PHILIPPINE ENGINEERING JOURNAL
PEJ 2009; Vol. 30, No. 1: 39-52

PERFORMANCE EVALUATION OF LOW COST MODULAR SOLAR DESALINATION AND DISINFECTION CHAMBER

Nolan Tolosa and Genandrialine L. Peralta
Environmental Engineering Graduate Program
University of the Philippines, Diliman

ABSTRACT

The low cost water desalination was designed and fabricated to reduce and eliminate microbiological and chemical pollutants. Total and fecal coliforms, pH and chloride were parameters used to determine the efficacy of treatment of saline water.

The 10-liter capacity Solar Desalination and Disinfection Chamber (SDDC) set-up consisted of 12.7 mm thick glass with dimensions of 0.9 x 0.9 x 1.2 m., equipped with thermocouple, cloth filtration and activated carbon filtration. The set-up was made to determine its performance on pathogen (total and fecal coliform) and chloride reduction of the saline water feed.

The SDDC prototype had the capacity to disinfect contaminated water containing an initial total and fecal coliform concentration of $\geq 16 \times 10^{6}$ *MPN/100 mL to a final value of <2 MPN/100 mL. Another important result was the reduction of chlorides from saline water from initial values ranging from 14,000 mg/L to 19,000 mg/L down to a concentration of only 1.0 mg/L. Chloride content is the main factor that contributes to water salinity. The volume of treated water ranged from 230 mL to 3,270 mL per day, depending on sunlight exposure and cloud cover. The measured optimum temperature ranged from 34 °C to 67 °C for an 8-hr exposure to the sun.*

1. INTRODUCTION

Fresh water has been ground- and surface-sourced and is being conserved through reuse. Although 70% of the planet is covered with water, 97.5% of this is the ocean which provides a large and virtually untapped source of water to solve increasing demand for fresh water. By difference, only 2.5% of the total water on earth is freshwater as shown in Figure 1a and about 69.5% of this is frozen in the icecaps and glaciers as shown in Figure 1b, leaving 30.2% non-renewable and about 0.3% renewable such as water found in lakes, rivers, reservoir, and underground sources ready for human consumption (Miller, 2003; Gowin, 2002; Al-Kharabsheh and Goswami, 2004).

Correspondence to: *Environmental Engineering Graduate Program, University of the Philippines, Diliman*

Received: January 9, 2007
Accepted: December 15, 2011

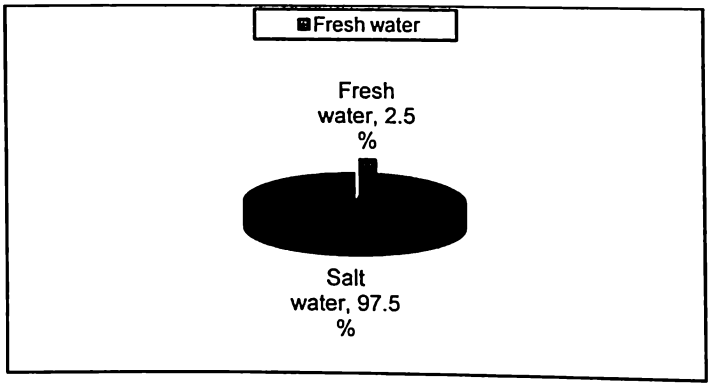

Figure 1a. Global fraction of salt and fresh water

Based on studies, half the world's population will have no access to fresh water by year 2015. By 2025, two-thirds of the world's population may live in countries with moderate to severe water shortages. During the 20th century, demand for water increased four-fold, more than double the rate of the growth of human population, while pollution and over-extraction of water sources in many regions of the world reduced the ability of supplies to meet the demand (Miller, 2003).

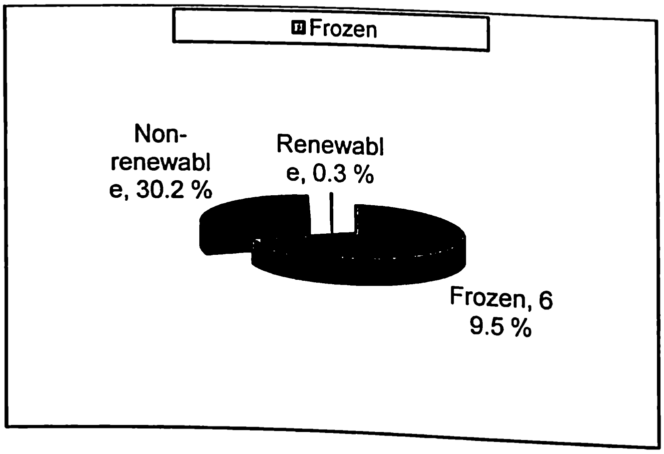

Figure 1b. Distribution of fresh water

1.1 Background

Desalination is a process that removes salts and other dissolved contaminants from saline or brackish water to make it potable. Desalination is a widely known method for treating saline water for drinking purposes. This process generally involves drawing source water (saline) and separating it into two (2) streams; the stream of desalted water (treated) which contains a minimal concentration of dissolved solids and minerals and the stream of liquid containing high concentrations of dissolved solids, minerals and other compounds.

1.2 Heat Flow of the Sun

The sun plays a dominant role in the planetary atmosphere wherein the solar radiation and particles are fundamental in the evolutionary process of the planet (Lammer et al., 2004). The energy of the sun is produced in its core through fusion of hydrogen to form helium. This energy flows toward the surface where it radiates and increases when the brightness of the sun increases. Knowledge of this global solar radiation in energy conversion is essential in the design optimization and prediction of the desalination system performance but determining the amount of global solar radiation using pyranometers requires expensive instrumentation (El-Sebaii & Trabea, 2005).

The solar radiation energy change happens gradually throughout the year when there is gradual change in the angle of incidence of the sunrays (Ferenc et al., 2002). Solar ultraviolet radiation, with wavelengths ranging from 290 nm to about 400 nm, is a very important component in our environment. The ultraviolet radiation spectrum can be further subdivided into the following sub-spectral classifications (Trabea and Salem, 2001):

- Near ultraviolet(380 – 300 nm)
- Middle ultraviolet (300 – 200 nm)
- Far ultraviolet (200 – 100 nm)
- Extreme ultraviolet (100 – 4 nm)

Ultraviolet light has been widely used for water disinfection applications. Within the ultraviolet radiation spectrum of 200 to 280 nm lies the region known as the germicidal range with an optimum wavelength of 254 nm, as shown in Figure 1c. Exposing microorganisms to radiation in this range will destroy their DNA within 3-5 seconds, effectively inactivating them. This is significantly faster compared with chlorine that takes between 20-45 minutes (McSherry et al., 2004).

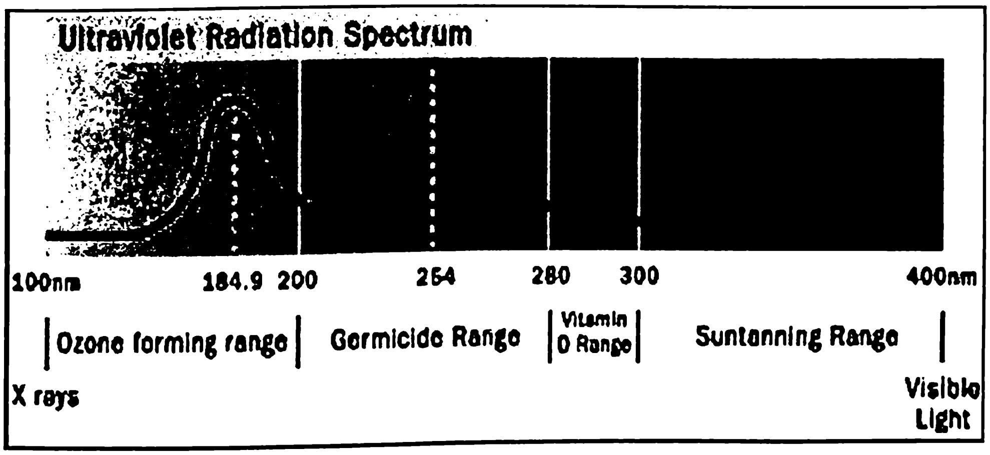

Figure 1c. Ultraviolet Radiation Spectrum.

1.3 Solar Desalination

Most solar water desalination plants use a single-stage flash distillation process where heat is generated from solar energy. This solar energy desalination plant produces fresh water by pumping seawater to the pre-treatment unit first and subsequently passes through distillation column. Solar desalination disinfects by destroying disease-causing bacteria by the action of heat and light from the sun.

The study focused on the performance of the solar desalination and disinfection chamber (SDDC) set-up. The study also evaluates the performance of the set-up in reducing chloride ion present in brackish or saline water. Characterization of raw and treated water using total and fecal coliform to evaluate the fate of disinfecting raw water and ensures treated water free from pathogens.

2. MATERIALS AND METHODS

This solar desalination study was conducted using a low cost modular solar still system. The primary considerations in selecting materials for the equipment were availability of materials, ease in operation and maintenance, economic viability, and UV and heat transmission capacity.

The study consists of two phases – i) design of the solar desalination equipment and ii) operation and experiment using the designed equipment. These are discussed in the following sections.

2.1 Design of Equipments

The solar still initially tested the performance of a 15^0 angle top cover in collecting water. But such a small angle of inclination rendered the distillate collector ineffective in catching the condensates that form on the top cover hence, a 45^0 angle cover was used instead of the 15^0 cover. The solar still set-up is composed of primary treatment, desalination, and filtration chamber, piping and tubing components. The conceptual design of the whole process is shown in Figure 2a.

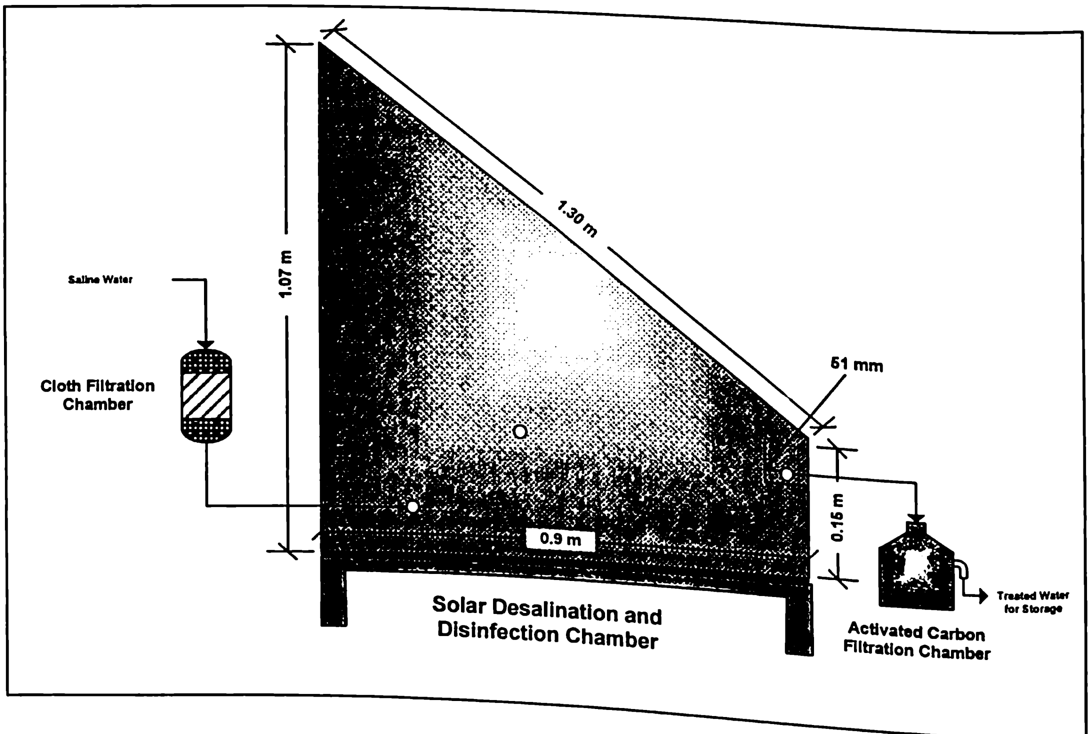

Figure 2a. Conceptual Design of Solar Desalination Process

The primary treatment involves a simple filtration system wherein saline water passes through the cloth filtration chamber (CFC). The filter media used in this process consist of small pore cloth (approximately 5.0 μm) as shown in Figure 2b. This ensures the removal of some suspended particles that was present in the seawater or brackish water that might hinder the desalination process. The chamber is made up of high-density polyethylene (HDPE) cylindrical tank and packed with cloth for easy maintenance with dimensions of 0.5 m in height and 0.4 m in diameter.

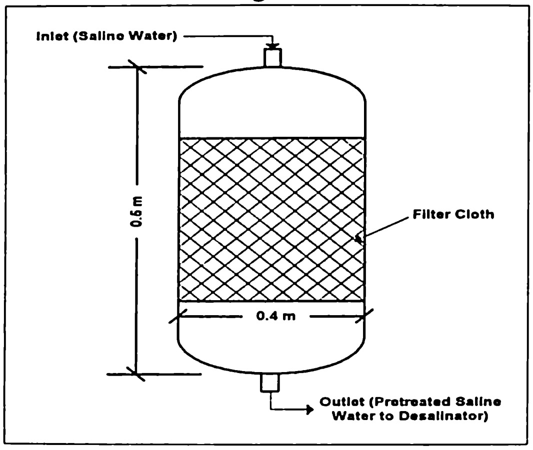

Figure 2b. Schematic diagram of the cloth filtration chamber (CFC)

The distillation column where the main process took place was the next step. The materials used in this vessel were any kind of black-heat absorbent material. In this case the black absorbent material used was a black cardboard. This black-heat absorbent material was located at the bottom of the chamber to maximize the operating temperature of the water as shown in Figure 2c. A thermocouple was used to measure the temperatures of the water and the water vapor; one directly submerged in the pool of water at the bottom of the chamber and the other at the top portion for vapor space inside the chamber, just below the top cover. The whole body of the vessel was made up glass or UV rated plastics including the cover that has a gutter in the side, which collects water drippings or condensates. These have dimensions of 0.81 m^2 at the base with 1.07 m in height as shown in Figure 2a.

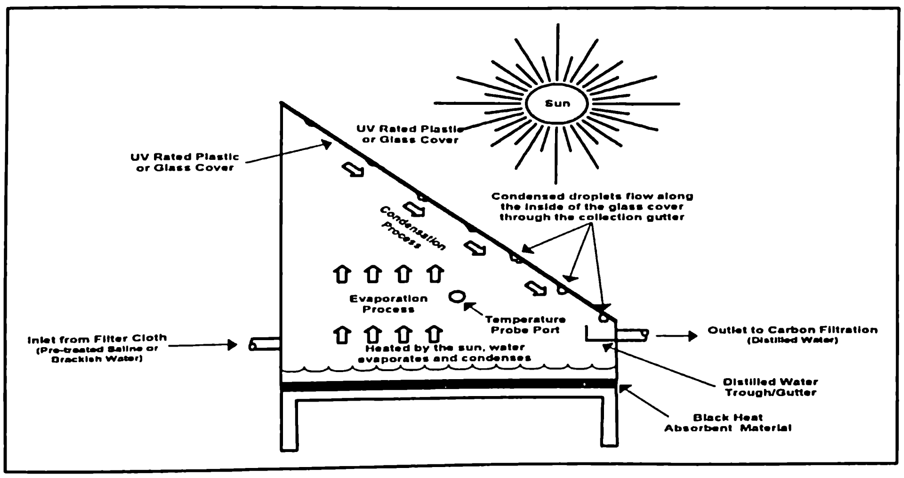

Figure 2c. Schematic diagram of solar desalination and disinfection chamber

The last part of the vessel is the carbon purifier. This was a small vessel that is made up of HDPE plastic as shown in Figure 2d. The vessel is filled with Activated carbon is used in this vessel as a filter media, to remove the pungent taste and odor in the distillate prior to storage. The filtration chamber has dimensions of 150 mm in height and 90 mm in diameter.

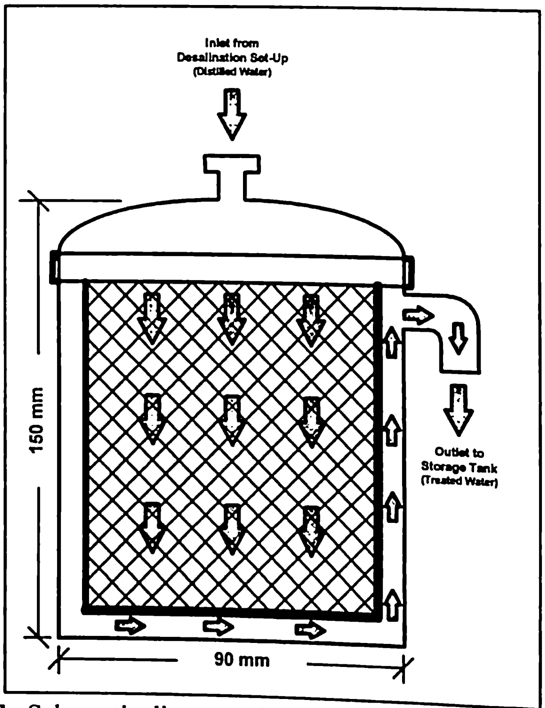

Figure 2d. Schematic diagram of activated carbon filtration chamber

Piping lines or small tubes made of rubber tubing were used to transport water from one vessel to another to prevent corrosion. Thermocouples were placed at strategic points in the distillation column for temperature monitoring. The black heat absorbent material made up of black cardboard is laid at the bottom of the distillation chamber to capture the heat from the sun.

2.2 *Raw Water Characterization*

Characterization of raw water was undertaken according to the standards set by the Philippine National Standards for Drinking Water (PNSDW). Chlorides, pH and total and fecal coliform measurements were conducted to know the fate of reducing and removing of these types of pollutants.

Chloride and pH measurements for both the treated and raw water were conducted using the Philippine National Standard for Drinking Water (PNSDW) as reference. The treated water must pass the PNSDW standards for these parameters to make it potable.

Only total and fecal coliform were chosen for microbiological examination to comply with Philippine National Standards for Drinking Water (PNSDW) standard of negative or negligible for total and fecal coliform for drinking water per 100 mL sample. Test results for microbiology were used to determine the efficiency of removing or reducing microorganisms. The multiple-tube fermentation technique was the method used for total and fecal coliform efficiency.

a. Treatment Procedure

The saline water was pre-treated first in the filter cloth chamber. Here, the suspended solids or particles were removed at the very start to eliminate interference during the desalination process. This also increased the removal efficiency of the pollutants.

Solar desalination and disinfection treatment of the prepared saline water were conducted between 8:30 a.m. to 4:00 p.m. The chamber was filled with 4 – 6 liters of raw water. Batches were processed at different temperature levels ranging from 34 to 70 ^{0}C, depending weather and sky conditions.

After a sufficient quantity of treated water was collected (approximately 1 liter), it was subjected to carbon filtration to further remove the dissolved pollutants that were entrained with the distillate. The samples were taken from the collection outlet after reaching the desired amount of collected water to analyze all the parameters of concern.

Saline water was first passed through the cloth filtration to remove suspended particles and reduce other pollutants present during the process. The pretreated water was then ready for the next step of the process. The pre-treated water from the cloth filtration was subjected to solar desalination and disinfection chamber for further treatment, wherein distillation and disinfection take place. The pre-treated water was introduced at the side of the chamber as shown in Figure 3c. This chamber has a capacity of 10 liters but, during the experiment, the volume of water to be treated was reduced to the maximum of 6 liters to increase the distillation efficiency and maximize the heat absorbed by the chamber. This chamber was exposed to sunlight where the process of evaporation and condensation takes place. The drippings from the top cover (glass) are allowed to flow along the inside of the cover onto a trough where treated water is collected. This process ensures that the water (treated) is free from residual contamination.

The treated water from desalination chamber is allowed to pass through an activated carbon filtration chamber for further removal of objectionable taste and odor by adsorption. This chamber was packed with activated carbon granules, as illustrated in Figure 3d. The chamber is about 4 inches in diameter and 5 inches in height, made up of high-density polyethylene (HDPE) plastic. The collected samples were brought to laboratory for analysis.

Laboratory analysis was carried out at the Environmental Engineering (EnE) laboratory at the University of the Philippines, Diliman. Parameters analyzed were chlorides, and total and fecal coliforms. These were the same parameters analyzed for raw water which should not be present in the treated water for it to be safe and potable. The experiments were conducted under sunny weather with 30 trials. The volume collected during the experiment varies depending on the sky condition. During cloudy conditions the volume collected was expected to be small but the trials were considered and included if the collected treated water was at least 200 mL enough for analysis.

3. DISCUSSION AND RESULTS

3.1 Characteristics of Raw and Treated Water

pH, chlorides, and total and fecal coliform properties of treated water were analyzed and the results were evaluated during the entire process. These characteristics of water measured in this study were based on the required parameter by the Philippine National Standards for Drinking Water (PNSDW). The range of values obtained for the different parameters were presented in Table 3a. Experiments done with 30 runs where average chloride values for raw and treated water were 16,431.17 mg/L and 0.27 mg/L with standard deviations of 1,735.53 and 0.36, respectively shown in Table 3b. While the pH average values for raw and treated water were 6.97 and 6.62 with standard deviations of 0.22 and 0.30. Based on the results, the standard deviation measures how far the numbers from their average is. As a result the values of the standard deviation were small and conclude that the data are close together.

Table 3a
Summary of values for raw and treated water

Parameters	Saline Water	Treated Water	PNSDW Standard	Methods
Chlorides, mg/L	14,180 – 19,143	nil – 1.0	250	Argentometric Method
pH	6.54 – 7.37	6.07 – 7.26	6.5 – 8.5	Glass Electrode Method
Total Coliforms, MPN/100mL	≥ 16 x 10^6	<2	<2	Multiple-Tube Fermentation Technique
Fecal Coliforms, MPN/100mL	≥ 16 x 10^6	<2	<2	Multiple-Tube Fermentation Technique

The pH value indicates whether the water is acidic or alkaline. It is usually measured on the scale of 0-14. Basically, the pH value may also signify whether the water is hard or soft. The resulting pH values shown in Figure 3a and Table 3b in the treated water are within the standard range of values except for selected trials which are a little below the required pH range of 6.5 to 8.5 by the Philippine National Standard for Drinking Water (PNSDW). The reduced pH after the distillation process may be due to CO_2 from atmosphere being absorbed by the water as it cools, forming carbonic acid; thus, lowering the pH. This occurrence is the same with what happens in acid rain formation wherein naturally occurring carbon dioxide (CO_2) dissolves in the condensing water vapor in air (Demirbas, 2004).

Table 3b
Average values and standard deviation of raw and treated water.

Parameters	Values		Average		Standard Deviation	
	Raw Water	Treated Water	Raw Water	Treated Water	Raw Water	Treated Water
Chlorides, mg/L	14,180 – 19,143	nil – 1.0	16,431.17	0.27	1,735.53	0.36
pH	6.54 – 7.37	6.07 – 7.26	6.97	6.62	0.22	0.30
Total Coliforms, MPN/100mL	≥ 16 x 10^6	<2	---	---	---	---
Fecal Coliforms, MPN/100mL	≥ 16 x 10^6	<2	---	----	---	---

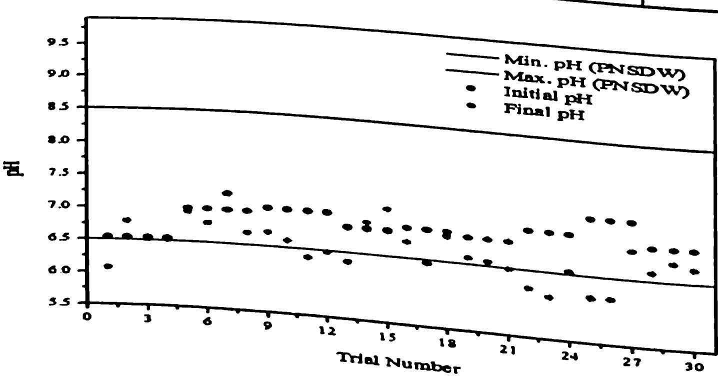

Figure 3a. pH profile for the raw and treated water.

Chloride concentrations in the treated water ranging from nil to 1.0 are within the PNSDW standard as shown in Figure 3b and Figure 3c. During the desalination process the percent removal of chloride for the entire experiment will not be lower than 99 % as indicates in Table 3c. Chloride content after this process was merely negligible in value.

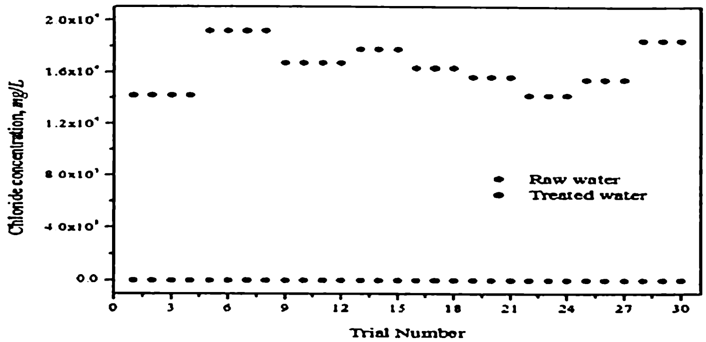

Figure 3b. Chloride concentration profile of raw and treated water.

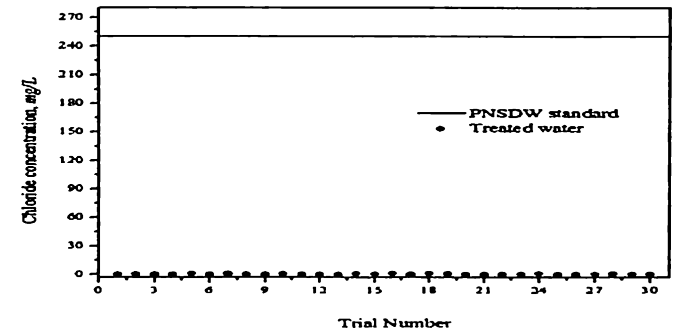

Figure 3c. Comparison of chloride values between Philippine National Standard for Drinking Water (PNSDW) and treated water.

The most serious threat to potable water supply is fecal contamination. Thus, total and fecal coliform concentrations of the raw and treated water were measured and compared. The results showed that raw and treated water total and fecal coliform count were $\geq 16 \times 10^6$ MPN/100 mL and <2 MPN/100 mL, respectively. The high coliform count for the raw sample was due to the source of the raw water sample. The sampling point for the raw saline water used for this experiment was along the highly-populated coastal area of Kawit, Cavite. The runoff from domestic wastewater of the residents contributes to the high values of total and fecal coliform. This was further validated that the total coliform obtained were fecal in nature as shown by the equal MPN values for total and fecal coliform. The treated water samples gave a negative result for total and fecal coliforms since the samples were subjected to a high temperatures of 34 to 69 ^{0}C during the SDDC treatment. Pathogens can also die off at temperatures as low as 50 ^{0}C, thus disinfection occurred during the treatment (Peralta et al., 2000).

Table 3c.
Percent (%) removal and chloride concentration values for raw and treated water.

Trials	Chloride Concentration, (mg/L)		PERCENT REMOVAL, %
	Raw Water	Treated Water	
1	14,180	0.00	100.00
2	14,180	0.25	100.00
3	14,180	0.00	100.00
4	14,180	0.00	100.00
5	19,143	1.00	99.99
6	19,143	0.00	100.00
7	19,143	0.50	100.00
8	19,143	0.00	100.00
9	16,662	0.00	100.00
10	16,662	0.50	100.00
11	16,662	0.00	100.00
12	16,662	0.00	100.00
13	17,725	0.00	100.00
14	17,725	1.00	99.99
15	17,725	0.25	100.00
16	16,307	0.75	100.00
17	16,307	0.00	100.00
18	16,307	1.00	99.99
19	15,598	0.50	100.00
20	15,598	0.00	100.00
21	15,598	0.00	100.00
22	14,180	0.00	100.00
23	14,180	0.25	100.00
24	14,180	1.00	99.99
25	15,421	0.00	100.00
26	15,421	0.00	100.00
27	15,421	0.25	100.00
28	18,434	0.50	100.00
29	18,434	0.25	100.00
30	18,434	0.00	100.00
Weighted Average	**16,431.17**	**0.27**	**100.00**

3.2 Temperature and Volume Collection

The liquid and vapor temperatures measured during the experiments are shown in Figure 3d and Table 3d – 3e. The temperature inside the solar still for liquid water and vapor ranges from 34.10 – 66.90 ^{0}C and 34.70 – 66.20 ^{0}C, respectively. The highest temperature reached by the water was during the summer where ambient temperature was the highest. On Figure 3f and Table 3e, the % recovery of treated water corresponds to the temperature during the entire experiment. The collected volume was also relative to temperature, wherein at the highest temperature level the volume obtained was the maximum. This is obvious in the % recovery results and ensured that the volume collected was used for the design modification of the solar still. During the first run of the solar still, the volume collection was not efficient due to the heat that escaped in the solar still since some of the sides of the equipment were not tightly sealed. In addition, the collection of the distillate was not efficient because some of the distillate collector was not yet installed. The collector system of the SDDC was extended to solve this problem.

Table 3d.
Temperature ranges per run for liquid and vapor, and percent recovered during entire process.

Parameters	Units	Values
Temperature Reading (Water)	Degrees Celsius (^0C)	34.1 – 66.9
Temperature Reading (Vapor)	Degrees Celsius (^0C)	34.6 – 66.2
Treated Water Recovered per Day	Percent (%)	3.83 – 54.50

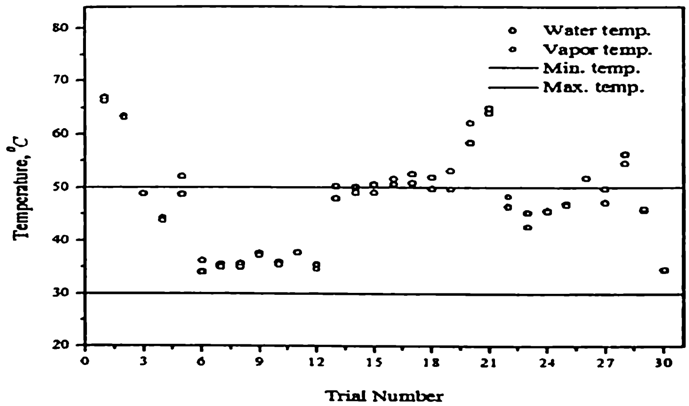

Figure 3d. Temperature profile of water, vapor and their expected minimum and maximum temperature.

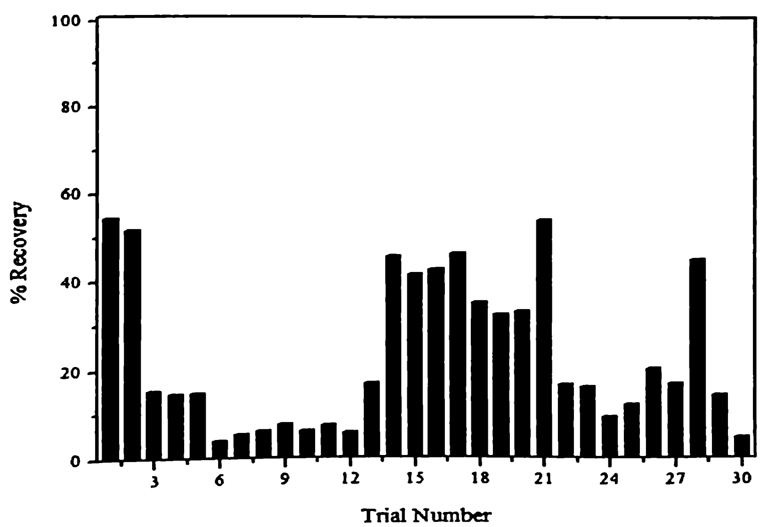

Figure 3e. Percent recovery profile of treated water using designed desalination set-up.

Table 3e.
Temperature profile for vapor and water with corresponding % recovery of treated water.

Trials	Temperature, °C		Treated Water, % Recovery
	Water	Vapor	
1	66.90	66.20	54.50
2	63.30	63.10	51.67
3	48.90	48.90	15.33
4	44.20	43.80	14.50
5	48.70	52.10	14.83
6	34.10	36.20	3.83
7	35.50	35.00	5.33
8	35.60	35.00	6.00
9	37.60	37.20	7.50
10	35.90	35.50	6.00
11	37.80	37.70	7.17
12	35.40	34.70	5.50
13	47.90	50.30	17.00
14	50.10	49.00	46.00
15	50.50	49.00	41.83
16	50.60	51.60	43.00
17	50.80	52.60	46.67
18	49.80	51.90	35.50
19	49.70	53.20	32.83
20	58.40	62.10	33.50
21	63.90	64.80	54.17
22	46.40	48.30	16.83
23	45.20	42.60	16.33
24	45.60	45.50	9.33
25	46.90	46.60	12.17
26	51.80	51.80	20.33
27	49.80	47.20	17.00
28	56.20	54.50	45.17
29	45.80	46.00	14.33
30	34.50	34.60	4.50
Weighted	47.26	47.57	

The maximum temperature attained per run was recorded and the corresponding volume of treated water generated. This information is relevant in assessing the feasibility of supplying the daily requirement per capita and in the design of the volume capacity of the SDDC. This is similar to 3 – 4 L/m^2 daily production of solar still studied by (Al-Kharabsheh and Goswami, 2003). The highest volume of distillated obtained using the SDDC set-up was three liters where liquid water temperature reading was about 67 ^{0}C. During the time where the temperature of the liquid was at maximum the weather and sky conditions were extremely hot and clear, respectively. At that moment the % recovery of treated water is about 54%. In contrary to 3.8% treated water recovered where the sky condition during the experiment was cloudy.

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The result of this study proved that the fabricated solar desalination and disinfection chamber (SDDC) is effective in desalinating and disinfecting saline water. The technical, environmental, and economical feasibility of the SDDC system can be summarized as follows:

1. The angle of inclination of the top cover of SDDC set at 45^0 from the horizontal was suitable to collect the condensate favorably.
2. An area of 0.81 m^2 of the pilot plant is sufficient to produce fresh water ranging from 230 – 3,270 mL per day.
3. SDDC is capable of removing contaminants and the following parameters all passed the Philippine National Drinking Water Standards - chloride, and total and fecal coliforms.

4.2 Recommendations

It is recommended for future researchers to investigate further the following undertakings:

1. Pilot testing of solar desalination and disinfection chamber in communities where potable water is scarce.
2. Modification of the pilot scale set-up to increase distillate generation over a 24-hr operation.
3. Use of indigenous SDDC material appropriate to the locality and evaluate in terms of economic aspects.
4. Collection of data during the wet season to have a more representative evaluation in terms of efficiency of pollutant removal.
5. Gathering of global radiation data to assess the highest solar intensity during test period.
6. Design of continuous flow set-up should be studied to know efficiency in comparison with a batch process.
7. More dilutions of raw water samples for bacteriological examination to identify the exact value of disease-causing microorganisms.
8. Identify the exact contact time exposure of treated water during sampling for microbiological examination to know the capability of disinfection.

REFERENCES

1. J.E. Miller, *Review of Water Resources and Desalination Technologies,* SAND 2003-0800 (2003).
2. P.J. Gowin, Seawater *Desalination using Nuclear Energy.* Heat Transfer Engineering . Taylor & Francis. 23:1 – 2 (2002).
3. S. Al-Kharabsheh and D.Y. Goswami, *Theoretical Analysis of a Water Desalination System Using Low Grade Solar Heat.* Journal of Solar Energy Engineering. Vol. 126. 774 – 780 (2004).
4. Lammer, H.; Ribas, I.; Grieβmeier, J.M.; Penz, T.; Hanslmeier, A.; Bienat, H.K. (2004). *A Brief History of the Solar Radiation and particle Flux Evolution.* Hvar Obs. Bull.
5. El-Sebaii, A.A. and Trabea A.A. (2005). *Estimation of Global Solar Radiation on Horizontal Surfaces Over Egypt.* Egypt J. Solids, Vol (28), No. (1).
6. Ferenc, K.; József, B.; Marianna, V. (2002). *Changes in Solar Radiation Energy and its Relation to Monthly Average Temperature.* Acta Montanistica Slovaca. Ročník 7, 3, 164-166

7. Trabea, A.A.; Salem, I. (2001). *Empirical Relationship for Ultraviolet Solar Radiation Over Egypt*. Egypt J. Sol., Vol. (24), No. (1)
8. McSherry, M.; Fitzpatrick, C.; Lewis, A. (2004). *An Optical Fiber Sensor for the Detection of Germicidal UV Irradiation Using Narrowband Luminescent Coatings*. IEEE Sensors Journal, Vol. 4, No. 5
9. Demirbas, A. (2004). *Bioenergy, Global Warming and Environmental Impacts*. Energy Sources, 26:225-236.
10. Peralta, G.L.; del Mundo, R.; Donasco, E.A. (2000). *Disinfection of Drinking Water using Flat-Plate Solar Collector*. University of the Philippines, Diliman and The World Health Organization, WPRO Manila. 90p.
11. Al-Kharabsheh, S.; Goswami, D.Y. (2003). *Experimental Study o fan Innovative Solar Water Desalination System Utilizing a Passive Vacuum Technique*. Elsevier. Solar Energy 75, 395-401.