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▶ **To cite this version:**

Daniel Beysens, Irina Milimouk, Vadim Nikolayev, Marc Muselli, Jacques Marcillat. Using radiative cooling to condense atmospheric vapor: a study to improve water yield. Journal of Hydrology, 2003, 276 (1-4), pp.1-11. 10.1016/S0022-1694(03)00025-8 . hal-01261660

HAL Id: hal-01261660
https://hal.science/hal-01261660

Submitted on 27 Jan 2016

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USING RADIATIVE COOLING TO CONDENSE ATMOSPHERIC VAPOR: A STUDY TO IMPROVE WATER YIELD

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Abstract: An inexpensive radiative condenser for collecting atmospheric vapor (dew) was tested in Grenoble (France). The surface temperature measurements are correlated with meteorological data (wind velocity, air temperature) and compared to the corresponding surface temperature of a horizontal Polymethylmethacrylate (Plexiglas) reference plate located nearby. The condenser surface is a rectangular foil (1 x 0.3 m^2) made of TiO_2 and $BaSO_4$ microspheres embedded in polyethylene. The foil has an angle θ with respect to horizontal. The under-side of the device, thermally isolated, faces the direction of the dominant nocturnal wind. Both a 2-D numerical simulation of the air circulation around the foil and experimental measurements shows that the angle $\theta = 30°$ is a good compromise between weak wind influence, large light-emission solid angle and easy drop collection. The study was conducted from November 25, 1999 to January 23, 2001. In comparison to the reference plate, it is found that water yield can be increased by up to 20 % and water collection greatly facilitated.

Keywords: Atmospheric deposition, Water, Hydrodynamics, Airflow, Hydrometeorology, Heat transfer

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INTRODUCTION

One can go back to ancient lore to find literature that water can be collected from dew (Jumikis, 1965). More recently, passive dew water collectors (i.e. without an energy supply) have been discussed by several authors. The massive dew collectors erected in France in the first quarter of the 20th century by Knapen (Knapen, 1929) and Chaptal (Chaptal, 1932) gave very low yields. They both followed a passive collector constructed by Zibold in Crimea (Ukraine) in 1912 (Milimouk and Beysens, 1995). The yield of the Zibold collector was greater because it made better use of nocturnal radiative cooling (Nikolayev *et al.* 1996, Beysens *et al*. 1998 and 2000). A good yield was obtained by Nilsson (Nilsson, 1996) using a small condenser made with a special foil specially designed to benefit from radiative cooling. In order to improve the yield of such dew water collectors that use radiative cooling to condense atmospheric vapor, the present systematic study was set up.

For the purposes of condenser optimization, meteorological parameters such as air temperature, air humidity (that define the dew temperature) and sky radiation (cloud cover) are imposed parameters that cannot be adjusted (Monteith 1957, Beysens 1995). In order to increase the yield of dew harvesting, it is however possible to (i) maximize the long wavelength emitting properties of the condensing surface (near infra-red), (ii) minimize the short wavelength absorption (sun visible light) (iii) lower the wind velocity on the condensing surface (iv) increase the condensation time, and (v) recover most of the water drops.

Below, it is shown how to construct an improved dew collector where all these conditions are fulfilled. The study was mainly directed to improve water yield in presence of strong wind, as regurlarly found in islands – and more precisely in Mediterranean islands.

OPTICAL PROPERTIES

A foil made with material elaborated by Nilsson and collaborators (Vargas *et al*. 1994, Nilsson, 1996) was used. This foil is 0.39 mm thick and made of 5.0 vol % of TiO_2 microspheres of 0.19 μm diameter, and 2.0 vol % of $BaSO_4$ of 0.8 μm diameter embedded in a matrix of low-density polyethylene (LDPE). It also contains approximately 1 vol % of surfactant additive. This

material is discussed by Nilsson *et al.*, 1994 and Nilsson, 1996, where it is explained why the foil improves the near infra-red emitting properties to provide radiation cooling at room temperature and why it efficiently reflects the visible (sun) light.

One of the major concerns with such synthetic foils is aging as polyethylene is sensitive to UV radiations. During the period of data collection (more than one year) no characteristic aging effects were observed. However, recent experimentation (Muselli *et al*, 2002) indicates that the average lifetime of the foil is of order 18 months (data are taken in Ajaccio, in Corsica island). Aging depends on the cumulated amount of UV radiation and is dependent on the measurement site.

WIND INFLUENCE

Wind is necessary to bring humid air towards the condenser but strong wind will lower and eventually cancel radiative cooling by heating effects. As a matter of fact, a study of dew events in Grenoble (Beysens *et al.*, 2001) showed that nearly all dew events occurred when wind velocity, as measured at 10 cm above an horizontal dew collecting surface, was less than 1 m/s.

It is one of the goal of the present study to increase the range of dew formation to larger wind velocities. One of the major applications is water recovery in islands, where wind is often strong. For this purpose, the study of a plane condenser that makes a non-zero angle with horizontal was decided. Such an arrangement has two benefits: it reduces the wind velocity very close to the condensing surface and it favors the sliding of the dew drops. The combined effects work best for angles close to 90°. However, since the emission solid angle towards the open sky decreases with angle, a compromise has to be found.

A numerical study was first undertaken. The circulation of air around a model plane of AB = 1.2 m (lateral) length and 10 mm thickness was studied (Fig.1). Computations were carried out using the FIDAP numerical Code (Khris, 1997) based on the Finite Elements digitization method using the Navier-Stokes equations. A two-dimensional study was performed. Wind velocity at the upstream section of the computation domain has been taken equal to a value of V = 10 m/s at the height H ≡ $\overline{OM}$ = 10 m above the ground (see Fig.1a). The main results of the study are concerned with streamlines and velocity distribution (by means of constant velocity

values lines) of the air circulation above the model and especially the plane surface. Figure 1a presents the streamlines around the condenser making an angle θ = 30° with horizontal. In Fig.1b is reported the wind speed evolution along the vertical axis with respect to the middle point of the inclined plane at point M such as H ≡ $\overline{OM}$. The main result is that the flow is still laminar although the air velocity is large at 10 m elevation. In addition, air flow close to the foil is seen to come from a vortex that recirculates air in the opposite direction with a much lower velocity, a well-known result.

The angle θ variation of the wind speed $V_{0.1}$, as measured at $\overline{KM}$ = $\overline{OM} - \overline{OK}$ = 0.1 m from the foil surface center K, see Fig.1a is scaled on Fig. 2 by the velocity V_{10} (= 10 m/s) at 10 m off the ground. As expected, $V_{0.1}$ is about 10 times less than the velocity measured at H = 10 m with a weak minimum at θ = 30°. This minimum can be understood as follows. When the angle θ increases, the high-pressure regions (to which correspond the lower wind velocities) lift from the plate and cross the point K. In K is therefore seen successively an increase of pressure (lowering of velocity) for small θ, then, for large θ, a decrease of pressure (increase of velocity). The minimum velocity is observed around θ = 30°.

Another quantity of interest is the height where the velocity suddenly decreases. In Fig.1b one can see that the magnitude of the velocity decreases steeply from the upper heights when H becomes less than some value H_0 shown in Fig.1b. Above H_0 the wind velocity increases according to a power law variation, as expected in the laminar flow limit (Pal Arya, 1988). The variation with angle θ of the layer of quiescent air $H_1 = H_0 - \overline{OK}$, rescaled by the foil height H_e = OK is reported in Fig.2. Here $\overline{OK} = \frac{AB}{2}\sin\theta$ = 0.6 $\sin\theta$ (m) is the elevation of the foil center. Fig.2 shows that the layer H_1 is nearly constant and of order 3 times the elevation of the foil center.

EXPERIMENTAL SETUP

The measurement site was located north of Grenoble (45°11’ latitude N, 5°42’ longitude E) approximately 215 m a.s.l., in the middle of a 10 km wide glacial valley, between the

Chartreuse and Vercors mountains (2100 m maximum elevation). Two dominant wind directions, N-NE and S-SW, characterize the wind regime.

A small condenser, 1 x 0.3 m^2 was made of the special foil that was maintained on a steel grid with mesh 13mm (Figs.3a-b). The foil and the grid were thermally isolated from below with a 20 mm thick sheet of polystyrene foam. Studies were carried out with and without thermal isolation. The surface temperature (T_c) was measured by means of a thermocouple fixed by tape on the foil surface, approximately in its center. The tape was transparent, and the bulb of the thermocouple was located near the tape edge, so that the thermocouple measured the foil surface temperature while being nearly unaffected by the presence of the tape. Systematic measurements were performed with two thermocouples, by varying sensor distance to tape edge–thermocouple and varying the color of the tapes. Only negligible variations were found.

The plane of the condenser made an angle θ with respect to horizontal; θ could be varied in the range [0 - 45°]. A reference condensing surface was used for comparison. It consisted of a 5mm thick, 0.4 x 0.4 m^2 plate of Polymethylmethacrylate polymer (PMMA, commercial name: Plexiglas), placed on a thermally isolated mount formed of an aluminum foil and a 5mm thick sheet of polystyrene foam. Plexiglas is a polymer whose long chain radiates in the near-infrared and thus behaves close to the black body (the emissivity factor is 0.94). In addition, PMMA is transparent to direct sun illumination. Aluminum reflects the infra-red radiation and increases the thermal isolation from below.

Dew mass was measured on PMMA. For this purpose, the PMMA plate was placed on an electronic, temperature compensated *Mettler Toledo* balance. The balance was protected from the wind up to the plate level, to lower the effect of an additional pressure from the wind. A wind effect was however noticeable in case of strong wind, it resumes in a vertical force due to the Bernouilli pressure. In Fig.4, there is a clear correlation between a noisy signal from the balance and the presence of strong wind. Both the foil condenser and the reference PMMA were set on a table 1 m off the ground, in an open area (Fig.3b).

The following physical parameters were recorded every 15 minutes in a data logger connected to a computer: (i) surface temperature of the reference plate T_{ref} (measured with a taped thermocouple as for T_c), (ii) condenser temperature T_c, (iii) water condensed mass on PMMA, (iv) relative air humidity H% (v) air temperature T_a, (vi) wind velocity V, with a cup

anemometer at 0.1 m above the plate. From Nov. 25, 1999 to Jan. 20, 2000, the stalling speed of the anemometer was 0.2 m/s. From Jan. 20, 2000 to Jan. 23, 2001, it was 0.5 m/s. The wind data are averaged over a period of 15 minutes. The dew temperature T_d was calculated from T_a and H%. Temperature was measured within 0.1 °C accuracy, and the wind velocity within 0.1 m/s for windspeed above the stalling velocity. A typical recording is shown in Fig.4.

During the period of study, frost formed sometimes instead of dew. Both come from a phase transition from atmospheric vapor, the difference being in the different latent heats (the latent heat of sublimation is different from that of condensation). However this difference did not influence our later analyses as it was always proceeded by comparing the condenser and the reference plate (for details, see Nikolayev et al., 2001).

RESULTS AND ANALYSIS

Typical data

Data were recorded from 25 November 1999 to 27 March 2000 for several foil inclination angles, and from 23 March 2000 to 2 March 2001 for the constant angle $\theta = 30°$.

In order to compare the yield of such an inclined condenser with the horizontal reference plate, a relative efficiency of cooling factor or "temperature gain" ΔT^* can be defined as

$$\Delta T^* = \frac{T_c - T_a}{T_{ref} - T_a}. \qquad (1)$$

The ratio ΔT^* was studied as a function of the following factors: isolation/no isolation beneath the foil; angle θ; wind velocity V (as measured at 0.1 m above the reference plate). A typical recording with average windspeed at $\theta = 45°$ is shown in Fig.4 where only few daytime data are considered. The temperature gain is nearly constant (mean value 0.93) till the morning, when it varies sharply, reaching sometimes negative values. This is due to the difference in shadow and direct sun illumination between the plate and the tilted condenser (compare Fig.4a and 4b). It is noticeable that the temperature gain is insensitive to the wind value, although it varies from a value lower than 0.2 m/s (stalling speed of the anemometer) till 1.4 m/s. When the wind is stronger, the signal of the balance (h, expressed in mm) becomes noisy, with a lowering of the signal because of the increasing Bernoulli pressure.

The temperature gain ΔT*

Heat losses by air convection on a plane surface is a classical problem (see e.g. Monteith and Unsworth, 1990). This problem is complicated in an open area where one has to account for small and large values of air flow velocities, and difference in air temperature, which mixes forced and free air convection. As already noted in the introduction, this work aims to focus on the cooling gain under strong wind. The numerical study above shows that the air flow is laminar even though the wind at 10 m off the ground is as high as 10 m/s. Then only the case of laminar forced convection will be discussed here. The temperature differences T_c-T_a and T_{ref} – T_a can be obtained from the evaluation of the heat flux issued from the reference and condenser surfaces.

The heat flux (Q) from air to a surface can be classically written as

$$Q = -\Lambda \frac{Ti - Ta}{\delta} = -\frac{1}{e}\Lambda Nu(Ti - Ta), \qquad (2)$$

with T_i the surface temperature (= T_c or T_{ref}) and Λ the air thermal conductivity. The number Nu is the Nusselt number, which relates the boundary layer thickness δ to a typical dimension e of the surface:

$$\mathrm{Nu} = \frac{e}{\delta} \qquad (3)$$

Measurement of heat losses are described by a Nusselt number that varies as a power (x) of the Reynolds number Re, resulting in (Monteith and Unsworth, 1990)

$$\mathrm{Nu} = \mathrm{E}\ \mathrm{Re}^{x} \sim \mathrm{V}^{x} \ . \qquad (4)$$

Here the velocity V is characteristic of the flow. The factor E is a numerical coefficient, which depends on the air viscosity and the particular geometry of the surface (the Prandtl number, which is a constant here, is hidden in E). For a horizontal plane surface, x = 1/2 if the flow is laminar ($Re<2\ 10^4$).

Cooling of the surface is ensured by radiative heat flux that is θ dependent. When θ = 0, radiative cooling is maximum.

The surface temperature is then a complicated function of θ and V:

$$\Delta T^* = F(\theta, V) , \qquad (5)$$

Windspeed dependence

A first question arises on how to decide which velocity is appropriate for use in Eq.(5). In the 2D simulation (Fig.2), the velocity ratio $V_{0.1}/V_{10}$ at 0.1 m and 10 m from the surface does not vary appreciably with θ. In the classical configuration of the reference plate (θ = 0) one can relate the measurement $V_{0.1}$ above the plate with the measurement V_{10} at 10 m above according to a classical power law variation, valid during the neutral conditions assumed here (see e.g. Pal Arya, 1988):

$$V(H) = V_{10}(H/10)^n, \qquad (6)$$

Here H is expressed in m. The exponent n depends on both the surface roughness and stability. For near neutral conditions and a clear area with a few buildings, n ≈ 0.3. The measurement of the wind velocity $V_{0.1}$ at 0.1 m above the reference plate, which is proportional to V_{10}, allows therefore the velocity to be determined in Eq.(5) within a constant.

The windspeed dependence of ΔT^* comes from the ratio of the Nusselt numbers corresponding to the plate at θ = 0 and θ ≠ 0, respectively. The dependence should then be low. This argument is qualitatively supported by the measurements reported in Fig.4 for the angle θ = 45° where ΔT^* does not vary appreciably for windspeed ranging from 0 to 1.4 m/s. Long term measurements (from Nov. 25, 1999 to Jan 23, 2001) are reported in Fig.5 for θ = 30°. Here all the data below the stalling speed have been suppressed. Windspeed as measured at 0.1 m from the plate (≈ 1 m from the ground) and at 10 m are both reported. The velocity at 10 m (upper axis) has been deduced by inverting Eq.6 with H = 1 m and n = 0.3. In Fig.5, there is no obvious variation of ΔT* with V. The mean value is $\Delta T^* = 1.19 \pm 0.05$ (three standard errors).

θ-dependence

Since ΔT^* does not vary appreciably with V in the laminar regime, the only remaining parameter is the tilt angle θ. The θ-dependence of ΔT^* corresponds to the Nusselt numbers and radiation flux and is very difficult to estimate. However, its asymptotic behavior can be determined. For θ = 0, $\Delta T^* \approx 1$; for θ ≥ 0, $\Delta T^* \geq 1$, as the wind, and therefore the heat losses on

the condenser, decreases while the radiation flux does not change appreciably; for $\theta >> 0$, $\Delta T^* < 1$, as the radiation flux strongly decreases. One thus expect ΔT^* to exhibit a maximum between 0 and 30° angle. In order to obtain the value of the maximum, we fit the experimental data to the simplest development in θ that exhibits a maximum, that is

$$\Delta T^* = A(1 + \frac{\theta}{\theta_0} - \frac{\theta^2}{2\theta_0\theta_1}) . \qquad (8)$$

Here A, θ_0 and θ_1 are the adjustable parameters. This notation highlights the maximum $\theta = \theta_1$)
Let us now discuss the results obtained with the data obtained between 25 November 1999 and 27 March 2000. The results are shown in Fig.6, which also contains the case where the lower part of the foil was not isolated. In spite of an important scatter of data, unavoidable when dealing with such atmospheric data, the following conclusions can be drawn:

(i) The isolated and non-isolated foils exhibit the same general trend but the non-isolated foil shows a gain $\Delta T^* < 1$ and the isolated foil a gain $\Delta T^* > 1$.

(ii) A least-squared fit of the isolated case data to Eqs.(12) gives $A = 1.08 \pm 0.5$, $\theta_0 = (87.5 \pm 300)°$, $\theta_1 = (19 \pm 20)°$ (three standard errors when weighing the data with their corresponding errors). As A=1 within the uncertainty, another fit with A=1 imposed gives (Fig.6) $\theta_0 = (57.54 \pm 36)°$, $\theta_1 = (21.23 \pm 6)°$ (three standard errors). The maximum gain corresponds then to this last value for θ_1 and the gain at this angle is $\Delta T^* (\theta_1) = 1.19 \pm 0.12$. Note that the gain extrapolated at 30° is $\Delta T^* (30°) = 1.15 \pm 0.12$ (three standard errors), which compares well with the average value for the data for $\theta = 30^\circ$ (Fig.5): $\Delta T^* = 1.19 \pm 0.05$ (three standard errors).

(iii) The data from the non-isolated case are more scattered. The same radiative and air flow behavior are thus assumed, i.e. the parameters θ_0 and θ_1 from the isolated case are imposed in the fit. The parameter A<1, which corresponds to a lowering of the radiative cooling heat flux by heat losses by conduction, is thus the only adjustable parameter. One finds $A = (0.63 \pm 0.09)$ (three standard errors when weighing the data with their corresponding errors). This value means that the absence of isolation beneath the foil lowers the gain by a factor as large as ≈ 40 %.

The “best” tilt angle

From the above study, the angle that provides the best result with respect to the temperature gain was about 21°. However, the efficiency of drop recovery by gravity is a key factor that must also be considered. Gravity leads to a pulling force acting on the drops that varies as $\sin\theta$. Accordingly, the best angle should be 90°, an angle where the water yield should be nearly zeroed because of ground irradiation. A compromise thus has to be found. Note that going from 21° to 30 ° increases the force by 40 % for a decrease in cooling gain of only 3.5 %. It can be thus considered that a good compromise between temperature gain and drop recovery by gravity is found for an angle of order $\theta = 30°$. At this angle, the gravity force acting on the drops is still 50% of the maximum available force, obtained at $\theta = 90°$, and the cooling gain remains in the order of 120 %.

CONCLUSIONS

Experiments performed with a working condenser model, coupled with numerical studies of the air flow near the condenser, show that an angle around $\theta = 30°$ should give the optimal result for dew production. At this angle a gain in cooling in the order of 20% was found with respect to a horizontal reference condenser. In addition, such an angle favors the sliding of water drops and thus facilitates simple recovery of water by gravity. A large prototype condenser (10 x 3 m^2) based on these principles is presently working at Ajaccio (Corsica island, France). Preliminary data (Muselli et *al*., 2002) show indeed that dew can be obtained with high yield for nocturnal winds till 4.5 m/s (at 10 m off the ground) and that dew drops naturally slide on the foil.

ACKNOWLEDGMENTS

The authors gratefully thank T. Nilsson for providing his condensing foil . J. Serose gave invaluable assistance in setting up the experiment and recording data system. G. Rey-Giraud is thanked for data acquisition. The authors are indebted to S. Berkowicz for a critical reading of the manuscript.

REFERENCES

Beysens D., 1995. The formation of dew. Atmospheric Research., 39: 215-237.

Beysens D., Milimouk I. and Nikolayev V., 1998. Dew recovery : old dreams and actual results. Proceedings of the First International Conference on Fog and Fog Collection, Vancouver (Canada), pp. 269-272.

Beysens D. and I. Milimouk, 2000. Pour des ressources alternatives en eau. Sécheresse, 11: 281-288.

Beysens, D., V. Nikolayev, I. Milimouk and M. Muselli, 2001: A study of dew and frost precipitation at Grenoble, France, *2nd Intern. Conf. on Fog and Fog Collection*, St John. pp. 329-331.

Chaptal, L, 1932: La lutte contre la sécheresse. - La captation de la vapeur d'eau atmosphérique. *La Nature (Paris)*, Vol. 60, 449-454.

Jumikis, A.R., 1965: Aerial wells: secondary sources of water. *Soil Sci.*, Vol. 100, No 2, 83-95.

Knapen M.A. Dispositif intérieur du puits aérien Knapen. In : *Extrait des mémoires de la société des ingénieurs civils de France (Bulletin de janvier-février 1929)* : Imprimerie Chaix, Paris, 1929.

Krhis S., 1997: Contribution de modèles de turbulence du premier ordre à la simulation numérique d'écoulements aérodynamiques en situation hors équilibre, *Thèse de Doctorat, Université de la Méditerranée, Marseille*, 08/10/1997, (to-day: OPTIFLOW Company).

Milimouk I., D. Beysens, 1995: Recueil d'articles sur la condensation de l'eau atmosphérique. *Rapport CEA-Saclay, DIST* 95002495.

Monteith, J.L., 1957. Dew. Quart. J. Royal Meteorol. Soc., 83: 322-341.

Monteith J.L. and Unsworth M.H., 1990. Principles of Environmental Physics (2nd edition). Routledge, Chapman and Hall, Inc., New-York.

Muselli M., D. Beysens, J. Marcillat, I. Milimouk, T. Nilsson, A. Louche, 2002: Dew water collector for potable water in Ajaccio (Corsica island, France). *Atmospheric Research (in press)*

Nikolayev, V.S., D. Beysens, A. Gioda, I. Milimouk, E. Katiushin. and J.-P. Morel, 1996: Water recovery from dew. *J. Hydrology*, Vol. 182, 19-35.

Nikolayev, V.S., D. Beysens and M. Muselli, 2001 : A Computer Model for Assessing Dew/Frost Surface Deposition. *Proceedings of the 2nd International Conference on Fog and Fog Collection*, St John's (Canada), 16-20 July, 2001; see http://www.opur.u-bordeaux.fr/Data%20Processing/FitDew-ST%20JOHN.pdf

Nilsson T., W.E. Vargas, G.A. Niklasson and C.G. Granqvist, 1994: Condensation of water by radiative cooling. *Sol. Energy*, Vol. 5(f), 310-317.

Nilsson T., 1996: Initial experiments on dew collection in Sweden and Tanzania. *Sol. Energy Mat. Sol. Cells* Vol. 40, 23-32.

Pal Arya S., 1988. Introduction to Micrometeorology. Academic Press, Inc., San Diego.

Vargas W.E., G.A. Niklasson and C.G. Granqvist, Nilsson T., 1994: Condensation of water by radiative cooling. *Sol. Energy*, Vol. 5(f), 310-317.

FIGURE CAPTIONS

Fig.1. 2-D simulation of air flow near a plate 1.2 m long, 10 mm thick, with windspeed V_{10} = 10 m/s at 10 m elevation with an angle $\theta = 30°$. (a) Streamlines. The height H = OM is counted from point O. K is the plate center. (b) Air velocity versus height. The height H_0 is determined from the intersection of the tangents to the curve H(V), as shown. In the region $H>H_0$, the variation V(H) exhibits a classical power law variation.

Fig.2. Angle variation of (i) air flow velocity $V_{0.1}$ at 0.1 m above the foil rescaled by the air velocity V_{10} at 10 m off the ground (= 10 m/s) and (ii) the maximum layer $H_1 = H_0 - \overline{OK}$ of quiescent air rescaled by the foil height OK. Here $\overline{OK} = \frac{AB}{2}\sin\theta$ = 0.6 $\sin\theta$ (m) is the elevation of the foil center. The wind velocity is set to be 10 m/s at 10 m above the foil. (From the 2D numerical simulation).

Fig.3. (a) The model condenser (schematic). F : foil (0.3 x 1 m^2); PS : 20 mm thick polystyrene foam; G: supporting grid (13 mm mesh); V: dominant wind direction (N-NE); T_c: bulb of the thermocouple taped (TP) on the surface, measuring the surface temperature. The plane of the condenser makes an angle θ with horizontal. (b). Condenser study in Grenoble. P : Plexiglas plate on an electronic Mettler Toledo balance. A: anemometer. C: condenser model (1 x 0.3 m^2).

Fig. 4. Dew recording (night of Jan. 3-4, 2000) for the tilt angle 45°. (a): air temperature T_a, dew temperature T_d, condenser temperature T_c and reference PMMA temperature T_{ref}. (b): temperature gain $\Delta T^* = \frac{T_c - T_a}{T_{ref} - T_a}$. The negative part corresponds to different temperature evolution under sun illumination between the plate and the tilted condenser (see (a)). (c): wind velocity. (d) dew volume (in mm) recorded on the reference plate PMMA.

Fig. 5. Reduced temperature gain ΔT* (see Eq.1) versus wind speed at constant angle θ = 30° (period Nov. 25, 1999 to Jan 23, 2001) in a semi-log plot. The upper axis corresponds to the wind speed at 10 m as deduced from Eq.6 (H = 1 m and n = 0.3). The data corresponding to wind speed lower than the stalling speed have been removed. The line is the best fit to a constant.

Fig. 6. Effects of foil thermal isolation and angle θ with horizontal on the temperature gain ΔT* (defined in Eq.1). The curve 1 (isolated foil, data: squares) corresponds to the best fit by Eq.8 with the amplitude A=1 imposed. The curve 2 (non-isolated foil, data: triangles) is the same as curve 1 with the amplitude as the only free parameter (A = 0.63 ± 0.09).