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Fog collection as a source of fresh water supply in the Kingdom of Saudi Arabia

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Abstract

In order to harvest water contained in fog, the topographical features and the climatic conditions of 27 cities in the Kingdom of Saudi Arabia were studied. The topography, altitude and orientation are some of the factors that determined the selection of the site. It was identified that the southwest of the region in the kingdom was the most suitable location for the fog-collection process. In order to evaluate the effectiveness of fog water collection and the site, three identical standard fog collectors (SFCs) with two different local collection materials were designed and manufactured. Experiments were conducted at two different locations in the area close to Abha, namely Soodha. The maximum amount of water collected was 22.9 L/m^2 in a day and 7.25 L/m^2 in a 2-h period. It was found that there was a high probability of fog when the relative humidity was higher than 95%. The results from the chemical analyses of eight sets of fog water samples collected were compared with World Health Organization drinking water standards. It was found that the level of heavy metals was negligible and the level of Fe was marginally high for the first flush only. The study indicates that in terms of both quality and magnitude of yield, fog is a viable source of water and can be successfully used to supplement water supplies in the fog-prone regions of the kingdom.

Introduction

The Kingdom of Saudi Arabia is an arid desert country without rivers and water lakes. Rainfall is both scarce and infrequent. The kingdom has one of the highest per capita water consumptions in the world. If the current rate of water consumption continues, there will be extreme shortage of water. To prevent severe water shortage in the kingdom, some stringent measures must be taken and new water sources must be identified.

The kingdom draws its water supply requirements from two main sources: water tables and desalination plants. Ground water is the main and most valuable resource of water and farms rely heavily on water tables. Seawater is needed for desalination plants and seawater always has a tendency towards scale formation and fouling problems due to dissolved salts and finely suspended solids. Hence, a low-cost and renewable method is required for areas where no seawater is available.

Fog collection

Fog is a cloud of already condensed small water droplets whose diameter ranges from 1 to 40 μm. The droplets fall at speeds ranging from less than 1 cm/s to approximately 5 cm/s (Schemenauer & Cereceda 1994a). Owing to the fine size of fog droplets and their low velocity, moisture is carried readily by breezes of even low velocity. A high relative humidity is necessary for the formation of fog. Fog water can be collected when fog comes in contact with objects. The aim of the present study is the evaluation of the possibility of obtaining water by means of fog collectors.

Fog collection directly from dense fogs is a resource that should be evaluated in areas where other traditional sources of water cannot meet the needs of the people and where water pipeline or desalination plants are impractical or too costly. The amount of water collected from fog is a function of the following (Louw *et al.* 1998):

- liquid water content of the fog;
- fog frequency and duration; and
- wind speed.

These criteria as well as accessibility must be taken into account during the selection of sites for fog collection.

Types of fog collectors

Fog collectors can be classified into two types (Al-Jayyousi & Mohsen 1999). They are:

(1) the cloud-water collector (CWC) and
(2) the standard fog collector (SFC).

The CWC, developed by Falconer & Falconer (1980), is made of plastic and comprises two 250-mm-diameter polypropylene discs separated by several polypropylene rods. Its disadvantages are that it is expensive and relatively difficult to manufacture. The SFC proposed by Schemenauer & Cereceda (1994b) is simple and inexpensive. It comprises a 1×1 m frame made of metal for rigidity to secure a standard 35% shade coefficient polypropylene mesh, which is placed on the frame in a double layer. The fog water collects on the mesh and the droplets join to form layer drops that fall under the influence of gravity into a trough below the frame secured for collection. The collector is completely passive. The SFC has been used successfully in many countries to evaluate fog water collection potential. The advancements made in fog and fog collection have been very well documented (Schemenauer & Bridgman 1998; Schemenauer & Puxbaum 2001).

Identification of a suitable location

Selection of a suitable site is vital to the success of a fog collection project. One of the main objectives of this research is to study the fog conditions existing in the kingdom by utilizing the meteorological data relevant to the fog obtained from the Ministry of Defense and Aviation, Presidency of Meteorology & Environment (PME) and the Statistical Yearbook (Central Department of Statistics 2001) covering the 5-year period from 1997 to 2001 and collected at about 27 Saudi Arabia meteorological surface stations, which are listed in Table 1. It can be seen from this table that the data cover the east to west coastal regions and also a few stations in the desert land.

A detailed study has demonstrated that data from standard meteorological stations are not suitable for identifying locations where fog water collection may be undertaken. To find a potential location for fog collection, a preliminary topographical and meteorological analysis of potential sites has to be followed up by a specialized observing programme at the site and actual in situ measurements with the SFC.

It has been reported (Akasakal 1998) that the forced convection due to orographic lifting in the southwestern mountainous region triggers heavy rainfall. The authors visited this region, and some observational studies showed that regions that are close to Abha in Asir Province may have foggy weather. Recently, it has been reported (Schemenauer *et al*. 2004) that all the ridges and mountain chains above 2000 m, from the south of Saudi Arabia to the north of Yemen, would potentially be good productive sites and should be evaluated for their fog collection potential. Care must be exercised when selecting a suitable site and in the orientation of the fog collector with regard to the direction of fog-bearing winds.

Table 1 Surface meteorological stations recording fog data in the kingdom

Sl. no.	Name	Latitude (°N)	Longitude (°E)
1.	Al-Qaysumah	28.3	46.1
2.	Wadi Al-Dawasir	24.5	45.1
3.	Al-Ahsa	25.2	49.5
4.	Sharurah	17.5	47.1
5.	Al-Baha	20.1	41.6
6.	Qurrayat	31.4	37.2
7.	Abha	18.2	42.5
8.	Najran	17.5	44.2
9.	Rafhah	29.6	43.5
10.	Ar'ar	30.9	41.1
11.	Hafr Al-Batin	27.9	45.5
12.	Turaif	31.7	38.7
13.	Bisha	20.0	42.6
14.	Al-Jawf	29.9	40.2
15.	Yan'bu	24.1	38.0
16.	Jizan	16.9	42.5
17.	Khamis Mushait	18.2	42.6
18.	Al-Wajh	26.2	36.4
19.	Qassem	26.4	43.9
20.	Hail	27.5	41.7
21.	Tabouk	28.3	36.5
22.	Taif	21.3	40.4
23.	Dhahran	26.3	50.1
24.	Madinah	24.5	39.6
25.	Makkah	21.5	39.8
26.	Jeddah	21.5	39.2
27.	Riyadh	24.6	46.7

Selection of materials

This research evaluates the feasibility of fog collection using various low-cost materials. The two important factors that determine the feasibility of implementing a fog water collection system are the expected yield and the quality thereof. Fog is mainly collected using collectors that are made from a special weave and percent shade coefficient polypropylene Raschel mesh (Schemenauer & Cereceda 1994b). This particular fog collector material is not available in the kingdom. However, other types of mesh, such as greenhouse shade nets and other local polypropylene nets with weave and percent shade properties close to those found in the SFC Raschel mesh, are available. The selection is based on several factors, such as availability, cost, durability, drainage of water, resistance to solar UV and shade coefficient. The materials chosen based on the above factors for use are manufactured in the kingdom, and two types of nets were selected. The first SFC surface was a black mesh with about a 35–45% shade coefficient and the second SFC surface was a flat, green polypropylene mesh with about a 60–70% shade coefficient. The supporting structure must be made of noncorrodable materials so that the collected water remains uncontaminated.

Experimental procedure

Collector panels were designed to withstand the structural stresses imposed by wind, humidity, and chemical or galvanic oxidation. The mesh net was fastened along both ends to vertical supports. The first black SFC surface comprised two layers of a flat, square net in an isosceles triangle weave supported by a post at either end, as shown in Fig. 1. The second green SFC surface comprised two layers of a flat, square net in a rectangular weave supported by a post at either end, as shown in Fig. 2. There was a gap of about 1 cm between the layers, and it was arranged perpendicular to the direction of the prevailing wind. The wind-carried fog droplets could easily pass around the collector. The mesh was pulled tightly over the frame with the support. The trough caught the water that ran down the mesh net and carried it to a pipe connected to a graduated collecting container.

In order to evaluate the effectiveness of fog water collection and the site, three identical 1.0 × 1.0 m SFCs (Schemenauer & Cereceda 1994b) with two different local collection materials, as described earlier, were manufactured, as shown in Fig. 3. Two collectors comprised a black SFC surface and the third collector comprised a green SFC surface. The frame was made of mild steel for rigidity and was painted to prevent rusting. The frame was supported by two posts of a metal base, which was also painted, 2 m above the ground. The vertical section of the collector frame was bolted to the upright posts with a 10 cm space in between to allow room for the trough to collect the fog water. The trough was made of an aluminium channel with a lengthwise section. The trough was centred under the frame and the trough was slightly sloped to drain the water to one end. Water dripped from the bottom of the mesh into the trough and then a gravity flow delivered the water to the container. Arrangements were made such that the vertical section of the collector

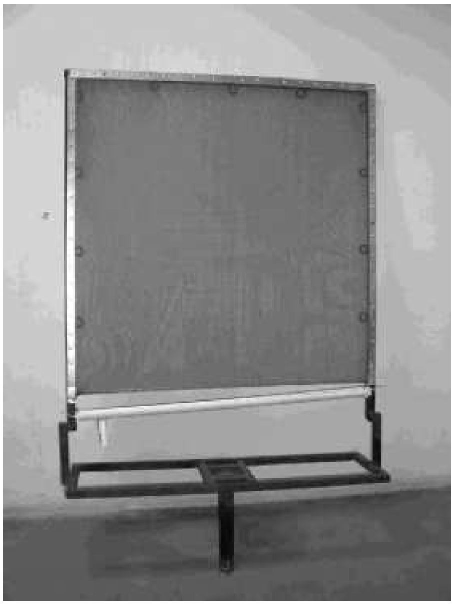

Fig. 2. Green fog collector mesh.

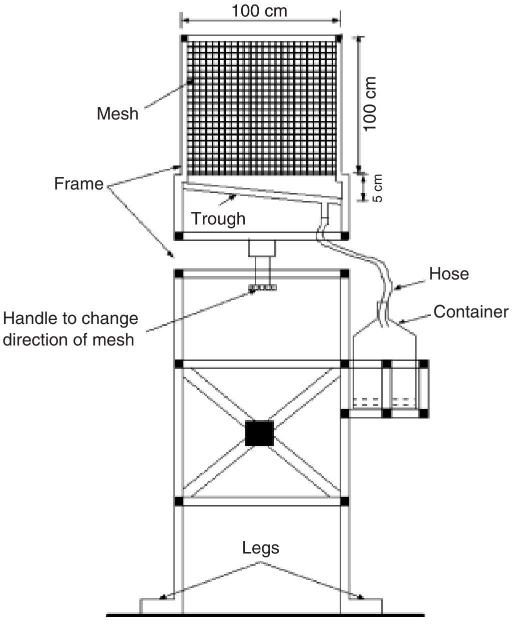

Fig. 3. Set-up of the standard fog collector.

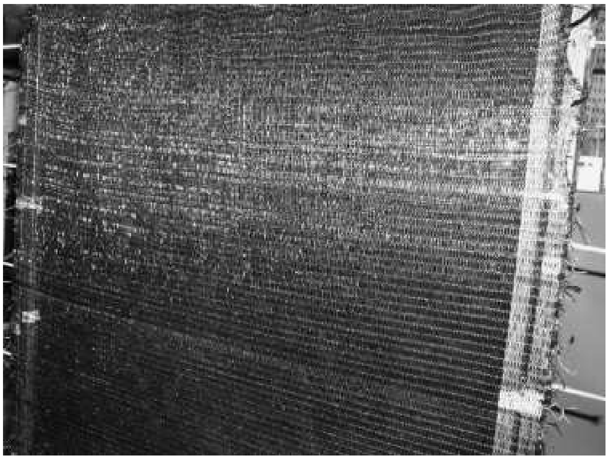

Fig. 1. Black fog collector mesh.

frame could be rotated manually to keep the panel of the collector normal to the wind.

Results and discussion

As observational studies showed that regions that are close to Abha may have foggy weather, experiments were conducted in this region. Abha is about 1700 km away from Dhahran, and the experiments were conducted in the mountainous area close to Abha, namely Soodha. The three SFCs were named as follows:

- Collector 1 – black mesh surface collector tested at site A.
- Collector 2 – black mesh surface collector tested at site B.
- Collector 3 – green mesh surface collector tested at the above two sites.

The distance between the above two sites was about 1.5 km, and experiments were conducted in the month of February 2005. The actual experimental set-up to evaluate the effectiveness of the fog collection surface is shown in Fig. 4.

Operational requirements included the measurement of the volume of the water collected and the recording of meteorological data, as changes in weather conditions may change the operational design of the collectors. The information used in this study came from instrumental and visual sources. The instruments used during this study were three SFCs, of which two were identical, meteorological instruments to measure the ambient temperature, relative humidity, speed of wind and visual measurements of fog water captured by the collectors. The data were recorded seven times a day, namely at 08:00, 10:00, 12:00, 14:00, 16:00, 18:00 and 20:00 h. Some typical experimental results in the month of February are shown in Table 2 and Fig. 5.

To evaluate the effectiveness of the mesh in fog collection, collectors 2 and 3 were tested at site B whereas collector 1 was tested at site A for the first 2 days of testing.

Fig. 4. Actual experimental set-up at the site.

For the remaining days of testing, collectors 1 and 3 were tested at site A, whereas collector 2 was tested at site B.

It was observed that when fog arrived, the environmental conditions changed notably. The temperature decreased abruptly, by more than 3 °C, and the relative humidity increased rapidly. From the visual measurements, it was observed that the highest frequency of fog was between 10:00 and 20:00 h for the first 2 days. Further, the period of wet fog reached its peak at about 16:00 h. There was a high probability of fog when the relative humidity was higher than 95%. The analysis of data for the two sites revealed that the fog frequency did not differ much between locations. Despite the similarity in the frequency of fog at the two sites, there was a marked difference in the amount of water collected. This may have been due to wind speed and its direction. The total fog water yield at site A exceeded that at site B. The maximum amount of water collected at site A was 22.9 L/m^2 in a day and 7.25 L/m^2 in a 2-h period.

The strands in the black-coloured mesh with an isosceles triangle weave were more closely packed and near vertical. The black colour strand arrangement enhanced the coalescence of the droplets, and a more voluminous runoff on the strand in this weave occurred than in the green-coloured one. Runoff on the strands of the green-coloured weave had a more horizontally oriented flow and, therefore, the runoff was slower. As a result, a droplet collected on a strand in the green colour weave mesh was more susceptible to dropping off the strand or to being blown away in the wind that accompanied fog deposition. This study serves to point out the feasibility of using other material for fog collectors. The maximum amount of water collected at site B by collector 3 (green mesh) was 12.9 L/m^2 in a day and 3.20 L/m^2 in a 2-h period.

When comparing the above values with the international figures, they provide a good indication that fog collection in the kingdom is feasible. If one assumes that the average amount of water collected per day was about 15 L/m^2 collecting area and the demand was about 300 L/day/person, then to provide water/day/person it would require 20 m^2 of collecting area. Thus, for a community of say 500 people, an area of 10 000 m^2 would be required. This can be met with the construction of 500 large fog collectors (LFCs) 10 m wide and 2 m high. It should be noted that the fog collectors were mounted vertically.

Chemical characteristic analysis of fog water collected

The actual implementation of fog collection with these collection nets should always include analysis of the quality of collected water to ensure that the collector does not impart any chemicals that would pose a threat to the

Table 2 Experimental results for fog collection in the Abha area

	Collector 1				Collectors 2 and 3				
Time (h)	T_{db} (°C)	RH (%)	V (m/s)	Yield (L)	T_{db} (°C)	RH (%)	V (m/s)	Yield 2 (L)	Yield 3 (L)
12 February 2005									
08:00	6.9	100	8.2	0	7.1	100	6.0	0	0
10:00	5.1	100	13.2	1.65	7.2	100	5.8	1.85	1.35
12:00	7.2	100	5.4	2.85	6.9	100	8.1	2.90	1.75
14:00	8.2	100	3.1	2.90	7.8	100	6.3	3.25	2.05
16:00	7.3	100	5.6	7.25	7.5	100	4.4	6.10	3.20
18:00	6.5	100	11.1	4.10	7.0	100	5.4	3.25	2.80
20:00	8.2	100	3.4	1.25	7.9	100	4.5	0.95	0.60
20:00 to 08:00				2.90				2.75	1.10
13 February 2005									
08:00	7.5	99.1	3.2	0	7.1	98.9	3.4	0	0
10:00	8.4	98.2	4.9	1.50	7.0	99.1	4.5	2.10	1.20
12:00	6.3	100	7.1	3.00	6.8	100	8.1	2.90	1.50
14:00	8.1	100	4.8	3.60	6.5	100	7.2	3.10	1.75
16:00	6.7	100	8.7	7.05	6.6	100	4.5	5.00	2.60
18:00	7.9	100	3.8	3.50	7.1	100	3.1	5.75	2.50
20:00	8.2	100	5.1	0.825	6.5	100	5.8	1.10	0.50
20:00 to 08:00				3.00				1.50	0.75

	Collectors 1 and 3				Collector 2				
Time (h)	T_{db} (°C)	RH (%)	V (m/s)	Yield 1 (L)	Yield 3 (L)	T_{db} (°C)	RH (%)	V (m/s)	Yield (L)
14 February 2005									
08:00	13.9	94.7	7.7	0	0	11.1	88.7	6.6	0
10:00	17.3	73.1	9.1	0	0	11.8	76.4	9.2	0
12:00	18.7	63.4	8.4	0	0	12.2	78.0	9.1	0
14:00	19.7	57.5	11.1	0	0	12.9	92.0	12.1	0
16:00	17.9	70.2	10.4	0	0	12.1	90.8	9.8	0
18:00	16.1	77.0	6.3	0	0	11.8	92.7	5.9	0
20:00	13.8	88.9	4.2	0	0	10.5	92.8	4.0	0
20:00 to 08:00				3.6	1.25				2.05
15 February 2005									
08:00	18.3	92.1	7.6	0	0	18.6	91.8	6.7	0
10:00	19.2	75.8	4.2	0	0	19.9	77.0	5.1	0
12:00	20.0	60.3	3.1	0	0	20.1	58.2	3.2	0
14:00	11.3	95.3	4.2	0	0	11.7	92.3	4.0	0
16:00	10.5	100	3.8	2.5	0.8	10.6	100	3.9	2.0
18:00	10.3	96.1	4.6	0.15	0.1	9.1	96.0	4.2	0.05
20:00	10.7	97.2	2.2	0	0	10.9	97.0	2.4	0
20:00 to 08:00				0	0				0

T_{db}, dry bulb temperature (°C); RH, relative humidity (%); V, wind speed (m/s).

health of the users. Therefore, a fog water quality monitoring programme was carried out to identify any contaminants from the collector material and atmospheric deposition. Generally, the water obtained from the fog is expected to be soft, neutral water of good quality with a very low content of minerals and metals. The quality of water depends on the composition of the ambient humidity and the conditions of the fog collection surface.

The chemical characteristics of fog water collected were analysed, and the quality of water discussed in this section is based on eight sets of water samples collected. The results from the chemical analyses of fog water collected were compared with the World Health Organization (WHO) drinking water standards (Furey 1998) and are shown in Table 3. The level of heavy metals was negligible due to the absence of heavy industries in the Abha area. It may be

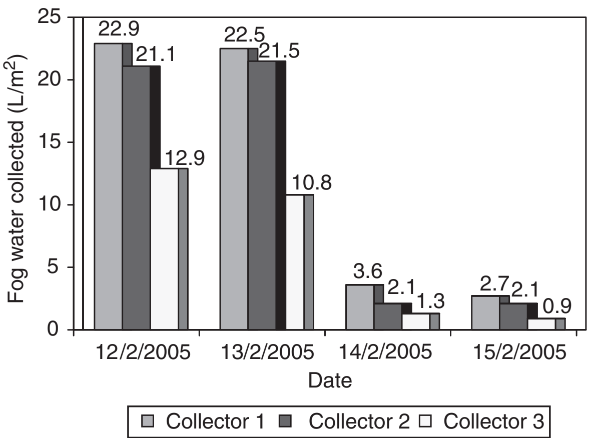

Fig. 5. Amount of total fog water collected by each collector.

noted that the high levels of Fe were associated with first flush only for black mesh collectors (samples 1 and 4). This may have been due to the presence of dust particles carried by the wind, but later samples showed a marked improvement in water quality. However, for the green mesh collector, the value was slightly higher. The quality of the fog water collected in remote areas like the Abha area meets drinking water standards. If one were to operate a fog collector in a polluted urban or industrial environment, one might have concerns about emissions entering the clouds and subsequently appearing in the fog water.

Conclusions

(1) It has been identified that regions that are close to the Abha area demand serious attention for fog collection studies. It has been clearly shown that substantial amounts of water can be obtained from persistent high-elevation fogs.
(2) The best time period to collect the water is about 16:00 h, with a dramatic decrease during midday. This study shows that locally available greenhouse shade nets can be used for fog collection, particularly in areas where the Raschel mesh is not available.
(3) Fog water collection will not be the total solution for the water shortages; this system will complement other water supply systems but will not replace them.

Table 3 Chemical characteristics of fog water sample analyses [results in ppm (mg/L) unless otherwise indicated]

	WHO Furey (1998)	Sample1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Detection limit
As	0.05	ND	ND	ND	ND	ND	ND	ND	ND	0.05
Ca	200	31.1	3.23	13.4	30.4	2.95	28.5	23.5	24.8	–
Cd	0.005	ND	ND	ND	ND	ND	ND	ND	ND	0.007
Cr	0.05	ND	ND	ND	ND	ND	ND	ND	ND	0.05
Cu	1.0	ND	ND	ND	ND	ND	ND	ND	ND	0.004
Fe	0.3	1.01	0.20	0.22	1.66	ND	0.24	0.64	1.06	0.03
Pb	0.05	ND	ND	ND	ND	ND	ND	ND	ND	0.1
Mg	125	3.24	0.24	1.52	3.37	0.20	2.66	2.22	3.00	–
Mn	0.3	0.060	ND	0.107	0.079	ND	ND	0.012	0.026	0.002
Ni	–	ND	ND	ND	ND	ND	ND	ND	ND	0.015
K	–	2.77	ND	ND	2.87	ND	2.17	0.23	1.10	0.1
Na	–	16.3	ND	8.55	16.5	ND	16.6	0.88	5.31	0.05
Se	0.01	ND	ND	ND	ND	ND	ND	ND	ND	0.13
Sr	–	0.106	0.008	0.045	0.104	0.006	0.096	0.056	0.068	–
S	–	7.89	1.71	5.60	7.79	1.52	7.83	3.30	4.86	–
Zn	–	ND	ND	ND	ND	ND	ND	0.212	0.120	0.002
Chloride	250	20.7	1.86	10.8	20.5	1.59	20.3	2.44	6.97	–
Fluoride	1.5	0.069	0.052	0.049	0.066	0.037	0.069	0.11	0.078	–
Nitrate	45	30.7	3.06	ND	30.5	2.42	30.3	3.74	9.90	0.02 (PQL)
Sulphate	400	21.9	5.81	15.6	22.7	4.25	21.6	9.88	13.2	–
pH	6–8.5	7.86	7.47	7.23	7.55	7.40	7.89	8.02	7.92	–
Conductivity (μS/cm)	–	258	35.2	134	259	30.9	260	123	165	–
Total hardness (as $CaCO_3$)	–	91.0	9.05	39.7	89.8	8.19	82.1	67.8	74.3	0
Total dissolved solids	–	200	20.0	70.0	190	20.0	150	70.0	140	–
Total suspended solids	–	ND	ND	ND	ND	ND	ND	ND	ND	1 (PQL)

Samples 1–3: from collector 1 (collected on February 12, 13 and 15, 2005).
Samples 4–5: from collector 2 (collected on February 12 and 15, 2005).
Samples 6–8: from collector 3 (collected on February 12, 13 and 15, 2005).
ND, not detected; PQL, practical quantitation limit; WHO, World Health Organization.

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