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THE CASE FOR ALTERNATIVE FRESH WATER SOURCES

D. Beysens [1, 2] and I. Milimouk [2, 3]

[1] Commissariat à l'Energie Atomique, Equipe du Supercritique pour l'Environnement, les Matériaux et l'Espace, Institut de Chimie de la Matière Condensée de Bordeaux, Av. du Dr. A. Schweitzer, F-33608 Pessac Cedex, France

[2] International Organization for Dew Utilization, 26, rue des Poissonniers, 33600 Pessac, France

[3] Centre National de Recherche Scientifique, Equipe du Supercritique pour l'Environnement, les Matériaux et l'Espace, Institut de Chimie de la Matière Condensée de Bordeaux, Av. du Dr. A. Schweitzer, F-33608 Pessac Cedex, France

Abstract

This paper describes alternatives to the traditional methods of obtaining fresh water. It covers the recovery of atmospheric humidity, fog and water vapour, in addition to seawater desalination, which is analysed briefly. It examines fog recovery while focusing more closely on how the condensation of atmospheric water vapour (dew) has been realised in the past and why higher yields can now be envisaged. Adsorption processes using regenerative desiccants are also considered.

Introduction

The assertion that water has always been the essence of life is nothing new. Water comes in many forms: spring water, sea and river water, rainwater, and fog and dew water. Yet water is becoming scarce and this scarcity is becoming a very real worry, proving to be one of the main obstacles to the economic development of countries lacking fresh water.

We will analyse "alternative" sources to the traditional water sources here. These alternative sources are 'new' water sources. In order to appreciate the problem fully, we must ask ourselves a few questions.

(1) What are current water requirements? Figures show that an inhabitant of a modern town consumes 100–400 litres of water daily. This is of course an inhabitant of a "rich" country as, even now, in some developing countries the figure does not exceed 20-30 litres per day. Furthermore, annual water consumption continues to grow, increasing fourfold over the last 50 years to stand currently at over 3×10^{15} litres (3,000km^3). This level of consumption is unlikely to decrease. A second question follows logically from the first:

(2) What are the main fresh water sources? The world's fresh water reserves are estimated at 35 million km^3 (compared to the combined total of 1,400 million km^3 of both fresh water and salt water). This includes glaciers and snow (24 million km^3), ground water (10.5 million km^3), artesian wells, rivers and lakes (0.1 million km^3). It also includes atmospheric precipitation, such as rain and snow (13,000km^3), which contributes to the sources mentioned above.
In addition to the traditional water sources, there are other possibilities to be considered here.

Seawater desalination

There is indeed much more water than dry land on the surface of the planet, hence the idea of using this other source of fresh water: desalinated seawater. However, the annual quantity of desalinated water worldwide only amounts to approximately $10 km^3$, not a vast figure given the amount of water processed.

Small solar stills can be used to desalinate seawater, using the greenhouse effect to evaporate the salted water and condense the water vapour on a pane of glass at outside air temperature. The water is then recovered by gravity[1]. The only energy required for this method is for collecting the seawater and extracting the brine. On the Saloum islands (Senegal), the method successfully produces small quantities of fresh water (a few litres per m^2 per day)[2].

When used on a larger scale, a major drawback of the traditional systems, which are based on distillation by evaporation-condensation cycles or filtration through a membrane, is that they are expensive owing to high energy consumption. The best systems burn at least a tonne of fossil fuel to produce approximately one hundred cubic metres of fresh water, at most, representing a current cost in the region of \$1 per m^3. The considerable influence on the climate is another serious consequence of such an increase in fossil fuel use. Moreover, the significant quantities of brine produced by all the techniques must also be taken into account.

Further difficulties lie in the fact that this method is particularly prone to contamination and the yield is inversely proportional to the increase in temperature of the water to be desalinated. It would therefore be interesting to consider other non-traditional methods of obtaining fresh water that are less expensive and more ecological.

Atmospheric water vapour

What are the sources and possibilities of obtaining more water?

Paradoxically, we have very extensive water reserves that we have difficulty in exploiting. The atmosphere contains $12{,}900 km^3$ of fresh water, composed of 98% water vapour and 2% condensed water (clouds), a figure comparable to the renewable liquid water resources of inhabited lands ($12{,}500 km^3$). The sums are easy, but being able (and knowing how) to obtain this water in liquid form is crucial. The first, fundamentally important, problem has been solved (cf. the following paragraph), but extracting liquid water from the atmosphere economically is another matter. It is difficult and sometimes costly and the techniques are not fully developed as yet.

Some physics

Air, composed primarily of nitrogen (78%) and oxygen (21%), contains varying amounts of water in vapour form, depending on its temperature and pressure. The amount of water in the atmosphere is calculated from its partial pressure (p) within the air mass. At a given temperature (and pressure), the partial pressure cannot exceed a certain level without condensation occurring; this is the saturation pressure (p_s). The relative humidity (RH) is then defined as the ratio of partial pressures ($HR=p/p_s$). The p_s rises in conjunction with the increase in air temperature (or pressure) and the water mass capacity of $1m^3$ of air also rises. For air at a given temperature and RH, the psychometric diagram – representing the mass fraction of water in the air at different temperatures and RH – allows the air's water saturation point to be ascertained. This is "dew temperature", the temperature at which water vapour condenses. For instance, the dew temperature of air at 20˚C and 80% relative humidity is 18˚C. The dew temperature falls to 10˚C if the RH is only 25%.

On most substrata, condensation occurs in the form of droplets, representing partial wetting of the substrate by liquid water. As they expand, the droplets touch and merge, their growth becoming self-similar over time[3]. The astonishing result is that with this growth, a substantial proportion of the medium remains dry (ideally 45%).

So how can water be obtained from the air? Firstly, there are methods that allow harvesting of the obvious manifestations: fog and dew.

Fog nets

Many places on Earth have favourable condensation conditions[4]. In the coastal deserts of West Africa (Namibia) and South America (Chile and Peru), for instance, ocean humidity condenses in the form of fog on the mid-range mountains (over 500m). For most of the year, this fog covers the whole coastal desert area in a thick grey veil.

Clearly, it is easier to collect fog than dew. Fog is already composed of droplets of suspended liquid water with a diameter below a few dozen µm. The water vapour condenses on small particles in the air (e.g. dust). Accordingly, the water is extracted by simply collecting the droplets mechanically. So-called "Spring Trees" in the

Canary Islands fulfil this role naturally[4,5]. In the 1960s, the Catholic University of the North in Antofagasta in northern Chile conducted the first conclusive experiments with nets[6,7]. Variations of these experiments by Schemenauer and his colleagues[8] on a larger scale in the 1980s led to the harvesting of drinking water for a small fishing village. Each collector consisted of a 48m² upright plastic mesh (Fig. 1) and despite the dry years, the structures yielded a daily average of 11,000 litres of water[9]. A major European programme in the late 1990s, in the Arequipa region of southern Peru, continued the experiments begun in Chile[10]. Very recently, but on a smaller scale, fog-collecting nets have been erected in the Canary Islands (Tenerife) and Namibia.

This method's productivity depends on the amount of condensed water in the atmosphere and requires the combination of two conditions. Firstly, the air temperature must be lower than dew point. Secondly, the atmosphere must offer condensation sites (such as solid or liquid hydrophilic surfaces).

Dew condensers

Fog, however, is an atmospheric phenomenon that occurs with any frequency in only a few places because it depends on the combination of several specific climatic conditions (we will not go into these here). Conversely, dew appears much more frequently and is less subject to the constraints of climatic and geographical coincidences. However, dew does not form just anywhere, although conditions are favourable if the air is even a little humid and the sky reasonably clear. Many hot countries suffer from a lack of water, yet it is present in significant quantities in the atmosphere. It hardly ever rains in the Sahel, for instance, but absolute humidity in the atmosphere's lower layer can reach approximately twenty grams per cubic metre during boreal summer owing to the southwest monsoon winds. The water-harvesting possibilities from the air are astonishing. By lowering the temperature ten degrees or so, approximately ten grams of water can be obtained from each cubic metre of air.

Unlike fog recovery using trees or nets, which is only feasible in certain very humid regions at high altitude such as in Chile or the Canary Islands, substantial dew formation can occur even in a relatively dry atmosphere, such as in continental desert. All it takes is for the substrate's temperature to fall to below dew temperature, the temperature at which water vapour is over-saturated and changes into liquid water, as explained above (Fig. 2).

- *Dominant factors*

A substrate's temperature depends on several factors. Heat exchanges can take place by conduction with the ground or the atmosphere itself and through radiation. The actual condensation process must also be taken into account, accompanied by latent heat production that increases the substrate's temperature.

The exchanges with the atmosphere, which tend to bring the medium to the same temperature as the atmosphere, cannot cool the substrate to dew temperature. The medium becomes closer to atmospheric temperature as wind levels increase since the thickness of the outer layer where thermal exchange takes place decreases proportionately (Fig. 2b).

To put it more simply, radiative exchanges have two antagonistic actions: heating (by solar radiation) and cooling (primarily in the infrared field). By day, the heating prevails over the cooling. At night, the reverse is true and the substrate cools down again. Of course, greenhouse gases present in the atmosphere, such as carbon dioxide and especially water vapour, restrict infrared cooling. The cooling can even be halted entirely by dense cloud cover.

Thus, two main categories of dew condenser can be identified. The first are the "massive" condensers that produce very high specific heat to maintain their temperature as constant as possible despite latent condensation heat levels (condensation on cave and cellar walls). Secondly, there are "radiative" condensers – which are lightweight and thermally insulated (natural dew) – whereby, ideally, energy from the radiative cooling only serves to compensate the latent heat uptake.

- *Dew "springs" and "ponds"*

Mankind began trying to collect dew as a source of fresh water long ago, and realised that water could appear for no apparent reason. Several accounts, and even legends, tell of dew being harvested artificially. In the Tourane steppe in the former USSR, for instance, there is a large artificial embankment composed of crushed stones. At the top of the embankment, there are Scythian religious constructions. Lower down, at 1.5m, two springs provide plentiful supplies of very pure cold water. Surprisingly, there are no natural springs near this artificial mound[11,12].

A further example can be found in Altaï, another region of Russia, where there are large kurgans (Scythian tombs), the tops of which measure 70m in diameter. A layer of permanent ice lies inside each, even though there is no permanent ice in the region[11,12]. Could this not be condensation?

We have also heard about artificial dew ponds in England, built in the Middle Ages[12,13]. They were emptied in the evening by the locals but by morning were full of water once again. Their construction was very straightforward: in dry areas, bowl-shaped hollows several cubic metres in size were dug in the ground. The base was covered with a layer of dry straw and another of clay. It was then covered with a pile of stones. The pond was now ready to function and began to fill with water even in the absence of atmospheric precipitation (rain or snow).

In the Canary Islands, vines are planted in the centre of a conical depression in volcanic ash and the dew is believed to be the source of the moisture required for their growth[6,14].

It therefore seems that atmospheric water condensers must have existed in the past. They are both familiar and alien to us. They are familiar thanks to numerous legends, stories and accounts, but are alien because currently we have few documents proving these tales to be true.

- *Massive aerial condensers*

The existence of such condensers in the 20th century can, however, be confirmed. Belgian Achille Knapen (honoured by the French engineers' association, the *Société des ingénieurs de France),* took 18 months, from July 1930 to the end of 1931, to build an immense tower in Trans-en-Provence. Within the tower was a "puits aérien", or "aerial well", which was nine metres high and one metre in diameter[15] (Fig. 3). However, this represented eighteen months' fruitless effort. Far from satisfying expectations, on the best nights, Knapen only recovered a bucketful of water and the construction fell into disuse.

Knapen was inspired by Léon Chaptal (head of the Agricultural Physics and Bioclimatology Station in Montpellier), who, in 1929, constructed a pyramid two and a half metres high and three metres wide[16]. In 1930, Chaptal's condenser had enabled approximately one hundred litres of water to be harvested during the six hottest months, between April and September. Less favourable conditions the following year caused this figure to halve.

Léon Chaptal in turn had been inspired by the encouraging results of a daring experiment by Russian engineer Friedrich Zibold. In the summer of 1900 in Feodosiya, Crimea, during the levelling of the forest district, Zibold discovered large conical piles of stones, approximately 600m³ in volume. In most cases, there were remains of terracotta piping surrounding these tumuli. Zibold thus drew the conclusion, which later proved to be incorrect[17,18] but which led to an amazing construction, that the stone stacks were dew condensers and that the tumuli supplied former Feodosiya with drinking water.

F. Zibold used two significant approaches in verifying his hypothesis. Firstly, in 1906, he wrote a book explaining the potential of atmospheric water condensation: "Underground Dew and New Theory on the Ground Origins of Spring Water"[12]. He then built a condenser (Fig. 4) that worked according to the very same principles, he thought, as those of the old condensers. Zibold chose as the location for his experiment a site at the top of mount Tepe-Oba, near Feodosiya, at an altitude of 288m. He built a stone condenser in the shape of a bowl, 1.15m deep and 20m in diameter. The bowl was filled with sea pebbles 10-40cm in diameter, stacked in the shape of a 6m-high truncated cone, 8m in diameter across the top. The condenser entered operation in 1912 and gave a daily yield of up to 360 litres. The experiments had to stop in 1915 owing to leaks in the base, and the condenser, partially dismantled, was completely abandoned. Today, only a huge 20m-diameter bowl remains, which we cleaned up in 1993 during our mission to Crimea[17,18]. Zibold is nevertheless regarded as a pioneer for having constructed a full-scale atmospheric condenser. It appears to be the world's only condenser to have provided a significant yield. So why did others fail? This question leads to the more fundamental question of whether passive condensation can be used to produce substantial quantities of water. Zibold and his successors made a serious mistake, as their collectors, which reached high temperatures, did not cool efficiently. Our theoretical studies, which take into account the different exchanges between the ground and the atmosphere[18], show that the yield decreases dramatically when the mass to surface ratio increases.

This is what happened in the case of massive condensers such as Chaptal's and Knapen's. Zibold's condenser owes its relative success to two elements in its construction: the stack formation of the sea pebbles allowed radiative cooling of the outer layers and prevented anything but the slightest thermal contact between the pebbles. The condensation mass to surface ratio therefore proved to be relatively important.

The "ideal" dew condenser is completely different to these early 20th century theories based on very large structures. It must be light so that it cools down quickly at night (Fig. 2). In fact it is like grass in a meadow which, when dew-covered, represents a major source of water for many living creatures, both large (sheep in Scotland, horses in Namibia) and small (insects). Even in the desert, this same process is used by some plants to obtain the water they need from their leaves.

- *Radiative aerial condensers*

The yield of radiative cooling condensers is limited by the radiated night power, which is in the region of 25 to 150 Watts/m². Ideally, if all this power were used to condense the water vapour, to compensate for the latent condensation heat (2500Joules/g at 20°C), a simple calculation shows that the maximum nightly yield could not exceed around one litre per m². One hectare could therefore produce 10,000 litres per night. Consequently, even if in practice "wild" dew on a natural ground surface does not exceed 0.5 litres per m², the dream of recovering dew is by no means unrealistic. Condensers made of polyethylene sheets were used for plant irrigation in Israel in the 1960s[19]. More recently, in 1986 in New Mexico (USA), condensers made of special foil produced sufficient water to supply young saplings[20,21].

Scientific attempts to create an efficient and cheap condenser have not yet been abandoned[22]. Firstly, as regards the quest for an inexpensive radiant material, a polyethylene film filled with titanium oxide micro-particles has been devised by Nilsson[23], who tested it in Tanzania[24] on a dew condenser consisting of a 1.44m² inclined plane. Yields of approximately 0.1 litres per m² were obtained. There is ongoing research into the architecture of these radiative condensers, whose greatest enemy is the wind since it heats the condensation surface. Inverted conical structures reminiscent of Zibold's condenser have recently been tested in Benin[25].

In 1995, we conducted a number of preliminary experiments on two sites in Tunisia on small horizontal dew-condensing plates (0.25m²). The first site was located in the desert (Tozeur) and the other on the coast (Hergla, 20km north of Sousse). In Tozeur, the work was carried out at the airport's meteorological station, with full benefit of the station's facilities for measuring ground temperature, wind speed, cloud cover, etc. In Hergla, the experiment was conducted on an open terrace, approximately 10m off the ground. The experiments resulted in the collection of quantitative data for validation of the model in Reference 18. They also underlined the key role of the condenser's architecture with regard to wind use, since the wind carries the water vapour necessary for the condenser to operate, but also heats it and can completely prevent condensation from occurring.

Since 1999, we have been taking parallel measurements of dew formation at the Grenoble centre of the French Atomic Energy Commission (CEA)[26] and at the University of Corsica's Vignola laboratory near Ajaccio[27]. The quantity of dew settling on a standard 0.16m² plate is weighed continuously and compared to the theory[18], which requires simultaneous local temperature, humidity and wind speed readings to be carried out on-site. The Vignola results are chemically analysed to monitor dew water quality. We have just built a large condenser (30m²) on this site for more extensive study of the problems related to dew recovery. Following studies on a 1:10 scale model and the digital simulation of airflow around a sloping plate, a decision was made to build a condenser comprising a 10m x 3m flat plate tilted at 30° and positioned perpendicular to the prevailing winds. This angle decreases the wind's (heating) influence and allows the dew drops to drip efficiently. The plate is positioned facing westwards so that the rising sun does not immediately shine directly on it. This positioning allows dew recovery to continue in the morning (precisely when the atmospheric temperature is closest to the dew temperature) even after sunrise (Fig. 5). The initial results are very encouraging, showing dew formation two to three times higher than on the standard plate, with daily yields from July to December 2000 of 0.1-0.4 litres/m².

- *Seawater condensers*

An alternative method to radiative cooling can be used on the coast. In this case, a heat exchanger cooled by deep-sea water (typically pumped from a depth of 500m, at a temperature of 4.5°C) receives a current of air[28] (which can be humidified by surface seawater dripping like rain in off-the-shelf seawater greenhouses available from a British company[19]). There is one such device on a platform in Crimea, near Katsiveli, opposite a division of the Ukraine Maritime Hydrophysics Institute[30]. Clearly, these systems require considerable energy for the pumps and ventilators (approximately 5KW per m^3 per day[28]). The energy linked to the high levels of latent heat of condensation, however, is provided by water pumped from the depths of the sea.

- *Adsorption-desorption on desiccants*

A third type of atmospheric water collector uses desiccants (silica aerogels, zeolites), which adsorb atmospheric water at ambient temperature. For regeneration, the desiccant needs to be heated to 150-300°C. The water vapour is then recovered by means of condensation at normal temperature. Here too, for the early equipment now on the market, a considerable energy supply – at least equal to the latent heat of evaporation – is necessary to recover the adsorbed water[32]. However, there are prototypes in which daylight provides this energy[33]. In this case, the method is as follows: air is ventilated at night over a bed of desiccants that adsorb the water vapour. During the day, the premises are closed, the greenhouse effect increases the temperature and, as in solar desalination pools, the water vapour is partially desorbed, condenses on a cold part and is collected. The only energy required is for the ancillary equipment (ventilators, etc.).

Conclusion

Atmospheric water vapour recovery for human needs, not yet exploited on a large scale, could become a reality in the future. Although at present only small amounts of water are recovered, this method is interesting because water could be obtained even in arid regions, including deserts. Perhaps one day an optimal condensation process will be found, making our water inexpensive and ecological.

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KEY TO FIGURES

Fig.1. Fog-collecting nets in Padre Hurtado (Chile). Each net is 4m tall and 12m wide. The site, which is at an altitude of 800m, comprises ten collectors. (Photo: R. S. Schemenauer)

Fig.2. (a) Correlation between dew deposits and temperature for the night of 26th to 27th November 1999 in Grenoble (France). Curves showing the calculated mass and the condensation plate temperature are automatically calculated according to the theory in Ref. 18, without considering evaporation. They show that the dew appears when there is a negative difference between plate and dew temperature. (Surface area of plate: 0.16 m^2; water obtained: 19 g. This represents 0.12 l/m^2.)

(b) Correlation between wind speed, cooling of the plate and dew deposits for the night of 6th to 7th January 2000 in Grenoble (France). The increase in wind (day 1, 03h 46min., shaded area) results in an inflection in plate temperature and dew deposits, both of which decline.

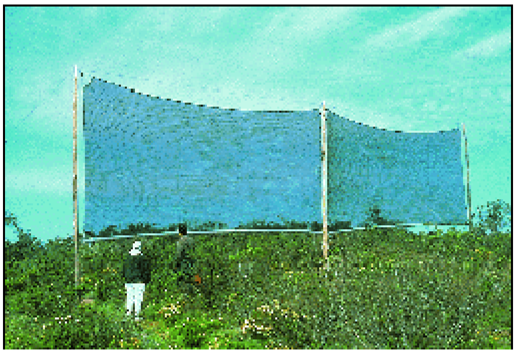
Fig.3. A. Knapen's condenser in Trans-en-Provence (France) in its present state. (Photo: D. Beysens)

Fig.4. Zibold's condenser (model reconstruction) in Feodosiya (Crimea, Ukraine). (Photo: D. Vinçon)

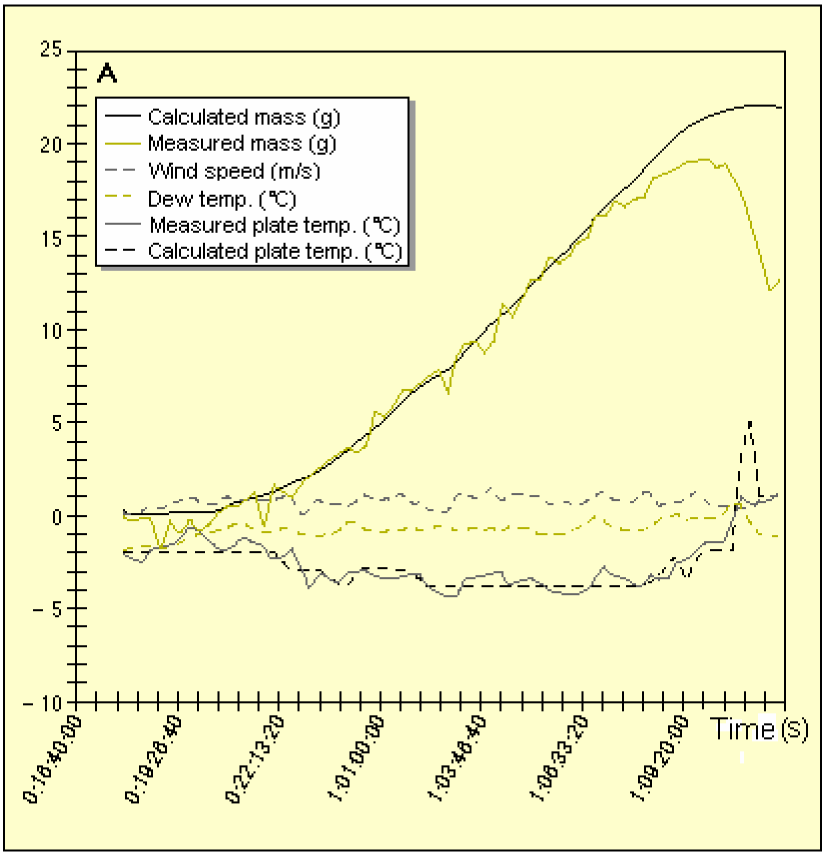
Fig.5. Vignola dew condenser. Dew also forms during the day, provided the sun does not directly heat the condensation surface. (Photo: D. Beysens)

Figures

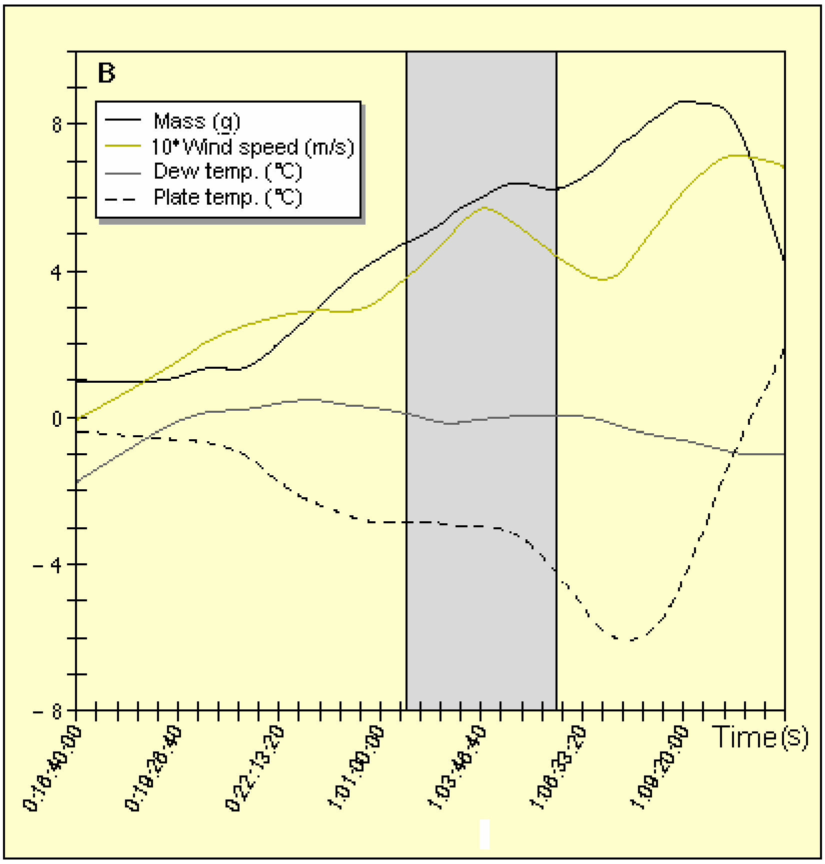
1.



2(a).

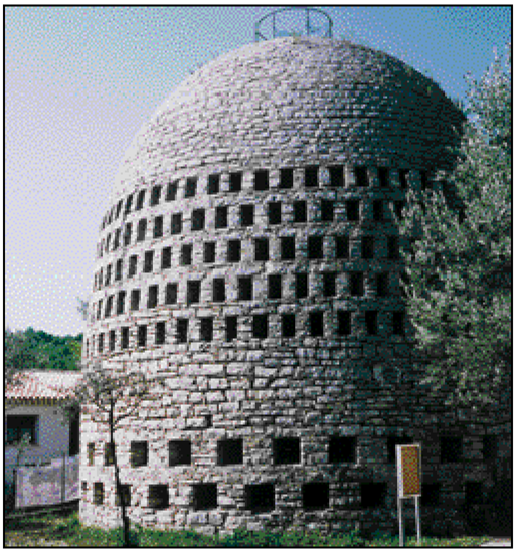

A
Calculated mass (g)
Measured mass (g)
Wind speed (m/s)
Dew temp. (°C)
Measured plate temp. (°C)
Calculated plate temp. (°C)
25
20
15
10
5
0
- 5
- 10
0:16:40:00
0:19:26:40
0:22:13:20
1:01:00:00
1:03:46:40
1:06:33:20
1:09:20:00
Time (s)

2(b).



B
Mass (g)
10*Wind speed (m/s)
Dew temp. (°C)
Plate temp. (°C)
8
4
0
- 4
- 8
0:16:40:00
0:19:26:40
0:22:13:20
1:01:00:00
1:03:46:40
1:06:33:20
1:09:20:00
Time(s)

3.



4.

5.