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Performance of an Air-Water Harvester Machine under Various Inlet Air Relative Humidity Conditions

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Abstract

Atmospheric water harvesting (AWH) using vapor-compression refrigeration systems has emerged as a promising approach for decentralized freshwater production. Although previous studies have investigated the effects of refrigeration-system configurations and operating parameters on water production, the influence of inlet air relative humidity on freshwater productivity, heat-transfer characteristics, and thermodynamic performance has not been comprehensively evaluated within a single experimental framework. This study experimentally investigates the performance of an air-water harvester operating at inlet relative humidities of 30%, 50%, and 70% under controlled laboratory conditions. Freshwater production, coefficient of performance (COP), total heat absorbed by the evaporator, and evaporator efficiency were evaluated using measurements of temperature, pressure, airflow velocity, electrical power consumption, and psychrometric properties. The results show that increasing inlet relative humidity significantly enhanced condensation and system performance, yielding the highest freshwater production of 0.345 kg and the maximum COP of 12.19 at 70% RH. In contrast, the highest evaporator efficiency (11.89%) and total heat absorbed by the evaporator (167.81 W) were obtained at 30% RH, where sensible heat transfer dominated the cooling process. The findings indicate that inlet air relative humidity strongly influences the distribution of sensible and latent heat transfer, thereby affecting both freshwater production and energy performance. This study provides an integrated experimental assessment of the thermodynamic response of refrigeration-based AWH systems to varying inlet humidity and offers practical guidance for optimizing system operation in humid tropical environments.

Keywords: *atmospheric water harvesting; evaporator heat transfer; inlet air relative humidity; thermodynamic performance; vapor-compression refrigeration.*

Abstrak

Pemanenan air dari atmosfer (*Atmospheric Water Harvesting*, AWH) menggunakan sistem refrigerasi siklus kompresi uap telah berkembang sebagai salah satu pendekatan yang menjanjikan untuk menghasilkan air tawar secara terdesentralisasi. Meskipun berbagai penelitian sebelumnya telah mengkaji pengaruh konfigurasi sistem refrigerasi dan parameter operasional terhadap produksi air, pengaruh kelembapan relatif udara masuk terhadap produktivitas air, karakteristik perpindahan panas, dan kinerja termodinamika belum dievaluasi secara komprehensif dalam satu kerangka eksperimen. Penelitian ini bertujuan menyelidiki secara eksperimental kinerja mesin pemanen air dari udara yang beroperasi pada variasi kelembapan relatif udara masuk sebesar 30%, 50%, dan 70% dalam kondisi laboratorium yang terkontrol. Parameter yang dianalisis meliputi produksi air tawar, koefisien performa (*coefficient of performance*, COP), total panas yang diserap oleh evaporator, dan efisiensi evaporator berdasarkan hasil pengukuran temperatur, tekanan, kecepatan aliran udara, konsumsi daya listrik, serta sifat-sifat psikrometrik udara. Hasil penelitian menunjukkan bahwa peningkatan kelembapan relatif udara masuk secara signifikan meningkatkan proses kondensasi dan kinerja sistem, dengan produksi air tawar tertinggi sebesar 0,345 kg dan nilai COP maksimum sebesar 12,19 yang dicapai pada kelembapan relatif 70%. Sebaliknya, efisiensi evaporator tertinggi (11,89%) dan total panas yang diserap oleh evaporator (167,81 W) diperoleh pada kelembapan relatif 30%, ketika perpindahan panas sensibel mendominasi proses pendinginan. Hasil penelitian ini menunjukkan bahwa kelembapan relatif udara masuk memberikan pengaruh yang signifikan terhadap distribusi perpindahan panas sensibel dan laten, sehingga memengaruhi produksi air tawar maupun kinerja energi sistem. Penelitian ini menyajikan evaluasi eksperimental yang terintegrasi mengenai respons termodinamika sistem pemanen air atmosfer berbasis refrigerasi terhadap variasi kelembapan relatif udara masuk serta memberikan dasar praktis untuk mengoptimalkan pengoperasian sistem pada lingkungan tropis yang lembap.

Kata kunci: pemanenan air dari atmosfer; perpindahan panas pada evaporator; kelembapan relatif udara masuk; kinerja termodinamika; sistem refrigerasi siklus kompresi uap.

1. Introduction

Water is one of the most fundamental human needs and plays a crucial role in sustaining public health, economic development, and social well-being. However, the global demand for freshwater continues to increase due to rapid population growth, urbanization, industrial expansion, and climate change. These factors have intensified freshwater scarcity in many regions worldwide, including several parts of Indonesia, particularly during prolonged dry seasons when conventional water resources become increasingly limited [1–4]. Consequently, developing sustainable, decentralized, and energy-efficient freshwater production technologies has become an urgent global challenge.

Conventional freshwater sources, including rainwater, rivers, lakes, springs, and groundwater, can be utilized to meet domestic water demands. Nevertheless, these sources generally require extensive treatment processes before becoming suitable for human consumption [3–4]. To overcome freshwater shortages, numerous water production technologies have been developed, including wastewater reclamation, seawater desalination, reverse osmosis, dew harvesting using mesh collectors, foil-based condensers, and wind-assisted atmospheric water collection systems [5–8]. Although these technologies have demonstrated promising performance, many require substantial infrastructure investment, high operational costs, or favorable geographical conditions. For example, seawater desalination is mainly applicable in coastal regions, whereas dew harvesting systems strongly depend on specific meteorological conditions, and wind-assisted harvesting systems are generally more suitable for large-scale installations [9–10]. These limitations motivate the development of alternative technologies that are economically affordable, energy-efficient, and capable of producing freshwater under a wide range of environmental conditions.

Among the emerging technologies, atmospheric water harvesting (AWH) based on vapor-compression refrigeration systems has attracted considerable attention because it directly extracts freshwater from ambient air by condensing water vapor on a cooled evaporator surface [11–14]. Compared with conventional water supply technologies, refrigeration-based AWH systems offer several advantages, including independence from existing water sources, relatively simple system configurations, modular installation, and suitability for decentralized household or community-scale applications. As a result, improving the thermodynamic performance and energy efficiency of AWH systems has become an active research topic in recent years.

Previous studies have investigated various design and operating parameters affecting the performance of refrigeration-based AWH systems. Thomas et al. [15] evaluated the influence of evaporator orientation and reported that a vertical evaporator produced the highest water yield of 0.3537 kg within 7 h at an average inlet relative humidity of 78%. Azhari [16] demonstrated that increasing the condenser tube diameter to 8 mm improved water production to 0.44 kg. Prasetya [17] reported that an evaporator pressure of 30 psi produced the maximum freshwater yield of 0.4384 kg, whereas Baskaran et al. [18] found that a 40 cm capillary tube achieved the highest water production of 1.097 kg at an average inlet relative humidity of 59%. More recent studies have also explored the effects of evaporator configuration, airflow characteristics, and refrigeration-cycle optimization on freshwater productivity and energy consumption [5,11,20–22].

Despite these advances, existing studies have predominantly focused on hardware modifications and refrigeration-cycle parameters, while the influence of ambient psychrometric conditions, particularly inlet air relative humidity, has received comparatively limited attention. More importantly, previous investigations have generally emphasized freshwater production as the primary performance indicator, whereas the combined effects of inlet relative humidity on freshwater productivity, coefficient of performance (COP), evaporator heat-transfer characteristics, and evaporator efficiency have not been systematically evaluated within a unified thermodynamic framework. Since inlet relative humidity directly governs the moisture content of air, dew-point temperature, condensation potential, and the balance between sensible and latent heat transfer, it fundamentally determines the overall energy utilization and water harvesting capability of refrigeration-based AWH systems [13,14,19]. Therefore, a comprehensive understanding of how relative humidity affects these interrelated thermodynamic processes remains lacking.

To address this knowledge gap, this study experimentally investigates the influence of inlet air relative humidity on the thermodynamic performance of an air-water harvester employing a vapor-compression refrigeration system. Experiments were conducted under three controlled inlet relative humidity conditions (30%, 50%, and 70%), and the system performance was evaluated in terms of freshwater production, coefficient of performance (COP), total heat absorbed by the evaporator, and evaporator efficiency. The novelty of this study lies in the comprehensive thermodynamic evaluation of inlet relative humidity by simultaneously quantifying its effects on water production, energy performance, evaporator heat-transfer characteristics, and the thermodynamic trade-off between sensible and latent heat transfer**.** The findings provide new insights for optimizing refrigeration-based atmospheric water harvesting systems, particularly for deployment in humid tropical regions where ambient moisture availability strongly influences system performance.

2. Material and Method

An experimental investigation was conducted to evaluate the effect of inlet air relative humidity on the thermodynamic performance of an air-water harvester employing a vapor-compression refrigeration system. The system performance was assessed under three controlled inlet air relative humidity conditions by comparing freshwater production, heat-transfer characteristics, and energy performance while maintaining the remaining operating conditions as constant as possible.

The experimental setup consisted of a vapor-compression refrigeration system integrated with an air-water harvesting unit. The refrigeration system comprised a ½ HP rotary compressor, condenser, capillary tube, and evaporator charged with R-134a refrigerant. R-134a was selected because of its stable thermodynamic properties, compatibility with small-capacity refrigeration systems, and widespread use in experimental refrigeration studies. The air-handling section included a humidifier, an axial fan, and an air duct to regulate the inlet air conditions supplied to the evaporator. The experimental apparatus was equipped with calibrated measuring instruments, including K-type thermocouples, digital pressure gauges, a digital thermometer, a data logger, an anemometer, a digital power meter, an electronic weighing scale, and a water collection container. These instruments were used to measure refrigerant temperatures and pressures, inlet and outlet air conditions, airflow velocity, electrical power consumption, and the mass of condensed water throughout the experiments. The evaporator served as the primary heat and mass transfer surface, where water vapor contained in the incoming air condensed into liquid water when the air temperature dropped below its dew-point temperature. To ensure repeatable operating conditions, the inlet air relative humidity was controlled using a humidifier and maintained at three prescribed levels of 30%, 50%, and 70% during the experiments. Figure 1 presents the schematic diagram of the experimental apparatus together with the locations of the measuring instruments used in this study.

The study consisted of independent and dependent variables. The independent variable was the inlet air relative humidity (RHin), which was varied at three different levels, namely 30%, 50%, and 70%. The dependent variables analyzed in this study included: Water production (kg), Coefficient of performance (*COP*), Total heat absorbed by the evaporator from the air (*Qt*), Evaporator efficiency.

$$Q_t = Q_d + Q_v + Q_{da} \tag{1}$$

Q_t is the total heat transfer rate (W), Q_d is the heat transfer rate from the condensed vapour (W), Q_v is the heat transfer rate from the uncondensed vapour (W) and Q_{da} is the heat transfer rate from the dry air (W).

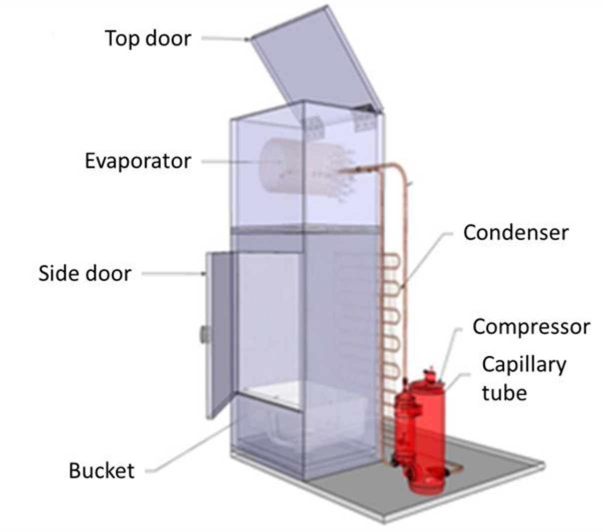

Figure 1. Experimental apparatus/schematic diagram of the experimental device

Prior to the experiment, all measuring instruments and system components were prepared and calibrated. Initial measurements of temperature, pressure, and relative humidity were recorded before the system operation started. The experiment began by activating the data logger and computer system, followed by operating the air-conditioning unit to achieve the desired inlet air relative humidity condition. After the required RH level was stabilized, the air-water harvester system was turned on.

The experiments were conducted under three inlet air relative humidity variations: 30%, 50%, and 70%. During each experiment, several parameters were recorded every hour for a total operating duration of 7 hours, from 09:00 to 16:00 local time. The measured parameters included: refrigerant temperatures at four measurement points (T_1, T_2, T_3, and T_4) , refrigerant pressures at four measurement points (P_1, P_2, P_3, and P_4), inlet and outlet air temperatures, inlet and outlet air relative humidity, air velocity, compressor electrical power consumption, water mass produced. Each experimental variation was repeated three times to improve data reliability and reduce measurement uncertainty.

Psychrometric analysis was conducted to determine the thermodynamic properties of moist air during the condensation process. The psychrometric properties were obtained using an online psychrometric calculator based on measured inlet air temperature, outlet air temperature, inlet relative humidity, and outlet relative humidity. The calculated parameters included: humidity ratio of moist air, dry air mass flow rate, water vapor mass flow rate, sensible heat transfer rate, latent heat transfer rate, total heat absorbed by the evaporator. The total heat absorbed by the evaporator from the air was determined from the sum of sensible heat, latent heat, and condensed water heat transfer. Thermodynamic analysis of the vapor compression refrigeration cycle was performed using refrigerant R-134a property tables. The refrigerant enthalpies at different operating states were determined from the measured temperatures and pressures. The enthalpy values used in the analysis included: h_1 is the enthalpy at evaporator outlet/compressor inlet, h_2 is the enthalpy at compressor outlet/condenser inlet, h_3 is the enthalpy at condenser outlet, h_4 is the enthalpy at evaporator inlet. Based on these enthalpy values, the refrigeration effect, compressor work, heat rejection, and coefficient of performance (*COP*) were calculated.

The coefficient of performance (COP) of the system was calculated using the following equation:

$$COP = \frac{Q_i}{W_c} = \frac{h_1 - h_4}{h_2 - h_1} \quad (2)$$

COP is the coefficient of performance, Q_i is the cooling load (J/kg) and W_c is the compressor work (J/kg).

The experimental data obtained from all variations were averaged from three repetitions for each operating condition. The results were then analyzed and presented in graphical and tabular forms to evaluate the effect of inlet air relative humidity on water production, evaporator heat absorption, evaporator efficiency, and system COP.

3. Results and Discussion

The performance of the air-water harvester was experimentally evaluated under three controlled inlet air relative humidity (RHin) conditions of 30%, 50%, and 70%. Each operating condition was tested in triplicate over a 7 h operating period to ensure the repeatability of the measurements. The experimental data included refrigerant temperatures and pressures, inlet and outlet air conditions, electrical power consumption, airflow velocity, and freshwater production. These measured parameters were subsequently used to determine the coefficient of performance (COP), total heat absorbed by the evaporator, and evaporator efficiency through thermodynamic and psychrometric analyses. Similar experimental methodologies have been widely adopted for evaluating refrigeration-based atmospheric water harvesting systems because they provide a comprehensive assessment of both heat-transfer characteristics and energy performance [13,14,21–23].

3.1 Effect of inlet air relative humidity on freshwater production

Figure 2 presents the average freshwater production obtained under different inlet air relative humidity conditions. Freshwater production increased from 0.205 kg at 30% RH to 0.309 kg at 50% RH, reaching 0.345 kg at 70% RH after 7 h of operation. Overall, increasing the inlet relative humidity from 30% to 70% enhanced freshwater production by approximately 68%, confirming that inlet humidity is one of the dominant operating parameters governing the productivity of refrigeration-based atmospheric water harvesting systems. More importantly, the results demonstrate that the thermodynamic state of the incoming air substantially influences how effectively the available refrigeration capacity is converted into freshwater production.

One-way analysis of variance (ANOVA) was performed to evaluate whether inlet air relative humidity significantly affected freshwater production. The analysis indicated a statistically significant effect of relative humidity on freshwater production ($p < 0.05$). Subsequent Tukey's HSD multiple-comparison test confirmed that the differences between humidity levels were statistically significant, indicating that the observed increase in freshwater production cannot be attributed to random experimental variation. The large effect size further suggests that inlet relative humidity is the dominant factor controlling freshwater productivity under the present operating conditions.

The increase in freshwater production reflects a progressive improvement in the utilization of the available refrigeration capacity rather than simply the presence of additional atmospheric moisture. Under low-humidity conditions, a considerable portion of the cooling capacity is consumed in conditioning the incoming air before effective condensation occurs. Consequently, only a limited fraction of the available refrigeration effect contributes directly to freshwater generation. As inlet humidity increases, a greater proportion of the available cooling capacity is utilized for moisture condensation, thereby increasing freshwater production without requiring modifications to the refrigeration system.

The observed trend agrees with previous studies demonstrating that atmospheric humidity strongly influences condensation performance. Zhang et al. [14] and Tu et al. [13] reported that increasing ambient humidity substantially enhanced freshwater production, while Mirmanto et al. [23] showed that improved evaporator heat and mass transfer increased condensate yield. However, quantitative differences exist among these studies because of variations in evaporator geometry, airflow conditions, refrigeration capacity, refrigerant type, and operating strategies. In contrast, the present study maintained identical refrigeration-system characteristics while varying only the inlet relative humidity, allowing the influence of humidity to be evaluated independently of other design variables.

Another important observation is that freshwater production did not increase proportionally with increasing relative humidity. Increasing RH from 30% to 50% increased freshwater production by approximately 51%, whereas a further increase from 50% to 70% produced only an additional 12% increase. This nonlinear behavior indicates that increasing atmospheric moisture alone cannot continuously enhance freshwater production. Instead, the condensation process gradually approaches the practical operating limit of the evaporator, causing additional moisture to produce progressively smaller improvements in condensate yield. Similar saturation behavior has been discussed in recent reviews of refrigeration-based atmospheric water harvesting technologies [20–22].

Overall, these results demonstrate that inlet air relative humidity governs not only the amount of freshwater produced but also the effectiveness with which the available refrigeration capacity is utilized for condensation. This finding provides a useful engineering basis for optimizing refrigeration-based atmospheric water harvesting systems operating in humid tropical climates, where maximizing condensation effectiveness is more critical than simply increasing the overall cooling capacity.

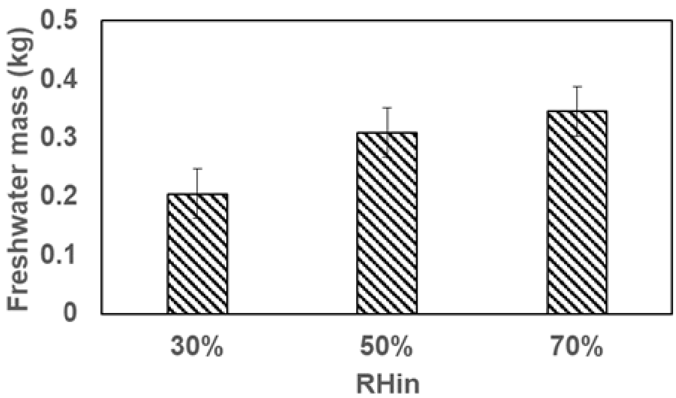

Figure 2. Average freshwater production under different inlet air relative humidity conditions. Error bars represent the standard deviation of three independent experiments.

3.2 Effect of inlet air relative humidity on the coefficient of performance (COP)

Figure 3 illustrates the variation in the coefficient of performance (COP) under different inlet air relative humidity conditions. The experimental results show that COP increased consistently with increasing inlet relative humidity, reaching 8.64, 9.95, and 12.19 at 30%, 50%, and 70% RH, respectively. Compared with the lowest humidity condition, the COP increased by approximately 41% at 70% RH, indicating a substantial improvement in the thermodynamic efficiency of the refrigeration-based atmospheric water harvesting system. This result demonstrates that humid operating conditions improve not only freshwater production (Section 3.1) but also the efficiency with which electrical energy is converted into useful refrigeration.

Unlike freshwater production, which reflects the amount of condensed water, COP represents the effectiveness of energy utilization within the refrigeration cycle. The higher COP observed at elevated humidity indicates that the additional cooling capacity generated by the evaporator was utilized more effectively without requiring a proportional increase in compressor power. In other words, the refrigeration effect increased more rapidly than the electrical energy consumption, resulting in improved system efficiency. This behavior is consistent with thermodynamic analyses of refrigeration-based atmospheric water harvesting systems reported in previous studies [24].

The increasing COP observed in the present study agrees with previous investigations reporting improved refrigeration performance under humid environmental conditions. Tu et al. [13] and Zhang et al. [14] showed that increasing ambient humidity enhanced system performance through improved condensation, whereas Kim et al. [10] and Wang et al. [6] emphasized the importance of enhanced evaporator heat-transfer characteristics in improving refrigeration efficiency. Although all of these studies reported positive effects of humidity, the magnitude of COP enhancement differs because of variations in evaporator geometry, refrigeration capacity, airflow rate, refrigerant type, and operating conditions. By maintaining identical system hardware and operating conditions while varying only the inlet relative humidity, the present study isolates the influence of humidity on system energy performance and minimizes the influence of other design variables.

Another important observation is that the increase in COP did not follow the same trend as freshwater production. While freshwater production exhibited a diminishing rate of increase at higher humidity (Section 3.1), COP improved by approximately 15% between 30% and 50% RH and by a further 23% between 50% and 70% RH. This difference suggests that water productivity and thermodynamic efficiency are not governed by identical mechanisms. As the evaporator approaches its practical condensation capacity, additional atmospheric moisture contributes progressively less to freshwater production, whereas the refrigeration cycle continues to utilize the available cooling capacity more efficiently. Consequently, the energetic benefit of operating under humid conditions becomes more evident in COP than in freshwater yield.

At the lowest humidity condition (30% RH), the refrigeration system operated less efficiently because a larger fraction of the cooling capacity was expended to condition the incoming air before effective condensation occurred. Consequently, the useful refrigeration effect associated with water production remained relatively low despite comparable compressor operation. Similar thermodynamic behavior has been reported by Mohan et al. [20], Li et al. [21], and Elsayad et al. [22], who concluded that humid climatic conditions improve refrigeration efficiency by increasing the proportion of cooling capacity effectively utilized for moisture condensation.

From an engineering perspective, these results indicate that improving COP requires not only favorable atmospheric humidity but also efficient utilization of the available refrigeration capacity. Therefore, future performance improvements should focus on reducing compressor energy consumption while enhancing evaporator effectiveness through improved surface geometry, airflow management, and condensate drainage. Such approaches are expected to provide greater gains in overall system efficiency than relying solely on naturally humid environmental conditions.

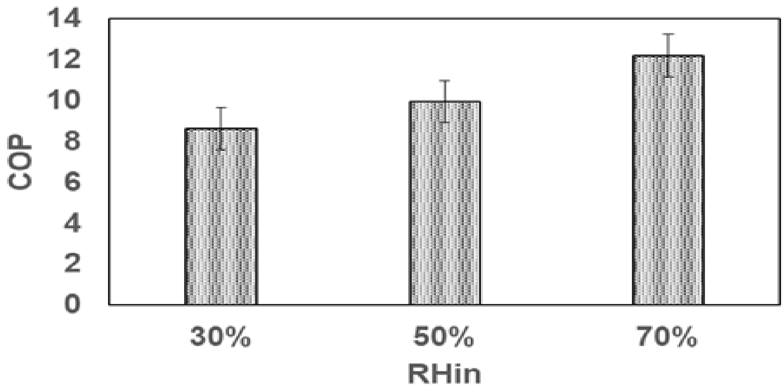

Figure 3. Average coefficient of performance (COP) of the refrigeration-based atmospheric water harvesting system under different inlet air relative humidity conditions. Error bars represent the standard deviation of three independent experiments.

3.3 Effect of inlet air relative humidity on the total heat absorbed by the evaporator

Figure 4 presents the total heat absorbed by the evaporator under different inlet air relative humidity conditions. The total heat transfer (Q_t) represents the combined thermal energy removed from the incoming air, including sensible cooling, latent heat released during condensation, and the cooling of the condensate. Unlike freshwater production and COP, which increased with relative humidity, the total heat absorbed by the evaporator decreased from 167.81 W at 30% RH to 143.94 W at 50% RH and 126.35 W at 70% RH. This inverse relationship indicates that total heat transfer alone cannot adequately describe the effectiveness of refrigeration-based atmospheric water harvesting systems.

The reduction in total heat absorbed despite higher freshwater production indicates a redistribution of the evaporator thermal load rather than a reduction in cooling capability. As discussed in Sections 3.1 and 3.2, increasing inlet humidity promotes condensation and improves refrigeration efficiency. Consequently, a larger proportion of the available refrigeration capacity is directed toward moisture removal instead of lowering the air temperature. The present results therefore suggest that system performance is governed not only by the magnitude of heat transfer but also by how efficiently that cooling capacity contributes to freshwater generation. This interpretation is supported by previous investigations. Wang et al. [6], Kim et al. [10], and Tu et al. [13] reported that operating conditions strongly influence the balance between sensible and latent heat transfer within the evaporator. Likewise, Li et al. [21] and Elsayad et al. [22] emphasized that humid atmospheric conditions modify evaporator energy utilization by increasing the contribution of condensation relative to air cooling. Although these studies primarily focused on freshwater production or overall system performance, the present results demonstrate that a reduction in total heat transfer can occur simultaneously with improved water productivity and higher COP. This apparent discrepancy arises because the effectiveness of the refrigeration system depends on the allocation of the available cooling capacity rather than on the absolute magnitude of heat removed.

Another noteworthy finding is that the highest total heat transfer (167.81 W) was obtained under the lowest humidity condition, where freshwater production and COP were the lowest. This result confirms that a larger thermal load does not necessarily correspond to better atmospheric water harvesting performance. Instead, it indicates that a substantial portion of the refrigeration capacity was expended on cooling the incoming air without producing a proportional increase in condensate. Conversely, under humid conditions, although the total heat absorbed decreased, a greater fraction of that energy contributed directly to moisture condensation, resulting in higher freshwater production and improved thermodynamic efficiency. Therefore, maximizing total heat transfer should not be regarded as the primary design objective for refrigeration-based atmospheric water harvesting systems.

From an engineering perspective, these findings suggest that evaluating evaporator performance solely on the basis of total heat transfer may lead to misleading conclusions. A more representative assessment should simultaneously consider total heat transfer, freshwater production, COP, and evaporator efficiency to determine how effectively the available refrigeration capacity is utilized. Such an integrated evaluation provides a more reliable basis for optimizing refrigeration-based atmospheric water harvesting systems operating under different climatic conditions, particularly in humid tropical regions where condensation effectiveness is more critical than maximizing the overall thermal load.

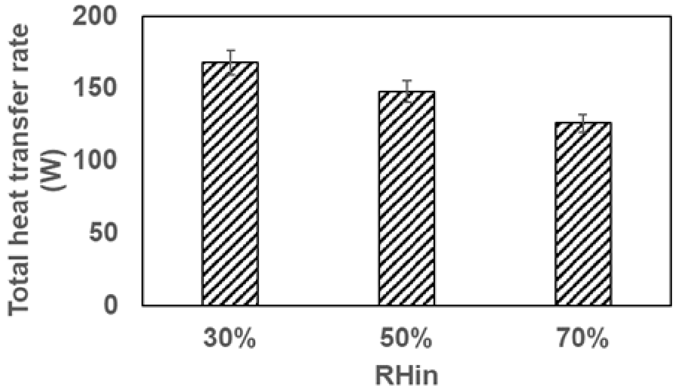

Figure 4. Average total heat transfer rate absorbed by the evaporator under different inlet air relative humidity conditions. Error bars represent the standard deviation of three independent experiments.

3.4 Effect of inlet air relative humidity on evaporator efficiency

Figure 5 presents the evaporator efficiency under different inlet air relative humidity conditions. The highest evaporator efficiency of 11.89% was obtained at 30% RH, whereas the efficiency decreased to 9.10% and 6.99% at 50% RH and 70% RH, respectively. Unlike freshwater production and COP, which increased with increasing inlet humidity, evaporator efficiency exhibited a continuous decline. This contrasting trend indicates that evaporator efficiency reflects a different aspect of system performance and therefore should not be interpreted in isolation.

The decrease in evaporator efficiency is closely associated with changes in the distribution of thermal energy within the evaporator rather than with a deterioration of its heat-transfer capability. As discussed in the previous sections, increasing inlet humidity enhanced freshwater production and improved COP by utilizing a greater fraction of the available refrigeration capacity for condensation. Consequently, the reduction in evaporator efficiency observed in the present study reflects a change in the mode of energy utilization rather than a loss of refrigeration performance. Similar behavior has been reported for refrigeration systems operating under different humidity conditions, where evaporator performance depends strongly on the balance between sensible and latent heat transfer [6,10,24].

An important implication of these results is that evaporator efficiency and system productivity do not necessarily follow the same trend. The highest evaporator efficiency was obtained at 30% RH, whereas the maximum freshwater production and COP occurred at 70% RH. This finding demonstrates that maximizing evaporator efficiency alone does not necessarily maximize freshwater generation. Instead, the effectiveness of an atmospheric water harvesting system should be evaluated according to how efficiently the available refrigeration capacity is converted into condensate rather than solely by conventional evaporator performance indicators. Similar observations have been reported by Zhang et al. [14], Kim et al. [10], and Mirmanto et al. [23], who showed that humid operating conditions improve water production even though the heat-transfer characteristics of the evaporator may differ substantially from those under drier conditions.

Another noteworthy observation is that the decrease in evaporator efficiency occurred simultaneously with reductions in the total heat absorbed by the evaporator (Section 3.3). This relationship suggests that increasing atmospheric humidity modifies the distribution of the refrigeration load instead of simply increasing the amount of heat transferred. Consequently, a lower evaporator efficiency should not be interpreted as evidence of poorer system performance but rather as an indication that the refrigeration cycle is operating under conditions where moisture condensation becomes the dominant objective. This interpretation is consistent with previous thermodynamic and psychrometric analyses of refrigeration-based atmospheric water harvesting systems [24].

From an engineering perspective, these findings indicate that evaporator efficiency should not be used as the sole performance indicator for refrigeration-based atmospheric water harvesting systems. A comprehensive evaluation should simultaneously consider evaporator efficiency, freshwater production, COP, and total heat transfer to determine how effectively the available refrigeration capacity is utilized under different environmental conditions. Such an integrated assessment provides a more appropriate basis for optimizing evaporator design and operating strategies, particularly for systems intended to operate in humid tropical climates where maximizing condensation efficiency is more important than maximizing sensible cooling.

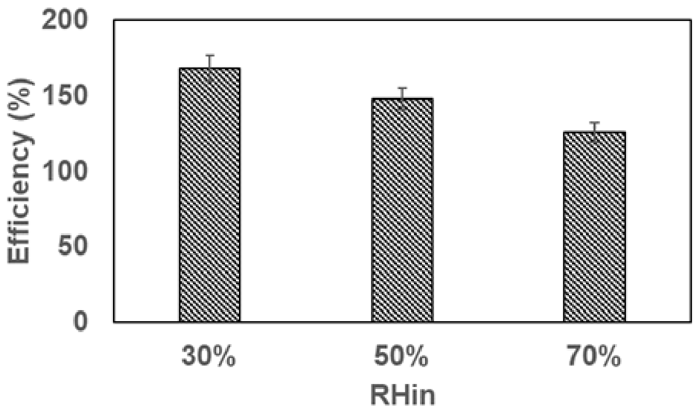

Figure 5. Average evaporator efficiency under different inlet air relative humidity conditions. Error bars represent the standard deviation of three independent experiments.

3.5 Overall thermodynamic interpretation and engineering implications

The combined experimental results demonstrate that inlet air relative humidity simultaneously influences freshwater production, coefficient of performance (COP), total heat transfer rate, and evaporator efficiency through different but interconnected thermodynamic mechanisms. Increasing the inlet relative humidity from 30% to 70% enhanced freshwater production by approximately 68% and increased COP by about 41%, whereas the total heat absorbed by the evaporator and evaporator efficiency decreased progressively. At first glance, these trends appear contradictory because conventional refrigeration analysis often associates higher heat transfer with improved system performance. However, the present results demonstrate that the performance of a refrigeration-based atmospheric water harvesting system cannot be adequately evaluated using a single thermodynamic parameter. Instead, the interaction among freshwater production, energy efficiency, and heat-transfer characteristics must be considered simultaneously.

A key finding of this study is that increasing atmospheric humidity changes the effectiveness with which the available refrigeration capacity is utilized rather than simply increasing the magnitude of heat transfer. Under relatively dry conditions, a substantial fraction of the refrigeration capacity is associated with cooling the incoming air, resulting in higher total heat transfer and higher evaporator efficiency. As humidity increases, a progressively larger fraction of the available cooling capacity contributes directly to moisture condensation. Consequently, freshwater production and COP continue to improve even though the total heat absorbed by the evaporator decreases. This observation indicates that the thermodynamic effectiveness of refrigeration-based atmospheric water harvesting systems is governed more by the distribution of refrigeration capacity between sensible and latent heat transfer than by the total amount of heat removed from the air. This integrated interpretation extends the individual observations presented in Sections 3.1–3.4 and provides a more comprehensive explanation of system behavior under varying humidity conditions.

The comparison with previous studies further supports this interpretation. Earlier investigations generally reported that increasing atmospheric humidity enhances freshwater production and improves refrigeration performance [13,14,23]. Other studies also discussed the influence of humidity on evaporator heat-transfer characteristics and refrigeration efficiency [6,10,20–22]. However, these studies mainly evaluated individual performance indicators independently. By simultaneously examining freshwater production, COP, total heat transfer, and evaporator efficiency under identical refrigeration-system operating conditions, the present study demonstrates how these parameters interact and explains why improvements in freshwater productivity may occur concurrently with reductions in total heat transfer and evaporator efficiency. This integrated thermodynamic interpretation provides a clearer framework for understanding the performance of refrigeration-based atmospheric water harvesting systems than considering each performance indicator separately.

From an engineering perspective, the present findings suggest that maximizing freshwater production should not be pursued by increasing cooling capacity alone. Instead, greater performance improvements are likely to be achieved by enhancing the fraction of refrigeration capacity utilized for moisture condensation. Practical approaches include optimizing evaporator geometry, increasing the effective heat-transfer area, improving airflow distribution, promoting rapid condensate drainage, and modifying surface characteristics to encourage stable dropwise condensation. Such strategies may increase freshwater productivity while maintaining high energy efficiency, particularly in humid tropical climates where atmospheric moisture is abundant.

Despite these contributions, several limitations should be acknowledged. The experiments were conducted using a single refrigeration system, fixed evaporator geometry, constant airflow velocity, and three discrete inlet relative humidity levels under controlled laboratory conditions. Consequently, the observed thermodynamic behavior may differ under variable climatic conditions, alternative refrigerants, different evaporator configurations, or dynamic operating environments encountered in practical applications. Furthermore, the present study focused on short-term system performance and did not investigate long-term operational issues such as condensate fouling, frost formation, or changes in evaporator surface characteristics. Future studies should therefore examine the combined effects of relative humidity, airflow velocity, evaporator design, and refrigeration capacity under a wider range of environmental conditions while incorporating long-term performance evaluation and optimization techniques. Such investigations would provide a more comprehensive basis for the development of high-efficiency refrigeration-based atmospheric water harvesting systems.

4. Conclusion

This study experimentally investigated the effect of inlet air relative humidity on the thermodynamic performance of an air-water harvester employing a vapor-compression refrigeration system. The experimental results demonstrated that inlet relative humidity is a key operating parameter governing freshwater production, refrigeration performance, and heat-transfer characteristics. Increasing the inlet relative humidity from 30% to 70% significantly enhanced the condensation process, resulting in the highest freshwater production of 0.345 kg and the highest coefficient of performance (COP) of 12.19 at 70% RH. These improvements were attributed to the greater moisture content in the incoming air, which promoted latent heat transfer and increased condensation on the evaporator surface. In contrast, the highest total heat absorbed by the evaporator (167.81 W) and the highest evaporator efficiency (11.89**%**) were obtained at 30% RH because the evaporator cooling capacity was primarily utilized for sensible cooling of dry air rather than moisture condensation. The results indicate that although lower humidity increases sensible heat removal, it does not improve freshwater productivity or overall energy performance.

Overall, the findings demonstrate a clear trade-off between sensible and latent heat transfer under different humidity conditions. High-humidity environments favor latent heat transfer, leading to greater water production and higher energy efficiency, whereas low-humidity conditions mainly enhance sensible cooling. These results provide useful guidance for optimizing refrigeration-based atmospheric water harvesting systems and suggest that such systems are particularly suitable for humid tropical regions, where they can achieve high freshwater productivity with relatively efficient energy utilization.

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