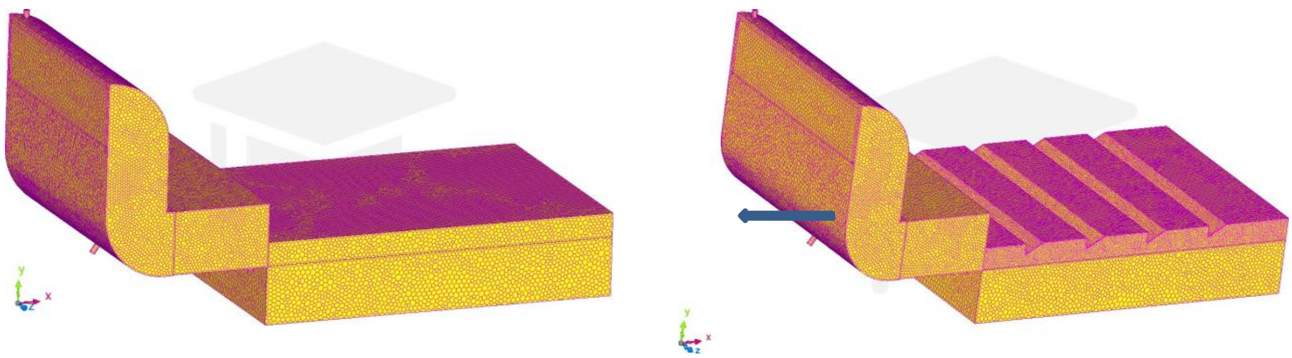
The momentum equation in the z-axis direction:

$$\frac{\partial(\rho w)}{\partial t} + \vec{\nabla} \cdot \left(\rho w \vec{V}\right) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z \quad (5)$$

The energy equation is written in the form of internal energy:

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)\right] + \vec{\nabla} \cdot \left[\rho\left(e + \frac{V^2}{2}\right)\vec{V}\right] = \rho\dot{q} - \frac{\partial(\rho p)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} + \rho\vec{f} \cdot \vec{V} \quad (6)$$

In CFD, meshing or discretization is used to convert a continuous fluid domain into a discrete computational domain. This approach allows fluid equations to be solved using numerical methods. An efficient mesh is very important in multiphase simulations because it impacts the accuracy of the simulation [50]. A hexahedron mesh was used here; this mesh has good resolution and high computational efficiency. For more detailed analyses, a polyhedral mesh was used in the present study, which can simulate the movements of objects along a high curvature (Figure 3). When creating a CFD simulation, it is also necessary to conduct a grid independence test [51, 52] as shown in Figure 4.



(a) (b)

Fig. 3. A CFD hexahedron mesh (a) without vortex generator (b) using vortex generator

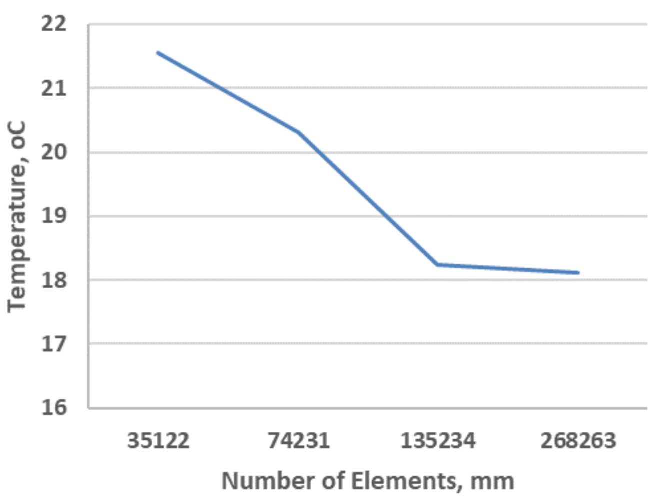


Fig. 4. Grid independence test

Data were collected using the tools listed in Table 1.

Table 1
Tools used in the study

No.	Factor	Tools	Specification
1	Temperature	Thermometer	40–400 °C, 0.09%
2	Solar radiance	Solar meter	0–2000 W/m^2
3	Wind velocity	Wind meter	0–30 m/s
4	Relative humidity	Hygrometer	10%–99%
5	Weight	Digital balance	0–20 kg ± 0,1

3. Results

The temperature of the water and the air flowing over the water significantly impact the rate of evaporation, while the condenser temperature determines the amount of water vapour that can be condensed, as shown in Figure 5.

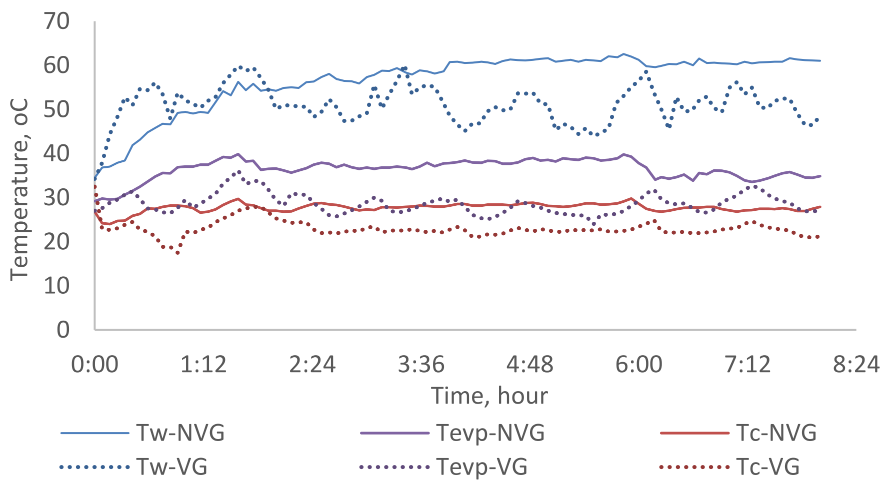


Fig. 5. Water temperature (Tw), air flow temperature (Tev) and condenser temperature (Tc) in the desalination units with (Tw-VG, Tev-VG and Tc-VG) and without a vortex generator (Tw-NVG, Tev-VG and Tc-VG)

As shown in Figure 5, the water temperature was lower with a vortex generator (Tw-VG) than without it (Tw-NVG). The average Tw-VG and TW-NVG were 51.42 °C and 58.06 °C, respectively. The air flow temperature is a mix of the temperature of the air entering from outside and the temperature of the evaporated water vapour. The air flow temperature was generally lower with the vortex generator (Tev-VG) than without it (Tev-NVG). Although Tev-VG was lower than Tev-NVG, the difference between the temperature of the water and that of the vapour in the D-VG was greater than the difference between the temperature of the water and the vapour in the D-NVG; these differences were 25.72 °C and 21.18 °C, respectively. This temperature difference is proportional to the pressure difference [28] and promotes evaporation. Tc-VG was lower than Tc-NVG; the average difference between these temperatures was 2.36 °C because Tev-VG entering the condenser is lower than Tev-NVG. The temperature during evaporation predicted by the simulation did not differ much from the temperature recorded in the experiment, as shown in Figure 6.

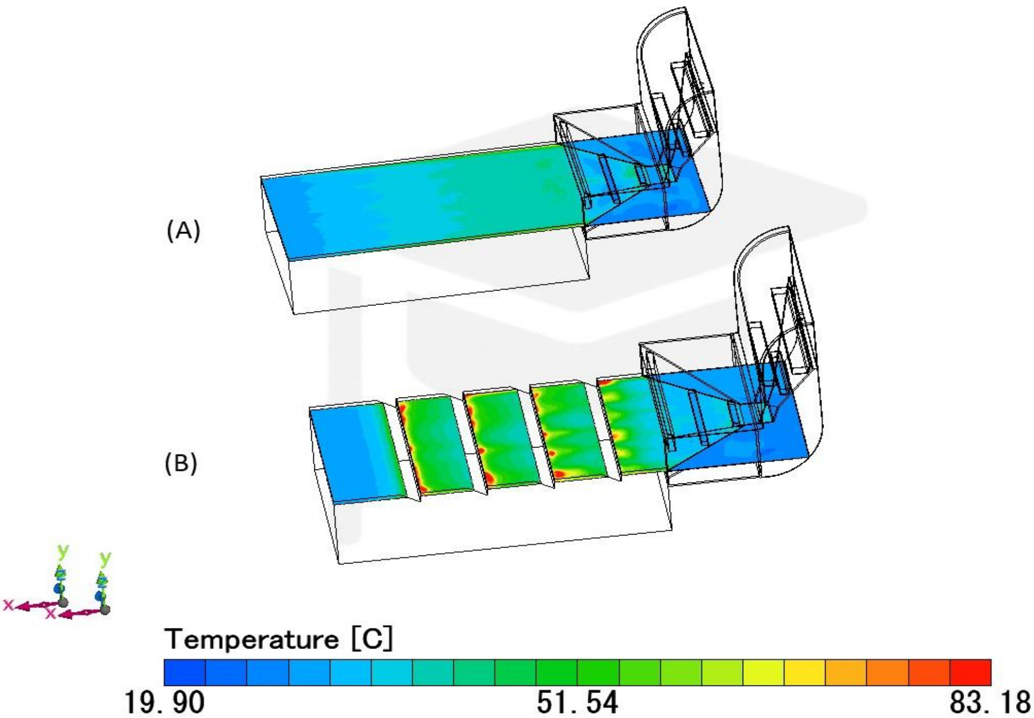
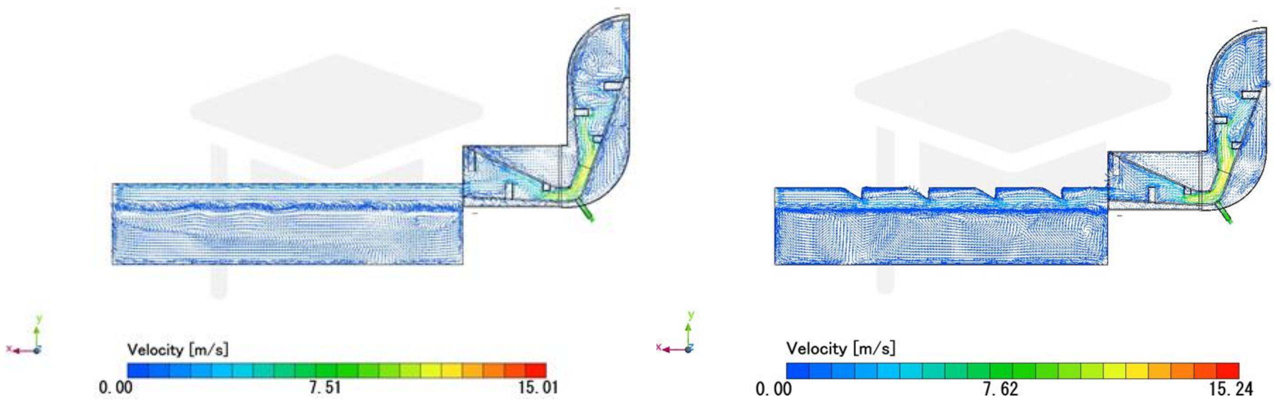


Fig. 6. Temperature distribution (A) without vortex generator (B) with a vortex generator

As shown in Figure 6, the temperature of the water surface with a vortex generator is about 50 °C; it is about 55 °C without the vortex generator. The speed of air flow increases around the tip of the vortex generator, thus reducing the water temperature. This increase in air flow speed can be seen in Figure 7.



(a) (b)

Fig. 7. Air flow velocity (a) without vortex generator (b) with a vortex generator

As shown in Figure 7, the rate of air flow without the vortex generator was about 2.28 m/s; without the vortex generator, the air speed tends to remain constant throughout the evaporation chamber. With a vortex generator, the air flow speed increases around the tip of the vortex generator. This increase in speed causes a drop in air pressure at the tip of the vortex generator; this drop does not occur without the vortex generator [53]. This shift increases the difference in air pressure, encouraging faster evaporation, as shown in Figure 8.

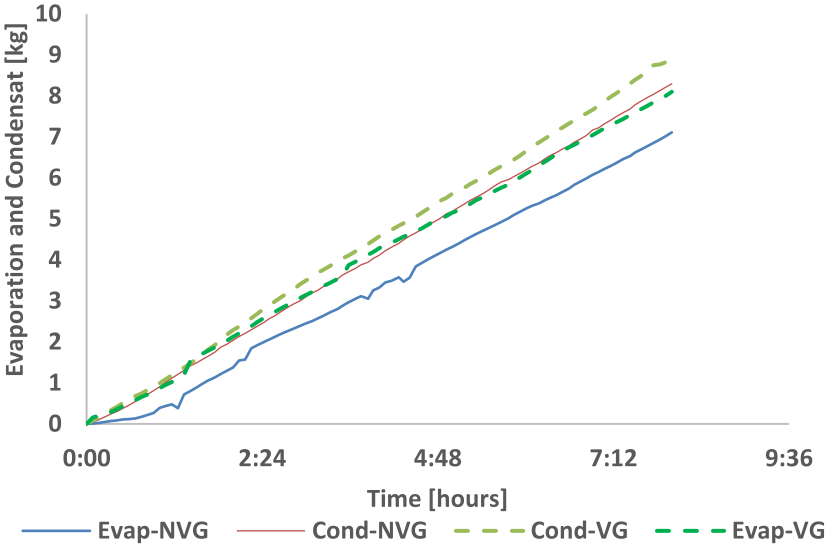


Fig. 8. Evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-NVG) a vortex generator

Figure 8 illustrates evaporation and condensation with (Evap-VG and Cond-VG) and without (Evap-NVG and Cond-VG) vortex generators. Evap-VG was consistently greater than Evap-NVG; on average, the difference was 1.13 times greater. Condensation was also greater with the vortex generator; the average relative humidity after evaporation was 56.5% without the vortex generator and 67.6% with it. With the vortex generator, 91% of the condensation evaporated; without it, only 86% of the condensation evaporated. Thus, the D-VG created more water vapour than the D-NVG. The Reynolds number (Re) was also higher with a vortex generator than without it. The Reynolds number is calculated as follows:

$$Re = \frac{\rho V x}{\mu}, \tag{7}$$

where the dynamic viscosity μ, density of air ρ and length x were taken as 1.954×10^{-5} kg/ms, 1.09 kg/m^3 and 0.025 m, respectively. The evaporation coefficient (h_{ew}) and convection coefficient (h_{cw}) can be calculated based on evaporation [54]; the results of evaporation per hour (m_w) for a solar still are [55] as follows:

$$m_w = \frac{h_{ew}\,(T_w - T_{evp})}{h_{fg}}\ x\ 3600, \tag{8}$$

where the latent heat of evaporation (h_{fg}) were taken as 2.372.099. The convection coefficient was obtained from the following equation:

$$h_{e,w-gi} = 0{,}0163\ x\ h_{cw}\left[\frac{P_w - P_{evp}}{T_w - T_{ev}}\right], \tag{9}$$

where P_w and P_{evp} are partial vapour pressure at the water surface temperature and partial vapour pressure at the evaporation chamber, respectively. The results can be seen in Table 2.

Table 2
Reynolds Number (Re), evaporation coefficient (h_{ew}) and convection coefficient (h_{cw})

	Re	h_{ew}	h_{cw}
Without vortex generator	6,626.29	1,148.92	124.76
With vortex generator	7,729.21	3,543.10	560.74

Without a vortex generator, Re was 6.626.29; with it, Re was 7,731.12, 1.15 times greater. A higher Reynolds number indicates more counter-rotating vortices [56] and also leads to an increase in the mass transfer coefficient [57], hence increasing the convection and evaporation rate, which is indicated by increasing the convection coefficient (h_{cw}) and evaporation (h_{ew}).

As mentioned above, greater evaporation leads to higher condensation. This finding also aligns with the simulation. Since the yield of water vapour was higher with the vortex generator than without it, the D-VG was more efficient than the D-NVG (Table 3).

The efficiency of the system is measured by the gained output ratio (GOR), which can be expressed as [58]:

$$GOR = \frac{\sum m_w \cdot h_{fg}}{Q_{in}} \quad (10)$$

Table 3
System efficiency and comparison

	GOR	η	
Flat plate evaporator	4.49		[59]
Thermal collector–evaporator	3.99		[60]
With vortex generator	1.53	76.1%	
Without vortex generator	1.34	66.4%	
Air heating counter flow	0.62		[61]
Air motion in solar still		55.6%	[62]
Natural circulation loop		45.15%	[63]

As shown in Table 3, efficiency or can be measured as GOR [64, 65]; the D-VG is 1.14 times more efficient than the D-NVG. Although several studies show higher GOR values, the system used is different and can be used in further research. However, when compared with solar desalination, the efficiency of using a vortex generator is higher. Therefore, a vortex generator is very useful for increasing the rate of evaporation.

4. Conclusions

The results of this study show that a vortex generator increases the rate of evaporation. In the unit with a vortex generator, evaporation occurred 1.13 times faster than without a vortex generator. This means that more fresh water was produced. Thus, a vortex generator can increase the efficiency of a desalination unit. In this study, GOR or efficiency increased from 1.53 in a unit without a vortex generator to 1.34 in a unit with a vortex generator. Therefore, it can be concluded that vortex generators can improve the performance of desalination equipment.

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