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Experimental Investigation of Condenser Performance in Freshwater Production from Seawater Desalination using Air-Conditioner Waste Heat

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ABSTRACT
Freshwater scarcity remains a critical global issue driven by population growth, urbanisation, and climate change. Humidification–dehumidification (HDH) desalination has attracted increasing attention as a small-scale and energy-efficient technology because it can operate using low-grade thermal energy, including waste heat from air-conditioning systems. This study experimentally evaluated the performance of a fin-tube condenser integrated into an HDH seawater desalination system powered by air-conditioner waste heat. The experimental system consisted of an air-conditioning unit, an evaporation tank, a fin-tube condenser, a cooling-water circulation unit, and instruments for measuring temperature, relative humidity, airflow velocity, and condensate yield. Experiments were carried out over three consecutive days under comparable operating conditions. The results showed that the inlet humid-air temperature ranged from 43.71°C to 45.14°C and decreased to 23.96–25.87°C after passing through the condenser. The relative humidity increased from 46.81–48.74% at the condenser inlet to 99.27–99.99% at the outlet, indicating that the humid air approached a saturated condition after cooling. The airflow velocity decreased from 1.02 m/s at the inlet to 0.63 m/s at the outlet, suggesting increased contact time between humid air and the condenser surface. The calculated dew-point condition also confirmed that the cooling process supported condensation inside the condenser. The cooling-side heat transfer rate increased from 12,272.03 W to 13,494.33 W, while the condenser effectiveness ranged from 71% to 74%. The actual condensate effectiveness production varied from 3,185 g to 3,569 g, corresponding to a condensation effectiveness of 92–95%. These findings indicate that the fin-tube condenser provides effective heat removal, supports near-saturated outlet conditions, and enables stable condensate production in an HDH desalination process. The proposed system demonstrates the potential of utilising air-conditioner waste heat for sustainable freshwater production and energy-efficient small-

scale desalination applications.

INTRODUCTION

Clean water is a basic necessity for human life. Population growth, industrial expansion, urbanisation, and climate change have increased the demand for clean water in many regions of the world (Alenezi & Alabaiadly, 2025). At the same time, the availability of freshwater sources continues to decline, encouraging the development of alternative technologies for sustainable clean-water production (Zhang & Wang, 2024). One of the most widely developed technologies to address this issue is seawater desalination, which separates salt and dissolved minerals from seawater to produce freshwater for domestic and industrial uses (Olufisayo & Olanrewaju, 2024). In this context, desalination is not only relevant as a water-treatment technology but also as a strategic approach for regions that have abundant seawater resources but limited access to freshwater.

Various desalination technologies have been developed, including reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), and humidification–dehumidification (HDH). Among these technologies, HDH systems offer several advantages, including simple construction, relatively low operating costs, and the ability to utilise low-temperature energy sources such as solar energy and industrial waste heat (Alenezi & Alabaiadly, 2025; Zhang & Wang, 2024). In an HDH system, freshwater production occurs through two main stages: humidification and dehumidification. During humidification, water is heated to produce humid air containing water vapour. During dehumidification, the water vapour is cooled, condensed, and collected as freshwater (Orfi et al., 2025). These characteristics make HDH desalination suitable for small-scale applications, especially when it can be integrated with available low-grade heat sources.

In recent years, the utilisation of waste heat as an alternative energy source for desalination systems has received increasing attention. Waste heat generated from industrial processes and air-conditioning systems has strong potential for reuse, thereby improving overall energy efficiency (Assareh et al., 2024). One common and accessible source of waste heat is the heat released by an air-conditioner condenser (Adegbola et al., 2021). Recent experimental research has shown that waste heat from residential split-type air conditioners can be utilised to drive evaporation–condensation seawater desalination at the household scale. Mugisidi et al. (2026) reported that airflow enhancement using vortex generators improved evaporation performance and supported freshwater production using readily available AC waste heat. This thermal energy, which is usually discharged into the environment, can be redirected as a heat source for the evaporation process in an HDH system, reducing dependence on external energy input and improving the sustainability of the desalination process (Mugisidi & Heriyani, 2024). Therefore, the integration of AC waste heat into HDH desalination provides a practical opportunity to convert unused thermal energy into a useful resource for freshwater production.

The success of the dehumidification process in an HDH system is strongly influenced by condenser performance (Al-Obaidi et al., 2025). The condenser functions as a heat-transfer medium that converts water vapour into liquid condensate through cooling (Krempaský et al., 2022). Condenser performance is affected by several parameters, including heat-transfer surface area, geometric configuration, fluid-flow characteristics, operating temperature, and the effectiveness of heat transfer on the condenser surface (Syaiful et al., 2021). Therefore, selecting an appropriate condenser design is a key factor in increasing freshwater production in HDH desalination systems.

Several studies have attempted to improve the condensation process in desalination systems. Previous research has reported that external condensers can improve freshwater productivity compared with conventional condenser configurations (Mahmood et al., 2021; Suhendar et al., 2022). Other studies have shown that modifying flow geometry using vortex generators can enhance heat transfer and

accelerate the condensation process (Abed, 2023; Luo et al., 2025). In addition, fin-tube heat exchangers are widely used because their extended fin surfaces provide a larger heat-transfer area, thereby improving heat-transfer rate and system efficiency (Adegbola et al., 2021). These studies indicate that condenser configuration plays an important role in determining the effectiveness of vapour cooling and condensate formation.

Although many studies have examined performance improvement in desalination systems, experimental studies that specifically evaluate the performance of fin-tube condensers in HDH systems using waste heat from air conditioners remain limited. Most previous studies have focused on evaporation enhancement, solar-energy utilisation, vortex-generator modification, or general airflow improvement, whereas the relationship between temperature reduction, relative humidity change, airflow velocity, dew-point condition, heat-transfer performance, and actual condensate production in AC waste heat-based HDH systems has not been widely discussed (Abed, 2023; Mugisidi & Heriyani, 2024). This gap is important because condenser performance cannot be evaluated only from temperature reduction, but also from humidity behaviour, airflow characteristics, dew-point condition, and the difference between theoretical and actual condensate production.

Based on this research gap, this study experimentally evaluates the performance of a fin-tube condenser integrated into an HDH seawater desalination system powered by AC waste heat. The performance evaluation includes temperature distribution, relative humidity, airflow velocity, dew-point condition, heat-transfer rate, condenser effectiveness, theoretical condensate mass, actual condensate mass, and condensation effectiveness. This study contributes by providing experimental evidence on how a fin-tube condenser supports heat removal and condensate formation in an HDH system using AC waste heat as the thermal energy source. The findings are expected to support the development of energy-efficient, small-scale desalination technology for sustainable freshwater production.

METHOD

This study employed a Humidification–Dehumidification (HDH) system that utilised waste heat from an air conditioner (AC) as the thermal energy source for the evaporation process. As illustrated in Fig. 1, the experimental system consisted of a split-type AC unit, heat exchanger, main tank, water pump, control tank, fin-tube condenser, vapour funnel, digital scale, condensate tank, and water tank. The heat released from the AC condenser was transferred through the heat exchanger to increase the seawater temperature in the main tank, thereby producing humid air and water vapour for the HDH process (Zhong et al., 2024). The humid air was then directed into the fin-tube condenser, where cooling and condensation occurred to produce freshwater.

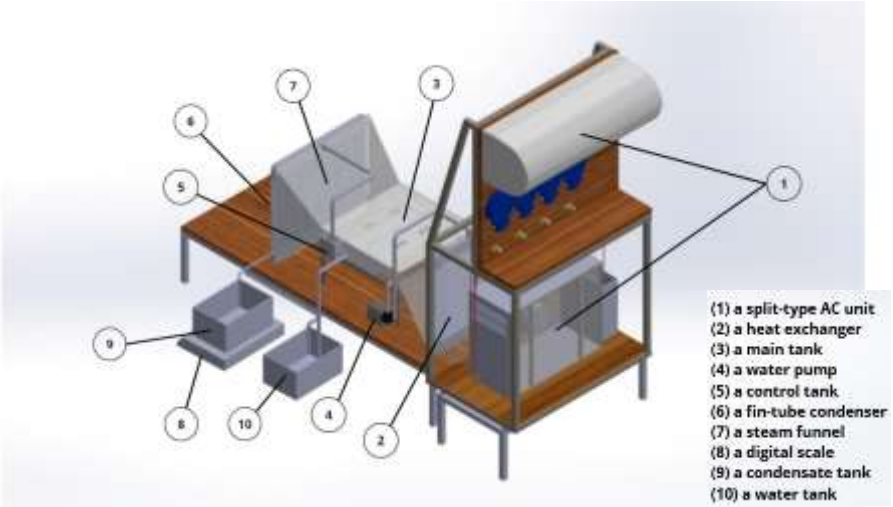


Fig 1. *Research Design*

The condenser used in this study was a fin-tube condenser. The technical specifications of the condenser are presented in Table 1. The condenser was selected because its finned surface provides a larger heat transfer area, which is important for improving the cooling and condensation process in a compact HDH desalination system. Table 1. The condenser used is a fin-tube type condenser with the specifications shown in Table 1.

Table 1. Condenser Specifications

No.	Parameter	Value	Units
1.	Condenser Length	558	mm
2.	Condenser Width	425	mm
3.	Condenser Thickness	16	mm
4.	Outer Tube Diameter	8	mm
5.	Inner Diameter of the Tube	7	mm
6	Number of Tubes	38	Pcs
7	Number of Fins	420	Pcs
8	Distance Between Fins	1	mm
9	Heat Transfer Surface Area	5,4	m^2

Fin-Tube Condenser Configuration in Fig. 2 shows the design and configuration of the fin-tube condenser, including the cooling-water inlet, cooling-water outlet, and distillate outlet.



Fig 2. *Fin-Tube Condenser Configuration*

The experimental parameters were measured using several instruments. The measurement instruments and their specifications are summarised in Table 2.

Table 2. Measurement Instruments

No	Tool	Function	Specification
1.	Digital Thermometer	Measuring temperature	-50℃ -110℃, ±0.1℃.
2.	Digital Hygrometer	Measuring relative humidity	10% – 99%, resolution 1%, accuracy ± 1 ℃
3.	Digital Scale 15 kg	Measuring condensation yield	0 – 15 kg, 0.005 kg
4.	Anemometer	Measuring wind speed	0 – 30 m/s, resolution 0.1 m/s

The digital hygrometer and anemometer were used as primary measurement instruments in this study. Their results, including inlet and outlet relative humidity and inlet and outlet airflow velocity, were included in the analysis and are reported in the Results and Discussion section. The digital thermometer was used to measure the humid-air and cooling-water temperatures, while the digital scale was used to measure the actual condensate mass produced during the experiment. The experiment was conducted for three consecutive days using the same operating duration for each observation day. During the experiment, seawater in the main tank was heated using waste heat from the AC unit. The heating process produced humid air and water vapour, which were then directed into the fin-tube condenser. Cooling water circulated through the condenser tubes to absorb heat from the humid air and support the condensation process.

Fig. 3 presents the research instrument design and sensor positions used during the experiment. The humid-air temperatures at the condenser inlet and outlet were measured using sensors T1 and T2. The relative humidity before and after the condenser was measured using sensors H1 and H2. The airflow velocity before and after the condenser was measured using sensors V1 and V2. The cooling-water inlet and outlet temperatures were measured using sensors T3 and T4.

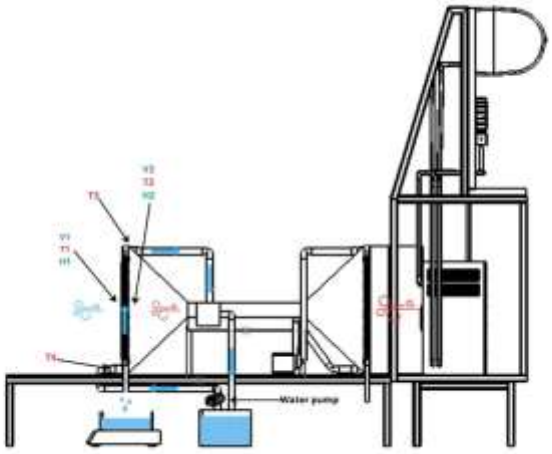


Fig 3. *Research Instrument Design and Sensor Positions*

The measured parameters included humid-air inlet temperature, humid-air outlet temperature, cooling-water inlet temperature, cooling-water outlet temperature, inlet relative humidity, outlet relative humidity, inlet airflow velocity, outlet airflow velocity, and condensate mass. These data were used to analyse the temperature distribution, relative humidity variation, airflow characteristics, heat transfer performance, dew-point condition, and condensate production of the fin-tube condenser.

The cooling-side heat transfer rate was determined from the cooling-water mass flow rate, the specific heat capacity of water, and the temperature difference between the cooling-water inlet and outlet. The vapour-side heat transfer rate was estimated from the vapour mass flow rate and the latent heat of vaporisation. The theoretical condensate mass was estimated based on the available condensation heat and the latent heat of vaporisation, while the actual condensate mass was measured directly using the digital scale (Poredoš et al., 2022).

In this study, condenser effectiveness and condensation effectiveness were treated as two different performance indicators. Condenser effectiveness refers to the ability of the condenser to transfer heat from humid air to cooling water. In contrast, condensation effectiveness refers to the ability of the condenser to convert the theoretically available condensate into actual freshwater production. Therefore, the condenser effectiveness values and condensation effectiveness values reported in this study represent different aspects of condenser performance and should not be interpreted as the same parameter.

Dew-point temperature was calculated from the measured humid-air temperature and relative humidity to evaluate whether the operating condition inside the condenser supported condensation. The calculated dew-point temperature values are presented and discussed in the Results and Discussion section together with the measured relative humidity and airflow velocity (Romps, 2021).

Finally, all experimental data were analysed descriptively and quantitatively to evaluate the performance of the fin-tube condenser in the AC waste heat-based HDH desalination system. The analysis focused on temperature reduction, relative humidity changes, airflow velocity, heat transfer performance, dew-point condition, actual and theoretical condensate production, condenser effectiveness, and condensation effectiveness.

RESULTS AND DISCUSSION

Temperature Distribution in the Condenser

Temperature distribution is one of the key parameters in evaluating condenser performance because it is directly related to the heat transfer process and condensate formation (Al-Obaidi et al., 2025). The average temperature data obtained during the three-day experiment are presented in Table 3.

Table 3. Average Temperature Distribution in the Condenser

Day	$T_{h,in}$	$T_{h,out}$	$T_{c,in}$	$T_{c,out}$	T_{Cond}
Day 1	44,98	23,96	17,92	24,16	21,69
Day 2	45,14	24,97	18,83	25,21	22,22
Day 3	43,71	25,87	17,54	24,02	20,78

Table 3 shows that the condenser inlet humid-air temperature $T_{h,in}$ ranged from 43.71°C to 45.14°C. This temperature range indicates that the waste heat from the air conditioner was able to provide sufficient thermal energy to support the humidification process. Meanwhile, the cooling-water inlet temperature $T_{c,in}$ ranged from 17.54°C to 18.83°C, creating a considerable temperature difference between the hot humid air and the cooling water.

The temperature difference between the humid air and the cooling water caused heat to transfer from the humid air to the cooling water through the tube walls and fins of the condenser (Saini et al., 2023). As a result, the humid-air temperature decreased after passing through the condenser, while the cooling-water temperature increased after absorbing heat from the humid air. This condition indicates that the dehumidification process occurred effectively and supported condensate formation during the experiment (Luberti & Capocelli, 2023).

Based on Fig. 4, the condenser inlet humid-air temperature remained relatively stable during the three-day experiment, with values ranging from 43.71°C to 45.14°C. This stability shows that the AC waste heat supplied relatively consistent thermal energy for the humidification process. In contrast, the humid-air outlet temperature decreased significantly to 23.96–25.87°C after passing through the condenser.

The graph also shows that the cooling-water outlet temperature $T_{c,out}$ was higher than the cooling-water inlet temperature $T_{c,in}$. This increase confirms that the cooling water absorbed heat from the humid air during the condensation process. Therefore, the decrease in humid-air temperature and the increase in cooling-water temperature demonstrate that heat transfer occurred effectively inside the fin-tube condenser.

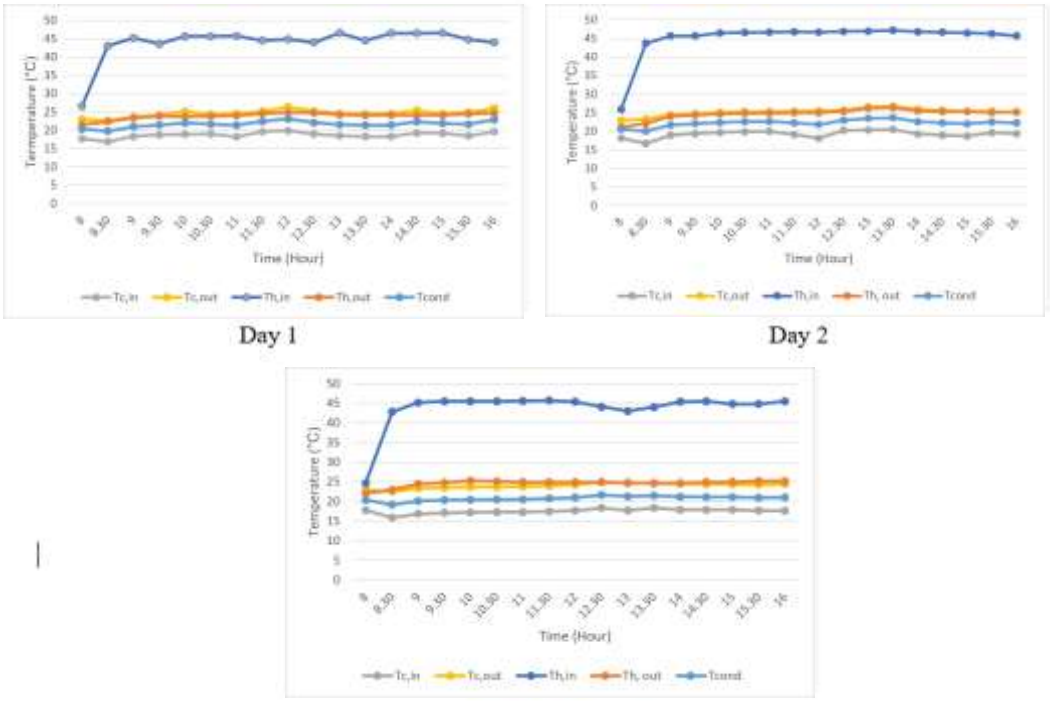


Fig 4. *Temperature Distribution Graph*

Relative Humidity, Airflow Velocity, and Dew-Point Condition

In response to the measurement parameters obtained using the digital hygrometer and anemometer, the relative humidity, airflow velocity, and calculated dew-point temperature are presented in Table 4. These data were added to clarify that the relative humidity and airflow velocity measurements were included as part of the experimental results.

Table 4. Average Relative Humidity, Airflow Velocity, and Dew-Point Temperature

Day	RH Inlet (%)	RH Outlet (%)	Airflow Inlet (m/s)	Airflow Outlet (m/s)	Dew Point (°C)
Day 1	46.81	99.34	1.02	0.63	23.84
Day 2	47.51	99.27	1.02	0.63	24.84
Day 3	48.74	99.99	1.02	0.63	25.87

Table 4 shows that the inlet relative humidity ((RH_{in})) ranged from 46.81% to 48.74%, whereas the outlet relative humidity ((RH_{out})) increased sharply to 99.27–99.99%. This increase indicates that the humid air approached a saturated condition after passing through the condenser. The near-saturation condition at the outlet confirms that the cooling process promoted water-vapour condensation inside the condenser.

The airflow velocity also decreased from an average inlet value of 1.02 m/s to an outlet value of 0.63 m/s. This reduction suggests that the fin-tube condenser geometry created flow resistance and increased the contact time between humid air and the cooling surface. Longer contact time can support heat removal and improve the opportunity for condensation, although it may also indicate additional flow resistance within the condenser.

The calculated inlet dew-point temperature ranged from 30.09°C to 30.93°C, while the outlet dew-point temperature ranged from 23.84°C to 25.87°C. The cooling-water inlet temperature, which ranged from 17.54°C to 18.83°C, was lower than the inlet dew-point temperature. This condition confirms

that the condenser provided a suitable thermal condition for condensation to occur. The outlet dew-point temperature was close to the outlet humid-air temperature because the outlet relative humidity approached saturation. This result supports the interpretation that the dehumidification process was effective during the experiment.

Condenser Heat Transfer Analysis

The heat transfer performance of the condenser was evaluated based on the cooling-side heat transfer rate, vapour-side heat transfer rate, and condenser effectiveness. The results are presented in Table 5 as the average heat transfer rate and condenser thermal data.

Table 5. Average Heat Transfer Rate and Condenser Thermal Effectiveness

Day	Cooling-Side Heat Transfer (W)	Vapour-Side Heat Transfer (W)	Effectiveness (%)
Day 1	12,273.03	17,860.63	73
Day 2	12,415.87	18,565.96	71
Day 3	13,494.33	19,140.75	74

Based on Table 5, the cooling-side heat transfer rate increased from 12,978.65 W on the first day to 13,494.33 W on the third day. This increase indicates that the condenser was able to absorb heat from the humid air effectively during the testing process.

The condenser effectiveness also showed an increasing trend, rising from 73% on the first day to 74% on the third day. In this section, the efficiency value refers specifically to condenser effectiveness, which describes the ability of the condenser to transfer heat from humid air to cooling water. The relatively high effectiveness indicates that most of the heat released by the humid air was successfully absorbed by the cooling water (Mugisidi et al., 2023b).

These results were influenced by the heat transfer surface area of the condenser, the presence of fins, and the temperature difference between the hot and cold fluids (Nurkholid et al., 2025). Therefore, the fin-tube condenser configuration used in this study provided good heat transfer performance in the AC waste heat-based HDH system (Heriyani & Mugisidi, 2025).

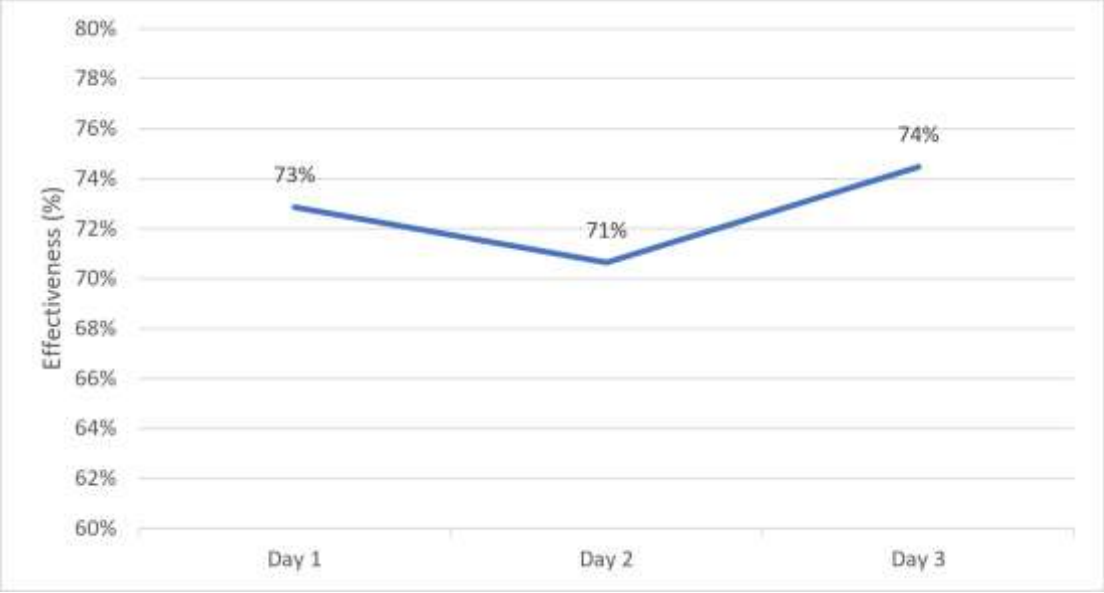


Fig 5. *Heat Transfer Graph*

Fig. 5 illustrates the increase in the cooling-side heat transfer rate from 12,272.65 W to 13,494.33 W. This trend indicates an improvement in the condenser's ability to transfer heat from humid air to cooling water. In addition, the increase in condenser effectiveness from 71% to 74% suggests that the

operating temperature was relatively stable and that the fin-tube structure provided sufficient heat transfer area for the condensation process. Although the vapour-side heat transfer rate fluctuated during the experiment, the effectiveness remained high. This condition indicates that the condenser continued to function effectively as a heat removal component in the HDH desalination system.

Condensate Production Analysis

Condensate production is a key indicator of the success of the dehumidification process in an HDH system (Kumar et al., 2023). Fig. 6 shows the comparison between actual and theoretical condensate production during the three-day experiment.

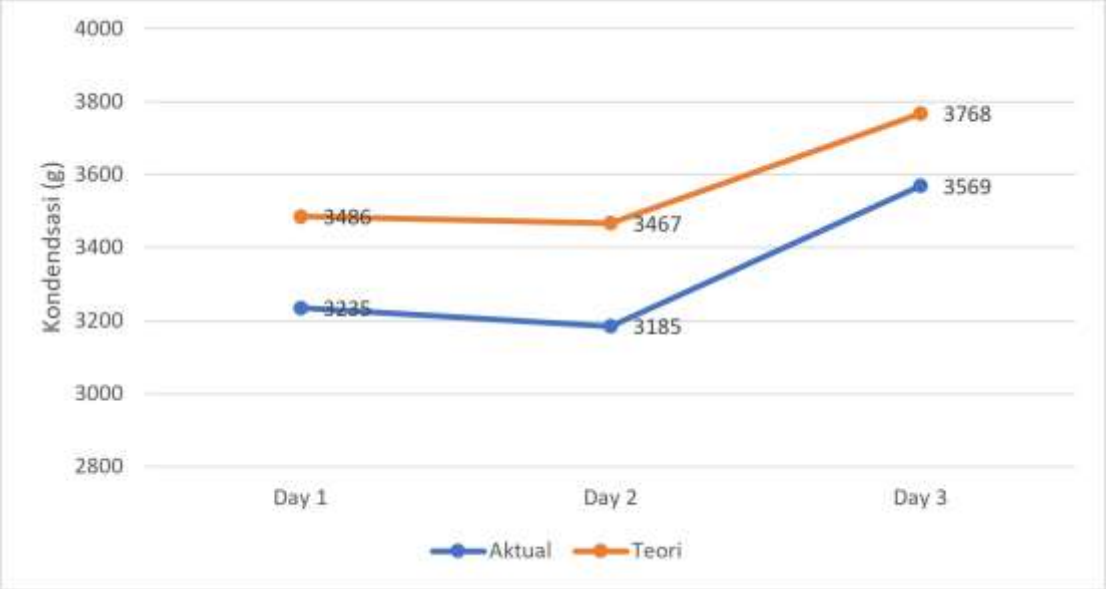


Fig 6. *Condensate Production Graph*

Fig. 6 shows that the theoretical condensate mass was consistently higher than the actual condensate mass. The actual condensate production ranged from 3,185 g to 3,569 g, while the theoretical condensate mass ranged from 3,467.49 g to 3,768.70 g. The difference between actual and theoretical condensate production may be caused by heat loss to the environment, thermal resistance in the condenser wall, non-uniform humid-air distribution, and incomplete condensation inside the condenser (Nabil et al., 2025). Table 6 presents the actual condensate mass, theoretical condensate mass, and condensation effectiveness. The table title and column headings were revised to clearly indicate that this table reports condensation performance, not condenser effectiveness.

Table 6. Actual and Theoretical Condensate Mass and Condensation Efficiency

Day	Actual condensate mass (g)	Theoretical condensate mass (g)	Condensation effectiveness (%)
Day 1	3,235	3,468.49	93
Day 2	3,185	3,467.06	92
Day 3	3,569	3,768.70	95

The test results show that the actual condensate mass ranged from 3,185 g to 3,569 g. The highest actual condensate production was recorded on the third day, reaching 3,569 g. This result is consistent with the increase in the cooling-side heat transfer rate, which also reached its highest value on the third day. The greater the heat removed from the humid air, the greater the potential for water vapour to condense into freshwater (Mugisidi et al., 2023a).

The condensation effectiveness ranged from 92% to 95%. The highest condensation effectiveness was obtained on the first day, while the lowest value occurred on the second day. The percentage sign has been consistently added to all condensation effectiveness values to improve clarity and formatting

consistency. In general, condensation effectiveness above 85% indicates that the fin-tube condenser was effective in converting water vapour into condensate.

The effectiveness values reported in Table 5 and Table 6 represent two different performance indicators. The condenser effectiveness in Table 5, ranging from 71% to 74%, describes heat transfer performance between humid air and cooling water. In contrast, the condensation effectiveness in Table 6, ranging from 92% to 95%, describes the ratio between actual condensate mass and theoretical condensate mass. Therefore, these two effectiveness values are not conflicting results but complementary indicators of condenser performance.

The results demonstrate that the use of AC waste heat combined with a fin-tube condenser can support an effective condensation process. The system has potential as an alternative freshwater production technology with relatively low external energy requirements, particularly for small-scale HDH desalination applications.

CONCLUSION

The experimental results demonstrated that the fin-tube condenser effectively reduced the humid-air temperature from 43.71–45.14°C at the inlet to 23.96–25.87°C at the outlet, indicating effective heat removal during the condensation process. The relative humidity increased from 46.81–48.74% at the condenser inlet to 99.27–99.99% at the outlet, showing that the humid air approached a saturated condition after passing through the condenser. The airflow velocity decreased from 1.02 m/s at the inlet to 0.63 m/s at the outlet, indicating increased flow resistance and longer contact time between humid air and the condenser surface. The calculated dew-point temperature also confirmed that the cooling condition inside the condenser was suitable for condensation.

The cooling-side heat transfer rate increased from 12,272.03 W on the first day to 13,494.33 W on the third day. The condenser effectiveness ranged from 71% to 74%, indicating the condenser's ability to transfer heat from humid air to cooling water. This value should be distinguished from condensation effectiveness, which ranged from 92% to 95% and represents the ratio between actual and theoretical condensate production. The actual condensate production varied between 3,185 and 3,569 g, whereas the theoretical condensate mass ranged from 3,467.49 to 3,768.70 g. The difference between actual and theoretical condensate production indicates the presence of heat loss, thermal resistance, non-uniform humid-air distribution, and incomplete condensation within the system.

Overall, the findings indicate that the fin-tube condenser has strong potential to enhance the performance of HDH desalination systems using AC waste heat. The combination of stable temperature reduction, near-saturated outlet humidity, adequate dew-point condition, and high condensation effectiveness demonstrates that AC waste heat can be effectively utilised as an alternative thermal energy source for small-scale freshwater production. Future studies are recommended to investigate the effects of cooling-water flow rate, airflow velocity variation, condenser geometry, and longer operating duration to further improve condensate production and overall system effectiveness.

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