Modeling and Simulation of Condensation on Plastic Condenser Cooling under Night Sky

Girja Sharan
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T. Madhavan
Indian Institute of Management, Ahmedabad

Abstract

The Kutch region of north-west India is hot and semiarid, chronically short of drinking water. Dew forms frequently in the areas near the coast, over a span of eight-month (October- May) coinciding with the entire dry part of the year. Dew water is potable and safe. Dew harvest systems - devices to condense and collect dew - have been developed which could be installed on building roofs (condenser-on-roof), open ground (condenser-on-ground) and on frames (condenser-on-frames). The key component is the condenser, made of thin plastic film insulated underneath, which cools at night by radiative exchange with cloud-free sky. Condensation occurs when the film cools to or below the dew point of the surrounding air and humidity level is high - upwards of 85%. Over the season of eight months, 15 – 20 mm of dew water can be harvested. In this region where rainfall is very erratic and in normal years only 300 mm, harvested dew water can be an appreciable supplement. It can also be a small but critical supply for plants in nurseries. Design principle of efficient dew condenser is discussed and dew water collection in some recently installed working systems reported.

Keywords: dew condenser, radiative cooling, drinking water, coastal arid areas

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Introduction

Dew is atmospheric water vapour condensing on surfaces cooled to or below, the dew point by radiative cooling. It is generally not considered an important source of moisture for humans because of small quantity and infrequent occurrence. This view may not be generally, as valid for coastal regions as it is for interior regions. Sharan and Prakash (2003) reported observing dew condensation frequently on the greenhouse envelop at Kothara , a village near the coast in the semiarid Kutch region in the north-west part of the country (φ 23° 14 N, λ 68° 45 E, at 21 m a.s.l.). Initial incidental observations were followed-up by installing gutters to collect and measure the volume. Year-long daily measurement showed that dew occurred over eight months from September to May, spanning the entire dry part of the year. It was absent from June to September – the entire rainy season. Dew nights were more numerous (103), compared to rainy days (17) in a normal four month rainy season. The fact that dew season coincides with dry period and dew nights are numerous, is interesting in a region where many villages survive on water hauled daily from long distance.

Dew water collection over eight-month season from 124 m^2 roof of the greenhouse, was close to 10 mm (1191 liters). Water was chemically tested and found potable. Some samples showed bacterial contaminants, transported by airborne dust. Assuming, four liters per day as the basic drinking water need of a person, a total of 1200 liters will be required over the dry period of 300 days; precisely the quantity collected from roof of greenhouse. Therefore, while the dew water yield was modest compared to rainfall (300 mm), it was enough to indicate that dew could provide a small but critical water security for families in this area. Note that the greenhouse envelop was not specifically intended for dew condensation. The theoretical maximum dew condensation that can be expected on a surface cooling by radiation to sky is of the order of 0.8 liter-$m^{-2}day^{-1}$. This is based on the available cooling power (25 – 100 Wm^{-2}) with respect to the latent heat of condensation (2.26 KJg^{-1}). The peak collection from the envelop (made of 200 micron transparent polyethylene film) in one night was only 0.362 liter/m^2. This suggests that if more efficient materials and methods are developed, a significantly larger amount of dew collection could be possible.

Objective

In view of the findings above, a project was started with the objective of developing efficient dew harvest mechanisms for use of people in coastal area. The project work carried out over four years included (a) review of literature (b) construction and trial of prototype condenser units with three different materials and (c) construction of practical systems that could be installed on roofs of buildings and on open ground.

Review of literature

Research on dew has been very limited in India. Raman et al (1973) measured dewfall at sixty locations to assess its possible contribution to root zone moisture in dry periods. Subramaniam and Rao (1983) studied dew fall in the north-west India in the context of afforesting sand dunes. There is no report of studies for possible use by humans. The earliest efforts to condense dew for human use were made by the Greeks. More such efforts were made in the early part of last century. Some of these have been carefully studied by contemporary scientists (Milimouk and Beysens 2005). Efforts were mostly unsuccessful. Massive structures often did not cool to dew point. Interest in accessing dew water has emerged again in the recent years. The new approaches are fundamentally different from the old ones.

Researchers in Sweden and France (Nilsson et al. 1994, Nilsson 1996, Nikolayev et al 1996, Beysens et al 2003) developed correct theoretical basis to build efficient radiative condensers. They developed light weight, radiative foils that gave higher yields. In the present work a similar approach was adopted. It was decided to build condensers using materials that have appropriate properties and are readily available (roofing sheets for instance) or can be easily produced by the local industry.

Prototype condenser units

The International Organization of Dew Utilization (www.OPUR.fr) developed small condenser units for dew measurement. Similar units, shown schematically in Figure 1, were used in this project to build prototype of different materials for trial.

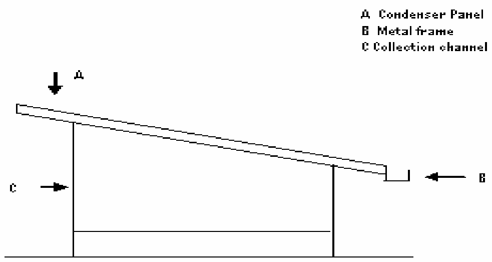

Figure 1: Schematic Diagram

Prototype units are made of three parts - panel (A) , frame (C) and collection gutter and accessories (B) . Panel is made of two separate sheets laminated together with adhesive. The sheet on top is made of material being tested for suitability to condense dew. The underside of this sheet is insulated with 25 mm thick plate of styrene foam. Panels are planar and square (1x1 m) mounted on the frame at 30° from the horizontal to facilitate draining by gravity. The collection accessories (channel and bottle) are also fastened to the frame. Higher end of the panel is 1.5 m from the ground. Following materials were selected to make prototypes for study.

Galvanized iron (GI) sheet: emissivity 0. 23, thickness 1.5 mm
Aluminium sheet: emissivity 0. 216 , thickness 1.5 mm
PETB Film (Polyethylene mixed with 5% TiO_2 and 2% $BaSo_4$): UV stabilized
emissivity 0.83, and thickness 0.3 mm.

The metal sheets were not expected to be used widely. Besides having low emittance these are expensive. The reason for including GI was that it is commonly used for roofing large factory sheds, warehouses etc. Condensation occurs on such roofs, but has never been measured. If measurement revealed appreciable yield, owners could be advised to make use of the roof to produce water simply by adding collection gutters and possibly also some insulation. Aluminium sheets are much less common, but some new industrial projects near the coast have these. The PETB film has been used by researchers from Sweden and France cited earlier , who reported it to be a more efficient radiator. Twelve small units were made , four each of the three materials. Four units (one of each material) were installed facing north, south , east and west , on open level ground away from buildings and trees. Dew water condensed during the night collected in the plastic bottle and the volume recorded each morning at 8 am.

Instrumentation

Ambient conditions at the test site - air temperature, relative humidity, wind speed were recorded every hour by a data logger (Weather Technologies India). Temperature sensor was standard Platinum RTD element (PT 1000) mounted inside weather shield coated with weather proof reflective white paint, sensor resolution 0.1 °C, accuracy is ± 0.2 °C; relative humidity sensor is solid state capacitive with accuracy is ± 3 % (resolution ± 0.1 %) range 0-99%; wind speed by a three cup anemometer 6 m above ground , starting threshold 0.3 m/s range 0-65 m/s, accuracy is better than ± 0.5 m/s. The temperature of the condenser surface was measured by a similar RTD element, bonded length wise to the surface with thermally conductive adhesive (Product no 34313 Loctite). The element was 3 mm wide, 10 mm long. On occasions a hand held IR thermometer (from EXTECH Instruments, France) was also used to verify surface temperature.

Results

Dew yield

Daily data of two years – 2005 and 06 was pooled and mean computed (**Table 1**). The volumes shown are without scraping the surfaces. Dew occurred in the area over a continuous span of eight months from - October to May. It is absent from June to September, the rainy season during which the sky is covered with clouds. Night time cloud cover observations taken at 20:30 and 23:30 were obtained from the Indian Meteorology Department Observatory at Naliya (Kutch), 10 km northeast of Kothara. Data showed that cloud cover begins to appear from early June and continues through September. The extent varied from 2 to 7 in June and July, 2 to 8 in August and September nights. After October the sky is again generally clear. Only some cover (2 octas) were recorded in January on a few occasions. There are two peaks during the season – one centered over March – April (summer), the other over October (fall). The dew occurrences are low in winter months, November to January. During this period nocturnal wind is from north or north-east. The moisture level in the air is low. From

February to May, during which dew forms frequently, nocturnal wind blow mainly from west or south-west; carrying high levels of moisture.

Table 2 shows the distribution of the dew amounts collected in one night. On most nights (60 %) it varied more or less uniformly between 50 to 250 ml / m^2. The peak was 550 ml / m^2 . Montieth (1963) reported peak dew yield on a night at many locations around the world on artificial surfaces. In Israel , Jamaica, England (south) and Munich it was 430 ml /m^2 , Germany Baltic coast 370 ml /m^2 , Moravia 250 ml /m^2 , France Montpellier 220 ml /m^2, Moscow 220 ml /m^2 and Romania 170 ml /m^2 .

The total amount collected over the season differed to a small extent with the orientation of the units. In general, it was higher in units oriented west and north. For instance, north and the west oriented units of PETB condensers collected nearly equal amount - 20 mm. The east faced unit collected 5% less and the south faced unit 15% less. A plausible reason could be that the north and the west faced units are not exposed to illumination in the morning as early as the others, permitting dew deposition for a little longer. Also for the same reason , east and south faced units may be loosing more by evaporation.

More significant difference in the amount collected however was made by the material of construction. Column (6) of the table shows the average collection from all four units of each of the three materials. Highest collection was in the PETB units (19.4 l/m^2) followed by GI (15.6 l/m^2) and aluminium (9 l/m^2) . The number of nights the dew collected in PETB and GI units was equal, 114-115. Dew nights were fewer for aluminium units. The PETB had the highest emissivity, giving it a greater cooling power.

Table 1: Seasonal Dew collection small trial condenser units - values are mean of two years 2005 and 2006 at Kothara

Condenser unit made of	North - faced (l/m^2)	South - faced (l/m^2)	East - faced (l/m^2)	West- faced (l/m^2)	All four (l/m^2)
PETB	20.282	17.255	19.703	20.332	19.4
GI	18.661	18.709	11.551	13.664	15.6
Aluminium	9.860	8.489	8.641	9.136	9
dew nights for PETB units were 108 and 120 in 2005 and 2006 respectively averaging 114 for GI units 108 and 122 in 2005 and 2006 respectively averaging 115 for aluminium units 69 and 86 in 2005 and 2006 respectively averaging 77					

Table 2: Amount of dew water collected per night (PETB units)

Quantity (ml/m^2)	Relative frequency (%)
1 – 50	12.2
51 - 100	16.9
101 - 150	13.0
151 - 200	17.4
201 - 250	16.1
251 -300	12.9
301 - 350	5.8
351 - 400	3.2
401- 450	1.7
451 - 500	0.7
501 -550	0.2

Simulation of Cooling and condensation

A mathematical model was made to represent the prototype unit and was used to gain insights into cooling and condensation processes via simulation.

Let

t	time (hour of day)
c_p	heat capacity of condenser sheet ($J/g\ ^0K$)
m	mass of condenser sheet (g)
A_c	surface area of condenser sheet (m^2)
$\in_s$	emissivity of sky, averaged (dimensionless)
$\in_{s1,}$	emissivity of condenser sheet, averaged (dimensionless)
T_c (t)	temperature of condenser sheet at time , t , (^0K)
T_a (t)	ambient temperature at time , t , (°K)
T_s (t)	sky temperature (°K)
Td (t)	dew point temperature at time ,t , (°K)
RH (t)	relative humidity at time , t , (%)
U (t)	wind velocity at time, t, (m/s)
σ	Stefan-Boltzman Constant ($5.670 \times 10^{-8}\ w/m^2\ K^4$)
F_{cs}	view factor between condenser and sky (dimensionless)
hi	heat transfer coefficient , conductive (W/m^2K).
ha	heat transfer coefficient ,convective (w/m^2K)
$h\upsilon$	vapor diffusion coefficient (w/K)
L	latent heat of condensation (2260 J/g)
E (t)	rate of condensation (g / s)
e_{amb}	water vapor pressure of air at ambient temperature (Pa)
e_{rad}	water vapor pressure of air near condenser surface (Pa)
ε	psychrometric constant (66 Pa / °K)

Following assumptions are made to simplify modeling.

1. Complex aerodynamics and its effects in close proximity of the surface are ignored.

2. It is assumed that the entire surface of the sheet remains at uniform temperature. This is reasonable in view of small area (1 m^2).
3. When condensation is on, there will be a film of water of varying thickness over the surface causing multiple effects - adding to the thermal mass, altering optical property, altering heat transfer coefficient. These are presently ignored.
4. For condensation to occur, surface must cool down to (or below) the dew point temperature. Our observations have shown that this is a necessary but not sufficient condition - high levels of humidity and calm conditions are also needed. Presently however, it is assumed that the condition necessary, is also sufficient.

Equation (1) shows the heat balance on the condensing surface of the prototype unit. The first expression on the right is gain from condensation, second , gain from the surrounding ; third gain through insulation and ; fourth , loss to sky via radiation. The view factor, $F_{cs,}$ is taken as one.

$$m\,c_p\,\frac{dT_c}{dt} = Ac * LE + A_c\,h_a\,(T_a - T_c) + A_c h_i (T_a - T_c) - A_c\,\varepsilon_{s1}\,\sigma\,(T_c{}^4 - T_s{}^4)$$

……………. (1)

The product, LE, is latent heat transfer when condensation is occurring. In accordance with the assumption (4) above,

$LE = 0$ if $T_c > T_d$

$$LE = \frac{hv(e_{amb} - e_{rad})}{\varepsilon} \quad \text{when } T_c \le T_d \qquad (2)$$

Equation (2) states that LE is proportional to the rate at which vapor is transported towards the colder condensing surface, from warmer air farther away, by diffusion driven by vapor pressure gradient and coefficient, $h\upsilon$. Nilsson et al (1994) have indicated that , $h\upsilon$, in magnitude is approximately equal to convective heat transfer coefficient, ha. Following empirical relations were used in the simulation program.

e_{ambs} = 610.78 * exp (T /(T + 238.3) * 17.2694) ... ... 3 (a)

e_{ambs} saturated water vapor pressure (p_a) at temperature T (°C)

e_{amb} = e_{ambs} * RH (%) / 100 ---------------- ... ... 3 (b)

water vapor pressure (P_a) at given RH and T

$$h_a = 2.0 + 3.8 \times U \qquad \text{(4)}$$

$\in_s$ = 0.736 + 0.00577 T_d ………… (5)

T_d here (°C)

$$T_d = T - ((100 - Rh)/5) \qquad \text{(6)}$$

Ta (°C)

Ts= Ta * (0.8 *(Td – 273.15)/250) $^{0.25}$ ………………… (7)

Ta and Td (°K)

Results and discussion

Simulations program was coded in Matlab using solver ode45. Measured data of ambient temperature, relative humidity and wind speed was converted into Fourier series and used as input to simulation. The wind speed data from the anemometer placed 6 m above ground was modified using power law relation – with exponent 0.6 - to represent speeds at 1 - 1.5m, close to the condensing surface. The dew point , sky temperature , vapor pressures and other factors dependent on ambient conditions are generated internally using relevant empirical relations. To start the simulation, Tc is arbitralily set at a value slightly below the (known) ambient temperature. The effect of this arbitrary choice disappears within about half hour. Working of the east – oriented PETB unit during the night intervening April 13-14 '05 was simulated. The dew collection on the morning of April 14 was 360 ml.

Inputs :

Tstart = 19 hrs April 13 ; Tend =07 hrs April 14.

Initial condition: Tc (start) = 300 °K (Ta was 306 °K)

Parameters : m = 200 g , Ac = 1 m^2 , cp = 1.85 J/gK , Fcs=1

hi = 0.7 (25 mm styrene foam insulation)

Fourier representations of Ta , RH, U , over the simulation span (Tstart to Tend) were given as input. Six harmonics were found sufficient to match the data.

Fourier coefficients								
	n	0	1	2	3	4	5	6
Ta	An	29.50	4.61	-2.18	1.17	-0.62	0.45	-0.05
	Bn		-7.70	0.09	-0.02	0.00	0.16	0.05
RH	An	70.62	-15.65	7.0	-5.46	-2.10	-1.92	-3.42
	Bn		26.47	1.89	-3.81	1.71	-2.08	-0.28
U	An	4.86	1.79	-1.13	0.51	0.27	-0.07	-0.27
	Bn		-2.53	-0.29	-0.18	0.17	0.35	-0.21

Table 3a shows the ambient conditions and the measured values of condenser temperature. All these are instantaneous values at the hour shown. It is seen that the condenser surface cooled to below dew point after 22 hrs. Soon afterwards, some condensation would have also begun as indicated by latent heat gain values (**Table 3b**). Latent heat gain increased after midnight remaining so till morning. This would suggest that condensation occurred over several hours, more after midnight. That is consistent with the facts that RH became high and wind speeds became lower after midnight. Total collection in the morning was 360 ml. Table 3b shows heat gains and losses obtained from simulation run. The values shown are mean of 15 minute intervals. This was done to get robust values. The solver uses intervals that are much too small. The pattern of cooling produced by simulation is similar in form to that of the measurements. The magnitudes however differ by about 2 to 2.5 degrees and further refinement of the simulation model would be desirable.

Practical systems to harvest dew

PETB was preferred to build large practical systems. Besides being efficient condenser, it is less expensive and local processors were able to supply. Metal sheets are not suited. However , yield from GI units are appreciable enough to encourage the owners of buildings with large GI roofs to harvest dew simply and cheaply by fitting the collection gear. The GI roofs are not insulated underneath, therefore the yields will be lower than the test condenser's. Adding a layer of insulation would improve yields.

Although the prototypes were mounted on frames, such an arrangement was not favored for large systems because in windy areas these will expensive. Instead techniques were developed to install systems over building roofs (Condenser-on-Roof) and over open ground (Condenser-on-Ground). There is large amount of wasteland near the coast , not suited for cropping. These can be used to produce good quality dew water. Two illustrations are given below.

Table 3a : Ambient conditions April 13-14, 2005

Time (hour)	Ambient Temperature (°C)	Wind speed (m/s)	Relative Humidity (%)	condenser Temperature Measured (°C)	condenser Temperature simulated (°C)	Dew point Temperature (°C)
19	33.1	6.6	39.6	27.1	(26.8)	21.0
20	31.1	5.5	68.0	27.3	27.5	24.7
21	28.4	3.9	78.5	23.7	25.5	24.1
22	26.9	3.6	85.2	22.6	23.9	23.9
23	25.7	3.5	88.0	21.8	21.9	23.3
0	24.6	1.1	90.2	19.7	21.7	22.6
1	23.3	6.6	93.7	19.6	21.4	22.0
2	23.3	3.1	93.7	19.9	20.0	22.0
3	22.6	2.5	94.7	18.7	19.9	21.5
4	22.2	2.3	95.1	18.3	19.3	21.2
5	21.3	0.6	95.7	15.3	18.7	20.4
6	20.7	2.6	96.1	15.3	17.3	19.9
7	19.6	1.0	96.3	15.2	17.6	18.9

Table 3 b: Heat gain and loss – values are mean of 15 minute Intervals (east oriented PETB April 13-14 '05)

Time (hour)	Lat heat gain (W)	Loss to sky (W)	Gain conductive (W)	Gain convective (W)
19.5	0	35.9	1.2	19.5
20	0.0	34.3	1.3	20.1
21	0.0	31.9	1.2	16.6
22	2.3	38.2	0.2	2.3
23	4.5	38.3	0.4	3.4
0	5.5	40.3	0.1	1.5
1	9.6	43.5	0.4	5.2
2	11.4	43.5	0.3	4.5
3	10.2	40.5	0.2	1.8
4	10.5	37.6	0.6	4.3
5	11.6	38.7	0.5	3.4
6	11.1	39.6	0.5	4.0
7	23.5	27.9	2.2	16.3

Condenser-on-Roof at Sayara (Kutch)

This system was installed at a school in village Sayara about 10 km from the coast of Arabian Sea. Three adjacent, gable-roofed buildings (**Figure 2)** were retrofitted with Condenser-on-Roof. All roofs were identical in pitch (15 degrees), and orientation – one half facing north, other south-and made with reinforced cement concrete. Combined roof area of three buildings is 360 m^2. Condenser panels of the type described above were overlaid on the roof surface covering it completely. Dew water flowed to the gutters and into the collection tanks on the floor. The yield from all three buildings in the season, January '06 to December '06, was 10.5 mm, and dew events numbered 100 **(Table 4).** The system continues to function requiring very little maintenance. The chemical analysis of samples of dew water showed it was potable with EC (0.24 dS / m) , PH (7.70), TDS (154 ppm) , Ca^{+2} + Mg^{+2} (1.50 me / lit) , Na^{+} (1.00 me / lit) , CO_3^{-2} (Trace), HCO_3^{-} (1.25 me / lit) Cl^{-} (1.50 me / lit).

Condenser-on-Ground - Panandhro

One large CoG was installed at Panandhro **(Figure 3)**. The installation consists of ten modules of the special ridge-and-trough condensers formed at the site. Ridges, each 35 m long, are built over gently sloping ground. Ridge is trapezoidal (top 50 cm, base 200 cm, two sides sloping 30 degree from horizontal, height 100 cm) and lined with the condensers described above. Each module has 85 m^2 surface, the ten together 850 m^2. Each module is connected to a common collection pipe at the lower end. The main storage is located in the middle. Partial Season Dew Collection from CoG Panandhro is shown in **Table 5**.

Table 4: Dew Yield - Sayara (CoR)

Month	Dew yield – all three buildings (liter)	Dew nights (no.)
January '06	220.40	9
February	750.70	13
March	1076.30	20
April	782.40	24
May	465.10	13
June-September	0	
October	451	21
November	34	-
December 06	0	0
Total	3780 (or 10.5 mm) (or 10.5 l/m^2)	100
Note : June to September is the rainy season generally with high cloud cover Total roof area of the school buildings - 360 m^2		

Table 5: Dew yield - Panandhro (CoG)

Month	Dew yield (liter)	Dew nights (no)
January 2007	221	3
February	1860	17
March	1597	18
April	1620	21
May	262	9
June- September	0	
October	585	10
November	400	6
December 2007	0	0
Total	6545 Or 7.7 mm 7.7 l/ m^2	84

Figure 2: Dew Harvest System at Sayara (CoR)

Figure 3: Dew Harvest System Panandhro (CoG)

Conclusions

1. The semiarid coastal region of Kutch in the north-west part of India is rich in dew resources. Dew occurs over a season of eight months - October to May, the quantity and frequency of occurrence are higher in summer (March-May) than in winter months(December-January). The numbers of dew nights are far more numerous (95 to 105) than the rainy days (17). Properly designed condensers made of reflective and high emissivity plastic film could collect up to 20 mm of dew water in the season. Although the quantity is modest compared to the rainfall (300 mm), it is an appreciable amount in a region chronically short of drinking water.
2. Prototype dew condensers were made from three materials - PETB film, galvanized iron roofing sheet and aluminium sheet. Over the season , highest collection was from the PETB units (19.4 l/m^2) followed by GI (15.6 l/m^2) and aluminium (9 l/m^2). PETB film is easy to work with and less expensive than metals.
3. Large dew harvest systems were developed using PETB film. The systems being promoted can be built over the roof of large buildings (Condenser-on-Roof) and over open ground (Condenser-on-Ground).

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