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PASSIVE RADIATIVE CONDENSERS TO EXTRACT WATER FROM AIR

Uređaji za ukapljivanje vodene pare iz okolnog zraka

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ABSTRACT: Radiative cooling allows atmospheric vapor to be condensed on a surface without an energy source. Data on atmospheric dew water condensers are presented, with emphasis on their application to islands and deserts where drinking water can be scarce. The chemical and bacteriological quality of water is also reported upon. The areas presently under investigation are situated in a variety of regions: continental (Grenoble - in an alpine valley; Brive-la-Gaillarde, Central Massif), coastal (Bordeaux - on the French Atlantic coast, and Zadar and Dubrovnik - on the eastern Adriatic coast), desert (Nizzana, NW Negev), the Mediterranean islands (Ajaccio on Corsica and Komiža on Vis in the Adriatic sea) and the Pacific Ocean (Tahiti, French Polynesia). In Ajaccio, two large 30 m^2 condensers have been operating since 2000.

Key words: radiative cooling, atmospheric vapor, condensation, dew, OPUR, water condenser, chemical and bacteriological quality of water

SAŽETAK: Uslijed hlađenja, nastalog noćnim zračenjem, na površinama dolazi do ukapljivanja vodene pare iz okolnog zraka, bez utroška energije. U radu su prikazani podaci o jačini rose i količini tako nastale vode iz rose i njenoj primjeni u pustinjama i na otocima gdje postoji oskudica pitke vode. Obavljena je kemijska i bakteriološka analiza dobivene vode. Promatrana su područja u različitim regijama: kontinentalnima (Grenoble u Alpama, Brive-la-Gaillarde, Central Massif), obalnima uz Atlantik (Bordeaux), uz obalu Mediterana (Zadar, Dubrovnik), pustinjskima (Nizzana, sjeverozapadni Negev), i na mediteranskim otocima (Ajaccio, Korzika), jadranskim otocima (Komiža, Vis) i na Tihom oceanu (Tahiti, Francuska Polinezija). Na Korzici su, u Ajacciu, dva instrumenta za mjerenje rose, svaki površine 30 m^2, u upotrebi od 2000. god.

Ključne riječi: radijacijsko hlađenje, vodena para, kondenzacija, rosa, OPUR, instrument za ukapljivanje rose, kemijska i bakteriološka kvaliteta vode

1. INTRODUCTION

The past century has been witness to several attempts to recover water from air. In literature, studies can be found on so-called "air wells" and "dew ponds" (Jumikis, 1965; Beysens, 2000) (the latter, however, capturing mist, Martin, 1909). The most famous air wells date from the pebble dew collector by Zibold (1912) in Feodosia, Crimea, which claimed to have once attained 360 $lday^{-1}$ (Milimouk, 1995). Further attempts by Chaptal (1932) and Knapen (1929) in France, using the same technique, produced very low yields except on very rare occasions. One should also note the interesting study of Awanou and Hazoume (1997) on dew produced in conic holes in the ground. Beysens and co-workers (Beysens, 1996; Nikolayev, 1996), who investigated the Zibold collector, showed that the low yield of such massive condensers was due to the difficulty in their reaching a temperature below the air dew point, as opposed to light-weight dew condensers that cool under a radiative process and can obtain much higher yields. This yield is limited by the cooling power, which lies in the range of 25 to 250 Wm^{-2} for clear skies, restraining the dew water yield to less than 1 lm^{-2} per night, taking into account the water latent heat of condensation (2500 Jg^{-1} at 20°C). Thus a surface of 100 x 100 m^2 can yield 10,000 l per night as a maximum. Even though, in practice, naturally-occurring dew does not exceed 0.5 lm^{-2} per night (h = 0.5 mm of equivalent precipitation), the dream to recover water from air is not an illusion. It is worthy to note that such water production, using radiative cooling, permits atmospheric vapor to be condensed on a surface without the need for an energy source.

Several experiments were carried out to improve the cooling material. The foil investigated by Nilsson and Vargas (Vargas, 1998; Nilsson, 1996) is an excellent compromise, as it radiates long-wave, nearly as a black body, and reflects visible light. This was coupled with the testing of ways to lower thermal losses by isolating the material on one side and by a design set-up reducing the negative effect of the wind. This is especially important for island condensers where the wind is often strong (Muselli, 2002). Finally, it was necessary to determine how best to recover the water drops by gravity.

Another aspect of this research involves studies in places where dew is naturally abundant but where other water resources are scarce. The areas presently under investigation are situated in a variety of regions: continental (Grenoble, in a French alpine valley), coastal (Bordeaux, France), Mediterranean (Zadar, Croatia), desert (Nizzana, NW Negev, Israel) Mediterranean islands (Ajaccio, Corsica), Adriatic islands (Vis, Komiža) and the Pacific ocean (Tahiti).

2. TESTING OF RADIATIVE DEW CONDENSERS

In the study on dew formation (Monteith, 1957; Beysens, 1995), meteorological parameters such as air temperature, air humidity (dew temperature) and sky radiation (cloud cover) are imposed parameters. However, to increase the yield of dew harvesting, it is possible to (i) maximize the emitting properties of the condensing surface (using a special foil), (ii) minimize the wind velocity on the foil, (iii) increase the condensation time, and (iv) recover most of the water drops.

The foil used in this study was made of microspheres of TiO_2 and $BaSO_4$ embedded in a sheet of polyethylene. This material is discussed by Vargas et al. (1998) and explains how the foil improves the emitting properties in the near infrared (to provide radiation cooling of room temperature surfaces) and how efficiently it reflects the visible (sun) light.

Weak wind (<1ms^{-1}) is necessary to bring humid air around the condenser. Strong wind, which increases heat losses, cancels the radiative cooling. Numerical and experimental studies by Beysens et al. (2003-a) were performed with a model at 1/10 scale, 1 x 0.3 m^2. This model condenser was made with the above foil put on a 3 cm thick polystyrene foam-insulating layer, and different angles from horizontal were investigated and compared with a reference plate. This reference plate was made of 5 mm thick, 0.4 x 0.4 m^2 plate of PMMA (Plexiglas), placed on a thermally insulated mount formed of 12.5 μm thick aluminum foil and a 5 mm thick sheet of polystyrene foam (Fig. 1), itself set on an electronic balance. In order to lower heat losses due to wind and also to recover water drops by gravity, the best angle with respect to horizontal appeared to be 30°.

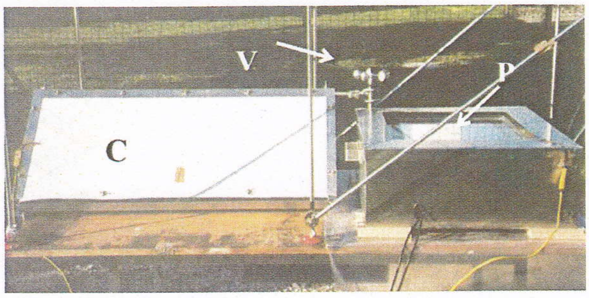


Figure1. Dew study in Grenoble. P: Plexiglas plate on an electronic Mettler Toledo balance. V: wind measurement. C: condenser model (1 x 0.3 m^2) with varying angle from horizontal.

Slika 1. Mjerenje vode od rose u Grenobleu na ploči od pleksiglasa na elektronskoj vagi Mettler-Toledo. V: mjerač vjetra, C: rosno ukapljivalo (1 x 0.3 m^2), postavljeni pod različitim nagibima prema tlu.

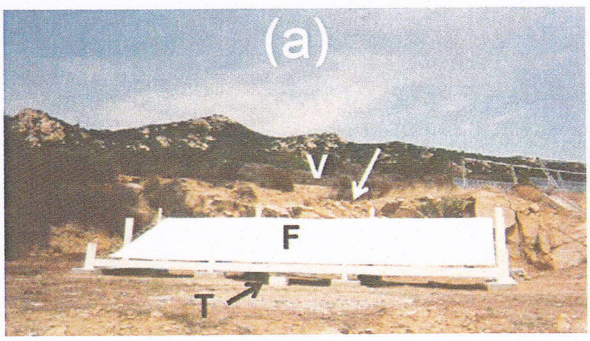
According to these initial studies, two 10 x 3 m^2 plane condensers have been established (Fig. 2) on the side of a hill. The site is in the Ajaccio Gulf (Corsica island, France; 41° 55' N; 8° 48' E), 400 m from the sea at 70 m elevation, on the mid-slope of a hill. The wind regime is characterized by a nocturnal wind with a NE dominant direction (1.8 ms^{-1} average) but with two diurnal dominant wind directions (NW and SW), characteristic of a Mediterranean island climate.

In the first condenser, the foil is fixed by lateral cables on a light grid attached by cables (Fig. 2a). The cables are fixed to beams anchored to the ground. There are 3 cm thick polystyrene foam plates sandwiched between the foil and the grid to provide thermal insulation. Water is gathered by gutters into a 25 l polyethylene tank. The hollow part of the device faces the direction of the dominant nocturnal wind (Fig. 2a-b). The condenser faces SW to remain shaded longer in the morning. It is precisely in the early morning that the air temperature is the lowest, thus closest to the dew-point temperature, favoring dew condensation. With such a configuration, we experienced dew formation even in the daytime, as long as the sun did not directly irradiate the foil.

The second condenser is similar to the former, however it is constructed on a firm sloping surface with proper insulation (Fig. 2b).

We compared the data obtained on the condenser and from a nearby reference plate located within 40 m on a terrace at 7 m above the ground. The reference plate was as previously described: 5 mm thick, 0.4 x 0.4 m^2 thermally isolated Plexiglas on an electronic balance. Dew point temperature, air temperature, wind velocity (at 10 cm above the plate) and wind direction (at 3 m above the plate and 10 m above the ground) were measured every 15 minutes. During the period July 22, 2000 – November 11, 2001 (478 days), we experienced 145 dew days for the reference plate (30%) and 214 dew days for the condenser (45%). The condenser yield was 767 l corresponding to an average of 3.6 l (0.12 mm) per dew day. The maximum yield in the period was 11.4 l (0.38 mm) (Muselli, 2002).

A comparison of the histograms of dew volumes obtained both on the reference plate and the condenser (Fig. 3) shows that the yield of both condensers is equivalent and significantly greater with respect to a simple PMMA plate. In particular, dew gained by using such a condenser does not correspond to the smallest events but to an increase in dew yield for average and large values.



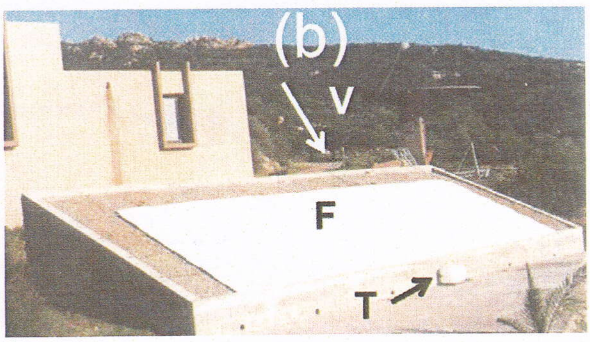


Figure 2. The 3x10 m^2 dew condensers at Ajaccio (Corsica island, France). F: foil; T: water collection tank; V: night wind.(a): elevation condenser; (b) ground condenser.

Slika 2. Rosno ukapljivalo 3 x 10 m^2 u Ajacciu na Korzici, F - folija, T - spremnik vode, V - noćni vjetar. (a) instrument iznad tla (b) instrument na tlu.

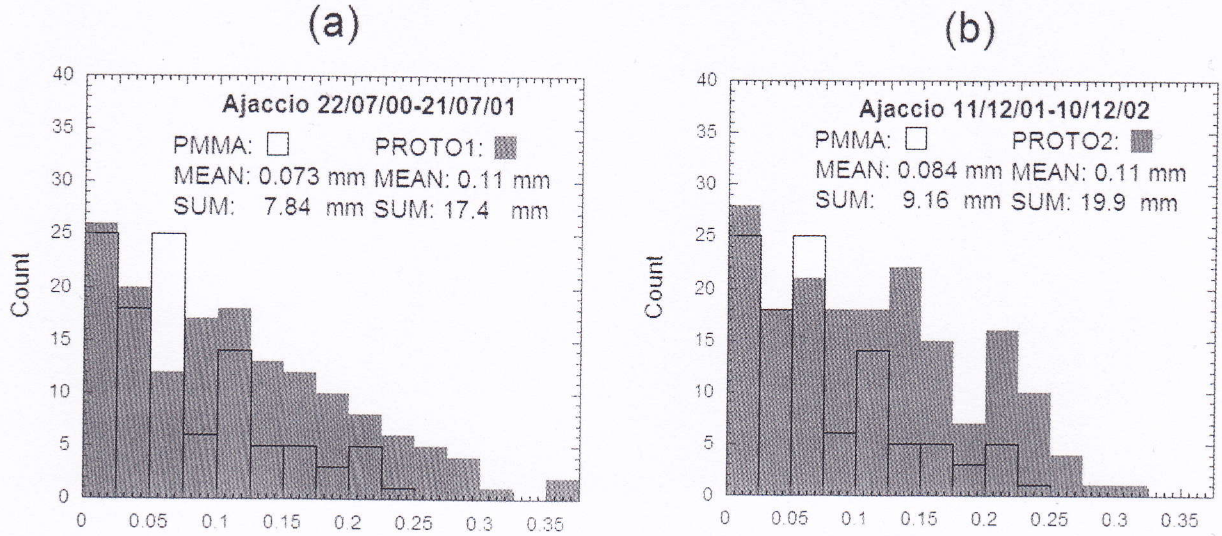


Figure 3. Comparison of water yields between the (a) Ajaccio elevation condenser from 22 Jul. 2000 – 11 Nov. 2001 and (b) Ajaccio ground condenser from 10 Dec. 2001 – 22 May 2002. All data are compared to the PMMA reference plate during the same period. "SUM" is the 1-year cumulated dew yield.

Slika 3. Usporedba količine vode dobivena u Ajaccio (a) ukapljivalom nad tlom u razdoblju od 22. srpnja 2000. do 11. studenog. 2001. i (b), ukapljivalom nad tlom u razdoblju od 10. prosinca 2001. do 22. svibnja 2002. Svi su podaci uspoređeni s referentnom plohom u istom razdoblju. SUM jest jednogodišnja količina vode od rose.

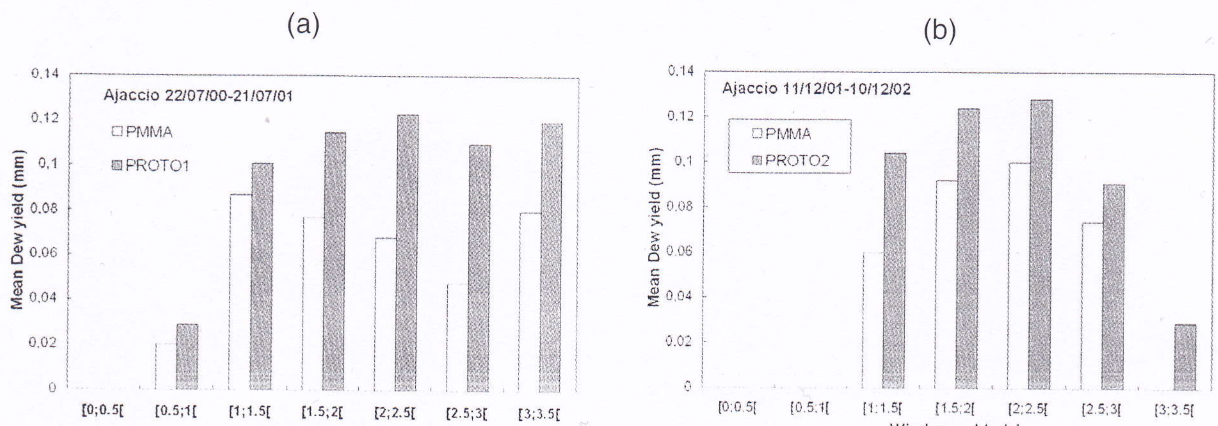


Figure 4. Dew yield in the elevation (P1), ground (P2) and PMMA plate (PMMA) condensers with respect to wind speed as measured at 10 m above the ground. (a) P1 between 22 July 2000 and 21 July 2001, (b) P2 between 11 December 2001 and 10 December 2002.

Slika 4. Podaci o količini vode od rose dobiveni na pokusnom poligonu na ukapljivalima iznad tla (P1), na tlu (P2) i PMMA-ploči (PMMA) u odnosu na brzinu vjetra mjerenu na visini od 10 m iznad tla. (a) P1 između 22. srpnja 2000. i 21. srpnja 2001., (b) P2 između 11. prosinca 2001 i 10. prosinca 2002.

It is also interesting to compare the dew yield with respect to wind velocity. This is an important aspect because winds are often strong on islands. Figure 4 shows that a high dew yield can be obtained with such condensers even with wind speeds as high as 3 ms^{1}. The gain is 40% higher than on a simple plate.

Nikolayev et al. (1996) proposed a method to determine the amount of condensed dew from the measurement of only a few parameters: surface (Tc) and ambient air (Ta) temperatures, air humidity, cloud cover N (in octets) and wind velocity V. When fitting the data, it appears that the ideal heat and mass transfer coefficient is not representative of the transfer under actual conditions. In order to account of these particular situations, Nikolayev et al. (2001) and Beysens et al. (2003-b) introduced two new numerical factors that correct the transfers (k for the heat transfer and g for the mass transfer). Fitting the surface temperature data gives k, and fitting the mass data gives g. These numerical factors are constant for a given condenser and are determined experimentally. In particular, a study of dew yield in different locations (Ajaccio, Bordeaux, Grenoble) with the same PMMA plate condenser shows that k and g do not vary much around $k = 2.9$ and $g = 0.21$. These numbers are different for a 30° tilted foil condenser as reported in Figure 5: $k \approx 1.3$, $g \approx 1$, meaning that the heat transfer is reduced and the mass transfer increased, leading effectively to a higher dew yield.

Figure 5a contains a fit of the condenser surface temperature ($k = 1.12$) and dew mass ($g = 0.74$) on the PMMA plate, and the fit obtained on the foil condenser ($k = 1.51$, $g = 1.15$) in Ajaccio. For the latter, the dew mass was measured at the beginning of dew condensation and at the time of dew collection.

3. POTENTIAL DEW PRODUCTION

At present, there is no universally accepted or standard method to measure dew. Indeed, dew is not really an atmospheric precipitation as it depends on the precise properties of the condensing surface. Nevertheless, it is important to compare potential dew water production in different regions. For the sake of comparison, we considered dew mass condensed on thermally isolated PMMA (see above) as a standard whenever possible (Grenoble, Ajaccio, Bordeaux). In some places, thermally isolated foil was used to condense dew (Ajaccio, Bordeaux, Brive, Nizzana). In other places, semi-quantitative measurements of dew on grass were performed with a scale ranging from 0 to 2: 0 (no or little dew < 0.05 mm), 1 (mean dew ≈ 0.05 - 0.15 mm), 2 (high dew > 0.15 mm) (Zadar, Dubrovnik, Komiža). When no direct measurements are available (e.g. Tahiti), an estimation can be made based on the amplitude of the difference between air temperature Ta and dew temperature Td as calculated from Ta and relative humidity. The following approximate relation, with Ta

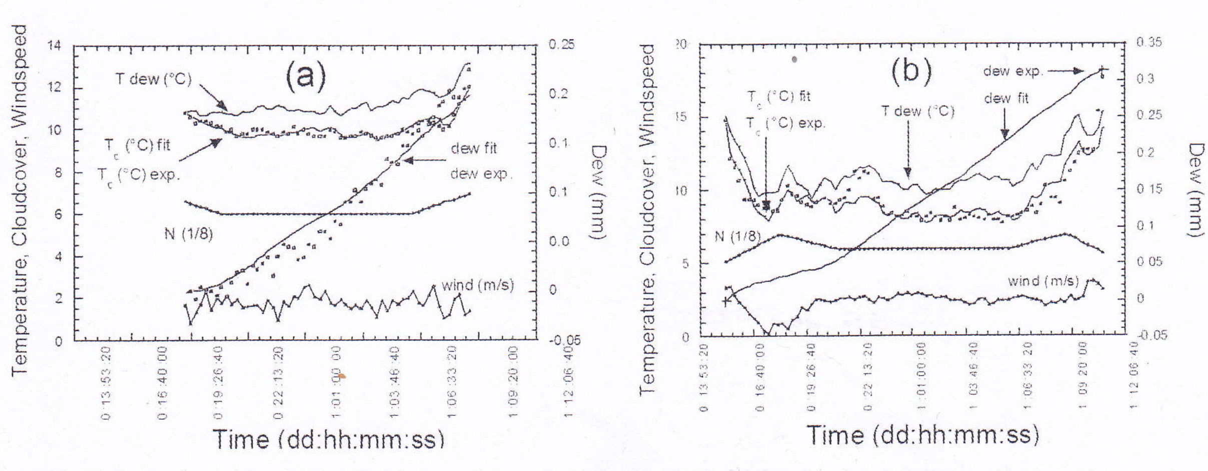


Figure 5. Example of a data fit (night 13–14 December 2000, Ajaccio). Data were recorded every 15 minutes. (a): PMMA reference plate, with $k = 1.12$ and $g = 0.74$. (b) Foil condenser, with $k = 1.51$ and $g = 1.15$. The dew mass (+) was measured at the beginning and the end of condensation.

Slika 5. Podaci kod pokusnog mjerenja (u noći 13/14. prosinca 2000, Ajaccio). Mjerenja su se obavljala svakih 15 minuta. (a): PMMA referentna ploča s $k = 1.12$ i $g = 0.74$. (b) Ukapljivalo rose s folijom $k = 1.51$ i $g = 1.15$. Količina rosne vode (+) mjerena na početku i na kraju ukapljivanja.

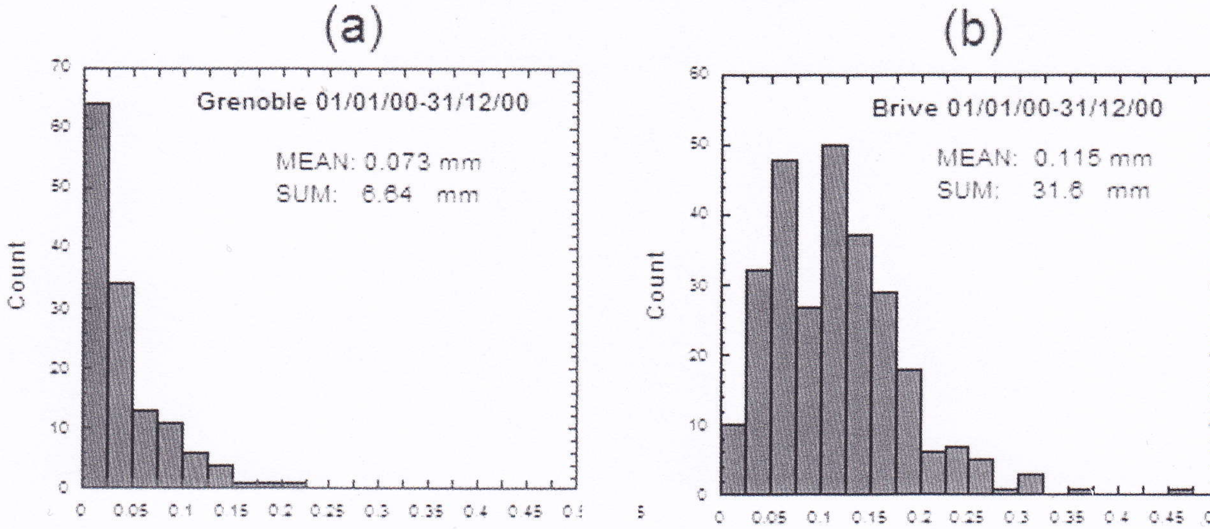


Figure 6: One-year dew histogram on two continental sites. The mean and cumulated values (sum) are also shown (a) Glacier alpine valley: Grenoble (45°11' N, 5°42' E) approximately 215 m a.s.l. Dew on PMMA. (b) West of the Central Massif volcanic area: Brive-la-Gaillarde 45°14' N, 1°22' E) approximately 150 m a.s.l. Dew on 1 m^2 foil.

Slika 6. Histogram prikazuje količinu vode od rose dobivenu tijekom jedne godine na dvije kontinentalne lokacije. Prikazane su srednje i kumulativne vrijednosti (sum). (a) Ledenjačka alpska dolina Grenoble (45°11' N, 5°42' E) oko 215 m nadmorske visine. Rosa na PMMA. (b) Zapadno od Central Massifa u vulkanskom predjelu Francuske Brive-la-Gaillarde 45°14' N, 1°22' E) na oko 150 m nadmorske visine. Rosa izmjerena na foliji površine l m^2.

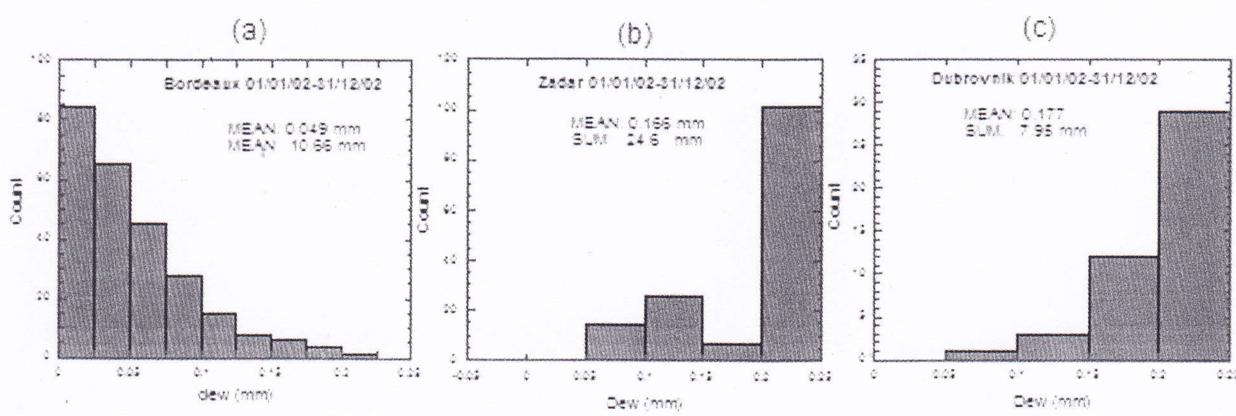


Figure 7. One-year dew histogram on three coastal areas. The mean and cumulated values (sum) are also shown (a) Ocean coast: Bordeaux (Pessac: 44° 47'45'' , 0°39'29'' W) approximately 17 m a.s.l. Dew on PMMA. (b-c) Mediterranean Adriatic coast of Croatia. Dew on grass with levels 0 - 1 - 2. (b) Zadar (44°8' N, 15°13' E) approximately 11 m a.s.l. (c) Dubrovnik (42°39' N, 18°5' E) approximately 10 m a.s.l.

Slika 7. Histogram prikazuje količinu rose dobivenu tijekom jedne godine na tri lokacije na priobalju. Prikazane su srednje i kumulativne vrijednosti (sum). (a) Obala oceana: Bordeaux (Pessac: 44°47'45'' N, 0°39'29'' W) na oko 17 m nadmorske visine. Rosa na PMMA. (b-c) Mediteranska jadranska obala u Hrvatskoj. Rosa na travi jačine 0-1-2. (b) Zadar (44°8' N, 15°13' E) na oko 11 m nadmorske visine. (c) Dubrovnik (42°39' N, 18°5' E) na oko 10 m iznad mora.

and *Td* in °C, gives a reasonable estimation of dew occurrence (but obviously not the dew yield):

$$h \sim (Td - Ta + 3) \text{ if } Td < Ta - 3\text{; otherwise } h = 0 \quad (1)$$

This relation simply expresses that dew forms when radiative cooling of the reference plate brings the plate temperature 3°C below air temperature. Below are some data.

3.1. Continental

According to Figure 6, the yield in Grenoble is markedly lower than the yield in Brive. This is because of lower humidity and smaller atmospheric transparency in this industrial valley.

3.2. Coastal

In Figure 7 the mean dew yield is important. The lower oceanic yield compared to the Mediterranean yield is presumably due to the higher amount and greater frequency of cloud cover near the ocean. Also the shape of the histogram is markedly different, with many high yield events. This is a very surprising result, to be confirmed with more quantitative measurements. Note that although the mean yield in Dubrovnik is slightly greater than in Zadar, the number of events is much smaller, making smaller the cumulated dew yield ("sum").

3.3. Islands

The number of events and the dew yield is important on islands (Fig. 8), due presumably to high humidity and good atmosphere transparency in spite of higher winds.

3.4. Desert

Deserts are characterized by lower humidity and high atmospheric transparency. Apart from being used as a source of drinking water, here dew can play a special role in the ecosystems as a regular source of water for small animals, plants, and biological crusts. Preliminary measurements (Tab. 1) show that even in mid-summer significant dew amounts can be collected, despite the shorter evening period available for radiative cooling. Dew water can thus be important, as shown in Table 1.

4. CHEMICAL AND BACTERIOLOGICAL QUALITY OF WATER

Dew water chemistry is dependent on the precise collector location as dew is generally the condensation of local vapor. Dew, coming from a condensation process, is generally less acidic and less mineralized than rain.

4.1. Ion measurements

Dew water, because of its low yield compared to rain, can concentrate chemical and biological

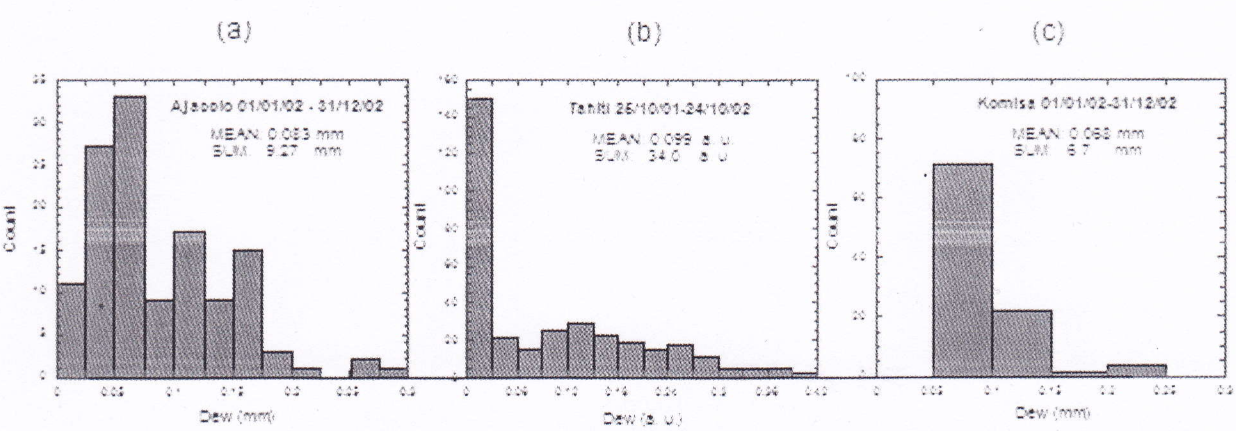


Figure 8. One-year dew histogram on three islands. The mean and cumulated values (sum) are also shown (a-c) Mediterranean islands. (a) Ajaccio on Corsica (41°55' N; 8°48' E), approximately 70 m a.s.l. Dew on PMMA. (c) Komiža on Vis (43°3' N; 16°6' E) approximately 11 m a.s.l. Dew on grass with levels 0 - 1 - 2. (b) Pacific island, Tahiti in French Polynesia (17°33' S, 149°35'W), approximately 200 m a.s.l. Estimation from Eq.1.

Slika 8. Histogram prikazuje količinu rose tijekom jedne godine na tri otočne lokacije. Prikazane su srednje i kumulativne vrijednosti (sum). (a, c) mediteranski otoci. (a) Ajaccio na Korzici (41° 55' N; 8° 48' E), na oko 70 m iznad mora. Rosa na PMMA. (c) Komiža na Visu (43°3' N; 16°6' E) na oko 11 m iznad mora. Rosa na travi jačine 0-1-2. (b) Otok na Pacifiku: Tahiti u Francuskoj Polineziji (17°33' S, 149°35' W), na oko 200 m nadmorske visine.

Table 1. Dew collection and pH in the NW Negev desert at Nizzana, Israel (30°53' N; 34°24' E), approximately 230 m a.s.l. Volume measurements using 1 m^2 foil.

Tablica 1. Skupljanje vode od rose i određivanje vrijednosti pH u sjeverozapadnom dijelu pustinje Negev u Izraelu (30°53' N; 34°24' E), na oko 230 m nadmorske visine. Količina mjerena na površini folije 1 m^2.

Date	Dew (mm)	pH	Date	Dew (mm)	pH
July 15-16, 2002	0.075	7.4	Oct 29-30, 2002	0.115	7.3
July 16-17, 2002	0.040	7.2	Nov 14-15, 2002	0.180	7.7
July 25-26, 2002	0.265	7.8			

pollutants and can thus also serve as a sensitive indicator for environmental safety. As an example, Figure 9 shows the SO_4^{2-} concentration in dew and rain measured on PMMA and/or foil in Ajaccio. It is striking that higher concentrations are observed only in dew and only when the wind is from a direction that passes a nearby electric plant powered by fuel. Except for these very rare events, the sulphate amount remains below the drinking water requirements (EU and WHO recommendation: 250 mgl^{-1}).

In Ajaccio there are sometimes relatively high concentrations of Fe (between 90 and 1700 μgl^{-1}, where EU recommends 200 μgl^{-1} and WHO 300 μgl^{-1} for drinking water) and Al (between 0.1 and 5.5 mgl^{-1}, where EU and WHO recommend 0.2 mgl^{-1} for drinking water). The corresponding events are correlated with the occurrence of aerosols coming from the Sahara settling over the Mediterranean area.

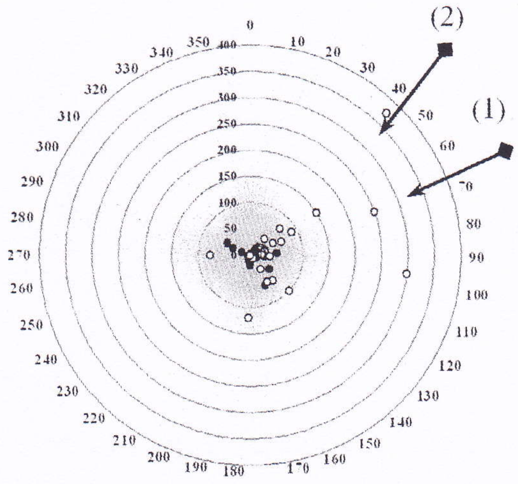


Figure 9. SO_4^{2-} concentration (mgl^{-1}) according to wind direction (degree) in polar coordinates (dew: ○; rain: ●); (1): electrical fuel plant direction; (2): nocturnal dominant wind direction. Axis is concentration (mgl^{-1}).

Slika 9. Koncentracija SO_4^{2-} (mgl^{-1}) u ovisnosti o smjeru vjetra (stupnjevi) u polarnim kordinatama (rosa: ○; kiša: ●); (1): strelica pokazuje smjer vjetra koji odgovara smjeru elektrane, (2): noćni prevladavajući smjer vjetra. Na osi je koncentracija u mgl^{-1}.

4.2. pH measurements

The alkaline or acidic character of dew depends mainly on the ions (sulphate, carbonate) present in the local atmosphere and also on the deposition of local aerosols on the condenser. It is beyond the scope of this review to analyze the details of such chemistry (see e.g. Okochi, 1996); we can only report on the data averaged over one year in Ajaccio (Fig. 10) and Bordeaux (Fig. 11) and compare them to rain. Dew pH is slightly acidic and rain is in general more acidic than dew. The examples of dew pH from Nizzana (NW Negev desert) are slightly alkaline, in contrast with the other measurements (Tab. 1).

4.3. Biology

Biological analyses by Beysens et al. (2003-c) show many harmless bacteria deposited from the ambient air. This is unavoidable as dew is collected in the open. When dew is harvested with care, very little contamination by focal bacteria is found, as in the small dew collector operated in Bordeaux. However, more significant biological pollution can be measured when such care cannot be taken (Muselli, 2003). In Ajaccio, on the 30 m^2 large collectors, the presence of microorganisms and especially of indicators of focal contamination (enterococcus and coliforms) listed in the EU legislation for drinking water means that, to remain potable, dew water from large collectors must be disinfected. This can be done by simple means.

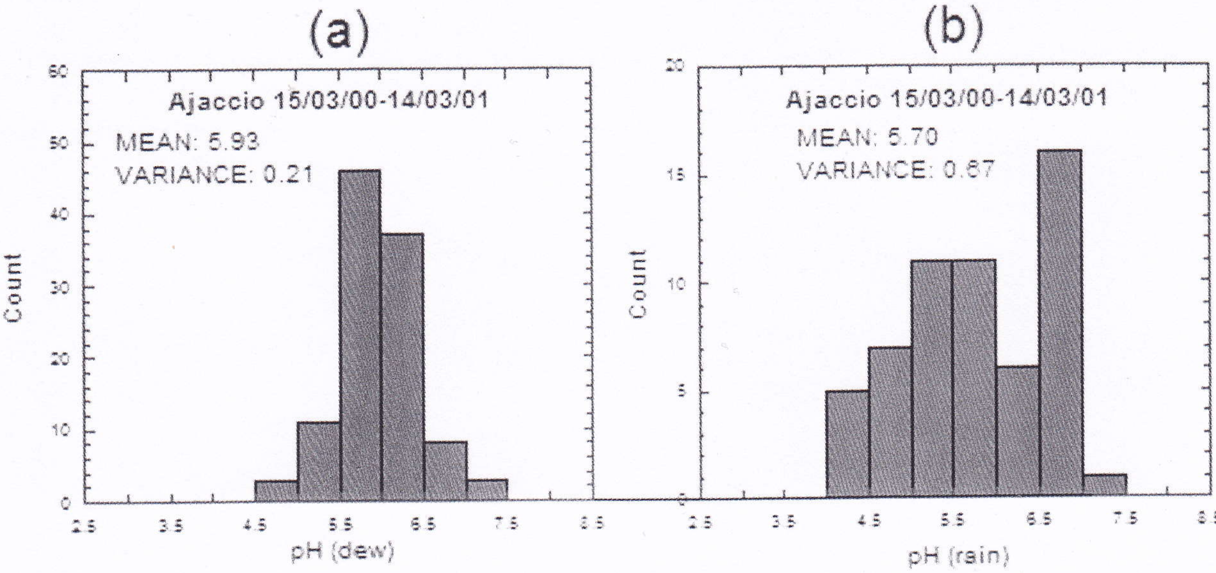


Figure 10. pH histogram for Ajaccio (a) dew and (b) rain. The rain pH is slightly more acidic than the dew pH and shows a larger variance.

Slika 10. pH histogram za Ajaccio (a) rosa i (b) kiša. pH kiše je nešto kiseliji nego pH rose i pokazuje veću varijancu.

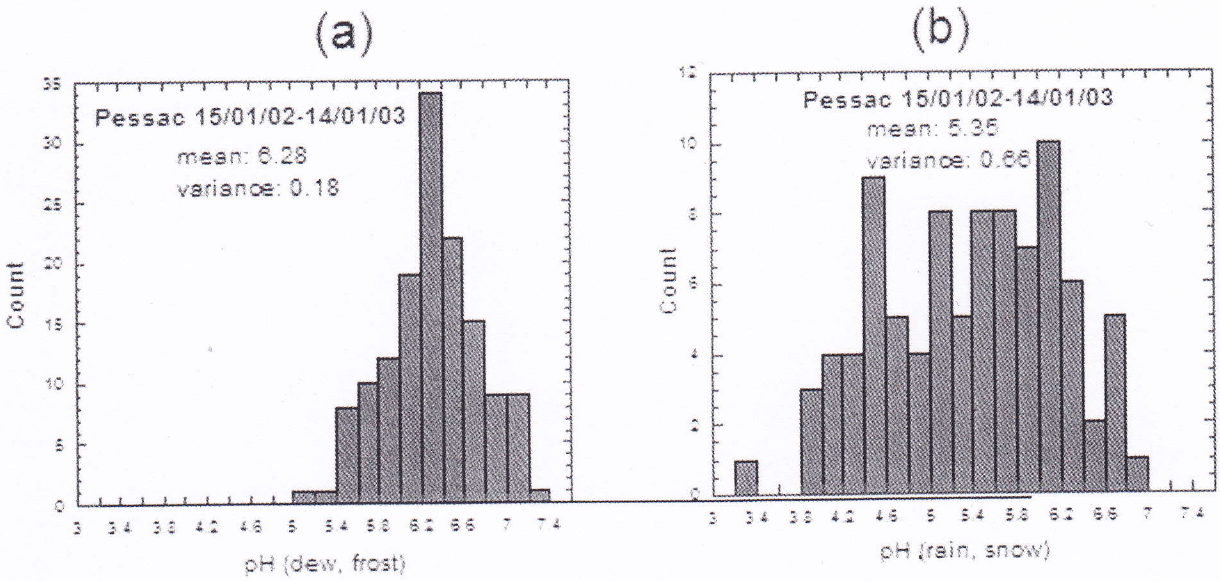


Figure11. pH histograms for Bordeaux (Pessac) (a) dew and frost, (b) rain and snow. The pH of rain is more acidic and the variance is larger than for dew.

Slika 11. pH histogrami za Bordeaux (a) rosa i mraz, (b) kiša i snijeg. pH kiše kiseliji je, a varijanca je veća nego za rosu.

5. CONCLUSION

The use of new and inexpensive radiative materials, together with well-designed architectures, enables liquid water to be condensed from the ambient atmosphere with a yield that is markedly greater than natural dew. However, dew water will be always limited by external factors, the more restrictive being the available radiative cooling energy, in the order of 25 – 250 Wm^{-2}, and the local air humidity. These factors practically limit the yield to 0.5 mm per night.

Dew water can be potable provided that prior chemical analyses are made in the area of collection. Special care should be taken to prevent contamination by microorganisms indicators of focal contamination. In this respect, small-scale collectors, which are easier to keep clean, are less difficult to handle.

The cost of such dew water is very much a function of local manpower costs. For France, the 30 m^2 Ajaccio condenser has a cost of 0.30 Euro per l. Accounting for only the foil manufacturing, and assuming a 2-year life span, the condensers can provide water at a cost of about 0.04 Euro per l.

We must also stress that such condensers not only obtain water from ambient air humidity, but can also collect any atmospheric precipitation, including rain and, to a lesser extent, fog water.

NOMENCLATURE

Ta: air temperature (°C); *Tc*: surface condenser temperature (°C); *Td*: dew temperature (°C); cloud cover *N* (octas); *k*: heat transfer coefficient; *g*: mass transfer coefficient; *h*: dew yield (mm)

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