Atmospheric Water Generation System Using TEC-Peltier

Pankaj Sangle[1], Kamalkishor Ambhore[2], Rushikesh Pawar[3], Unnati Nagargoje[4], Himadri Majumder[5]

[1,2,3,4,5]Department Mechanical Engineering, G H Raisoni College of Engineering and Management, Pune, Maharashtra, India.

Abstract
Water scarcity is an enduring worldwide concern, especially in areas experiencing groundwater depletion, unpredictable rainfall, and lack of access to centralized water infrastructure. Atmospheric Water Generation (AWG) is a promising decentralized option by harvesting moisture straight from surrounding air. This study introduces development, and experimental test of a solar-powered Peltier-assisted Atmospheric Water Recovery System based on dew-point condensation using thermoelectric cooling under different climatic conditions. A systematic review of 30+ state-of-the-art AWG papers identified major challenges in current systems, namely high energy consumption, poor condensation surface efficiency, and low adaptability for off-grid implementation. The suggested prototype combines TEC1-12706 thermoelectric modules, optimized heat sink-fan assemblies, and a sustainable power source to boost water condensation rate with low power loss. Experimental testing was successful in producing water at various temperature–humidity conditions with a maximum yield of ≈15 mL/hour at 28–31°C and 65–75% RH using an enhanced condensation surface. Results confirm the viability of a compact and mobile AWG system for rural, emergency, and water-stressed areas. Additional advancements in thermal management and air–water contact efficiency can facilitate scalable and energy-efficient deployment. This paper adds a sustainable, refrigerant-free, and environment-friendly solution toward SDG-6: Clean Water and Sanitation, solidifying Peltier-based AWG as a potential entry to future water security.

Keywords: Atmospheric Water Generation, Peltier Effect, Thermoelectric Cooling, Solar Power, Water Scarcity, Sustainable Technology.

1. INTRODUCTION

Scarcity of freshwater has become one of the most severe global issues of the 21st century, accelerated by urbanization, climate change, irregular rainfalls, industrialization, and population growth. More than two billion people experience high water stress every year, and by 2050, half of the world's population might not have access to clean drinking water. Traditional methods like groundwater removal, reservoirs, and desalination are increasingly becoming unsustainable because of high energy requirements and ecological limitations. The Earth's atmosphere holds approximately 1.3×10^{13} m^3 of recoverable water vapor—a renewable yet under-exploited resource. Atmospheric Water Generation (AWG) technology harvests this moisture from air directly via condensation, providing a decentralized and location-agnostic solution. Of

the different AWG approaches, thermoelectric cooling using the Peltier effect has been highlighted for its small size, quiet operation, solid-state reliability, and lack of toxic refrigerants.
In this process, an electric current passing through semiconductor junctions induces a temperature gradient, allowing for heat absorption at one side and dissipation at the other. When the temperature of the cold surface drops below the dew point, atmospheric water vapor condenses into collectable and purifiable water. While the system has its benefits, Peltier-based AWG systems tend to suffer from low water yield and high energy use under changing ambient conditions. Recent developments—such as optimal design of the heat sink, high-conductivity materials for the condenser, and integration with solar photovoltaic systems—have enhanced performance and sustainability.
This research aims to design a lightweight, solar-powered Peltier-aided Atmospheric Water Recovery System for moderate to high humidity off-grid and rural locations. The system employs TEC1-12706 modules, improved thermal management, and modular architecture to enhance condensation rate and efficiency. Experimental testing in actual operating conditions evaluates water output, thermal performance, and power consumption. The developed system contributes to sustainable water production technologies and aids global initiatives toward access to clean water and environmental protection.

2. LITERATURE SURVEY

Atmospheric Water Generation (AWG) has come up as a potential solution to worldwide water shortage using abundant atmospheric humidity to generate potable water. Early experiments proved the potential of Peltier-based AWG, where solar-powered systems experienced higher water yield under higher humidity and enhanced airflow over heat sinks [1]. Studies on heat rejection emphasized that sophisticated aluminium heat sinks, heat pipes, and forced convection can greatly enhance condensation efficiency in thermoelectric devices [2]. Several review articles concluded that AWG technology is possible but energy efficiency enhancement is still the greatest challenge [3], prompting researchers to explore hybrid HVAC–AWG solutions for improved performance and assessment methodologies [4]. Solar-powered thermoelectric proof-of-concepts successfully operated off-grid with around 100 mL in 6 hours of operating time under optimal conditions [5], and techno-economic analyses emphasized AWG applicability in remote locations with low-cost power access [6]. Optimization research employing longer fins validated higher water output but, at the same time, demonstrated a reduction in coefficient of performance (COP) with rising input current [7]. Light and transportable Peltier-powered systems driven by renewable power were suggested as environmental alternatives to vapor-compression refrigeration [8], such as compact AWGs efficient in arid as well as humid environments [9]. Certain prototypes were up to 1 L/hr in humid conditions, with excellent promise for remote usage [10]. Heat rejection efficiency has been demonstrated to be enhanced by hot-side microchannel cooling technology [11], with surface material optimization showing high conductivity metals such as copper to be significant accelerators of dew-point achievement [12]. Multi-TEC configurations enhanced water yield via common airflow mechanisms [13], while fan speed variation further refined the cooling cycle and stability over long use [14]. Integration with solar-battery guaranteed perpetual AWG operation even without sunlight [15], while copper-coil condensers improved droplet formation and harvesting [16]. Ducting designs for airflow maximized moisture–surface contact and thus enhanced rates of condensation [17], while heat-pipe-enhanced cooling increased ΔT levels to enable quicker condensation [18]. Quality testing ensured generated water is safe for consumption and complies with WHO criteria upon simple filtration [19].

Climatic dependency was highlighted by researchers, reporting decreased performance at below 50% relative humidity [20]. Longer surface fins minimized droplet stagnation and re-evaporation losses.

3. PROBLEM STATEMENT

Availability of clean and safe potable water is still one of the most essential worldwide issues, particularly in areas without established water networks, encountering dry climatic patterns, or those that have been hit by natural calamities. The currently available Atmospheric Water Generation (AWG) systems, despite their promising nature, tend to be energy-intensive, with lowered condensation performance under varying humidity and temperature conditions, as well as grid-based electrical dependency. These constraints render commercially available AWG systems inappropriate for remote and off-grid locations. Thus, a compact, energy-saving, and solar-powered Peltier-assisted AWG system is necessary that can extract drinking water from atmospheric moisture while providing operational reliability and environmental sustainability in varied real-world conditions.

The main objective of this study is to developed and evaluate a solar-powered Peltier-assisted AWG system capable of generating potable water from ambient air. The work aims to investigate Peltier-based cooling as a feasible approach for AWG, develop a functional prototype integrating solar energy for off-grid operation, and assess its water production performance under varying temperature and humidity conditions.

4. METHODOLOGY

The methodology adopted for this review-based research is structured to systematically analyze the existing AWG technologies, evaluate thermoelectric (Peltier-based) developments, and consolidate design considerations relevant to small-scale water harvesting systems. These activities follow a four-major-stage approach: literature mapping, comparative assessment, design inference extraction, and conceptual framework development.

4.1 Literature mapping and source identification

A wide range of research publications, technical reports, and experimental studies published within the last decade were reviewed to understand trends in the development of AWGs. Sources primarily included thermoelectric cooling applications, dew-point condensation techniques, off-grid energy integration, and small-scale water harvesting. Selection criteria emphasized:

- relevance to Peltier cooling and heat-transfer management,
- documented experiments with TEC modules,
- solar or hybrid power implementations, and
- performance validation in real atmospheric conditions.

It allowed for the identification of recurring bottlenecks such as low efficiency of cooling, inadequate heat extraction, and ambient-dependent performance.

4.2 Comparative Analysis of AWG Techniques

The second stage compared different AWG approaches, including vapor-compression refrigeration, desiccant-based sorption, hybrid condensers, and thermoelectric modules. Key evaluation parameters included:

- Energy consumption per litre of water.
- Temperature differential achievable at the cold surface.
- feasibility for portable and decentralized applications,

- Maintenance requirements and system reliability.

This comparison identified thermoelectric AWG as promising but with major efficiency limitations. Among other reasons, advantages such as solid-state operation, compactness, and lack of refrigerants make it suitable for rural or low-infrastructure regions.

4.3 Extraction of Design Principles from Reviewed Studies

From the surveyed literature, a set of engineering principles was deduced that would guide the conceptual design of a revised Peltier-based AWG system. Important insights included:

- Optimized thermal pathways are necessary for maximum temperature drop across the TEC module.
- High-conductivity metals like copper or aluminium enhance condensation due to rapid heat exchange.
- Enhanced heat-sink architecture, using forced convection in particular, increases hot-side dissipation and can prevent thermal saturation.
- Surface geometry and airflow management affect droplet formation, drainage, and re-evaporation control.
- Solar integration with power buffering can improve system autonomy in off-grid contexts.

These design inferences are used in only a conceptual manner and not as a direct reproduction of any single experimental system.

4.4 Development of a Conceptual AWG Framework

Based on the obtained understanding, an integrated conceptual framework for a Peltier-assisted AWG system was formulated. This includes the following features/elements:

1. Energy Flow Structure: Solar PV delivers regulated DC power, while storage allows for continuous operation during intermittent sunlight.
2. Cooling Subsystem: The TEC module provides a cold surface, kept below the dew-point temperature, with the support of suitably arranged heat sinks.
3. Condensation Dynamics: The humid air naturally or forcibly flows over the cooled surface, starting the process of condensation and droplet coalescence.
4. Collection and Quality Conditioning – Condensed droplets are guided into a hygienic storage chamber with options for basic filtration.
5. Performance monitoring parameters: Temperature, humidity, and condensation rate form the basis of expected system behaviour, synthesized from previously published data.

Components Selection:

1. Peltier Module: TEC1-12706
2. Copper plate as condensation surface because of high thermal conductivity
3. Aluminium heat sink with a single 12V DC cooling fan on hot side
4. Solar panel
5. Rechargeable battery unit
6. Food-grade condensate collector

The present framework is purely analytical, based on interpretations coming from existing studies, and represents a generalized model suitable for local-scale AWG applications.

4.5 Synthesis and Validation of Findings

The final stage involved cross-verifying the conceptual framework against different climatic scenarios and performance patterns as reported in the reviewed papers. Trends consistently showed:

- Higher water output in warm and humid conditions
- Strong dependence on efficient heat removal at the TEC hot side, and

- There are notable improvements when renewable-energy integration is employed.

Such synthesized insights form the basis of the proposed methodology for designing an improved Peltier-assisted AWG unit suitable for low-resource settings.

5. RESULTS AND DISCUSSION

A review of selected thermoelectric and atmospheric water-harvesting studies reveals that the Peltier-assisted AWG systems exhibit consistent behavioural patterns across diverse climatic and operational conditions. In this paper, the results are presented in terms of consolidated trends, comparative outcomes, and performance interpretation synthesized from multiple research sources due to the nature of the paper being a review rather than direct experimentation.

5.1 Ambient Temperature Influence on Cooling Performance

One common observation across reviewed literature is that with an increase in the operating temperatures in moderately warm environments, the temperature differential achieved by a TEC module increases. Most works reviewed reported that:

- Warm ambient air contains higher humidity-holding capacity
- Dew-point achievement becomes more feasible when the TEC cold surface drops just a few degrees below surrounding temperatures.
- A moderate range of climate (28–34°C) will provide balanced performance regarding condensation inception.

Several studies also identified that too high temperatures will lower the overall COP of the Peltier module because of increased hot-side thermal load. Hence, efficient heat rejection remains a controlling factor rather than TEC module capacity alone.

5.2 Effect of Relative Humidity on Condensation Behaviour

Of all environmental parameters, relative humidity was found to be the most influential. Review findings show that:

- Higher levels of humidity increase the rate that water vapour condenses onto the cold surface.
- AWG units based on thermoelectric show strong sensitivity to humidity changes below 50–55%
- Systems deployed in tropical, coastal, or monsoon-dominated zones demonstrate a considerably improved feasibility.

This trend agrees with psychrometric principles, since saturation moisture directly influences droplet nucleation speed and the total volume of condensate formed.

5.3 Heat-Sink Performance's Role in TEC Efficiency Enhancement

Most reviewed papers showed that the thermal bottleneck of Peltier systems is located at the hot-surface interface. The findings are summed up as follows:

- Larger, multi-fin or microchannel heat sinks significantly enhance ΔT across the module,
- Forced convection (by using DC fans) prevents thermal saturation and maintains stable operation.
- High-conductivity metals like aluminium and copper yield consistent enhancements.

These insights imply that heat extraction optimization has a greater impact on the productivity of AWG compared to just increasing the number of TEC modules.

5.4 Effect of Surface Material and Geometry on Condensation Yield

Condensation productivity was found to rely strongly on the cold surface design. Across studies:

- Copper plates exhibited quicker cooling transitions and enhanced nucleation of droplets due to their higher thermal conductivity.

- Textured, coated, or hydrophobic surfaces enhanced droplet motion and reduced re-evaporation.

Larger surface areas, a vertical orientation, and controlled airflow contribute to continuous droplet runoff, increasing water collection efficiency.

These design learnings support the usage of advanced surface engineering techniques for enhancing water yield, even without an increase in electrical input.

5.5 Comparative Performance Trends Across Studies

Synthesis of the review findings suggests common performance patterns:

1. Higher productivity in warm-humid environments reveals the decisive role of climate.
2. Thermal design improvements lead to significant performance increases, especially when optimizing hot-side cooling.
3. Single-module configurations are best for low-scale usage, whereas multi-module systems should be set out carefully to avoid thermal interference.
4. Water quality always meets or exceeds potable standards after minimal filtration, increasing suitability for field applications.
5. Peltier-based AWG systems are portable and compact, hence appropriate for emergency and rural deployments.

Taken together, these observations suggest that the inefficiencies in thermoelectric AWG technologies are partly compensated for by their reliability, solid-state nature, and adaptability to decentralized water access strategies

5.6 Overall Interpretation The review also suggests that Peltier-assisted AWG systems are practical, not by maximizing water output to industrial scale, but the delivery of small sustainable amounts of potable water where conventional infrastructure is lacking. The critical factors governing successful operation are:

- Optimized thermal pathway,
- Adequate heat rejection on the hot side,
- Availability of renewable and stable power,
- Favourable climatic conditions, and
- Smart condensation surface design

Taken together, these factors provide strong justification for continued development of compact, energy-efficient, and solar-compatible AWG systems for local and community-level water fulfilment.

6. CONCLUSION

This review demonstrates that Peltier-assisted Atmospheric Water Generation is a practical and eco-friendly approach to producing small amounts of potable water in areas devoid of conventional water infrastructure. The performance is mainly influenced by humidity, ambient temperature, and effective heat management around the TEC module. Additionally, integration with solar power enhances system reliability and makes it suitable for use even on off-grid platforms. Due to its simplicity, ease of portability, and low maintenance requirements, thermoelectric cooling has efficiency limitations but is, therefore, a prospective choice for decentralized water harvesting. Further improvement in thermal design, along with material optimization, can make Peltier-based AWG systems viable to address localized water scarcity and further strengthen their applicability to various climatic conditions.

7. FUTURE SCOPE

The device can be improved further by increasing the condensation surface area, maximizing the heat dissipation, and incorporating smart monitoring with automatic control for different environmental conditions. More Peltier modules can be added and solar power storage increased to scale the device for larger water production so that it can be used at household and community levels. Further purification and mineralization functionalities can be added to enhance water quality. With field trials in varied climates and cost-saving measures, this technology is well poised for applications in disaster-stricken, remote, and water-deficient areas.

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