SOLAR DISTILLATION

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An authoritative survey of a comprehensive range of solar stills

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A comparative study of their design, construction and performance

•

Economic evaluation and assessment

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Extensive bibliography and literature citation

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SOLAR DISTILLATION

A Practical Study of a Wide Range of Stills and Their Optimum Design, Construction and Performance

by

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SOLAR DISTILLATION

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PREFACE

The vital importance of supplying drinking water to the whole human population has been recognized by the U.N.O. which has declared 1981-90 as the International Drinking Water Supply and Sanitation Decade (IDWSSD). At the end of this program it is contemplated that the drinking water requirements of at least half the world's population will have been met. Considering the fact that an estimated 2 billion people go without fresh water today, this is indeed an ambitious goal. Consumption of water, unfit for drinking on account of bacteria/germs or excess of salts, is a major health hazard, which alone is a sufficiently strong reason to undertake a massive scheme to supply fresh water to all, who do not have it.

The system for supply of drinking water in a region with abundant fresh water (lakes/rivers/underground etc.,) is very different from one corresponding to places without any such source e.g. deserts, marshy lands etc., which may have only brackish water. Economic considerations may render distillation of saline/brackish water a better choice than supplying water by trucks or by laying long pipe-lines from a distant source. It may happen that, with a modest supply of fresh water, a region, hitherto considered as waste-land, becomes economically exploitable. There are several methods of distillation to choose from. Most of the conventional water distillation plants are energy-intensive and require scarce electric power or fossil fuel for operation; however solar energy despite being a much lower grade energy, is ideally suited for this job. The choice of solar energy has become even more attractive on account of the ten-fold rise in petroleum crude prices as compared to that in the beginning of 1970. Further, solar energy is not a monopoly and the technology involved in distillation of saline water using solar energy is relatively simple; a very large component of the fabrication (men and materials) of solar stills can be indigeneous and maintenance can be carried out by semiskilled or unskilled operators.

Considerable amount of literature, dating back to the Arab alchemists of 1551, exists on solar stills; the work has attracted renewed interest in recent times. Unfortunately, no exhaustive study has been published till now, despite the importance of the topic. Although some review articles have been published, they are either outdated or are inadequate in scope, giving a glimpse of only few aspects of the subject. The need for a relatively unified and comprehensive account of the various aspects of solar distillation has been felt by the solar-energy community for a long time; the present monograph is an attempt to this end.

A brief historical review has been presented in the introductory chapter along with a qualitative discussion on the fundamental aspects of solar stills and the identification of basic energy transfer mechanisms. Chapter 2 consists of a discussion on the basic heat and mass transfer relations, necessary for a proper understanding of the operation of a still. The single basin solar still has been studied in detail in Chapter 3, using the steady state theory as well as the periodic heat transfer model developed in Chapter 2; transient analysis has also been given. Besides these, the effect of using various dyes on the performance of the still, and the nocturnal production have also been discussed. Other aspects such as materials and effect of various meteorological and still parameters on the performance of the still have also been considered. Chapter 4 discusses the multi-effect solar stills and the double basin solar still in detail. Inclining a solar still with respect to the horizontal, as is done with flat-plate solar collectors, increases the distillate output of a still; this aspect has been examined in Chapter 5. In particular the "Multiple-Wick Solar Still" has been discussed in some detail as it seems to offer significant advantages over the other designs. Chapter 6 discusses various other stills of rather exotic designs. The solar still green-house combination, which can lead to selective agriculture in regions having a supply of brackish water has been discussed in Chapter 7, a periodic analysis of a "Still on the roof" concept is the quantitative highlight of the chapter. The monograph has been rounded-off with a discussion of the economic aspects of using solar stills.

M.K.S. system of units has been adopted throughout the book. The cost prices have been given in U.S. Dollars (wherever possible). A list of symbols used in the text has been compiled in the end in conformity with the usual practice in the solar energy community.

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CONTENTS

1. INTRODUCTION

1.1. IMPORTANCE

Water is a basic necessity of man along with food and air; the importance of supplying hygienic potable/fresh* water can hardly be overstressed. Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry. However, use of water from such sources is not always possible or desirable on account of the presence of large amount of salts and harmful organisms. The impact of many diseases afflicting mankind can be drastically reduced if fresh hygienic water is provided for drinking. Further, the rapid industrial growth and population explosion all over the world has resulted in a large escalation of demand for fresh water; this invariably leads to acute fresh water shortages since the natural sources of water can meet the demands to a very limited extent. Added to this is the problem of pollution of the rivers and lakes by the industrial wastes and the large amounts of sewage. Thus there is scarcity of fresh water even in cities, towns and villages near lakes and rivers. Dangerous pollutants left on open ground also find their way into the underground reservoirs along with rainwater. In fact on a global scale man-made pollution of natural sources of water is turning out to be the single largest cause for the fresh water shortage. Besides this there are several regions on the earth, e.g. the deserts, which have inhospitable climatic conditions and have only brackish water sources. In such places fresh water will have to be provided not only for domestic use, but also for agricultural needs. It would be no exaggeration to say that by the end of this century, supply of adequate quantities of fresh potable water could become one of the most serious problems confronting man.

With the official launching in New York, U.S.A. on 10th November, 1980, of the International Drinking Water Supply and Sanitation Decade (IDWSSD), the United Nations Organisation set into motion a major initiative that should have a direct impact on at least half the world's population by 1990. According to present estimates, over 2000 million people are without reasonable access to a safe and adequate water supply. Developing countries (e.g. India) have

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*Less than or about 500 parts per million of salt.

given utmost priority to rural water supply in their development plans. Major U.N. organisations like UNDP, WHO and the World Bank are actively involved in promoting projects aimed at supplying drinking water in Indian villages. Between 25 to 30 per cent of the UNICEF's assistance to programs for children is invested in water supply. The UNDP and World Bank have been involved in a global project aimed at low cost water supply techniques and to facilitate the testing and selection of water supply hand pumps.

The only inexhaustible sources of water are the oceans. Besides, there are also several, hitherto unused, big lakes, inland seas and underground natural reservoirs containing salt/brackish water. The chief drawback, obviously, is the very large salinity of such water. One of the attractive schemes to tackle the problem of water shortage is the distillation of such water resulting in desalination; this water may be mixed with brackish water (if hygienically desirable) to increase the amount of fresh water and bring the concentration of salts to around 500 parts per million. The conventional distillation processes such as multi-effect evaporation, multi-stage fresh evaporation, thin film distillation, reverse osmosis and electrodialysis are not only energy intensive but are also uneconomical for not too large demands of fresh water. However, the developments in the use of solar energy have demonstrated that it is ideally suited for desalination, when the demand of fresh water is not too large. The rapid escalation in the costs of fuels has made the solar alternative more attractive; in certain remote arid regions, this may be the only alternative. The least that can be said in favor of solar distillation (distillation of saline water by the use of solar energy) is that it is a viable option for providing hygienic potable water for a single house or a small community in most places of the earth. Further, the development of green-houses has resulted in minimizing the water requirements for carrying on agriculture on a small scale; thus solar desalination can support small scale agriculture in regions having only brackish water sources.

1.2. HISTORICAL REVIEW

Solar distillation has been in practise for a long time. The earliest documented work is that of the Arab alchemists in 1551 (Mouchot, 1869). In his review, Mouchot writes:*

> "One uses glass vessels for the solar distillation operation . . . . According to the Arab alchemists, polished Damascus concave mirrors should be used for solar distillation."

In their historical review on desalination of water, Nebbia and Menozzi (1966) mention the work of Della Porta which he published in 1589. The apparatus used by Della Porta is illustrated in Fig. 1.1 and his own description of the experiment is as follows:

*Translated from original text in French.

"*About Distilling**

. . . . insert these into wide earthen pots full of water, so that the vapors may thicken more quickly into water. Turn all this apparatus, when it has been very carefully prepared, to the most intense heat of the sun's rays: for immediately they dissolve into vapors, and will fall drop by drop into the vases which have been placed underneath. In the evening, after sunset, remove them and fill with new herbs. Knot-grass, also commonly called "sparrow's tongue", when it has been cut up and distilled is very good for inflammation of the eyes and other afflictions. From the ground-pine is produced a liquid which will end all convulsions if the sick man washes his limbs with it: and there are other examples too numerous to mention. The picture demonstrates the method of distilling."

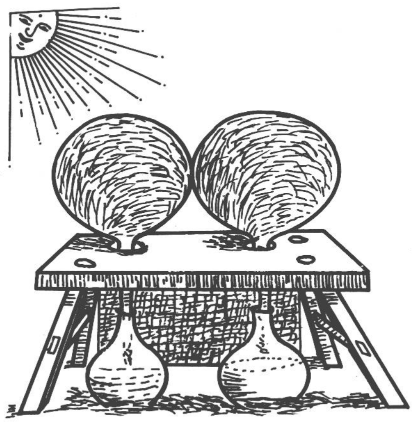

Fig. 1.1. Solar distillation apparatus of Della Porta. (After Della Porta, 1589).

The great French chemist Lavoisier (1862) used large glass lenses, mounted on elaborate supporting structures, to concentrate solar energy on the contents of distillation flasks. The use of silver or aluminium coated glass reflectors to concentrate solar energy for distillation purposes has also been described by Mauchot (1869). Thus, it appears that in 19th century scientists were familiar with harnessing solar energy for distillation not only by direct exposure to the sun but also by concentrating sun's rays by means of mirrors and lenses.

The conventional solar distillation apparatus, (commonly known as the solar still), was first designed and fabricated in 1872 near Las Salinas in Northern Chile by Carlos Wilson, a Swedish engineer. This was a large basin-type solar still, meant for supplying fresh water to a nitrate mining community (Harding, 1883). Several wooden bays of size 1.14m × 61.0m were joined together to yield a total surface of area 4700 m^2, which was covered with glass. The bottom of the bays, exposed to the sun, was blackened with logwood dye and alum. Brackish water was poured into the bays which, upon evaporation, aided

*English translation from Latin text.

by solar energy, condensed over the glass cover and trickled down into the collectors. This device was in operation for about 40 years and yielded more than 4.9 Kg of distilled water per square meter of the still surface on a typical summer day (Harding, 1883). It is worth noting that this output compares very well with the distilled water output from the present day solar stills. The device was, however, abandoned later on when cheaper and more convenient methods of desalination of water came into vogue. The major problem with the still was the rapid accumulation of salts in the basin making regular flushing of the still a necessity.

No work on solar distillation seems to have been published after 1880's till the end of the First World War. With the renewal of interest, several types of devices have been described, e.g. roof type, V-covered, tilted wick, inclined tray, suspended envelope, tubular and air inflated stills etc. Use of metal coated reflectors as solar concentrators for application in solar distillation has been described by Kausch (1920); Pasteur (1928) also used several concentrators to focus solar rays onto a copper boiler containing water. The steam generated from the boiler was piped to a conventional water-cooled condenser in which distilled water was accumulated. The efficiency of this device was less than 50%. Abbot (1938) used cylindrical parabolic reflectors (aluminium coated surface) to focus solar energy onto evacuated tubes containing water. He also devised a 'clock-work' arrangement to track the motion of the sun. Although efficiencies as high as 80% could be achieved, the boiling of water in the tubes created some problems. During the Second World War, Maria Telkes (1945) developed air inflated plastic stills for the U.S. Navy and Air Force for use in the emergency life-rafts. The arrangement consisted of an inflatable transparent plastic bag inside which a porous felt pad was suspended with collector bottles placed at the bottom. Whenever it was required to be used, the felt pad was to be saturated with sea water. Water evaporates from the pad on account of incident insolation and condenses on the interior surface of the bag. Distilled water gets collected in the bottles kept at the bottom. As many as 200,000 of these stills were used by the Navy during the war.

The next stage was to improve the operating efficiencies of the various types of solar distillation devices. Forced air circulation was tried in stills to enhance the vapor condensation rate. Several investigators have attempted to make use of the latent heat of vaporization in either multiple-effect systems or for preheating the brine to increase the output of the stills. Several large scale distillation plants and integrated schemes for combining electric power generation and desalination of water have also been suggested as a way of improving the overall operating efficiency of the plant.

The basin-type solar still (also called as the greenhouse type, roof-type, simple or conventional type) is in the most advanced stage of development. Several workers have investigated the effect of climatic, operational and design parameters on the performance of such a still. Cooper (1969a, 1973a) has proposed a computer simulation for analysing the performance of such a still. Frick (1970) has also proposed a mathematical model for the still based on the thermic circuits and the Sankey diagrams; his analysis is based on the assumption of sine wave heat flow. Hirschmann and Roefler (1970) have considered periodic insolation in estimating the effect of heat capacity on the performance of the still. The periodic and transient analyses have also been presented by Baum *et al.* (1970), Nayak *et al.* (1980) and Sodha *et al.* (1980), respectively. Apart from the common basin-type solar stills, several other types of stills have also been recently proposed and studied, viz.,

1. multiple-effect stills (Oltra, 1972; Bartali, 1976)
2. tilted tray or inclined-stepped solar stills (Howe, 1961; Akhtamov *et al.*, 1978)
3. tilted, wick type and multiple wick type solar stills (Frick and Somerfeld, 1973; Sodha *et al.*, 1980b; Moustafa, 1979)
4. solar film covered still and wiping spherical stills (Norov *et al.*, 1975; Umarov *et al.*, 1976; Menguy *et al.*, 1980)
5. solar still greenhouse combination (Selcuk, 1970, 1971; Sodha *et al.*, 1980b)
6. indirectly heated solar stills (Soliman, 1976; Malik *et al.*, 1973, 1978; Sodha *et al.*, 1981).

Depending upon their expected life span and application, the various solar stills are categorised into "permanent" (e.g. glass covered stills), "semi-permanent" (e.g. plastic stills) and "expandable" (e.g. double-tube and floating stills) type solar stills; it is expected that the last variety would ultimately prove very inexpensive and easy to handle and transport.

1.3. BASIC PRINCIPLES

A conventional solar still is simply an airtight basin, usually made out of galvanized iron sheet in rectangular shape. It has a top cover of any transparent material, e.g. glass, and the interior surface of its base is blackened to enable absorption of solar energy to the maximum possible extent. Brackish or saline water is poured into the still to fill it partially, which is then exposed to the sun. The glass cover permits solar-radiation to get into the still, which is absorbed predominantly by the blackened base. Consequently, the water gets heated up and hence the moisture content of the air trapped between the water surface and the glass cover increases. The base also radiates energy in the infra-red region which is reflected back into the still by the glass cover; glass is not transparent in the long wavelength region. Thus, the glass cover traps the solar energy inside the still; it also reduces the convective heat losses. The glass cover is usually sloped on one side to enable the water vapor, which condenses on the interior surface, to trickle into a collector.

The most important parameter affecting the output of a solar still is, obviously, the intensity of the solar radiation incident on the still. If Q_t (in Joules/m^2 day) is the amount of solar energy incident on the glass cover of a still and Q_e (in Joules/m^2 day) is the energy utilized in vaporizing water in the still, then the daily output of distilled water M_e (in Kg/m^2 day) is given by

$$M_e = Q_e/\mathcal{L}$$

where $\mathcal{L}$ (in Joules/Kg) is the latent heat of vaporization of water. The efficiency η of the still is given by

$$\eta = \frac{Q_e}{Q_t}$$

It is worthwhile to note that the efficiency of a typical basin-type solar still is quite low and is not greater than 35%.

Figure 1.2 illustrates the principal energy exchange mechanisms in a basin-type solar still. A very large part of the solar radiation, direct and diffuse, falling on the still is absorbed in the blackened base. Small reflection losses occur at the glass surface, the water surface and to a very small extent at the base. The energy absorbed at the base is largely transferred to the water in the still and a small fraction of it is lost to the ground by conduction through the base. Energy is transferred from the water to the glass cover principally by the water vapor evaporating from the water surface and then losing its heat of vaporization to the glass cover upon condensation. Heat is also transferred to the glass cover from water by free convection of the trapped air in the still. The glass cover absorbs a part of the heat radiated from the water surface. A small part of the incident solar energy is also absorbed by the glass cover. The heat thus absorbed by the glass cover is lost to the atmosphere by convection and radiation. Energy exchange also occurs on account of change of sensible heat content of the saline water entering the still, the distillate leaving the still and the brine that accumulates in the still. Thermal losses may also occur due to the leakage of water vapor and the water from the still. A study of the basin-type solar still must take these factors into account. Thus, while the incoming energy is

(1) Solar radiation and
(2) Atmospheric radiation

the outgoing energy comprises of

(1) Convection to atmosphere
(2) Radiation to atmosphere
(3) Reflection to atmosphere
(4) Ground conduction
(5) Edge conduction and convection
(6) Vapor leakage
(7) Brine leakage from basin
(8) Sensible heat of condensate and overflow.

Figure 1.2 illustrates the various components of the energy balance and their direction.

The main components of the energy loss for a typical set of parameters are as follows (Bloemer *et al.*, 1961b):

		Per cent of solar radiation
(1)	Evaporation of distillate (efficiency)	31
(2)	Ground and edge heat losses	2
(3)	Solar radiation reflected from still	11
(4)	Solar radiation absorbed by cover	5
(5)	Radiation from basin water to cover	26
(6)	Internal convection	8
(7)	Re-evaporation of distillate and unaccounted-for losses	17
		100