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Water purification by direct solar distillation process in isolated households

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ABSTRACT. This study aims at contributing to the production of drinking water by solar distillation process. Salt raw water and brackish water were used in this process. The objective of this work was to attend rural or isolated households by offering a social and simple utilization technology with low cost materials and good quality water production. The solar drinking water purification has a four-sided pyramidal glass cover allowing the action of sun rays during the day. Water level in the evaporation pan, cover inclination, and water quality were assessed at two points: a) between the parallels 27°10' and 27°50'S latitude and meridians 48°25' and 48°35'W longitude, from 2003 to 2005, with maximum production of 6.2 L m^{-2} day, and monthly averages from 3.1 to 3.7 L m^{-2} day. b) in the parallels 5°47' and 5°57'S latitude and meridians 35°12' and 35°22'W longitude, from 2003 to 2004, with monthly averages of 3.0 to 3.7 L m^{-2} day. Water quality, physical, chemical and bacteriological parameters comply with recommendations of the World Health Organization (WHO).

Keywords: direct solar distillation, solar water purification, water desalting, water treatment.

Potabilização de água por processo de destilação solar direta para residências isoladas

RESUMO. Este estudo visa contribuir com a produção de água potável, pelo processo de destilação solar. Foi utilizada no processo, água bruta salgada e salobra. Objetiva-se atender residências rurais ou isoladas, oferecendo uma tecnologia social de simples utilização, com materiais de baixo custo e produção de água com qualidade. O Potabilizador Solar possui cobertura de vidro, em forma de pirâmide, com quatro faces, permitindo a ação dos raios solares durante todo dia. Foram testada, altura da lâmina d'água na bandeja de evaporação, inclinação da cobertura e a qualidade da água, em dois pontos: a) entre os paralelos 27°10' e 27°50' de latitude S e os meridianos 48°25' e 48°35' de longitude W, entre 2003 a 2005, com produção máxima de 6,2 L m^{-2} dia, e médias mensais entre 3,1 e 3,7 L m^{-2} dia. b) nos paralelos 5°47' e 5°57' de latitude S e os meridianos 35°12' e 35°22' de longitude W, entre 2003 e 2004, com médias mensais de 3,0 a 3,7 L m^{-2} dia. Os parâmetros de qualidade de água, físicos, químicos e bacteriológicos estão em conformidade com recomendações da Organização Mundial de Saúde (OMS).

Palavras-chave: destilação solar direta, potabilização solar de água, dessalinização de água, tratamento de água.

Introduction

Direct solar distillation is an old process which simulates the continuous phenomenon of the hydrological cycle. The solar distillation is presented as a simple system consisting of a shallow tank with a transparent glass cover, with a stable volume. Solar radiation goes through the glass and heats the water, increasing its evaporation rate. The water vapor rises, condenses when in contact with the cooler glass, and distilled water flows to be captured by a channel, leaving behind the salts, minerals and most other impurities, including harmful microorganisms (RAY; JAIN, 2011). Solar distillation techniques have been used for more than about 200 years.

The chemist Lavoisier applied large glass lenses to concentrate solar energy into distillation bottles in 1862 (ANIRUDH BISWAS, 2012). In 1872, in the north of Chile, distillation techniques were applied for the production of drinking water for mining workers in the town of Las Salinas. It consisted of 64 tanks with 60 m^2 each, made of wood, painted in black, with inclined glass covers. The total area reached 4,459 m^2 for the purpose of producing 20,000 liters of drinking water (RAY; JAIN, 2011).

Other information presented a still with a black shallow basin to retain salt water and to absorb solar radiation (KREITH; KREIDER, 1978). The amount of distilled water depends on the type of cover (plastic or glass), amount of water, solar radiation, temperature and humidity and wind speed, among others (NANDWANI, 2006). Glass and plastic were used as covers in desalination from 1963 to 1979 (TIWARI; TIWARI, 2008). Glass is considered a better material in the long term, and plastic such as polyethylene is better for a short term (QIBLAWEY; BANAT, 2006/2007). We found studies with inclinations of 10, 20, 35 and 45º for water and half water covers (CAPPELLETTI, 2002).

Researches indicate that the average slope angle ideal for each month ranges from -8.89 to +49.91° to the horizontal. The negative sign indicates that the cover faces north. In May, June and July, the inclination to the south is not recommended for a better use of sunshine at this latitude. However, the ideal average for the year on the island of Masirah, is 20.63°, facing south. This position is acceptable to ensure a high rate of utilization of sunshine and facilitate the drainage of the condensate (CERDA et al., 2002). But, the angle of slope of the glass cover influences the amount of solar radiation that enters in the distiller. The more orthogonal to the glass surface is the angle of incidence, the better. If at incident angles of 90°, about 90% of the radiation is transmitted, and almost any direct radiation goes through the glass at angles of 20°. Inclinations for Brazilian latitudes must be between 0 to 35° approximately. The distance between the glass and the water surface should not be longer than 5 or 6 cm, so that still operates with greater efficiency (AL-ISMAILY; PROBERT, 1990). The cover of the distiller must provide condensation in the form of droplets flowing to the channel. This effect is associated with decreased wettability of the glass.

To obtain a better efficiency in solar stills it is necessary that the raw water is heated to the maximum and the water level is low (SA, 2012). Some authors indicate in their experiments that the productivity of a solar still, with raw water levels measuring 1.5, 3.0 and 4.0 cm has increased as decreased the water level due to solar radiation absorbed by the base (black) (SUNEJA; TIWARI, 1999). We found experiments with average production of water ranging from 1.3 to 5.6 L m^{-2} day (CAPPELLETTI, 2002). Data indicate an annual average of 6 L m^{-2} day in countries where the value of horizontal insolation reaches an annual average of 5,500 Kcal m^{-2} day (AL-HAYEK; BARDAN, 2004). Studies on a still in Algeria, with ambient temperature of around 40°C in the summer, the internal water temperature reached 60-75°C, so the yield is influenced by solar radiation and water temperature. A significant increase in the production of distillate was obtained not only during the day but also at night, when water on the base of the still is cooled (COMETTA, 1977). For very cloudy days, solar radiation decreases since clouds are responsible for 25 to 30% (on average) of the reflection of solar radiation reaching the Earth (SOUZA et al., 2006). It is found a small production in the early hours of the day and a maximum production at hours with the highest solar radiation intensity (12 a.m. to 3 p.m.), decreasing when approaching the nighttime. It was found also that 30% of daily production is obtained during the night when the outside temperature decreases and favors the condensation of steam on the glass. On the other hand, even on totally cloudy days, the still produces an average 3.8 L m^{-2} day (ONU, 2011). By assuming an average sunshine of 250 W m^{-2} in 24 hours, 9 L m^{-2} day could evaporate. In practice, heat loss affects the daily yield, and a production of 4 to 5 L m^{-2} day could be expected.

This study presents a technology for water purification with direct solar distillation in a device called a solar water purifier (Figure 1), in a pyramidal form, from raw seawater, synthetic brackish water, brackish water pre-filtered by bank filtration technique, groundwater brackish water and contaminated brackish water (sewage). This research provides a social technology that includes easy replicability, low-cost construction, and effectiveness in treating water, minimizing waterborne diseases. It is included in this research the distiller in the form of four-sided pyramid, where the structure allows a better use of solar radiation during the day, combined with studies on the inclination of the faces and the water depth in the evaporation pan to improve the production of distillate.

Material and methods

The first step of the experiment was conducted in the laboratory to study the inclination of glass cover and water level on the evaporation pan. In the second part, the respective pilot devices have been developed. The following illustration depicts the general operation of the device for the production of water by direct solar distillation (Figure 1).

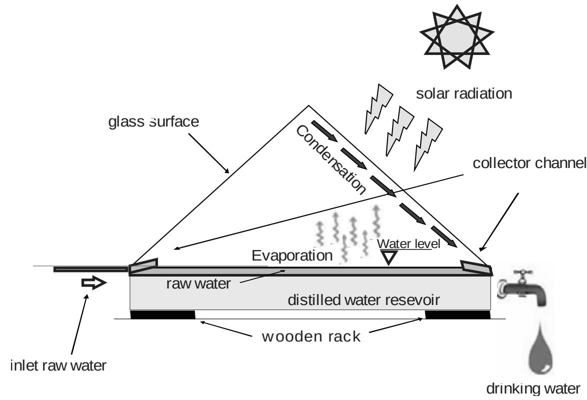

Figure 1. Solar water purifier design.

Determination of the best inclination for the pyramid glass cover

Laboratory tests determined the best slope of the glass cover, by evaluating the production during 4 hours with temperature variations according to the proposed inclinations (Figure 2). The tests had two stages: producing water vapor on contact with the glass to determine the minimum possible inclination that allows the flow of condensed water, and the other producing vapor inside the pyramidal cover.

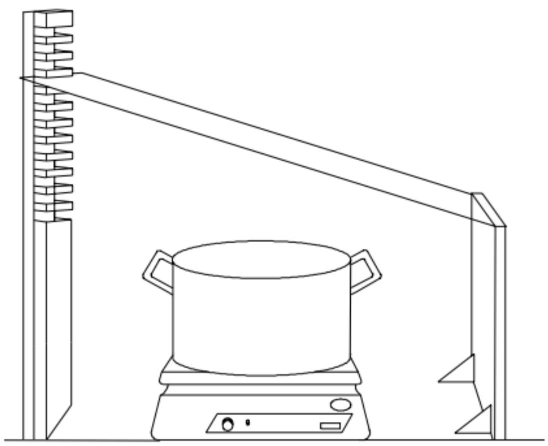

Figure 2. Schematic of the test slope.

Four glass pyramids were built by varying their inclinations by 15, 25, 30 and 45°, and by maintaining the base area at 0.35 x 0.35 m for all the pyramids, applying water temperatures of 60, 70 and 80°C for each inclination. The temperature inside of the pyramid was controlled by thermocouple sensors until it reaches 50, 60, 70 and 80ºC.

Determination of the best water level on the raw water evaporation pan

Laboratory tests started from the creation of an intense illumination atmosphere, considering as possibilities the same situations of climatic variations. Thus, we found the best thickness for water level inside the evaporation pan, through temperature variation and water production. The following steps were used: a) water was heated by four mirrored incandescent lamps (1,000 Watts) coupled into a wooden structure over the glass pyramid (Figure 3), b) temperatures of the water inside the pyramid and temperatures of the internal and external atmosphere were measured to obtain the temperature gradient; c) the water level on the evaporation pan inside the pyramid was constantly fed with raw water from a reservoir (Figure 3), and d) water level was varied by using a device that allowed the variation in the height of the pyramid in relation to the raw water reservoir (water fountain for birds). The volume of 50 mL of water evaporated was used for each water level tested, and the time to evaporate the 50 mL volume was measured in each trial. This graduation was controlled in the raw water reservoir for equipment supply.

Figure 3. Pilot for determining the best water level on the evaporation pan for inclination at 45º

Production and quality of the treated water

The pilot solar purifier was designed on a glass fiber quadrangular structure, with a reservoir for treated water, with a raw water evaporation pan on its upper part forming a 1 m^2 water surface and a 1 cm water level. There is a glass pyramid-shaped dome, with an inclination of 25 degrees from the horizontal, with silicon at the junction interfaces above the pan. There are glass fiber troughs on the inner part of the square base perimeter, for the collection of the produced water. For raw water supply, there is a 5-L glass bottle capsized in a support of 250 mL (bird fountain type system) internally supplying the pan for the process evaporation (Figure 1). The equipment was tested between the parallels 27°10' and 27°50' of south latitude and meridians 48°25' and 48°35' west longitude from Greenwich (Florianópolis, Santa Catarina State), from 2003 to 2005 with raw sea water, brackish water and fresh contaminated water. However, between parallel 5°47' and 5°57' south latitude and between meridians 35°12' and 35°22' west longitude from Greenwich (Natal, Rio Grande do Norte State), from May, 2003 to March, 2004, with sea water and brackish water. The efficiency of the equipment was measured by the production and quality of the treated water. The main analyzed physical-chemical and bacteriological characteristics were: conductivity, apparent color, true color, odor, pH, taste, salinity, total dissolved solids, turbidity, total and fecal coliforms. Analyses were performed according to APHA - Standard Methods for Examination of Water and Wastewater (APHA/AWWA/WPCF, 2005).

Results and discussion

Determination of the best inclination of the glass cover

By using the pilot shown in Figure 2, the flow efficiency was 100% of the condensate from the inclination of 15º, by visual observation. With a 8 hour-time interval, the best inclination tested as a function of the internal atmosphere temperature and water production was 25º. For 80ºC (internal), when the cover inclination increased, there was a greater production with 25º slope, and productions were similar for inclinations of 15, 30 and 45º. Similar results were found in studies dealing with 10, 20, 35, and 45º for one face and two faces structures (CAPELLETTI, 2002). Use rates of solar insolation are directly related to the ease of drainage of the condensate (CERDA et al., 2002). However, we found that under suitable sunshine availability, there might be a loss of condensate by reevaporation, if it is not rapidly taken to an adequate reservoir (AL-ISMAILY; PROBERT, 1990). We also observed that the period between 11 a.m. and 14 p.m. has the greatest production of distillate (ROSA; FILHO, 2007). This fact also opposes on the orthogonality of the surface being the best at 90% and with a 20º of inclination there is almost no direct radiation that passes through the glass (AL-ISMAILY; PROBERT, 1990). This phenomenon inserts more variables to be studied in the operation of the equipment in relation to the incidence of direct radiation on the water in the pan and the increase or decrease in temperature with deviations of the radiation.

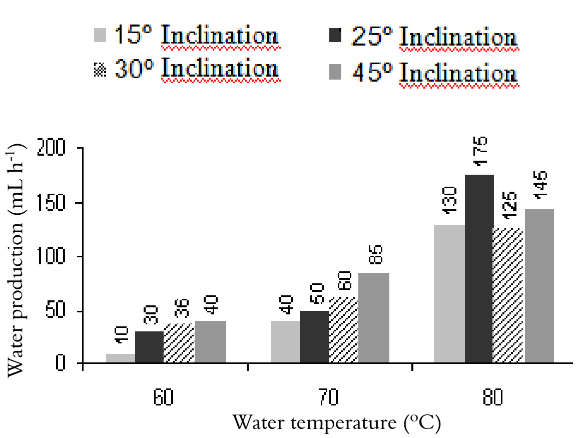

Figure 4. Water production according to water temperature and glass cover inclination.

Determination of the water level on raw water evaporation pan

The lower the water level on the pan the greater the evaporation of raw water, which may increase the production of water. Figure 5 shows the time spent to evaporate 50 mL of water according to the water level thickness inside the equipment with base of 0.35 x 0.35 m. For a water level tested at 1.5; 3.0; 4.0 cm, the best production was achieved with a level of 1.0 cm, with constant solar incidence, which allowed an increase in temperature, corroborating previous studies (SÁ, 2012; SUNEJA; TIWARI, 1999).

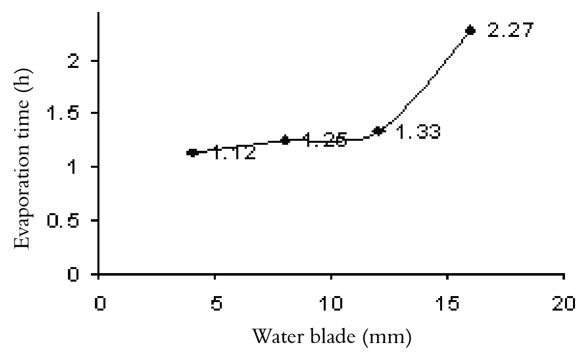

Figure 5. Time of evaporation of 50 mL of water according to the water level.

Water production

Figure 6 shows the average water production according to room temperature and global solar radiation in October and November 2003 and March 2004 at the parallels 27°10' and 27°50'S latitude and meridians 48°25' and 48°35'W longitude. Figure 7 shows the average water production and the mean room temperature in May 2003 and March 2004, at the parallels 5°47' and 5°57'S latitude and meridians 35°12' and 35°22'W longitude. Figure 6 compares the mean values of water production, demonstrating that the production in November 2003 and March 2004 were similar, emphasizing that solar radiation was higher in November 2003 than in March 2004, because the mean of the latter month was calculated by considering only five values. In Figure 7 we verified that the water production depended on room temperature although it had presented a small variation compared with results of minimum, average and maximum monthly production. Importantly, when the day was not so cloudy or not cloudy at all, the water production increased. However, at high temperatures and radiation and low influence of winds, the water production was very low due to the difficulty of condensation, since the glass temperature and equipment inner temperature were very close.

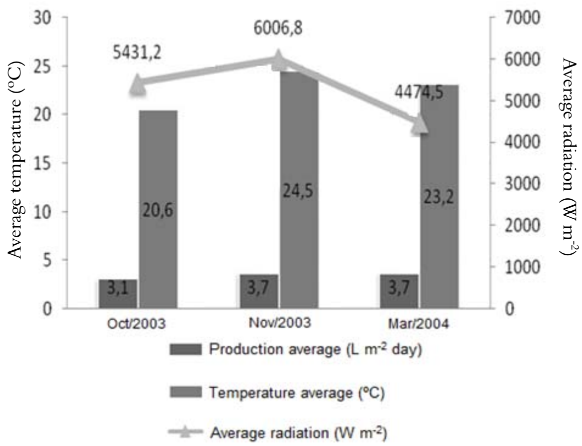

Figure 6. Water average production according to the mean values of room average temperature and solar radiation – Florianópolis, Santa Catarina State.

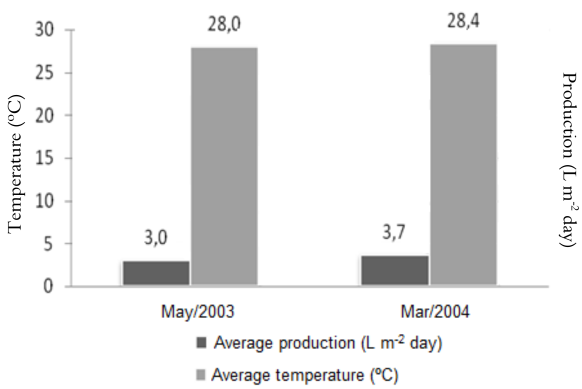

Figure 7. Water average production according to room average temperature – Natal, Rio Grande do Norte State.

We obtained 6.2 L m^{-2} day in just one day at the location 27°10' and 27°50' south latitude and 48°25' and 48°35' west longitude from Greenwich. But also for the location 5°47' and 5°57' south latitude and 35°12' and 35°22' longitude west from Greenwich, the monthly means remained between 3.0 and 3.7 L m^{-2} day, enabling a theoretical estimation of a mean of 3.4 L m^{-2} day, and an equipment for 8 L day^{-1} with dimension of 2.35 m² day^{-1} of surface water on the evaporation pan. One still can theoretically produce 8 and 4 L m^{-2} day to a yield of 50%. For 35% of insolation, it could produce 4 to 5 L m^{-2} day (KALOGIROU, 2005).

These statements are similar to our results. In other studies, we found productions with means of 3.8 L m^{-2} day for cloudy days (ONU, 2011). On very cloudy days, there is a loss of solar radiation by reflection from 25 to 30% on average, which showed a decreased production previously (SOUZA et al., 2006). Previous studies carried out at LAPOA-UFSC, with a pyramid-shaped dome and a 45° inclination, average water productions of 3.5 and 1.3 L m^{-2} day were obtained, respectively. In this work, the water production was similar to the inclinations of 45 and 25°.

Quality of the treated water

Table 1 and 2 present mean values for water quality parameters and compare with values of World Health Organization (WHO, 2011).

Table 1. Characteristics of the water and of the raw water.

Localization	27°10' and 27°50' S latitude and 48°55' and 48°35' W longitude						
Water type	Salt (sea water)		Salt (pre-filtered)		Brackish ground water		World Health Organization WHO
Parameter	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Treated water
Apparent color (Pt/Co)	18	9	8	1	125	22	15
True color (Pt/Co)	10	4	3	0	65	12	
Turbidity (NTU)	1.72	0.43	0.62	0.36	1.22	0.98	5
pH	8.1	5.9	8.2	7.4	8.0	6.5	From 6.0 to 9.5
Odor	NO	NO	NO	NO	SE	NO	Non-Objectionable
Taste	S	NO	SS	NO	SE	NO	Non-Objectionable
Total Coliform (MPN 100 mL^{-1})	>2400	0	200	0	1200	0	Absence in 100 mL
E. Coli (MPN 100 mL^{-1})	200	0	40	0	0	0	Absence in 100 mL
Conductivity x 1000 (μS cm^{-1})	54200	120	57000	20	760	50	
Total dissolved solids (mg L^{-1})	34705	124	24117	25	5140	118	1000
Salinity (‰)	33	0	32	0	0.4	0	

According to tables 1 and 2, the water quality, for any type of water treated, was within drinking water standards of the World Health Organization (WHO, 2011). Some parameters have been completely removed as coliforms and salinity. However, for parameters of conductivity and dissolved solids between types of raw water, the removal was between 93.4 and 100%, respectively. For the parameters apparent color and true color, the removal was 50 and 100% due to dilution of a more volatile material.

The turbidity removal was between 19.7 and 96.1%, it could have been higher if the initial value of turbidity was higher, but this parameter was within drinking water standards. Parameters of odor and flavor were a little more complicated to be characterized, because the water took on the characteristics from the resin applied to the glass fiber used in the evaporation pan and in the treated water reservoir.

Table 2. Characteristics of the water and of the raw water.

Localization	5°47' and 5°57' S latitude and 35°12' and 35°22' W longitude						
Water type	Salt (sea water)		Salt (pre-filtered)		Brackish ground water		World Health Organization WHO
Parameter	Raw water	Treated water	Raw water	Treated water	Raw water	Treated water	Treated water
Apparent color (Pt/Co)	172	12	2	0	77	2	15
True color (Pt/Co)	2	0	0	0	13	1	
Turbidity (NTU)	29.0	1.5	0.8	0.7	15.0	0.6	5
pH	6.6	6.6	6.5	4.0	6.9	5.8	From 6.0 to 9.5
Odor	NO	NO	NO	WR	WS	WR	Non-Objectionable
Taste	S	NO	SS	WR	ND	ND	Non-Objectionable
Total Coliform (MPN 100 mL^{-1})	>2400	0	600	0	>2400	0	Absence in 100 mL
E. Coli (MPN 100 mL^{-1})	200	0	500	0	1100	0	Absence in 100 mL
Conductivity x 1000 (μS cm^{-1})	36800	20	11470	510	12620	120	
Total dissolved solids (mg L^{-1})	55320	305	7580	1580	70590	580	1000
Salinity (‰)	33	0	32	0	0.4	0	

Conclusion

Tests on face slopes of 15, 25, 30 and 45° presented effectiveness in the condensate flow runoff. An inclination of 25° and water level of 10 mm, a pyramid installed between parallels 27°10' and 27°50' (south) and meridians of 48°25' and 48°35' (west), reached a monthly average between 3.1 L m^{-2} day. In the parallels between 5°47' and 5°57' (south) and meridians of 35°12' and 35°22' (west), it was obtained a monthly average production of 3.0 L m^{-2} day. Parameters monitored was in accordance with (WHO).The solar water purifier is effective in treating brackish and salty waters. The pyramidal structure facilitates the uptake of solar radiation. Recommendations: Lower water level to 10 mm; Caring for re-evaporation losses quickly draining the destillate; To produce 8 L day^{-1}, it will be necessary to increase the evaporation pan to 2.35 m^2; Consider a stabilization period for the resinous paint applied to the glass fiber.

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