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DEW AND ATMOSPHERIC WELLS IN MEDITERRANEAN CLIMATES

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Introduction

From a comprehensive description of mechanisms involved in the formation of dew, we analyze field experiments in Crimea (Ukraine) and in Southern France during the 20th century. The aim of these experiments was to built large dew-catchers, so-called atmospheric wells, which could be useful in dry regions.

The Physics of Dew

General mechanisms

The first phenomenon involved in the formation of dew is the spontaneous formation ("nucleation") of a liquid drop from humid air. Since the drop nucleates on a substrate, this process is called "heterogeneous nucleation", in contrast to "homogeneous" nucleation when the drop forms in the surrounding atmosphere. This requires that the temperature of the substrate (T_s) be lower than that of the surrounding atmosphere (T_r) or, more precisely, that the saturation pressure (p_s) of water at T_s is smaller than the saturation pressure (p_r) at T_r. Heterogeneous nucleation allows condensation for a temperature difference (or equivalently, pressure difference $\Delta p=p_r-p_s$) which is much smaller than that needed for homogeneous nucleation. For instance, saturated water vapor at 20°C would condense in the case of homogeneous nucleation only around 0°C; experience shows that dew forms at much higher temperature.

Nucleation is indeed a process where, to form a liquid drop, it is necessary to overcome an energy barrier which is the cost of formation of the interfaces liquid-vapor and liquid-substrate. This energy barrier depends on the wetting properties of the substrate (Figure 1). It is zero for complete wetting (water forms a wetting film), and maximum for a liquid droplet that does not wet the substrate (complete drying). More generally, the substrate is, naturally or not (pollution), covered with fatty substances so that the water-substrate contact angle is around 90°.

Another important phenomenon is intimately associated to condensation: the release of the latent heat of condensation, that has to be evacuated through the substrate. Transfer of mass and heat transfer are two aspects of the same condensation phenomenon.

Growth of one isolated droplet

Once a droplet of water has nucleated on the substrate, it grows at the expense of the surrounding atmosphere. We assume that atmosphere has a velocity U, parallel to the substrate. The molecules of water diffuse in a boundary layer where U=0 and randomly hit the droplet, resulting in a concentration gradient around the drop. Calculations by Beysens et al. (1991) show that, for a mutual diffusion coefficient of water into air (D_{12}), the volume $V \sim R^{D_d}$ (here $D_d=3$ is the drop dimensionality) of a liquid drop of radius R is proportional to a reduced time t^*,

$$V \sim t^* \qquad (1)$$

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that is, $R \sim (t^*)^{\mu_s}$ (2)

with $\mu_s = 1/D_d = 1/3$ (3)

Here $t^* \sim U^{*1/2} \Delta p D_{12}\, t$ (4)

and $U^* = U(\nu D^2{}_{12})^{-1/3}$ (5)

with ν the kinematic viscosity of air.

When the velocity U is small (quiet air), the boundary layer becomes very large and (3) becomes

$$t^* \sim U^* \Delta p D_{12}\, t \qquad (6)$$

A complication may arise when the heat of condensation cannot be released through the substrate. In this case, the temperature of the drop increases and the growth slows down and can even stop (Beysens et al., 1991; Beysens and Knobler, 1992). This is especially the case for the fastest growths when air velocity is large. "Effective" growth law exponents $\mu_s < 1/3$ can be measured in such conditions.

Note (i) that the above analysis does not imply a precise knowledge of the microscopic mechanisms of growth and (ii) that the perimeter of the drop is a key place for the growth process. It is at this location that the temperature gradient drop-substrate is a maximum, and thus that the mass transport is also a maximum.

Growth of a droplet pattern

In fact, droplets that grow on a substrate are in constant interactions, a phenomenon that leads to quite general laws. A peculiarity of this growth process is that the interactions are geometrically constrained by the substrate: 2-dimensional interactions for a planar substrate, the most common case, unidimensional for a line, like the thread in a spider web, etc., one can even consider fractal substrates.

Two drops interact by fusion or coalescence. When droplets grow they will enter into contact at their perimeter at one moment or another. They form a new drop with a volume which is the sum of the volume of each initial drop. Fusion is energetically favorable in terms of interfacial energy. The center of mass of the new drop is approximatively at the barycenter of the two "parents". This has the interesting properties of leaving room on the substrate for further condensation and growth, as shown by the surface coverage of the new droplet, equal to $2^{2/3}\pi R^2$, to be compared to $2\pi R^2$ (case of two "parents" of same radius).

Several stages of growth can be characterized, depending on the interactions between the droplets, the defects of the substrate and the effects of terrestrial gravity.

Growth without significant interactions

This first stage is characterized by a small surface coverage (ratio A=surface area covered by the drops/surface area of the substrate), leading to negligible coalescence events. The average droplet radius of the pattern (<R>) grows like that of a single drop,

$$\langle R \rangle \sim (t^*)^{\mu_s} \qquad (7)$$

Self-similar regime

This is a very intriguing regime where the pattern evolution remains self-similar in time. It happens when the surface coverage exceeds typically 40%, leading to important interactions by coalescence between the droplets.

The first apparent effect of coalescence is the speeding-up of the growth (Figure 2). The second effect is the stabilization of the surface coverage to a constant (and universal) value, $A \approx 55\%$. The constancy of A is the result of two opposing effects. Continuous condensation tends to produce an increase in A, resulting in turn in an increase in the number of coalescences, which then tends to lower A, as noted above. We are therefore led to the paradox of a continuous increase of condensed mass at constant surface coverage. This constant surface coverage is the hall-mark of the self-similarity of the pattern evolution. A pattern at time t^*_i is identical (statistically speaking) to a pattern at time t^*_j provided that all distances are expressed in units of the average droplet

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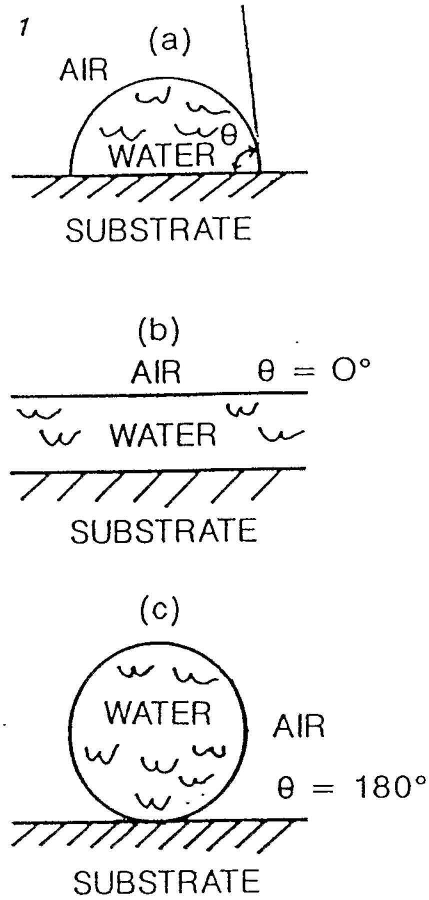

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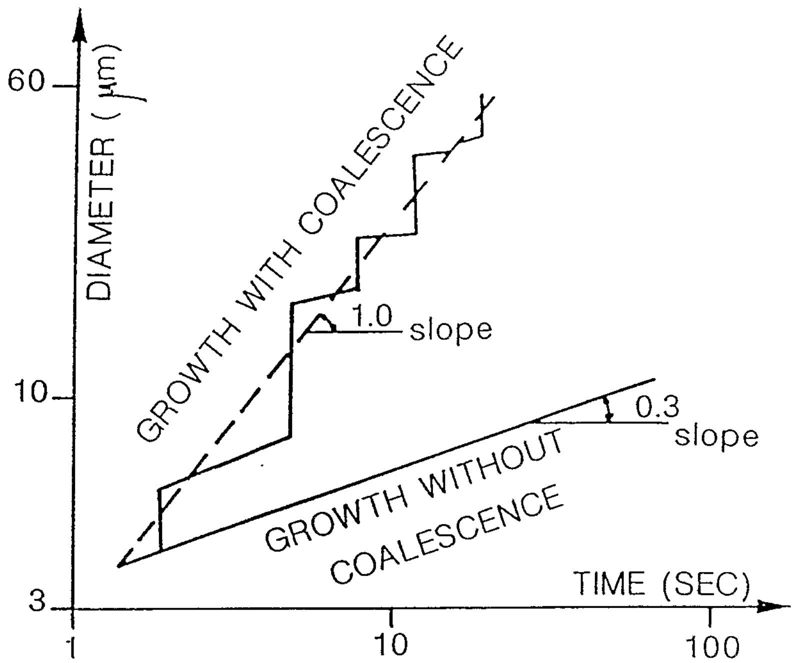

Figure 1. Energy barrier and the wetting properties of the substrate.

Figure 2. Droplet growths and coalescence.

Figure 3. Increasing of the droplet growth and stabilization of the surface coverage.

Figure 4. A whole range of droplet "families" *(Photo by Beysens)*

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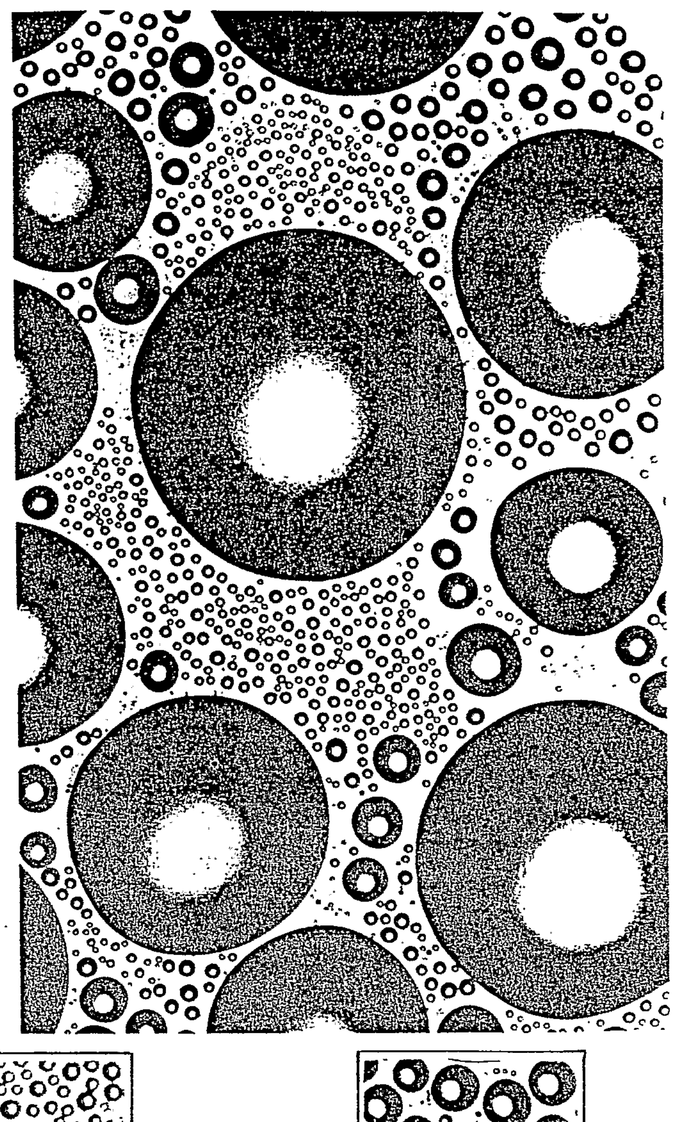

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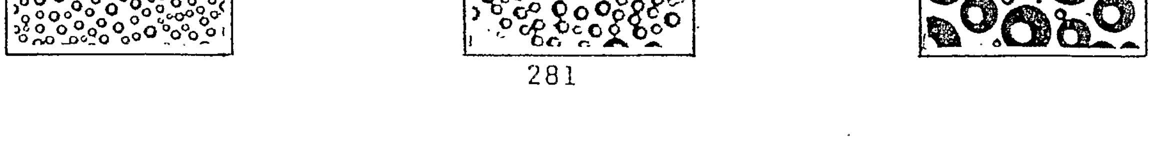


radius <R(t*j)> (pattern at t*j) and <R(t*i)> (pattern at t*i). See figure 3.

The time dependence of <R> can be shown to be (Beysens et al. 1991; Beysens and Knobler, 1992):

$$<R>\sim(t^*)^{\mu_a} \qquad (8)$$

with $\mu_s=\mu_a \cdot (D_d)/(D_d-D_s)$ (9)

Here D_d is the droplet dimensionality (=3), and D_s is the substrate dimensionality. For the usual situation where the substrate is a plane, D_s=2 and

$$\mu_s=3 \;,\; \mu_a=1 \qquad (10)$$

The growth is then considerably accelerated by coalescence (Figure 2).

Appearance of new "families" of droplets

Depending on the experimental conditions, new tiny droplets can nucleate in the space left free after a coalescence. These droplets form a new "family", which exhibits all the features (growth laws, surface coverage) of the first generation of droplets. After a while the substrate is covered by a whole range of "families" (Figure 4). Although the surface coverage exhibits the same (universal) value for each family, the total surface coverage is seen to increase and ultimately reaches unity.

Effects of the substrate heterogeneity

The stages 2 and 3 are often altered because the substrate is not perfect. The chemical and geometrical heterogeneities have the effect of pinning down the perimeter of the drops. The drop that results from the coalescence of two drops is no longer hemispherical, instead it is cigar shaped. The surface left free does not compensate for the growth; the surface coverage is seen to continuously increase; interconnected droplet structures form, leading to pseudo-wetting film.

Gravity effects. Steady state

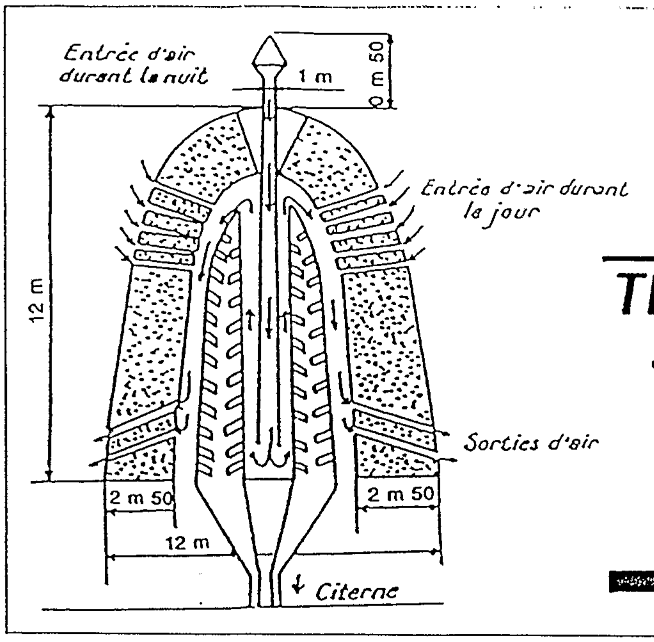
Gravity causes the largest drops to flatten end eventually flow, which has the merit of cleaning the surface and enables a new generation of droplets to nucleate. A steady state can thus be reached, with the continuous formation of new droplet patterns and the flow of the largest drops.

It must be noted that to any condensation process corresponds also a thermal release in the substrate. The heat generated by condensation has to be evacuated so that the process does not stop by itself. The humidity and temperature (vapor pressure) of the ambiant air has also to be maintained at the desired level. Dew formation on vegetation can be effective in the open air from sunset to sunrise because cooling is ensured by radiation effects (Lhomme and Jimenez, 1992). In contrast, dew formation is most effective on massive structures in the morning because of conduction and inertial effects. These remarks introduce the following section, devoted to a number of attempts to extract humidity from atmosphere.

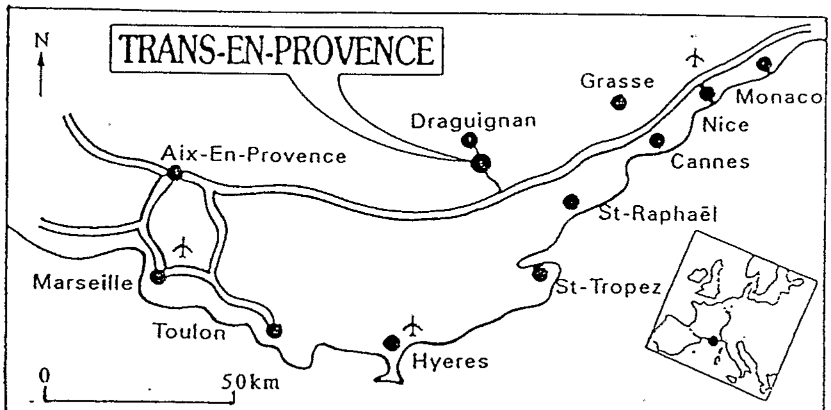
Drought, dew and atmospheric wells

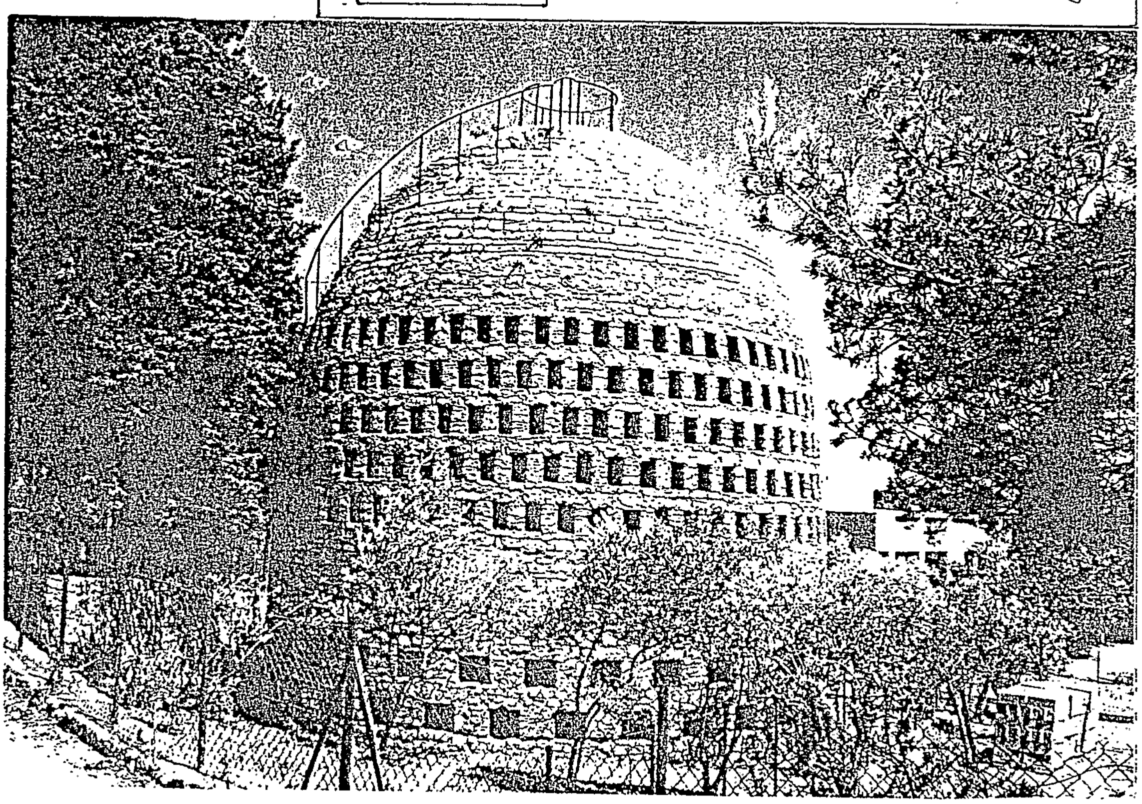
Discovery of Theodosia dew-catchers

An antique supply channel network without any spring was discovered almost at the beginning of the 20th century, above Féodosiya (previously, Theodosia) a city of 60,000 inhabitants on the Black Sea Coast (Crimea, Ukraine). Féodosiya is 100 km east of Yalta. In antiquity, Theodosia was a colony founded by the Greeks in ~600 B.C. and destroyed by the barbarians (IIIth century A.D.). It was one of the flourishing Grecian colonies of which the most famous city was Ponticapée (nowadays, Kerch, Crimea, Ukraine). During water supply works in a drought period, the discovery of huge stone heaps at the head of the network led the russian engineer Zibold to the conclusion that it was possible to rebuild a natural water collector, a so-called atmospheric well, to catch dew. Works were stopped by the Soviet Revolution but Hitier (1925) presented the russian trials at the French Academy of Agriculture and the project continued in Southern France.



Figures 5. The Trans atmospheric well. Location, photography and cross-section.





French atmospheric wells

L. Chaptal, head of the Bioclimatological Station in Montpellier (Hérault), made further trials using a small pyramid (3 m x 3 m x 2.32 m). The maximum daily discharge was 2.5 litres in summer (Chaptal, 1932).

Trials continued in the thirties in Trans-en-Provence (Var), a small city (Figures 5). A construction (12 m high and 12 m in diameter) was built by A. Knapen, a belgian engineer (Chaptal, 1932). In fact, the prelimary project was to build two atmospheric wells in Algeria where the temperature difference between night and day is higher than in Southern France. To buy building-plots was rather complicated in Algeria, while on the other hand A. Knapen had bought land in Trans. The Trans dew-catcher never produced high quantities of water, but it is now unique worldwide and hence preserved and restored under the authority of J.-P. Portheret, mayor of the city (Gioda and Acosta Baladón, 1991; Acosta Baladón, 1992) (Figures 5).

Other trials through the World

Studies performed on dew by Chaptal were well-known because the *Organisation Météorologique Internationale*, the previous name of WMO before the Second World War, admitted their quality (Damagnez, 1958). Following Chaptal's example scientists proposed to build large dew-catchers in Lybia (Sensidoni, 1945), and in Mauritania (Masson, 1948). However Reis F. Cunha (1964) was the only one who succeeded, by building a small stone wall on Cape Verde Is. The wall (2.5 m x 1.0 m x 1.8 m) which was installed on Serra Malegueta (Santiago) had a waterproof basement. It never produced dew water and indeed it could only produce fog water in this mountanious and oceanic climate.

Conclusions

Dew is a neglected water resource and all the trials with large dew-catchers which were performed in the 20th century were unsuccessful. However, dew-catcher apparatus produce up to one litre.day^{-1} and may be useful in individual survival equipments.

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