Deskripsi Artikel

- Judul Jurnal : Environmental Progress & Sustainable Energy
- Judul Artikel : Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat
- Penulis : **Dan Mugisidi**, Oktarina Heriyani, Rifky, Widodo, Ahmed Rahmani, Amir Khalid.
- Status Penulis : Penulis Pertama, Kontributor.
- Peringkat : Q2

ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

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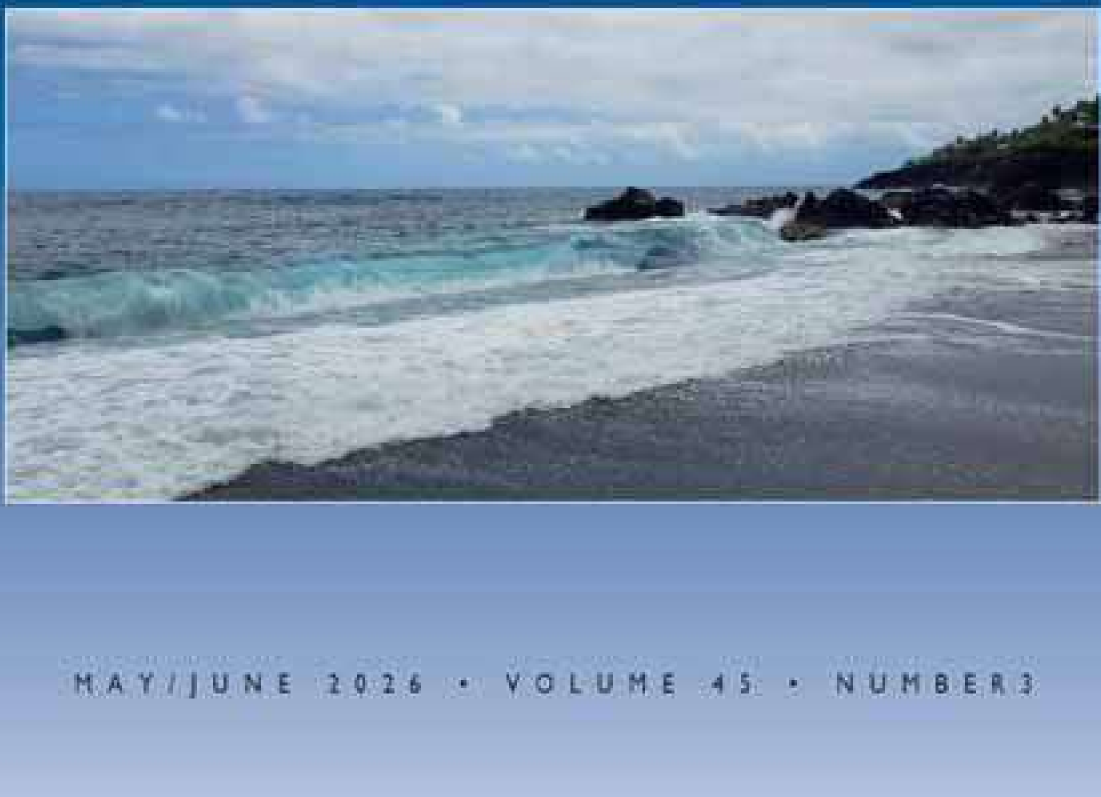

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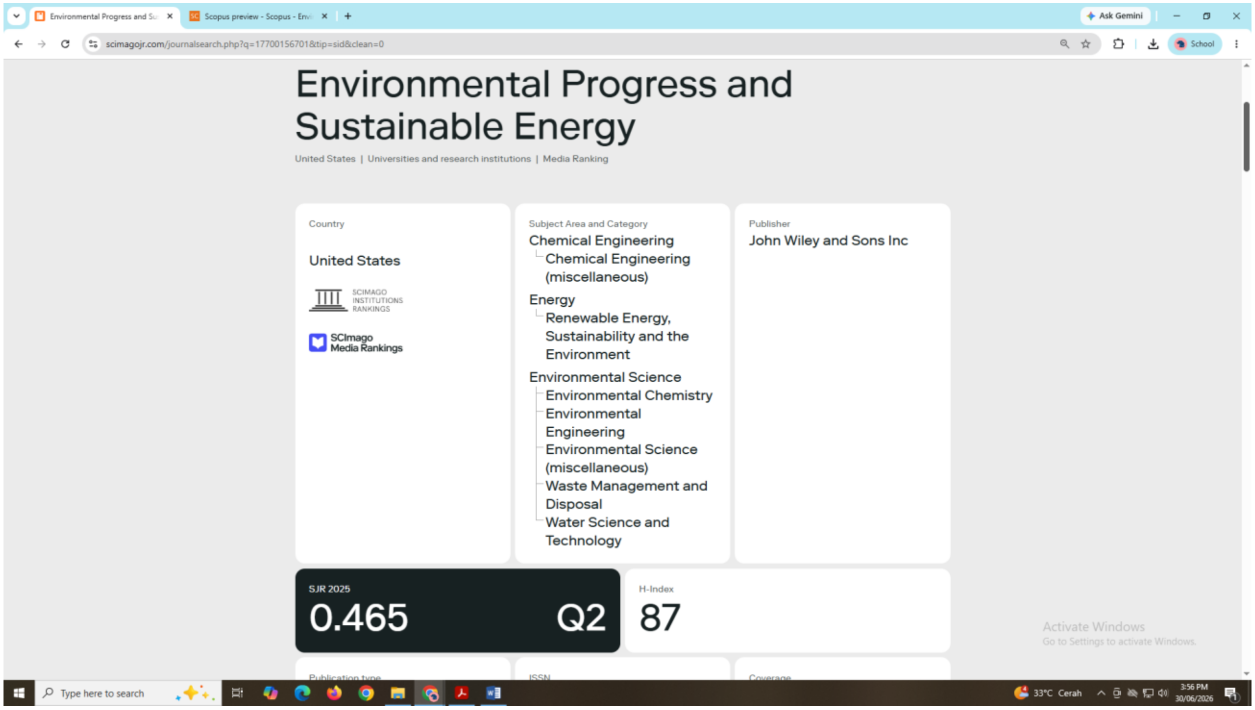

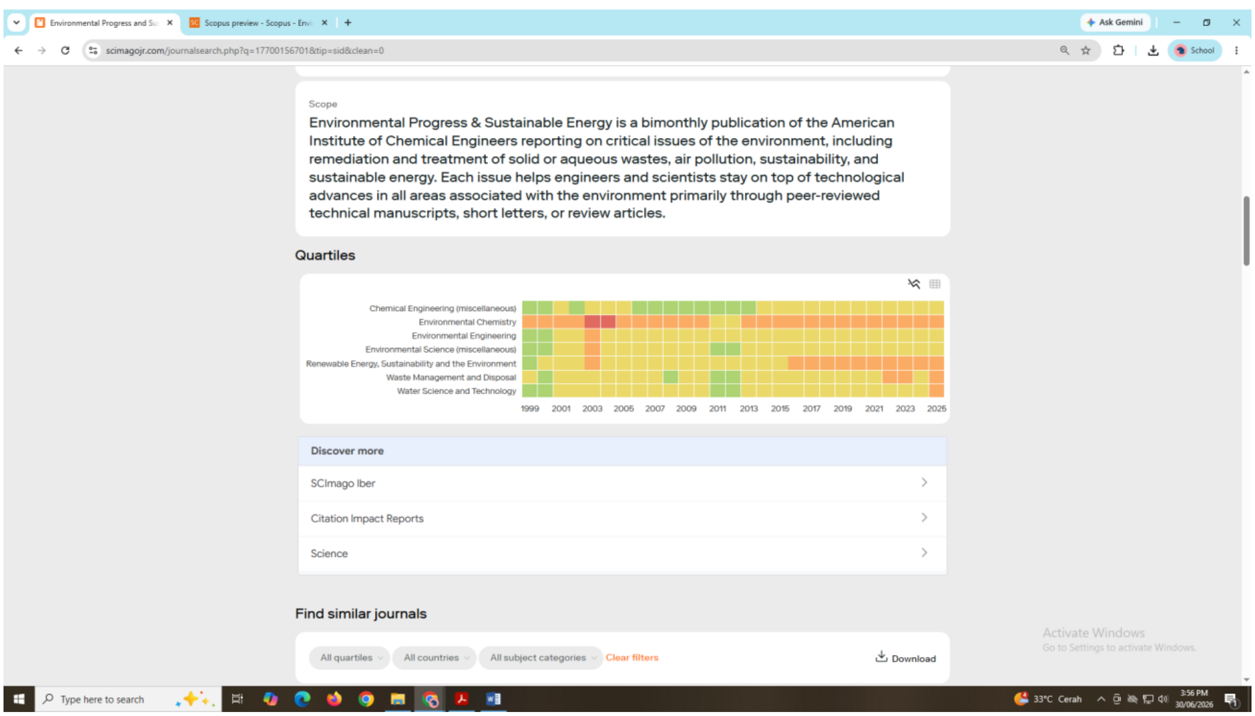

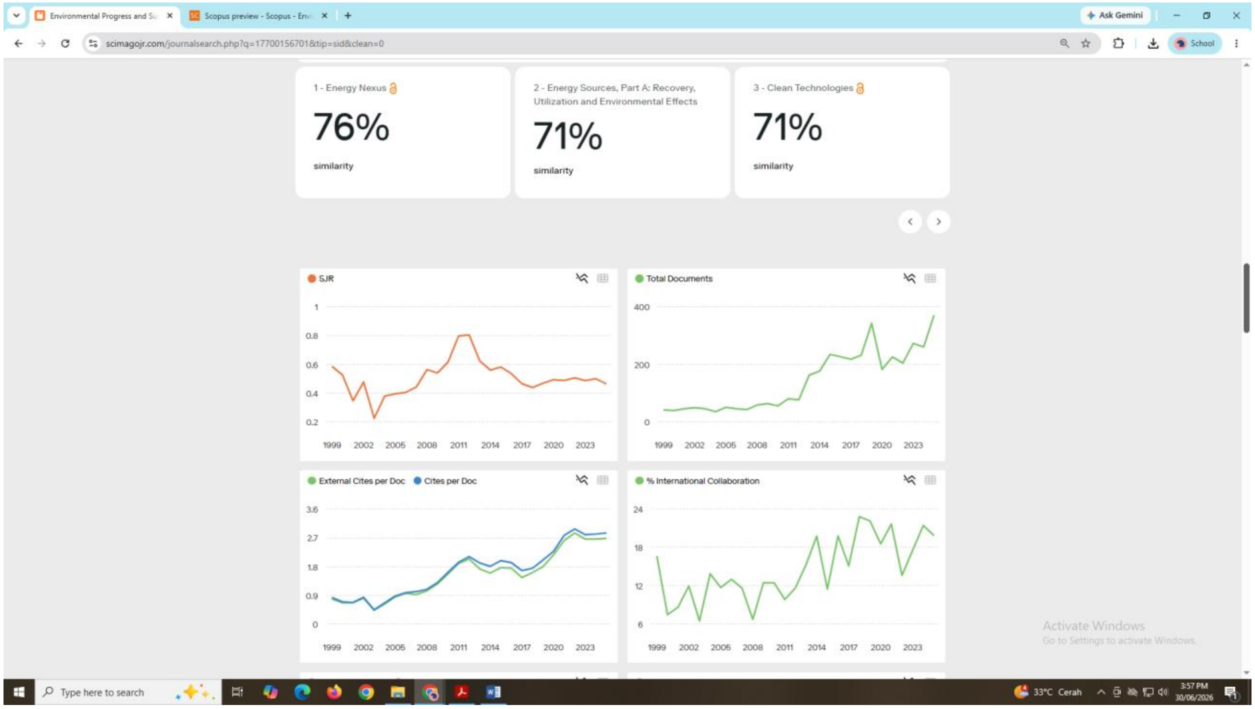

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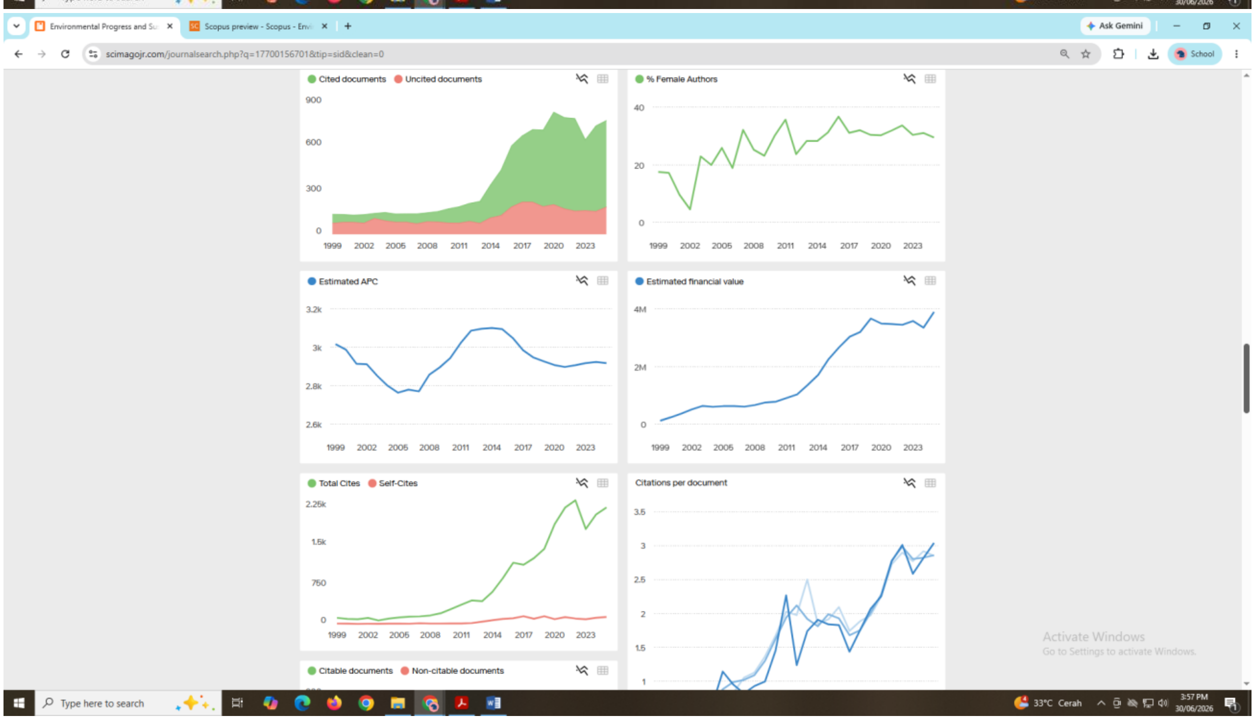

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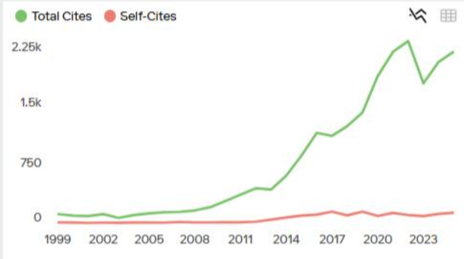

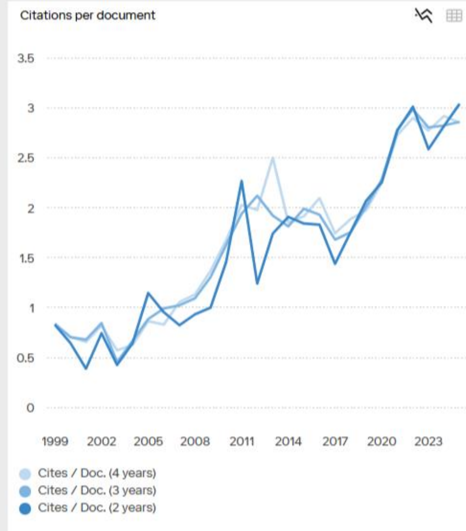

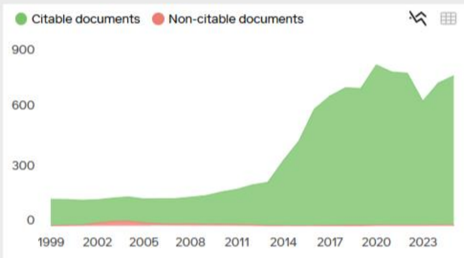

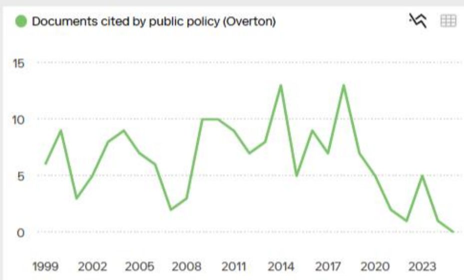

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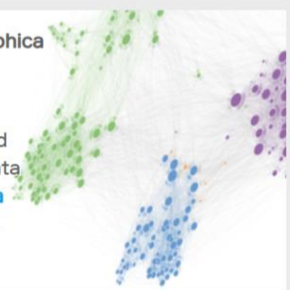

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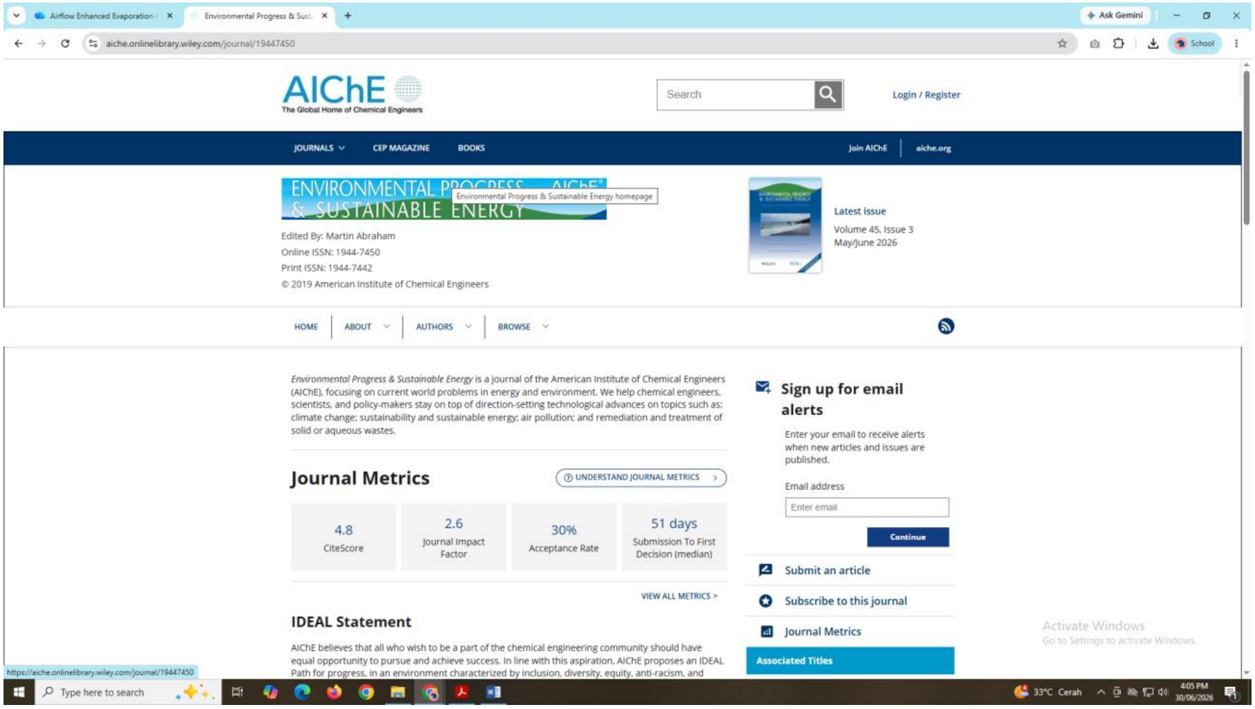

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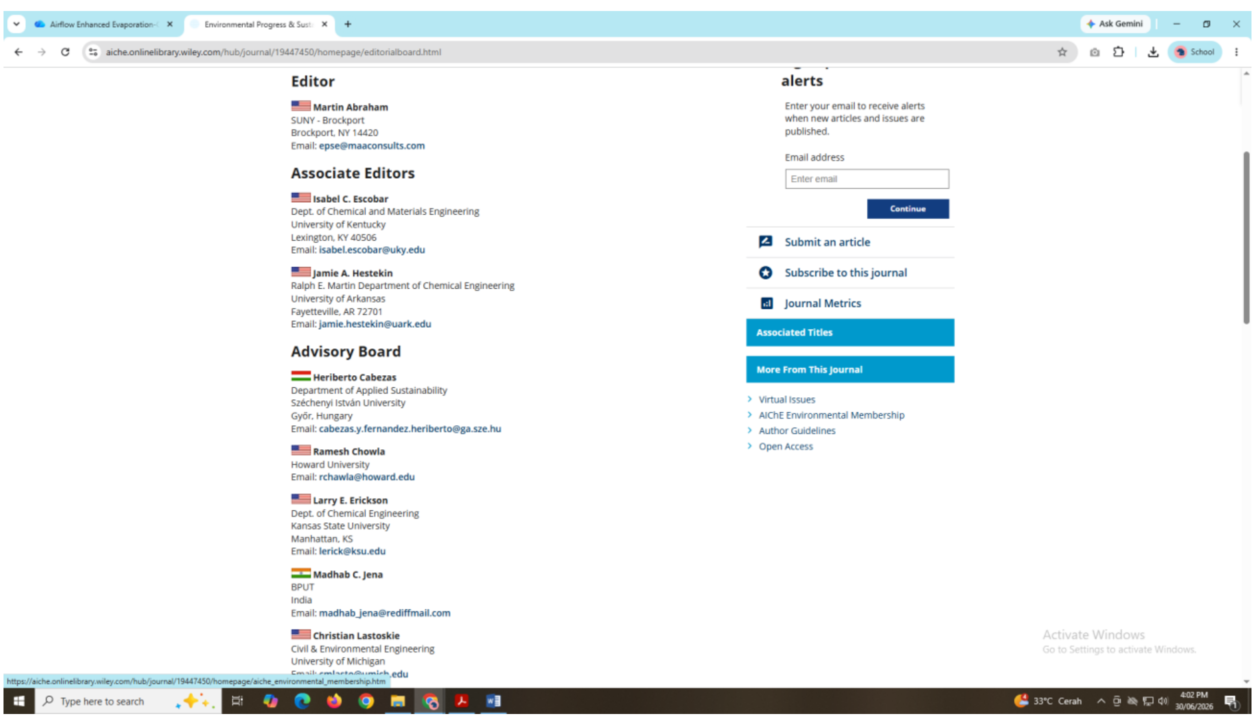

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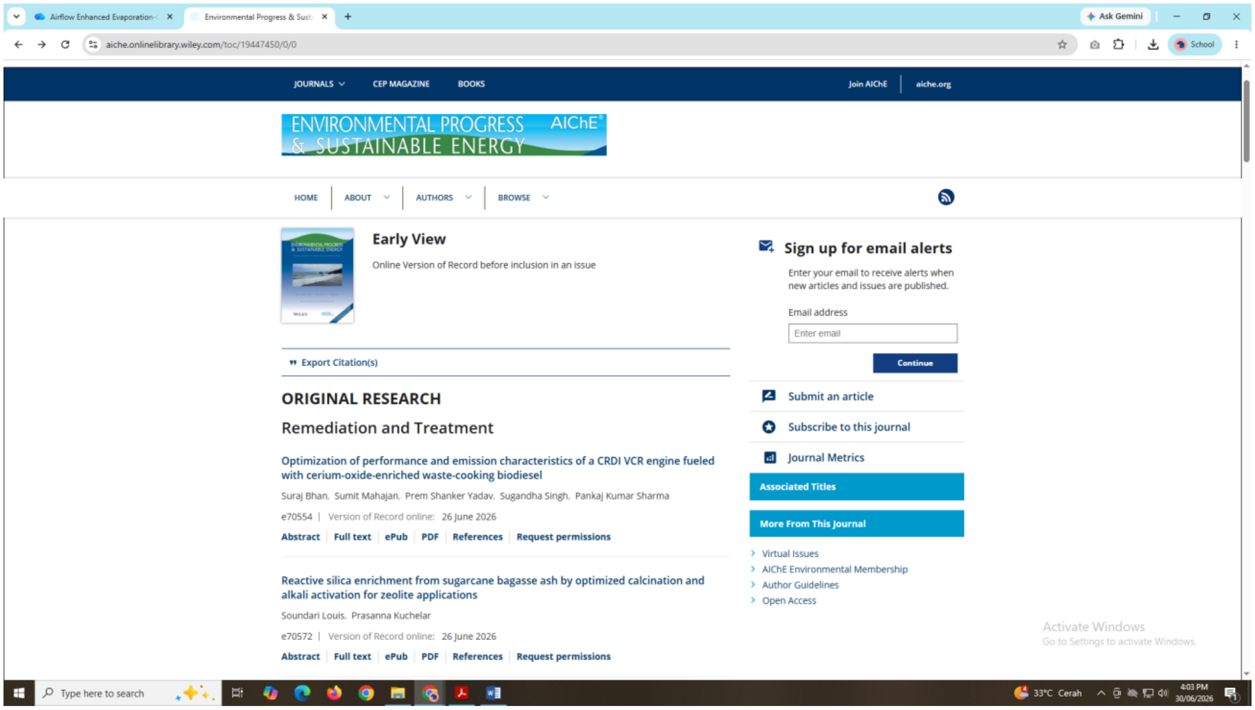

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BUKTI KORESPONDENSI

ARTIKEL JURNAL INTERNASIONAL BEREPUTASI

Judul artikel	:	Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat
Jurnal	:	Environ Progress and Sustainable Energy. 2026; e70555. doi:10.1002/ep.70555
Penulis	:	Mugisidi D, Heriyani O, Rifky, Widodo, Rahmani A, Khalid A

No.	Perihal	Tanggal
1.	Bukti konfirmasi submit artikel dan artikel yang disubmit	13 Maret 2026
2.	Bukti konfirmasi review	5 Mei 2026
3.	Bukti konfirmasi submit revisi, respon kepada reviewer, dan artikel yang diresubmit	30 Mei 2026
4.	Bukti konfirmasi artikel accepted	8 Juni 2026
5.	Bukti konfirmasi artikel published online	19 Juni 2026

1. Bukti Konfirmasi Submit Artikel dan Artikel yang Disubmit (13 Maret 2026)

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

Manuscript submitted to Environmental Progress & Sustainable Energy

1 message

Environmental Progress & Sustainable Energy <epseeditorialoffice@wiley.com> Fri, Mar 13, 2026 at 2:13 PM
Reply-To: Environmental Progress & Sustainable Energy <epseeditorialoffice@wiley.com>
To: Dan Mugisidi <dan.mugisidi@uhamka.ac.id>

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Dear Dr. Dan Mugisidi,

Thank you for submitting your manuscript "Evaporation–Condensation Seawater Desalination Using Household Air Conditioner Waste Heat" to Environmental Progress & Sustainable Energy. Your unique manuscript ID is: 9984576.

We will confirm this submission with all authors of the manuscript.

As submitting author, you will be the primary recipient of communications from the journal. You will be responsible for responding to editorial queries and making updates to the manuscript if needed.

You can visit the manuscript details page at any time to track the status of your manuscript.

MANUSCRIPT DETAILS

Kind regards,
Environmental Progress & Sustainable Energy

2. Bukti Konfirmasi Review
(5 Mei 2026)

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

Major revision requested: 9984576

2 messages

Environmental Progress & Sustainable Energy <epseeditorialoffice@wiley.com> Tue, May 5, 2026 at 5:33 AM
Reply-To: Environmental Progress & Sustainable Energy <epseeditorialoffice@wiley.com>
To: Dan Mugisidi <dan.mugisidi@uhamka.ac.id>

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Dear Dr. Dan Mugisidi,

Thank you for submitting your manuscript 9984576, titled "Evaporation–Condensation Seawater Desalination Using Household Air Conditioner Waste Heat", to Environmental Progress & Sustainable Energy.

After careful assessment, our editorial team has decided your manuscript requires major revisions in order to proceed with the peer review process and be considered for publication. Reviewer comments are included at the bottom of this email to assist you in revising your manuscript.

We ask that you return your revised manuscript by August 02, 2026. If you need more time, please let us know. We are happy to discuss an extended deadline.

When submitting your revised manuscript, you will be asked to upload an author response letter that details the revisions you have made in response to editor and reviewer comments. You may also be required to show revisions made within the manuscript files. Please follow any journal-specific guidelines for formatting and submitting revisions outlined in the author guidelines page.

When you have finished revising your manuscript, follow the link below to submit your revision:

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Thank you for submitting your work to Environmental Progress & Sustainable Energy. We look forward to receiving your revised manuscript.

Kind regards,
Dr. Jamie Hestekin
Environmental Progress & Sustainable Energy

Handling editor comment:

> “
>
> After careful analysis of reviewer comments, it is recommended that this manuscript undergo major revisions. Please provide a copy, a marked copy, and an explanation of changes. At this point he manuscript will be re-reviewed for possible publication in EP&SE.

The following reviewer comments were taken into consideration during the peer review process.

"

Reviewer 1 Comments to the Author

The manuscript presents a promising concept with acceptable experimental-CFD agreement. However, the lack of direct freshwater production measurement, missing uncertainty analysis, incomplete COP calculation details, and several inconsistencies in data presentation currently prevent acceptance. The authors should address the major comments as below, before resubmission.
Questions for the Authors:
1. What was the salinity of the feedwater? The term "seawater" is used, but was actual seawater or synthetic brine used? What was the initial and final salinity?
2. How was fouling or scaling on the evaporator surface managed? Seawater desalination typically suffers from salt precipitation on heated surfaces. Was this observed during experiments? If not, why?
3. What is the estimated payback period or cost per liter of freshwater produced? While not required for a technical manuscript, such an estimate would strengthen the claims of practical feasibility.
4. The introduction should be updated, some literatures may be included such as: 1. Solar Energy, 2025, 288, 113321; 2. Nano Energy, 2025, 137, 110781; 3. Advanced Functional Materials, 2025, 36, e10564; 4. Advanced Sciences, 2025, 12(46), e13258; 5. J. Mater. Chem. A, 2024, 12, 4046-4056; 6. J. Mater. Chem. A, 2024, 12, 4046-4056;

Is the AC condenser fan able to maintain required airflow when the channel area is very small (e.g., 0.006 m²)? Did the fan operate at reduced flow or stall? Was fan power or current monitored?

Reviewer 2 Comments to the Author

The manuscript by Mugisidi et al. utilised waste heat from residential AC units to drive an evaporation-based desalination system. The Experimental is fine. However, the following points should be addressed before the manuscript is accepted.
1.The manuscript is not well organized. English should be improved here and there.
2.Regarding many previous studies on using waste heat from residential AC units to drive an evaporation-based desalination system, I believe that the authors should at the very least have cited these work, which is arguably relevant, and further that they should have made an attempt to discuss the differences between the references and their work. The authors should do comparison with others in the literature, and do more investigation for comparison Vortex generators with other generators and utilisation of AC waste heat with other waste heat.
3.Will the liquid water condense on the top of the container during the collection of water by this device, thereby affecting the experimental results?
4.More details about measurement devices should be described further; it is necessary to give specifications, accuracy, measuring range, etc.
5.The authors should make further discussion on their observations

6. The authors should make further discussion on their observations.

In summary, I recommend publication of the manuscript with a major revision of the text.

Reviewer 3 Comments to the Author

General Evaluation
The manuscript addresses a significant opportunity in sustainable engineering by utilizing low-grade waste heat from residential split-type air conditioners (AC) for seawater desalination. The topic is highly relevant for coastal households and small-island infrastructure where freshwater is scarce. The study successfully combines experimental validation with Computational Fluid Dynamics (CFD) simulations. However, while the technical descriptions are clear, certain sections require more rigorous quantitative positioning and discussion of long-term operational challenges to meet the standards of a high-impact research article.
Recommendation
The manuscript is technically robust and provides a viable solution for water-scarce regions. By addressing the specific quantitative comparisons and long-term maintenance considerations mentioned below, the contribution will be significantly more credible and ready for publication. Thus, the manuscript can be accepted for publication after Minor revision as detail Detailed Evaluation and Suggestions as follows:
Detailed Evaluation and Suggestions
Abstract
Clearly identifies the problem of water scarcity and the underutilized potential of AC waste heat. It summarizes the methodology (CFD and experimental) and the primary findings regarding vortex generators and optimal channel geometry. However, the abstract is descriptive but could be strengthened with more precise performance indicators. Thus, it is recommended to include the specific maximum freshwater production rate (e.g., 950–980 mL/h) and the exact range of COP improvement in the abstract to provide immediate quantitative value.
Introduction (Pages 6-7)
While the introduction successfully identifies the significant potential of utilizing AC waste heat for desalination, the State of the Art should be expanded by comparing it with other household waste heat recovery (WHR) technologies to strengthen the system's positioning within the green technology landscape. The identified Research Gap is relevant, but it is suggested that the authors more sharply define why this integrated solution is superior to standalone systems, such as solar stills, particularly in the context of urban space constraints. Regarding Novelty, the use of vortex generators (VG) to enhance air turbulence in domestic AC systems is a significant contribution; however, the authors must more explicitly emphasize that the primary novelty lies in the channel geometry optimization that balances evaporation rates with machine performance integrity (COP). Finally, concerning the Goals, the research objectives align with the methodology, but it is highly recommended that the authors formulate more measurable goals, specifically in establishing technical optimization parameters that are directly applicable to the HVAC

manufacturing industry.

2. Methods (Page 9–14)
Provides a detailed description of the desalination unit (DU) integration with the refrigeration loop. The instrumentation table (Table 1) and the mesh independence study (Table 2) ensure high reproducibility and numerical stability. While the physical setup is detailed, the specific salinity or feedwater characteristics are not explicitly defined. Thus, it is recommended to add information regarding the initial salinity of the seawater used in experiments, as this directly affects the saturation vapor pressure (Ysat) and evaporation flux (\dot{m}) described in your equations.
Results and Discussion (Page 15–17)
Effectively demonstrates the correlation between air channel cross-sectional area and evaporation rates. The use of vortex generators is shown to enhance local turbulence and disrupt the boundary layer, which is scientifically sound. The linear correlation (R2 > 0.95) between CFD and experimental data is excellent. However, the discussion on the trade-off between evaporation and AC performance (COP) is present but needs a more critical comparison. Thus, it is suggested to provide a direct comparative table or graph showing the "Percentage Loss in COP" versus "Freshwater Yield" for each channel size. This would help practitioners understand the exact efficiency cost of maximizing water production.
Evaluation on Heat Rejection and COP Correlation
The paper notes that smaller channel areas cause a greater pressure drop, which hinders heat rejection and lowers the COP. However, there is limited discussion on how variations in ambient temperature (Ta) or humidity (Ha) would affect the system's stability in real-world tropical environments. Tuus it is suggested to include a brief sensitivity analysis or discussion on how different ambient conditions (e.g., peak summer vs. monsoon) might shift the optimal cross-sectional area of 0.015–0.025 m^2 and also discuss the thermal Marangoni effect mentioned in section 2.1 in more detail within the results to explain surface-driven fluid motion improvements.

Conclusion and Future Outlook
The conclusions are well-supported by the data, showing that the system can meet basic drinking water requirements (approx. 2.5–3.5 L/day) for a household. It is suggested to add the summary result in relation on the Novelty emphasis on more explicitly state that the novelty lies in the household-scale integration that balances AC operational integrity (COP) with decentralized water production.
For the Future Outlook, the current section is a bit brief. It is suggested to add recommendations regarding:
Regarding the scaling and maintenance, how salt accumulation in the heated tank will be managed over long-term operation.
Related to Water Quality Testing, future verification of the distillate purity (TDS, pH) to ensure it meets WHO drinking water standards.

Reviewer 4 Comments to the Author

1. English must be improved.

2. The Journal's standards for referencing must be considered.
3. The most important quantitative results must be mentioned in the abstract.
4. The problem statement should be clearly explained.
5. I recommend expanding your literature review by adding recent papers studying innova-tive configurations of solar powered (ADS, HDH, RO, ….etc) desalinations systems for off-grid sustainable freshwater production:
**Sustainable freshwater production using sorption-based atmospheric water harvesting: Sorbent materials, system design configurations, thermodynamic models, and future per-spectives, International Communications in Heat and Mass Transfer, 2026.*
**Dynamic numerical modeling and performance assessment of a hybrid photovoltaic ther-mal collector adsorption desalination system for sustainable water-energy nexus, Solar En-ergy, 2025.*
** Performance Assessment of Hybrid Adsorption/Humidification-Dehumidification Desali-nation Cycle Powered by Dish/Stirling Concentrated Solar Power System for Sustainable Freshwater Production Maximization, Process Safety and Environmental Protection,2025.*
**Novel Solar Distillation Dome: New Approach for Sustainable Freshwater Production Augmentation, IEEE Explore, 2025.*
** Enhanced performance of a hybrid adsorption desalination system integrated with solar PV/T collectors: Experimental investigation and machine learning modeling coupled with manta ray foraging algorithm, Applied Thermal Engineering, 2024.*
6. The advantages of the proposed study compared with the previous similar studies also need more clarification in the existing introduction.
7. Explain the key geographic and demographic factors influencing the feasibility and effi-ciency of the hybrid residential AC/desalination system potential, and clarify how these fac-tors vary.
8. How to select the input and operational parameters for the AC split unit and single effect desalination unit, please give detailed justifications and discussion.
9. The authors must conduct a statistical analysis thorough model validation to ensure the model accuracy with respect to freshwater production and waste heat recovery.
10. Provide limitations and future outlooks for the research
11. Most of Figures lack the necessary quality and clarity, making it difficult for the reader to understand their content. Improving the quality of these figures is essential for the audi-ence.

Dan Mugisidi <dan.mugisidi@uhamka.ac.id> Tue, May 5, 2026 at 2:40 PM
To: Heriyani Oktarina <oktarina@uhamka.ac.id>

[Quoted text hidden]

3. Bukti Konfirmasi Submit Revisi Pertama, Respon kepada Reviewer, dan Artikel yang Diresubmit (30 Mei 2026)

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

Revised manuscript submitted to Environmental Progress & Sustainable Energy

1 message

Environmental Progress & Sustainable Energy <no-reply@atyponrex.com> Sat, May 30, 2026 at 8:58 AM
To: Dan Mugisidi <dan.mugisidi@uhamka.ac.id>

Dear Dan Mugisidi,

Your revised manuscript “Airflow-Enhanced Evaporation–Condensation Seawater Desalination Using Residential Air Conditioner Waste Heat” has been successfully submitted and is being delivered to the editorial office of *Environmental Progress & Sustainable Energy* for consideration.

Further information about your submission will be emailed to you by the journal editorial office. You may review your submission using the following link:

https://submission.wiley.com/submissionBoard/1/53d30d09-fc7b-48b3-b1c2-200cae1c31bb

Thank you for your manuscript submission.

Sincerely,
The Editorial Staff at Environmental Progress & Sustainable Energy
epseeditorialoffice@wiley.com

We sincerely thank the Editor and Reviewers for their valuable comments and constructive suggestions, which have significantly improved the quality and clarity of the manuscript. All comments have been carefully considered, and the manuscript has been revised accordingly. Detailed responses to each reviewer comment are provided below, and all corresponding revisions have been highlighted in the revised manuscript.

Handling editor comment:

"After careful analysis of reviewer comments, it is recommended that this manuscript undergo major revisions. Please provide a copy, a marked copy, and an explanation of changes. At this point the manuscript will be re-reviewed for possible publication in EP&SE.

The following reviewer comments were taken into consideration during the peer review process.

"

Reviewer 1 Comments to the Author

The manuscript presents a promising concept with acceptable experimental-CFD agreement. However, the lack of direct freshwater production measurement, missing uncertainty analysis, incomplete COP calculation details, and several inconsistencies in data presentation currently prevent acceptance. The authors should address the major comments as below, before resubmission.

Questions for the Authors:

1. What was the salinity of the feedwater? The term "seawater" is used, but was actual seawater or synthetic brine used? What was the initial and final salinity?

   We thank the reviewer for this important comment. The revised manuscript now explicitly clarifies the feedwater characteristics used in the experiments. Natural seawater was used rather than synthetic brine, with an initial salinity of approximately 35 ppt, which is within the typical range of natural seawater salinity. During operation, continuous evaporation and make-up seawater addition gradually increased the salinity to approximately 55 ppt after 8 h of operation. This increase in salinity was also discussed in the revised Results and Discussion section because it slightly reduced water activity and the evaporation driving force during prolonged operation. The corresponding clarification has been added to the Experimental Setup page 6 and Discussion sections of the revised manuscript (page 13).

2. How was fouling or scaling on the evaporator surface managed? Seawater desalination typically suffers from salt precipitation on heated surfaces. Was this observed during experiments? If not, why?

   During the experiments, continuous evaporation and make-up seawater addition gradually increased the seawater salinity from approximately 35 ppt to nearly 55 ppt after 8 h of operation. The increase in salinity reduced the water activity and saturation vapor pressure at the liquid surface, thereby slightly decreasing the evaporation driving force during prolonged operation. Nevertheless, the seawater level was maintained using continuous make-up water and the evaporation process primarily occurred in the evaporator basin rather than on the heat exchanger surface. Consequently, severe salt scaling was not observed on the heat exchanger during the experimental period, although small amounts of salt deposits gradually accumulated at the bottom of the evaporator basin after prolonged operation. The closed heat exchanger configuration minimised direct salt precipitation on the heating surface because no local evaporation occurred inside the heater. In addition, the relatively moderate operating temperature (50–60 °C), continuous circulation flow, and forced airflow helped suppress local supersaturation and scaling formation, thereby maintaining relatively stable evaporation behaviour throughout the experiments. However, for long-term continuous operation, periodic brine discharge or gradual seawater replacement may still be required to prevent excessive salt accumulation and maintain stable desalination performance. The information has been updated in page 13 of the revised manuscript.

3. What is the estimated payback period or cost per liter of freshwater produced? While not required for a technical manuscript, such an estimate would strengthen the claims of practical feasibility.

A preliminary economic estimation was conducted to evaluate the practical feasibility of the proposed system. The desalination unit produced approximately 950–980 mL/h of freshwater, corresponding to about 7.6–7.8 L during 8 h of operation. Since the system utilises waste heat from the residential AC condenser, the primary additional operational cost originates from the reduction in AC performance after integration with the desalination unit. Based on the observed COP reduction from 3.92 to 3.02 and assuming a cooling capacity of 2.64 kW, the additional electricity consumption was estimated to be approximately 1.61 kWh during 8 h of operation. Using the Indonesian household electricity tariff, the additional operational cost was estimated at approximately USD 0.13 per operating cycle, corresponding to about USD 0.017/L of freshwater produced. Although this estimation does not include capital investment, maintenance, or long-term operational costs, the result indicates that the proposed system has promising potential for low-cost household-scale freshwater production by utilising readily available AC waste heat that would otherwise be rejected to the environment. The revision has been updated on pages 14-15 of the revised manuscript.

4. The introduction should be updated, some literatures may be included such as: 1. Solar Energy, 2025, 288, 113321; 2. Nano Energy, 2025, 137, 110781; 3. Advanced Functional Materials, 2025, 36, e10564; 4. Advanced Sciences, 2025, 12(46), e13258; 5. J. Mater. Chem. A, 2024, 12, 4046-4056; 6. J. Mater. Chem. A, 2024, 12, 4046-4056;

We thank the reviewer for the valuable suggestion. The Introduction section has been substantially revised and updated by incorporating the recommended recent studies. Additional discussions were added regarding sustainable desalination technologies, solar-driven and hybrid desalination systems, interfacial evaporation enhancement, photothermal evaporation mechanisms, salt-rejection behaviour, and low-grade thermal energy utilisation. In particular, recent studies from Solar Energy (2025, 288, 113321), Nano Energy (2025, 137, 110781), and J. Mater. Chem. A (2024, 12, 4046–4056) were incorporated to strengthen the discussion on evaporation enhancement, heat and mass transfer intensification, and salt accumulation behaviour in thermal desalination systems. Furthermore, the updated literature review now better positions the present study within the context of decentralised and energy-efficient freshwater production technologies while clarifying the novelty of integrating residential AC waste heat recovery with vortex-generator-assisted airflow enhancement for household-scale desalination applications. The suggested references and related discussions have been incorporated into the Introduction section, particularly on pages 4 of the revised manuscript.

Is the AC condenser fan able to maintain required airflow when the channel area is very small (e.g., 0.006 m²)? Did the fan operate at reduced flow or stall? Was fan power or current monitored?

At the smallest channel area (0.006 m²), increased flow confinement generated higher pressure losses, restricting condenser airflow and reducing heat rejection effectiveness. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions. Because the residential split-type AC operated as a factory-integrated commercial system, the condenser fan current and standalone fan power were not monitored separately. Therefore, the reduction in COP was used to indirectly indicate the increased aerodynamic resistance associated with smaller channel geometries.

The revisions have been incorporated on page 13-14 of the revised manuscript.

Reviewer 2 Comments to the Author

The manuscript by Mugisidi et al. utilised waste heat from residential AC units to drive an evaporation-based desalination system. The Experimental is fine. However, the following points should be addressed before the manuscript is accepted.

1.The manuscript is not well organized. English should be improved here and there.

We thank the reviewer for this valuable comment. The manuscript has been carefully revised to improve its overall organisation, clarity, and readability. Several sections, including the Introduction, Methods, Results and Discussion, and Conclusion, were restructured to improve the logical flow and consistency of the presentation. In addition, the English language throughout the manuscript has been thoroughly revised and proofread to improve grammar, sentence structure, and academic writing quality.

2.Regarding many previous studies on using waste heat from residential AC units to drive an evaporation-based desalination system, I believe that the authors should at the very least have cited these work, which is arguably relevant, and further that they should have made an attempt to discuss the differences between the references and their work. The authors should do comparison with others in the literature, and do more investigation for comparison Vortex generators with other generators and utilisation of AC waste heat with other waste heat.

We thank the reviewer for the valuable suggestion. The Introduction section has been substantially revised and updated by incorporating the recommended recent studies. Additional discussions were added regarding sustainable desalination technologies, solar-driven and hybrid desalination systems, interfacial evaporation enhancement, photothermal evaporation mechanisms, salt-rejection behaviour, and low-grade thermal energy utilisation. The suggested references and related discussions have been incorporated into the Introduction section, particularly on pages 3–5 of the revised manuscript

3.Will the liquid water condense on the top of the container during the collection of water by this device, thereby affecting the experimental results?

We thank the reviewer for this valuable comment. During the experiments, noticeable condensation was not observed on the upper inner surface of the container apart from the designated cooling condensation section. This behaviour was attributed to the forced airflow generated by the condenser fan, which continuously transported the generated water vapour toward the condensation section before significant vapour accumulation could occur inside the chamber. As a result, most condensation occurred on the intended cooler condensation surface where freshwater was collected.

In addition, the airflow inside the channel helped maintain relatively continuous vapour transport, thereby reducing the possibility of undesired condensation on other chamber surfaces. Therefore, the influence of unintended condensation on the measured freshwater production was considered negligible.

4.More details about measurement devices should be described further; it is necessary to give specifications, accuracy, measuring range, etc.

We thank the reviewer for this valuable suggestion. Details regarding the measurement instruments have been incorporated into the revised manuscript. Table 1 explicitly includes the measurement range and accuracy of each device used in the experiments, including the PT100 thermocouples, weighing scale, humidity meter, anemometer, pressure gauge, and pressure meter to improve the clarity, reproducibility, and reliability of the experimental methodology and measurement procedures.

5.The authors should make further discussion on their observations.

We thank the reviewer for this valuable suggestion. The revised manuscript now includes additional discussion and interpretation of the experimental observations throughout the Results and Discussion section. In particular, further explanations were added regarding the influence of channel cross-sectional area on airflow velocity, pressure drop, evaporation enhancement, and AC coefficient of performance (COP). Additional discussion was also incorporated to clarify the role of vortex generators in promoting airflow mixing, turbulence intensity, and boundary-layer disruption near the air–water interface.

Furthermore, the revised manuscript now discusses the influence of seawater salinity increase during prolonged operation, the relationship between airflow confinement and condenser heat rejection effectiveness, and the practical implications of the observed trade-off between freshwater production and AC operational performance. Additional explanation regarding ambient temperature and humidity sensitivity, CFD validation results, and the potential need for periodic brine discharge during long-term operation was also incorporated to strengthen the interpretation and practical relevance of the observed results.

In summary, I recommend publication of the manuscript with a major revision of the text.

Reviewer 3 Comments to the Author

General Evaluation

The manuscript addresses a significant opportunity in sustainable engineering by utilizing low-grade waste heat from residential split-type air conditioners (AC) for seawater desalination. The topic is highly relevant for coastal households and small-island infrastructure where freshwater is scarce. The study successfully combines experimental validation with Computational Fluid Dynamics (CFD) simulations. However, while the technical descriptions are clear, certain sections require more rigorous quantitative positioning and discussion of long-term operational challenges to meet the standards of a high-impact research article.

Recommendation

The manuscript is technically robust and provides a viable solution for water-scarce regions. By addressing the specific quantitative comparisons and long-term maintenance considerations mentioned below, the contribution will be significantly more credible and ready for publication. Thus, the manuscript can be accepted for publication after Minor revision as detail Detailed Evaluation and Suggestions as follows:

Detailed Evaluation and Suggestions

Abstract

Clearly identifies the problem of water scarcity and the underutilized potential of AC waste heat. It summarizes the methodology (CFD and experimental) and the primary findings regarding vortex generators and optimal channel geometry. However, the abstract is descriptive but could be strengthened with more precise performance indicators. Thus, it is recommended to include the specific maximum freshwater production rate (e.g., 950–980 mL/h) and the exact range of COP improvement in the abstract to provide immediate quantitative value.

Introduction (Pages 6-7)

While the introduction successfully identifies the significant potential of utilizing AC waste heat for desalination, the State of the Art should be expanded by comparing it with other household waste heat recovery (WHR) technologies to strengthen the system's positioning within the green technology landscape. The identified Research Gap is relevant, but it is suggested that the authors more sharply define why this integrated solution is superior to standalone systems, such as solar stills, particularly in the context of urban space constraints. Regarding Novelty, the use of vortex generators (VG) to enhance air turbulence in domestic AC systems is a significant contribution; however, the authors must more explicitly emphasize that the primary novelty lies in the channel geometry optimization that balances evaporation rates with machine performance integrity (COP). Finally, concerning the Goals, the research objectives align with the methodology, but it is highly recommended that the authors formulate more measurable goals, specifically in establishing technical optimization parameters that are directly applicable to the HVAC manufacturing industry.

> We sincerely thank the reviewer for the constructive and insightful comments. The Introduction section has been substantially revised to better position the proposed system within the broader green technology and waste heat recovery (WHR) landscape (page 3-5). Additional discussions were incorporated regarding previous household-scale waste heat recovery desalination technologies, including HDH-, membrane-, and heat-pump-assisted systems integrated with residential air-conditioning units. These additions clarify the advantages and limitations of existing systems, particularly their dependence on solar collectors, auxiliary heating devices, multi-stage humidification arrangements, or complex thermal integration schemes.
>
> To address the reviewer's concern regarding the research gap, the revised manuscript now more explicitly highlights the practical advantages of the proposed system compared with conventional standalone desalination systems such as solar stills. In particular, the proposed configuration utilises readily available residential AC infrastructure and does not require large solar collection areas, making it more suitable for urban and household-scale applications where installation space is limited. This aspect has been emphasised to strengthen the positioning of the proposed system as a compact and decentralised desalination approach.

The novelty statement has also been revised and sharpened. The revised manuscript now clearly emphasises that the primary novelty does not solely lie in the use of vortex generators, but more importantly in the optimisation of channel geometry to achieve a balance between evaporation enhancement and AC operational performance integrity. The study demonstrates that smaller channel areas increase airflow velocity and evaporation rates but simultaneously increase pressure losses that reduce condenser airflow effectiveness and AC COP. Therefore, the proposed work establishes an optimal channel cross-sectional range (0.015–0.025 m^2) capable of achieving high freshwater production rates while maintaining acceptable AC performance. This optimisation-based contribution has now been explicitly highlighted in both the Introduction and Abstract sections.

Furthermore, the research objectives were refined to become more measurable and application-oriented. The revised manuscript now explicitly states that the study aims to establish technically applicable operating and geometric parameters, including optimal channel cross-sectional area, airflow modification strategy, evaporation performance, and acceptable COP operating limits, which may provide useful design guidance for future HVAC-integrated desalination applications and compact household-scale freshwater production systems.

2. Methods (Page 9–14)

Provides a detailed description of the desalination unit (DU) integration with the refrigeration loop. The instrumentation table (Table 1) and the mesh independence study (Table 2) ensure high reproducibility and numerical stability. While the physical setup is detailed, the specific salinity or feedwater characteristics are not explicitly defined. Thus, it is recommended to add information regarding the initial salinity of the seawater used in experiments, as this directly affects the saturation vapor pressure (Ysat) and evaporation flux (\dot{m}) described in your equations.

We thank the reviewer for this valuable comment. Additional information regarding the feedwater characteristics has been added to the revised manuscript. The seawater used in the experiments had an initial salinity of approximately 35 ppt, which is within the typical range of natural seawater salinity. During the experiments, continuous evaporation gradually increased the seawater salinity to approximately 55 ppt after 8 h of operation. However, the seawater level was maintained using continuous make-up water addition, which helped maintain stable operating conditions throughout the tests. This discussion has been incorporated into the revised manuscript on page 6 and 13.

Results and Discussion (Page 15–17)

Effectively demonstrates the correlation between air channel cross-sectional area and evaporation rates. The use of vortex generators is shown to enhance local turbulence and disrupt the boundary layer, which is scientifically sound. The linear correlation (R2 > 0.95) between CFD and experimental data is excellent. However, the discussion on the trade-off between evaporation and AC performance (COP) is present but needs a more critical comparison. Thus, it is suggested to provide a direct comparative table or graph showing the "Percentage Loss in COP" versus "Freshwater Yield" for each channel size. This would help practitioners understand the exact efficiency cost of maximizing water production.

We sincerely thank the reviewer for the constructive suggestion. The revised manuscript has been expanded to more clearly discuss the trade-off between freshwater production and AC operational performance under different channel geometries on page 14. As suggested, additional comparative discussion was incorporated to highlight the relationship between freshwater yield and the corresponding COP reduction at different channel cross-sectional areas.

The results indicate that smaller channel areas increased airflow velocity because of the reduced flow passage area, which enhanced convective heat and mass transfer near the air–water interface and consequently increased evaporation rates and freshwater production. However, the same flow confinement simultaneously generated larger pressure losses inside the channel, restricting condenser airflow effectiveness and reducing AC COP. Therefore, the observed variation in evaporation rate and COP did not indicate a direct cause–effect relationship between the two parameters; instead, both responded independently to changes in airflow characteristics induced by channel geometry.

The revised discussion now more explicitly explains this airflow-driven trade-off and clarifies that the optimal operating condition was achieved at channel cross-sectional areas of 0.015–0.025 m², which provided high freshwater production rates (approximately 950–980 mL/h) while maintaining acceptable AC operational performance. This additional analysis was included to improve the engineering interpretation and practical applicability of the proposed desalination system for future HVAC-integrated freshwater production applications.

Evaluation on Heat Rejection and COP Correlation

The paper notes that smaller channel areas cause a greater pressure drop, which hinders heat rejection and lowers the COP. However, there is limited discussion on how variations in ambient temperature (Ta) or humidity (Ha) would affect the system's stability in real-world tropical environments. Thus it is suggested to include a brief sensitivity analysis or discussion on how different ambient conditions (e.g., peak summer vs. monsoon) might shift the optimal cross-sectional area of 0.015–0.025 m² and also discuss the thermal Marangoni effect mentioned in section 2.1 in more detail within the results to explain surface-driven fluid motion improvements.

We sincerely thank the reviewer for this valuable suggestion. Additional discussion regarding the influence of ambient temperature (Ta) and ambient humidity (Ha) has been incorporated into the revised manuscript. Although the present study was conducted under controlled laboratory conditions and did not include seasonal variation experiments, the revised discussion now clarifies how different ambient conditions may influence the evaporation driving force and condenser heat rejection performance in practical tropical environments.

Higher ambient temperatures would likely increase evaporation potential because warmer air can hold more moisture and increase the temperature difference between the heated seawater surface and surrounding air. However, elevated ambient temperatures may simultaneously reduce condenser cooling effectiveness and further decrease AC COP, particularly at smaller channel cross-sectional areas where airflow resistance and pressure losses are already significant. Conversely, under high-humidity conditions, the vapor pressure gradient between the seawater surface and surrounding air would decrease, potentially reducing evaporation rates and shifting the optimal operating condition toward slightly larger channel cross-sectional areas with lower airflow resistance and more stable condenser performance.

In response to the reviewer’s comment, the discussion was also refined to focus more explicitly on airflow-driven evaporation enhancement mechanisms supported by the experimental and CFD results, particularly the roles of airflow velocity, turbulence intensity, boundary-layer disruption, and vapor transport near the air–water interface.

Conclusion and Future Outlook

The conclusions are well-supported by the data, showing that the system can meet basic drinking water requirements (approx. 2.5–3.5 L/day) for a household. It is suggested to add the summary result in relation on the Novelty emphasis on more explicitly state that the novelty lies in the household-scale integration that balances AC operational integrity (COP) with decentralized water production.

For the Future Outlook, the current section is a bit brief. It is suggested to add recommendations regarding:

Regarding the scaling and maintenance, how salt accumulation in the heated tank will be managed over long-term operation.

Related to Water Quality Testing, future verification of the distillate purity (TDS, pH) to ensure it meets WHO drinking water standards.

We sincerely thank the reviewer for the constructive comments and positive evaluation of the conclusions. In response to the reviewer’s suggestion, the Conclusion section has been revised to more explicitly emphasise the primary novelty of the present work, namely the development of a household-scale desalination system that balances freshwater production enhancement with AC operational integrity through channel geometry optimisation and airflow modification. The revised conclusion now highlights that the proposed system not only increases evaporation performance through vortex-generator-assisted airflow enhancement, but also establishes an optimal channel cross-sectional range (0.015–0.025 m^2) capable of maintaining acceptable AC COP while achieving high freshwater production rates. This optimisation-based contribution was emphasised to strengthen the practical relevance of the study for decentralised HVAC-integrated freshwater production applications.

In addition, the Future Outlook section has been expanded to include discussion regarding long-term operation and salt accumulation management. The revised manuscript now clarifies that although severe scaling was not observed on the heat exchanger surface during the experiments, gradual salt accumulation occurred at the bottom of the evaporator basin due to continuous evaporation and increasing seawater salinity. Therefore, periodic brine discharge, gradual seawater replacement, or routine cleaning procedures may be required during long-term operation to prevent excessive salt accumulation and maintain stable desalination performance. These additions were incorporated to improve the practical applicability and long-term operational perspective of the proposed desalination system.

In the present study, freshwater quality was preliminarily evaluated through TDS and pH measurements, which indicated that the produced freshwater remained within the acceptable range for clean water quality. More comprehensive water quality verification based on WHO drinking water standards will be considered in future studies.

Reviewer 4 Comments to the Author

1. English must be improved.

We thank the reviewer for this valuable comment. The manuscript has been carefully revised to improve its overall organisation, clarity, and readability. Several sections, including the Introduction, Methods, Results and Discussion, and Conclusion, were restructured to improve the logical flow and consistency of the presentation. In addition, the English language throughout the manuscript has been thoroughly revised and proofread to improve grammar, sentence structure, and academic writing quality.

2. The Journal's standards for referencing must be considered.

We thank the reviewer for this comment. All references and in-text citations have been carefully revised and reformatted to comply with the Journal's required numbered referencing style and formatting guidelines.

3. The most important quantitative results must be mentioned in the abstract.

We thank the reviewer for this valuable suggestion. The abstract has been revised to include the most important quantitative findings of the study. Specifically, the revised abstract now explicitly reports the maximum freshwater production rate (approximately 950–980 mL/h), the optimal channel cross-sectional area range (0.015–0.025 m^2), the observed AC COP range (from 3.92 to approximately 3.02 under the most restrictive channel configuration), and the CFD validation results showing coefficients of determination exceeding 0.95 with average deviations below 10%. These additions were incorporated to provide clearer quantitative insight into the system performance and practical feasibility directly within the abstract.

4. The problem statement should be clearly explained.

We thank the reviewer for this valuable comment. The Introduction section has been revised to more clearly state the research problem addressed in the present study. The revised manuscript now explicitly explains that although residential air-conditioning systems continuously reject significant amounts of low-grade waste heat, this thermal energy is typically discharged to the environment without practical utilisation. At the same time, household-scale desalination systems such as solar stills often suffer from low freshwater productivity, dependence on solar irradiation, and large installation space requirements, particularly in urban environments.

The revised problem statement also clarifies that previous AC-assisted desalination systems generally relied on complex thermal integration, auxiliary heating systems, or multi-stage HDH configurations, while limited studies have investigated simple household-scale direct-evaporation systems that simultaneously optimise freshwater production and AC operational performance. In addition, the influence of airflow channel geometry and vortex-generator-assisted airflow enhancement on the trade-off between evaporation rate and AC coefficient of performance (COP) has not been sufficiently investigated. These aspects are now more explicitly presented in the revised manuscript to strengthen the motivation, research gap, and practical relevance of the proposed study.

5. I recommend expanding your literature review by adding recent papers studying innovative configurations of solar powered (ADS, HDH, RO, ….etc) desalinations systems for off-grid sustainable freshwater production:

*Sustainable freshwater production using sorption-based atmospheric water harvesting: Sorbent materials, system design configurations, thermodynamic models, and future per-spectives, International Communications in Heat and Mass Transfer, 2026.

*Dynamic numerical modeling and performance assessment of a hybrid photovoltaic ther-mal collector adsorption desalination system for sustainable water-energy nexus, Solar Energy, 2025.

* Performance Assessment of Hybrid Adsorption/Humidification-Dehumidification Desali-nation Cycle Powered by Dish/Stirling Concentrated Solar Power System for Sustainable Freshwater Production Maximization, Process Safety and Environmental Protection,2025.

*Novel Solar Distillation Dome: New Approach for Sustainable Freshwater Production Augmentation, IEEE Explore, 2025.

* Enhanced performance of a hybrid adsorption desalination system integrated with solar PV/T collectors: Experimental investigation and machine learning modeling coupled with manta ray foraging algorithm, Applied Thermal Engineering, 2024.

> We sincerely thank the reviewer for these valuable suggestions. The Introduction section has been expanded by incorporating the recommended recent studies related to sustainable and off-grid freshwater production systems, including adsorption desalination (ADS), humidification–dehumidification (HDH), solar distillation, atmospheric water harvesting, and photovoltaic thermal (PV/T)-assisted desalination technologies. The added literature now provides broader discussion regarding innovative hybrid desalination configurations, low-grade thermal energy utilisation, thermodynamic enhancement approaches, and sustainable water–energy integration strategies for decentralised freshwater production.
>
> In particular, the revised literature review now includes discussion of recent ADS- and HDH-based desalination systems powered by solar thermal and PV/T technologies, highlighting their capability for improving freshwater productivity and energy efficiency in off-grid applications. Additional references regarding atmospheric water harvesting, hybrid adsorption desalination systems, and advanced solar distillation configurations were also incorporated to strengthen the positioning of the present work within the broader sustainable desalination and green technology landscape. These additions help clarify the differences between the proposed AC waste heat-driven desalination system and previously reported solar-assisted or adsorption-based desalination technologies, while further emphasising the novelty and practical advantages of the present household-scale airflow-enhanced configuration.

6. The advantages of the proposed study compared with the previous similar studies also need more clarification in the existing introduction.

> We thank the reviewer for this important suggestion. The Introduction section has been revised to more clearly clarify the advantages of the proposed study compared with previously reported desalination systems. The revised manuscript now explicitly highlights that many previous household-scale desalination technologies relied on solar collectors, auxiliary

heaters, adsorption beds, membrane systems, evaporative condensers, or multi-stage HDH configurations, which may increase system complexity, installation space requirements, and operational cost.

In contrast, the proposed system utilises readily available residential split-type AC infrastructure as a continuous low-grade waste heat source without requiring additional solar collectors or complex thermal integration. Furthermore, unlike many previous studies that mainly focused on thermodynamic cycle integration, the present work emphasises airflow-driven evaporation enhancement through vortex-generator-assisted turbulence and channel geometry optimisation. The revised Introduction now more explicitly explains that the primary contribution of the study lies in establishing an optimal channel cross-sectional range capable of balancing evaporation enhancement and AC operational integrity (COP). In addition, the combination of experimental investigation and CFD analysis provides deeper insight into airflow behaviour, pressure losses, evaporation characteristics, and condenser performance, thereby strengthening the engineering applicability of the proposed household-scale desalination system.

7. Explain the key geographic and demographic factors influencing the feasibility and efficiency of the hybrid residential AC/desalination system potential, and clarify how these factors vary.

We thank the reviewer for this valuable comment. The revised manuscript now includes additional discussion clarifying the practical application context of the proposed system. In particular, the manuscript explains that the proposed household-scale AC-assisted desalination system is especially suitable for tropical and subtropical coastal regions where residential air-conditioning usage is already widespread and freshwater accessibility may be limited. The discussion also clarifies that ambient temperature, relative humidity, and urban space availability may influence system feasibility and operational performance. Compared with conventional solar stills that require relatively large installation areas, the proposed compact configuration may offer advantages for urban household applications where space is limited but residential AC systems are already available. In addition, the achieved freshwater production rate indicates the potential applicability of the proposed system for small household-scale drinking water production.

8. How to select the input and operational parameters for the AC split unit and single effect desalination unit, please give detailed justifications and discussion.

We thank the reviewer for this important comment. The revised manuscript now provides further justification for the selection of input and operational parameters of both the residential split-type AC unit and the single-effect desalination unit. The AC unit was selected to represent a typical household-scale system commonly used in tropical residential buildings. A residential split-type AC unit was operated under normal cooling conditions, and its rejected condenser heat was utilised as the thermal input for the desalination unit without modifying the main refrigeration cycle. This selection was intended to evaluate the practical feasibility of recovering readily available low-grade waste heat from existing domestic AC infrastructure.

The operational parameters of the desalination unit were selected to systematically evaluate the trade-off between evaporation enhancement and AC operational performance. The channel cross-sectional area was varied because it directly controls airflow velocity, pressure drop, boundary-layer thickness, and condenser heat rejection effectiveness. Smaller channel areas increase airflow velocity and enhance convective heat and mass transfer at the air–water interface, thereby increasing evaporation. However, they also increase flow resistance and pressure drop, which can reduce condenser airflow effectiveness and lower AC COP. Conversely, larger channel areas reduce pressure losses and improve AC performance but decrease evaporation intensity. Therefore, the selected range of channel cross-sectional areas was used to identify an optimal operating window rather than simply maximising freshwater production.

The vortex generator configuration was selected to enhance airflow mixing and boundary-layer disruption near the air–water interface without requiring additional energy input. The parameters were therefore chosen to evaluate whether passive airflow modification could improve evaporation while maintaining acceptable AC performance. Based on the combined evaporation and COP results, a channel cross-sectional area of 0.015–0.025 m^2 was identified as the optimal range, achieving high freshwater production while maintaining acceptable AC operational integrity.

9. The authors must conduct a statistical analysis thorough model validation to ensure the model accuracy with respect to freshwater production and waste heat recovery.

We thank the reviewer for this important comment. Additional model validation and statistical comparison discussions have been incorporated into the revised manuscript to strengthen the reliability of the numerical model in predicting freshwater production and thermal performance. The CFD predictions were validated against experimental measurements under different channel cross-sectional areas and vortex-generator configurations. Statistical agreement between the numerical and experimental results was evaluated using the coefficient of determination (R^2) and average deviation analysis.

The comparison demonstrated strong linear correlations between CFD predictions and experimental measurements, with coefficients of determination exceeding $R^2 > 0.95$ for both NVG and VG configurations. In addition, the average deviations between numerical and experimental results were approximately 6–10%, remaining within the commonly accepted validation range for thermal–fluid studies. The revised manuscript also includes additional discussion regarding the relationships among airflow characteristics, evaporation enhancement, pressure drop, and AC coefficient of performance (COP) under different channel geometries. These analyses confirm that the numerical model provides sufficiently accurate prediction of evaporation behaviour and AC operational response under the investigated operating conditions.

10. Provide limitations and future outlooks for the research

We thank the reviewer for this valuable suggestion. The revised manuscript now more clearly discusses the limitations and future outlook of the present study. In particular, the Conclusion section has been expanded to clarify that the experiments were conducted under controlled laboratory conditions using a single residential split-type AC configuration, which may limit the generalisability of the results under different environmental and operational conditions.

In addition, the revised manuscript now includes future research directions related to long-term operation, ambient-condition sensitivity, scaling behaviour, and system scalability for practical household applications. Discussion regarding gradual salt accumulation in the evaporator basin and the need for periodic brine discharge or cleaning procedures during prolonged operation has also been incorporated.

11. Most of Figures lack the necessary quality and clarity, making it difficult for the reader to understand their content. Improving the quality of these figures is essential for the audience.

We thank the reviewer for this valuable comment. The figures in the revised manuscript have been substantially improved to enhance their clarity and readability. Several figures were reformatted using higher-resolution images, larger font sizes, clearer axis labels, thicker lines and markers, and improved legend arrangements to make the trends easier to distinguish

Airflow-Enhanced Evaporation–Condensation Seawater Desalination Using Residential Air Conditioner Waste Heat

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ABSTRACT

Water scarcity remains a major global challenge, particularly in developing countries with limited freshwater access. At the same time, increasing use of residential air-conditioning (AC) systems generates substantial low-grade waste heat that is typically rejected into the environment. This study investigates a household-scale evaporation–condensation desalination system driven by waste heat recovered from a residential split-type AC unit. The proposed system integrates vortex-generator-assisted airflow enhancement within a compact evaporation channel to intensify heat using channels with different cross-sectional areas under vortex-generator (VG) and non-vortex-generator (NVG) configurations. Air temperature, relative humidity, evaporation rate, seawater salinity, and AC coefficient of performance (COP) were measured, while computational fluid

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dynamics (CFD) simulations were performed to analyse airflow and evaporation behaviour. The results showed that vortex generators enhanced airflow mixing and evaporation performance. Maximum freshwater production of approximately 950–980 mL/h was achieved at channel cross-sectional areas of 0.015–0.025 m². Although COP decreased from 3.92 to approximately 3.02 under the most restrictive channel configuration, the values remained within the typical residential AC operating range. The CFD predictions showed strong agreement with experiments, with $R^2 > 0.95$ and average deviations below 10%. A preliminary economic analysis estimated the operational cost at approximately USD 0.017/L of freshwater produced. The proposed system demonstrates promising potential for decentralised and energy-efficient household freshwater production using readily available AC waste heat.

Keywords: desalination; waste heat; air conditioning; vortex generator; CFD simulation

Highlights

- Waste heat from a split-type domestic AC unit was utilised to power a household-scale desalination unit.
- Vortex generators enhance local turbulence and boundary-layer disruption, increasing evaporation but with a smaller impact than geometric variation.
- CFD–experimental validation shows good agreement, confirming model reliability for optimisation.
- An optimal channel area of 0.015–0.025 m² provides the best balance between COP and evaporation effectiveness.
- The proposed approach offers a feasible, affordable desalination method for coastal households using existing AC infrastructure.

1. Introduction

Although water is a basic need for human life, freshwater resources, which represent only about 2.8% of total global water resources, are limited[1] Moreover, a 15% increase in population may result in a water shortage of up to 40% of total water demand.[2,3]. Water scarcity can trigger humanitarian, political, and social conflicts.[4] This challenge is particularly pronounced in many coastal and tropical developing regions, where limited freshwater resources and growing populations increase vulnerability to water shortages and present challenges in accessing clean water.[5–7]

Global warming, another critical issue, has intensified the use of air conditioning (AC) units in tropical regions.[8,9] During operation, AC units reject low-grade heat (50–80 °C) into the environment without recovery,[10] thus constituting a widely available but underutilised thermal resource. In dense urban areas, the accumulation of waste heat from AC units can increase local ambient temperatures by up to 1 °C,[11,12] thereby exacerbating the urban heat island effect. Recovering this waste heat therefore offers a dual benefit: improving energy utilisation and mitigating localised thermal accumulation.

One potential approach to utilising this waste heat is evaporation–condensation desalination, whereby hot air is directed over seawater to generate vapour that is subsequently condensed into freshwater. The use of waste heat from AC units as a thermal source can drive the desalination process while simultaneously reducing environmental thermal discharge and producing freshwater as a valuable by-product. Airflow over water surfaces has been shown to significantly enhance evaporation by increasing convective heat and mass transfer at the air–water interface.[13] and influence distillation productivity in evaporation–condensation desalination systems.[14]

1.1 Literature review on desalination using Air Conditioner

Previous studies have investigated heat pumps, solar thermal systems, photovoltaic thermal (PV/T) systems, and AC-assisted desalination technologies, including multistage flash distillation

(MSF), membrane distillation (MD), adsorption desalination (ADS), and humidification–dehumidification (HDH), to improve thermal efficiency and reduce energy consumption.[15–20] Although hybrid desalination systems driven by low-grade thermal energy have shown promising capability for improving freshwater productivity and energy,[21–23] many existing systems are designed for relatively large-scale applications and commonly require solar collectors, auxiliary heating systems, or complex thermal integration.

Recent studies have also explored the recovery of waste heat from residential AC systems for simultaneous cooling and freshwater production. Condenser waste heat from vapour-compression refrigeration systems has been reported to provide sufficient low-grade thermal energy for seawater heating and evaporation in HDH and membrane-based desalination systems.[24–27] Nevertheless, many proposed systems still depend on solar-assisted heating, evaporative condensers, multi-stage humidification arrangements, or additional thermal components, increasing complexity and installation cost.

Evaporation enhancement remains a key factor governing freshwater productivity because thermal desalination strongly depends on heat and mass transfer at the air–water interface. Previous studies have shown that improving airflow characteristics, turbulence intensity, and boundary-layer disruption significantly enhances evaporation and vapour transport.[28,29] Other enhancement techniques, including thin-film evaporation, wick structures, porous materials, and photothermal evaporation, have also demonstrated improved freshwater productivity.[30,31] Previous investigations further reported that lowering pressure above the water surface increases driving force of evaporation due to higher vapour pressure at the liquid surface.[32]

Based on these considerations, the present study investigates a residential split-type AC waste-heat-driven desalination system combined with vortex-generator-assisted airflow enhancement. In contrast to many previous solar-driven or multi-component HDH desalination systems, the proposed configuration focuses on a compact household-scale arrangement utilising existing residential AC infrastructure. Hot air rejected from the condenser is directed through an evaporation channel above the brine surface, while vortex generators intensify airflow mixing and turbulence near the air–water interface. Combined experimental investigation and CFD analysis were performed to evaluate evaporation behaviour, freshwater production, and AC operational performance, thereby contributing to decentralised and energy-efficient desalination technology development.

1.2 Statement of Industrial Relevance and Novelty

This study is relevant to applications in which energy efficiency and resource recovery are increasingly important, such as heating, ventilation, and air conditioning (HVAC), desalination, and sustainable residential building. Residential AC units continuously discharge low-grade waste heat that is generally released without productive utilisation. The proposed system demonstrates how this waste heat can drive a compact evaporation–condensation desalination process capable of producing freshwater at the household scale, particularly for coastal housing, tourism facilities, and small-island infrastructure.

Our previous study demonstrated that vortex generators significantly enhanced evaporation in AC-assisted desalination systems,[33] but the work was limited to numerical analysis without experimental validation or evaluation of system-level performance.

The novelty of the present study lies in its integration of vortex-generator-assisted airflow enhancement with a compact household-scale desalination system driven by residential split-type AC waste heat. In contrast to previous AC-assisted desalination studies that focused mainly on thermodynamic cycle integration or HDH configuration, this work emphasises airflow-driven evaporation intensification through channel geometry modification and turbulence enhancement. The study further evaluates the trade-off between evaporation enhancement and AC operational performance under different channel cross-sectional areas using combined CFD simulations and experimental validation.

This study therefore aims to design, analyse, and validate a household-scale desalination unit utilising waste heat from a residential split-type AC system. The effects of channel geometry and vortex generators on airflow behaviour, evaporation enhancement, air temperature reduction, and AC coefficient of performance (COP) were systematically evaluated using experimental measurements and CFD simulations.

2. Materials and Method

2.1. Desalination unit description

The desalination unit (DU) was integrated with a residential AC system to recover condenser waste heat for freshwater production through evaporation–condensation processes. In this system, saline feedwater is heated using AC waste heat to generate water vapour, which is then condensed on a cooler surface to produce distilled water.

Natural seawater with an initial salinity of approximately 35 ppt was placed inside an evaporator chamber and heated indirectly by a heat exchanger containing freshwater circulated from the AC condenser waste heat loop. The increased seawater temperature promoted evaporation, and the generated vapour subsequently condensed on a cooler surface to produce freshwater. In addition, airflow from the AC condenser was directed through a channel above the water surface to enhance evaporation through forced convection by increasing airflow velocity, turbulence intensity, and vapour transport near the air–water interface. The airflow channel was configured with cross-sectional areas of 0.006, 0.012, 0.018, 0.024, 0.030, 0.036, and 0.042 m^2, each tested with and without vortex generators (VG and NVG). The vortex generators enhanced airflow mixing and boundary-layer disruption, thereby improving heat and mass transfer during evaporation. The experimental setup is shown in Fig. 1.

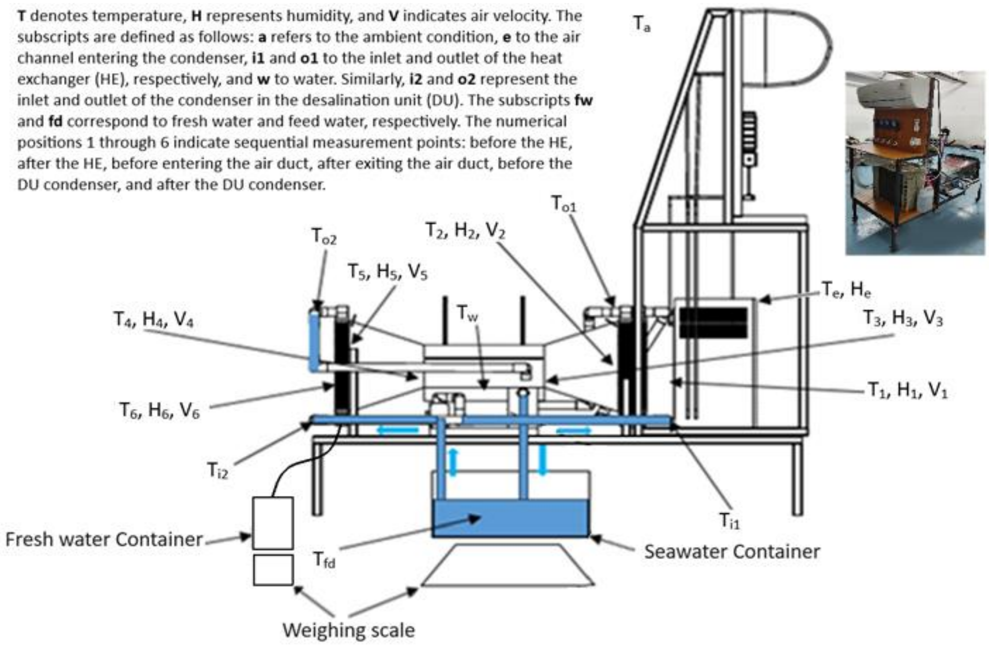

Fig. 1. Experimental rig

2.2. Experimental setup and procedures

The data in this study were obtained experimentally and compared using the CFD simulation. The instruments used are presented in Table 1.

Table 1. The experimental instruments

Device	Range	Accuracy
Thermocouples PT100	−50–110 °C	±0.1°C
Weighing scales	0–20 kg	±0.05%
Humidity meter	10%–99%	±1%
Anemometer GM-816	0–30 m/s	±5%
Pressure Gauge Class 1,6	0–550 psi	±1.6%
Pressure meter PCE-PDA 1 L	±2 kPa	±0.5%
Salinity Refractometer ATC	0 – 100 ppt	±1 ppt

To enhance airflow mixing and evaporation performance inside the channel, a delta-wing vortex generator (Fig. 2a) was selected because it efficiently directs airflow and generates strong vortices with relatively low flow resistance.[34] The ratio of channel height to vortex generator height was set at 0.47 to balance vortex formation and flow obstruction, thereby enhancing mixing while limiting aerodynamic losses.[35,36] In addition, a spacing-to-channel-length ratio of 0.18 was applied to sustain vortex interaction and turbulence,[37] while a 45° attack angle was selected to optimise vortex strength, flow attachment, and thermo-hydraulic performance.[38] The simulated evaporation region

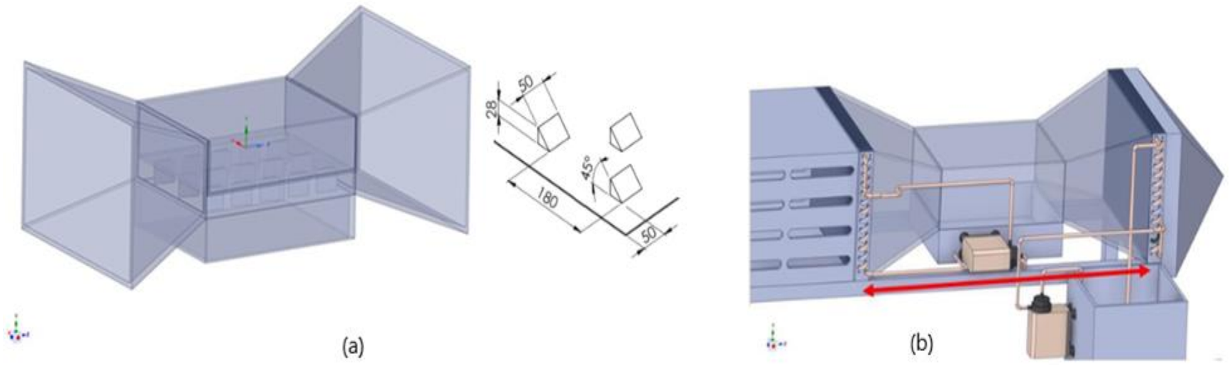

Fig. 2. Vortex generator (a) and evaporation zone (b)

is indicated by the red arrows in Fig. 2b, while areas outside this region were excluded from the model scope.

The results were validated using CFD simulations performed with Cradle CFD based on its continuity, momentum, and energy equations. Detailed governing equations and numerical settings are provided in **the supplementary material**.

An octagonal mesh was employed because it provides better grid quality and smoother element transition in complex geometries compared with conventional triangular or quadrilateral meshes, thereby improving numerical stability and simulation accuracy. A mesh size of 0.05 with a refined region of 0.02 was used, resulting in 532,624 elements based on the mesh independence study (see Table 2).

Table 2. Mesh independence study

No.	No. of elements	Evaporation rate (kg/s m^3)	Difference (%)
1	141,567	0.003998	-
2	221,325	0.004489	0.12
3	532,624	0.004623	0.03
4	821,653	0.004623	0.00
5	1,036,877	0.004623	0.00

The mesh independence study was conducted using five mesh densities. The evaporation rate became constant beyond 532,624 elements, indicating that further refinement would have a negligible influence on the simulation results. A relative deviation below 10% was considered acceptable for establishing mesh independence.[39–41]

The simulations focused on evaporation dynamics inside the airflow channel downstream of the AC condenser, where inlet air temperatures reached approximately 55 °C. The channel cross-sectional area was varied from 0.042 to 0.006 m^2 to systematically evaluate the effect of airflow confinement on evaporation performance and AC operation. The maximum area of 0.042 m^2 was selected to represent a relatively low-confinement condition, corresponding to approximately two-thirds of the estimated effective condenser fan flow area. The area was then gradually reduced to 0.006 m^2 to increase airflow velocity over the seawater surface and intensify convective heat and mass transfer. However, reducing the channel area also increased pressure drop and airflow resistance, allowing the study to identify the trade-off between evaporation enhancement and AC COP reduction.

Because the desalination unit was directly integrated with the AC system, the operational parameters were selected to represent practical residential operating conditions while evaluating the trade-off between evaporation enhancement and AC performance. Smaller channel areas increased airflow velocity and evaporation intensity, but also increased pressure losses and reduced condenser heat rejection effectiveness, thereby lowering AC COP. Conversely, larger channel areas reduced pressure losses but weakened evaporation enhancement. The vortex generator geometry was adopted from previous thermo-fluid studies[33] to enhance airflow mixing and boundary-layer disruption with minimal aerodynamic penalty.

AC performance was evaluated by measuring refrigerant pressure and temperature at several points in the refrigeration loop, as illustrated in Fig. 3. Since the residential split-type AC operated as a factory-integrated commercial unit, condenser fan current and standalone fan power were not measured separately. Therefore, the performance evaluation was based on overall system COP variation before and after integration with the desalination unit. The experiments employed a residential split-type AC unit (SHARP AH-A9BEY2, 1 PK), representing a typical household cooling system in tropical regions. The operating temperature range of 50–60 °C corresponded to practical condenser waste heat conditions during normal AC operation while remaining sufficiently low to minimise severe scaling formation.

The following expressions were used to calculate the performance of the vapour compression refrigeration system[42] ,process refer to Fig.3:

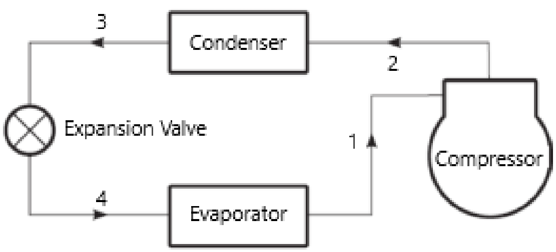

Fig. *3.* Schematic of the refrigeration loop

Compression process (process 1–2):

$$W_c = (h_2 - h_1) \quad (1)$$

Heat rejection process (process 2–3):

$$Q_c = (h_2 - h_3) \tag{2}$$

Throttling (process 3–4):

$$h_3 = h_4 \tag{3}$$

Heat absorption (process 1–4):

$$R_e = (h_1 - h_4) \tag{4}$$

Coefficient of performance (COP):

$$COP = \frac{R_e}{W_c} \tag{5}$$

3. Results and Discussion

The experiment evaluated evaporation and condensation behaviour using temperature and relative humidity measurements. As shown in Fig. 4a, the air temperature decreased for both NVG and VG configurations due to evaporative cooling, while Fig. 4b shows that smaller channel cross-sectional areas produced larger humidity fluctuations because of stronger airflow interaction. The relative humidity distribution supports the temperature and evaporation trends. As hot air from the AC condenser passed over the seawater surface, additional water vapour was generated, increasing the local relative humidity. However, RH did not increase uniformly because it depends not only on the amount of vapour added, but also on the local air temperature. Warmer air can hold more

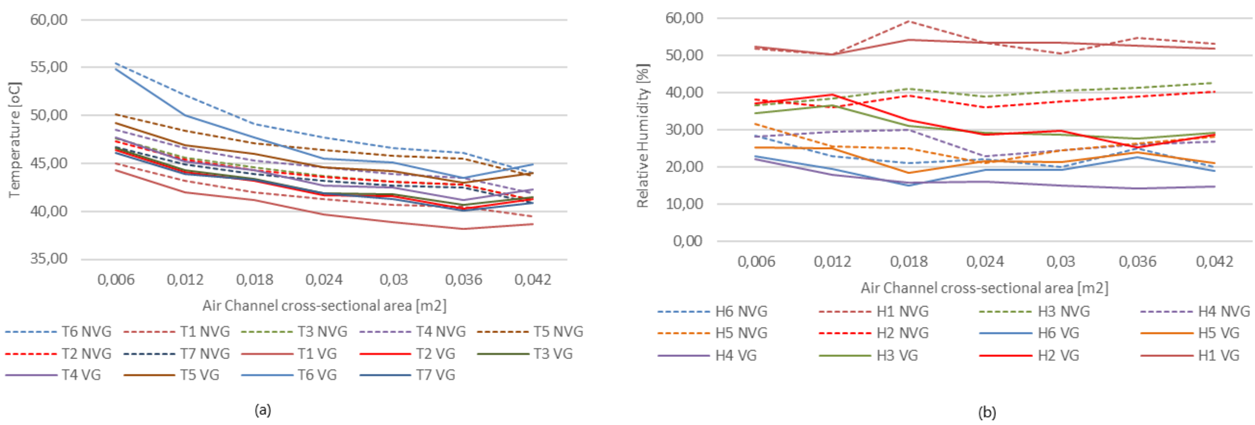

Fig. 4. Desalination unit temperature (a) and relative humidity (b)

moisture, [43] therefore, some positions near the condenser fan showed lower RH despite active evaporation. Smaller channel areas produced stronger airflow interaction and larger RH fluctuations, indicating more intensive vapour transport and mixing. In contrast, larger channel areas showed more uniform RH values because of lower airflow velocity and weaker local disturbance. The VG configuration further promoted local mixing, although the RH variation remained strongly governed by channel geometry and temperature distribution. The desalination unit reduced incoming hot-air temperature by approximately 6–11 °C.

Although the experiments were conducted under controlled laboratory conditions, ambient temperature and humidity are expected to influence evaporation driving force and condenser heat rejection in practical tropical environments. Higher ambient temperatures may enhance evaporation but simultaneously reduce condenser cooling effectiveness and AC COP, particularly in smaller channel areas with higher airflow resistance. Conversely, high ambient humidity may reduce the vapor pressure gradient and shift the optimal operating condition towards slightly larger channel cross-sectional areas with lower pressure losses.

Consistent with the observed temperature and humidity distributions, Fig. 5a shows that increasing the channel cross-sectional area consistently reduced evaporation for both NVG and VG

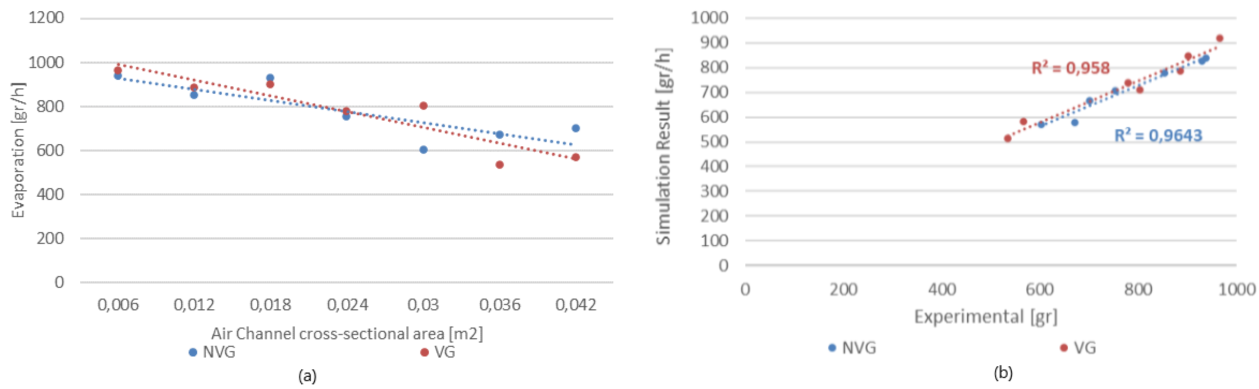

Fig. 5. Evaporation results for each channel cross-sectional area (a) and comparison of the experimental and simulation results (b)

configurations because larger areas decreased airflow velocity and convective heat and mass transfer.[28] Smaller areas generated higher airflow velocity and shear stress, thinning the boundary layer above the water surface and enhancing vapour diffusion. The VG configuration further increased evaporation by inducing longitudinal vortices that enhanced turbulence, airflow mixing, and boundary-layer disruption,[44,45] although channel geometry remained the dominant factor.

A comparison between the experimental and CFD results demonstrated strong agreement, with coefficients of determination of R^2 = 0.9643 and R^2 = 0.958 for NVG and VG configurations (Fig. 5b), respectively.[46,47] Average deviations remained within the accepted validation threshold, reaching 10% for NVG and 6% for VG,[48,49] confirming that the CFD model reliably predicts evaporation behaviour across different channel geometries. The produced freshwater had a TDS of approximately 71 ppm and a pH of 6.5, which remain within the acceptable ranges specified by WHO[50] and the Indonesian Ministry of Health regulations for clean water quality.[51] These results also indicate that seawater was not significantly carried over into the condensation section, since the seawater used in this study had a TDS of 31,710 ppm and a pH of 7.7, which are within the typical ranges for seawater, namely a TDS of approximately 29,000–39,000 ppm[52] and a pH ranging from 7.5 to 8.4.[53]

At the smallest channel cross-sectional area (0.006 m^2), the increased flow confinement produced higher pressure losses and reduced condenser airflow effectiveness. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions. Although the fan power and electrical current were not monitored separately from the AC system, the reduction in the overall AC COP indirectly reflects the increased aerodynamic resistance experienced by the condenser airflow under smaller channel geometries.

During operation, continuous evaporation and the addition of make-up seawater gradually increased salinity from approximately 35 ppt to nearly 55 ppt after 8 h. The higher salinity reduced water activity and saturation vapor pressure, slightly decreasing evaporation driving force.

Nevertheless, severe scaling was not observed on the heat exchanger because evaporation mainly occurred in the evaporator basin rather than on the heating surface. Small salt deposits gradually accumulated at the bottom of the basin, while moderate operating temperatures (50–60 °C), continuous circulation, and forced airflow helped suppress local supersaturation and scaling formation. However, long-term operation may still require periodic brine discharge or seawater replacement.

Since the residential split-type AC operated as a factory-integrated commercial system, the condenser fan current and standalone fan power were not monitored separately, AC operational performance was evaluated using the COP, calculated from Equations (1)–(5). Conventional residential AC systems generally exhibit COP values between 3.02 and 4.04 [54,55], while the baseline COP of the AC unit used in this study was 3.92. After integration with the desalination unit, smaller channel areas produced higher pressure losses, restricting condenser airflow and reducing heat rejection effectiveness, thereby lowering COP. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions.

As shown in Fig. 6, COP increased progressively with increasing channel cross-sectional area because larger channels reduced airflow resistance and pressure drop. However, evaporation and

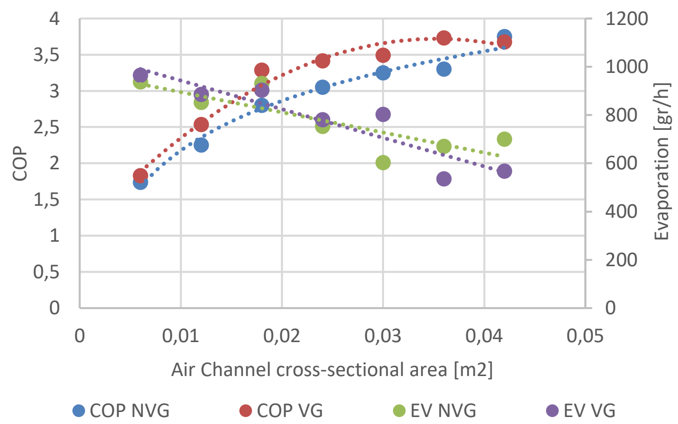

Fig. 6. COP of Split model AC compare with evaporation for each cross-sectional area

COP did not exhibit a direct cause–effect relationship; both responded independently to airflow characteristics induced by channel geometry. Smaller channel areas increased airflow velocity and evaporation, while the associated pressure losses simultaneously reduced condenser performance and COP. Thus, the observed changes in evaporation and COP were primarily governed by airflow velocity and pressure-drop effects rather than direct interaction between the two parameters.

A preliminary economic analysis showed that the system produced approximately 950–980 mL/h of freshwater (7.6–7.8 L during 8 h of operation). Based on the observed COP reduction from 3.92 to 3.02 and a cooling capacity of 2.64 kW, the additional electricity consumption was estimated at approximately 1.61 kWh per 8 h cycle, corresponding to an operational cost of about USD 0.13 or USD 0.017/L of freshwater produced. Although capital and maintenance costs were not included, the results indicate promising potential for low-cost household-scale freshwater production using readily available AC waste heat.

4. Conclusion

This study demonstrates that waste heat from residential split-type AC units can drive an evaporation–condensation desalination process. Increasing the channel cross-sectional area reduced air temperature by approximately 6–11 °C and improved AC performance by lowering pressure drop and enhancing heat rejection, although freshwater production decreased accordingly. The system produced approximately 950–980 mL/h of freshwater, indicating the potential to satisfy basic household drinking water requirements. A preliminary economic analysis estimated the additional operational cost at approximately USD 0.017/L of freshwater produced. Experimental–CFD validation showed strong agreement ($R^2 > 0.95$), with deviations of 6–10%, confirming the reliability of the numerical model. Smaller channel areas enhanced evaporation but reduced AC COP because of higher airflow resistance and pressure losses, whereas a channel area of 0.015–0.025 m² provided the best balance between freshwater production and AC efficiency.

Although the study was conducted under controlled conditions using a single AC configuration, the results demonstrate the feasibility of household-scale desalination using AC waste heat. Future work should investigate long-term operation, varying environmental conditions, and system scalability. While severe scaling was not observed on the heat exchanger surface, gradual salt accumulation occurred at the bottom of the evaporator basin during prolonged operation, indicating that periodic brine discharge, seawater replacement, or routine cleaning may be required for stable long-term performance.

Author Contributions

Dan Mugisidi: Conceptualization; Methodology; Investigation; Supervision; Formal analysis; Funding acquisition; Writing - original draft; Writing - review & editing. **Oktarina Heriyani:** Conceptualization; Software; Data curation; Investigation; Supervision; Project administration. **Rifky:** Methodology; Investigation; Validation; Formal analysis; Supervision; Writing - review & editing. **Widodo:** Conceptualization; Methodology; Software; Validation; Visualization. **Amir Khalid:** Conceptualization; Visualization; Writing - review & editing. **Ahmed Rahmani:** Conceptualization; Validation; Writing - review & editing

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Conflict of Interest Statement

The authors declare no conflicts of interest.

Data Avaibility Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

ORIGINAL RESEARCH

Sustainable Energy

Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat

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Abstract

Water scarcity remains a major global challenge, particularly in developing countries with limited freshwater access. At the same time, the increasing use of residential air-conditioning (AC) systems generates substantial low-grade waste heat that is typically rejected into the environment. This study investigates a household-scale evaporation–condensation desalination system driven by waste heat recovered from a residential split-type AC unit. The proposed system integrates vortex-generator-assisted airflow enhancement within a compact evaporation channel to intensify heat using channels with different cross-sectional areas under vortex-generator (VG) and non-vortex-generator (NVG) configurations. Air temperature, relative humidity, evaporation rate, seawater salinity, and AC coefficient of performance (COP) were measured, while computational fluid dynamics (CFD) simulations were performed to analyze airflow and evaporation behavior. The results showed that vortex generators enhanced airflow mixing and evaporation performance. Maximum freshwater production of approximately 950–980 mL/h was achieved at channel cross-sectional areas of 0.015–0.025 m^2. Although COP decreased from 3.92 to approximately 3.02 under the most restrictive channel configuration, the values remained within the typical residential AC operating range. The CFD predictions showed strong agreement with experiments, with $R^2 > 0.95$ and average deviations below 10%. A preliminary economic analysis estimated the operational cost at approximately USD 0.017/L of freshwater produced. The proposed system demonstrates promising potential for decentralized and energy-efficient household freshwater production using readily available AC waste heat.

KEYWORDS
air conditioning, CFD simulation, desalination, vortex generator, waste heat

1 | INTRODUCTION

Although water is a basic need for human life, freshwater resources, which represent only about 2.8% of total global water resources, are limited.[1] Moreover, a 15% increase in population may result in a water shortage of up to 40% of total water demand.[2,3] Water scarcity can trigger humanitarian, political, and social conflicts.[4] This challenge is particularly pronounced in many coastal and tropical developing regions, where limited freshwater resources and growing populations increase vulnerability to water shortages and present challenges in accessing clean water.[5–7]

Global warming, another critical issue, has intensified the use of air conditioning (AC) units in tropical regions.[8,9] During operation, AC units reject low-grade heat (50–80°C) into the environment without recovery,[10] thus constituting a widely available but underutilized thermal resource. In dense urban areas, the accumulation of waste heat from AC units can increase local ambient temperatures by up to 1°C,[11,12] thereby exacerbating the urban heat island effect. Recovering this waste heat therefore offers a dual benefit: improving energy utilization and mitigating localized thermal accumulation.

One potential approach to utilizing this waste heat is evaporation–condensation desalination, whereby hot air is directed over seawater to generate vapor that is subsequently condensed into freshwater. The use of waste heat from AC units as a thermal source can drive the desalination process while simultaneously reducing environmental thermal discharge and producing freshwater as a valuable by-product. Airflow over water surfaces has been shown to significantly enhance evaporation by increasing convective heat and mass transfer at the air–water interface[13] and influence distillation productivity in evaporation–condensation desalination systems.[14]

1.1 | Literature review of desalination using AC

Previous studies have investigated heat pumps, solar thermal systems, photovoltaic thermal (PV/T) systems, and AC-assisted desalination technologies, including multistage flash distillation (MSF), membrane distillation (MD), adsorption desalination (ADS), and humidification–dehumidification (HDH), to improve thermal efficiency and reduce energy consumption.[15–20] Although hybrid desalination systems driven by low-grade thermal energy have shown promising capability for improving freshwater productivity and energy,[21–23] many existing systems are designed for relatively large-scale applications and commonly require solar collectors, auxiliary heating systems, or complex thermal integration.

Recent studies have also explored the recovery of waste heat from residential AC systems for simultaneous cooling and freshwater production. Condenser waste heat from vapor–compression refrigeration systems has been reported to provide sufficient low-grade thermal energy for seawater heating and evaporation in HDH and membrane-based desalination systems.[24–27] Nevertheless, many proposed systems still depend on solar-assisted heating, evaporative condensers, multistage humidification arrangements, or additional thermal components, all of which increase complexity and installation cost.

Evaporation enhancement remains a key factor governing freshwater productivity because thermal desalination strongly depends on heat and mass transfer at the air–water interface. Previous studies have shown that improving airflow characteristics, turbulence intensity, and boundary-layer disruption significantly enhances evaporation and vapor transport.[28,29] Other enhancement techniques, including thin-film evaporation, wick structures, porous materials, and photothermal evaporation, have also demonstrated improved freshwater productivity.[30,31] Previous investigations further reported that lowering pressure above the water surface increases the driving force of evaporation due to higher vapor pressure at the liquid surface.[32]

Based on these considerations, the present study investigates a residential split-type AC waste-heat-driven desalination system combined with vortex-generator-assisted airflow enhancement. In contrast to many previous solar-driven or multi-component HDH desalination systems, the proposed configuration focuses on a compact household-scale arrangement utilizing existing residential AC infrastructure. Hot air rejected from the condenser is directed through an evaporation channel above the brine surface, while vortex generators intensify airflow mixing and turbulence near the air–water interface. Combined experimental investigation and CFD analysis were performed to evaluate evaporation behavior, freshwater production, and AC operational performance, thereby contributing to decentralized and energy-efficient desalination technology development.

1.2 | Statement of industrial relevance and novelty

This study is relevant to applications in which energy efficiency and resource recovery are increasingly important, such as heating, ventilation, and air conditioning (HVAC), desalination, and sustainable residential building. Residential AC units continuously discharge low-grade waste heat that is generally released without productive utilization. The proposed system demonstrates how this waste heat can drive a compact evaporation–condensation desalination process capable of producing freshwater at the household scale, particularly for coastal housing, tourism facilities, and small-island infrastructure.

Our previous study demonstrated that vortex generators significantly enhanced evaporation in AC-assisted desalination systems,[33] but the work was limited to numerical analysis without experimental validation or evaluation of system-level performance.

The novelty of the present study lies in its integration of vortex-generator-assisted airflow enhancement with a compact household-scale desalination system driven by residential split-type AC waste heat. In contrast to previous AC-assisted desalination studies that focused mainly on thermodynamic cycle integration or HDH configuration, this work emphasizes airflow-driven evaporation intensification through channel geometry modification and turbulence enhancement. The study further evaluates the trade-off between evaporation enhancement and AC operational performance under different channel cross-sectional areas using combined CFD simulations and experimental validation.

This study therefore aims to design, analyze, and validate a household-scale desalination unit utilizing waste heat from a residential split-type AC system. The effects of channel geometry and vortex generators on airflow behavior, evaporation enhancement, air temperature reduction, and AC coefficient of performance (COP) were systematically evaluated using experimental measurements and CFD simulations.

2 | MATERIALS AND METHODS

2.1 | Description of the desalination unit

The desalination unit (DU) was integrated with a residential AC system to recover condenser waste heat for freshwater production through evaporation–condensation processes. In this system, saline

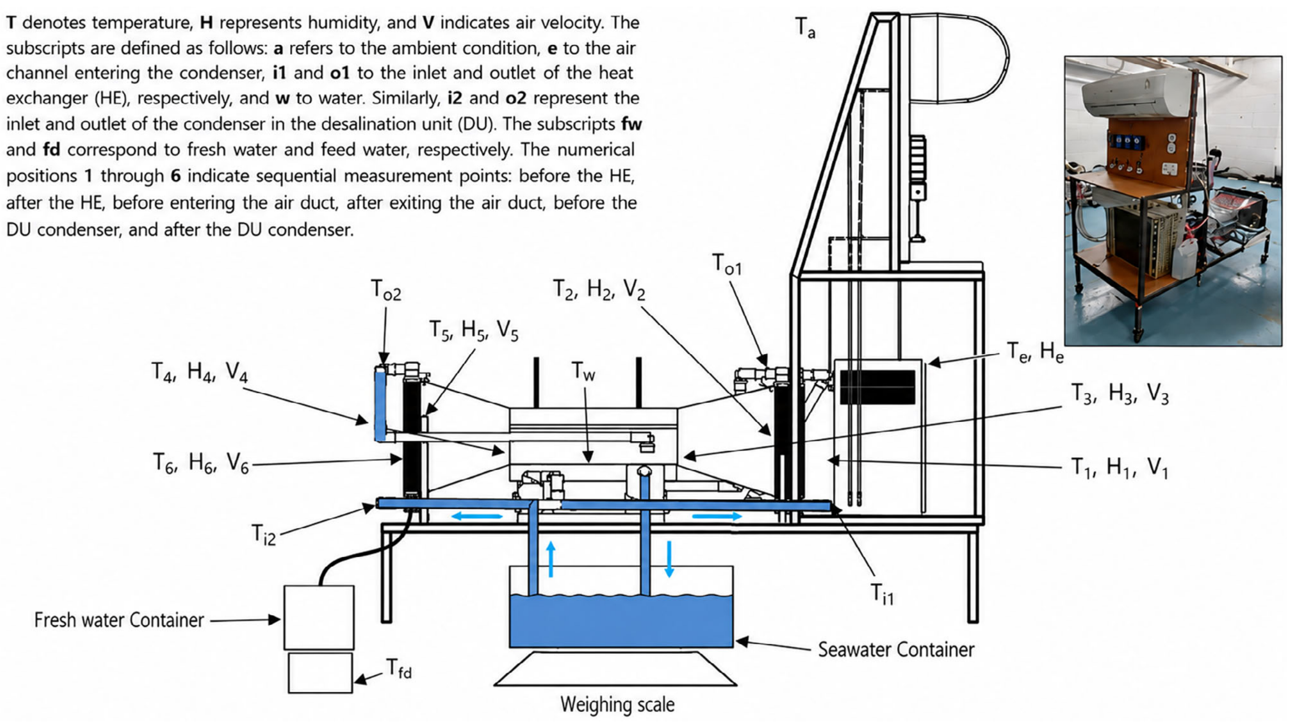


FIGURE 1 Experimental rig.

feedwater is heated using AC waste heat to generate water vapor, which is then condensed on a cooler surface to produce distilled water.

Natural seawater with an initial salinity of approximately 35 ppt was placed inside an evaporator chamber and heated indirectly by a heat exchanger containing freshwater circulated from the AC condenser waste heat loop. The increased seawater temperature promoted evaporation, and the generated vapor subsequently condensed on a cooler surface to produce freshwater. In addition, airflow from the AC condenser was directed through a channel above the water surface to enhance evaporation through forced convection by increasing airflow velocity, turbulence intensity, and vapor transport near the air–water interface. The airflow channel was configured with cross-sectional areas of 0.006, 0.012, 0.018, 0.024, 0.030, 0.036, and 0.042 m^2, each tested with and without vortex generators (VG and NVG). The vortex generators enhanced airflow mixing and boundary-layer disruption, thereby improving heat and mass transfer during evaporation. The experimental setup is shown in Figure 1.

2.2 | Experimental setup and procedures

The data in this study were obtained experimentally and compared using CFD simulation. The instruments used are presented in Table 1.

To enhance airflow mixing and evaporation performance inside the channel, a delta-wing vortex generator (Figure 2a) was selected because it efficiently directs airflow and generates strong vortices

TABLE 1 Experimental instruments.

Device	Range	Accuracy
Thermocouples PT100	−50–110°C	±0.1°C
Weighing scales	0–20 kg	±0.05%
Humidity meter	10%–99%	±1%
Anemometer GM-816	0–30 m/s	±5%
Pressure gauge class 1,6	0–550 psi	±1.6%
Pressure meter PCE-PDA 1L	±2 kPa	±0.5%
Salinity refractometer ATC	0–100 ppt	±1 ppt

with relatively low flow resistance.[34] The ratio of channel height to vortex generator height was set at 0.47 to balance vortex formation and flow obstruction, thereby enhancing mixing while limiting aerodynamic losses.[35,36] In addition, a spacing-to-channel-length ratio of 0.18 was applied to sustain vortex interaction and turbulence,[37] while a 45° attack angle was selected to optimize vortex strength, flow attachment, and thermo-hydraulic performance.[38] The simulated evaporation region is indicated by the red arrows in Figure 2b, while areas outside this region were excluded from the model scope.

The results were validated using CFD simulations performed with Cradle CFD based on its continuity, momentum, and energy equations. Detailed governing equations and numerical settings are provided in Appendix S1.

An octagonal mesh was employed because it provides better grid quality and smoother element transition in complex geometries

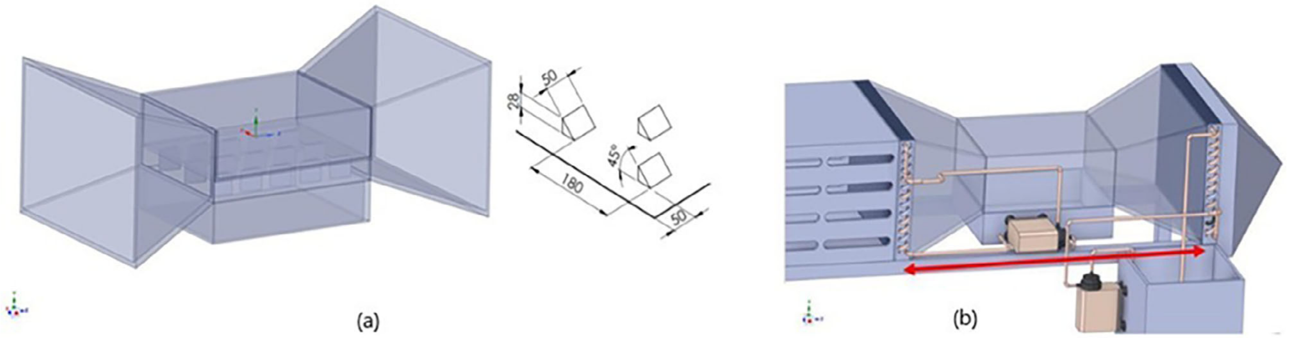


FIGURE 2 Vortex generator (a) and evaporation zone (b).

TABLE 2 Mesh independence study.

No.	No. of elements	Evaporation rate (kg/s m^3)	Difference (%)
1	141,567	0.003998	–
2	221,325	0.004489	0.12
3	532,624	0.004623	0.03
4	821,653	0.004623	0.00
5	1,036,877	0.004623	0.00

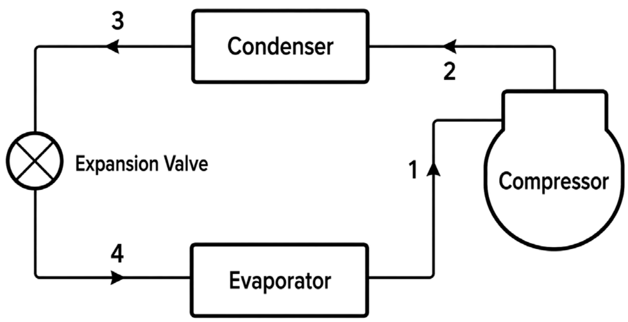


FIGURE 3 Schematic of the refrigeration loop.

compared with conventional triangular or quadrilateral meshes, thereby improving numerical stability and simulation accuracy. A mesh size of 0.05 with a refined region of 0.02 was used, resulting in 532,624 elements based on the mesh independence study (see Table 2).

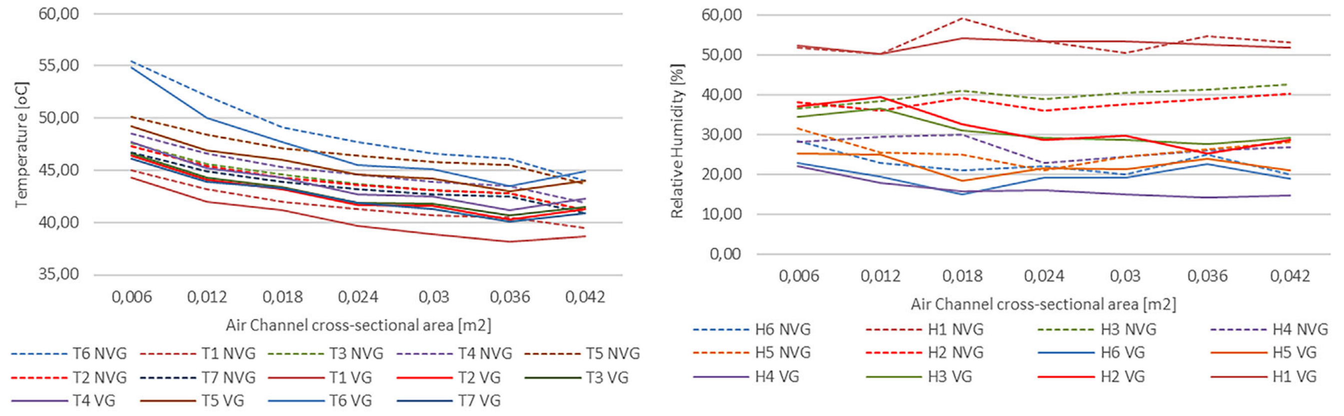
The mesh independence study was conducted using five mesh densities. The evaporation rate became constant beyond 532,624 elements, indicating that further refinement would have a negligible influence on the simulation results. A relative deviation below 10% was considered acceptable for establishing mesh independence.[39–41]

The simulations focused on evaporation dynamics inside the airflow channel downstream of the AC condenser, where inlet air temperatures reached approximately 55°C. The channel cross-sectional area was varied from 0.042 to 0.006 m^2 to systematically evaluate the effect of airflow confinement on evaporation performance and AC operation. The maximum area of 0.042 m^2 was selected to represent a relatively low-confinement condition, corresponding to approximately two-thirds of the estimated effective condenser fan flow area. The area was then gradually reduced to 0.006 m^2 to increase airflow velocity over the seawater surface and intensify convective heat and mass transfer. However, reducing the channel area also increased pressure drop and airflow resistance, allowing the study to identify the trade-off between evaporation enhancement and AC COP reduction.

Because the desalination unit was directly integrated with the AC system, the operational parameters were selected to represent practical residential operating conditions while evaluating the trade-off between evaporation enhancement and AC performance. Smaller channel areas increased airflow velocity and evaporation intensity, but also increased pressure losses and reduced condenser heat rejection effectiveness, thereby lowering AC COP. Conversely, larger channel areas reduced pressure losses but weakened evaporation enhancement. The vortex generator geometry was adopted from previous thermo-fluid studies[33] to enhance airflow mixing and boundary-layer disruption with minimal aerodynamic penalty.

AC performance was evaluated by measuring refrigerant pressure and temperature at several points in the refrigeration loop, as illustrated in Figure 3. Since the residential split-type AC operated as a factory-integrated commercial unit, condenser fan current and standalone fan power were not measured separately. Therefore, the performance evaluation was based on overall system COP variation before and after integration with the desalination unit. The experiments employed a residential split-type AC unit (SHARP AH-A9BEY2, 1 PK), representing a typical household cooling system in tropical regions. The operating temperature range of 50–60°C corresponded to practical condenser waste heat conditions during normal AC operation while remaining sufficiently low to minimize severe scaling formation.

The following expressions were used to calculate the performance of the vapor compression refrigeration system,[42] the process refers to Figure 3:



(a) (b)

FIGURE 4 Desalination unit temperature (a) and relative humidity (b).

Compression process (processes 1–2):

$$W_c = (h_2 - h_1) \quad (1)$$

Heat rejection process (processes 2–3):

$$Q_c = (h_2 - h_3) \quad (2)$$

Throttling (processes 3–4):

$$h_3 = h_4 \quad (3)$$

Heat absorption (processes 1–4):

$$R_e = (h_1 - h_4) \quad (4)$$

Coefficient of performance (COP):

$$COP = \frac{R_e}{W_c} \quad (5)$$

3 | RESULTS AND DISCUSSION

The experiment evaluated evaporation and condensation behavior using temperature and relative humidity measurements. As shown in Figure 4a, the air temperature decreased for both NVG and VG configurations due to evaporative cooling, while Figure 4b shows that smaller channel cross-sectional areas produced larger humidity fluctuations because of stronger airflow interaction. The relative humidity distribution supports the temperature and evaporation trends. As hot air from the AC condenser passed over the seawater surface, additional water vapor was generated, increasing the local relative humidity. However, RH did not increase uniformly because it depends not only on the amount of vapor added but also on the local air temperature. Warmer air can hold more moisture,[43] therefore, some positions near the condenser fan showed lower RH despite active evaporation. Smaller channel areas produced stronger airflow interaction and larger RH fluctuations, indicating more intensive vapor transport and mixing. In contrast, larger channel areas showed more uniform RH values because of lower airflow velocity and weaker local disturbance. The VG configuration further promoted local mixing, although the RH variation remained strongly governed by channel geometry and temperature distribution. The desalination unit reduced incoming hot-air temperature by approximately 6–11°C.

Although the experiments were conducted under controlled laboratory conditions, ambient temperature and humidity are expected to influence evaporation driving force and condenser heat rejection in practical tropical environments. Higher ambient temperatures may enhance evaporation but simultaneously reduce condenser cooling effectiveness and AC COP, particularly in smaller channel areas with higher airflow resistance. Conversely, high ambient humidity may reduce the vapor pressure gradient and shift the optimal operating condition towards slightly larger channel cross-sectional areas with lower pressure losses.

Consistent with the observed temperature and humidity distributions, Figure 5a shows that increasing the channel cross-sectional area consistently reduced evaporation for both NVG and VG configurations because larger areas decreased airflow velocity and convective heat and mass transfer.[28] Smaller areas generated higher airflow velocity and shear stress, thinning the boundary layer above the water surface and enhancing vapor diffusion. The VG configuration further increased evaporation by inducing longitudinal vortices that enhanced turbulence, airflow mixing, and boundary-layer disruption,[44,45] although channel geometry remained the dominant factor.

A comparison between the experimental and CFD results demonstrated strong agreement, with coefficients of determination of $R^2 = 0.9643$ and $R^2 = 0.958$ for NVG and VG configurations (Figure 5b), respectively.[46,47] Average deviations remained within the accepted validation threshold, reaching 10% for NVG and 6% for VG,[48,49] confirming that the CFD model reliably predicts evaporation behavior across different channel geometries. The produced

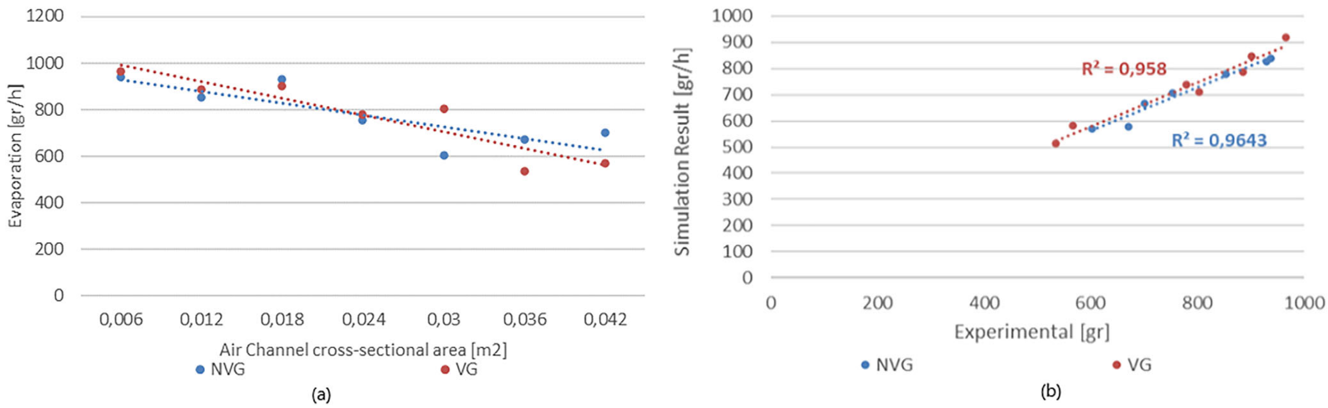


FIGURE 5 Evaporation results for each channel cross-sectional area (a) and comparison of the experimental and simulation results (b).

freshwater had a TDS of approximately 71 ppm and a pH of 6.5, which remain within the acceptable ranges specified by WHO[50] and the Indonesian Ministry of Health regulations for clean water quality.[51] These results also indicate that seawater was not significantly carried over into the condensation section, since the seawater used in this study had a TDS of 31,710 ppm and a pH of 7.7, which are within the typical ranges for seawater, namely a TDS of approximately 29,000–39,000 ppm[52] and a pH ranging from 7.5 to 8.4.[53]

At the smallest channel cross-sectional area (0.006 m^2), the increased flow confinement produced higher pressure losses and reduced condenser airflow effectiveness. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions. Although the fan power and electrical current were not monitored separately from the AC system, the reduction in the overall AC COP indirectly reflects the increased aerodynamic resistance experienced by the condenser airflow under smaller channel geometries.

During operation, continuous evaporation and the addition of make-up seawater gradually increased salinity from approximately 35 ppt to nearly 55 ppt after 8 h. The higher salinity reduced water activity and saturation vapor pressure, slightly decreasing the evaporation driving force. Nevertheless, severe scaling was not observed on the heat exchanger because evaporation mainly occurred in the evaporator basin rather than on the heating surface. Small salt deposits gradually accumulated at the bottom of the basin, while moderate operating temperatures (50–60°C), continuous circulation, and forced airflow helped suppress local supersaturation and scaling formation. However, long-term operation may still require periodic brine discharge or seawater replacement.

Since the residential split-type AC operated as a factory-integrated commercial system, the condenser fan current and standalone fan power were not monitored separately. AC operational performance was evaluated using the COP calculated from Equations (1)–(5). Conventional residential AC systems generally exhibit COP values between 3.02 and 4.04,[54,55] while the baseline COP of the AC unit used in this study was 3.92. After integration with the desalination unit, smaller channel areas produced higher pressure losses, restricting condenser airflow and reducing heat rejection effectiveness, thereby lowering

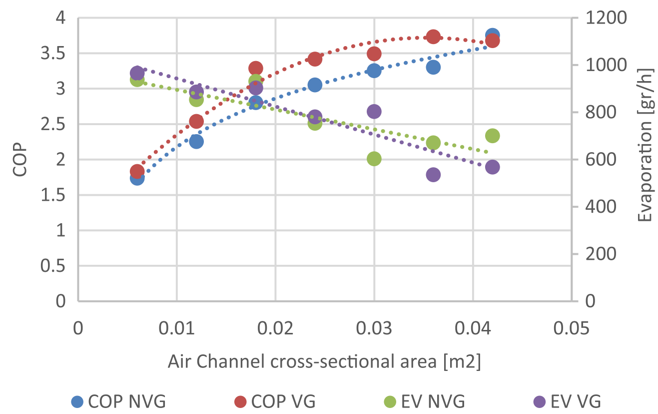


FIGURE 6 COP of split-type AC compared with evaporation for each cross-sectional area.

COP. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions.

As shown in Figure 6, COP increased progressively with increasing channel cross-sectional area because larger channels reduced airflow resistance and pressure drop. However, evaporation and COP did not exhibit a direct cause–effect relationship; both responded independently to airflow characteristics induced by channel geometry. Smaller channel areas increased airflow velocity and evaporation, while the associated pressure losses simultaneously reduced condenser performance and COP. Thus, the observed changes in evaporation and COP were primarily governed by airflow velocity and pressure-drop effects rather than by direct interaction between the two parameters.

A preliminary economic analysis showed that the system produced approximately 950–980 mL/h of freshwater (7.6–7.8 L during 8 h of operation). Based on the observed COP reduction from 3.92 to 3.02 and a cooling capacity of 2.64 kW, the additional electricity consumption was estimated at approximately 1.61 kWh per 8 h cycle, corresponding to an operational cost of about USD 0.13 or USD 0.017/L of freshwater produced. Although capital and maintenance costs were not included, the results indicate promising potential for low-cost household-scale freshwater production using readily available AC waste heat.

4 | CONCLUSION

This study demonstrates that waste heat from residential split-type AC units can drive an evaporation–condensation desalination process. Increasing the channel cross-sectional area reduced air temperature by approximately 6–11°C and improved AC performance by lowering pressure drop and enhancing heat rejection, although freshwater production decreased accordingly. The system produced approximately 950–980 mL/h of freshwater, indicating the potential to satisfy basic household drinking water requirements. A preliminary economic analysis estimated the additional operational cost at approximately USD 0.017/L of freshwater produced. Experimental–CFD validation showed strong agreement ($R^2 > 0.95$), with deviations of 6%–10%, confirming the reliability of the numerical model. Smaller channel areas enhanced evaporation but reduced AC COP because of higher airflow resistance and pressure losses, whereas a channel area of 0.015–0.025 m^2 provided the best balance between freshwater production and AC efficiency.

Although the study was conducted under controlled conditions using a single AC configuration, the results demonstrate the feasibility of household-scale desalination using AC waste heat. Future work should investigate long-term operation, varying environmental conditions, and system scalability. While severe scaling was not observed on the heat exchanger surface, gradual salt accumulation occurred at the bottom of the evaporator basin during prolonged operation, indicating that periodic brine discharge, seawater replacement, or routine cleaning may be required for stable long-term performance.

AUTHOR CONTRIBUTIONS

Dan Mugisidi: Conceptualization; writing – review and editing; investigation; methodology; writing – original draft; formal analysis; funding acquisition; supervision. **Oktarina Heriyani:** Conceptualization; investigation; software; data curation; project administration; supervision. Conceptualization; investigation; data curation; formal analysis; supervision. **Amir Khalid:** Writing – review and editing; visualization; conceptualization. Conceptualization; visualization; validation; software; writing – review and editing. **Ahmed Rahmani:** Writing – review and editing; validation; conceptualization.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat

Dan Mugisidi (GB)

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ORIGINAL RESEARCH

Sustainable Energy

ENVIRONMENTAL PROGRESS & SUSTAINABLE ENERGY

Airflow-enhanced evaporation–condensation seawater desalination using residential air conditioner waste heat

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Abstract

Water scarcity remains a major global challenge, particularly in developing countries with limited freshwater access. At the same time, the increasing use of residential air-conditioning (AC) systems generates substantial low-grade waste heat that is typically rejected into the environment. This study investigates a household-scale evaporation–condensation desalination system driven by waste heat recovered from a residential split-type AC unit. The proposed system integrates vortex-generator-assisted airflow enhancement within a compact evaporation channel to intensify heat using channels with different cross-sectional areas under vortex-generator (VG) and non-vortex-generator (NVG) configurations. Air temperature, relative humidity, evaporation rate, seawater salinity, and AC coefficient of performance (COP) were measured, while computational fluid dynamics (CFD) simulations were performed to analyze airflow and evaporation behavior. The results showed that vortex generators enhanced airflow mixing and evaporation performance. Maximum freshwater production of approximately 950–980 mL/h was achieved at channel cross-sectional areas of 0.015–0.025 m^2. Although COP decreased from 3.92 to approximately 3.02 under the most restrictive channel configuration, the values remained within the typical residential AC operating range. The CFD predictions showed strong agreement with experiments, with $R^2 > 0.95$ and average deviations below 10%. A preliminary economic analysis estimated the operational cost at approximately USD 0.017/L of freshwater produced. The proposed system demonstrates promising potential for decentralized and energy-efficient household freshwater production using readily available AC waste heat.

KEYWORDS
air conditioning, CFD simulation, desalination, vortex generator, waste heat

1 | INTRODUCTION

Although water is a basic need for human life, freshwater resources, which represent only about 2.8% of total global water resources, are limited.[1] Moreover, a 15% increase in population may result in a water shortage of up to 40% of total water demand.[2,3] Water scarcity can trigger humanitarian, political, and social conflicts.[4] This challenge is particularly pronounced in many coastal and tropical developing regions, where limited freshwater resources and growing populations increase vulnerability to water shortages and present challenges in accessing clean water.[5–7]

Global warming, another critical issue, has intensified the use of air conditioning (AC) units in tropical regions.[8,9] During operation, AC units reject low-grade heat (50–80°C) into the environment without recovery,[10] thus constituting a widely available but underutilized thermal resource. In dense urban areas, the accumulation of waste heat from AC units can increase local ambient temperatures by up to 1°C,[11,12] thereby exacerbating the urban heat island effect. Recovering this waste heat therefore offers a dual benefit: improving energy utilization and mitigating localized thermal accumulation.

One potential approach to utilizing this waste heat is evaporation–condensation desalination, whereby hot air is directed over seawater to generate vapor that is subsequently condensed into freshwater. The use of waste heat from AC units as a thermal source can drive the desalination process while simultaneously reducing environmental thermal discharge and producing freshwater as a valuable by-product. Airflow over water surfaces has been shown to significantly enhance evaporation by increasing convective heat and mass transfer at the air–water interface[13] and influence distillation productivity in evaporation–condensation desalination systems.[14]

1.1 | Literature review of desalination using AC

Previous studies have investigated heat pumps, solar thermal systems, photovoltaic thermal (PV/T) systems, and AC-assisted desalination technologies, including multistage flash distillation (MSF), membrane distillation (MD), adsorption desalination (ADS), and humidification–dehumidification (HDH), to improve thermal efficiency and reduce energy consumption.[15–20] Although hybrid desalination systems driven by low-grade thermal energy have shown promising capability for improving freshwater productivity and energy,[21–23] many existing systems are designed for relatively large-scale applications and commonly require solar collectors, auxiliary heating systems, or complex thermal integration.

Recent studies have also explored the recovery of waste heat from residential AC systems for simultaneous cooling and freshwater production. Condenser waste heat from vapor–compression refrigeration systems has been reported to provide sufficient low-grade thermal energy for seawater heating and evaporation in HDH and membrane-based desalination systems.[24–27] Nevertheless, many proposed systems still depend on solar-assisted heating, evaporative condensers, multi-stage humidification arrangements, or additional thermal components, all of which increase complexity and installation cost.

Evaporation enhancement remains a key factor governing freshwater productivity because thermal desalination strongly depends on heat and mass transfer at the air–water interface. Previous studies have shown that improving airflow characteristics, turbulence intensity, and boundary-layer disruption significantly enhances evaporation and vapor transport.[28,29] Other enhancement techniques, including thin-film evaporation, wick structures, porous materials, and photothermal evaporation, have also demonstrated improved freshwater productivity.[30,31] Previous investigations further reported that lowering pressure above the water surface increases the driving force of evaporation due to higher vapor pressure at the liquid surface.[32]

Based on these considerations, the present study investigates a residential split-type AC waste-heat-driven desalination system combined with vortex-generator-assisted airflow enhancement. In contrast to many previous solar-driven or multi-component HDH desalination systems, the proposed configuration focuses on a compact household-scale arrangement utilizing existing residential AC infrastructure. Hot air rejected from the condenser is directed through an evaporation channel above the brine surface, while vortex generators intensify airflow mixing and turbulence near the air–water interface. Combined experimental investigation and CFD analysis were performed to evaluate evaporation behavior, freshwater production, and AC operational performance, thereby contributing to decentralized and energy-efficient desalination technology development.

1.2 | Statement of industrial relevance and novelty

This study is relevant to applications in which energy efficiency and resource recovery are increasingly important, such as heating, ventilation, and air conditioning (HVAC), desalination, and sustainable residential building. Residential AC units continuously discharge low-grade waste heat that is generally released without productive utilization. The proposed system demonstrates how this waste heat can drive a compact evaporation–condensation desalination process capable of producing freshwater at the household scale, particularly for coastal housing, tourism facilities, and small-island infrastructure.

Our previous study demonstrated that vortex generators significantly enhanced evaporation in AC-assisted desalination systems,[33] but the work was limited to numerical analysis without experimental validation or evaluation of system-level performance.

The novelty of the present study lies in its integration of vortex-generator-assisted airflow enhancement with a compact household-scale desalination system driven by residential split-type AC waste heat. In contrast to previous AC-assisted desalination studies that focused mainly on thermodynamic cycle integration or HDH configuration, this work emphasizes airflow-driven evaporation intensification through channel geometry modification and turbulence enhancement. The study further evaluates the trade-off between evaporation enhancement and AC operational performance under different channel cross-sectional areas using combined CFD simulations and experimental validation.

This study therefore aims to design, analyze, and validate a household-scale desalination unit utilizing waste heat from a residential split-type AC system. The effects of channel geometry and vortex generators on airflow behavior, evaporation enhancement, air temperature reduction, and AC coefficient of performance (COP) were systematically evaluated using experimental measurements and CFD simulations.

2 | MATERIALS AND METHODS

2.1 | Description of the desalination unit

The desalination unit (DU) was integrated with a residential AC system to recover condenser waste heat for freshwater production through evaporation–condensation processes. In this system, saline

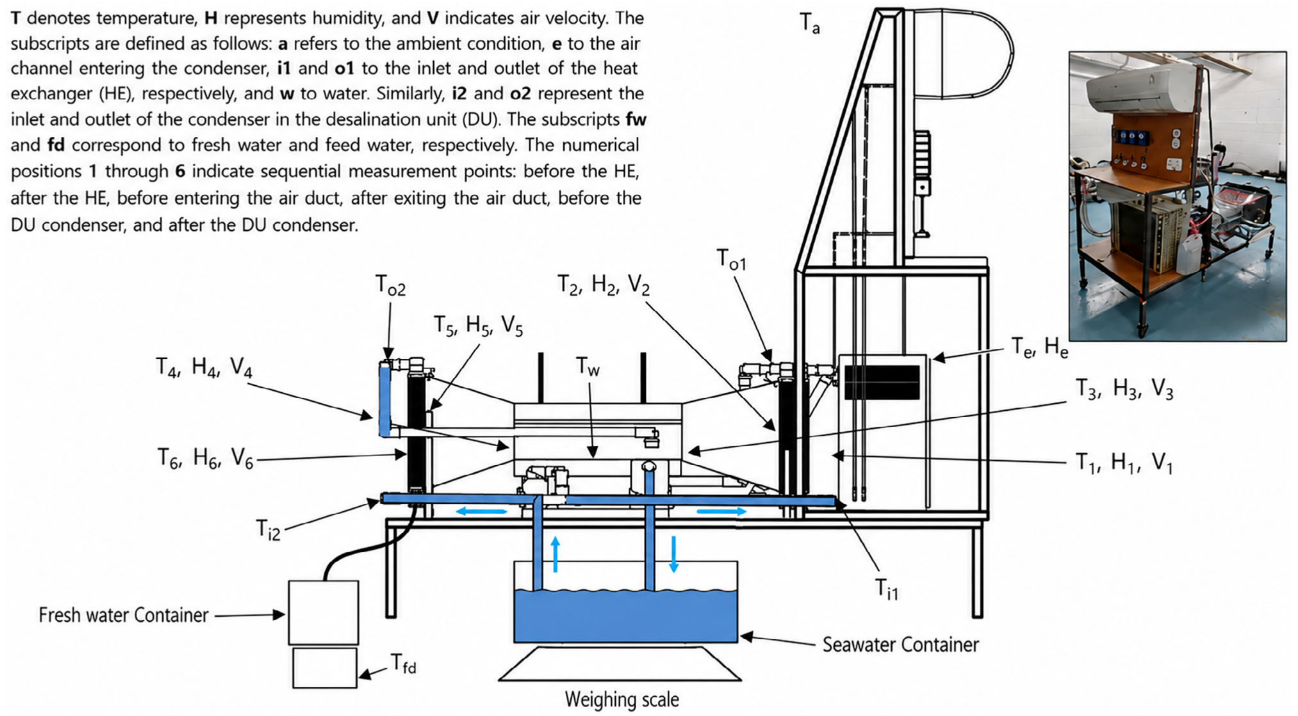


FIGURE 1 Experimental rig.

feedwater is heated using AC waste heat to generate water vapor, which is then condensed on a cooler surface to produce distilled water.

Natural seawater with an initial salinity of approximately 35 ppt was placed inside an evaporator chamber and heated indirectly by a heat exchanger containing freshwater circulated from the AC condenser waste heat loop. The increased seawater temperature promoted evaporation, and the generated vapor subsequently condensed on a cooler surface to produce freshwater. In addition, airflow from the AC condenser was directed through a channel above the water surface to enhance evaporation through forced convection by increasing airflow velocity, turbulence intensity, and vapor transport near the air–water interface. The airflow channel was configured with cross-sectional areas of 0.006, 0.012, 0.018, 0.024, 0.030, 0.036, and 0.042 m^2, each tested with and without vortex generators (VG and NVG). The vortex generators enhanced airflow mixing and boundary-layer disruption, thereby improving heat and mass transfer during evaporation. The experimental setup is shown in Figure 1.

2.2 | Experimental setup and procedures

The data in this study were obtained experimentally and compared using CFD simulation. The instruments used are presented in Table 1.

To enhance airflow mixing and evaporation performance inside the channel, a delta-wing vortex generator (Figure 2a) was selected because it efficiently directs airflow and generates strong vortices with relatively low flow resistance.[34] The ratio of channel height to vortex generator height was set at 0.47 to balance vortex formation and flow obstruction, thereby enhancing mixing while limiting aerodynamic losses.[35,36] In addition, a spacing-to-channel-length ratio of 0.18 was applied to sustain vortex interaction and turbulence,[37] while a 45° attack angle was selected to optimize vortex strength, flow attachment, and thermo-hydraulic performance.[38] The simulated evaporation region is indicated by the red arrows in Figure 2b, while areas outside this region were excluded from the model scope.

The results were validated using CFD simulations performed with Cradle CFD based on its continuity, momentum, and energy equations. Detailed governing equations and numerical settings are provided in Appendix S1.

An octagonal mesh was employed because it provides better grid quality and smoother element transition in complex geometries

TABLE 1 Experimental instruments.

Device	Range	Accuracy
Thermocouples PT100	−50–110°C	±0.1°C
Weighing scales	0–20 kg	±0.05%
Humidity meter	10%–99%	±1%
Anemometer GM-816	0–30 m/s	±5%
Pressure gauge class 1,6	0–550 psi	±1.6%
Pressure meter PCE-PDA 1L	±2 kPa	±0.5%
Salinity refractometer ATC	0–100 ppt	±1 ppt

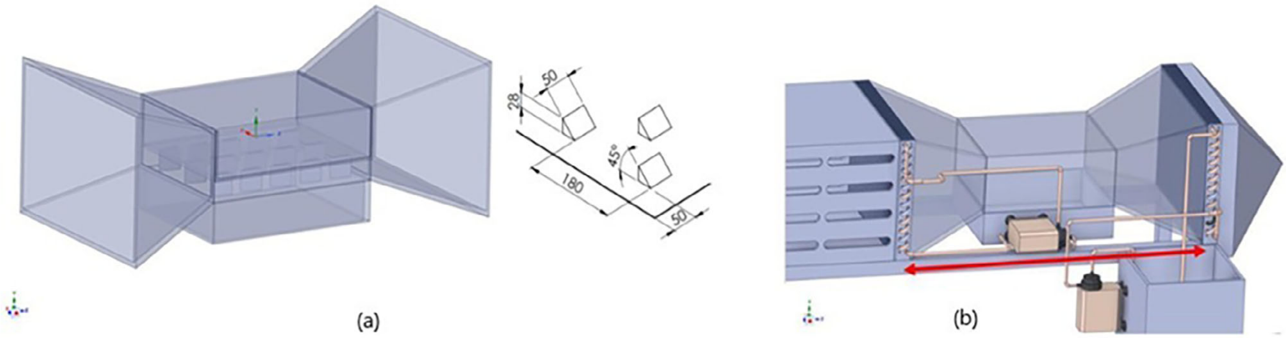


FIGURE 2 Vortex generator (a) and evaporation zone (b).

TABLE 2 Mesh independence study.

No.	No. of elements	Evaporation rate (kg/s m^3)	Difference (%)
1	141,567	0.003998	–
2	221,325	0.004489	0.12
3	532,624	0.004623	0.03
4	821,653	0.004623	0.00
5	1,036,877	0.004623	0.00

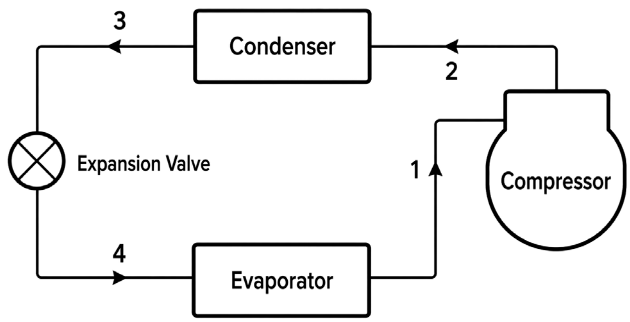


FIGURE 3 Schematic of the refrigeration loop.

compared with conventional triangular or quadrilateral meshes, thereby improving numerical stability and simulation accuracy. A mesh size of 0.05 with a refined region of 0.02 was used, resulting in 532,624 elements based on the mesh independence study (see Table 2).

The mesh independence study was conducted using five mesh densities. The evaporation rate became constant beyond 532,624 elements, indicating that further refinement would have a negligible influence on the simulation results. A relative deviation below 10% was considered acceptable for establishing mesh independence.[39–41]

The simulations focused on evaporation dynamics inside the airflow channel downstream of the AC condenser, where inlet air temperatures reached approximately 55°C. The channel cross-sectional area was varied from 0.042 to 0.006 m^2 to systematically evaluate the effect of airflow confinement on evaporation performance and AC operation. The maximum area of 0.042 m^2 was selected to represent a relatively low-confinement condition, corresponding to approximately two-thirds of the estimated effective condenser fan flow area. The area was then gradually reduced to 0.006 m^2 to increase airflow velocity over the seawater surface and intensify convective heat and mass transfer. However, reducing the channel area also increased pressure drop and airflow resistance, allowing the study to identify the trade-off between evaporation enhancement and AC COP reduction.

Because the desalination unit was directly integrated with the AC system, the operational parameters were selected to represent practical residential operating conditions while evaluating the trade-off between evaporation enhancement and AC performance. Smaller channel areas increased airflow velocity and evaporation intensity, but also increased pressure losses and reduced condenser heat rejection effectiveness, thereby lowering AC COP. Conversely, larger channel areas reduced pressure losses but weakened evaporation enhancement. The vortex generator geometry was adopted from previous thermo-fluid studies[33] to enhance airflow mixing and boundary-layer disruption with minimal aerodynamic penalty.

AC performance was evaluated by measuring refrigerant pressure and temperature at several points in the refrigeration loop, as illustrated in Figure 3. Since the residential split-type AC operated as a factory-integrated commercial unit, condenser fan current and standalone fan power were not measured separately. Therefore, the performance evaluation was based on overall system COP variation before and after integration with the desalination unit. The experiments employed a residential split-type AC unit (SHARP AH-A9BEY2, 1 PK), representing a typical household cooling system in tropical regions. The operating temperature range of 50–60°C corresponded to practical condenser waste heat conditions during normal AC operation while remaining sufficiently low to minimize severe scaling formation.

The following expressions were used to calculate the performance of the vapor compression refrigeration system,[42] the process refers to Figure 3:

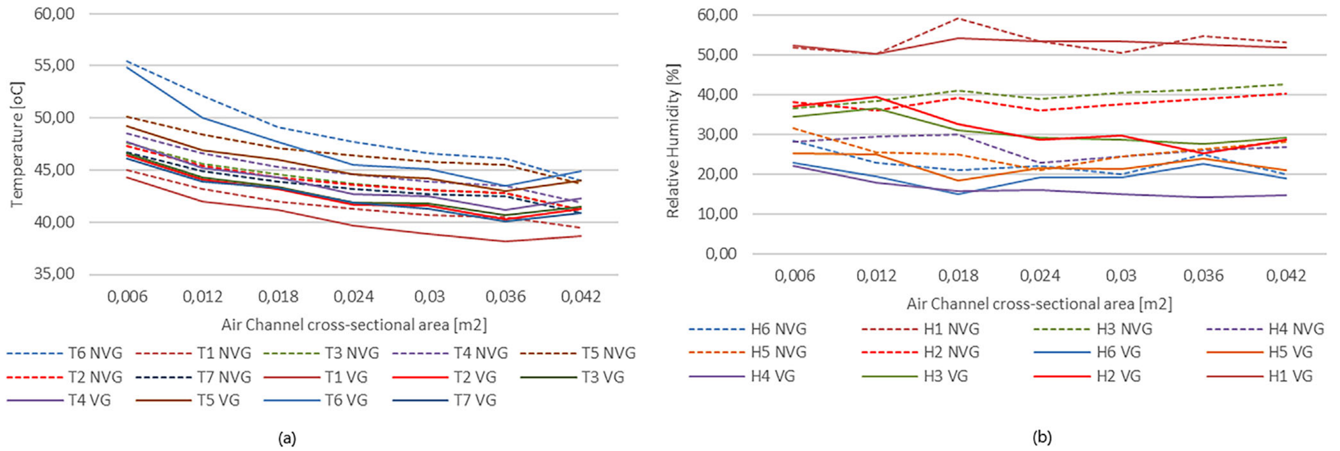


FIGURE 4 Desalination unit temperature (a) and relative humidity (b).

Compression process (processes 1–2):

$$W_c = (h_2 - h_1) \tag{1}$$

Heat rejection process (processes 2–3):

$$Q_c = (h_2 - h_3) \tag{2}$$

Throttling (processes 3–4):

$$h_3 = h_4 \tag{3}$$

Heat absorption (processes 1–4):

$$R_e = (h_1 - h_4) \tag{4}$$

Coefficient of performance (COP):

$$\mathrm{COP} = \frac{R_e}{W_c} \tag{5}$$

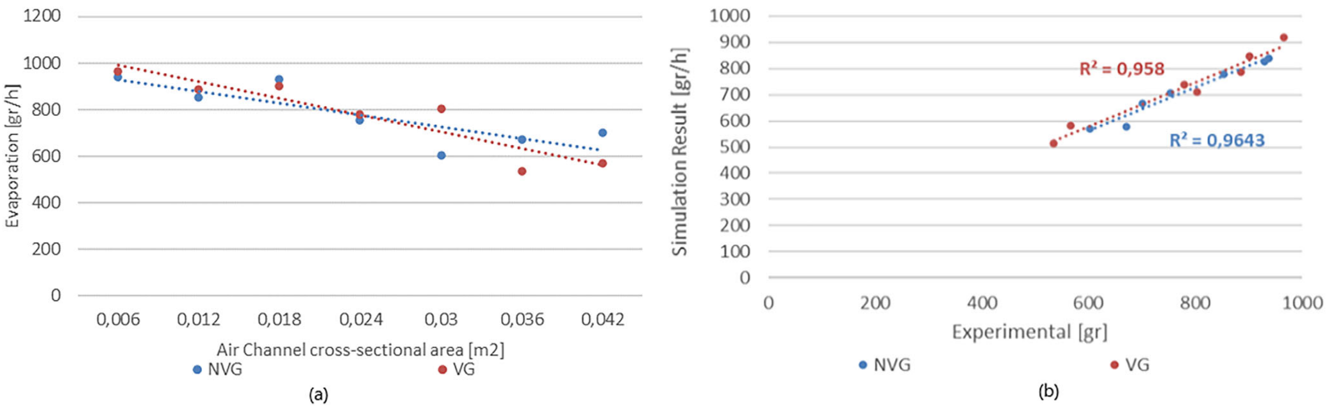
3 | RESULTS AND DISCUSSION

The experiment evaluated evaporation and condensation behavior using temperature and relative humidity measurements. As shown in Figure 4a, the air temperature decreased for both NVG and VG configurations due to evaporative cooling, while Figure 4b shows that smaller channel cross-sectional areas produced larger humidity fluctuations because of stronger airflow interaction. The relative humidity distribution supports the temperature and evaporation trends. As hot air from the AC condenser passed over the seawater surface, additional water vapor was generated, increasing the local relative humidity. However, RH did not increase uniformly because it depends not only on the amount of vapor added but also on the local air temperature. Warmer air can hold more moisture,[43] therefore, some positions near the condenser fan showed lower RH despite active evaporation. Smaller channel areas produced stronger airflow interaction and larger RH fluctuations, indicating more intensive vapor transport and mixing. In contrast, larger channel areas showed more uniform RH values because of lower airflow velocity and weaker local disturbance. The VG configuration further promoted local mixing, although the RH variation remained strongly governed by channel geometry and temperature distribution. The desalination unit reduced incoming hot-air temperature by approximately 6–11°C.

Although the experiments were conducted under controlled laboratory conditions, ambient temperature and humidity are expected to influence evaporation driving force and condenser heat rejection in practical tropical environments. Higher ambient temperatures may enhance evaporation but simultaneously reduce condenser cooling effectiveness and AC COP, particularly in smaller channel areas with higher airflow resistance. Conversely, high ambient humidity may reduce the vapor pressure gradient and shift the optimal operating condition towards slightly larger channel cross-sectional areas with lower pressure losses.

Consistent with the observed temperature and humidity distributions, Figure 5a shows that increasing the channel cross-sectional area consistently reduced evaporation for both NVG and VG configurations because larger areas decreased airflow velocity and convective heat and mass transfer.[28] Smaller areas generated higher airflow velocity and shear stress, thinning the boundary layer above the water surface and enhancing vapor diffusion. The VG configuration further increased evaporation by inducing longitudinal vortices that enhanced turbulence, airflow mixing, and boundary-layer disruption,[44,45] although channel geometry remained the dominant factor.

A comparison between the experimental and CFD results demonstrated strong agreement, with coefficients of determination of $R^2 = 0.9643$ and $R^2 = 0.958$ for NVG and VG configurations (Figure 5b), respectively.[46,47] Average deviations remained within the accepted validation threshold, reaching 10% for NVG and 6% for VG,[48,49] confirming that the CFD model reliably predicts evaporation behavior across different channel geometries. The produced



19 **FIGURE 5** Evaporation results for each channel cross-sectional area (a) and comparison of the experimental and simulation results (b).

freshwater had a TDS of approximately 71 ppm and a pH of 6.5, which remain within the acceptable ranges specified by WHO[50] and the Indonesian Ministry of Health regulations for clean water quality.[51] These results also indicate that seawater was not significantly carried over into the condensation section, since the seawater used in this study had a TDS of 31,710 ppm and a pH of 7.7, which are within the typical ranges for seawater, namely a TDS of approximately 29,000–39,000 ppm[52] and a pH ranging from 7.5 to 8.4.[53]

At the smallest channel cross-sectional area (0.006 m^2), the increased flow confinement produced higher pressure losses and reduced condenser airflow effectiveness. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions. Although the fan
15 power and electrical current were not monitored separately from the AC system, the reduction in the overall AC COP indirectly reflects the increased aerodynamic resistance experienced by the condenser airflow under smaller channel geometries.

During operation, continuous evaporation and the addition of make-up seawater gradually increased salinity from approximately 35 ppt to nearly 55 ppt after 8 h. The higher salinity reduced water activity and saturation vapor pressure, slightly decreasing the evaporation driving force. Nevertheless, severe scaling was not observed on the heat exchanger because evaporation mainly occurred in the evaporator basin rather than on the heating surface. Small salt deposits gradually accumulated at the bottom of the basin, while moderate operating temperatures (50–60°C), continuous circulation, and forced airflow helped suppress local supersaturation and scaling formation. However, long-term operation may still require periodic brine discharge or seawater replacement.

Since the residential split-type AC operated as a factory-integrated commercial system, the condenser fan current and standalone fan power were not monitored separately. AC operational performance was evaluated using the COP calculated from Equations (1)–(5). Conventional residential AC systems generally exhibit COP values between 3.02 and 4.04,[54,55] while the baseline COP of the AC unit used in this study was 3.92. After integration with the desalination unit, smaller channel areas produced higher pressure losses, restricting condenser airflow and reducing heat rejection effectiveness, thereby lowering

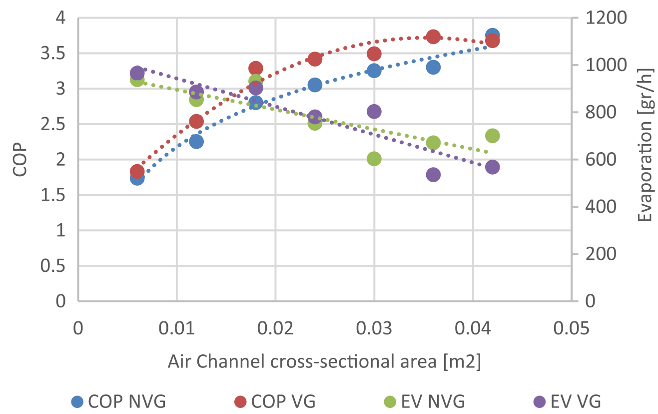


FIGURE 6 COP of split-type AC compared with evaporation for each cross-sectional area.

COP. Nevertheless, the condenser fan remained operational throughout the experiments without observable flow interruption or stall conditions.

As shown in Figure 6, COP increased progressively with increasing channel cross-sectional area because larger channels reduced airflow resistance and pressure drop. However, evaporation and COP did not exhibit a direct cause–effect relationship; both responded independently to airflow characteristics induced by channel geometry. Smaller channel areas increased airflow velocity and evaporation, while the associated pressure losses simultaneously reduced condenser performance and COP. Thus, the observed changes in evaporation and COP were primarily governed by airflow velocity and pressure-drop effects rather than by direct interaction between the two parameters.

A preliminary economic analysis showed that the system produced approximately 950–980 mL/h of freshwater (7.6–7.8 L during 8 h of operation). Based on the observed COP reduction from 3.92 to 3.02 and a cooling capacity of 2.64 kW, the additional electricity consumption was estimated at approximately 1.61 kWh per 8 h cycle, corresponding to an operational cost of about USD 0.13 or USD 0.017/L of freshwater produced. Although capital and maintenance costs were not included, the results indicate promising potential for low-cost household-scale freshwater production using readily available AC waste heat.

4 | CONCLUSION

This study demonstrates that waste heat from residential split-type AC units can drive an evaporation–condensation desalination process. Increasing the channel cross-sectional area reduced air temperature 27 by approximately 6–11°C and improved AC performance by lowering pressure drop and enhancing heat rejection, although freshwater production decreased accordingly. The system produced approximately 950–980 mL/h of freshwater, indicating the potential to satisfy basic household drinking water requirements. A preliminary economic analysis estimated the additional operational cost at approximately USD 0.017/L of freshwater produced. Experimental–CFD validation showed strong agreement ($R^2 > 0.95$), with deviations of 6%–10%, confirming the reliability of the numerical model. Smaller channel areas enhanced evaporation but reduced AC COP because of higher airflow resistance and pressure losses, whereas a channel area of 0.015–0.025 m^2 provided the best balance between freshwater production and AC efficiency.

Although the study was conducted under controlled conditions using a single AC configuration, the results demonstrate the feasibility of household-scale desalination using AC waste heat. Future work should investigate long-term operation, varying environmental conditions, and system scalability. While severe scaling was not observed on the heat exchanger surface, gradual salt accumulation occurred at the bottom of the evaporator basin during prolonged operation, indicating that periodic brine discharge, seawater replacement, or routine cleaning may be required for stable long-term performance.

AUTHOR CONTRIBUTIONS

Dan Mugisidi: Conceptualization; writing – review and editing; inves- 14 tigation; methodology; writing – original draft; formal analysis; funding acquisition; supervision. **Oktarina Heriyani:** Conceptualization; inves- 13 tigation; software; data curation; project administration; supervision. Conceptualization; investigation; data curation; formal analysis; super- 8 vision. **Amir Khalid:** Writing – review and editing; visualization; conceptualization. Conceptualization; visualization; validation; software; writing – review and editing. **Ahmed Rahmani:** Writing – review and editing; validation; conceptualization.

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CONFLICT OF INTEREST STATEMENT

1 The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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