

Research Article

# New Solar Still with the Suction of Wet Air: A Solution in Isolated Areas\*

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**Abstract** A theoretical and practical scheme of a new model of solar still is proposed. The peculiarity of this system is the implementation of some ideas from a simple solar still that permits to get an efficiency of 56,89% (following Penman Law) and of 44,467% (following Kudish formula). The research, done in 2010 at the Venice Ca' Foscari University (Italy), allows to obtain significant amount of drinkable water from seawater at low temperature using solar radiation. New features allow to combine a continuous flow during the process with suction of humid air in the solar still. Continuous flow eliminates system scaling and stagnation, whereas suction of humid air removes condensation on the internal surface of transparent cover. The combination of these two features with a couple of heat exchangers and a system designed for tropic climates minimizes the energy loss toward the external environment. Evaporating water is routed in copper pipes drawn by a cold salty solution entering the system. Vapor in the pipes is then condensed, and the condensation energy is given back to the cold salty solution, increasing the efficiency of the system. The solar still was built using a software created for this specific purpose, thus permitting simulation with a good approximation of the yield under different climates and solar radiation density. This kind of technology is indicated for use in tropical areas, as well as for small isolated communities, where electric network connections or conventional energy sources are unavailable.

**Keywords** solar still; high efficiency; solar radiation; suction of vapor; continuous flow

## 1 Introduction

In recent years, a strong sensitization in environmental themes and in a better use of natural resources has hit public opinion. Acknowledgments have taken place of the

limitation of environmental resources, which are seen as goods instead of renewable and infinite sources. Due to the important role of these resources for life quality, particular care is needed for the management of these assets, especially water.

Lack and pollution of water is a critical issue for human health and for agriculture. Indeed, the use of poor quality water for the irrigation of dry areas gives rise to a decrease of agricultural production, including environmental damage to soil and groundwater tables [2].

Desertification is also a serious problem in dry areas. This natural phenomenon, which involves a lowering of groundwater tables and an increase in groundwater salts, deadly affects ecological systems at different levels [1]. On the other hand, desert as well as tropical areas exhibit a high energetic potential through sunlight, thus providing a potential key to the development of these regions, as underlined by Galal and Hussein [4]. In the last years, the development of new techniques for the desalination providing drinkable water with lower costs has helped to face some of these problems, whereas a branch of desalination studies handles an environmentally friendly approach.

Conceiving a process similar to the natural water cycle, one can realize more efficient and productive solar still models. In the natural process, the environmentally friendly solar still produces desalted water through one or more phases of the water cycle, for example, evaporation or condensation. The aim of the present study is the experimental investigation of a new model of solar still, along with the determination of its efficiency characteristics. This new model presents some technical improvements that allow to increase daily production, especially the production suitable to the energy supply for isolated communities.

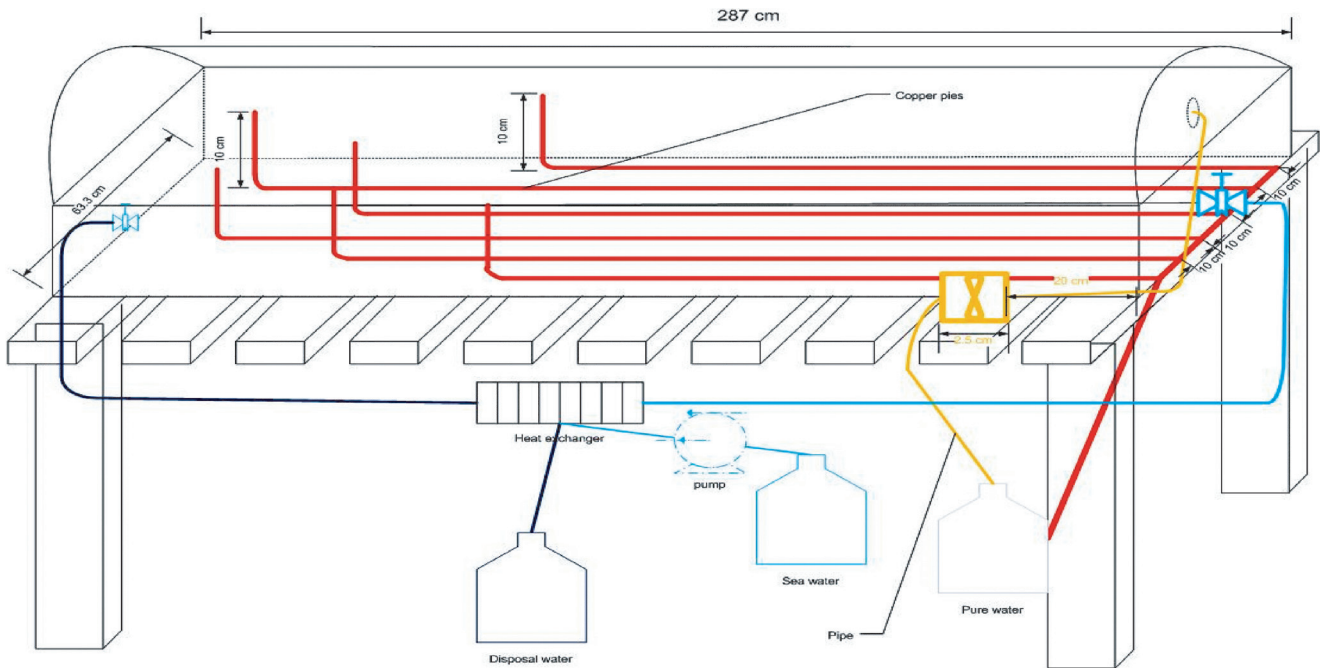
## 2 Methodology

### 2.1 Background

The basic principle of a typical traditional solar still is the greenhouse effect. Solar radiation heats the system in a

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**Figure 1:** Setup of the solar still showing the parts realizing the continuous flow (blue) and the equipment for the suction of wet air (red).

greenhouse-like arrangement through a transparent cover being converted in a dark basin from irradiating to heating energy. Salt water, heated while in the basin, evaporates, and then condensates inside the system under the cover, which is in turn at a slightly lower temperature due to the contact with external air. Condensation typically flows along the internal surface of the glass covering, being then collected out of the edge of the glass and it is then transferred outside.

Solar still efficiency depends on three factors:

- (i) manifold structure;
- (ii) heat conservation;
- (iii) structure and design of the solar still [5].

One of the most important parameters that determine the solar still efficiency is the difference in temperature between the basin water (which has to evaporate) and the glass surface (upon which condensation occurs) [7]. In 1961, Dunkle [3] first showed that mass transfer depends on the temperature difference between the water body and the condensation surface; in particular, as expected, the water production of the solar still, as well as its efficiency, increases with temperature difference.

The system built for this research is based on a simple and common design of solar still. In particular, the basin is a layer of aluminum painted with black opaque enamel on top of a wood bottom structure, completely isolating the system from the external surroundings. A layer of 5 cm polyurethane was placed at the bottom for better isolation. A semicircular transparent cover was used for the

present research to have the highest light transmission [8]. A transparent layer of polycarbonate was used for its good light transmission (about 88%).

## 2.2 Continuous flow

Several technical novelties have been actually introduced in our system with respect to the usual solar stills. In Figure 1, a scheme illustrates our solar still. First of all, a continuous controllable flow of water is established: new salt water is introduced into the solar still from one side, and in the opposite side the concentrate water is drawn out. An elongated shape of the solar still was built to prolong the flow path and hence retention time, so as to accumulate heat and evaporate more of the brackish water before discharging it. Seawater enters the solar still with a temperature that will vary according to seasons and site, usually from 0 °C up to about 33 °C, whereas the outgoing waste water is at a higher temperature, up to a theoretical maximum of 100 °C. However, this value can vary depending on retention time, sunshine, and temperature inside the solar still. Thus, it was decided not to discharge this hot water, which would waste this precious source of heat and lower the efficiency of the solar still. The exiting brine is collected and routed to a heat exchanger in countercurrent flow with the seawater that is entering the solar still. The heat exchanger in turn raises the temperature of the input seawater, thus further increasing the efficiency and so the evaporation rate. Hence, a heat cycle is established, which during the day leads to a gradual increase of the solution thermal energy, thus increasing the yield of

the solar still. A specific software was developed to calculate the best length of the solar still for different climates. In the presented experiment, a 287 cm long solar still model was set up.

### 2.3 Air suction

A second aspect that has been implemented in this solar still was based on the Le Chatelier principle: if a chemical system at equilibrium experiences a change in concentration, temperature, volume, or partial pressure, then the equilibrium shifts to counteract the imposed change and a new equilibrium is established. In the present case, that of a system formed by water and air, the solution tends to get an equilibrium with the layer of air on the top of it. In this situation there is a given quantity of mass and energy steam that is transferred from the liquid phase to the air, where the liquid tends to evaporate even though this equilibrium will not be obtained.

The basic idea in our case is to force the evaporation, after which the wet air is taken out continuously by a small fan. This process allows to eliminate some typical solar still problems like:

- (i) a continuous vapor deficit;
- (ii) the use of expensive and fragile glass;
- (iii) the lack of light transmission into the solar still caused by the condensation of vapor in the covering;
- (iv) the possible formation of algae or bacteria colonies on the same covering, which can pollute the pure water.

The condensation of vapor outside the main body of the solar still was realized directly using the stream of seawater entering into the system. To achieve heat and energy exchange between the two phases, suction pipes are made of copper, a material with high conductivity and relatively low cost. The air vents of pipes are positioned in the opposite side where the seawater enters, because in this area the water temperature is higher, with the highest ratio of evaporation.

The copper pipes have to be L-shaped, ticking slightly above the water, so as to affect as much as possible the boundary layer formed above the surface of the solution that is evaporating. Along the length of the L-shaped pipes, vapor is moving backward with respect to the entering salt water. This is necessary to get the lowest possible temperature in order to have a higher ratio of condensation based on Molier diagram. Inside the copper pipe, there is a mixture of moist air and pure water. This mixture is collected by a basin where gravity separates the two phases. As the water stays inside the basin, the air comes back to the solar still through a conduit.

Such close loop minimizes the losses of “precious” moisture from the system. A small fan was placed at the entrance of the solar still to create a draft in the system and at the same time a slight suction into the copper pipes.

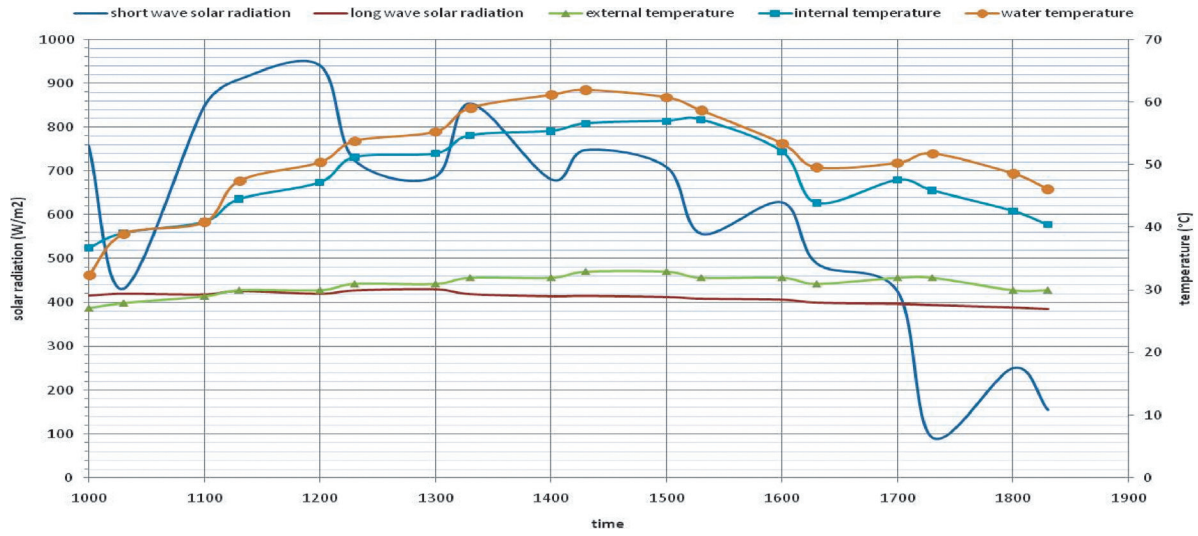
A research developed by Rahim and Taqi in 1992 [10] showed an increase of the efficiency of the system, due to the suction of air, of 31.1%. When taking into account the energy consumption of the fan, the added efficiency rise was still at 29.5%. This increase in the efficiency was due to water particles absorption during the passing from liquid to vapor upon the complete release within the same solution. However, in a common solar still with condensation on the transparent surface, a part of energy is released inside of the greenhouse, but another part is lost in heating the cover, whereas some is in turn lost directly to the outside environment. With a condensation within the same solution, all the changing phase energy is transferred to the target.

It is worth remarking that the solar still is completely autonomous and independent of any external source of power. Both the water pump and the fan are connected to a small photovoltaic panel. This panel, working with solar radiation, provides the required electric energy. Figure 1 depicts the final configuration of the solar still.

### 3 Results

The testing was limited to three days of readings because the system had a steady performance and production of pure water throughout the duration. The experimentation lasted from July 11 to July 13, with a operation time that ranged from 10:00 a.m. to 6.30 p.m. with data collection every 30 minutes. This period was mainly decided by a logistic issue being the solar still's exposure to direct solar radiation during that time. The site of this test was at the experimentation farm of Ca' Foscari Venice University (45.21 °N, 11.57 °E). The solution (seawater) was collected 200 m close to Venice (Adriatic Sea). The chemical analysis conducted on the seawater was done at the laboratories of chemistry. The analysis reported a salinity  $PSS = 33$  with a density  $\rho = 1024.8 \text{ kg.m}^{-3}$ . The aim of this analysis was to calibrate the size of the solar still. In fact, changing the salinity changes in turn the amount of seawater capable of evaporating before the creation of scales. The incoming seawater temperature was around  $T_{wat} = 26.1 \text{ }^\circ\text{C}$  throughout all the experimentation period.

The recorded parameters are the intensity of solar radiation  $R_a \text{ (W.m}^{-2}\text{)}$ , ambient temperature  $T_{env} \text{ (}^\circ\text{C)}$ , the temperature inside the solar still  $T_{in} \text{ (}^\circ\text{C)}$ , and the temperature of water contained in the solar still  $T_{watin} \text{ (}^\circ\text{C)}$ . The production of drinkable water at the end of the day of experimentation was also recorded. A radiometer Kipp & Zoneln, positioned at a height of 1.5 m, was used to record solar radiation, with a frequency of 5-minute reading intervals. Figure 2 reports the conditions in a typical day of the research, with a comparison of detected temperature against the amount of radiation in the surrounding of the solar still.



**Figure 2:** Comparison between the temperature detected against the amount of radiation in the environment around the solar still during a typical day of experimentation.

**Table 1:** Production of pure water per day and total amount of solar radiation.

Date	Water output (l)	Water output per square meter $\phi_p$ ( $\text{l.m}^{-2}.\text{day}^{-1}$ )	Total solar radiation $R_a$ ( $\text{MJ.m}^{-2}$ )
June 11	10.65	5.86	31.9
June 12	9.99	5.50	30.8
June 13	9.78	5.38	30.6

Table 1 shows the results recorded during the period of experimentation. It is worth noting that a net output between ( $\phi_p$ ) 5.3 and  $5.8 \text{ l.m}^{-2}.\text{day}^{-1}$  was achieved.

Radiation interpolation versus yield of pure water per day made it possible to define a line of performance as shown in Figure 3, based on the following relation:

$$Y = 0349x - 5288, \quad (1)$$

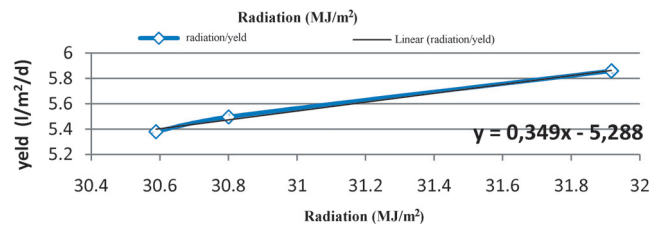
where the  $Y$ -axis reports the production of desalinated water per day  $\phi_p$  ( $\text{l.m}^{-2}.\text{day}^{-1}$ ) and the  $X$ -axis the solar radiation ( $\text{MJ.m}^{-2}$ ).

Maximum theoretical evaporation was calculated using a simplified formula of Penman [9]:

$$E_{\text{PEN}} \approx 0,047R_s \sqrt{T+9,5} - 2,4 \left( \frac{R_s}{R_A} \right)^2 + 0,09(T+20) \left( 1 - \frac{\text{RH}}{100} \right), \quad (2)$$

where  $R_s$  is the solar radiation density ( $\text{MJ.m}^{-2}.\text{day}^{-1}$ ),  $T$  the temperature (K), RH the relative humidity (%),  $R_a$  the external solar radiation ( $\text{MJ.m}^{-2}.\text{day}^{-1}$ ).

Comparing the recorded output of the solar still during the experimentation period and the theoretical calculation



**Figure 3:** Linear interpolation of radiation and yield of pure water.

from the Penman formula, we can define a first calculation of the solar still efficiency. The result showed that the solar still works with an efficiency of 56.9%. On the other hand, one can apply the Kudish formula for the efficiency [6]:

$$\text{Efficiency} = \frac{Q_v \phi_p}{I} 100, \quad (3)$$

where  $Q_v$  is the energy necessary to evaporate 1 kg of pure water at  $T = 40^\circ\text{C}$ , that is,  $2434 \text{ kJ.kg}^{-1}$ .  $\phi_p$  is the production of pure water by the solar still ( $\text{l.m}^{-2}.\text{day}^{-1}$ ) and  $I$  is the total amount of radiation energy that enters the system ( $\text{kJ.m}^{-2}.\text{day}^{-1}$ ). With this formula, the efficiency of the solar still is found to be about 44.5%.

#### 4 Conclusions

The innovative model of solar still presented in this paper proved its capability to produce drinkable water with a yield per square meter of 5.8 liters per day. The solar still performances are based on three main points:

- (i) suction pipes
- (ii) heat exchange between vapor and entering water
- (iii) continuous cycle operation.



This research was done in Venice (Northern Italy), but the design and the idea of the solar still were set for tropical climates, with different solar radiation angles, intensity and external ambient temperatures. For example, the cover was designed with a semicircular shape optimized for tropical climates. A solar still with the same characteristics was made in Trujillo (Peru) in February 2011. In this case, the highest solar radiation with a better ray angle actually gives rise to the calculated efficiency. Several parameters in the solar still design are linked by operational feedbacks. In particular, choices are to be made depending on the use of the solar still: would it be in urban areas such as an overcrowded megalopolis where clean water supply is lacking, in communities close to salt water sources, or in rural and mountain areas where specific water pollution problems may be present? The main parameters that make the solar still flexible and adaptable to specific needs are as follows:

- (i) covering (shape, pitch)
- (ii) geometry (solar still orientation, basin slope and shape, suction pipes geometry)
- (iii) flow rate (entering water, suction)
- (iv) operational parameters (heat exchanger, solar panel)
- (v) materials (covering, basin bottom, suction pipes).

Work is in progress to include all these parameters in a software simulating the operation of the solar still under different conditions, thus allowing to design the solar still model depending on the specific needs of a community, as well as the specific characteristics of a desired location. Finally, it is worth remarking that the presented solar still does not need external power supply; it is portable, inexpensive, and quite efficient. This has already attracted the interest of several nongovernmental organizations and several governments of developing countries, as well as the United Nations, which included the solar still in the program IDEASS, Innovation for Development and South-South Cooperation ([www.ideassonline.org](http://www.ideassonline.org)).

A new experiment, with a new prototype, is starting in Venice in 2012 based on the same principles. The new prototype has some arrangements that can increase the efficiency of the system.

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