Solar Still - Improved Distillation

Herbert Weidner [a]

Abstract: An analysis of the steam cycle in an humidification-dehumidification desalination system shows that reheating of the air can drastically improve the steam absorption in the humidifier. This multiplies the production of potable water and makes the apparatus required for a multi-stage system superfluous.

Introduction

The huge amounts of salt water that exist on earth are useless as drinking water. One way to remove the salt is to generate water vapor and to condense it on a cooled surface. In primitive systems, the cooling is usually neglected, resulting in small daily amount of potable water. Another weak point is the lack of wind within the plant, which frees the water surface from the thermally insulating boundary layer and transports the generated moist air to the cooling surface. The diffusion can do neither of the two tasks satisfactorily. More promising is a solar humidification-dehumidification desalination system (HDH), which avoids technical compromises and is composed of separated functional blocks. Its *four* basic components are a humidifier, a dehumidifier, a heater and a cooler.

1. The humidifier: Each water surface is covered with a thin, saturated vapor layer (relative humidity(RH) = 100%). When the RH of the ambient air is lower, steam diffuses from the boundary layer into the air and is immediately replaced by new steam. Diffusion is a slow process and has to be replaced by wind to transport the steam to the condenser. The steam generation rate can be increased by enlarging the water surface, heating and by producing small water droplets, that evaporate quickly. It is *not* enough to produce a lot of hot steam which is not removed from the water surface.
2. The dehumidifier is always a chilled condenser: To get as much dissolved water as possible out of the air, moist, warm air sweeps past a cold surface to cool it below the dew point. Since the RH can not exceed 100%, the excess water condenses on the cooling surface and the cooled, still very humid air (RH = 100%) must be replaced by warm, moist air. Therefore, wind *must* blow. Increase airspeed and create turbulence!
3. The heater: The higher the temperature and the surface area of the water, the more steam is produced. Steaming costs energy that is extracted from the water. Heating is required in order not to reduce the supply of steam. In full sunshine, the collector can deliver a thermal output of about 400 W per square meter. At temperatures above 70 °C, the usable power drops noticeably. If enough steam is generated at low temperatures, the collector does not have to be protected from the wind.
4. The cooler: A solar still is not an energy store. Therefore, the entire received power *must* be dissipated immediately. Cold seawater is well suited, but chemically aggressive and is not available everywhere. In arid areas, only cooling with relatively warm air remains. Because of the low specific heat of air you need huge cooling surfaces and high air velocity.

The yield of potable water increases with two additional measures: a reheater, discussed below, and the reuse of cooled steam to reduce energy consumption.

a) 24. May 2018, email: herbertweidner@gmx.de

Simple systems

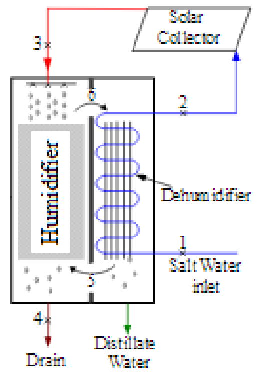

Fig. 1: Simple HDH desalination

Although the single-stage solar HDH unit shown in Fig. 1 contains the basic components, the system is far from optimum for several reasons. The large amount of cold cooling water is hardly preheated in the condenser (1→2) and has to be heated strongly in the collector (2→3) so that the evaporation in the humidifier may start. That requires an oversized collector. More seriously, most of the hot water leaves the plant unused. This loss can be reduced in a multi-stage HDH desalination unit[1]. However, the amount of distillate does not increase proportionally despite multiple effort.

In comparison with single-chamber stills, an HDH system has two advantages: the cooled steam is (a) reused and (b) creates a circulation through both chambers. But, the resulting airspeed is insufficient to wipe the saturated vapor layers from the surfaces. More seriously: When the circulating vapor enters the humidifier, no water can be absorbed because the relative humidity is already 100%. In the lower part, the air must first be heated *before* water can be absorbed. The solution is simple: Heating reduces the RH. Therefore, it's a good idea to heat the circulating air *before* it reaches the humidifier. That needs to be explained more precisely.

The water transport by air

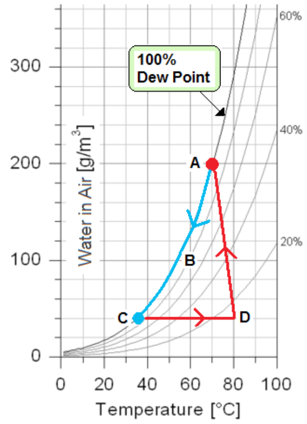

Fig. 2: Amount of water in air across a range of temperatures

Air can dissolve a small amount of water, you get moist air or fog. Fig. 2 shows how the maximum amount (left curve = 100% = steam saturated air) depends on the temperature.

Going from any point on this curve to the right, the air gets drier and the relative humidity decreases, the water content in a given volume remains constant. Example: Consider an air volume with a temperature of 35 °C, which is saturated with water vapor (point C). When the air is heated to 80 °C, the relative humidity (RH) drops from 100% to 17% (point D). Dry air can absorb a lot of water (we may ignore the fact that the volume increases by about 14%).

There is no permanent state to the left of the "dew point" curve. If you cool humid air too much, fog arises, it rains and all surrounding objects get wet by the dew. The relative humidity can not exceed 100%.

We first explain why the yield of potable water in the concentric solar still[2] is limited in the described construction (see Fig. 3). Subsequently, we show how the yield can be considerably increased by an additional heater near the lower end of the condenser.

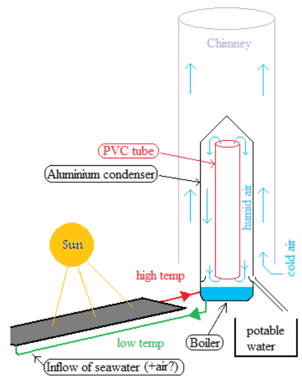

Fig. 3: A a solar still with concentric condenser

We assume that the collector heats the salt water in the boiler to 70 °C and that the condenser is cooled to 35 °C at the bottom (just above the boiler). Now we follow the movement of a small air volume of 10^{-3} m³ and start at the upper opening of the PVC pipe.

1. Although the water in the boiler is 70 °C, we assume that the air temperature is only 60 °C (point B in Fig. 2). The air volume is *not* saturated and contains about 100 mg of water. (The reason will be apparent later)
2. The moist air is cooled by the cold aluminum tube as it sinks. Due to the final temperature of 35 °C, the air can contain only 40 mg, so 60 mg of water is condensed and flows into the gutter. During the entire cooling process, the relative humidity

of the air volume is 100% (B→C).

3. For several reasons, the fast movement of the air volume around the lower end of the PVC pipe is problematic: When the humid air leaves the condenser, its RH is 100%. Therefore, no additional water vapor can be absorbed. It takes time to raise the temperature from 35 °C to 70 °C before additional water can be absorbed. As soon as the air volume rises in the PVC pipe, it is too late to heat and the vapor layer above the water surface is too far away to be absorbed. In short: *when the air approaches the water surface, it is too cold and too humid to absorb a lot of extra water.*
4. Therefore, it is unavoidable that damp, unsaturated air with a temperature of 60 °C (or less) rises in the PVC pipe (point B). That is way below the desired target point A in Fig. 2.

Fig. 4 shows an estimation, how the temperature (red) and water content (blue) of a small volume of moist air change on their way through the concentric still. As the air sinks along the cooling surface (B→C), the temperature drops from 60 °C to 35 °C and the RH is 100%. Since the dew point can not be exceeded, 60 mg of water must condense on the cooling surface.

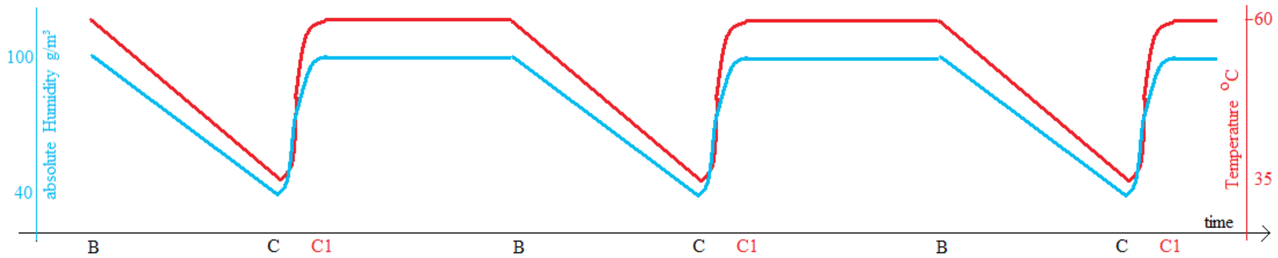

Fig. 4: Changes in the temperature and water content of a small air volume (10^{-3} m^3) during the circulation in the concentric condenser. The letters on the horizontal axis refer to Fig. 2

Now follows the short period C→C1, when the volume of air moves near the bottom of the PVC pipe. It moves almost parallel to the water surface before it rises inside the PVC pipe. During this time span, the air temperature should raise from 35 °C to 70 °C in order to absorb a lot of water vapor. It is hardly possible to accomplish both tasks satisfactorily in this short period of time. This essential process step needs to be improved.

Reheating the moist air

The Concentric Solar Still[2] works, but it delivers far less distillate than expected. The cause is clear: The air is too cold (35 °C) and too humid (RH = 100%) when leaving the dehumidifier (point C). Before it can absorb steam from the water surface of the boiler, it *must* be dried and heated.

The treatment steps are shown in Fig. 2 and Fig. 5:

- The air volume is saturated with water vapor (RD = 100%) before passing through the additional heater (point C).
- Heating without water supply reduces the relative humidity. After heating to 80 °C, the relative humidity of the air volume drops to 17% or so (C→D). The extremely dry air thirsts for water. Experiments will show to what temperature the air should be heated, because the energy demand also increases.
- As soon as the dry air comes close to the vapor layer above the water surface, it absorbs 160 g of water and cools down to about 70 °C (D→A). A turbulent mixing is done very fast.
- The transport of air in the PCV pipe does not change any data.
- While the very humid air descends along the condenser (A→C) and cools down to 35 °C, 160 mg of water *must* condense on the cooling surface. This is 166% more than without additional heating.

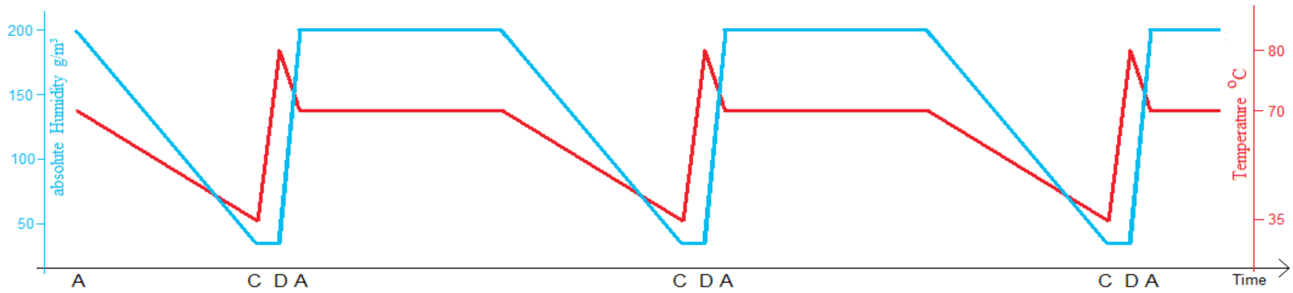

Fig. 5: Changes in the temperature and water content of a small air volume (10^{-3} m^3) during the circulation in the improved concentric condenser. The letters on the horizontal axis refer to Fig. 2

Because of the additional heating, the air volume in the improved concentric condenser can transport considerably more steam from the water surface to the condensation surface. After increasing the temperature in the reheater to 100 °C or more, the air can absorb even more vapor over the water surface of the boiler.

Power requirement and installation of the reheater

In [2], the following internal dimensions were proposed for the concentric still: diameter = 0.4 m and length = 3 m. At an (assumed) internal wind speed of 0.5 m/s, 0.031 m^3 of humid air flow through the reheater per second. It takes 1500 W to heat this air volume by 45 °C. For space reasons, an electrically operated heater should be used, powered by a PV system. It must not be switched on until the steam is already circulating in the proper direction. If the additional heating fails, potable water will still be produced, albeit in much smaller quantities. The measurement and control of the power actually consumed in the heater can be used for remote monitoring of the system.

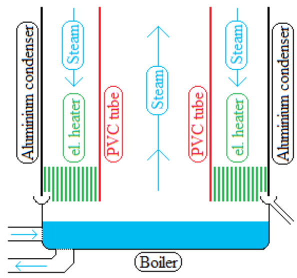

Fig. 6: Installation of the electric air heater.

In Fig. 6 it can be seen that probably only one set of electrically heated resistance wires is compact enough to heat the cooled vapor. The radiant heat of the hot wires helps to generate steam over the water surface.

Fig. 2 shows that with the selected model data, 160 g of water can be taken from each cubic meter of circulating steam. At a wind speed of 0.5 m/s, this results in a production rate of 18 liters of potable water per hour. Increased heating power increases the amount of distilled water - provided that the boiler generates *enough steam!* Remarkably, the water temperature in the boiler does not affect the result. It would be a milestone in water distillation if someone managed to produce enough steam at low temperatures. With an enlarged concentric still with integrated heating, you can condense any amount of steam.

Enhacement of the evaporation

If the circulating air is strongly overheated after condenser, check whether the boiler generates enough steam. If the deficiency can not be compensated by warmer water and an enlarged surface, steam production can be increased by the additional generation of tiny droplets. Well-known methods are:

Blowing air into the water to generate bubbles. When the bubbles burst, tiny drops appear and water vapor saturated air escapes. Spraying salt water through nozzles has a comparable effect. But this can cause a problem: after the droplets have evaporated, fine salt dust remains, which is carried by the circulating air to the condenser and makes the potable water salty again.

[1] M. Zamen, S. Soufari, M. Amidpour, Improvement of Solar Humidification-Dehumidification Desalination Using Multi-Stage Process, Iranian Institute of Research and Development in Chemical Industries, 2009?
[2] H. Weidner, A Concentric Solar Still-Details, 2018