Arab Academy for Science, Technology, and Maritime Transport
The International Maritime and Logistics Conference "**MARLOG 14**"
"Artificial Intelligence Implementations
Towards Shaping the Future of Digital World"
23 – 25 February 2025

PERFORMANCE COMPARISON OF ATMOSPHERIC WATER GENERATORS USING BUCKINGHAM PI THEOREM AND DIMENSIONLESS ANALYSIS

Mahmoud S. Baioumi [(1)*], Ahmed A. Hanafy [(2)] and Hassan A. ElGamal [(3)]

(1) Mechanical Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, P.O. 1029, Aboukir, Alexandria, Egypt.
MSSBaioumi@aast.edu

(2) Mechanical Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, P.O. 1029, Aboukir, Alexandria, Egypt.
a_a_hanafy@aast.edu

(3) Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt.
Hassan.elgamal@alexu.edu.eg

Keywords: Atmospheric Water Generator (AWG); Water scarcity; Buckingham Pi Theorem; Sustainable water solutions; Vapor Compression Cycle (VCC); Dimensionless Analysis.

ABSTRACT: Access to clean drinking water remains a global challenge, exacerbated by population growth, urbanization, and climate change. This issue is particularly critical in maritime environments, where ships, ports, and offshore facilities face limited access to freshwater resources. Atmospheric Water Generators (AWGs), which extract water from air humidity, offer a sustainable solution. Rising demand for AWGs in regions such as the Middle East and Asia Pacific highlights their importance in addressing water scarcity. The present study presents the development of an AWG prototype using the Vapor Compression Cycle (VCC), designed to enhance water production efficiency and minimize energy consumption. The system integrates a PCB and DHT-22 sensors to monitor temperature and humidity, with data collected via Arduino and displayed using LabVIEW. To ensure a fair comparison with similar AWG systems, Buckingham Pi Theorem was applied for dimensionless analysis, normalizing variables such as temperature, humidity, air velocity, surface area, and water collection rate. The performance of the developed prototype was systematically compared to other AWG systems from the literature, all evaluated under similar average environmental conditions of 22–24°C temperature and 60–63% relative humidity. Reported performance metrics from studies on AWG systems indicate water generation rates ranging between 0.95 and 1.78 L/hr, with energy consumption values of 0.75–0.84 kWh/L. In contrast, the developed AWG prototype demonstrated a water generation rate of 2.1 L/hr with an energy consumption of 0.73 kWh/L, showing significantly improved performance. These results validate the efficiency of the improved design and demonstrate its superiority under equivalent conditions. The findings underscore the potential of the developed AWG prototype to advance AWG technology, providing a sustainable solution to water scarcity in maritime contexts while conserving energy and minimizing reliance on external water sources.

1. INTRODUCTION

Atmospheric Water Generators (AWGs) are advanced systems designed to condense water from ambient air using the Vapor Compression Cooling (VCC) cycle. The VCC Cycle is preferred over other methods due to its superior efficiency in extracting water from air, scalability for various applications, and compatibility with renewable energy sources, making it both cost-effective and environmentally sustainable. It can also be powered by renewable energy sources such as wind turbines and solar panels, alongside conventional electricity. The results obtained from AWG systems highlight the relationship between water production rates, temperature, humidity, and electricity consumption, highlighting the prototype's efficiency [1]. To ensure comprehensive evaluation and comparison, the Buckingham Pi Theorem and Dimensionless Analysis are employed to reduce variables into dimensionless parameters, or Pi terms. This approach transforms performance-influencing variables into manageable groups, enabling comprehensive analysis and facilitates unbiased comparisons across different systems and conditions, enabling insights into performance under equivalent operating environments [2]. The application of these methods allows for evaluating both the developed AWG prototype and existing systems, identifying advancements and areas for improvement. After reviewing studies employing the VCC cycle, only those with comparable parameters, including temperature, air speed, relative humidity, water production rate, and characteristic length, as detailed in the Theoretical Work section were selected. These parameters provided a robust basis for assessing the performance of the AWG prototype against existing systems under equivalent conditions.

2. LITERATURE REVIEW

The following literature review provides detailed insights into existing studies and findings utilizing the Vapor Compression Cycle (VCC) in AWG systems. Patel et al. [3] developed an Atmospheric Water Extracting (AWE) device using a vapor compression refrigeration cycle (VCC), which condenses air moisture on the evaporator coil based on psychrometric conditions. They tested the device in a climatic chamber under seven conditions: humid and warm, humid, and mild, humid, and cold, dry, and warm, dry and mild, mild, and mild humid and warm. The device had a minimum energy intensity of 0.75 kWh/L at a rate of 1.78 L/hr in warm-humid conditions and a maximum of 4.71 kWh/L at a rate of 0.28 L/hr in mild-dry conditions. They found that AWE devices are most effective in hot and humid regions. Alsheekh et al. [4] made experimental, theoretical, and numerical study of air purification and water generation by air conditioning and refrigeration equipment. Their unit was based on a standard compressive cooling cycle principle. Their experimental setup was established and tested for different days with different climatic conditions, during September and August. Their theoretical data were accomplished by the (EES) program and the Numerical study by (ANSYS 2020R2) to verify and study more cases in a short period of time. Their maximum production rate was 45.7 L/Day with the system's coefficient of performance (COP) of 3.4. Ahmad et al. [5] aimed to evaluate the performance of atmospheric water generators (AWG) under hot and humid climate conditions to address the problem of freshwater scarcity. Their research was based on three basic approaches. Primary data was collected by measuring the AWG's daily water output, temperature, and humidity over a year. The field study was conducted in Sharjah, UAE, under real outdoor conditions. The results showed that both air humidity and temperature significantly impact the water extraction rate. The device achieved a maximum water generation rate of 0.95 L/hr in February with energy consumption of 0.84 kWh/L, and the minimum rate of 0.13 L/hr in January with 1.98 kWh/L energy consumption. The ideal operating conditions for the machine were 22°C and 63% relative humidity. Their study concluded that AWG technology could be a viable solution for water scarcity in regions with appropriate environmental conditions. While these studies demonstrate the potential of VCC-based AWG systems, significant challenges persist in enhancing efficiency and minimizing energy consumption. The present research addresses these challenges by introducing a novel AWG prototype, enhanced the water production and reduced the energy usage. Leveraging the Buckingham Pi Theorem for dimensional analysis, the present study systematically compares the prototype's performance with existing systems, providing a valuable contribution to the advancement of sustainable AWG technology.

3. THEORETICAL WORK

The Buckingham Pi Theorem provides a robust framework for understanding and comparing physical systems across varying experimental conditions and scales with theoretical predications. By reducing variables into dimensionless Pi terms, the theorem facilitates comparative analysis, exposing critical relationships between system parameters. This method is particularly effective in analyzing the performance of Atmospheric Water Generators (AWGs) under diverse environmental conditions [6]. **Figure 1** illustrates the theoretical operation of the Atmospheric Water Generator (AWG), showcasing its main components and the process flow for water generation through the Vapor Compression Cycle.

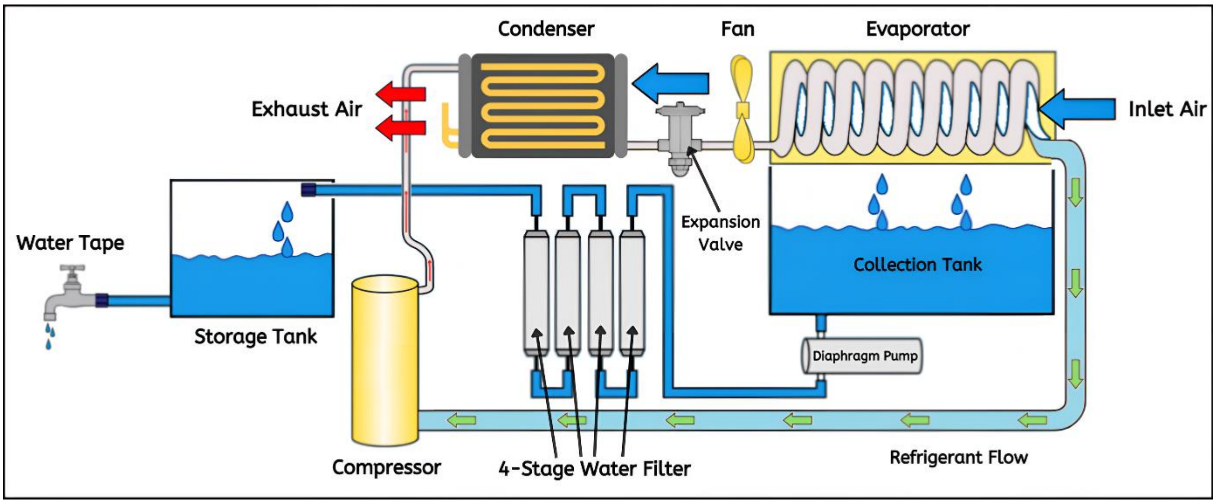


Figure 1: Schematic diagram of the Atmospheric Water Generator using VCC

The Buckingham Pi Theorem was applied after extracting results from the developed prototype. A thorough search identified three relevant studies employing the same water harvesting technique. These studies met the following criteria:

1. Sufficient experimental trials detailing the amount of water produced in each trial.
2. Documentation of the weather conditions (temperature and relative humidity) for each trial, along with the water production and electricity consumption.
3. Utilization of the same Vapor Compression Cycle (VCC) harvesting technique [7].

Using these selected works, the Buckingham Pi Theorem and Dimensionless Analysis were applied. Pi groups were created, and key parameters for comparison were identified. For each research paper, Pi groups were formed based on reported results and parameters such as temperature, prototype dimensions, characteristic length, density, relative humidity, water harvested, and electricity consumed. These Pi groups were then aligned with the main parameters used for comparison.

Subsequently, the main parameters (Pi groups) from each previous work were compared to the present results using MATLAB, employing 3D plotting for visualization [8]. The development of the Pi equations involved the careful selection of suitable and common comparison parameters. These parameters (Temperature, Relative Humidity, and Reynolds Number relative to the Amount of Water harvested) were chosen to effectively demonstrate the device's efficiency in a rigorous and standardized manner. The results demonstrated the superiority of the developed AWG prototype. Specifically, the prototype achieved a water generation rate of 2.1 L/hr with an energy consumption of 0.73 kWh/L, significantly outperforming the other systems. In comparison, one study reported a maximum generation rate of 1.78 L/hr with 0.75 kWh/L, another achieved 1.9 L/hr (45.7 L/day) with a COP of 3.4, and a third recorded a peak rate of 0.95 L/hr with 0.84 kWh/L energy consumption. These findings validate the prototype's optimized design, demonstrating its superior efficiency under equivalent conditions. The MATLAB-employed 3D plots (detailed in Section 5.1.1) further illustrate the prototype's performance advantage. These visualizations compare the dimensionless Pi groups derived from the prototype and the referenced studies, highlighting consistent superiority in water production and energy efficiency.

The variables considered are Q, P, RH, T, L, ρ, μ, V, and Cp which are the amount of water harvested (Volume flow rate), power consumption, relative humidity, temperature, characteristic length, density, dynamic viscosity, velocity of air and the specific heat respectively. The dimensions considered are M, L, t, and K which are the mass, length, time, and temperature respectively. The suitable parameters as dimensions are V, ρ, μ and T which are the air velocity, density, viscosity, and temperature respectively. We can thus proceed as follows:

Number of variables **(n)** = **9**, Number of dimensions required **(k)** = **4**, therefore the **Pi** terms are as follows:

n – **k** = **9** – **4** = **5 Π** terms.

Therefore: $\mathbf{\Pi_1} = P\,(V^{a1}\,\rho^{b1}\,\mu^{c1}\,T^{d1})$, $\mathbf{\Pi_1} = (M\,L^2\,t^{-3})\,(L\,t^{-1})^{a1}\,(M\,L^{-3})^{b1}\,(M\,L^{-1}\,t^{-1})^{c1}\,(K)^{d1}$

M: $1+b_1+c_1=0$, L: $2+a_1-3b_1-c_1=0$, t: $-3-a_1-c_1=0$, K: $\boxed{\mathbf{d_1=0}}$, $\boxed{\mathbf{c_1=-2}}$, $\boxed{\mathbf{a_1=-1}}$, $\boxed{\mathbf{b_1=1}}$ (1)

So, $\mathbf{\Pi_1} = P\,(V^{-1}\,\rho\,\mu^{-2}\,T^0)$, That is; $\mathbf{\Pi_1} = \frac{P\,\rho}{V\,\mu^2}$ (2)

Repeating the same for: $\mathbf{\Pi_2} = Q\,(V^{a2}\,\rho^{b2}\,\mu^{c2}\,T^{d2})$, $\mathbf{\Pi_2} = (L^3\,t^{-1})\,(L\,t^{-1})^{a2}\,(M\,L^{-3})^{b2}\,(M\,L^{-1}\,t^{-1})^{c2}\,(K)^{d2}$

M: $b_2+c_2=0$, L: $3+a_2-3b_2-c_2=0$, t: $-1-a_2-c_2=0$, K: $\boxed{\mathbf{d_2=0}}$, $\boxed{\mathbf{c_2=-2}}$, $\boxed{\mathbf{a_2=1}}$, $\boxed{\mathbf{b_2=2}}$ (3)

So, $\mathbf{\Pi_2} = Q\,(V\,\rho^2\,\mu^{-2}\,T^0)$, That is; $\mathbf{\Pi_2} = \frac{Q\,V\,\rho^2}{\mu^2}$ (4)

The same for: $\mathbf{\Pi_3} = RH\,(V^{a3}\,\rho^{b3}\,\mu^{c3}\,T^{d3})$, $\mathbf{\Pi_3} = (M^0\,L^0\,t^0\,K^0)\,(L\,t^{-1})^{a3}\,(M\,L^{-3})^{b3}\,(M\,L^{-1}\,t^{-1})^{c3}\,(K)^{d3}$

M: $b_3+c_3=0$, L: $a_3-3b_3-c_3=0$, t: $-a_3-c_3=0$, K: $\boxed{\mathbf{d_3=0}}$, $\boxed{\mathbf{c_3=0}}$, $\boxed{\mathbf{a_3=0}}$, $\boxed{\mathbf{b_3=0}}$ (5)

So, $\mathbf{\Pi_3} = RH\,(V^0\,\rho^0\,\mu^0\,T^0)$, That is; $\mathbf{\Pi_3} = RH$ (6)

Also, the same for: $\mathbf{\Pi_4} = Cp\,(V^{a4}\,\rho^{b4}\,\mu^{c4}\,T^{d4})$, $\mathbf{\Pi_4} = (L^2\,t^{-2}\,K^{-1})\,(L\,t^{-1})^{a4}\,(M\,L^{-3})^{b4}\,(M\,L^{-1}\,t^{-1})^{c4}\,(K)^{d4}$

M: $b_4+c_4=0$, L: $2+a_4-3b_4-c_4=0$, t: $-2-a_4-c_4=0$, K: $-1+d_4=0$, $\boxed{\mathbf{d_4=1}}$, $\boxed{\mathbf{c_4=0}}$, $\boxed{\mathbf{a_4=-2}}$, $\boxed{\mathbf{b_4=0}}$ (7)

So, $\mathbf{\Pi_4} = Cp\,(V^{-2}\,\rho^0\,\mu^0\,T^1)$, That is; $\mathbf{\Pi_4} = \frac{Cp\,T}{V^2}$ (8)

Finally, the same for: $\mathbf{\Pi_5} = L\,(V^{a5}\,\rho^{b5}\,\mu^{c5}\,T^{d5})$, $\mathbf{\Pi_5} = (L)\,(L\,t^{-1})^{a5}\,(M\,L^{-3})^{b5}\,(M\,L^{-1}\,t^{-1})^{c5}\,(K)^{d5}$

M: $b_5+c_5=0$, L: $1+a_5-3b_5-c_5=0$, t: $-a_5-c_5=0$, K: $d_5=0$, $\boxed{\mathbf{d_5=0}}$, $\boxed{\mathbf{c_5=-1}}$, $\boxed{\mathbf{a_5=1}}$, $\boxed{\mathbf{b_5=1}}$ (9)

So, $\mathbf{\Pi_5} = L\,(V^1\,\rho^1\,\mu^{-1}\,T^0)$, That is; $\mathbf{\Pi_5} = \frac{\rho\,V\,L}{\mu}$ (10)

Here are the Pi equations that were created and used for the dimensionless comparison:

$$\mathbf{\Pi_1} = \frac{P\,\rho}{V\,\mu^2}\ ,\ \mathbf{\Pi_2} = \frac{Q\,V\,\rho^2}{\mu^2}\ ,\ \mathbf{\Pi_3} = RH\ ,\ \mathbf{\Pi_4} = \frac{Cp\,T}{V^2}\ ,\ \mathbf{\Pi_5} = \frac{\rho\,V\,L}{\mu} = \mathrm{Re}$$

Therefore: $\mathbf{Q'} = \frac{\Pi 2}{\Pi 5^{\,2}}$, $\mathbf{P'} = \frac{\Pi 1}{\Pi 5^{\,2}}$, That is; $\mathbf{Q'} = \frac{\mathrm{Q}}{\mathrm{L}^2\,V}$, $\mathbf{P'} = \frac{\mathrm{P}}{\rho\ \mathrm{V}^3\,\mathrm{L}^2}$ (11)

Where $\mathbf{Q'}$, $\mathbf{P'}$, RH, $\frac{Cp\,T}{V^2}$, and Re are the dimensionless volume flow rate, the dimensionless power consumption, the relative humidity, the dimensionless temperature, and Reynolds number respectively.

Therefore: $\frac{\mathbf{Q}}{\mathbf{L^2}\,V} = \mathbf{f}\,\left(\frac{\mathrm{P}}{\rho\,\mathrm{V}^3\,\mathrm{L}^2}\right.$, RH, $\frac{Cp\,T}{V^2}$, Re) (12)

The dimensionless relations above allowed for a comprehensive and standardized comparison of different AWG systems, ensuring that the results were not influenced by varying operational conditions or scales. This approach ensures that the fundamental relationships governing the system are not obscured by variations in experimental conditions or scales. Consequently, it enhances the validity and generality of the comparative analysis, providing a solid foundation for evaluating and optimizing the performance of the Atmospheric Water Generators (AWGs) in the present study [9].

4. EXPERIMENTAL WORK

The experimental setup for the present study involves the construction and operation of an Atmospheric Water Generator (AWG) system within a controlled environment. The setup allows for the systematic variation of temperature and humidity, enabling precise data collection on key parameters such as temperature, humidity, airflow, and water production rates. These measurements are critical for calculating dimensionless parameters, including the Reynolds number and the dimensionless temperature, which provide a basis for comparing the results with other studies. The design of the AWG system emphasizes safety and sustainability, adhering to stringent user safety protocols and ensuring that the produced water meets World Health Organization (WHO) standards for potable water quality [10]. Furthermore, the system's design aligns with Sustainable Development Goals (SDGs), specifically

SDG 6 (Clean Water and Sanitation) [11], SDG 7 (Affordable and Clean Energy) [12], and SDG 13 (Climate Action) [13], underscoring its contribution to broader environmental and social objectives [14].

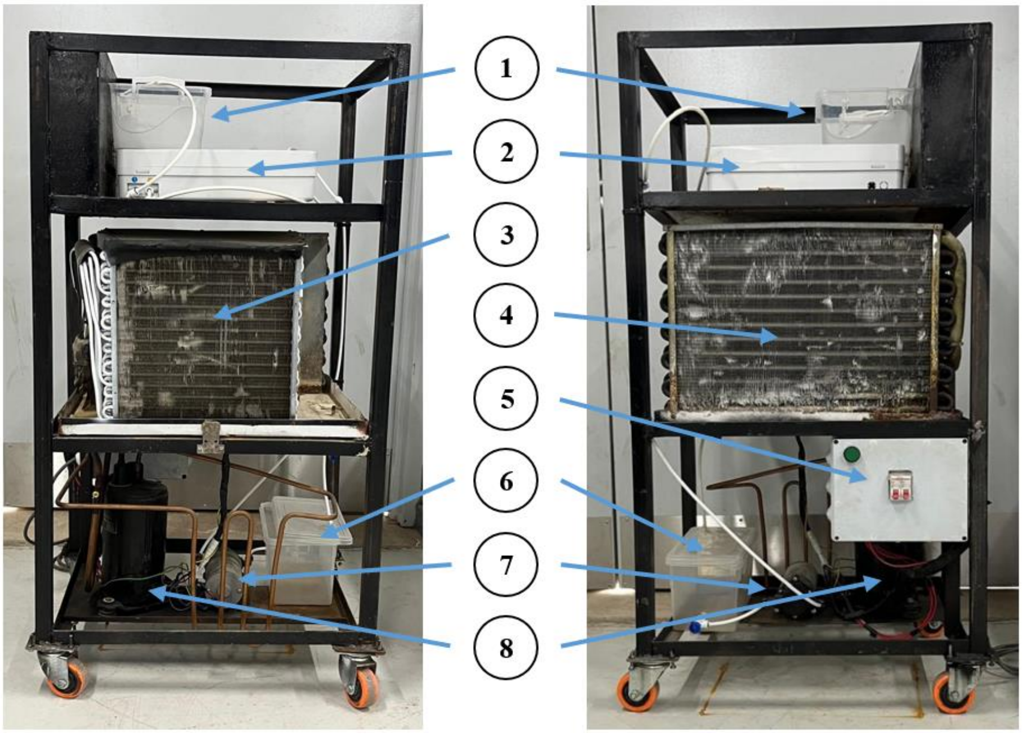
4.1. Experimental Setup

Several studies have conducted research using prototypes of varying sizes and capacities under different environmental conditions. To ensure fair and generalized comparisons across these studies, the Buckingham Pi Theorem was employed. This method enables dimensionless analysis, allowing results from diverse systems and conditions to be effectively compared, providing a robust foundation for evaluating the performance of the developed AWG system. The experimental setup for the present study focuses on the implementation of an Atmospheric Water Generator (AWG) system utilizing Vapor Compression Cooling (VCC) technology to extract water from ambient air through condensation. The system comprises key components, including a compressor, condenser, expansion valve, and evaporator, all operating within a classical refrigeration cycle to lower the air's dew point and facilitate water vapor condensation [15]. The condensed water is collected in a tank and pumped through a four-stage water filter designed to remove rust, impurities, odors, and taste before being stored in a tank for drinking and human use. To ensure precise monitoring and control, a printed circuit board (PCB) was developed, integrating DHT-22 sensors for temperature and relative humidity measurements at critical points, thermocouples for temperature readings, hygrometers for relative humidity, an airflow meter to measure air movement, and a graduated cylinder measures the mass of water collected. An Arduino-based system collects data from these sensors, which are displayed via a LabVIEW interface, and recorded in an Excel spreadsheet for further analysis. The system is designed to operate using various energy sources, including photovoltaic panels for solar power, a Savonius turbine for wind energy, and conventional electrical outlets, with a daily water production goal of at least 7 liters of drinkable water. Emphasis is placed on optimizing water production efficiency to minimize energy consumption, aligning with sustainability goals. The conducted work and comparative analyses were grounded in a comprehensive survey of prior research on AWG systems, particularly those employing the VCC technique. The Buckingham Pi Theorem was applied to ensure a fair comparison of the developed prototype against existing systems. Few research papers published detailed results concerning water harvesting, with most studies providing only average or overall water generation rates for entire experiments. Therefore, only studies that provided detailed parameters such as water production, temperature, relative humidity, and energy consumption for each experimental run were selected. These selected studies formed the basis for the comparative evaluation, highlighting the developed system's enhanced performance and efficiency. As shown in **Figure 2**, the numbered components will be discussed in the following context. The numbers correspond to the following elements:

1. **[Storage Tank]**: Stores the purified water produced by the AWG system, ready for use.
2. **[4-Stage Water Filter]**: A multi-stage filter that removes impurities from the condensed water.
3. **[Evaporator]**: Cools the air below the dew point to condense water vapor into liquid.
4. **[Condenser]**: Releases the heat absorbed during the process, completing the refrigeration cycle.
5. **[Control Panel]**: Contains system wiring, switches, and push button.
6. **[Collection Tank]**: Gathers the condensed water before it is pumped to the filtration system.
7. **[Diaphragm Pump]**: Transfers the collected water from the collection tank to the water filter.
8. **[Compressor]**: Compresses the refrigerant, driving the cooling cycle that enables water condensation [16].

The system's dimensions and component specifications were calculated to ensure optimal performance:

A. **Condenser**: The condenser measures 0.52 m in **width**, 0.36 m in **height**, and 0.11 m in **thickness**, designed to efficiently release heat and facilitate the condensation of water vapor.
B. **Evaporator**: The evaporator is sized at 0.36 m in **width**, 0.35 m in **height**, and 80 mm in **thickness**, optimized to lower the air's dew point and enhance the condensation process.
C. **Compressor**: The compressor is **rated** at **1700** W of power, selected for its ability to maintain the necessary pressure within the system.
D. **Suction Fan**: The suction fan operates with an **average air speed** of **2.4** m/s and provides a sufficient airflow rate to ensure adequate airflow through the system, maximizing condensation efficiency.



[A] [B]

Figure 2: **[A] Air Inlet** of Atmospheric Water Generator, and **[B] Air Outlet** of Atmospheric Water Generator

4.2. Methodology

Three sensors were mounted on the evaporator face, arranged in an inverted triangular pattern with sufficient spacing to cover the entire surface area as shown in **Figure 3**. This layout was determined after an extensive review of studies exploring optimal sensor configurations for three-sensor systems [17]. The chosen layout proved to be the most efficient for accurately capturing temperature and relative humidity data [18].

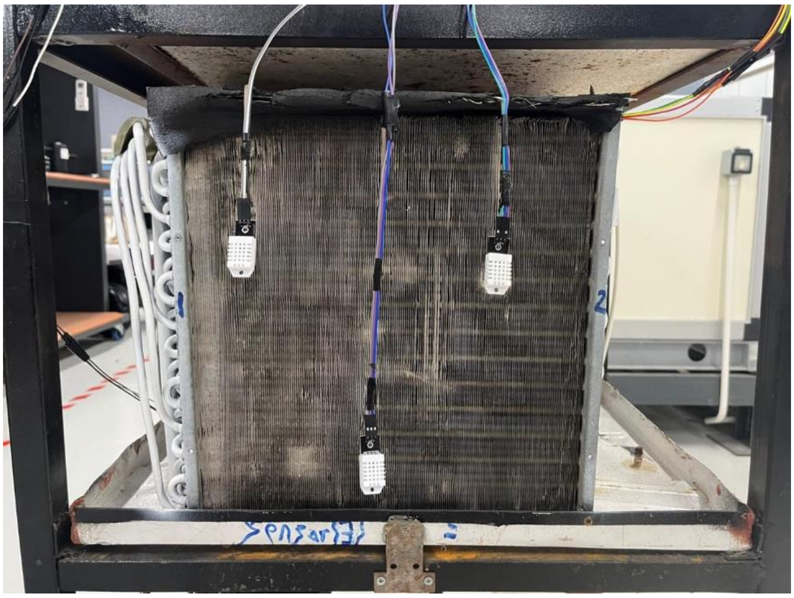


Figure 3: Inverted Triangular Sensor layout on the Evaporator's face

This configuration ensured accurate readings of the surrounding air before it entered the evaporator (i.e., the surrounding air). A similar arrangement of three sensors was installed in the section between the evaporator and condenser to measure the temperature and relative humidity of the air after passing over the evaporator's coils and fins. The air flowed through the system at an average speed of 2.4 m/s, driven by a suction fan positioned between the evaporator and condenser. Although airflow speed variations could occur, these do not significantly impact the results. As when applying the dimensionless analysis using the Buckingham Pi Theorem, the intent of the theorem is to generalize comparisons across all studies, making variations in airflow speed irrelevant. The evaporator coils, being below the dew point, facilitated the removal of moisture from the air and reduced its temperature. The condensed water was collected in a tank and measured at the end of each 1-hour trial using a graduated cylinder. Experimental trials were conducted under various environmental conditions. During periods of high relative humidity (RH), higher water production rates were observed, whereas lower RH levels resulted in reduced production. However, controlling environmental parameters was deemed unnecessary, as the Buckingham Pi Theorem was used to generalize the results. This ensures fair comparisons across different environmental conditions for each study. The final two sensors were positioned centrally on the condenser face to measure the outlet air temperature and relative humidity as the air exited the system. For each stage, the readings from the respective group of sensors were averaged to obtain a representative value. All sensors were connected to a printed circuit board (PCB) housing an Arduino Nano, which was used to analyze and optimize the collected data. The results were displayed via a LabVIEW interface and recorded in an Excel sheet for further analysis.

5. EXPERIMENTAL RESULTS

In **Figure 4**, the presented 3D graph offers a detailed comparison of water production rates in Atmospheric Water Generators (AWG) under varying environmental conditions, specifically the dimensionless temperature ($\frac{Cp\ T}{V^2}$) and relative humidity (RH). The vertical axis represents the dimensionless volume flow rate of water collected ($\frac{Q}{L^2\ V}$), which is a critical indicator of the system's efficiency in harvesting water from the air. This graph compares the performance of the AWG system developed in the present study, depicted by the author, with the results from three other research papers, represented by Patel et al. [3], AlSheekh et al. [4], and Ahmad et al. [5].

5.1. Comparative Analysis of Key Performance Factors

This comparative analysis utilizes the Buckingham Pi Theorem, a method for reducing complex systems to dimensionless groups, which enables the study of the main factors affecting system performance. In the present case, the theorem is applied to the factors of temperature (T), relative humidity (RH), and the water production rate (Q). These parameters correspond to dimensionless Pi groups:

A. **X-axis (Π_4)** is a critical factor influencing the water condensation process in Atmospheric Water Generators (AWGs). Higher temperatures generally increase the air's capacity to hold moisture, which can enhance condensation when the air is cooled below its dew point. In the present analysis, temperature is expressed as part of the dimensionless group $(\frac{Cp\,T}{V^2})$ in the Buckingham Pi Theorem.
B. **Y-axis (Π_3)** shows the relative humidity (RH) of the air, which significantly affects the amount of moisture available for condensation. Higher RH increases the potential water yield from the AWG system. In the Buckingham Pi Theorem framework, RH is represented as $\mathbf{\Pi_3}$ and is crucial for understanding how varying moisture content in the air impacts system performance.
C. **Z-axis (Π_2)** represents the dimensionless volume flow rate of water collected $(\frac{\mathrm{Q}}{\mathrm{L}^2\,V})$, a key measure of the AWG system's efficiency. Higher flow rates indicate better performance. In the present analysis, it is represented by $\mathbf{\Pi_2}$ and is an essential metric for comparing the effectiveness of various AWG systems.

5.1.1. Performance Evaluation of AWG Systems

The present results on the graph, display the results from the AWG system developed in the present study, consistently show the highest dimensionless volume flow rate $(\frac{\mathrm{Q}}{\mathrm{L}^2\,\mathrm{V}})$ across various combinations of dimensionless temperature $(\frac{\mathrm{Cp\,T}}{\mathrm{V}^2})$ and relative humidity (RH). The results demonstrate the effectiveness of the prototype developed in the present research, as indicated by its performance relative to the systems represented by Patel et al. [3], AlSheekh et al. [4], and Ahmad et al. [5].

AlSheekh et al. [4] results are closest to the present results, indicating that their results are relatively comparable to those of the prototype developed in the present study. However, they still fall short in terms of water production, especially under conditions where the present results show significant spikes in volume flow rate. Patel et al. [3] also shows relatively good performance but remains consistently below both the present results and that of AlSheekh et al. [4]. This suggests that while the system represented by Patel et al. [3] is effective, it does not match the efficiency of the prototype in the present study, particularly at higher temperatures and relative humidity levels. Ahmad et al. [5] present a system that produces significantly lower water volumes across all tested conditions. This system's performance is the least comparable to the prototype developed in the present study, underscoring the superiority of the design and experiments carried out in the present research as explained in section 5 (Experimental Results).

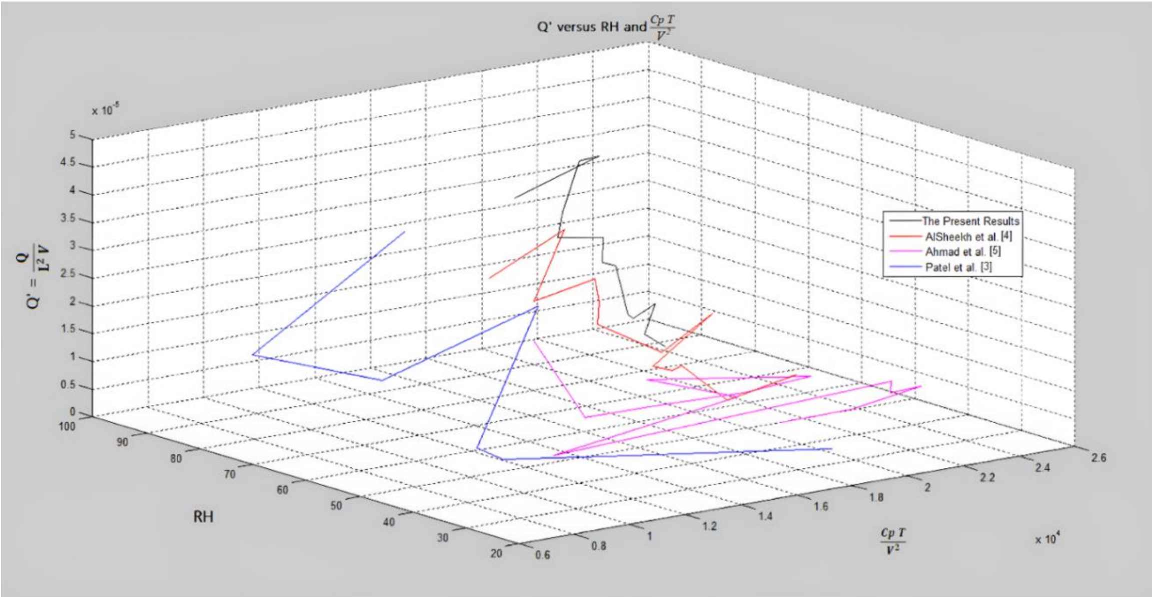


Figure 4: 3D Line Plot - Relation between Dimensionless Volume Flow Rate (Q') versus RH and Dimensionless Temperature

The comparison clearly demonstrates that the AWG system developed in the present research exhibits superior performance in terms of water production, even under the same conditions of temperature and relative humidity. The present results demonstrate superior performance over other systems across all tested conditions, highlighting the effectiveness of the design choices and conditions implemented in the present prototype. **Figure 4** has been remodeled using polynomial fitting, as shown in **Figure 5**.

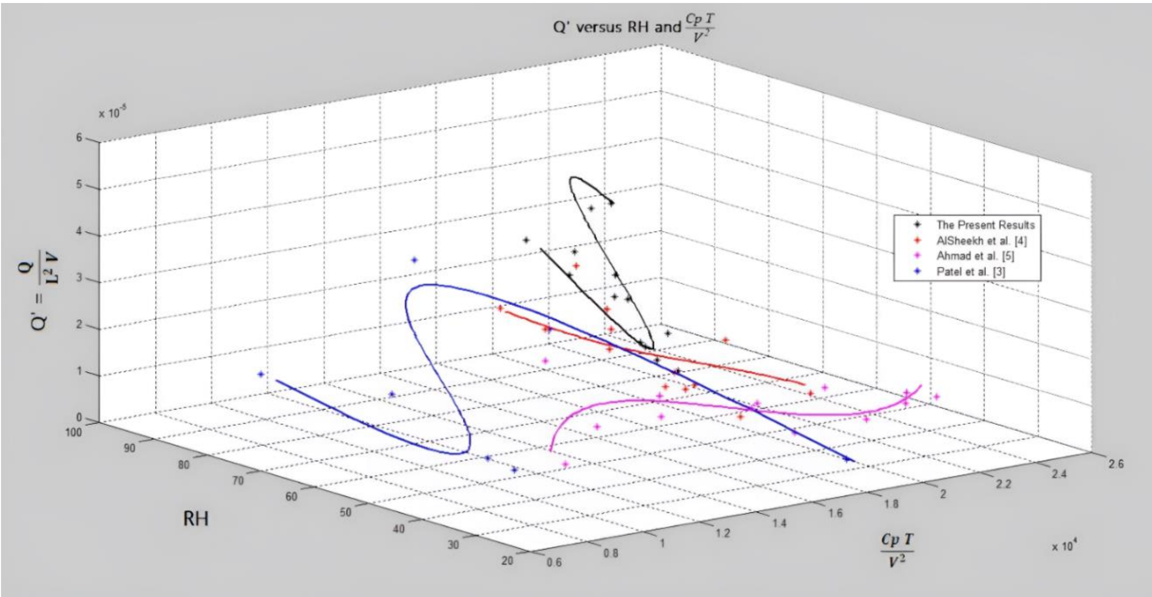


Figure 5: 3D Polynomial Fit Analysis of Dimensionless Volume Flow Rate (Q') versus RH and Dimensionless Temperature

Furthermore, to provide a more comprehensive visualization, a 3D surface contour representation has been developed and presented in **Figures 6** and **7** with different views, offering deeper insights into the relationships and variations within the data.

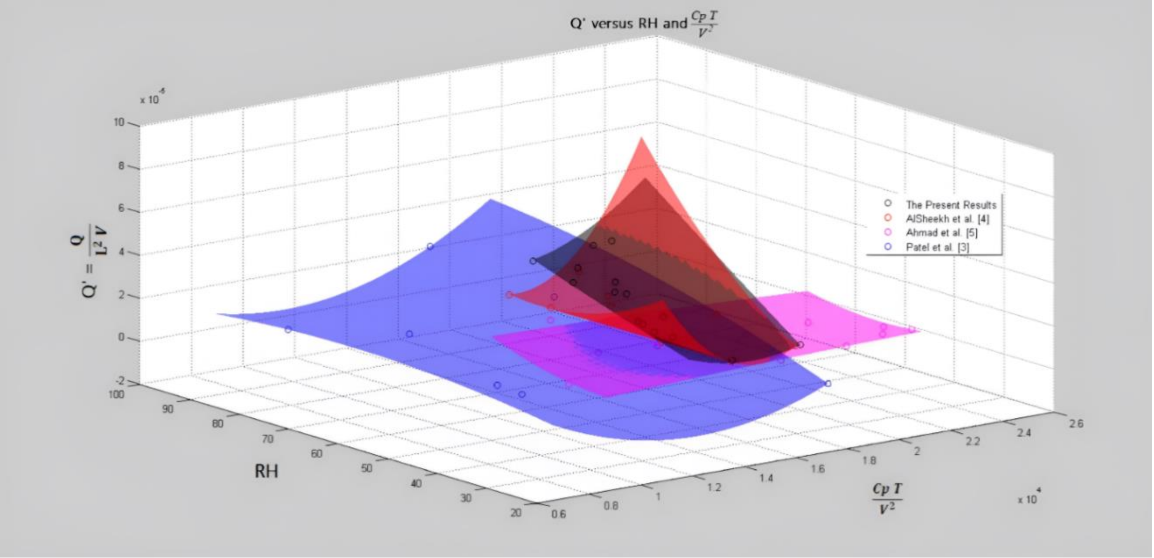


Figure 6: 3D Surface Contour Visualization of the relation between Dimensionless Volume Flow Rate versus RH and Dimensionless Temperature

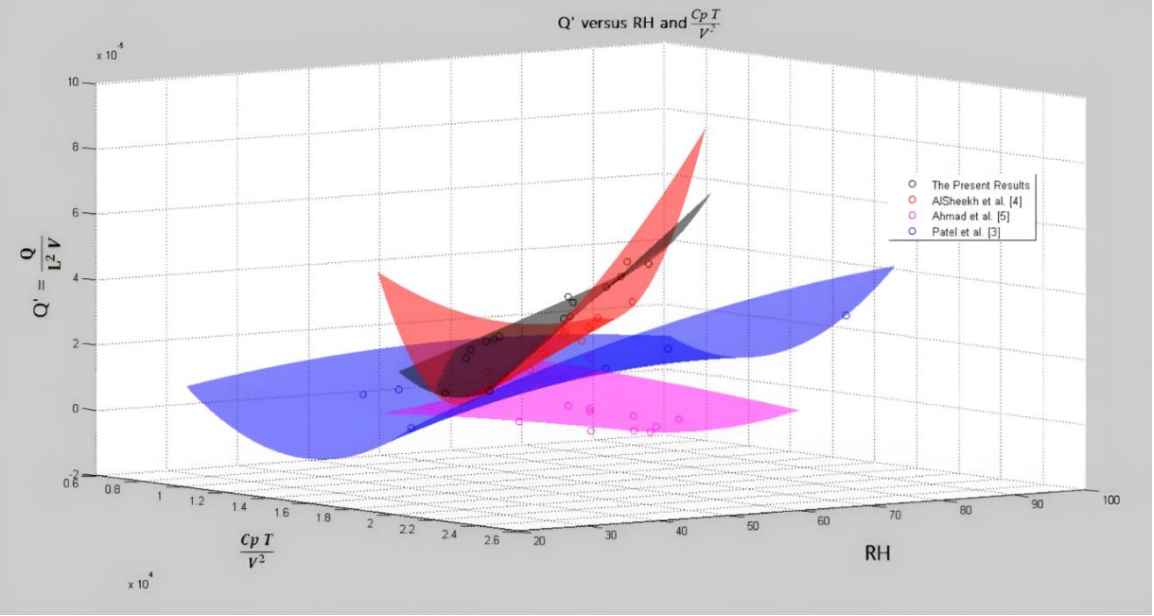


Figure 7: 3D Surface Contour Visualization of Dimensionless Volume Flow Rate versus RH and Dimensionless Temperature – Inversed Axes View

5.1.2. Consistency of System Performance

By comparing the present results with Patel et al. [3], AlSheekh et al. [4], and Ahmad et al. [5], it is observed that most of the trends remain consistent across different systems. This reinforces the effectiveness of using Buckingham Pi Theorem to analyze the performance of AWGs across various studies. The consistent trends seen in Patel et al. [3] and AlSheekh et al. [4] curves validate the predictive capability of dimensionless analysis, confirming that similar relationships exist between temperature, humidity, and volume flow rate in different AWG systems.

The remarkable performance of this device, characterized by significantly increased water harvesting rates, illustrates the success of the modifications implemented during its development. This enhancement marks a significant achievement in the field of atmospheric water generation, showcasing the potential for improved solutions to address global water scarcity challenges effectively.

5.1.3. Analysis of Discrepancies in Previous Studies

However, in the graph, Ahmad et al. [5] results deviate significantly from the expected trend. While most of the systems exhibit a coherent relationship between temperature, humidity, and water production, their graph shows a different behavior, indicating potential discrepancies or errors in the data.

There are several potential reasons for these discrepancies, including Measurement inaccuracies as the sensors used to measure relative humidity, temperature, or volume flow rate in this experiment may have been improperly calibrated, leading to inconsistent data. Additionally, human or data recording errors could have occurred during data recording, entry, or transcription, leading to inaccuracies in the plotted results [19]. Variability in atmospheric condition as the experiments were conducted in an environment where atmospheric conditions are inherently unstable and can change rapidly. Factors such as fluctuations in atmospheric pressure and surrounding temperature, among other environmental variables, may have influenced the system's performance, adding variability to the results [20].

5.2. Comparative Analysis of Results

The present research has successfully developed a reliable Atmospheric Water Generator (AWG) system that demonstrates a substantial improvement in water harvesting efficiency compared to existing models. Using Buckingham Pi Theorem and Dimensionless Analysis, the study demonstrated that all the prototypes evaluated in the research operated efficiently, harvesting high amount of water under various conditions, with some prototypes showing higher performance than others. However, the prototype of Ahmad et al. [5] exhibited comparatively lower efficiency, particularly in more challenging conditions characterized by reduced temperatures and relative humidity. The dimensionless analysis validated that most systems followed similar tends. The present results, representing the prototype, consistently demonstrated superior performance compared to AlSheekh et al. [4], Patel et al. [3], and Ahmad et al. [5]. Alsheekh et al. [4] results that were notably close under varying conditions but encountered some limitations in high humidity and temperature scenarios. Patel et al. [3] showed commendable performance but generally remained slightly lower, while Ahmad et al. [5] exhibited some variability, indicating potential opportunities for further improvement.

6. CONCLUSION

The AWG system developed in the present study represents a more efficient solution to atmospheric water generation, particularly under challenging environmental conditions, positioning it as a promising technology to address global water scarcity. The prototype achieved a water generation rate of 2.1 L/hr

with an energy consumption of 0.73 kWh/L, showcasing its improved design and superior performance compared to existing systems. By applying the Buckingham Pi Theorem and Dimensionless Analysis, the present study normalized key parameters such as temperature, relative humidity, and air velocity, ensuring fair and unbiased comparisons across systems. A significant contribution of the present work lies in validating prior studies using Buckingham Pi Theorem and clarifying discrepancies in the results of the prior works, as highlighted in Section 5.1.3. Furthermore, the findings confirm that the present prototype aligns with and enhances the existing body of research, offering a sustainable and efficient solution for water harvesting in diverse environmental conditions.
Future research should focus on optimizing power consumption further and incorporating it into the dimensionless analysis to enhance system performance. Additionally, the methodology applied in the present study can be extended to evaluate other water harvesting techniques beyond the VCC, broadening its applicability, and contributing to the advancement of sustainable water generation technologies.

7. APPENDIX

This appendix outlines the technical specifications, calibration details, and operational limitations of the measurement instruments used in the study, ensuring reproducibility and precision.

7.1. HI9564 Thermo-hygrometer (Hanna Instruments)

The **HI9564** is designed for measuring temperature and humidity in harsh environments. It offers a temperature range of 0–60°C and a relative humidity (RH) range of 20–95%, with high accuracy (± 0.5°C for temperature and ± 2% for RH between 50–85%). This ISO-compliant device stores calibration data on an internal microchip, ensuring reliable performance and minimal error margins [21].

7.2. UNI-T UT333S Mini Temperature and Humidity Meter

The **UNI-T UT333S** is a compact device suitable for measuring temperature and humidity across varied conditions. It has a temperature range of -10–60°C and an RH range of 0–100%, with accuracies of ± 1°C and ± 5% (for RH between 20–80%), respectively. CE and UKCA certified, the meter requires regular calibration to maintain its precision [22].

7.3. General Tools DLAF8000 4-in-1 Environmental Airflow Meter

This **versatile 4-in-1 device** measures air speed, temperature, relative humidity, and light intensity, making it ideal for comprehensive environmental monitoring. It operates within ranges of 0.1–30 m/s for air speed, 0–50°C for temperature, 10–95% for RH, and 0–20,000 Lux for light, with accuracies of ± 3–4% for air speed, ± 1.2°C for temperature, and ± 4% for RH below 70%. It features a Type K thermocouple and requires periodic calibration for accurate results [23].

7.4. DHT-22 Precision Digital Temperature & Humidity Sensor Module

The **DHT-22 sensor module** is used for environmental monitoring and HVAC systems, measuring ambient temperature (-40–80°C) and RH (0–100%) with high accuracy (± 0.5°C for temperature and ± 2% for RH between 20–90%). This pre-calibrated sensor is easy to use, requiring no additional calibration, and delivers reliable results with minimal error margins [24].

[A] [B] [C] [D]

Figure 8: **[A]** HI9564 Thermo-hygrometer for Temperature and Relative Humidity Measurement, **[B]** Uni-T UT333S Digital Temperature and Humidity Meter, **[C]** Air Speed, Temperature, Humidity, and Light Meter with 'K' Port, and **[D]** DHT22 Single-Bus Digital Temperature and Humidity Sensor

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