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VACUUM DESALINATION SYSTEM FOR SEAWATER AT LOW TEMPERATURES

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ABSTRACT

In this paper a proposed apparatus for seawater desalination at low temperature and low pressure is discussed. Based on the idea of Torricelli barometer, water vapor above seawater and water vapor above fresh water are forced to gather in a tube connecting the two water sources in nearly vacuum environment. Creating temperature difference between the two water sources develops large pressure difference between the saturated water vapor pressures above the two water sources. This pressure difference forces water vapor to move from the hotter seawater surface to condense in the cooler fresh water area. The apparatus automatically substitutes the evaporated seawater and transmits the fresh water to where it is needed, i.e. no energy is required to feed the apparatus with seawater or to transfer fresh water. The apparatus also automatically get rid of brine (more salty seawater due to evaporation) by replacing with fresh warm seawater. The variability of atmospheric surface pressure due to season change or the passage of atmospheric systems that can disturb the apparatus performance is also considered. The study indicates, theoretically, that this technique which was known to be suitable for small-scale freshwater needs can yield one order of magnitude larger than expected. Theoretically, it is shown that with the simple proposed apparatus, the estimated fresh water yield can be more than 10 m^3 per day. Experiments are required to test the idea.

Keywords: Vacuum desalination; Low temperature; Converging nozzles; Sonic flow.

1. INTRODUCTION

Fresh water is necessary for plants, animals, and human to survive. It is even essential for economic development. The increase in human population as well as the requirement for economic gross necessitates vast demand of fresh water. The gap between natural resources of fresh water and human demands increases. Part of the problem comes out due to human activities. In Middle East the problem is worst as the area is climatologically dry, beside most of fresh water sources come from areas outside its borders. On the other hand the oceans cover more than 70% of the earth's area. The demand to desalinate the seawater and (or) brackish water becomes a necessary choice. Historically sailors used to boil seawater to separate fresh water from salt, also clay are used as a filter to trap salt and (or) impurities. Today sophisticated techniques use these two ideas of distillation and filtration of seawater and brackish water to produce large amount of fresh water (Ullah and Rasul 2019; Giwa et al 2017; Ghaffour et al. 2013). In this paper a proposed apparatus for vacuum desalination of seawater at low temperature that is known to be suitable for small-scale freshwater needs is discussed (Rashid et al. 2016, Yessley and Mathews 2013; Muthunayagam et al. 2005; Gude and Nirmalakhandan 2009).

2- The proposed apparatus

Figure 1 shows the proposed apparatus that consists of two rooms 1 and 3 that are connected by the tube 7. Room 1 (0.5mx0.5mx0.3m) is raised by pipe 2 and Room 3 (1mx1m base dimension) is raised by five pipes 8 and 9 as clarified in Fig. 1(b). Other dimensions are clarified in the figure. Pipe 2 that raises room 1 is immersed in a tank of fresh water while the pipes raising room 3 are immersed in a lake of seawater. A stopcock "11" is located at the top of room 3 while each pipe has a stopcock at its lower end. A pressure sensor "5" is attached to each of the rooms 1 and 3, and a vacuum pump "6" is connected to room 1.

2-1 Apparatus set up

At the start all the stopcocks at the end of the pipes are closed while stopcock 11 is opened. Fresh water is then poured through 11 until full fill; this will need less than 1.5 cubic meters. Stopcock 11 is then closed and the stopcocks at the end of the pipes are opened. The water levels, which depend on atmospheric pressure, take approximately the heights shown in Fig. 1. The areas above seawater in both rooms 1 and 3 as well as the area inside tube 7 are then full with water vapor having pressure related to the water temperature, Fig. 2.

2-2 Apparatus operation

Heating the water surface in Room 3 to about 35°C and cooling the area of Room 1 to a value < 10°C (a value between 5°C and 10°C) creates pressure difference between the water vapor in the two Rooms >40 mb, see Table 1. This large pressure difference forces the water vapor in room 3 to move to room 1 where it condenses and comes out through the pipe 10. Both the levels of fresh water and seawater that depends only on atmospheric pressure remain constant. The evaporated water from room 3 is replaced from the seawater lake to preserve the height level that is only function of atmospheric pressure. This process persists as long as the temperature difference is maintained. As indicated in Fig. 1 solar energy can be used for heating the upper layer of water inside Room 3. Additional source of energy that can be generated from sun and wind is necessary to:

a- Heating the upper one meter of the pipes 9 to about 40°C, aiming to raise the sea water inside the pipes to 35°C. This heating is necessary to replace the evaporated surface water of Room 3 especially during night and cloudy days. This heating also causes seawater circulation in Room 3 where hot water rises from the heated tubes and cool brine water, due to evaporation, sink in pipe 8 (Fig. 1-b). This circulation is necessary to get rid of brine water that is replaced by fresh seawater.

b- Cooling the area inside Room 1 to temperature below 10°C. Note that the hot water vapor that comes from Room 3 require efficient cooling system to keep Room 1 temperature below 10°C.

As mentioned above seawater and fresh water levels depend only on atmospheric surface pressure. It is known that beside the small diurnal variation of surface pressure that is less than 5 mb, there is seasonal variation, Fig. 3, and the variation due to the passage of atmospheric systems that can lead to change of the order ±10 mb. Figure 3 shows that surface pressure has mean maximum value of about 1020 mb in January and mean minimum value around 1009 mb in July. There is also the effect of water vapor pressure that reduces the actual pressure inside the apparatus. One can estimate that atmospheric surface pressure has maximum value less than 1040 mb and minimum value larger than 950 mb. These two limits correspond to water level less than 10.6 meter and greater than 9.6 meter. The design of Fig. 1a takes the effect of these changes into consideration such that the level of seawater in Room 3 has minimum height of 10 cm and maximum height

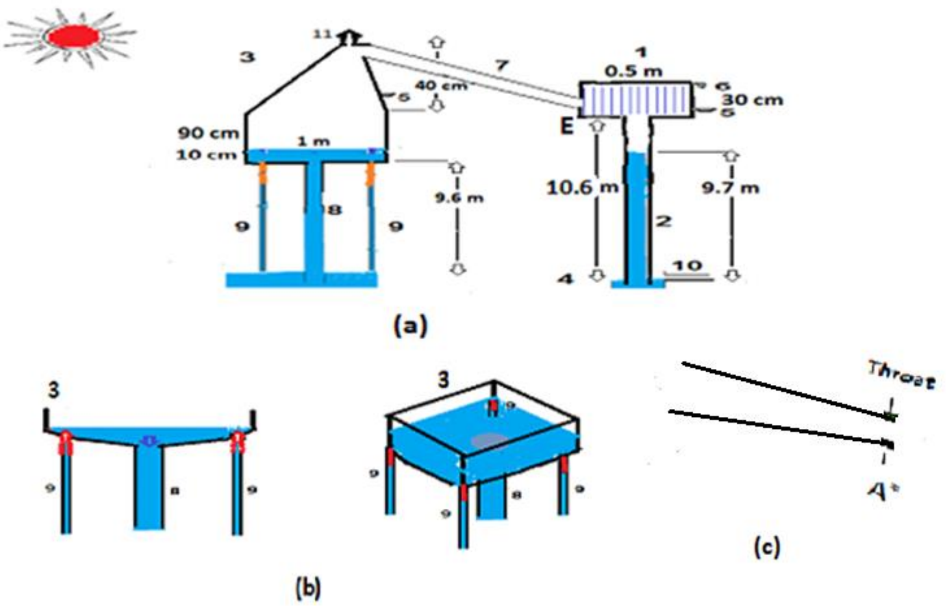

Fig. 1: (a) Apparatus; (b) Room 3 (c) converging nozzle.

less than one meter. On the other hand the height of fresh water does not exceed the length of pipe 2.

Table 1: Water temperature(0-35°C), saturated vapor pressure and vapor density

T °C	Saturated Vapor Pressure (mb)	Densityg/m³
0	6.1	4.9
5	8.7	6.9
10	12.3	9.6
15	17	13
20	23.4	17
25	31.7	23
30	42.5	30
35	56.3	43

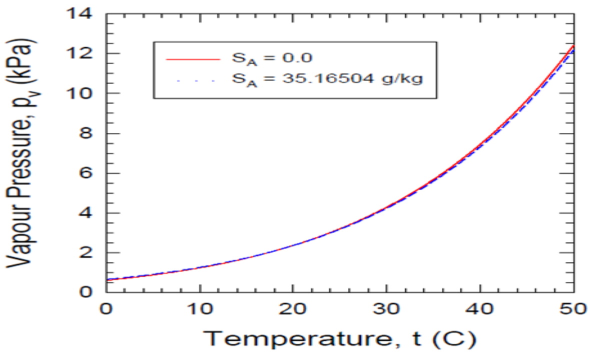

Fig.2: Water vapor pressure versus temperature for fresh (salt S_A=0.0) and seawater (salt S_A=35.16504 g/kg).

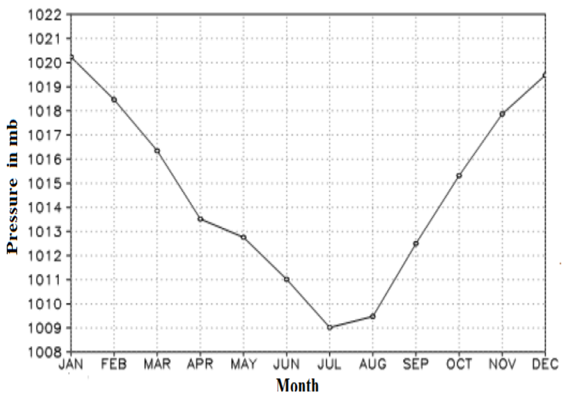

Figure 3: Monthly mean surface pressure over Egypt.

3- Expected fresh water yield

3-1 Theoretical estimation of fresh water yield

3-1a The first approach

The above idea for desalination depends on the transfer of water vapor, which is evaporated from brine at Room 3, to Room 1 due to pressure difference. The flow rate of water vapor "$\dot{m}$" can be estimated by the equation:

$$\dot{m} = V * \rho * A \qquad (1)$$

Where ρ is density of water vapor, A is the outlet area of Tube 7 connected to Room 1 marked E in Fig. 1a. V is the velocity developed due to the pressure difference between the two rooms. The pressure difference that leads to acceleration is given by:

$$\frac{dV}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial s} \qquad (2)$$

Since the pressure differences of water vapor as indicated by Table 1 is more than 4000 Pascal, the water vapor density in Room 3 is 0.043 kg/m³, and the tube 7 length $= 1.5\, m$, a very large acceleration is indicated by equation (1). Thus one expects that the water vapor velocity V^* can reach the sound velocity that is given by:

$$V^* = C = \sqrt{\gamma R T} \qquad (3)$$

C is sound velocity. For water vapor $\gamma = \frac{C_p}{C_v} = 1.33$, R=461 J/Kg K. Since Mach number M ($=\frac{V}{C}$) >0.3, the temperature "T" and density "ρ" of the water vapor gas is expected to be modified due to compressibility according to the relations (see for example Zucker and Biblarz, 2002):

$$\frac{T_0}{T^*} = \frac{\gamma - 1}{2} M^2 + 1 \qquad (4)$$

$$\frac{P_0}{P^*} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{\gamma}{\gamma-1}} \qquad (5)$$

$$\frac{\rho_0}{\rho^*} = \left[1 + \frac{\gamma - 1}{2} M^2\right]^{\frac{1}{\gamma-1}} \qquad (6)$$

Suffices 0 and * refer to background variables (at Room 3) and at E respectively. T_0=308K and $\rho_0 = 0.043\ \frac{Kg}{m^3}$. When M=1 the gas velocity reaches the sound wave, in this case T^* and ρ^* are obtained from (4) and (6); then (1) gives:

$$\dot{m} = 10.9 * A^{*} \frac{kg}{s} \qquad (7)$$

If A^*=78.54 cm^2 (circle with radius 5 cm)

then $\dot{m} = 0.0856 \frac{kg}{s} = 7.4 \frac{m^3}{day}$.

An important remark indicated by (7) is that the flow rate is function of A^* when other parameters are fixed. This remark is questionable since there is no guarantee that there is enough water vapor in Room 3 to continuously feed Room 1. In other words there must be another condition necessary to justify the yield. This point is discussed in section 4.

Since we need M=1 to obtain maximum yield, one can replace tube 7 by a converging nozzle to assure that V reach the velocity of sound; in this case the mass flow out of the throat, where cross section area is minimum, is known (Zucker and Biblarz, 2002). Theoretically there are three possibilities that need to be tested. The first is using a normal tube with constant cross section area as indicated in Fig. 1a. The second is to use a converging tube, Fig. 1c, to connect Room 3 and Room 1. The third is to use a convergent-divergence tube where the throat will be between the two ends of the tube. Since no experimental tests are performed due to lack of capability, I will theoretically estimate the maximum fresh water yield. If we assume that water vapor in the area up to the throat is a perfect gas and the effect of friction force is negligible, which are acceptable postulates especially when dealing with low pressure area. Also, assuming that the process is adiabatic, up to the throat, since the gas is isolated then one can assume that the process is isentropic. There are many research papers dealing with the onset of condensation for a wet sonic steam flowing through converging nozzle or a divergent-convergent nozzle (see for example Yang et al. 2019, Farag et al. 2015, Ding et al. 2015, Dykas et al. 2016). Figure 4 shows a typical result for the behavior of wet steam as it flows through a convergence-divergence nozzle. The figure indicates that, as the steam is accelerated in the nozzle temperature and pressure fall in accord with supersonic expansion. Droplets formation due to cooling leads to energy release that tries to reestablish equilibrium state. The release of energy disturbs the decreasing pressure as indicated in the figure. The figure reveals that wetness commences after the throat. In the following it is assumed that wetness starts after the throat.

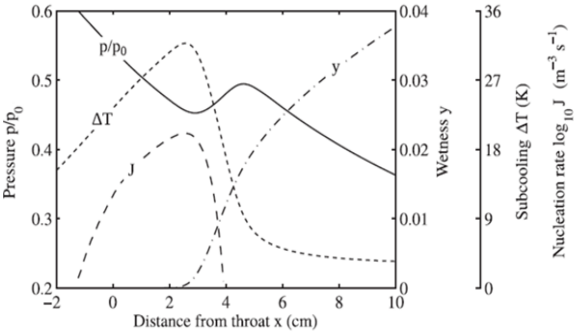

Fig. 4: Typical behavior of sonic wet steam through converging-diverging nozzle. (After Starzmann et al. 2018)

3-1b The second approach

As mentioned above compressible gas laws should be applied. To assure sonic flow converging tube can be used instead of the tube 7, Fig. 1c. In what follows any variable at the throat is assigned an upper suffix (*). In this case we can design the tube to assure that Mach number M=1 at the throat where the cross section area is A^*. The velocity of the water vapor gas that flows through the throat will have the sound speed given by:

$$V^{*} = C = \sqrt{\gamma R T^{*}}$$

In this case the flow of water vapor "$\dot{m}$" from Room 3 through the throat, that depends only on the condition of Room 3 is given by the equation (see for example Zucker and Biblarz, 2002):

$$\dot{m} = P_0 A^{*} \sqrt{\frac{\gamma}{RT_0}} M \left(1 + \frac{\gamma - 1}{2} M^2\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \qquad (8)$$

One can show that the maximum flow of water vapor as indicated by (8) occurs when M=1 provided that the values of the other parameters are constant. Substituting the background values in (8) when M=1 gives:

$$\dot{m} \sim 10.04 A^{*} \frac{kg}{s} \qquad (9)$$

If A^*=78.54 cm^2 (circle with radius 5 cm), then:

$$\dot{m} \sim 0.07885 \frac{kg}{s} \sim 6.8 \frac{m^3}{day}$$

Note that the fresh water yield is of the same order as the first approach. Equation (9) indicates that one can increase the fresh water yield by increasing the area of the throat. The important question that arises, is there enough water vapor available in Room 3 to continually feed Room 1 by the required amount?

4- Necessary condition for estimating fresh water yield

To derive this condition an experiment by Augusto, 2013 (referred after as A13) is discussed. A13 studied the behavior of water vapor in closed chamber system displayed in Fig.5. The system comprises three major components: a vaporization chamber (VC); a vacuum pump (VP) and a vapor condenser (CD). The chamber VC that has cross section area of 0.015 m^2 and height 1.1 m contains 1.5 kg of water that occupies the volume CV1 as shown in the figure. The water temperature is initially 25°C. The volume CV2 that has initially air has the same water temperature and normal atmospheric pressure (about 1013 mb). As illustrated in Fig. 5 sensors for measuring temperature and pressure are attached and data are stored. Vacuum pump is attached to evacuate air from CV2 and condenser to condense water vapor evaporated from CV1.

A13 experiment starts by reducing the pressure in CV2 by the vacuum pump. In the initial stage, while the pressure in CV2 is reduced, but above the saturation pressure of water, no significant change for the water temperature occurs. This is because evaporation at the free water surface is ruled by diffusion of water vapor in the still air in the chamber. Since the amount of water vapor evaporated in this stage is relatively small, the energy of vaporization that is extracted from the water is small and thus no significant temperature change occurs. As the pressure in CV2 reaches the water saturation pressure, the water in CV1 starts boiling (known as flash point). In this case considerable amount of water evaporates and significant energy (energy of vaporization) is taken from the water. The liquid water temperature in CV1 starts to drop significantly as well as the saturation water vapor. A13 discusses the output data from the experiment. What is of interest to us from A13 work is Fig. 6. The figure displays the time evolution of water vapor flux, water temperature, pressure in CV2, water vapor pressure in CV2. As one can notice during the first 23 seconds of the experiment, when the pressure in CV2 is larger than the saturated water vapor pressure, the water temperature did not change (Fig. 6a) as well as water vapor pressure (Fig. 6b) and water vapor flux (Fig. 6c). On the other hand, total pressure in CV2 decreases sharply as the vacuum pump removes out air from CV2 (Fig. 6d). After the first period and as the pressure in CV2 reaches the value of the saturated water pressure (flash point) of the water in CV1 which is only function of the water temperature, abrupt changes occur. Figure 6 shows, at the flash point, significant decrease of water temperature, significant jump of water vapor pressure to the value of the saturated water vapor, and significant jump of water vapor flux (Figs.6a, 6b, and 6c). Continuous decrease of vapor pressure, saturated vapor pressure, and water vapor flux occur after this jump.

What is interesting to our work is Fig. 6c. The figure indicates that the maximum flux of water vapor is about 1.2x10^{-3} kg/s under the conditions prescribed above. A13 through many experiments show that:

1- The maximum flux of water vapor is function of water temperature as well as the water volume.

2- The initial volume (temperature) of the water is negatively (positively) proportional with the magnitude of the drop of water temperature after the flash point with initial volume being much more effective.

3- The larger is the initial volume of the water, the higher is the superheating degree and consequently the rate of water vapor evaporation.

A13 experiment, Fig. 4, that led to the water vapor flux in Fig. 6c has 1.5 kg of water at 25°C. The water surface area is 0.015 m^2 and the maximum flux as indicated by Fig. 6c is 1.2x10^{-3} kg/s that corresponds to the evaporation of thickness layer 0.08 mm/s. The water mass in Room 3, Fig. 1a, is more than 100 kg with water surface heated to 35°C. From A13 experiments one can speculate that the maximum flux of water vapor obtained by the apparatus displayed in Fig. 1a will be more than $50*1.2x10^{-3}$ kg/s. This value corresponds to the evaporation of about 0.06 mm/s from the water surface in Room 3. If it is assumed that the amount of water vapor that will flows to Room 1 from Room 3 is $50*1.2x10^{-3}$ = 0.06 kg/s, then the fresh water yield is expected to be about $5m^3$/day. On the other hand, the yield of fresh water obtained in section 3-1b is about 7 m^3/day. One can conclude that the area of the throat assumed in section 3-1b should be reduced such that fresh water yield is 5 m^3/day. One can easily show that to get the possible 5 m^3/day yield according to the above discussion A^* must be about 57.64cm^2 (circle with radius about 4 cm). This yield can be increased by increasing the surface area of Room 3. For example, if the Room 3 floor is 2mx2m instead of 1mx1m the yield will be about $20m^3$/day and A^* about 230 cm^2 (circle with radius 8.5 cm).

It should be noted that the amount of fresh water that is expected to condense in Room 1 is cannot be reduced. Vacuum pump 6 that is attached to Room 1 will remove out any excess of water vapor plus any dissolved gases that come out from seawater.

The challenge is to keep the surface temperature for seawater in Room 3 at 35°C and the area inside Room 1 at temperature between 5°C to 10°C. For this purpose, the water in the upper one meters of pipes 9 are heated to about 40°C (so that the sea water inside this part of the pipes is about 35°C) to continuously replace the evaporated water. As indicated above, fresh water yield can be 5 m^3/day for the parameter stated in section 3-1b when the throat section is 57.64 cm^2. In this case the amount of water that is evaporated each second is about 58 grams. If the pipe 9 diameters are 6 cm then each pipe of the 4 pipes will contain about 2800 grams of water at 35°C. In this case there is enough heated water to replace the evaporated layer for about 3 minutes. If the three minutes is enough to reheat the water inside the upper one meter of the four pipes to 35°C, then the process of desalination will continue otherwise we should

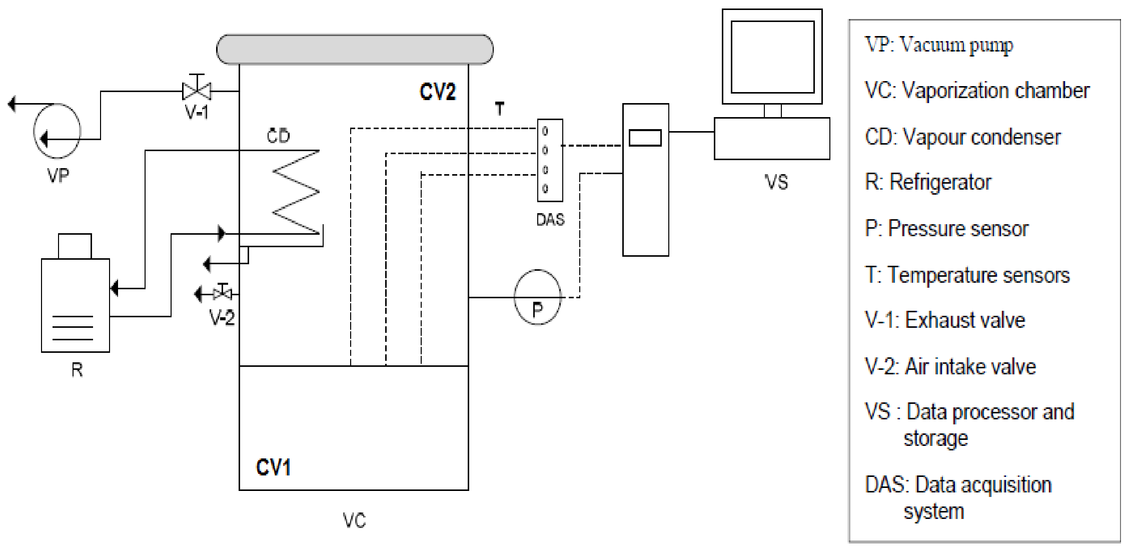

Fig. 5: Schematic diagram of a low-pressure system used by Augusto 2013.

only 84% (77.7%) of what estimated above if Room 1 temperature is 5°C (10°C). This is because at Room 1 temperature 5°C (10°C) the saturated water vapor pressure 8.7mb (12.3mb) increase the length of heated part of pipes 9 or change these pipes with pipes having larger diameters.

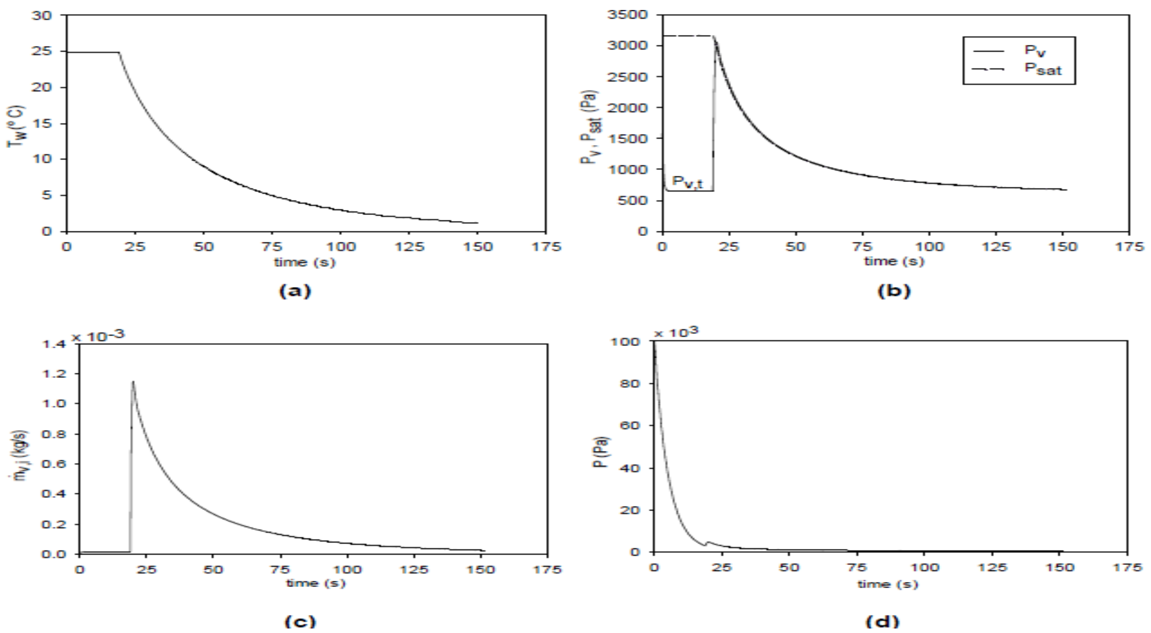

Fig. 6: Evolution of: (a) water temperature (T_w) in CV1; (b) water vapor pressure in CV1 (P_v), solid line and saturation water pressure (P_{sat}) dashed line in Pa. (c) Water vapor flux $(\dot{m}_v)$ in Kg/s. (d) Pressure in CV2 in Pa.(After Augusto 2013)

5- SUMMARY AND CONCLUSION

An apparatus for seawater desalination at low temperature (~ 35°C) and low pressure (< 100 mb) is considered. The apparatus consists of two containers that are almost evacuated from air and connected by a tube. One of the containers is raised by a tube that is immersed in fresh water tank. The other container is raised by five tubes that are immersed in Seawater Lake. The heights of the tubes are about 10 meters. Heating the surface of seawater to about 35°C and cooling the environment above the fresh water to about 5°C creates large pressure difference between the two containers. As a result vapor is forced to flow towards the fresh water container where it condenses and comes out from a tube attached to the fresh water tank. Automatically, the seawater is compensated from the seawater lake. The process continues without height levels change for both seawater and fresh water. Theoretically, it is shown that with the simple proposed apparatus, the estimated fresh water yield can be more than 10 m^3 per day.

The system of heating the seawater causes circulation that feed fresh brine and removes old brine that is more salty due to evaporation. The apparatus, also, takes into account the variability of surface pressure that can affect the water height with a value around 90 cm. This pressure change is due to season and (or) the passage of atmospheric high and low pressure systems. Heating the seawater surface is achieved by sun energy. Additional source of energy is required to create the brine circulation; cooling the environment above the fresh water container and heating the brine surface at night and during cloudy days. Sun and wind energies are possible suppliers to that energy.

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نظام لتحليه مياه البحر عند حرارة منخفضة

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الملخص العربى

مقدم فى هذا البحث مقترح لجهاز تحلية مياه البحر عند حرارة وضغط منخفضتان. الجهاز المقترح يتكون من وعائين مفرغين من الهواء تقريبا ومتصلين بإنبوب مخروطى الشكل. أحد الوعائين مرفوع بأنبوب مغمور فى مياه عذبة والآخر مرفوع بخمس أنابيب مغمورة فى مياه مالحة. إرتفاع الأنابيب حوالى عشرة أمتار. يتم تسخين سطح الماء المالح عن طريق تسخين الجزء العلوى لأربعة من الأنابيب الحاملة للوعاء الذى يحوى مياه البحر بالإضافة الى التسخين بالطاقة الشمسية لتكون حرارة سطح الماء المالح حوالى 35 درجة مئوية ويتم إحلالها تلقائيا عن طريق الماء الساخن من الأنابيب الأربعة. كذلك يتم تبريد شبه الفراغ فى الغرفة الأخرى التى تعلو الماء العذب الى حوالى 5 درجات مئوية . فى هذه الحالة يحدث فرق كبير فى ضغط بخار الماء بين الغرفتين مما يتسبب فى تدفق بخار الماء من الغرفة الدافئة إلى الغرفة الباردة حيث يتكثف ويخرج ماء عذب من الأنبوب أسفل الغرفة تلقائيا إلى حيث يراد. مستوى سطح الماء بالغرفتين يبقى ثابتا حيث يعتمد فقط على الضغط الجوى. الماء زائد الملوحة والذى تنخفض حرارته بسبب التبخير يخرج من الإنبوب الخامس الذى يتوسط قاعدة غرفة الماء المالح بسبب حدوث دورة يرتفع فيها الماء المالح الساخن من الأربع أنابيب التى تم تسخينها ونزول الماء الأكثر ملوحة البارد (بسبب التبخير) من الإنبوب الخامس وسط قاعدة إناء الماء المالح.

نموذج الجهاز المقترح يأخذ فى الإعتبار التغير فى الضغط الجوى اليومى، الفصلى، وكذا بسبب مرور المرتفعات والمنخفضات الجوية والتى تتسبب فى تغير إرتفاع سطح الماء بأكثر من نصف متر. ولذلك فمن المتوقع أن يعمل الجهاز بكفاءة فى جميع الظروف. هذه الدراسة أوضحت أن تحلية المياه عن طريق التبخير تحت ظروف منخفضة من الحرارة والضغط والمعروف أنها مناسبة لإنتاج كمية محدودة من المياة العذبة يمكن أن تعطى كميات كبيرة من المياه المحلاه. فى هذه الورقة تم نظريا حساب كمية المياه العذبة التى يمكن حصادها بإستخدام الجهاز البسيط المقترح والتى قدرت بأكثر من 10 متر مكب يوميا. يبقى أهمية إختبار هذه الطريقة وحساب تكلفة تحلية المتر المكعب (الجدوى الإقتصادية).