HYBRID WIND-POWER-DISTILLATION PLANT

by

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This paper reports and elaborates on the idea of a solar distiller and an off-shore wind power plant operating together. The subject under discussion is a single-stage solar distillation plant with vaporization, using adiabatic expansion in the gravitational field inside a wind power plant supporting column. This scheme divides investment costs for electric power and distillate production. In the region of the Adriatic Sea, all electric power produced could be "converted" to hydrogen using less than 10% of the distillate produced.

Key words: *hybrid wind-power-distillation plant, reversible flashing process, integrated systems, renewable energy*

Introduction

Distilled water is widely used in the chemical and food industries, as additional supply water for steam boilers, for onboard consumption on ships and for the production of hydrogen and oxygen by means of electrolysis. There is a greater number of seawater stills, but multi-stage flash distillation plants produce 64% of all desalinated water in the world.

The seawater warmed up inside these plants usually enters the first evaporator, where only a small percentage evaporates due to the heat of hot steam produced from an industrial process co-located with the distillation plant or from a cogeneration configuration.

Thus, the steam created condenses in the evaporator chamber and preheats the incoming seawater. The none-vaporated water remaining in the first evaporator is throttled down to a lower pressure in the second evaporator, where additional steam is generated adiabatically; this process is repeated in other adiabatic evaporators until the remaining hot brine water is sufficiently cooled. For the smallest possible consumption of hot steam, it is worth building a great number of evaporator stages in this type of large-capacity still. It is also important for the steam-heat source to have the lowest possible temperature, *i. e.*, the lowest availability, to achieve the highest possible efficiency of the whole, possibly cogenerating, plant.

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There are many papers in the literature which deals with seawater desalination systems driven by renewable energies.

Reali *et al.* [1] presented basic technological features of simple solar stills utilizing tubes for sea water desalting. The evaporation section comprises horizontal transparent thin-walled plastic half-filled with sea water which absorbs solar radiation. The condensation section is physically separated from the evaporation section, in a shaded space below it, and comprises horizontal plastic or metal tubes.

Velmurugan *et al.* [2] attempt to enhance the productivity of the solar stills by connecting a mini solar pond, stepped solar still and a single basin solar still in series. They also perform an experiment by replacing the single basin solar still into a wick type solar still and study day and night productivity.

Nakatake *et al.* [3] proposed a newly designed, maritime lifesaving small distiller consisting of a windmill and a number of horizontal concentric cylindrical partitions in contact with saline-soaked wicks. The proposed distiller can be driven by wind only, without human power or electricity.

Eltawil *et al.* [4] presents a hybrid desalination system that constitutes of wind turbine and inclined solar water distillation integrated with main solar still. A small wind turbine is used to operate a rotating shaft fitted in the main solar still to break boundary layer of the basin water surface.

Dev *et al.* [5] performed an experimental study of inverted absorber solar still and single slope solar still at different water depth and total dissolved solid.

Kalogirou in [6] covers a large variety of systems used to convert seawater into fresh water suitable for human use. Paper also covers a variety of systems, which can be used to harness renewable energy sources; these include solar collectors, photovoltaics, solar ponds, and geothermal energy. Also some general guidelines are given for selection of desalination and renewable energy systems.

Review and state-of-the-art of the most important developments of the wind power desalination is presented by Ma *et al.* [7].

If, however, the heat necessary for warming up the seawater is obtained from solar radiation, the criterion for optimization of the whole plant is different, particularly for the case in which a part of the complete still plant is composed of off-shore wind power plant structure elements. Such exploitable elements include a moored floating platform and hollow wind turbine support columns. Of this case, the type of still conceived and tested in [8] is a good example. The pressure of the seawater warmed by a low-temperature heating source is decreased by raising the water up in the vertical column in one stage. In an off-shore wind power-still, the heating source is a shallow seawater pond that acts as the solar collector. The water, warmed in the pond, rises up along the vertical column and boils adiabatically at a certain height. The steam goes to the condenser while the cooled brine water is returned back to the pond by the return pipe. Here, the pressure drop, which causes adiabatic evaporation, does not result in a conventional “flashing process” but a partially reversible process: the pressure drop causes the hot water to rise in the gravitational field and carries out the frictional work between the steam bubbles and the surrounding liquid. Thus, the motion of the hot liquid with bubbles is upward, and the cooled liquid is sent downward, back to the pond, which is achieved without a circular pump. Nor is a pump necessary, according to the scheme presented later in this paper, for the distillate evacuated from the condenser.

Disintegration of fluid in two phases in a gravitational field

This process begins in the hot updraft flow at the height of the y_2 column (fig. 1.), where the first nucleation of vapor in the superheated liquid occurs. In the figure, "1" marks the state in which the pressure of the hot liquid is equal to the saturation pressure at that temperature. The disintegration of the superheated liquid into two phases, with the occurrence of the first sustainable bubble whose radius is greater than the critical value, corresponds to state "2". The disintegration process ends with state "3", in which the vapor phase separates from the liquid and rises toward the wall of the turbine supporting column, upon which it condenses. The cooled liquid that rose to the level of column y_3 flows over the edge and falls down to the descending pipe and further on to the pond. The numerical data given in the figure refer to a hot water temperature of 40 °C and a cooled water temperature of 30 °C.

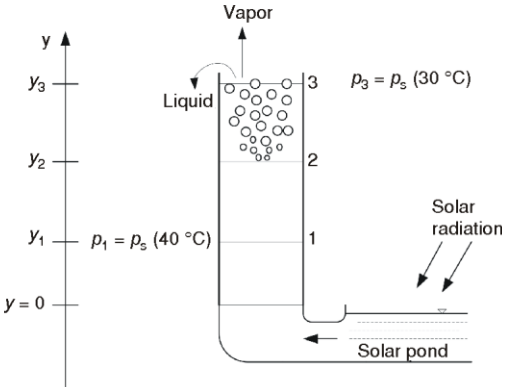

Figure 1. Hot liquid states in the vertical column

The 1-2-3 process is generally shown in the *h*-*s* diagram of stable states close to the saturated-liquid line $x = 0$ in fig. 2. State 2 is not in the normal *h*-*s* diagram of stable states but rather in the metastable state of superheated liquid. State 3^s is a fictive state that would be obtained by an equilibrium adiabatic expansion, unlike the actual disintegration process, which ends with state 3. The diagram shows the relationships between the changes in enthalpy and the heights in the column required by the first law of thermodynamics, that is:

$$h + gy = \text{const.} \tag{1}$$

for all parts of the process. The kinetic energy of turbulent motion in all of the stages is shown as dissipated. In part 2-3, there is also the internal frictional work between the steam bubbles and liquid, which is essential for raising the liquid over the column upper edge.

In the original paper [8], the whole 1-3 process can be described by the term "reversible flashing process". Strictly speaking, it is the case in its smaller part for the existence of only a small enthalpy decrease $h_1 - h_3$ equal to the potential energy increase $g(y_3 - y_1)$. There is no such transformation of enthalpy into potential energy of the outer field in a conventional flashing process, such as throttling.

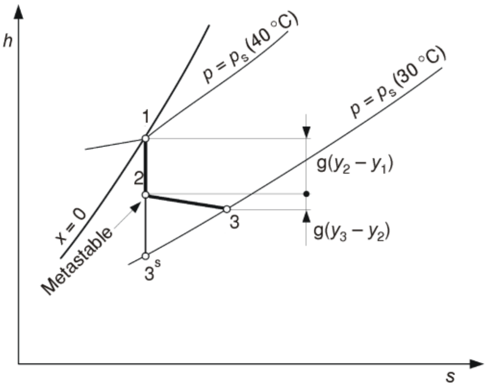

Figure 2. *h*-*s* process diagram

The *h*-*s* diagram in fig. 2 shows an actual 1-2-3 process and a fictive 1-2-3^s3 process, where the actual process is modeled by breaking it into a 1-2-3^s reversible process and an irreversible process 3^s-3, which leads to the work obtained in 2-3^s as frictional work in the 3^s-3 process. The efficient work spent for the potential energy increase is $g(y_3 - y_1)$, part of which is g($y_3 - y_2$). accompanied by frictional work in zone 2-3, equal to $h_3 - h_3^s$.

It is assumed that the first supercritical bubble will occur when the liquid is superheated by 5.0 K, therefore, at the pressure corresponding to the saturation pressure at 35.0 °C. The definiteness of states 1, 2, 3^s, and 3 ensures that the specific internal friction work during disintegration can be estimated as $T_3(s_3 - s_2)$, specifically:

$$w_{f2,3} = 303(s_3 - s_1) = 600 \text{ J/kg} \tag{2}$$

On the other hand, the total integral $-\int_1^3 v\mathrm{d}p$ is roughly:

$$\frac{(v_1 + v_3)(p_{s(40\,^\circ\mathrm{C})} - p_{s(30\,^\circ\mathrm{C})})}{2} = 882 \text{ J/kg} \tag{3}$$

This equation generally has a good correspondence with eq. (2) because this integral expresses the sum of the internal friction work and the kinetic and potential energy changes.

Hybrid wind-power-distillation plant scheme

Figures 3, 4, and 5 show the basic construction of an off-shore wind-power-distillation plant [9]. The wind turbine support column is immerged in the sea with its lower part and moored while at sea level, a floating closed shallow pond – the solar collector – is connected to it. The hot water outlet from the pond is connected with a hot water vertical column inside the support column, (1), as shown in fig. 3. By means of its telescopic extension, (2), and its pulling and pushing device, (8), this column has a changeable height.

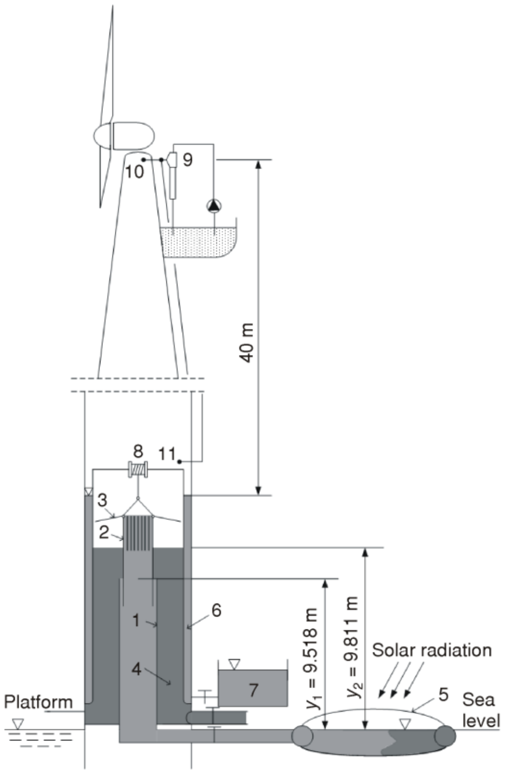

Figure 3. Scheme of the still in stationary drive

In the stationary state, the still operates by maintaining a sufficient sub-pressure in the upper part of the support column hollow, and the hot seawater moves upward along the vertical column and its telescopic extension. The generated steam goes upward and condenses while the non-evaporated cooled liquid overflows from the extension, (2), to the surrounding column annular space, (4). From there, it returns to the pond, (5), to be warmed up. According to the scheme given in fig. 4, cold seawater is added to this pond to replace the produced condensate-distillate and for the permanent brine outlet, which is necessary to maintain the allowed constant amount of salt dissolved in the pond.

As stated previously, the condensate is created by vapor condensation upon the upper internal surface of the plant support column. It flows down to the space with an annular cross-section, (6), as shown in fig.

3; from here, it is drained as a final product under hydrostatic pressure, (7). The sub-pressure is maintained in the steam space by heat transfer from the outer column surface and by a vacuum pump, (9), which ejects noncondensable gases.

Non-condensable gas inlets are placed close to the top of the column, (10), and immediately above the condensate surface, (11). The hot water column height changeability is necessary due to the different operating temperatures of the pond water, and it can be achieved by means of an electric motor and a chain drum, (8).

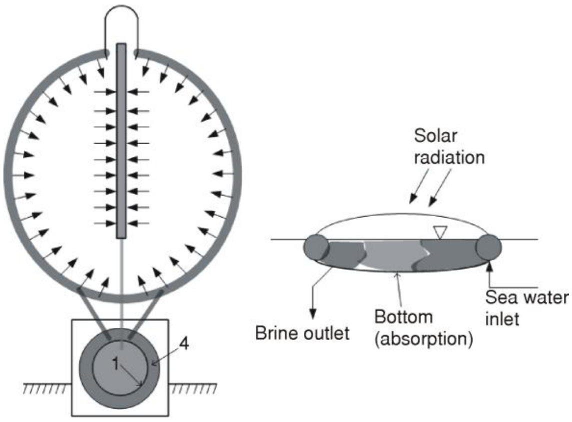

Figure 4. Closed pond-collector

The shallow pond-collector can be a partly inflated floating structure with a transparent cover and pipes connected to a hot water column, (1), and the cooled water annular space in the column, (4), as shown in fig. 3. The cooled water pipe that feeds the pond is integrated in the pond as a periphery canal system (fig. 4) with many inlet openings to the pond, close to its bottom.

Thus, cooled water fills the lower part of the pond, near the bottom; the hot water outlet from the pond goes through a system of openings leading to the outlet pipe through the middle of the pond (fig. 4). These openings are closer to the water surface in the pond. Finally, a device near the pond lets in the surrounding seawater into the pond at an amount equal to the distillate and brine outlet flow produced. The device is based on a floating body reacting to a change in the water level in the pond. The transparent cover can float on the pond water surface and is in the form of two thin foils with closed air cells in between.

Operating conditions in the still

To provide insight into the overall size and capacity of the wind-power-distillation plant, the central Adriatic region was chosen for an average day in January and one in July.

According to [10], in January, the mean temperature for the central Adriatic region is 9.7 °C. According to [11], between 10^{00} and 15^{00} hours, the mean temperature for the area relatively close to Dubrovnik is about 1.0 °C higher than the daily mean temperature. It is therefore assumed that, for this approximate calculation, the mean temperature during the use of solar power is $t_{\mathrm{os}} = 10.7$ °C.

On the other hand, the total solar irradiation per 1 m^2 of a horizontal plate is about 1.80 kWh per day. The radiation actually begins at 8^{30} hours and lasts until 16^{15}. The plant is assumed to be in the quasi-stationary regime from 10^{00} to 15^{00} hours. The part of the total radiation corresponding to this period of the day is calculated to define its average power. According to the known arrangement of the total radiation intensity for a particular latitude, for the stated operation period of 5 hours, we obtain 85% of the total irradiated energy, with an average intensity of:

$$G = \frac{0.85 \cdot 1800}{5} = 306 \ \mathrm{W/m^2}$$

For an average day in July, the daily mean temperature is 24.0 °C; the mean temperature between 8^{00} and 19^{00} hours is approximately 1.5 °C higher than the daily mean, and therefore t_{os} = 25.5 °C. The total solar irradiation is 7.4 kWh/m^2 per day. The radiation actually begins at 5^{00} hours and ends at 19^{00}. We use the plant in the quasi-stationary regime from 7^{00} to 18^{00}. According to the known daily radiation schedule, for the stated operation period of 11 hours, the mean radiation intensity is:

$$G = \frac{0.85 \cdot 7400}{11} = 572\ \mathrm{W/m^2}$$

Collector efficiency

The pond-collector efficiency is defined as the ratio of heat received and the total radiation available at the collector surface. For the characteristic circumstances described, the efficiency depends on the hot water temperature and the temperature decrease in the column-evaporator. We chose 40.0 °C as the characteristic hot water temperature for January and 30.0 °C as the temperature after its adiabatic evaporation. Thus, the water is superheated after the pressure decreases in the evaporator at 10 °C, which is within the recommended values. The assumed hot water temperature is not optimal; however, the results will give a reliable insight into the maximum possible capacity of the still and the influence of certain operating parameters on its capacity.

The efficiency depends on the ratio $(t_{\mathrm{abs}} - t_{\mathrm{os}})/G$ at the abscissa and on the collector type. According to [12], for the assumed circumstances and for water at distiller temperatures of 40/30 °C, the efficiency is negligibly small if the shallow pond is open. For a pond closed by a one-layer transparent cover with glass characteristics and an absorbing bottom, the ratio $(t_{\mathrm{abs}} - t_{\mathrm{os}})/G$ is 0.079 while the efficiency is approximately 0.30. The water temperatures assumed for July are 55/45 °C. In this case, the ratio $(t_{\mathrm{abs}} - t_{\mathrm{os}})/G$ for the efficiency is 0.043, and the efficiency is approximately 0.53. Both efficiencies are 10% lower then according to diagram in [12]. The reason for that are specifics off-shore circumstances.

Working parameters in characteristic regimes

During the quasi-stationary regime in January, the hot water saturation pressure is $p_{\mathrm{s}(40\,°\mathrm{C})}$ = 7380 Pa. For an atmospheric pressure of 100000 Pa, there is a corresponding sub-pressure of 92600 Pa, and the height above the water level in the pond is $y_1 = y_{(40)}$ = 9.518 m. For a cooled water saturation temperature of 30.0 °C, $y_2 = y_{(40)}$ = 9.811 m. These two water level heights are shown in fig. 3 for static conditions, neglecting hydraulic pressure losses.

During the quasi-stationary regime in July, the saturation pressures are $p_{\mathrm{s}(55\,°\mathrm{C})}$ = = 15740 Pa and $p_{\mathrm{s}(45\,°\mathrm{C})}$ = 9582 Pa while the corresponding hot water column height is $y_{(55)}$ = = 8.72 m.

For the regime in January, the evaporated water flow $\dot{m}_{\mathrm{v}}$ is part of the hot water inflow from the pond to the column $\dot{m}_{\mathrm{hw}}$, $\dot{m}_{\mathrm{v}(30\,°\mathrm{C})} = x\dot{m}_{\mathrm{hw}}$ while the evaporated part x is determined from the energy balance before and after the adiabatic disintegration of hot water into two phases. Neglecting the potential energy changes, this balance becomes an enthalpy balance:

$$\dot{m}_{\mathrm{hw}} h'_{(40\,°\mathrm{C})} = \dot{m}_{\mathrm{hw}}(1-x) h'_{(30\,°\mathrm{C})} + \dot{m}_{\mathrm{hw}} x h''_{(30\,°\mathrm{C})} \tag{4}$$

It follows that the evaporated portion of hot water is $x = x_3 = 0.0172$ (fig. 1). With this value, the specific volume of the homogenous two-phase flow at the top of the column is:

$$v_3 = 0.567\ \mathrm{m^3/kg} \tag{5}$$

Analogous to this calculation, for the July regime, it is:

$$h'_{(55\ ^\circ\mathrm{C})} = (1-x)h'_{(45\ ^\circ\mathrm{C})} + xh''_{(45\ ^\circ\mathrm{C})} \tag{6}$$

and

$$x = 0.0175$$

as well as

$$v_3 = 0.343\ \mathrm{m^3/kg} \tag{7}$$

The corresponding steam flows, *i.e.*, the distillate flows, depend on the bottleneck in the still capacity. This bottleneck is represented by the condenser surface and the condenser heat transfer coefficient, as well as the total temperature difference over the condenser wall. For January, the heat transfer through the condenser wall is:

$$\dot{Q}_\mathrm{c} = A_\mathrm{c} k(30 - 10.7) \tag{8}$$

The condenser area is equal to the area of the supporting column upper part. For a 3.0 m average diameter and 40.0 m height, this area is $A_\mathrm{c} = 3\pi 40 = 377\ \mathrm{m^2}$.
The heat transfer coefficient is:

$$\frac{1}{k} = \frac{1}{\alpha_\mathrm{out}} + \frac{\delta}{\lambda} + \frac{1}{\alpha_\mathrm{in}} \tag{9}$$

where α_out is the heat transfer coefficient on the outer side of the column. According to the empirical formula in [13]:

$$\alpha_\mathrm{out} = 5.7 + 3.8\mathrm{w} \tag{10}$$

where w [ms^{-1}] is the wind speed and $w = 6.0$ m/s. It follows that:

$$\alpha_\mathrm{out}\ 28.5\ \mathrm{W/m^2K}$$

Furthermore, the heat resistance of the heat transfer through the column steel wall and the resistance for the condensation on the inside are neglected. For an outer resistance coefficient $1/\alpha_\mathrm{out} = 0.0585$, it becomes:

$$\frac{\delta}{\lambda} = \frac{0.020}{50} = 0.0004 \ll 0.0585$$

and

$$\frac{1}{\alpha_\mathrm{in}} = \frac{1}{9000} = 0.00011 \ll 0.0585$$

A relatively high condensation heat transfer coefficient α_in in this estimation is appropriate for relatively small heat flows, determined only by the outer heat transfer resistance. Thus, the results are small, and the heat transfer into space by means of radiation is not calculated. It would increase $\dot{Q}_\mathrm{c}$ by approx. 18% (January). Therefore, assuming $k \approx \alpha_\mathrm{out}$, it follows that:

$$\dot{Q}_c = 377 \cdot 28.5 \cdot 19.3 = 207369\ \mathrm{W}$$

The steam flow is:

$$\dot{m}_\mathrm{v} = \frac{207.3}{h''_{(30\ ^\circ\mathrm{C})} - h'_{(30\ ^\circ\mathrm{C})}} = 0.085\ \mathrm{kg/s} \quad (\text{approx. } 1.5\ \mathrm{m}^3 \text{ distillate per day})$$

Let us now turn to the July regime. Heat flow is:

$$\dot{Q}_\mathrm{c} = 377 \cdot 28.5(45 - 25.5) = 209517\ \mathrm{W}$$

The steam flow is:

$$\dot{m}_\mathrm{v} = \frac{209.5}{h''_{(45\ ^\circ\mathrm{C})} - h'_{(45\ ^\circ\mathrm{C})}} = 0.087\ \mathrm{kg/s} \ \ (\text{approx. 3.4 m3 distillate per day})$$

The necessary pond–collector size

The January regime requires a pond with an area of A_coll such that the heat received in, $\dot{Q}_\mathrm{p}$:

$$\dot{Q}_\mathrm{p} = \dot{Q}_\mathrm{c} = A_\mathrm{coll} G \eta_\mathrm{coll}\ \ [\mathrm{W}] \tag{11}$$

For $\dot{Q}_\mathrm{c}$, G, and η_coll in January, it follows that $A_\mathrm{coll} = 2260\ \mathrm{m}^2$.
For $\dot{Q}_\mathrm{c}$, G, and η_coll in July, it follows that $A_\mathrm{coll} = 691\ \mathrm{m}^2$.
For further estimations, we assume that $A_\mathrm{coll} = 2000\ \mathrm{m}^2$.

The start up of the plant and the nocturnal regime

The plant begins by warming the water in the pond and then exhausting the air from the supporting column hollow by the vacuum pump. Thus, there is no water in the lower part of the supporting column hollow, and the tubes connecting the ascending column and descending annular channel with the pond-collector are shut by the valves. After obtaining the necessary vacuum in the column hollow and the necessary water temperature in the pond, the valve connecting the pond with the ascending column, (1) in fig. 3, opens, and hot water rises along the ascending column. At the height y_1 (fig. 1), the first steam bubbles occur, and in the upper part of this column, within the cluster of channels in its telescopic extension, (2) (fig. 3), the two phases originate. The steam separates and rises, and the liquid flows over to the descending annular channel, (4) (fig. 3). The valve on the liquid return pipe opens, establishing a stationary flow of hot water upward as the cooled liquid returns back to the pond. The steam goes further upward while the condensate descends along the column wall to the condensate annular channel, (6), and to the condensate tank, (7) (fig. 3).

With decreasing solar radiation during the day and at night, the solar energy inflow stops. We anticipate continuation of the distilling process with water and steam circulation, however, with greatly decreased intensity, on account of the energy accumulated in the water pond during the sunny part of the day. The reason for nightly maintenance of the process is to avoid the start up procedure every morning. The transfer to the decreased nocturnal intensity of the process is automatically achieved in the following way. At sunset, during plant operation, the water temperature in the pond falls faster than the water temperature in the steam space inside the wind-turbine supporting column. The telescopic extension of the ascending column rises. However, when the temperature difference between the hot water and

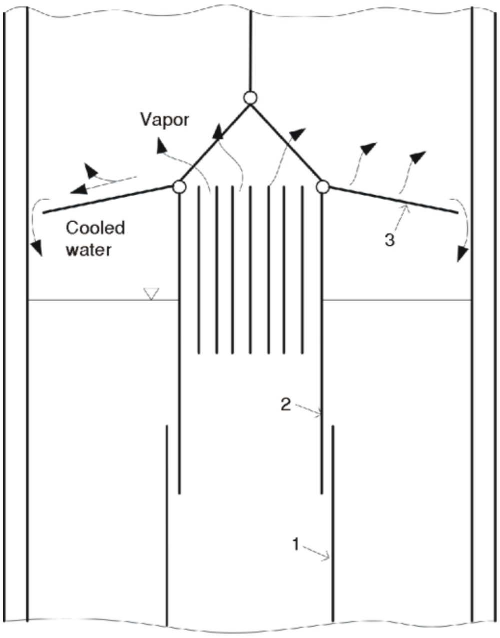

Figure 5. Telescopic extension with plate flange

the saturation temperature in the steam space falls below approximately 5 °C, the boiling process in the telescopic extension channels stops. The circulation of hot and cooled water will decrease greatly, yet it will continue due to the maintenance of at least a small difference in temperature in the ascending and descending column-channel. To maintain such a low temperature difference of few degrees centigrade, the ascending column and telescopic extension walls should be made of an appropriate material or should be heat-insulated. The process of steam extraction from hot water occurs as the water flows over the plate flange, (3), as shown in fig. 3 and 5.

The nocturnal regime with very low circulation intensity has only one practical purpose: the maintenance of circulation. It will cause the temperature in the ascending column to increase again at sunrise. Therefore, when it is 5 or 6 °C higher than the saturation steam temperature in the column, the boiling process will automatically be established again in the telescopic extension, the circulation will increase, and the intensive working regime of circulation and steam generation with two-phase flow will be established.

Relationship between the produced distillate and the wind turbine electric work

We assume 2500 kW for the nominal wind turbine power with a working time of 1800 hours per year for the central Adriatic region. Thus, an average of 12329 kWh is produced each day, and the mean power at the generator terminals is 514 kW during a 24-hour period. The value of 1 kWh at this power plant threshold is somewhat smaller than the price for consumers and is approximately 0.10 € per kWh. This amount corresponds to approximately 1230 € per day. The simultaneous daily mean production of distilled water is approximately 2500 kg per day. With the distillate retail price of 0.8 € per kg, our estimate of the wholesale would be 0.400 € per kg. The value of the daily produced distillate would therefore be approximately 1010 € per day, or approximately 75% of the value of the electrical work generated (electrical energy).

The amount of rainwater collected from the covered pond-collector surface is independent of the distillate production and amounts to 300 kg/m^2 per year, which is approximately 1640 kg per day in this case.

The production of the distillate occurs at a place where the production of electric energy is unstable. Taking this into account and to avoid transport of that energy to mainland, the best solution might be accumulation of that energy in hydrogen by process of distillate electrolysis.

Let us establish the relation between the amounts of distillates produced and electric energy for their electrolysis. Let us assume that the process is ideal, reversible in the thermodynamic sense, and that, from a distillate at a pressure of 1.0 bar and a temperature of 25.0 °C, H_2 and O_2 are produced, both at a standard pressure of 1.0 bar and a temperature of 25.0 °C. In this case, the entropy of 1 kmol of water is 69910 J/K. For the 1 kmol of H_2, produced the entropy is 130570 J/K, and for 1/2 kmol O_2, the entropy is 102500 J/K. The heat brought from the ambient is, in this case, $T_o\Delta S_s$ = 298.15(130570 + 102500 – 69910) = = 48646154 J/kmol = 2702564 J/kg of water. The energy balance of the ideal electrolyzer include enthalpy of destilate, heat brought from the ambient and electrical work generated by wind turbine as input flows, gives:

$$\dot{m}_\mathrm{d} h_\mathrm{d}^\mathrm{o} + \dot{m}_\mathrm{d} 2703 + 514 = \dot{m}_\mathrm{d} \frac{16}{18} h_{\mathrm{O}_2}^\mathrm{o} + \dot{m}_\mathrm{d} \frac{2}{18} h_{\mathrm{H}_2}^\mathrm{o} \tag{12}$$

or

$$\dot{m}_\mathrm{d} = \frac{514}{283097} = 0.001816\,\mathrm{kg/s} = 157\ \mathrm{kg\ per\ day}$$

The amount of distillate used in this way is only approximately 6% of the quantity produced. In the actual electrolytic process, the heat is not taken from the ambient. Instead, the increased entropy in the reaction is covered by dissipated electrical work, and the actual electrical energy spent is approximately 50-60% greater than the theoretical value. According to that the quantity of destilate for hydrogen production is approximately 4% of the quantity produced.

Conclusions

The distillation of seawater in the one-stage hybrid plant described herein is technologically simple and economically justified because an already existing wind power plant structure is adapted for distillate production. The distillate production inside the wind turbine support column is almost a self-sustaining process, *i. e.*, the process requires a relatively small additional power for start up and vacuum maintenance (vacuum pump drive).

Nomenclature

A – area, [m^2]
h – enthalpy, [kJkg^{-1}]
G – total solar irradiation, [Wm^{-2}]
g – gravitational acceleration, [ms^{-2}]
k – overall heat transfer coefficient, [Wm^{-2}K^{-1}]
$\dot{m}$ – mass flow, [kgs^{-1}]
p – pressure, [Pa]
$\dot{Q}$ – rate of heat flow, [W]
S – entropy, [Jkmol^{-1}K^{-1}]
ΔS_s – entropy increase due to irreversibility, [Jkmol^{-1}K^{-1}]
s – entropy, [Jkg^{-1}K^{-1}]
T – absolute temperature, [K]
T_o – standard temperature, [K]
t – temperature in Celsius, [°C]
v – specific volume, [m^{3}kg^{-1}]
w – wind velocity, [ms^{-1}]
w_f – specific frictional work, [Jkg^{-1}]
x – vapor quality, [–]
y – height, [m]

Greek symbols

α – convective heat transfer coefficient, [Wm^{-2}K^{-1}]
δ – thickness, [m]
λ – thermal conductivity, [Wm^{-1}K^{-1}]
η – efficiency, [–]

Subscripts

abs – absorber of radiant energy
c – condenser
coll – collector
d – distilled water
in – inner
hw – hot water
out – outer
OS – atmospheric environment
s – saturation
v – vapor

Superscripts

o – standard state
' – saturated liquid
" – saturated vapor

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