Dew

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20-03-2024

Everyone knows or has experienced dew, when the ground and plants are wet on the morning of a clear, calm night or when water runs down the walls and windows of kitchens and bathrooms. But where does dew come from ? Its origin has long been a mystery. From alchemists to scientists, many scholars have developed theories of varying degrees of rigor. It was only in the middle of the 20th century that a global interpretation of dew was developed. Dew is beneficial for plants and animals, but can humans use it as a new source of water ? How can dew be harvested ? What are the chemical and biological qualities of dew ? Is it drinkable ? All these questions are answered in this article.

1. Dew : a long history of mysteries

Everyone knows what dew is. But where does **dew** come from ?

Natural dew is a ubiquitous phenomenon, already mentioned in the oldest literature. For example, in the Hebrew Bible (Ecclesiastes 1:2), the famous words "All is vanity" actually correspond to the word dew in Hebrew, emphasizing the beauty and brilliance of dew but also its ephemeral nature. In Japanese culture, many haikus have been written about dew. These are just a few of the many examples of dew used in art and literature.

In contrast to natural dew, which is formed mainly outdoors, there is **another dew**, which is called **mist**, and is found on the cold walls of caves and in damp rooms, such as kitchens, bathrooms and laundry rooms. The difference comes from the **origin of the cooling** : the natural dew comes from a radiative exchange with the cold sky and is only effective outside, while the other "dew" comes from a cooling by contact. It is the same "dew" as the "breath patterns" that form on a glass when you breathe on it.

Men have indeed been fascinated by dew for a long time. They did not understand how water could cover the ground and plants at night when the sky was clear. An important step was taken with Leroy (1751) [1] who understood that water can dissolve in the air like sugar in water, the higher the temperature, the greater the dissolution. The cooling of hot and humid air thus inevitably leads to the extraction of liquid water, precisely at the dew point temperature. Wells (1866) [2] carried out the first complete study of dew condensation but did not explain the reason for night-time cooling. This last process was highlighted by Jamin (1879) [3] with the **radiative cooling**. It was only much later that Monteith (1957) [4] formalized dew formation using a complete energy balance.

1.1. Dew, a new source of water?

Figure 1: Collection of dew water by alchemists [Source: adapted from Mutus Liber, 1677 [1]]

Dew water has long been overlooked as an additional source of water. However, it can be a **source of fresh and pure water for plants, animals and humans**. Dew water is indeed drunk by many small animals and insects, especially in arid and semi-arid regions (but not only, there are many examples of animals, such as cats and dogs, drinking dew water in our countries). It is said that the survival of horses in Namibia, abandoned after the First World War, is due to the fact that they could suck dew from the railroad tracks.

The first documented human use of dew water is probably the collection of dew by alchemists, noted in the book Mutus Liber (1677) [5], called the "Dumb Book" because it consists only of drawings. In Figure 1, dew is collected at night (noted by the moon) on horizontal leaves stretched on sticks. The water is then collected by pressing the leaves onto a basin. The following documented attempts concern massive dew **condensers**, working on temperature inertia, corresponding to a collection of mist. Such condensers are described below in section 2.3.

Radiative condensers have been the subject of several studies since the testing of massive condensers. Many areas of science and technology are indeed concerned with the process of **condensation and collection of** mist and dew, allowing many ideas for improvement to be experimented with: optics and atmospheric physics, radiative, conductive and convective heat exchange, hydrodynamics, chemistry, biology. Simple large planar condensers were erected (Figure 2a), more sophisticated dew factories consisting of "V" grooves (Figure 2b) were built. Many other types of radiative dew condensers (cone-shaped, origami, etc.) have been designed to increase cooling and dewdrop collection. They are presented in the book Dew Water (2018) [6].

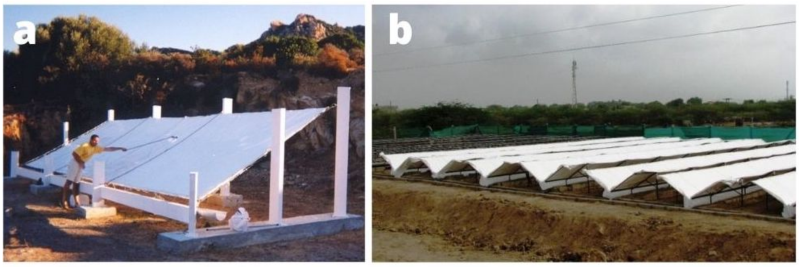

Figure 2. some large radiative dew condensers. (a) In Ajaccio (Corsica island, France). [Source: Photo D. Beysens]. (b) In Kothara (North-West India) [Source: Photo G. Sharan]

The interest of these radiative condensers is their **simplicity, their cost-effectiveness, their robustness** (they can still function even if partially damaged), and the fact that **no energy is required**. The process is sustainable, clean, and produces good quality water. However, the yield is limited to the available energy, about 60 W.m^{-2}, which limits the water yield to about 1 L.m^{-2}. However, the real yield is often much higher because the technologies used allow the recovery of low precipitation, usually lost.

1.2. Dew on plants

Dew condensation on plants can provide moisture and help combat periods of drought. Plants can take up water through their leaves to compensate for depleted water tables and survive drought. More complex scenarios can **help plants**, however. For example, the biological soil crust (Read: Lichens, surprising pioneer organisms) can retain and use dew water to increase the concentration of dissolved organic nitrogen, coupled with the fixation of atmospheric nitrogen by cyanobacteria and cyanolichens. Dew can also extend the life of seedlings under drought stress conditions.

On the other hand, dew, in addition to high relative humidity, can influence the occurrence of plant diseases, as moisture on plant surfaces promotes the **development of pathogens** and increases the frequency of disease in many crops. Cryptogamic diseases are observed on grass, banana and potato leaves. However, the development of these fungi can sometimes be beneficial. This is the case for the elaboration of some sweet wines. For example, the famous "noble rot" of the Sauternes vineyard is known to come from the action of the *Botrytis Cinerea* fungus.

2. How to collect the dew?

2.1. The dew yield

According to the previous sections, the collection surface must **reach the dew point to trigger condensation**. The surface area will therefore be lower than the air temperature and heat losses, increased by the wind, will be present. An energy balance can be written where, in steady state, the radiative cooling power R (in W.m^{-2}) (see Cooling comes from the sky) counterbalances the heating by the air losses, proportional to the difference between the air temperature, T_a, and the dew point temperature, T_d, and the heating by the latent heat release (Read: Pressure, Temperature and Heat), such that

$$R + a(T_a - T_d) + L(dm/dt)/S = 0.$$

Here S (in m^2) is the condensation area and a (in W.m^{-2}.K^{-1}) is the heat transfer coefficient [7], which increases with wind speed. The condensed mass is m (kg), related to the condensed volume V (m^3) by the density of the water r (kg.m^3) by $m = rV$. The time is noted t (in s). The quantity L is the latent heat (in J.kg^{-1}). We can easily deduce the volume of condensed water per unit area, classically expressed in liters per square meter, or mm. For the ideal case where the atmosphere has a high relative humidity , giving$T_a \sim T_d$, the maximum efficiency, limited only by the available power (see Figure 1 in Focus Cooling comes from the sky for its value as a function of air temperature and humidity) is of the order of 1 mm per night.

2.2. The radiative dew collectors

The oldest dew condenser known to us is reported in the "Mute Book" for Alchemists (Mutus liber, 1677 [5]) where sheets are attached horizontally to sticks and then wrung out by hand (Figure 1). In dew collectors, **two processes** must be considered, **the condensation of dew and the collection of drops**. Both processes are important. According to the previous section, dew yield increases with radiative power and decreases with wind speed. In Focus 1, details on radiative cooling are given. It is shown that the **cooling power is proportional to the emissivity (equal to the absorptivity) of the condensing surface -** the ability of a material to emit and absorb light - and the difference in the emissivity of the atmosphere with 1. This shows that, under given conditions of atmospheric emissivity and wind speed, **dew performance can be improved** by (i) decreasing the emissivity of the atmosphere, (ii) increasing the emissivity of the condensing surface, (iii) decreasing the heat exchange with the surrounding air, and (iv) increasing the efficiency of dew drop collection.

The emissivity of the atmosphere (item (i)) can be **reduced** by considering a condenser design that utilizes only the zenith angle of the atmosphere, where the emissivity of the atmosphere is lowest (see Figure 2 of Focus 1). The emissivity of the surface (point (ii)), if not too low, is that of water and cannot be changed. However, having a substrate with low emissivity and thus**absorptivity** only for the solar radiation spectrum allows for better cooling of the condenser at the end of the day and in the morning, making the dew condensation time longer.

Figure 3. Various dew collectors: a: Plan; b: Cone [Source: Photo O.Clus]; c: Origami and egg-box [Source: Photo D.Beysens]

Point (iii) concerning heat loss can be satisfied by using hollow shapes that reduce the influence of wind. A good thermal insulation should also be realized under the condensation surface to reduce the heat loss with the air. **Heat loss can be reduced by using symmetrical or quasi-symmetrical hollow structures** (grooves, origami, egg boxes, inverted pyramids, hollow cones, see figure 3). Grooves act as hollow shapes except when the wind is aligned with the rows (Sharan et al., 2017 [8], see Figure 2b). However, simple flat shapes, such as those encountered with roofs, can perform well if properly designed (see Figures 3 and 4).

Regarding drop collection, point (iv), passively **collecting** weak dew events **by gravity** without scraping is indeed a major challenge. There is a fundamental contradiction between having a zenith-facing surface and having a maximum surface tilt angle to facilitate gravity-based drop sliding. It has been shown [9] that a surface tilt angle between **20° and 30°** gives the best results.

Figure 4. drops sliding on a corrugated galvanized iron roof in Combarbala, Chile, with a small angle of inclination (≈15°). P: Part painted with additives (OPUR [12]) where dew forms and drops slide on the corrugations (arrows). NP: Unpainted part where dew does not form. [Source: J.-G. Minonzio]

Many materials have been tried to collect the drops by gravity. A first solution is to increase the natural wiping effect of the drops from the edges, which, by sliding earlier, sweep the other drops. An increase in dew yield of up to 400% has been observed with origami shapes [10]. Increasing the edge length has, however, a limit as it can also increase the heat exchange. Another solution is to locally increase the angle with the horizontal, as is the case for example with corrugated steel roofs (Figure 4). The **wetting properties of the surface** are also important. For example, additives give better slip (and emissivity) properties to paints, as shown in Figure 4. Increasing the roughness by sandblasting also gives good results because the number of nucleation sites [11] is increased. **Micro-grooved surfaces** are found to significantly improve drop collection. There is an extensive literature on the subject because improved drop slip also increases the efficiency of heat exchangers by a significant factor. However, although several solutions exist in the laboratory to improve drop collection, such as the "Lotus" effect, where the clinging of drops on the surface is very weak (Read: Between protection and defense: the plant cuticle), they roll down easily, the main **challenge remains the aging of materials** . It is very difficult to maintain good sliding properties over many operating cycles, especially in outdoor conditions. Paints with additives have been shown to last at least 10 years. Low-density polyethylene sheets with a UV additive can last 3 to 4 years. Sandblasting and grooving, although not yet systematically tested outdoors, seem to be a good solution for long life.

2.3. solid dew collectors

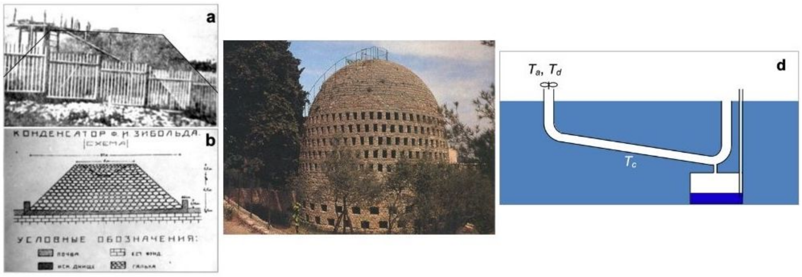

Figure 5. massive condensers. (a-b) Zibold condenser. (a) Photo with the platform for instrumentation (adapted from Tougarinov, 1935 [15]). The condenser is highlighted by black lines.(b) Schematics. [Source: Adapted from Totchilov, 1938 [16]. (c) Knapen condenser in Trans-en-Provence (France), still visible (2017) [Source: Photo D. Beysens]. (d) Schematic of an underground massive condenser where air is only blown in if T_a, the air temperature < T_c, the underground temperature or if T_c < T_d, the dew point temperature of the air.

Massive condensers work by thermal inertia, cooled below the dew point temperature during the coldest time of the year. The Russian engineer Zibold believed - erroneously, see Nikolayev et al. (1996) [13] - that dew water was an important source of water used by the ancient Greeks to supply the 101 fountains of Feodosia (Crimea, Ukraine). Zibold, however, mistook the numerous piles of stones on the hill above the city for dew condensers. He built a massive dew condenser in 1914 (Figures 5ab; Mylymuk-Melnytchouk and Beysens, 2016 [14]) based on these stone piles: a truncated cone made of marine pebbles with a hollow at the top. The very low water yield was supposed to be due to cracking of the condenser base. The project was definitively stopped with the Bolshevik revolution of 1917. Archaeological excavations on Mount Tepe-Oba above Feodosia later proved that these rock piles were Scythian or Greek tombs, protected by rocks (Nikolayev et al. 1996 [13]) against grave robbers, the hollow at the top corresponding to the traces of the unsuccessful efforts of the robbers

Soviet scientists [14], as well as their Belgian (Knapen [17]) and French (Chaptal [18]) counterparts, who had heard of the Zibold condenser, became interested again in the collection of dew water by this massive condenser technique. However, although Knapen built a fairly sophisticated condenser (Figure 5c), the efficiencies were always found to be very low because the inertia was for durations of days or weeks, not seasons. Such low efficiencies simply reflect the fact that the average temperature of massive condensers rarely falls below the dew point temperature of the air. Chaptal deconstructed his condensation pyramid "so as not to mislead future generations". Although disappointing, the efficiencies of massive condensers could be improved by new studies taking into account the **temperature of the subsoil,** as for the Canadian wells where the inertia gives much longer condensation times, and by using more sophisticated technologies (Figure 5d).

2.4. Active Dew Collectors

Cooling can also be provided by an active device similar to those used in refrigerators. Power, usually electrical, must be supplied. Commercial systems exist (see for example www.candew.ca, the efficiency is of the order of 0.5 -1 kWh/L depending on atmospheric conditions. However, they are still quite expensive.

3. Can we drink the dew water ? Chemical and biological quality

Dew water is the result of the condensation of water vapor. One might think that it is as pure as distilled water. However, dew forms **on a substrate outside**. The dew-atmosphere and dew-substrate **interactions** will then give dew water its specific chemical and biological properties.

3.1. Chemical composition

Dew can interact with its substrate by **partially dissolving it** (e.g. when the substrate is zinc [19]). Dew also interacts with the atmosphere. The latter is characterized by gases, which can be absorbed by water, and aerosols, which settle on the substrate, acting as nucleation sites [11] for dew condensation and reacting with the condensed water. Three steps then govern the chemical composition of the dew: (i) the formation of dew on the deposited solids, (ii) the dissolution of the soluble part of these deposits by the dew water, and (iii) the absorption of gases into the dew solution.

Carbon dioxide plays a special role in the formation of liquid phase acidity because of its high and constant concentration. An important pathway in the formation of alkalinity (carbonate) is through condensation nuclei (nucleation [11] and droplet formation) as well as aerosol trapping. The ability to capture particles, e.g. $CaCO_3$ from buildings or carbon particles from diesel cars, is very important for the chemical composition of the dew and is strong at the beginning of the condensation process and weakened at the end. The acidity of dissolved CO_2, SO_2 and NO_x (x = 1, 2) is mainly neutralized by Mg^{2+}, Ca^{2+} and NH_4+; sometimes a slight alkaline character is observed in the dew samples. The dew events with the highest ionic concentration occur after long periods without rain. It should be noted that the elevated concentrations in dew water of SO_2 (yielding sulfuric acid), NO (nitrous acid) and NO_2 (nitric acid) are mainly of**anthropogenic origin**, i.e. originating from **air pollution by human activities** (industry, agriculture, transport).

The absorption of very soluble gases by atmospheric water is very fast. It will therefore not be affected by the short dew formation time. In equilibrium with atmospheric CO_2, the concentration of HCO_3^- is an exponential function of the pH value. When the pH of the solutions is above 6.35 (pKa1 of H_2CO_3), the [HCO_3^-] concentration can become significant. But the components of the atmospheric multiphase system are most likely not in equilibrium with atmosphericCO_2 due to complex chemical compositions, microphysical processes and heterogeneous interactions. The concentration of HCO_3^- can then only be obtained by analytical estimation and not by derivation from Henry's law [20].

The composition of dew water is thus a function of both the**long-range convected atmosphere and locally produced gases and aerosols**. The source of anthropogenic and natural species can be found by various techniques, including air mass trajectories and stable isotope analyses. In general, regional urban pollution has a significant influence on dew water chemistry. In Table 1, the average composition of dew and a low mineralized spring water (Mt. Roucous) are presented for comparison; they compare relatively well.

Table 1. Chemical composition of dew measured in Bordeaux (annual average, after Beysens et al., 2006 [21]). It compares well with the Mont Roucous spring water, which has a low dissolved solids concentration.

Measurement	Dew	Mt Roucous
pH	5.88	6.0
Conductivity (µS/cm)	29 (25°C)	25 (20°C)
Na^+, mg/l	2.85	2.80
K^+, mg/l	0.25	0.40
Ca^{++}, mg/l	0.35	1.20
Mg^{++}, mg/l	0.35	0.20
Cl^-, mg/l	4.8	3.20
SO_4^{--}, mg/l	2.5	3.30
NO_3^-, mg/l	0.5	2.30
NO_2^-, mg/l	<0.01	
Dry residue (180°C), mg/l	10.3	19.0

3.2 Biological characteristics

Biological contamination of substrates comes from the **deposition or droppings of** insects, birds, and small mammals, decomposition of organic debris, and atmospheric deposition of suspended microorganisms, as well as from human contamination. Contamination is generally unavoidable because dew condensers are placed in an open environment. The biological effects associated with dew are different in nature depending on whether the substrate is living, such as plants, or inert.

The biological quality of dew water collected from inert substrates depends on whether the microorganisms deposited on the substrate are safe for humans. Analyses are generally performed on (i) aerobic bacteria measured in colony forming units [22] at 22 °C and (ii) at 36 °C. The first group (i) generally corresponds to harmless, plant-based microorganisms from the environment. The second group (ii) is contributed mainly by insects, bird droppings, mammals and human contamination. More specific research on human microorganisms (Enterococus, Coliforms) has also been conducted.

Contamination by microorganisms is fortunately limited by ultraviolet solar irradiation of the dew condenser surfaces [21]. Nevertheless, biological analysis of dew and rain shows that the World Health Organization limits are often exceeded. **To become potable, disinfection, e.g. by chlorination, is therefore recommended.**

4. Biological sterilization by condensation

The fact that condensation can occur anywhere on a substrate, even in areas of difficult access, can be used to **disinfect rooms and medical instruments** (e.g. endoscopes) provided that a sterilizing or antiseptic agent is added to the steam (Marcos-Martin et al., 1996 [23]). These additives are chemical vapors (e.g., ethylene oxide, formaldehyde, chlorine dioxide or hydrogen peroxide). Sterilization is indeed the result of complex chemical reactions involving alkylation or oxidation and reduction reactions, which produce free radicals such as the **hydroxyl radical**, one of the most powerful oxidants.

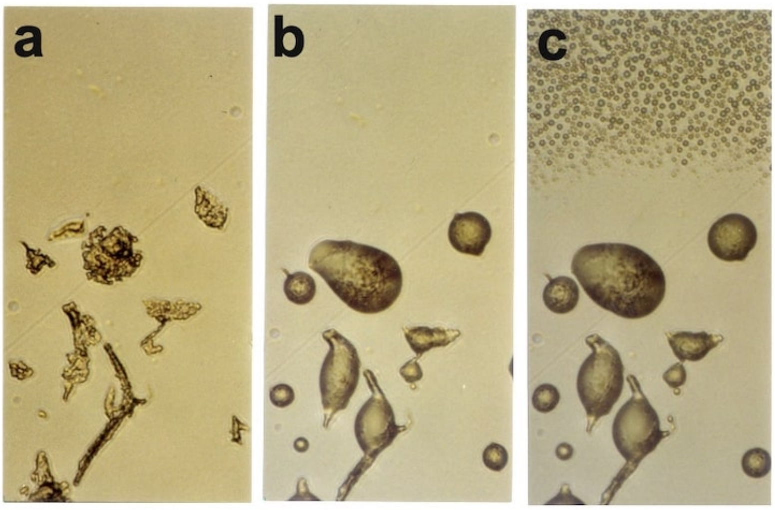

Figure 6. Freeze-dried spores of Bacillus macerans on silanized glass. Experimental conditions: water-saturated air at 37 °C, substrate maintained at 18 °C and flow rate of $10^{-6} m^3 s^{-1}$. Time after the start of the vapor flow: (a) 0s; (b) 0.5s; (c) 3s.). [Source: Photo D.Beysens]. In (b) the organic materials are wetted while the substrate remains dry.

Figure 6 shows the condensation on a substrate (fluorochlorosilane FClSi coated glass) where the water drops have a contact angle of 90-110°. On the substrate are initially deposited freeze-dried spores of Bacillus macerans (Figure 6a). When water-saturated air at 37 °C is blown onto the substrate, condensation initially occurs only on the spores (Figure 6b). Later (Figure 6c), condensation can be seen on the bare substrate, with an inhibited nucleation region [11] around the wet spores. This phenomenon is typical of hygroscopic materials such as droplets of aqueous NaCl solutions where the saturation pressure is lower than that of pure water droplets at the same temperature. Note that if the water vapor was stopped at the stage shown in Figure 6b, no condensation on the substrate would have occurred even though the microorganisms were wet with water (and sterilizing additives if they were included in the vapor). This invisible condensation process is called "microcondensation". Sterilization by moist air plus additives or steam plus additives without air is currently applied by some companies to disinfect hospital rooms and sterilize surgical instruments (see for example Advanced Sterilization Products [24] and Bioquell [25]).

5. Take-home messages

Dew is often mistakenly considered as a form of precipitation and **confused with fog**. Natural dew must also **be differentiated from fog, which is the result of condensation of water** on the cold walls of caves and damp rooms where the cooling comes from the thermal inertia of the wall.

The efficiency of natural dew is mainly **limited by the available cooling energy**, which hardly exceeds 100 $W.m^{-2}$, leading to a theoretical maximum efficiency of about 1 $L.m^{-2}$ per night.

Natural dew can make a **significant contribution to the water balance** and provide additional water for desert plants and animals, not only in arid and semi-arid areas, but also during dry summer seasons when drought can last for several weeks or months.

Dew harvesting for human use has recently reached a stage of near realization due to a better understanding of the associated physics and thermodynamics, the combination of new materials and the shapes of condensers, conical, pyramidal, origami.

The **chemical properties** of the dew water come from the substances (gases and aerosols) present in the atmosphere near the condenser. They can also be related to the interaction with the condensation substrate itself.

Biological contamination of dew water comes from spores and bacteria of plant, animal and human origin. It is atmospheric in origin or comes from direct deposition by insects, birds, small mammals, humans and airborne microbes. This contamination is usually unavoidable because dew condensers are placed in an open environment. This means that dew water **must be disinfected for use as a beverage**.

Sterilization by fogging. Similar to dew condensation, but indoors, sterilization of medical instruments and hospital rooms is done by condensing water with specific sterilizing elements.

Notes and references

Cover image. [Source: https://pixabay.com/ - Royalty free image]

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Pour citer cet article: **Auteur :** BEYSENS Daniel (2024), Dew, Encyclopédie de l'Environnement, [en ligne ISSN 2555-0950] url : http://www.encyclopedie-environnement.org/?p=16535
