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Design Development and Validation of Peltier Heat Pump-Based AWGs

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Abstract: ***This work was undertaken in response to the urgent need to develop sustainable and energy-efficient solutions to address global water scarcity. The research is founded on the potential of Peltier-based systems to offer a low-maintenance and compact atmospheric water generation and to determine optimal geometries of the collector units in various climatic conditions. The study presents a comparative analysis of three Peltier heat pump-based Atmospheric Water Generator (AWG) designs, each utilizing five parallel-connected Peltier modules with a shared heat sink configuration. In the first configuration, the hot side of the modules has an Aluminium finned plate coated with a solid desiccant. While the system is off, the desiccant soaks up moisture from atmospheric air. Upon being turned on, the Peltier modules transfer heat to the hot side, facilitating the desorption of adsorbed moisture that is further directed to the cold side to be condensed. The second design extends this idea by adding a liquid desiccant in a tank that is embedded with the hot side of the modules. A honeycomb or geometrically structured insert that is partially immersed in the desiccant solution increases the exposed surface for contact of air and the solution. Moisture adsorption takes place when the modules are off and desorption begins as soon as the modules are powered by heating the solution. In both the first and second designs, the released vapor is directed towards the cold side for condensation. The water yield performance of both systems was determined at the same energy input in different dry-bulb temperatures and relative humidity. Furthermore, various desiccant materials were also evaluated to examine how effective they were. This study offers insights for the optimization of AWG systems by emphasizing the advantages and limitations of the two designs in the areas of energy efficiency, water yield, and system complexity, based on environmental conditions and operational requirements.***

Keywords: AWG, Peltier Heat Pump, Desiccant, Adsorption, Condensation

1. Introduction

Among various AWG designs, cooling-based condensation systems continue to dominate research and deployment owing to their simplicity and effectiveness, particularly under high humidity. These systems typically employ vapor-compression or absorption refrigeration, which, though effective, are space-consuming and energy-intensive. On the other hand, thermoelectric cooling via Peltier modules offers a compact, solid-state alternative that is maintenance-free and refrigerant-free, highly advantageous for portable or off-grid applications despite an inherently lower coefficient of performance (COP) [2][3]. Water scarcity remains one of the most critical global challenges of the 21st century. With over two billion people currently living in regions facing freshwater scarcity, the need for decentralized and sustainable water generation technologies has never been more urgent [1]. Climate change, industrialization, and population growth continue to deplete conventional freshwater sources, especially in arid and coastal regions. In this context, Atmospheric Water Generators (AWGs), which extract moisture from the air and convert it into potable water, offer a promising solution [2].

While traditional AWG systems often rely on vapor-compression heat pumps, these systems are usually bulky, expensive, and energy-intensive. The need for compact, energy-efficient alternatives motivated the development of alternatives using thermoelectric Peltier modules, which offer a solid-state, environmentally benign, and noiseless cooling mechanism. Peltier-based AWGs are particularly suited for small-scale or remote applications where portability, affordability, and energy efficiency are paramount. Moreover, integrating desiccants into these systems—both solid and liquid—can significantly enhance water harvesting performance by enabling improved control of moisture absorption and condensation phases.

Numerous studies have reviewed the classifications and working principles of AWG systems. For instance, Bhatia [3] provided an overview of AWG technologies, categorizing them into cooling condensation and desiccant-based systems. Das and Ghosh [4] evaluated renewable-powered AWGs, emphasizing the importance of sustainable design choices for water generation in off-grid areas.

Basic prototypes using Peltier-based condensation alone have also been reported. Kumar et al. [5] developed a direct Peltier cooling-based AWG to demonstrate its feasibility for domestic use. Similarly, Patel et al. [6] designed a low-cost Peltier water generator for rural deployment. However, these designs are often limited by condensation yield and high energy consumption due to unoptimized thermal management and limited surface area for heat transfer.

To overcome these drawbacks, researchers have increasingly turned to desiccant-assisted Peltier systems. Desiccant materials can absorb, or adsorb moisture from air, and later release it upon heating—creating a two-phase separation between dehumidification and condensation. This approach offers the potential for enhanced water yield and reduced energy requirements by recovering latent heat and using thermoelectric modules for targeted heating and cooling.

A number of studies have investigated solid desiccant-based AWGs integrated with Peltier modules. For instance, Kabeel et al. [7] demonstrated a silica gel-based AWG with solar-assisted regeneration. Talebian and Arami-Niya [8] studied zeolite materials for water recovery. Jain et al. [9] used activated alumina for efficient sorption, while Al-Amoudi [10] investigated porous ceramic composites for high-capacity adsorption systems.

In parallel, significant progress has been made in liquid desiccant-based Peltier AWGs. Davoudi et al. [11] explored calcium chloride ($CaCl_2$) for liquid absorption in a compact hybrid setup. Gao et al. [12] tested LiCl-based systems for greenhouse integration. Jain et al. [13] analyzed Triethylene glycol (TEG) as a desiccant in conjunction with thermoelectric cooling. Zheng et al. [14] evaluated multiple solutions to identify optimal desiccant mixtures under different climatic conditions.

Several recent papers have even considered hybrid configurations using both solid and liquid desiccants, aiming to leverage the advantages of each. Cattani et al. [15] introduced performance indices for such systems, while Sharpe et al. [16] and Summers and Asiabanpour [17] investigated improved thermal management techniques for combined desiccant-Peltier systems. These works, while valuable, often lack comparative analysis under consistent design and operational parameters. Additionally, few papers systematically evaluate the performance of solid and liquid desiccant systems under identical energy input conditions or consider practical aspects like climatic adaptability and optimization of cycle timing.

Considering the above, the present study was undertaken with the following key objectives:

- To develop a compact, economical, and energy-efficient AWG system that improves upon conventional bulky and high-energy vapor compression-based units.
- To design two AWG prototypes, one employing solid desiccant and another using liquid desiccant integrated with Peltier thermoelectric modules.
- To conduct a comparative study between solid and liquid desiccant systems under identical energy input and geometric design conditions.
- To analyse the influence of design-level parameters, desiccant material properties, operational cycle timings, environmental conditions representative of various geographical locations on AWG performance

Through this study, we aim to identify optimal design configurations and operational strategies for maximizing water yield and minimizing energy use in 2 small-scale Peltier heat pump-based AWGs using both solid and liquid desiccants.

2. Peltier Heat Pump

The Peltier heat pump is a solid state thermoelectric that transfers heat via the Peltier effect, whereby electricity is used to make the heat to be absorbed on one of the surfaces (cold end) and released at the other (hot end). It is made with p-type and n-type semiconductor couples between two ceramic plates. Once a direct current (DC) voltage is applied, a temperature gradient is created across the module and due to this it can be an ideal compact and portable cooling solution where it is required [18], such as in Atmospheric Water Generators (AWGs). Its coefficient of performance (COP) is lower than vapor-compression systems [19], but it has several important advantages including: it does not use moving parts or refrigerants; it requires minimal maintenance; and it can control the temperature very precisely, and is thus suitable to small-scale, low-power water harvesting applications.

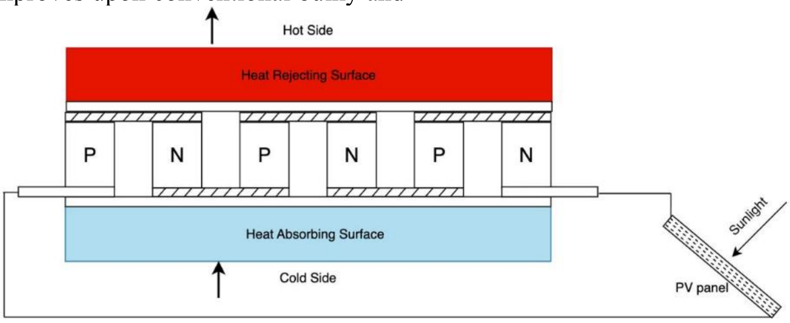

Figure 1: Schematic of Solar based Peltier heat pump

Peltier module specifications considered in both the designs in the present study**:**

Peltier Module type: TEC-12706
Power at hot side P_{hot} : 45 W
Power at cold side P_{cold} : 35 W
Number of Peltier modules n_m : 5
Base-plate Length L : 8 cm
Base-plate Width W : 8 cm

3. Design 1: Solid desiccant-based Peltier AWG

The solid desiccant-based Peltier AWG design comprises five connected Peltier modules forming shared hot and cold surfaces. The hot side of each module consists of an Aluminium finned plate (specifications provided separately). The cold-side is a copper plate with a hydrophilic coating. A solid desiccant is coated over the fins to increase the surface area for moisture absorption. The hot and cold sides are connected through a common acrylic duct. A fan is installed at the inlet of the hot-side plate. Air enters the system through the fan. During the adsorption phase, air passes through the solid desiccant-coated fins for a predetermined duration. During this period the Peltier module remains switched off. Once the solid desiccant becomes saturated with moisture, the Peltier module is activated. The Aluminium plate is heated during the desorption (regeneration) stage. The adsorbed moisture is released from the desiccant-coated plate. The moist air is directed to the cold-side copper plate via a U-shaped duct. During the condensation stage, the moist air condenses on the surface of the cold-side copper plate. As a result, condensed water is collected at the bottom of the duct.

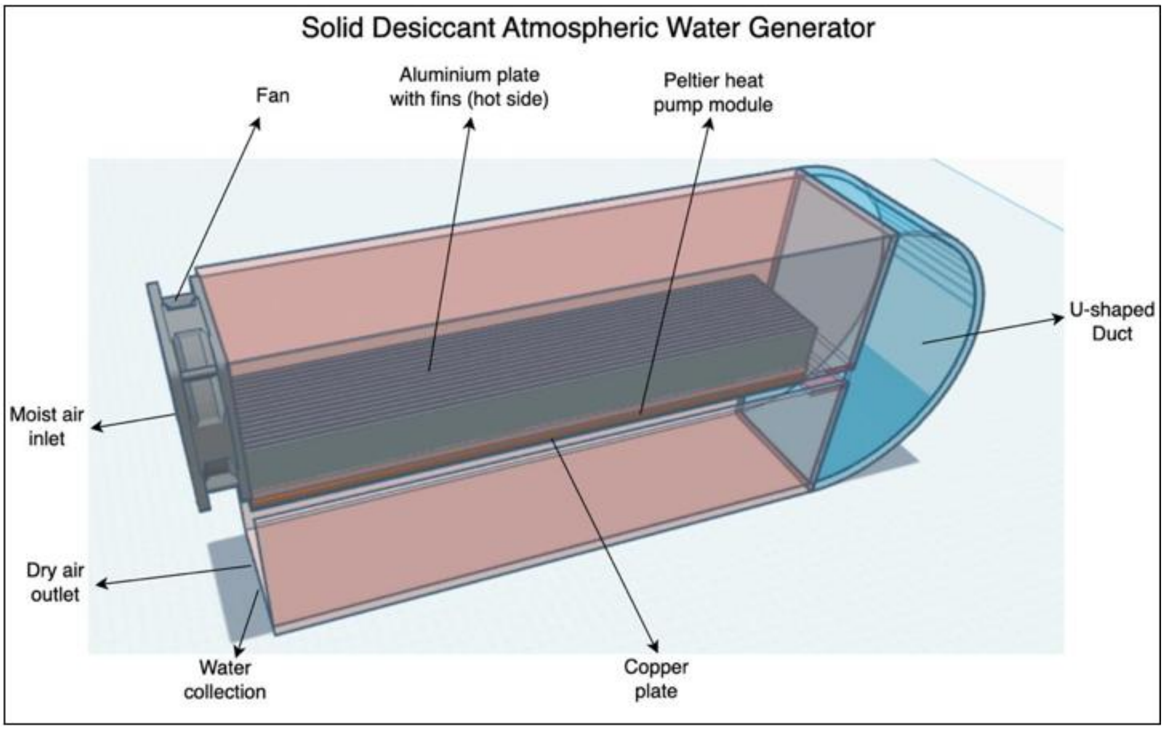

Figure 2: Solid desiccant-based AWG model design

3.1 Solid desiccant Hot plate side specifications

Hot Plate: Aluminium finned plate
Fin height h_f = 3 cm
Fin length l_f = 8 cm
Fin thickness t_f= 2 mm
Number of fins n = 16
Area of the base plate $A_b = L\,W$
Area of one fin $A_f = 2\,h_f\,l_f$
Area of all fins together $A_{ft} = A_f\,n$
Effective surface area $A_{ef} = A_{ft} + (A_b - (t_f\,n))$

Solid desiccant coating specifications:
Desiccant coating thickness = t_d
Area of desiccant coated: $A_{des} = A_{ef}$
Mass of desiccant coated $m_{des} = \rho_d\,A_{des}\,t_d$ (1)

3.2 Adsorption Process

Mass flow rate of air

$$\dot{m}_{air} = \rho_{air}\,A_{inlet}\,V_{air} \quad (2)$$

Mass moisture in the air flow

$$\dot{m}_{moist} = \dot{m}_{air}\,\omega \; [20] \quad (3)$$

Adsorption Capacity

$$C_{ads} = a\,RH^b\,exp(-cT)[21] \quad (4)$$

Table 1: Solid Desiccant properties [21]

Desiccant	a	b	c (1/K)	Regen Temp (K)	Density (ρ_d)(kg/m³)
Silica Gel A	0.35	1.2	0.01	403	700
Activated Alumina	0.3	1.1	0.008	453	850
Zeolite 13X	0.25	1.3	0.015	473	750

Mass of moisture adsorbed

$$m_{ads} = m_{des}\,C_{ads} \quad (5)$$

Saturation/adsorption time

$$t_{sat} = m_{ads}/\dot{m}_{moist} \quad (6)$$

Where:
ρ_{air} = Density of air
A_{inlet} = Inlet duct area
V_{air} = Air velocity
ω = Specific humidity
T = Dry bulb temperature
RH = Relative humidity

3.3 Desorption/Regeneration Process

Heat Required for desorption or regeneration of moisture from solid desiccant= Total heat required to raise temperature of desiccant + Evaporative heat of moisture

$$Q_{regs} = m_{ads} C_p \Delta T + m_{ads} h_{fg} \quad (7)$$

where C_p = Specific heat of water
h_{fg} = Latent heat of moisture

Time required for desorption process

$$t_{regs} = Q_{regs} / (P_{hot}\ n_{modules}) \quad (8)$$

3.4 Condensation Process

Heat required to be removed for condensation

$$Q_{cond} = m_{ads} h_{fg} \quad (9)$$

Time Required for Condensation process

$$t_{cond} = Q_{cond} / P_{cold} \quad (10)$$

Mass of condensed water

$$m_{conds} = \eta\ m_{ads} \quad (11)$$

where η = Condensing efficiency

Total cycle time solid desiccant

$$t_{cycles} = t_{sat} + t_{regs} + t_{cond} \quad (12)$$

Yield per day for solid desiccant

$$Y_{solid} = m_{conds}(86400/t_{cycles}) \quad (13)$$

4. Design 1: Liquid desiccant-based Peltier AWG

Liquid desiccant-based Peltier AWG design contains five connected Peltier modules forming a common hot and cold surface. The hot-side of the module is attached with an Aluminium tank. Tank specifications given below. The cold-side is a copper plate with a hydrophilic coating. The tank is filled with liquid desiccant solution. Finned or honeycomb structures can be used to increase the surface area. A surface area multiplier is used to consider this effect during calculations. The hot and cold-side are connected with a common acrylic duct. A Fan is inserted at the inlet of the duct from the hot side plate. Air from the atmosphere enters into the model through this fan. In the Adsorption phase air flows over the liquid desiccant solution surface for a certain time. During this time the Peltier module is switched off. Once the liquid desiccant solution is saturated with moisture, Peltier module is switched on. Aluminum plate gets heated in the desorbing or regeneration stage. The adsorbed moisture gets released from the liquid desiccant solution tank. This moist air gets directed to the cold-side copper plate via a U-shaped duct. In the condensation stage moist air starts condensing on the cold-side copper plate wall. Hence water is collected at the bottom of the duct. The desorption and condensation processes occur simultaneously.

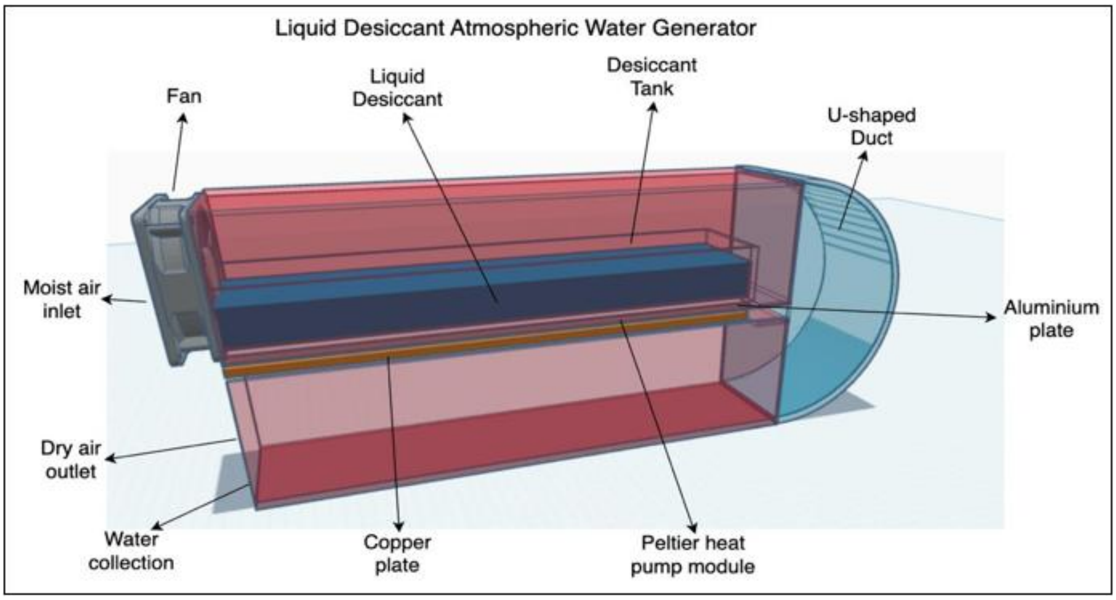

Figure 3: Liquid desiccant-based AWG model design

4.1 Liquid desiccant Hot side specifications

Hot Plate: Aluminium solution tank
Desiccant solution level in tank t_{ld} = 3 cm
Liquid multiplier m = 3 [22]
Area of the base plate = A_b
Total area of the base plate $A_{tb} = nA_b$

4.2 Adsorption Process

Mass of liquid desiccant/solution $m_{sol} = \rho_{dl} A_{tb}\ t_{ld}$ (14)
$where$, ρ_{dl} = Density of liquid desiccant solution

Adsorption Capacity of solution

$$C_{adl} = a\ RH^b\ exp(-cT)\ [21] \quad (15)$$

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Table 2: Liquid Desiccant properties [21]

Desiccant	a	b	c	Specific Heat (C_{ps})(kJ/kg·K)	Regen Temp (°C)	Density (ρ_{dl}) (kg/m³)
Lithium Chloride (LiCl)	0.42	1	0.0075	2650	338	1240
Triethylene Glycol (TEG)	0.3	1	0.0055	2200	413	1125
Calcium Chloride ($CaCl_2$)	0.38	1.1	0.0065	2550	343	1280

Mass of moisture adsorbed $m_{adl} = m_{sol}\ C_{adl}$ (16)

Saturation/adsorption time $t_{sat} = m_{adl}\ C_{adl}/\dot{m}_{moist}m$ (17)

4.3 Desorption/Regeneration Process

Heat Required for Desorption/Regeneration = Total heat required to raise temperature of solution + evaporative heat of moisture

$$Q_{regl} = m_{sol}C_{ps}\Delta T\ + m_{moist}h_{fg} \quad (18)$$

Time for desorption $t_{regl} = Q_{regl}/\ (P_{hot}\ n_{modules})$ (19)

4.4 Condensation Process

Heat required to be removed for condensation

$$Q_{conl} = m_{adl}h_{fg} \quad (20)$$

Time Required for Condensation

$$t_{cond} = Q_{conl}/P_{cold} \quad (21)$$

Mass of condensed Water

$$m_{condl} = \eta\ m_{adl}\ [23] \quad (22)$$

Total cycle time of liquid desiccant

$$t_{cyclel} = t_{sat} + t_{regl} + t_{cond} \quad (23)$$

Yield per day for liquid desiccant

$$Y_{liquid} = m_{condl}(86400/t_{cyclel}) \quad (24)$$

5. Results and Discussions

During mathematical modelling of the solid (Equation 1 to Equation 13) and liquid desiccant (Equation 14 to Equation 24) design modules were carried out to determine key performance parameters. Key parameters identified during the adsorption phase include the mass of moisture adsorbed and the time required for adsorption. During the desorption (or regeneration) phase, the mass of moisture released, the heat input required, and the duration of the desorption process were determined. In the condensation phase, the mass of moisture condensed, the heat removed, and the time required for condensation were recorded. The total cycle time has been calculated by calculating the sum of all process timings. Finally, the yield of water per cycle and yield of water per day have been calculated. The same procedure has been repeated for various solid and liquid desiccants by varying their thermo-physical properties. The quantity of water obtained has been calculated in respective cases. Three types of results have been discussed in this work which include: the effect of yield with model level parameters, the effect of solid and liquid desiccant material effect on water yield, and the climatic condition of the various locations such as dry bulb temperature and relative humidity on water yield.

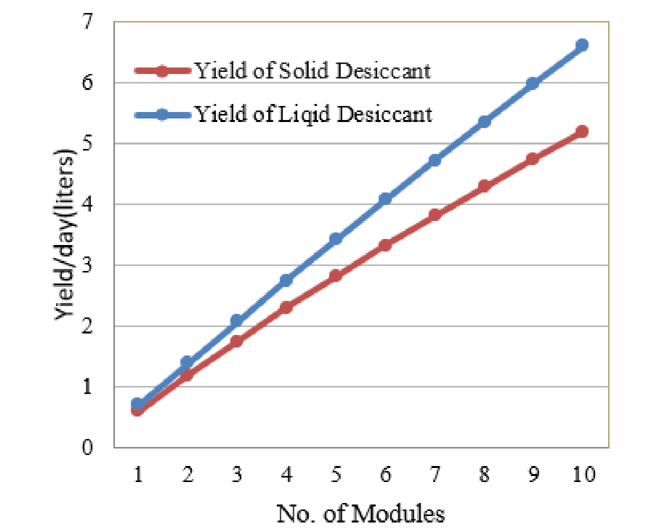

Figure 4: Variation of water yield with no. of modules

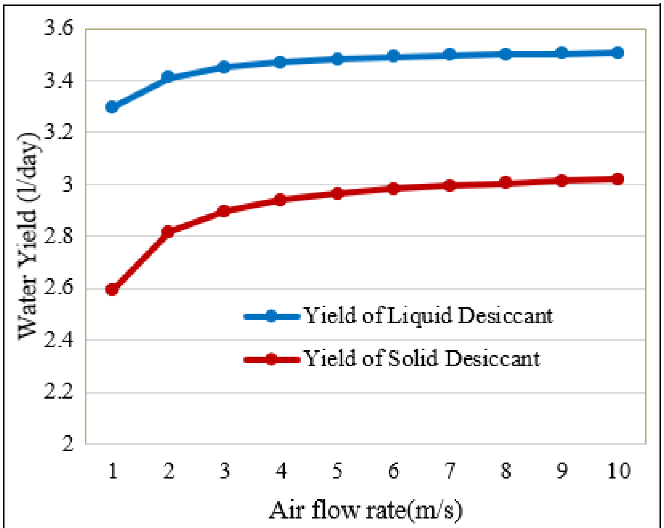

Figure 5: Variation of water yield with flow rate of air

Figure 4 shows the relation between the water yield and the number of modules. With an increase in the number of modules the base area of the hot-side and cold-side plate would increase. Hence, the total adsorption capacity would increase too. Additionally, with an increase in the number of modules heat or energy also increases. This enhances the desorption and condensation processes. Hence, the water yield increases with the number of modules. Figure 4 shows an increasing trend in both solid and liquid desiccants as the number of Peltier modules increase.

Figure 5 shows the variation of water yield with air flow rate or fan speed. Both solid and liquid desiccants show a similar trend of increasing yield up to 5 m/s, after which they remain constant. Hence it is found that for a five-module system, the maximum yield is obtained at 5 m/s fan speed.

Figure 6 and Figure 7 showcase the water yield quantities of various solid and liquid desiccants respectively. Silica Gel A, Activated Alumina and Zeolite solid desiccants were considered for the solid desiccant analysis. Silica Gel A performs better than the other solid desiccants. The reason for this is that a solid desiccant's yield depends not only on adsorption capacity but also on the regeneration temperature, the density of the solid desiccant shown in Table 1. A liquid desiccant's performance depends on solution concentration, density, specific heat capacity, regeneration temperature of the solution and their adsorption capacities. These parameters are shown in Table 2. Figure 8 & 9 shows the cycle timings of adsorption, desorption and condensation for solid and liquid desiccants respectively. For solid desiccants as shown in Figure 8, adsorption and desorption processes take more time compared to condensation. These process durations are known to depend on the quantity of solid desiccant used. This suggests that the mass of solid desiccant can be increased by enhancing its thickness, thereby extending the adsorption and desorption durations. As shown in Figure 9, the adsorption time for liquid desiccants is significantly shorter compared to the desorption and condensation phases. Hence, the heat input during the desorption and condensation stages must be increased to enhance performance. This can be achieved by increasing the number of Peltier modules.

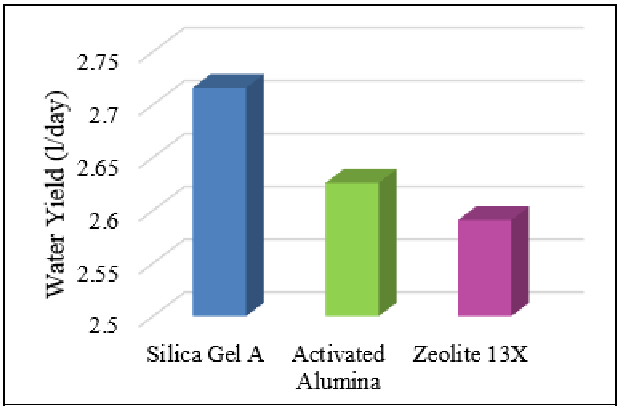

Figure 6: Variation of water yield with type of solid desiccant

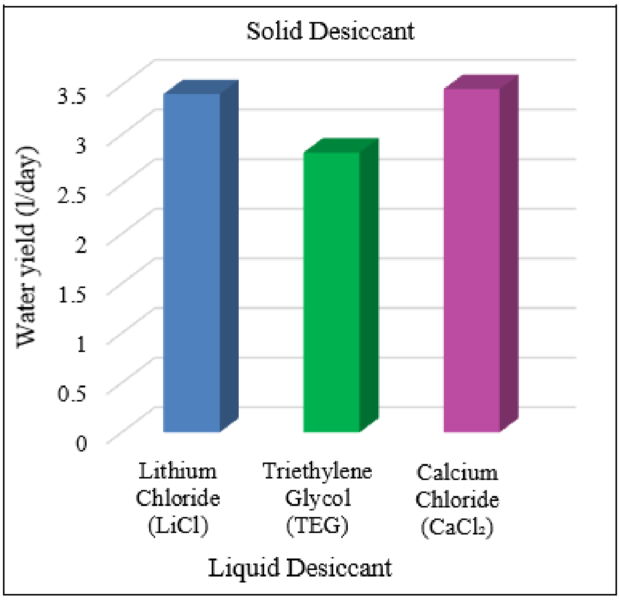

Figure 7: Variation of water yield with type of liquid desiccant

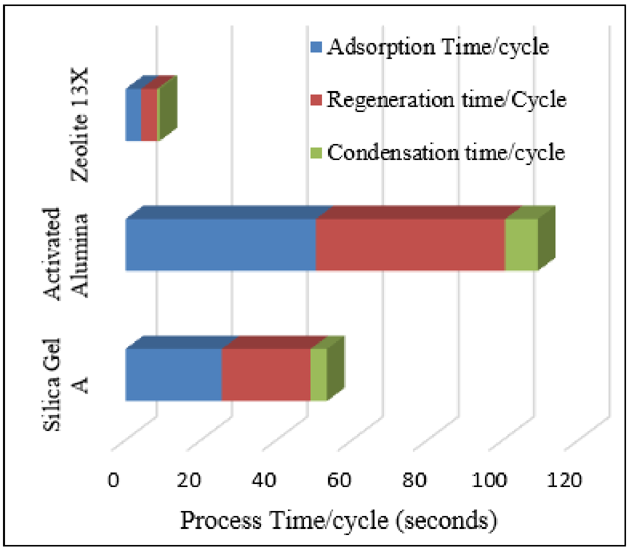

Figure 8: Variation of process time for a cycle with solid desiccant

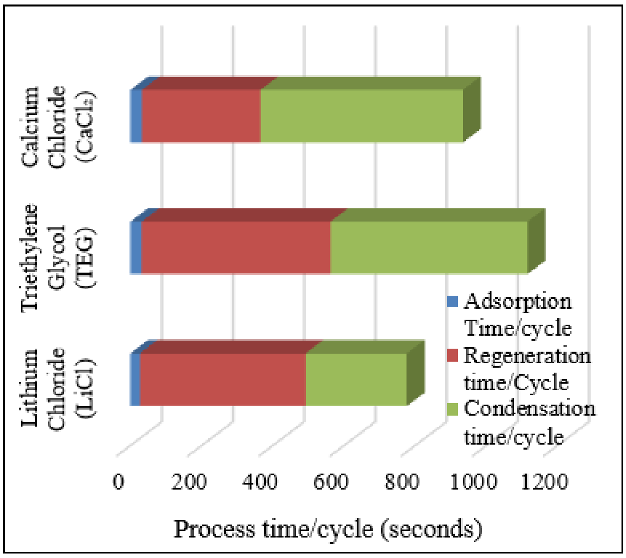

Figure 9: Variation of process time for a cycle with liquid desiccant

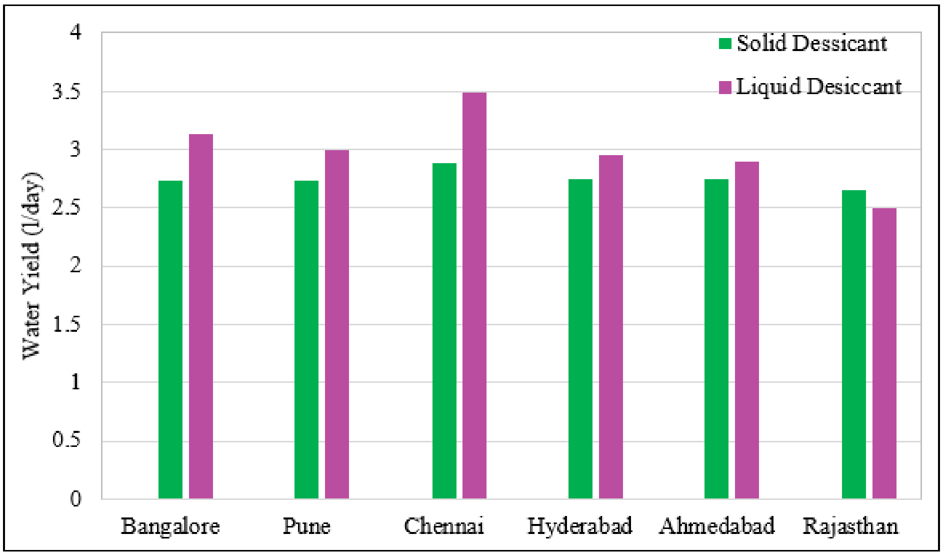

Figure 10: Variation of water yield with location

The climatic data for various common and extreme climates of different regions were collected for this analysis. Climatic data such as dry bulb temperature and relative humidity were used to plot Figure 10. Under these conditions, the water yield has been compared across various locations using solid and liquid desiccants. It is inferred that under high humidity conditions, liquid desiccants perform better, such as in Chennai and other coastal locations. Under dry, low-humidity conditions, such as those in Rajasthan, solid desiccants have demonstrated better performance than liquid desiccants.

6. Future Scope of Work

- Fabrication of the prototypes and comparing experimental values with mathematical modelling.
- Developing continuous operation mode model to increase the water yield compared to batch mode operation.
- Modifying the design parameters according to the results obtained from present analysis for better performance.

7. Conclusions

1) Two Peltier heat pump-based solid and liquid AWGs, have been designed to generate drinking water requirements.
2) Numerical analysis has been performed on solid and liquid based AWGs performance at the constant energy input.
3) Comparatives work have been performed to know the following:
   - The effect of design level parameters such as number of Peltier modules and flow rate of air on water yield in both the designs.
   - The influence of desiccant material properties on performance. Best performing desiccant has been found among solid as well as liquids.
   - The cycle timings of both the designs, discussed short comes and suggested possible solutions to overcome it to improve performance.
4) The influence of various locations based climatic parameters have been compared on water yield in both designs.
5) Both models designed for fully Solar operational input power.
6) Hence, Design analysis shows the development possibility of compact, economical and energy efficient AWGs compared to conventional bulk, expensive, high energy consuming vapour compression heat pumps.

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Dr. Arshi Banu P S received the B.Tech., M. Tech., and Ph.D. degrees in Mechanical Engineering from reputed government universities in India. Currently working as Professor (APSG) in Hindustan Institute of Technology a& Science. She has over 18 years of teaching and research experience in the areas of thermal engineering, energy systems, and fluid mechanics. Her research work includes numerous publications in indexed journals, book chapters, and patents.