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Autonomous Solar-Powered Desalination of Seawater using Low Pressure and Temperature

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Abstract

Despite the Earth being composed of 70% water, only a minor fraction of 2.5% is fresh while the remaining is saline, thus being unconsumable. Among the fresh available, only 1% is readily accessible. To tackle this problem, desalination has been recognized as one of the most effective. However, the huge reliance on fossil fuels to operate the desalination plants is not sustainable economically on the long run. Thus, solar energy integrated desalination technologies will provide an alternative which is more sustainable. This project demonstrates the concept of an autonomous small-scale vacuum desalination system which is powered by a solar charged battery using low cost equipment. The system produces fresh consumable water by removing unwanted particles and soluble from the seawater through a process of heating the seawater to a low temperature of 55 ºC. The heated water is then subjected to a low surrounding pressured of -95 kPa (gauge, at sea level) in a Vacuum Tank in which the water boils. The water vapour is then passed through a copper pipe that is exposed to the normal ambient temperature of about 25 ºC, wherein it condenses back into fresh liquid water that flows into a second Tank. Thus desalination has taken place.

Keywords

Desalination; Low pressure; Low temperature; Autonomous.

Introduction

This paper discusses the scope of desalination and how renewable energy sources such as solar power could be used as a solution to the existing resources issues. The objective of the project is to find a solution to tackle the existing freshwater crisis through a sustainable approach of solar-powered desalination. The project focuses on desalination via distilling seawater to produce fresh water suitable for consumption.

Only 1% of the fresh water is readily available while the remaining are trapped in snowfields, glaciers or mixed with earth. Among various implementations, designs and techniques, solar-powered desalination has been recognised as one of the effective solutions to enhance freshwater production mainly due to its sustainable approach. Other means of supply and production of freshwater demand large amount of energy which is sourced from non-renewable fossil fuels [4]. Even so, only about 1% of the world's water resources is satisfied by those fossil-fuel consuming desalination plants [2]. It is also stated that solar-powered desalination eliminates the reliance on grid power [4], hence introducing a sustainable approach. This renewable solar power also provides a cheaper alternative to generate power at affordable costs in rural, remote and poor regions.

At least 67% of the world's population is predicted to live in regions experiencing freshwater scarcity. UN World Water Development reports that 3.7 billion people are currently affected by water scarcity and this number could rocket to 5.7 billion by 2050. The "Aqueduct Water Stress Projections" conducted by World Resources Institute projects the impact and likelihood of water scarcity by 2040 due to the increasing global demands and supply of water [6]. Most of the countries in the high or extremely high category have access to seawater, which makes the feasibility of desalination more promising. A research by Word Health Organisation [8] in 2017 found out that 785 million people are affected by the lack of basic drinking water. 144 million people use water from contaminated sources like ponds, river and lakes due to the scarcity of fresh water. This has resulted in an average death of 297,000 children under the age of 5 and about 829,000 people annually due to unsafe drinking water [8]. These avoidable deaths are caused due to the lack of fresh water sources available in the poor rural areas of the world.

On the other hand, more and more countries and cities are seeking solutions other than water-storage dams or ground-water for drinking supplies as natural calamities often affect those supplies directly [9]. Thus, for example, "The goal to achieve 'water security', using desalination, is a top priority of majority of Australia's capital cities" [9].

This work reports an autonomous process of desalination of sea water, using the renewable, solar energy. The process is thus of low cost and reliable. It involves heating sea water to a low temperature of about 55 ºC in a vacuum tank wherein the pressure is reduced to -95 kPa (gauge, at sea level) using a vacuum pump. Thanks to the low surrounding pressure, the heated water boils. The water vapour is then passed through a copper pipe that is exposed to the normal ambient temperature of about 25 ºC, wherein it condenses back into fresh liquid water that flows into a second tank; and desalination of the sea water has taken place. The energy required for the whole process would be solar. The main tasks for that energy are 1) Heating the sea water; and 2) Operating the vacuum pump.

Literature Review

Some designs [1,4,5,7] inheriting the concept of using solar energy for desalination were reviewed. A design with a vacuum mechanism [4], created by balancing the atmospheric and the hydrostatic pressures in the supply and discharge pipes, that draws the water from the saline water tank to the evaporator. The design has the evaporator and condenser positioned at least 10 m higher than saline water tank (seawater) to create a natural vacuum. This eliminates the need of a vacuum pump, thus saving energy. The saline water is evaporated and then condensed into fresh water inside the pipes which is positioned in a descending position and fresh water is collected inside another tank.

Another design [6] inherited the principle of humidification and dehumidification for water desalination using solar energy. A waterflow controlled the flow of seawater pumped into copper pipes using a water pump. The temperature in each part is kept tracked before the water being sprayed into the humidifier where hot sea water is mixed with dry air in the humification chamber, then condensed to fresh water by passing through the dehumidification chamber. The brine is then collected under the humidifier. Although this process of desalination is seen as the most promising compatible with renewable energy, very few literatures have been reported, thus having research limitations. Educator-based system used in desalination [1] reduces the pressure required, thus lowering the temperature required for the evaporation process. The educator used in this system increases the productivity and efficiency by maximising the energy regeneration during condensation [1]. Using the system of the greenhouse solar desalination technology, a type of semi-passive solar technology that exploits the cycles of evaporation-condensation, the educator will minimise valuable heat energy wasted to the ambient air during condensation. Similar to other vacuum desalination technologies, this process requires the use of a vacuum pump to reduce pressure in order for evaporation to occur at low temperature. The use of the educator will create a partial vacuum in the system by continuously drawing the water vapor from the evaporation chamber, eliminating the use of vacuum pump, thus reducing both the pressure of the evaporation process and the energy.

Methodology

The current set up is divided into 3 parts (figure 1); the mechanical, mechatronic and the power supply aspects represented by the black, green and red coloured links respectively.

- The mechanical aspect discusses the process of how the vacuum desalination occurs at low pressure and temperature. It describes the process of how seawater is transported into the Vacuum Tank 1 after being heated and condensed through the Condenser into Vacuum Tank 2 as clean water.
- The mechatronic aspect discusses how the system is made autonomous by programming five equipment in the setup; the Temperature Sensor, the Ultrasonic Sensor, the Heating Coil, the Water Pump and the Vacuum Pump. The Arduino is coded to control, directly or through the 4 Channel Relay Module, the function of each equipment and how they work with each other to make the system autonomous.

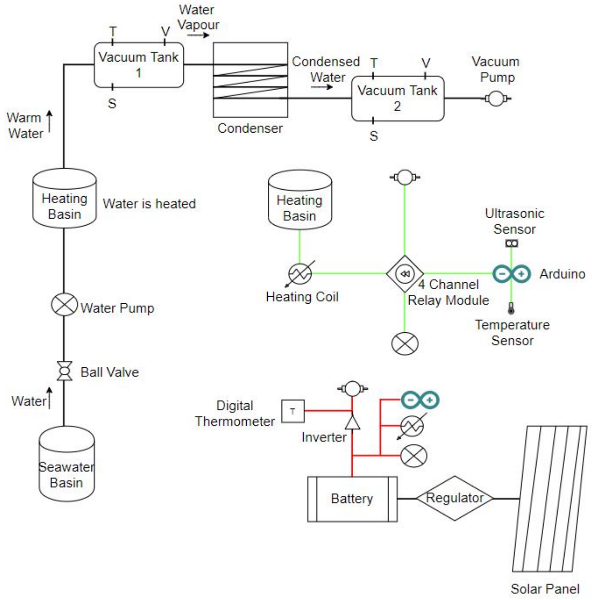

Figure 1. Schematic diagram of the current rig

The whole system is powered by a 12V rechargeable battery which is sourced by a solar panel. Solar energy from the sun is converted into electrical energy stored in the battery through the Regulator. Through an AC to DC Inverter, the Digital Thermometer and the Vacuum Pump is powered. The Heating Coil, the Water Pump and the Arduino (which powers the Ultrasonic Sensor and Temperature Sensor) are all 12V DC which is directly powered by the battery.

Implementations to achieve autonomous system

The Arduino controls the function of each core electronic equipment to make the system autonomous. It sends signals to the input pins of the 4 Channel Relay Module. The Ultrasonic Sensors and the Temperature Sensors are connected to input of the Relay Module while the Water Pump, Heating Coil and the Vacuum Pump are connected to the output of the Arduino.

i. First, the Ultrasonic Sensor detects the water level in the Heating Tank. If the water level is under 2L, the Arduino signals the 4 Channel Relay Module to start the Water Pump. Once water level in the Heating Tank reaches 2L, the Water Pump switches off and the Heating Coil starts.
ii. The Waterproof Temperature Sensor monitors the temperature of the water in the Heating Tank which is heated to 55 ºC. It takes about 24 minutes to heat the water to 55 ºC (from 22 ºC).
iii. Once the temperature reaches 55º C, the 4 Channel Relay Module triggers the Vacuum Pump immediately while switching off the Heating Coil. The Vacuum Pump operates for 30 seconds. During this duration, the pressure of both tanks reaches the desired -95 kPa.

After 30 seconds, the Relay switches off the Vacuum Pump. The Ultrasonic Sensor detects the water level in the Heating Tank and thus, Step i to iii is repeated, getting the water ready for the next run while waiting for the desalination process to finish (5 minutes).

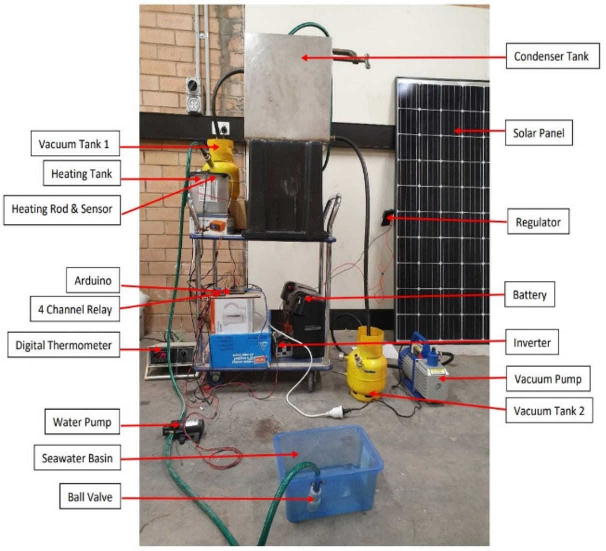

Figure 2. Setup of current rig to run the experiment

Experiment

i. The Water Pump (42 W) transports water from the Seawater Basin into the Heating Tank. The Ball Valve is always open.
ii. The Ultrasonic Sensor in the Heating Tank detects the water level. After 2L of water is reached, the Water Pump is stopped, and the Heating Coil (120 W) is started.
iii. The water in the Heating Tank is heated to 55 °C (from 22 °C). Once the desired temperature is reached, the Heating Coil is switched off and the Vacuum Pump (746 W) is switched on immediately.
iv. The valve of the Vacuum Tank 1 is closed after 2L of water has been sucked. After -95 kPa pressure is achieved in both tanks, the Vacuum Pump is switched off.
v. Step i to iii is repeated automatically once the Vacuum Pump switches off, getting the water heated, ready for the next run.
vi. After waiting for 5 minutes, the resultant clean water is collected from Vacuum Tank 2. The brine from the Vacuum Tank 1 is also drained and the next process is started.

Results

Water collected

The test resulted in an average of 125.9 ml of clean water per 2 litres of 'seawater' after every cycle (table 1). Had the experiment data been calculated from Test 4 to Test 10, an average of 137.43 ml of water would have been observed.

S.N	Water Heating Temperature °C	Time taken for water to heat s	Temp in Tank 1 °C	Pressure in Tank 1 kPa	Pressure in Tank 2 kPa	Wait Time s	Resultant Water Collected ml	Approx. water loss ml
1	55	25	43.5	-95	-95	10	105	15
2	55	24	42.1	-95	-95	9	92	15
3	55	25	41.6	-95	-95	8	100	13
4	55	23	49.2	-95	-95	7	130	17
5	55	25	49.9	-95	-95	6	139	11
6	55	23	51.1	-95	-95	5	143	14
7	55	23	52.7	-95	-95	5	138	14
8	55	24	52.1	-95	-95	5	135	15
9	55	23	51.2	-95	-95	5	140	14
10	55	25	52.1	-95	-95	5	137	14
Average	55	24	48.55	-95	-95	6.5	125.9	14.2

Table 1. Results collected from 10 experimental runs

The reason for less water collection during the first three tests was due to the initial temperature of the Vacuum Tank 1. As the seawater was heated in the Heating Tank before being vacuumed into Tank 1, the initial temperature of the tank is at RTP. As a result, the seawater heated at 55 °C would instantly cool down upon entering Tank 1 (table 1), dropping the temperature of the seawater. As a result, desalination would take place at a lower initial temperature.

Between tests 4 to 10, the Vacuum Tank 1 was warmed from RTP to about 40 °C before each cycle. This allowed the seawater to experience less temperature drop when it was transported to the Vacuum Tank from the Heating Tank. Compared to the initial temperature average of 42.4 °C of Test 1 to 3 to 51.2 °C of Test 4-10, the amount of resultant water collected can be observed as a significant improvement in the later tests; average of 99 ml in the first three tests with Vacuum Tank 1 at RTP to average of 137.4 ml to in Tests 4 to 10 after warming Vacuum Tank 1 to about 40 °C.

Water loss

The average loss of water in the system was about 14.2 ml (table 1). The water loss in the system was calculated by adding the brine from Vacuum Tank 1 after draining and the resultant water collected in Vacuum Tank 2. The water loss was due to some water droplets being stuck in the system (the Vacuum Tanks, Rubber Hose Pipes and the Copper Pipes).

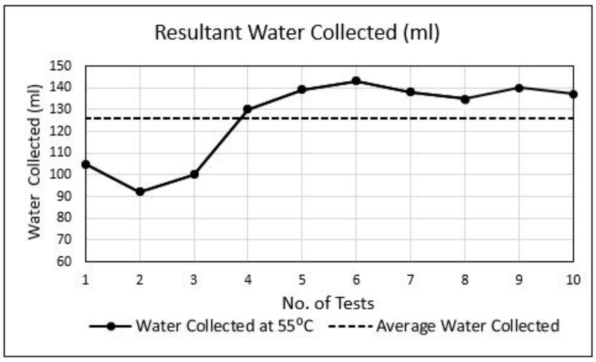

Figure 3. Resultant water collected from the experiment.

Also, during the process of the Vacuum Pump sucking warm water from the Heating Tank to Vacuum Tank 1, some of the water may be left in the Heating Tank due to the pipe not in contact with the base of the Tank. The pipe was positioned in this way to prevent blockage of suction during the process of vacuuming.

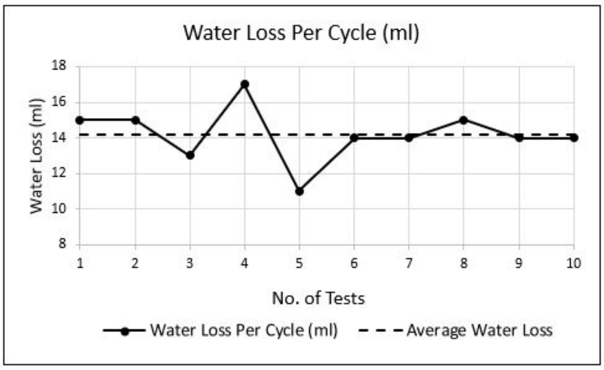

Figure 4. Water loss per cycle during each run.

As an example of the process used in this work, in a typical (average) cycle of desalination producing fresh water from sea water, the following figures have been obtained

- Initial amount of sea water: 2 l
- Fresh water obtained: 0.125 l
- Water pump (42 W) running for 30 s
- Vacuum pump (746 W) running for 27 s
- Heating coil (120 W) heating water from room temperature (22 °C) to 55 °C: 24 minutes
- Total cycle time (Water pump + Heating Coil + Vacuum pump + Wait time [5 minutes]): 30 minutes
- Energy required to bring 0.125 l of sea water from 22 °C to 100 °C then evaporate it: 324 kJ
- Energy to operate Water pump + Heating coil + Vacuum pump: 194 kJ
- Energy saving: 100 ([324 – 194] / 324) = 40 %
- Water production: 100 (0.125 / 2) = 6.3 %

Thus, while the water production rate is rather low, the energy saving is however very significant.

On the other hand, this experiment has been conducted using low cost equipment and setup. Water production rate would most likely be improved significantly with a future, better setup. Also, production on large scales using low-pressure and low-temperature desalination methods as presented in this work, with the endless amount of available seawater might produce enough fresh water for the world's need, as the energy required is relatively low, the setup simple, and the equipment low-cost.

Conclusion

This work has demonstrated the concept of a solar-powered desalination plant on a small scale. It continues on an existing desalination setup from a previous project. Through the use of low-cost equipment on a small scale, the setup has demonstrated desalination using low pressure and low temperature with practical results and great energy savings.

As the objective of this work is to make the existing system autonomous, this research demonstrated the applicability of the desalination system in poor regions and hard-accessibility areas where both freshwater and power are limited. Freshwater can be supplied in these regions with the implementation of this system due to its low setup cost, low energy consumption and autonomous operation capability that requires minimum maintenance.

All the equipment in the system were powered by a rechargeable battery that was recharged using a solar panel. The battery when fully charge through solar energy could still be used to operate the system even in the absence of sunlight. The equipment used in the project consumed low energy, and equipment like the vacuum pump that demanded higher energy were restricted to short run time.

Some water loss was found to be trapped in the condensing coil. This loss thus could be easily eliminated or reduced with better incline angle for the coil. Another obvious improvement is to replace the coil-tube condenser with a parallel plate condenser which has a much larger condensing area. A parallel plate condenser is expected to increase significantly the water production rate.

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