Solar Still - Improved Distillation

Herbert Weidner [a]

Abstract: An analysis of the steam cycle in an humidification-dehumidification desalination system shows that the yield of potable water increases when the steam is transported by dry and preheated air. The system can distill 86% of the theoretically possible maximum amount.

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 separates the vapor layer that covers the water surface from the liquid and transports the generated humid air to the cooling surface. The diffusion can do neither of the two tasks satisfactorily. A solar humidification-dehumidification desalination system (HDH), composed of separated functional blocks meets the minimum requirements of an effective technical system. 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. It is better replaced it 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 the wind speed and create turbulence!
3. The heater: The higher the temperature and the surface area of the water, the more steam is produced. The evaporation costs energy that is extracted from the water. Heating is required in order to maintain the supply of steam. In full sunshine, a (cool) collector can deliver a thermal output of about 400 W per square meter. Since the usable power decreases with increasing temperature, the collector should remain as cool as possible. Then, 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.

In order to increase the yield of potable water and to reduce energy consumption, additional measures are introduced:

- The reuse of the cooling air of the condenser.
- An additional (electric) heater to dry the air so it can absorb as much steam as possible.

Both items are discussed below.

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a) 29. May 2018, email: herbertweidner@gmx.de

Simple systems

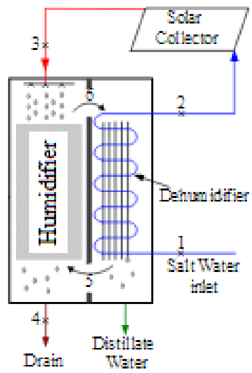

Fig. 1: Simple HDH desalination

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. the 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 the advantage that the cooled steam creates a circulation through both chambers. But, the resulting wind speed is insufficient to wipe the saturated vapor layers from the surfaces. More seriously: When the circulating vapor enters the humidifier (see tag 5 in Fig. 1), no water can be absorbed because the relative humidity is already 100%. In the lower part of the humidifier, the air must first be heated *before* water can be absorbed. It is *not* the job of the humidifier to warm the air!

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

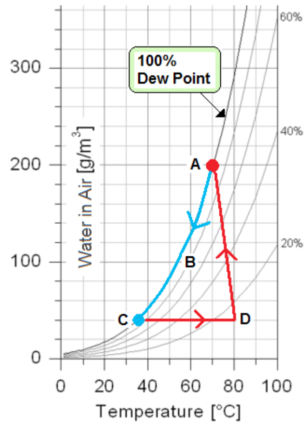

Fig. 2: Amount of water in air across a range of temperatures

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 13% (point D). Dry air can absorb a lot of water (we ignore the fact that the volume increases slightly). 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.

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.

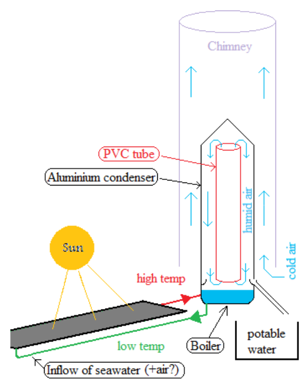

Fig. 3: A solar still with concentric condenser

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 (RH = 80%) and contains about 100 mg of water. (The reason will be apparent later)
2. The moist air is cooled by the cold aluminum wall as it sinks down. Due to the final temperature of 35 °C, the air can contain only 37 mg, so 63 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 50 °C or 60 °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 descends 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.

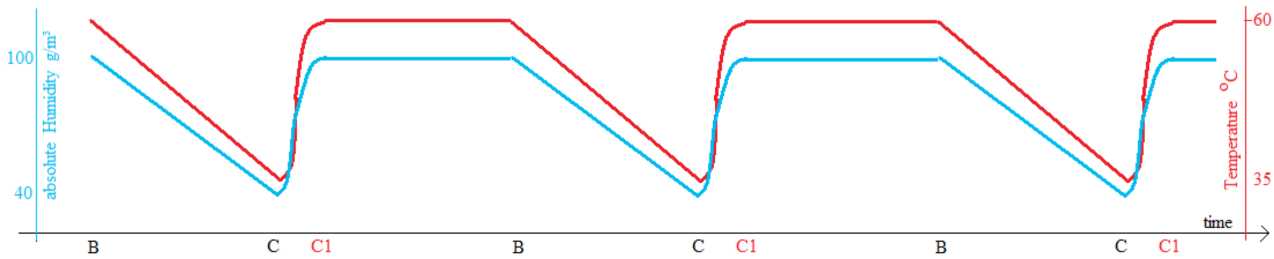

Fig. 4: Changes in the temperature and water content of a small air volume (10^{-3} m^3) during the circulation in the concentric condenser. The letters on the horizontal axis refer to Fig. 2

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 (closed circulation)

The Concentric Solar Still[2] works, but it delivers less distillate than expected. The cause: 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. An air volume (≈ 10^{-3} m³) is treated as 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 13% or so (C→D). The extremely dry air thirsts for water. Experiments will show which minimum temperature ist necessary, because the energy demand also increases.
- As soon as the hot and 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). Turbulence speeds up mixing.
- 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.

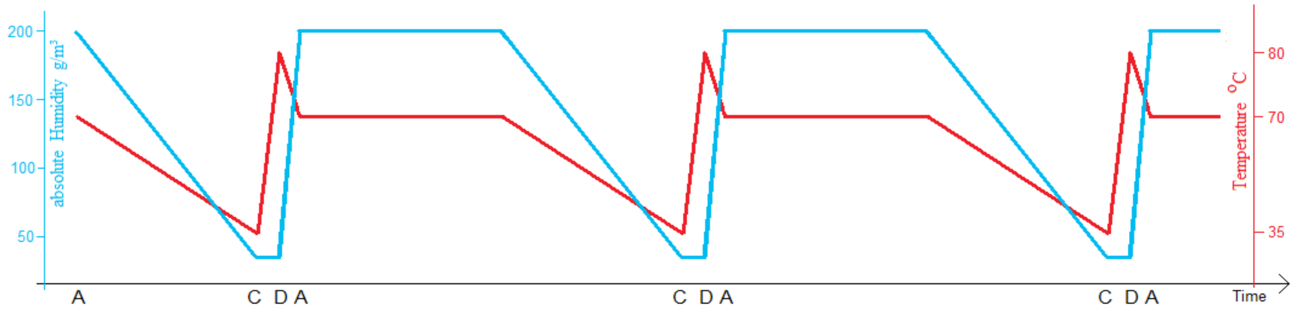

Fig. 5: Changes in the temperature and water content of a small air volume (10^{-3} m^3) during the circulation in the improved concentric condenser. The letters on the horizontal axis refer to Fig. 2

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 dimensions were proposed for the concentric still: internal diameter of the aluminum tube = 40 cm and length = 300 cm. We assume that the collector produces 6000 W thermal power and maintains the temperature of the salt water in the boiler at 70 °C. The condenser cools the humid air down to 35 °C.

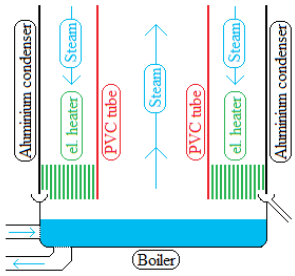

Fig. 6: Installation of the electric air heater.

1. As the enthalpy of vaporization of water is about 2300 J/g, the evaporation rate in the boiler is 2.61 g/s. It takes 61 seconds to produce 160 g of steam. (Per hour, a maximum of 9.4 liters of water can be evaporated.)
2. Assuming that moist air of RH = 70% rises in the PVC pipe, the air volume 0.17 m^3 must be moved during this period (Mollier diagram). Since the inner diameter of the PVC pipe should be 27 cm, the wind speed should be at least 0.05 m/s. Such a low speed has the advantage that it can be made by natural convection, if the aluminum condenser has a sufficient height. Then, no fan is necessary. On the other hand, the speed is insufficient to wipe the vapor layer from the water surface.
3. The humid air flowing through the reheater must be heated from 35 °C (RH = 100%) to 80 °C. According to the Mollier diagram, a power of 146 W is needed and the RH drops to 12%. 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.

In Fig. 6, it can be seen that a 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 potable water condense on the cooling surface per cubic meter of moist air passing by. At a wind speed of 0.05 m/s, this results in a production rate of 3.3 liters of potable water per hour (35% of the maximum possible amount). Increased heating power increases the amount of distilled water - provided that the boiler generates *enough steam!* In thermal seawater desalination, the generation of sufficient water vapor at low temperatures is a bottleneck.

Preheating the dry outside air (no air circulation)

In the just-described distillation unit, the cooled air, which is saturated with water vapor, *must* be heated so it gets dry and can absorb fresh water vapor in the humidifier. Since solar stills are usually operated in arid areas, there are large amounts of warm, dry air (RH < 30%). It may be easier and more economical to use preheated outside air and to do without a closed air circuit.

The air-cooled condenser of the cylindrical cooling tower delivers a large amount of warm air (~70 °C) that does not need to be blown into the chimney uselessly. Any part can be taken and reheated up to about 120 °C or more. Because of the extremely low relative humidity, the hot air is ideally suited to absorb a large amount of water in the boiler even at low wind speeds.

Here, a modification of the concentric distillation tower is described, which allows a much larger water surface for evaporation. Comparing Fig. 7 and Fig. 3, there are several differences: Dry outside air is sucked in and heated to 120 °C or so. The size of the eheater is not critical, because the air heating takes place outside the condenser tower. The hot air flows over the enlarged water surface of the boiler to absorb as much vapor as possible. Spiral baffles can extend the path of the air over the water surface. Experiments will show if it is worthwhile to reheat the moist air before it rises in the PVC pipe (The following calculation shows that this wastes a lot of energy). The hot water from the solar collector trickles down the inside of the PVC pipe as a thin coating (Falling film evaporator) and drips into the boiler. The hot water partially evaporates and increases the water content of the rising air.

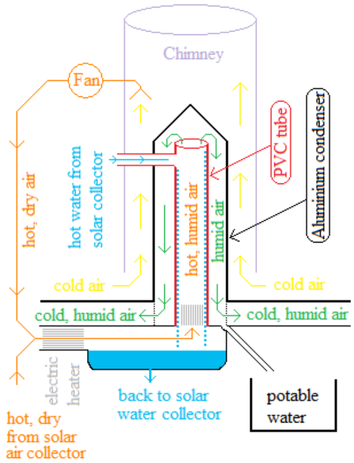

Fig. 7: An improved solar distiller with 86% efficiency

At the upper end of the PVC pipe, the air flow is directed downwards, cooled by the condenser and discharged to the outside. If the outer surface of the condenser tower is cooled sufficiently well, the steam temperature inside decreases from 70 °C (top) to 35 °C (bottom). Most of the of water dissolved in the humid air condenses and runs into the storage tank. The small amount of water that is still contained in the exhaust air is lost. It costs too much energy to heat saturated air.

While the plant, which is proposed in Fig. 3, may be built without energy-consuming pumps, the proposal shown in Fig. 7 requires several pumps: Two cross-flow fans to blow the process air into the destiller. The hot water from the solar collectors has to be pumped to the top of the condenser tower. Of course, this pump should be attached to the outlet of the boiler.

Power requirement

We use the dimensions of the concentric still[2]: internal diameter of the aluminum tube=40 cm and length=300 cm. We assume that the collector produces 6000 W thermal power and maintains the temperature of the water in the boiler at 70 °C. The condenser cools the humid air down to 35 °C.

1. One cubic meter of ambient air (35 °C, RH = 30%) is drawn in, heated to 120 °C (partly in an air filled collector and partly in an electrically operated heater). This reduces the relative humidity to about 1%. The total energy amounts to 80 kJ, resulting in a heating power of 750W. By adding preheated air from the chimney, the heating power can be reduced.

2. The dry air sweeps over the water surface of the boiler, absorbs 0.9 kg of water vapor and cools down to 70 °C. As the enthalpy of vaporization of water is about 2300 J/g, the evaporation rate in the boiler is 2.61 g/s. It takes 107 seconds to produce 280 g of steam. The air is now steam-saturated and requires a volume of 1.22 m³.

3. Not recommended, because uneconomic: To increase the water content, the air at the lower end of the PVC pipe is heated to 75 °C. As a result, RH drops to 80% and additional water

can be absorbed from the wall of the pipe. The very small increase in temperature requires a power of 8200 W and increases the water content of the air by 36%. It's no good idea to heat the humid air. Probably the thin layer of water on the inside of the PVC pipe is sufficient to ensure vapor saturation of the rising air.

4. If the additional heating according to point 3 is dispensed with, the entire supplied power of 6750 W must be dissipated through the aluminum wall of the condenser to the ambient air. As the humid air is cooled to 36 °C, 240 g of water condenses and runs into the storage tank. The volume of escaping air shrinks to 1 m³ and contains only 40 g of water (RH=100%). Reuse is not worth it. It saves heating energy when dry ambient air at the same temperature is used instead.
5. The average wind speed in the plant is 0.16 m/s, *8.1 liters of potable water* are condensed every hour (86% of the maximum possible amount).

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.

Results

- It is not a good idea to heat humid air. It is even worse to use precious steam for it. It takes 82 kJ of energy to heat 1 m³ of dry air (RH = 10%) from 50 °C to 60 °C. If this amount of air were saturated with steam (RH = 100%), the energy requirement would rise to 290 kJ.
- Air must be dried before it absorbs steam.
- The condenser must be cooled extremely well. The cooling surfaces must be made of very good heat-conductive metal.
- An optimized plant should be able to distill 90% of the theoretically possible maximum amount of water.

[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