Solar Still - Improving the Steam Transport

Herbert Weidner [a]

Abstract: In a humidification-dehumidification desalination system, the steam should be transported to the cooling surface by dry and preheated air. The required air temperature and heating power are calculated.

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. To accelerate the evaporation, the water must be preheated. The necessary energy can be calculated quickly, as the steady-state evaporation rate is always equal to the amount of heat added to the liquid per unit of time (heating power) divided by the latent heat of evaporation.

To evaporate 1 g of water you need approximately 2300 J of heat. This means: If you heat the water with 1000 W, it takes 38 minutes to evaporate 1 kg. According to the physics energy law, this is independent of the size of the tank, temperature of the air, humidity, and other parameters. You may need to add additional power to heat up the feed water to the equilibrium evaporation temperature.

All physical formulas only apply if certain boundary conditions are met, which are not always explicitly stated. The calculated amount of steam can only develop if it is immediately removed from the water surface. Unfortunately, this prerequisite is often overlooked. This is probably the main reason that most solar stills deliver far less potable water than what has just been calculated. If one relies on the very slow diffusion, the vapor remains in the environment of its origin and can not be expelled by increasing the temperature. Steam must be *actively* transported to the condenser.

The three main parameters that control the evaporation rate of a body of water are: the surface area, the wind speed and the partial pressure of water in the air.

1. First consider the surface area. As a body of water gets more spread out, then more of the water particles are exposed to the air and will therefore be given more of a chance to evaporate. A convex, outwardly curved surface (drops of water) evaporates more water than a flat surface.

2. The airspeed across water affects evaporation. We just have to realize that when the wind blows it will sweep away the air-borne water particles from the surface of the water. This will reduce the number of water molecules close to the water reducing the rate of water molecules going back into the liquid. When the rates are equal, so there's no *net* evaporation. Once individual molecules have separated from the liquid, they must be avoided from being able to return.

3. If the blowing air is already saturated with water (100% humidity) it won't matter how fast the air is blowing, net evaporation won't happen. Only when a *dry air flow* arrives, much water vapor can be absorbed and transported away. The partial pressure of water in air is a measure of how much water is already in the air. This is important because just as the water evaporates a water molecule into the gas, the water molecules can go back from the gas into the body of water. When these two processes proceed at equal rates the net evaporation rate of water from the body of water stops. Hot, dry air can absorb much more water molecules than cold, dry air.

Why is the temperature not mentioned? The temperature of the water says how energetic the water molecules are. The more energetic the molecules are, the more likely they are to break free from the liquid and get into the air. That's right, but: Our goal is to generate plenty of potable water, not just steam. High temperature does not eliminate the salt. With reverse osmosis, the water is produced without the need for steam. In a solar distillator, steam and high temperature are necessary tools, but not the target. Are there any ways to save energy and produce steam at low temperatures? Dissolved

a) 21. June 2018, email: herbertweidner@gmx.de

salt lowers the vapor pressure of water at any temperature. There are few measurements of how contaminants affect the evaporation of water. For simplicity, pure water is assumed for all subsequent calculations.

Water and wind have the same temperature

Evaporated water vapor is removed from a surface by replacing some of the circulating air with fresh make-up air with lower specific moisture content. Assume that the wind has 40% relative humidity and is at the *same* temperature as the water. For low temperature, the amount of steam produced can be calculated using proven rules of thumb. We need:

v =velocity of air above the water surface (m/s)

a = water surface area (m^2)

x_s = *maximum humidity ratio of saturated air at the same temperature as the water surface (kg/kg) (kg H_2O in kg Dry Air)*

x = humidity ratio air (kg/kg); (kg H_2O in kg Dry Air)

With these values, you can predict the amount of evaporated water per hour (kg/h)

$g = (25 + 19 \cdot v) \cdot a \cdot (x_s - x)$

Example a: A boiler contains 70 °C warm water; the wind blows over the 2 m² surface at a speed of 2.7 m/s; Before the warm air hits the water, the relative humidity is 40%. The Mollier diagram gives the values x_s = 0.28 kg/kg and x = 0.087 kg/kg. The evaporation from the surface can be calculated as 30 kg/h. The heat supply required to maintain the temperature of the water in the boiler can be calculated as 19 kW.

Fig. 1 shows that the necessary wind speed becomes smaller when the injected air has a low relative humidity.

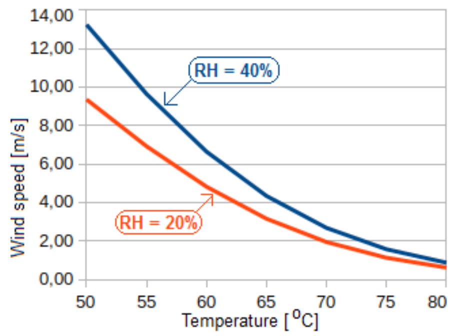

Fig. 1: Wind speed over a warm water surface to blow away the generated steam (30 kg/h).

Example b: Now, the temperature of the water is only 60 °C, which reduces the steam pressure. The Mollier diagram gives the values x_s = 0.155 kg/kg and x = 0.055 kg/kg. In order to produce 12 kg/h of steam, we need the wind speed 1.8 m/s and the heating power 7.7 kW.

In both examples, about 1.5 liters of potable water per kW and hour are distilled.

Humidification of hot air with steam

It is in general good energy economy to increase the air temperature as much as possible. The increased moisture transport capacity of air at higher temperature out-weights the increased energy-consumption for heating the dry air to higher temperature! We will also see that with increasing temperature less and less air has to be moved. This also reduces the energy expenditure.

In the following example we consider a time span of one second. Ambient air (mass = m_A; T_1 = 35 °C; RH = 30%) is drawn in and heated to 100 °C (in an air filled collector or in an electrically operated heater) in order to reduce the relative humidity to 2% or so. As the air expands, the amount of dissolved water remains 10 g/kg. (Mollier diagram: h_1 = 130 J/g). At this temperature, every cubic meter of air could absorb up to 900 g of water - an ideal vehicle for steam transport to the condenser! (At 60 °C, the maximum moisture content is only 150 g/m³!)

It is not a good idea to spray water into the hot, dry air, because it cools down the air. Cold air can only transport little water. You have to separate two tasks:

1. Water must be evaporated. The required energy can be gathered by large solar collectors.
2. The steam must be separated from the water surface and transported to the cooling surface.

For the latter, very hot and dry air is well suited. The hot air has only the tasks of detaching the saturated vapor layer from the water surface, absorbing the vapor and transporting it to the condenser. It is a good idea to blow the hot air from many nozzles directly onto the water surface[1]. A turbulent flow destroys the saturated vapor layer on the water surface and absorbs the vapor much faster than would be possible by diffusion.

Let's assume that the water is heated to 60 °C with 10 kW and steam evaporates from the surface. As the *enthalpy of vaporization* of water is 2358 J/g, the evaporation rate in the boiler is 4.24 g/s. This amount of moist air must be blown off as quickly as possible, so that new steam can arise. The saturated steam has an enthalpy of h_2 = 2610 J/g. Above the water surface, the hot, dry air and the saturated steam mix, keeping the total energy constant. After mixing, the humid air has the enthalpy

$$h_{total} = \frac{h_1 \cdot m_A + h_2 \cdot m_W}{m_A + m_W} = \frac{130\,J/g \cdot m_A + 2610\,J/g \cdot 4.24\,g}{m_A + 4.24\,g}$$

Step one is done: the relationship between the injected air mass m_A and the specific enthalpy of the exiting moist air can be tabulated.

The specific enthalpy h_{total} of the moist air depends on the temperature T and the relative humidity. To simplify the calculation, let us assume that the temperature of the hot air only decreases by a few degrees when it absorbs the cooler steam. Now, in a second step, we can calculate the necessary volume of air that has to be blown over the water surface of the boiler. It is a bit cumbersome to read enough data points in the Mollier diagram. In Fig. 2, this was done for five different temperatures of the injected air, all of which exceed the water temperature of the boiler.

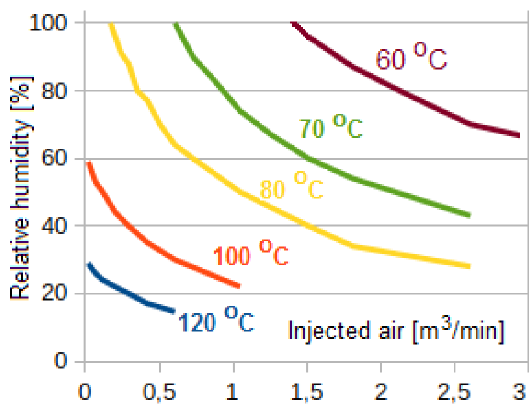

Fig. 2: The relative humidity of the exiting moist air as a function of the injected air volume (at 35 °C).

Some remarks: The relative humidity can not exceed 100%. It must therefore be constantly brought in new air to fully absorb the produced steam.

If the injected air is about the same temperature as the water in the boiler (here: 60 °C), it can absorb and transport a small amount of steam. This can only be compensated by excessive air. It costs a lot of energy to heat a large air volume from 35 °C to 60 °C.

The fresh air requirement becomes smaller and smaller as the temperature rises. As the amount of air decreases, so does the energy required for heating. This is also influenced by the relative humidity. Increasing the end temperature T_2 from 60 °C to 120 °C has the somewhat surprising consequence that the required heating power is drastically reduced.

An example: If ambient air (T_1 = 35 °C; RH = 30%) is warmed up to the final temperature T_2 and the reduction of the air volume according to Figure 2 is taken into account, the required heating power P can be estimated using the formula: $P \approx 29\,kW \cdot e^{-T_2/17^0 C}$.

Results

It is very economical to blow in hot air (T_2 > 100 °C) and to humidify it with steam. Further details of an effective, solar operated distillation unit have already been described[2].

[1] A. Kabeel, M. Abdelgaied, M. Mahgoub, The performance of a modified solar still using hot air injection, 2015
[2] H. Weidner, Solar Still - Improved Distillation, 2018