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Dew plant for bottling water

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Abstract

In a context of climate change and increasing need of fresh water in the world, rain and dew water can have a significant impact as new sources of water, especially in arid and semi-arid areas. The aim of the paper is to demonstrate that atmospheric moisture can be harvested and processed into safe drinking water comparable in quality and price to reverse osmosis processed water available in the market. The paper describes the construction and functioning of a water production plant in northwest India (Kothara). Rain and dew are collected; for dew special attention has to be taken. In particular, special condenser architecture (ridges) is designed using Computational Fluid Dynamics simulation and improved condensing surfaces are operated. Dew yields are estimated from the meteo data and using simulation. From the figures an economic model is derived; it comes out that water passively harvested from atmospheric moisture may be cheaper than that from reverse osmosis and does not pollute the environment, supporting the importance of dew and rain resources to provide supplementary supply of potable water in arid and semi-arid environment.

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Highlights

-Construction of a drinking water production plant to harvest atmospheric moisture

-Atmospheric moisture gives water comparable in quality and price to reverse osmosis

-Atmospheric moisture water is clean and does not pollute the environment

-Dew yields estimated from meteo data and Computational Fluid Dynamics

-Derivation of an economic model

Keywords

Dew Harvest, Rain Harvest, Drinking water, Coastal Arid Areas, Dew Condenser, Computational Fluid Dynamics.

1. Introduction

The increasing need of fresh water in the world and especially in arid or semi-arid regions led recently to seriously consider rain and dew precipitations as new source of water. Collecting rain water is simple, but harvesting dew is more challenging. Although long ignored, dew water offers indeed a renewable complementary source of potable water for arid or isolated areas. There are many legends that report dew harvesting as noted by Beysens and Milimouk (2001) and Mylymuk-Melnytchouk and Beysens (2016). It is only recently that dew condensers have been constructed on accurate physical grounds, enabling dew to be collected with a sufficient yield.

What is dew? Dew is produced from air water vapor condensation on a substrate that gets cooled because of nocturnal negative radiation balance between the substrate and atmosphere. Yields are primarily limited by the available cooling energy, which does not exceed 100 Wm⁻ ², leading to a theoretical maximum yield of the order of 0.8 Lm^{-2} per night. Practically, due to heat losses with wind, cloud coverage and limited air humidity, the maximum yield is rather 0.6 Lm⁻² per night as observed by Clus et. al. (2009). In the last decades systematic investigations of high yield radiative materials with hydrophilic properties for water condensation at small supersaturation and improved drop recovery have been performed (see the review by Tomaszkiewicz et. al. (2015)). The simplest condensers are planar panels made of high emissivity plastic film insulated underneath that are oriented 30° with horizontal, the "best" angle as determined by Beysens et. al. (2003). The above film has been elaborated by Nilsson (1996) and is manufactured by OPUR (2016). Its color is white; it is made of low density polyethylene (LDPE) film containing a few percentages of TiO₂ and BaSO₄ microparticles with high infra-red emissivity. It also contains food proof, water insoluble surfactant, which enhances dew drops collection. Such condensers can harvest 15-20 mm of dew water in the season at the dew plant site (see below, section 4).

Other condensing architectures have been elaborated. Conical shapes have been used by Berger et. al. (1992), Kounouhewa and Awanou (1999) and Clus et. al. (2009). Similar to cones, inverted pyramids have been generated by Jacobs et. al. (2008). Sharan et. al. (2011) produced a serie of ridges. High yields have been obtained by Beysens et al. (2013) with periodical structures of origami shapes. Roofs condensing dew water have been built and operated successfully by Beysens et. al. (2007) and Sharan et. al. (2007a; 2007b). Large dew condensers have been developed and field-tried in India in the recent years by Sharan (2011)

and Sharan et. al. (2011). Three different models were developed for large scale applications – condenser-on-roof, condenser-on-ground and condenser-on-fence.

The said experimentation is carried out in a village called Kothara of the district Kutch situated in the north-western India, in a hot semi-arid zone. Kothara receives an average of 200-300 mm rainfall in a year. Pan evaporation is as high as 2000 mm due to the lack of vegetation cover of the land. This extremely high evaporation process causes almost all water bodies, large and small, go completely dry immediately after 2-3 months of rainy season. Despite being a semi-arid zone where there is acute problem of drinking water, rain water harvesting is not popular among the households in this region. This is due mainly to the fact that rainfall besides being low is also concentrated over just a few days in a year, making large storage structure necessary. Therefore groundwater remains the only source of water, which is unsuitable not only for drinking purpose but for irrigation also at times. Shortage of potable water is chronic and widespread in Kutch. It is especially of concern in villages near the coast. They get water on tanker-trucks daily from long distances. It is practically untenable to depend on these municipality run tankers for drinking water because the supply is limited and scarce. It forces residents to all sorts of alternative arrangements for drinking water. One of them is production of potable water from brackish groundwater through reverse osmosis (RO) filtration. RO comes with its own environmental threats. It causes groundwater level going down year on year. Pumping out this ever depleting groundwater has become increasingly costlier. Potable water obtained from RO is only about 50% of the total processed. The rest, which has too high dissolved solids, is disposed off in the surrounding, leading to accelerated degradation of top soil and groundwater quality. It has negative impact on flora and fauna of the region. Although the technology of RO filtration has been becoming more efficient and increasingly less expensive, RO process is not a sustainable solution of drinking water problem in the long run. Unregulated disposal of reject water from households and commercial vendors is leading to degradation of surroundings, top soil and ground water. Greater use of atmospheric moisture - dew and rain water - can reduce dependence on RO process. The Kutch region gets ~ 300 mm of rain over 15 to 20 days during the monsoon season, June to September, in a very erratic way. During some years, rain does not happen. Dew occurs from October to May with 100 to 115 dew-nights and 20-25 mm of dew water over the season. While the condensers are specifically engineered to condense dew, rain can be routinely harvested using the same surface. Thus, a suitably designed plant can potentially harvest 320-325 mm of atmospheric moisture during the year.

Kothara (Fig. 1) has 2200 households and a population of 7000. It has piped supply pumped out from 135 m depth. Water is not potable – Total Dissolved Solids (TDS) vary over the months from 1500 ppm to 2800 ppm. It is used for wash and also given to cattle.

In this paper are described details of a drinking water production plant designed to harvest atmospheric moisture and process it into drinking water for local sale. Its functioning with respect to local meteorological conditions is characterized by Computational Fluid Dynamics (CFD) and modelling from meteorological data.

2. Quality of dew water

Chemical and biological tests had already been performed by Sharan (2011) and Sharan et al. (2011) in four locations around the Kothara dew plant site: Suthari (13 km), Sayara (111 km), Panandhro (82 km) and Satapar (420 km). The results are shown in Table 1, with Suthari the most representative site considering the distances. The data show that dew is safe and potable according to Indian regulation. Studies in other parts of the world found that dew water is potable once disinfected (see Tomaciewicz et al., 2015 and refs therein).

| Properties | | Dew (| mean) | | Requirement (acceptable limit) | Permissible if no alter- nate source |
|---|----------|----------|----------------|------------|--------------------------------------|--|
| Measurement sites | Suthari | Sayara | Panan- dhro | Satapar | | |
| pН | 6.9 | 7.17 | 4.74 | 6.85 | 6.5 -8.5 | 6.5 -8.5 |
| Conductivity, | | | | | | |
| 25°C, µS/cm | 930 | 520 | 1002 | 230 | - | - |
| Total Dissolved | | | | | | |
| Solids, mg/L | 610 | 340 | 660 | 155 | 500 | 2000 |
| Turbidity, Nephelometric Turbidity unit | 1 | 2 | 1 | 2 | 1 | 5 |
| Colour, Hazen unit | 2 | 3 | 2 | 3 | 5 | 15 |
| Odour | Agreeab. | Agreeab. | Agreeab | Agreeab. | Agreeab. | Agreeab. |
| Chlorides, mg/L | 161 | 57 | 57 | 32 | 250 | 1000 |
| Fluorides, mg/L | 0.46 | 1 | 0.87 | Not detect | 1 | 1.5 |
| Sulfates, mg/L | 53 | 30 | 80 | 17 | 200 | 400 |
| Acidity | 80 | 60 | 45 | 30 | No specif. | No specif. |
| Total hardness | | | | | | |
| (as CaCO3) | 228 | 96 | 480 | 95 | 200 | 600 |
| Phenolphtalein | Not | Not | Not | Not | No specifi- | No specifi- |
| alkalinity | detect. | detect. | detect. | detect. | cations | cations |
| Total alkalinity as | | | | | | |
| calcium carbonate, | 200 | 200 | 60 | 90 | 200 | 600 |
| mg/L | | | | | | |
| Bacteriological | | | | | Not | Not |
| quality: E. coli or | | | | | detectable | detectable |
| thermotolerant | - | - | Absent | Absent | in 100 ml | in 100 ml |
| coliform bacteria | | | | | sample | sample |
| Bacteriological | | | | | | |
| quality: Most Pro- | | | | | | |
| bable Number | - | - | < 2 | < 2 | < 2 | < 2 |
| index/100 mL | | | | | | |

Table 1. Quality of dew water at four locations in the Kutch area and specifications fromIndian Standard (2012) for drinking water (adapted from Sharan, 2011 and Sharan et. al.,2011).

3. Dew plant

The plant is constructed in Kothara, a village which is in the Kutch district of Gujarat state of India. The project started in August 2013 and the construction work a few months later. The plant is situated at 23°07'36.08"N 68°55'50"E (Fig. 1).



Figure 1. The region of Rann of Kutch (Gujarat, Northwest India). The black arrow indicates the location of the plant where water harvesting from dew and rain is being carried out.

This dew harvesting plant is rated to process on an average 500 liters of water daily. It has four main components (Fig. 2): (i) catchment where moisture is harvested, (ii) sand filter (iii) raw water cistern for storage and (iv) purifier and packaging unit. The catchment is erected on level wall compacted ground over a rectangular, $40 \times 16 \text{ m}^2$ plot. In appearance it is similar to an array of solar panels of solar power installations. First, angle iron mounts are grouted to the ground at carefully marked locations as shown in Fig. 2a. Seen from longitudinal end each row has an 'M' profile with gutter in the middle. Mounts have side slope of 30° from horizontal. This angle is the "best" angle to enhance dew droplet recovery by gravity while not diminishing the radiative cooling, as demonstrated by Beysens et al. (2003). This form was selected (over others) to make the facility compact and to provide more condensing area per unit land area. There are 15 modules or rows of the mounts (Fig. 2b). There is a 50 cm wide access walkway between two adjacent rows for cleaning and repairs. Each of the fifteen rows of panels, made of two planes inclined at 30° from horizontal facing each other, are separated by a distance of 0.225 m. The distance between the top of each "V" is 0.5m. Each plane of the "V" is 1m wide, 18m long and 0.025m thick; it is a sandwich with 0.025m styrene foam board in the middle and plastic film wrapped around. The total surface area of all these 15 V-shaped rows of mounts is, hence, 540 m² ($2 \times 15 \times 18 \times 1$ m²). This is the overall catchment area of this facility.

The condenser panels are prepared at the site and installed over the mounts (Fig. 2c). The top and lower edges of the panels rest on the top (ridge) and lower purl (eve) of the mounts. The installation of the panels is a painstaking task. It is done with a team of skilled workmanship. The lower edge of the panel is first fastened into grippers starting from one end to the other in small stretches at a time. The process is then repeated for the top edge. Condenser panels are installed first on one half of each row. This process is then repeated for the other half of the rows. This procedure ensures that there is enough room to maneuver for the team of installers. Partially finished condenser field can be seen in Figs. 2a-c. The gripper assembly (channel and zig-zag springs) used is similar to those being used in the greenhouses (Fig. 2d). This procedure ensures that the panels remain planar to permit rapid draining, and also remain tight to overcome wind pressures. It has been observed that wind gusts do not lift or depress the panels appreciably. This is the most crucial point of the erection of the plant for the throughout. Top surface of the panels forms the catchment. This procedure also guarantees easy removal and replacement as and when needed.

All fifteen primary gutters (running from left to right) drain into the one common secondary gutter. This gutter runs to the nodal cabin (Fig. 3) that moves raw water to the cistern via a sand filter. Both the primary and secondary gutters are made of half-pipes of PVC, primary of 150 mm diameter and secondary of 250 mm. Gutters have 2% slope. Half pipes are set firmly on the concrete base. The fully finished condenser field is shown in Fig. 3.



Figure 2. Dew water harvest plant as set up in Kothara showing the erection of condensers. a,b: Structure with gutters; c-d: Mounting the foil on Styrene foam panels.



Figure 3. Fully finished dew plant.

Dew water is harvested during the dew season (October to May). On clear nights the top surface begins to cool gradually after dusk by losing heat via radiation to sky. Under suitable conditions (clear sky, highly humid coastal breeze) the surface cools below the dew point temperature of surrounding humid air causing condensation to occur. Condensed water flows down the sloping sides by gravity into the central gutter. Condensation can continue over several hours of the night often extending till early morning. Rainwater is of course simply intercepted and harvested by the panels during the rainy season (through June to September). As seen in Fig. 2a, the raw water thus harvested from the catchment flows into the secondary gutter which takes it to cistern via a sand filter. It is a $150 \times 60 \times 60$ cm³ storage chamber made of concrete and built partly below grade. Walls of the chamber are 15 cm thick. Lower portion of the chamber houses the filter bed, 30 cm deep. Filter medium is washed river sand of 1 mm to 2 mm granular size. Upper portion of the filter chamber is provided with lockable door for maintenance access. Raw water enters the chamber just above the bed via perforated PVC pipe of 10 cm diameter. Water flows down by gravity through the bed and flows out via the outlet pipe similar to the inlet pipe. Both the inlet and outlet pipes have four holes per row of 1 mm diameter. A gate valve is provided just above the filter bed for dewatering in case of clogging. No run-off from outside or rain water can enter the sand filter chamber. The raw water is made to flow through a 30×30 cm² chamber with a steel grate (mesh size 10×10 mm²) before the sand filter to trap leaf litter, dry vegetative material, other larger pieces of trash in the water stream. The masonry cistern $20 \times 2 \times 1.5$ m³ storage of 60 m³ is below the purifier room. The cistern is provided with an air vent on top and an overflow release outlet with a one way valve at the level just below the inlet water pipe from the sand filter. The overflow release valve opens only when there is an excess of water in the cistern.

Processing and packaging unit is located inside the cabin right above the cistern. The purification unit is made up of the following stages: (1) Micro filtration - to remove physically the micro particles from the raw water by means of disposable candles having perfect μ m size of porosity for filtration (specification: size of cartridge 20"; size of membrane: 5 μ m). (2) Carbon filtration - general carbon pre-filter for removal of physical impurity from 50 to 30 μ m, removal of chemical impurity (color and odor), removal of biological impurity, removal of chlorine and other organic impurities (specification: size of membrane: 5 μ m; operating flow rate: 0.2 m³ per hour; operating pressure: 0.5 Kg.cm⁻²). (3) GAC filtration - general carbon filter removes bad odor of chemicals and other smells (size of

cartridge 20"; size of membrane: 5 μ m). (4) Ultra filtration membrane element to desalt the raw water for reducing sand bacteria (size of cartridge: 10"; size of membrane: 0.1 μ m). (5) UV filtration - the purpose of this stage is to disinfect water with help of UV rays. It results into the removal of biological impurities up to 95% (operating flow rate: 0.2 m³ per hour; operating pressure: 0.5 Kg.cm⁻²). (6) Post carbon filtration - silver carbon to add taste in the drinking water (operating flow rate: 0.2 m³ per hour; operating pressure: 0.5 Kg.cm⁻²; carbon rating: Silver activated).

4. Meteorological data and dew potential

Climate in North-West India is characterized by a prolonged hot and dry season and a mild winter. The main seasons are: (i) summer, from February to May, with nocturnal wind blowing mainly from West or South-West; (ii) monsoon season, from June to September; (iii) winter, from October to January, where nocturnal wind is from North or North-East.

Day temperature even in winter is about 31°C, which rises to over 45°C in summer. In general, days are dry but night time humidity is high, especially from March to July. Although the rainy season is normally four months long, the average number of rainy days is only about five. However, the sky remains cloud covered that prevents dew from forming in this season.

In order to give an overview of the meteo conditions at Kothara, Fig. 4 reports typical data obtained during the dry season between October 2004 to May 2005 by Sharan et al. (2007a). These data are expected to be representative as no major changes have been observed in the Kutch weather during the last 10 years. These data are air temperature T_a , relative humidity *RH* or dew point temperature T_d , windspeed *V*, wind direction and cloud cover, *N*, in oktas. Wind speed measured at the ground level was extrapolated to 10 m above the ground to match the meteo standards according to the classical logarithmic variation (see e.g., Monteith and Unsworth, 1990) $V(z) = V_{10} \ln(z/z_c)/\ln(10/z_c)$. Here z_c (taken here to be 0.1 m) is the roughness length. As dew duration is unknown, only data at 05:00 are considered. This hour is representative of dew formation conditions. Dew yield is measured on an un-insulated, corrugated galvanized iron roof not thermally isolated, with low emissivity 0.23. A multiplicative coefficient (factor 1.4, see Sharan et al., 2007a) is thus applied to extrapolate these data for thermally isolated condenser with emissivity close to unity. In Fig. 4 are also reported the night time cloud cover. The data show that the sky is generally clear. Cloud cover begins to appear from the month of June and continues through September. Total cloud cover

in August and September is found to be 4 oktas. After October the sky is again generally clear. Fig. 4 also presents the evolution of air temperature and dew point temperature. One notices that the low dew during December and January is due to a significant deficit in RH that makes the dew point temperature too far from air temperature. The reason for such a low RH (and somewhat greater windspeed) corresponds to a different atmospheric circulation regime; air from the North being less humid according to the season.

Most data are obtained for wind speeds below 4 m.s⁻¹ (5 m elevation) or 4.7 m.s⁻¹ (10 m elevation) as per the plot shown in Fig. 4. These values are typical of dew formation (see Tomaszkiewicz et al., 2015 and Refs. therein). Wind direction statistics corresponding to the dew events are contained in Fig. 4. Dew forms mainly for wind directions 240° - 360° and 0° - 100° (from SW to NE). It is paradoxical that sea breeze, which corresponds to the wind direction between 130° and 310° (SW to NW), does not give rise to a maximum of dew events. However, the 250° direction (SW) indeed corresponds to a peak in dew yields.

The number of dew events and dew yield depends primarily on relative humidity and then on the wind regime according to the season. Local measurements (Fig. 4) show that relative humidity decreases after the monsoon up to December, and then increases until the end of May, where the monsoon begins. Accordingly, mean wind main direction increases from 50° to 300° . More than the sea breeze, the wind regime associated with the monsoon is important.



Figure 4. Correlated evolution of dew yield in mm/day (black line), air temperature T_a in °C (grey line), dew point temperature T_d in °C (black dotted line), windspeed V in m.s⁻¹ (dark grey), wind direction (thin black line; in units of 10°) and cloud cover data N (oktas; in the lower section). The data have been smoothed. (Adapted from Sharan et al., 2007a).

Nightly dew yield (dh/dt) (mm d⁻¹) can be evaluated at any location globally according to an analytical model (Eq. 1) elaborated by Beysens (2016). Dew is assumed to be harvested on a planar surface with an emissivity of 1:

$$\left(\frac{dh}{dt}\right)_{1} = \begin{cases} \left\{0.37 \times \left[1+0.204323 \,H - \,0.0238893 \,H^{2} - \left(18.0132 - 1.04963 H + \,0.21891 \,H^{2}\right) \times 10^{-3} T_{d}\right] \times \\ \left(\frac{T_{d} + 273.15}{285}\right)^{4} \left(1-N/8\right) \\ 0 \end{cases} + \left[0.06 \left(T_{d} - T_{a}\right)\right] \times \left(1+100 \times \left\{1 - \exp\left[-\left(\frac{V}{V_{0}}\right)^{20}\right]\right\}\right) & if \quad positive \\ if \quad negative \\ (1) \end{cases}$$

Here *H* is the site elevation (km), T_a and T_a are the dew point and air temperatures (°C), respectively, *N* is the cloud cover (oktas), and *V* is the wind velocity (m.s⁻¹) at 10m elevation. The model can be applied at a given time typical for dew formation, such as sunrise, or incrementally every period of time, in which case the model would be divided by the appropriate factor. For this study, only data at 05:00 in the morning were considered as they are representative of nightly conditions. The wind velocity component (*V*) is equivalent to 1 when $V < 4.4 \text{ m s}^{-1}$ and 0 otherwise because in nearly all cases, dew cannot form when wind velocity exceeds this limit (Beysens, 2016). The model also includes an empirical equation for sky emissivity proposed by Berger et al. (1992). The simplicity of the model and its dependency on readily obtainable meteorological data lends itself toward wide applications in dew forecasting and hindcasting. It has been validated with experimental data obtained in 10 different sites with different climates, including Ajaccio (France), Bahar-Dar (Ethiopia), Bordeaux (France), Grenoble (France), Kothara (India), Mirleft (Morocco), Tahiti (French Polynesia), Bakou (Azeibaïdjan) and Zadar and Cres (Croatia).

The result for Kothara is shown in Fig. 5 for the dew season 2004-2005 (from October to May). This plant has not been tested in the year 2015 due to the sad demise of the first author (GS). Therefore the comparison is being made with a metal units tested here over several years. As noted above in section 4.1., Sharan et al. (2007a) reported that a condenser made of galvanized iron sheets shows yield nearly 40% less than those of PE film of which the present plant is made. While sizing the surface area of the plant it was assumed that the yield will be exactly 15 mm for dew. Simulations are close to that. The galvanized iron unit, uninsulated, yielded 7.2 mm.



Figure 5. Dew yield estimation from Eq. 1.

5. Numerical simulations

The aim of the CFD numerical is to estimate the dew water output with respect to the meteorological parameters. This is a very general and difficult task and up to now several simplifications have been made to retain only the most important parameters. As the actual yield depends on the supersaturation reached by the condensing substrate, the determination of the temperature drop (T_a - T_c) (T_c is the condenser surface temperature) with respect to air temperature is a good indicator of the dew yield as outlined by Clus et al. (2009). The simulation will be thus only concerned with the thermal exchanges with atmosphere where wind velocity and wind direction are the main parameters.

The radiative condenser is basically a thermal machine whereby several characteristics must be simulated, (i) radiative material thermal properties (thickness, heat conductivity, heat capacity), (ii) radiative cooling power, function of the atmospheric conditions (T_a , RH, cloud cover), the condenser exposure and its shape, and (iii) the incoming diffusive and convective (free or forced) heat, the value of which is a function of the windspeed and the condenser architecture. The surface to air heat transfer coefficient was determined analytically only for planar surfaces with laminar air flow (Nikolayev at al., 1996) with adding free convection (Jacobs et al., 2006). For more complex surfaces, a semi-empirical description is needed (Guyer and Brownell, 1999). As a consequence, the analytical description of dew condensation in complex structures subject to outdoor natural wind is extremely difficult. Moreover, dew condensation occurs frequently with weak wind and the free and forced (wind) convections can be of a comparable order of magnitude. The relation between a 10 m meteorological wind and the local air flow tangential to a surface making a variable angle with horizontal has already been simulated in Beysens et al. (2003). The main result was that the tangential velocity is found to be at a minimum when $\alpha \approx 30^{\circ}$.

As supersaturation also depends on *RH* and T_a , in the following only typical night conditions are considered: clear sky *N*=0, $T_a = 288.15$ K (15°C), *RH* = 80%. These conditions correspond to a dew point temperature $T_d = 11.8$ °C. Standard numerical values are used for the air properties (density, thermal conductivity, specific heat, etc., see Table 2).

The commercial software, COMSOL Multiphysics, was used to analyze the heat transfer and fluid flow taking place around the condenser plant. The goal of this modeling effort is to predict the temperature of the condenser surfaces for different values and direction of air velocity. In the fluid domains, the continuity equations as well the Navier-Stokes and the energy conservation equations have to be solved simultaneously.

A part of the heat transfer from the air to the surface of the condenser happens by forced convection. In this case, the complete energy equation has to be solved in the fluid domain using the velocities found from the solutions of the continuity equation and conservation of momentum equation (Navier-Stokes). The energy equation describing this heat transfer process is given by:

$$\rho C_p \frac{DT}{Dt} = k \nabla^2 T \tag{2}$$

where ρ is the density of air, C_p is the specific heat of air, k is the thermal conductivity of air, and T, the air temperature. The effect of convection on the heat transfer process is taken into account in the derivative term DT/Dt of Eq. 2:

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + V.grad(T)$$
(3)

where V is the velocity field in the air. The steady- state case was solved such as the time derivative term $\partial T/\partial t$ in Eq. 3 is set to zero.

The temperature of the condenser will be lower than that of the ambient air due to the radiative cooling. Natural convection will thus appear, enhancing heat transfer between air and condenser.

This effect is taken into account by a temperature dependence of the fluid density (buoyancy effect) in the conservation of momentum equation.

The heat transfer at the surface of the condenser is expressed by conduction, convection and radiation. In the solid domain, conduction is modeled using a simple heat equation. No-slip boundary condition is for all condenser surfaces. For velocity less than 5 m.s⁻¹, the Reynolds number defined as Re=V L/v ($L\approx1$ m is condenser typical lengthscale; $v = 1.3\times10^{-5}$ m².s⁻¹ is air kinematic viscosity) keeps below 5×10^{5} , the value of the critical Reynolds number for a horizontal plate (see Rohsenow et al., 1998). It thus ensures laminar flow conditions.

All of the meshes created in COMSOL were physics controlled and automatically generated. The meshes varied in size ranging from a coarser mesh all the way up to a normal mesh.

5.1. Condenser geometry

The three-dimensional model of the plant is presented in Fig. 6. The dimension considered is $30 \times 30 \times 10 \text{ m}^3$. The plant consists in rows of parallel "V". Seven identical rows were integrated in order to limit the number of cells and the time calculation. A row is made of two planes inclined at 30° from horizontal facing each other and separated by a distance of 0.225 m. The distance between the top of each "V" is 0.5m. Each plane is 1m wide, 18m long and 0.025m thick. Each plane of the "V" is mimicked by Styrofoam, 0.025 m thick, considering however pure LDPE emissivity ($\varepsilon_c = 0.83$). This emissivity is slightly smaller than that of foil used in the real plant where pigments are inserted in a LDPE film. However, it corresponds to a possible aging of pigments inside the LDPE film and is thus conservative.



Figure 6. Dew plant schematics used in the numerical simulation.

5.2. Boundary Conditions for heat transfer

Thermal boundary conditions are the following. (1) Styrofoam / air. Continuity at the interface, meaning that heat exchange occurs at this interface by flux conservation. (2) Source / flux on the interface Styrofoam/air. One fixes an exchange radiation flux surface /sky, with emissivity 0.83 for Styrofoam, corresponding to LDPE, and 0.8 for the sky (Eq. 4 below). (3) Ambient air temperature is T_a =288.15K. Temperatures at the entrance of fluid domain and ground temperature are at T_a . (4) Thermal insulation at the interface air- Styrofoam below the condenser surface.

5.3. Radiative cooling

The relative cooling energy is the difference between the energies received and emitted by a body. The flux emitted by the condenser (radiated plus reflected contribution) can thus be written as:

$$\phi_e = \varepsilon_c \sigma T^4 + (1 - \varepsilon_c) G \tag{4}$$

Here ε_c is the emissivity of the condenser, *G* is the flux received by the condenser, $(1-\varepsilon_c)G$ is the reflected flux. Boundary parameter settings of COMSOL consider two types of radiation,

"surface-with-ambient" and "surface-with-surface". The surface-with-ambient type is used when the geometry is plane or convex. The surface does not receive the flux that comes from the other parts of the geometry; it only receives the flux coming from the ambient (sky). Examples of such surfaces are horizontal or tilted planes. The total received flux is $\varepsilon_s \sigma T_s$, where ε_s is the sky emissivity and T_s is the sky temperature.

The surface-with-surface type is applied if the geometry is concave or if two geometries are facing each other. This is precisely the case of the "V" structure considered here. The received total flux is $G = G_m + F_{am} \sigma T^4$, with G_m the flux that comes from the other part of the geometry; F_{am} is the ambient view form factor. It describes the factor of form which corresponds to ambient (sky) environment. The ambient emissivity is taken to 1.

5.4. Sky model

Several models describe the sky by giving a value for the sky emissivity, ε_s . However, the sky radiance of the clear sky is not isotropic and ε_s exhibits an angular variation with respect to the angle θ with the zenith. An angular variation of ε_s is, however, difficult to implement. The model was thus simplified by simply considering the value $\varepsilon_s = 0.80$, which corresponds to an angle average as outlined by Nikolayev et al. (1996). As the code assumes the sky emissivity to be equal to 1, the lower sky emissivity was taken into account by replacing T_a by $T_a^* = \varepsilon_s^{1/4} T_a$. The flux emitted by the sky can thus be written as:

$$\phi_s = 1 \sigma \left(T_{am}^* \right)^4 = \varepsilon_s \sigma T_{am}^4 \tag{5}$$

5.5. Boundary Conditions for air flow

Boundary conditions for air velocity are as follows. (i) "Entry". Air velocity follows the classical logarithmic variation with respect to elevation z (see e.g. Monteith and Unsworth, 1990):

$$V(z) = V_{10} \ln(z/z_c) / \ln(10/z_c),$$
(6)

where z_c (taken here to be 0.1 m) is the roughness length. (ii) "No-slip" on plate and ground. (iii) "Open frontier" on ceiling and the two vertical sides of the fluid domain. (iv) "Convective flow" at the exit.

| | $k(\mathrm{Wm}^{-1}\mathrm{K}^{-1})$ | $C_p \left(\mathrm{J \ kg}^{-1} \mathrm{K}^{-1} \right)$ | ho (kg m ⁻³) |
|------------|--------------------------------------|---|--------------------------|
| Air (15°C) | 0.025 | 1005 | 1.22 |
| Styrofoam | 0.035 | 1300 | 30 |

Table 2. Thermophysical properties of air and condenser materials used in the simulations.

5.6. Validation of the model

Comparison with a real system is the most reliable and most convenient way to validate a simulation model. Experiments conducted in Pessac (France) by Beysens et al. (2005) on a horizontal plane condenser were considered to validate the simulation. A set of data including temperature cooling $\langle \Delta T \rangle = T_a \cdot \langle T \rangle$ and wind velocity are compared with the results of the simulation for laminar, forced convection. The results are very sensitive to the precise value of the condenser emissivity. Therefore, in a first step, emissivity is finely adjusted in the simulation to fit the data of a reference experiment. Then another simulation with that emissivity value is compared with the other experimental data. Good agreement is obtained, thus validating the model for forced convection. In the case of natural convection, one uses the same emissivity value. Concerning mixed convection, the model cannot be used because of the very complex hydrodynamics and thermal couplings between natural and forced convection.

5.7. Results

One considers in the simulation three main wind directions: 90° (perpendicular to rows), 45° (45° with respect to rows) and 0° (parallel to rows). Simulations are performed with typical wind speeds at 10 m elevation V_{10} ranging from 0.5 to 4 m.s⁻¹ by steps of 0.5 m.s⁻¹.

In Fig.7 is reported the temperature map on the condenser surface and in Fig. 8 the wind velocity field in a vertical section parallel to the wind direction, for a wind speed of 2.5 m.s⁻¹, and three wind directions (0°, 45° and 90°). The first rows efficiently lower wind speed for the other rows, and the following rows present a similar velocity field.





Figure 7. Temperature map on the condenser surface at $V_{10} = 2.5 \text{ m.s}^{-1}$ for three wind directions (a) 90°, (b) 45° and (c) 0°.







Figure 8. Air velocity field in a vertical section paralell to the wind direction at $V_{10} = 2.5 \text{ m.s}^{-1}$ for three wind directions (a) 90°, (b) 45° and (c) 0°.

In order to characterize the better orientation with respect to dominant winds, one compares the three wind directions at different wind speeds. In addition is reported the case of a plane of 1m^2 for sake of comparison. One considers as relevant parameter the space average of temperature cooling $\langle \Delta T \rangle = T_a - \langle T \rangle = 15^{\circ}\text{C} - \langle T \rangle$ (Fig. 9). One finds that the cases 45° and 90° cool more

efficiently, in a manner similar to a plane inclined at 30° . Wind along the rows (0°) give the lowest cooling, as anticipated from enhanced heat exchange with air.



Figure 9. Wind speed dependence of the difference $\langle \Delta T \rangle = T_a - \langle T \rangle$ between ambient air temperature and mean surface temperature. Different wind orientations are shown. For comparison are given the results for a 1m² plane at 30° from horizontal with 0° wind orientation directed towards the hollow part.

In Fig. 9 dew is seen to form (when $\langle \Delta T \rangle > 3 \ ^{\circ}$ C) for quite different orientations of wind with respect to the row orientation. The orientations giving the highest yield correspond to having wind oriented between 45° and 90° of the row, the best configurations.

6. Economics

Three / fourth of the residents in the Kutch district get their supply for household use (drinking, cooking) from an open well, the only one to serve the entire village. Well water is chemically potable (TDS is 248 ppm) but contaminants are commonly present - coliform organisms and others. Large number of residents has ailments attributed to prolonged use of poor quality water. Well water is free at the site, some get it delivered for a fee. It is not uncommon for the well to dry up completely in summers or remain dry altogether during drought years. Residents then buy untreated water from vendors who bring them tankers from a few locations outside the village. These good water sources are depleting, prices increasing and quality deteriorating. There are three water bodies in Kothara itself , which retain water till about February and cater to cattle.

The remaining one-fourth of the residents have installed their own RO machines at home. There are 440 RO plant in operation in 2014. The RO appliances cost between INR 3500 to INR 15000 (USD 50 to 230), with running costs of about INR 100 (USD 1.5) per month. Typically permeate to condensate ratio of home RO units is 1:5.

Households typically use 30 L of potable water daily using 150 L of feed. Reject water (130 L) is disposed off just outside the homes. All RO owners together dispose off nearly 53000 L of reject water daily with solids estimated at 143 kg or close to a ton per week. One entrepreneur has set up a commercial RO plant (of throughput 2000 liters per hour) and is selling water at INR 0.5 (USD 0.0075) per liter at the plant. The convenience and cost-effectiveness is making RO process the main means to meet the needs. But unregulated disposal of reject water from household and commercial vendors is however leading to degradation of surroundings, top soil and ground water. Despite the advantages, RO is not sustainable in regions like this one where aquifers are already strained and soils widely salt-affected. Most of the eight hundred villages experience shortage of safe potable water for residents and livestock. Out of these about 150 villages experience much greater difficulty. These are categorized as "no source" villages and have to depend on water transported from long distances daily.

Radiation cooling of artificial surfaces can produce a maximum of only 0.8 liter/m² per night. Our plastic condensers have recorded here a peak yield of 0.6 liter/m² per night. It is to be noted that clean and leak-proof plastic surface makes an excellent catchment for rain harvest. One square meter condenser can harvest 300 mm of rain water and 20 mm of dew water in their respective normal seasons. Making allowance for collection and conveyance losses of 15%, inevitable in large working installations, the potable water output will be 272 liters/m². Being able to harvest rain and dew water from the same catchment will improve the economic viability of rain harvest systems.

Total cost of the 540 m² harvest surface plant was INR 1,500,000 (USD 22,500) or INR 2778/m² (USD 41.7 /m²). It included the civil works INR 1500/m² (ground preparation, cistern, gutters, installation of mount array, purifier cabin), mounting frames INR 370 per m², condenser panels materials and fabrication and installation INR 463 per m², the rest was site supervision. Instrumentation - a data logger for meteorology parameters, water testing apparatus - is excluded as it was for research and will not be needed for working installations at users. The functioning is expected to last 10 - 15 years, corresponding to 0.1 - 0.07 INR /liter (0.0015 - 0.001 USD/liter), to be compared to RO (0.5 INR/liter or 0.0075 USD/liter at the plant).

From the above figures, it thus comes out that water passively harvested from atmospheric moisture can be cheaper than that from RO and does not pollute the environment.

7. Concluding remarks

An important argument in favor of dew is that the amount of water that can be obtained is potentially very large and is limited only by the technology used. Importance of dew resources to provide supplementary supply of potable water in arid areas has now been widely appreciated. In view of this, several research groups in the world are working to develop more efficient and affordable dew condensing technology. Nanotechnology is being used to create new materials for dew water extraction without external energy. It is expected that higher yielding dew condensers will become a reality soon. Thus, while the rain water is limited, dew water is not. As technology improves, more can be harvested.

Although passive collection of dew is very appealing, one can however ask whether active means can be also affordable. On our request Roland Wahelgren of Canada Dew estimated the possible water production using their Can Dew 2500 model air-water generator under actual weather conditions of Kothara. Simulations over each of the twelve months showed that water production will vary from a minimum of 1500 liters per day in January to a maximum of 3200 liters per day in July. This can be tapped to meet human needs and possibly that of greenhouse crops. While 40% of the water could be extracted from air in colder months, in July 90% was extracted by the air water generator. Cost of product water was computed as 0.55 kWh/L, which is not high. The upfront investment for such active means is limiting, which in this case was upwards of \$200,000. Further R&D is needed to bring down the initial costs to make this very large and sustainable dew resource commercially viable.

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