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Refining the use of evaporation in an experimental down-draft cool tower

D.Pearlmutter, E. Erell, Y. Etzion, I. A. Meir, H. Di

The Center for Desert Architecture and Urban Planning
The J. Blaustein Institute for Desert Research
Ben-Gurion University of the Negev
Sede-Boqer Campus 84990 Israel

Abstract

Direct evaporative cooling has long been recognized as an energy-efficient and cost-effective means for space conditioning in hot dry areas. In order to extend the use of evaporative cooling to include exterior or semi-enclosed spaces, a down-draft evaporative 'cool tower' was integrated in a 500 m² glazed courtyard located at the heart of a building complex in the arid Negev Highlands of southern Israel, designed by the authors. The present article describes the development of the cooling tower system, undertaken in three phases:
(i) *Prototype analysis.* Performance of a small-scale tower was monitored, and comparisons were drawn between varying rates and mechanisms of water and air supply. The results indicated a potential for substantial temperature reduction on the

order of 10°C under summer daytime conditions, but meager cooling output when using a natural draft system. Mechanical-forced air flow was thus utilized in the actual tower.
(ii) *Field monitoring.* The cool tower, approximately 10 meters in height and 10 m^2 in cross-sectional area, was operated and monitored during a summer season; its performance was analyzed using a series of water supply mechanisms and operating modes. The system produced a peak cooling output of just over 100 kW, with a wet bulb temperature depression of close to 85-95% during all hours of operation, and a water consumption rate of approximately 1-2 m^3 /day.
(iii) *Refinement*. Potential improvement in the system's operation was investigated through the development of a wind capture mechanism for increasing inlet pressure and air flow to the space. Both fixed and dynamic capture units were investigated, with wind speed and direction as well as internal air speeds measured in the small-scale prototype tower. The wind capture unit with the simplest configuration and best performance is recommended for future integration in the full-scale tower.

Keywords: Cooling systems;Israel;Down-draft cool tower; Evaporative cooling

1. Background

Evaporative cooling is an energy-efficient and cost-effective means for improving interior comfort in hot dry regions. The direct evaporative cooling tower (DECT) developed at Sede-Boqer, in the arid Negev Highlands of southern Israel, is a particular application of evaporative cooling which has been developed to provide cooling for a relatively large, semi-enclosed inhabited space. In this system, the ambient air enters the tower at the top, is cooled by the evaporation of water, and leaves the tower at the bottom. The exit air, with a lower dry-bulb temperature and a higher relative humidity than that of the ambient, is supplied into the lowest part of the central covered courtyard of the multi-use building complex, thus providing cooling for the occupants of the space.

The principle of evaporative cooling is based on the relatively large amount of energy required to convert water from its liquid form into its gaseous form, vapor. While the heat energy required to raise the temperature of water by 1°C is a mere 4.18 kJ/kg, the specific latent heat of vapoization is 2257kJ/kg [1]. In the case of an evaporative cooling system, this energy is supplied primarily by the intake air, whose heat content and capacity to hold vapor are indicated by its dry bulb temperature and relative humidity. The combined high temperature and low humidity typical of daytime summer air in arid climates such as that of the Negev Highlands (average daily maximum in July of 32°C at 30% relative humidity) provide promising conditions for the efficient, large-scale utilization of the evaporative process for cooling of inhabited spaces.

Historical uses of evaporation for the cooling of interior air are well known in such areas, as typified by the traditional Middle Eastern wind scoop ('malqaf' or 'badgir'), which could be used to channel air passing a wetted mat or pool of water [2]. The most common contemporary application of evaporative cooling is what is popularly known as the 'desert cooler' or 'swamp cooler' - a perforated box with wet pads on three sides through which outside air is drawn by means of an electric fan. The air introduced into the interior space may only be cooled to about 3-6°C above the ambient wet bulb temperature [3], so that large quantities of air are required to achieve thermal comfort, if the ambient wet bulb temperature is fairly low.

In recent years, the application of the evaporative cooling has broadened to include the climatization of large 'open,' or semi-enclosed public spaces, such the Avenue of Europe at Expo '92 in Seville, Spain [4], or the proposed 'solar oasis' in Phoenix, AZ, USA [5]. Notable for its use in this context is the 'down-draft' evaporative cool tower, which capitalizes on the vertical flows generated by thermal convection: the cooled air, both denser and more moist than its surroundings, tends to sink and draw ambient air in its wake. The rate of air exiting the down-draft tower, then, is ideally controlled by the temperature differential between the cooler air inside the tower and the warmer outdoor air [6]. Such a thermosiphonic process is based on 'free convection,' which occurs in the presence of a local thermal imbalance, with subsequent differences in air density leading to the movement of air from a zone of high pressure to one of lower pressure.

The movement of air inside an evaporative cool tower may also occur as a result of 'forced convection,' produced when air is deflected by a solid object or driven by mechanical means. As in the traditional 'badgir,' wind pressure may be utilized through a capture mechanism to increase the flow of ventilation air, or like the modern desert cooler, the tower may include an electric fan to increase circulation.

In the case of free convection, the thermal force driving the air through an evaporative cool tower is created by the introduction of water at the top of the tower. Initial cooling may be caused by the evaporation of water in the form of a fine spray. The water drops fall through the tower, so that the air inside it remains moist - close to saturation, if sufficient water is provided. Since the density of a gas is inversely proportional to its temperature, the cooler air inside the cool tower is denser than the ambient air. The force driving the air through the tower may be calculated by integrating this density difference along the height of the tower and multiplying by the acceleration due to gravity [7]. The magnitude of the thermosiphonic force thus depends on the temperature difference between the air at the inlet at the top of the tower and the outlet at the bottom. This difference is greatest if the ambient air is warm and very dry; if enough water is added to the airflow to produce saturation conditions throughout the length of the tower; and if the height of the tower is large.

As mentioned above, the energy required to evaporate water is two orders of magnitude greater than that required to cool the same quantity of water by 1°C. A single water drop in a non-saturated environment experiences heat, mass and momentum transfer processes [8], as following:

(i) The temperature gradient at the drop-air interface provokes a net heat transfer from the air to the drop surface, if the air is warmer than the drop.

(ii)The concentration of water vapor near the water surface gives way to water diffusion from the drop surface to the non-saturated air. This water diffusion needs a previous

evaporation of water from the drop; due to the latent energy of this phase change, this mass transfer is strongly coupled to the heat transfer.
(iii) If there is a relative movement between the drop of water and the surrounding air, a transfer of momentum between them will occur. This transfer of momentum tends to increase the rate of both heat and mass transfer. Thus the physical action of the water drops falling through the interior air of the cool tower may accelerate the cooling process.

The first two phenomena have opposite effects on the thermal state of a typical drop of water. The heat transfer tends to *increase* the drop temperature, whereas the latent energy absorbed by the evaporated water (mass transfer) causes a *decrease* in the temperature of the drop. Equilibrium is reached when the drop is cooled down to the wet bulb temperature. The latent energy required to evaporate more water, reducing the size of the drop, is supplied by the surrounding air, so the latter is cooled. Thus, the evaporation of a drop of water occurs in two stages: first, it is cooled to the equilibrium temperature, and second, its radius decreases.

The parameters which determine the likelihood that a drop of water will evaporate entirely under given environmental conditions are drop diameter and the length of time the water is in the airstream - determined largely by the height of the tower. Rodriguez et al. [9] showed that in the cool tower in the Rotunda of the Expo'92 in Seville, air temperature dropped by 12°C within the first meter of the tower if the mean diameter of the drops was 14 μm, but if water drops of 62 μm mean diameter were sprayed, air temperature was reduced only gradually, requiring the full 15 meter height of the tower for a reduction of 11°C. It follows that if the mean diameter of the water drops is large, most of the energy taken up by the water vapor in the form of latent heat will be removed from the drops, causing a decrease in the temperature of the water. If direct cooling of the air is required, drop diameter should theoretically be small, and the tower tall enough, so that total evaporation is achieved. If the surface beneath the tower is to be accesible to people. e.g. a plaza, total evaporation should be guaranteed under most meteorological conditions. Otherwise, it may be desirable to design a shallow pool where excess water is collected and recycled.

Maximum cooling occurs if the air is brought to saturation: the air cannot be cooled by evaporation beyond the thermodynamic wet-bulb temperature. Once this temperature is reached, the only means of increasing the cooling output of an evaporative cool tower of a given height is to increase the air flow rate, while maintaining the outlet temperature at the dewpoint.

Zaslavsky [10] and others have proposed the construction of 'aeroelectric' power stations, incorporating down draft cool towers with a height of hundreds of meters. The thermal convection in towers of such enormous height could be very great. However, for the purposes of space cooling, the height of an evaporative cool tower is usually limited by practical considerations such as structural strength, expense or architectural form. The potential for pure thermodynamic convection in such a tower is therefore inherently limited. Gueta [7] describing an experimental tower 21 m high constructed in Eilat, Israel, and operated under very favorable climatic conditions, reported a wind speed of 1.3 m/sec at the outlet, and a temperature reduction of 2.4°C relative to ambient air temperature. Cunningham and Thompson [11] report an airspeed of less than 0.7 m/sec at the outlet of a cool tower constructed in a test building in Arizona, USA.

Increasing the cooling output of a down-draft evaporative cool tower of moderate height thus requires a larger flow rate than can be attained by free convection alone. This implies the utilization of a mechanical fan to force air through the tower, or, where possible, making use of a wind scoop to harness local breezes.

If the inlet of an evaporative cool tower is symetrical and is not fitted with an appropriate scoop, the disruption to the airflow caused by wind blowing perpendicular to its axis results in a reduction of the flow rate through the tower relative to still air conditions [12]. Wind tunnel studies of various inlet configurations indicate that the reduction of airspeed due to turbulence can be reduced by up to 40% by simple modifications to the geometry of the inlet, such as installing a curved lip. The study further indicates that symetrical inlets are more effective when ambient wind speeds are less than 40% of the airspeed due to thermal forces inside the tower. However, once ambient wind speeds become greater than this value, asymetrical scoops oriented towards the prevailing winds are significantly more effective. The precise horizontal orientation of the scoop was shown to have relatively little effect on the efficiency of the scoop up to angles of about 60° from the direction of the ambient wind.

2. Prototype analysis

In the initial stage of the project, prior to construction of the cool tower in the building complex, a one-third scale tower was installed in a small semi-enclosed courtyard and tested using a number of different mechanisms for air circulation and types of sprayers for water supply (Table 1). This prototype tower, approximately 3.5 m high and 1 m^2 in cross-sectional area, consisted of a lightweight plastic sleeve assembled on a rigid frame and was monitored by electronic temperature and humidity sensores at its inlet and outlet. The airflow rate for each system was calculated according to measured airspeeds and the effective opening area of the air supply system. Based on the temperature differential and rate of airflow through the system, the capacity for air cooling, or maximum cooling power (P_{max}) of each configuration my be calculated:

$$P = Av\Delta tCp\rho \quad (1)$$

in which:

P=cooling power (kW);
A=cross-sectional area of entry (fan) opening (m^2);
v=velocity of airflow (m/s);
Δt=maximum temperature differential between entry and exit air (^{o}C);
C_p=specific heat of air ($kJ/kg^{o}C$) and
ρ=density of air (kg/m^3).

Results of this preliminary stage of testing, led to several general conclusions. While the potential for substantial temperature reduction was indicated (on the order of 10°C under summer daytime conditions), the intensity of natural down draft due to thermal convection alone was observed to be very weak. This was observed initially in testing the effects of free convection, and further in tests employing electric fans, whose results are shown in Table 1. Since the magnitude of cooling is a direct function of the air flow generated, the effectiveness of the system proved to be heavily dependent on the sufficient provision of forced draft. Thus while the configuration supplying the highest volume of air did not achieve the greatest temperature depression, it did achieve the highest cooling capacity.

Table 1

Prototype testing: configurations and results.

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Configuration	Water supply	Air supply (m^3/h)	Δt_{max} (°C)	P_{max} (kW)
1	Fine spray	100	7.0	0.2
2	Fine spray	745	10.9	2.4
3	Coarse spray	1150	5.8	2.0
4	Fine spray	1150	8.0	2.8

In terms of water supply, it was seen that a system of 'misters', which emit a relatively fine spray, provided both greater temperature reduction and cooling capacity than a system of coarser sprayers, presumably due to the increased evaporative effect of a greater surface contact area between smaller droplets and supply air.

3. Field testing

The DECT with forced draft is integrated in the building complex of the Blaustein International Center for Desert Studies, designed by the Desert Architecture Unit at Sede-Boqer. The multi-use complex has an approximate floor space of 1500 m², including 500 m² of internal covered courtyard; its height ranges from one to three-storeys. The courtyard covering consists of a selective glazing material which is highly reflective at steep solar incidence angles, thus acting as a broad shading device over the entire space during the summer, with peripheral upper windows allowing ventilation underneath its surface. (Fig. 1).

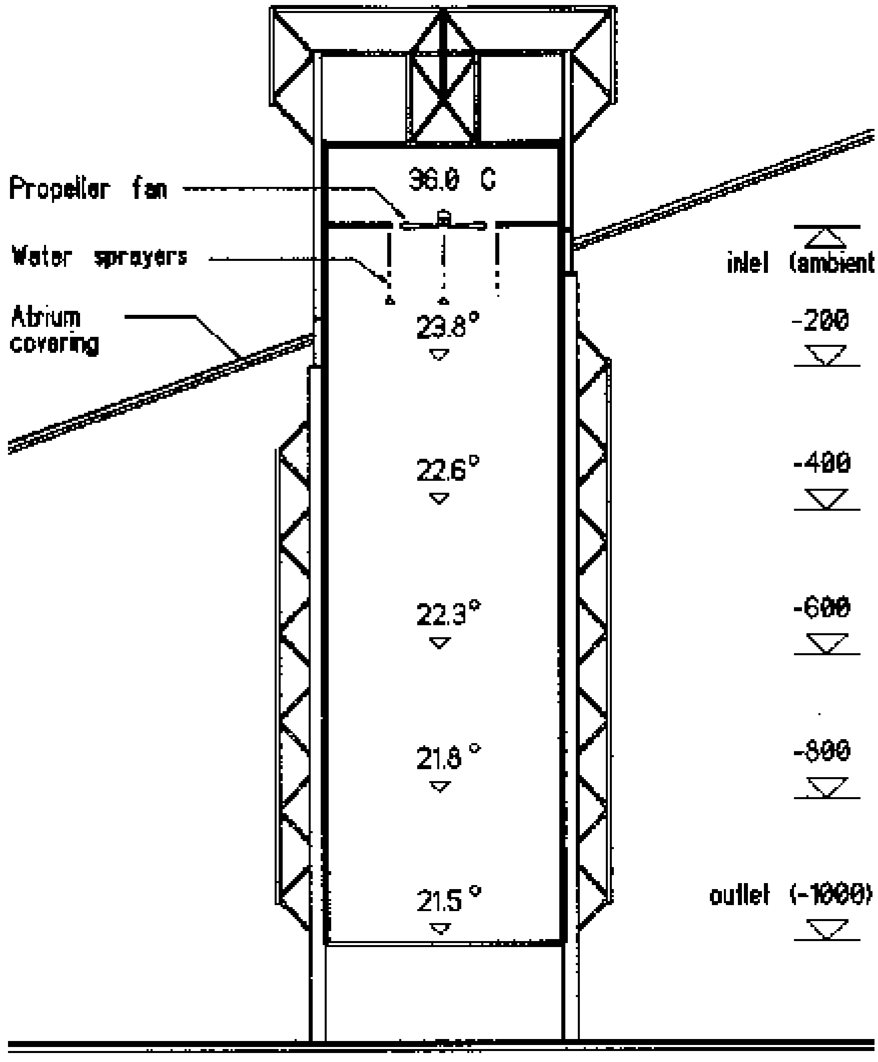

Fig. 1. Schematic section of evaporative cooling tower, showing installation in glazed courtyard and typical temperature profile during summer daytime operation.

The tower has a steel pipe frame structure and lightweight rigid envelope and is located at the center of the building's courtyard. Its effective height is 10 m and its diameter 3.75 m. In light of the findings from the initial prototype testing, mechanical forced air flow was utilized, with a 48 inch propeller fan at the top of the tower introducing ambient air into the tower at a measured rate of 36,000 m^3/hr. The air stream passes through a spray of water droplets, which are directed downwards together with the air.

The testing focused on several research objectives, with the overall aim of evaluating the tower's potential to provide cooling under the given conditions. This potential was gauged firstly as a function of water droplet size, by comparing different densities and types of spray heads. Also evaluated were the critical operating parameters of the system, in particular the rate of air flow through the tower, both aided by mechanical means and by natural draft alone, and the amount of water consumed by the system due to evaporation.

Different numbers and types of sprayers were used in the different experiments:
(i) coarse spray consisting of larger droplets was provided by household shower head sprayers, and
(ii) a fine mist of smaller droplets (diameter approximately 800 microns) by 'misters' used in landscape irrigation. Ultrafine atomizers which produce a fog consisting of droplets in the range of 5-150μ, while theoretically advantageous (see Ref.[9]), were not used in this stage due to practical considerations such as sensitivity to clogging. In one configuration, a plastic net was hung through the length of the tower for the purpose of increasing the effective area of contact between water and air. The cooling experiments employing the DECT were carried out during the summer of 1993, from June to October, after the building was completed and occupied. The experimental configurations included:

i) reference configuration: water supplied by a mixture of six shower heads and six sets of vertically spaced misters, airflow fan assisted;
ii) supply from six shower heads only, airflow fan assisted;
iii) supply from six sets of misters only, airflow fan assisted;
iv) supply as in (i) with a plastic mesh and
v) supply as in (i) with no operation of the fan. The shower heads or misters were distributed uniformly around the perimeter, with the former hung immediately below the

level of the fan and the latter spaced at even vertical increments of 1.5 m. Operation of the fan was from 9:00 to 18:00 hours during all days in which forced convection was used.

Parameters measured included ambient and tower dry-bulb air temperatures (at inlet, outlet, and two-meter vertical intervals within the tower), exterior and interior relative humidity, the rate of air flow through the tower and the daily water consumption. For a representative day in each period, several measures of cooling performance were calculated. In addition to the dry-bulb temperature depression, or the differential between ambient (inlet) and supply (outlet) air temperatures, the cooling efficiency, or 'wet-bulb depression' ratio, was calculated as the ratio of the decrease in actual dry-bulb temperature to the ideal decrease at saturation, at which the wet-bulb temperature is attained (the closer to 100% the value of the efficiency, the better the evaporative procedure of the water droplets.) Calculation of the cooling power for each system was further modified to normalize for varying ambient conditions, yielding an overall cooling performance factor (P_{norm}):

$P_{norm} = P(W_s - W)_1 / (W_s - W)$. . . . . (2)

where P is cooling power (kW) (see Eq.(1), W the moisture content of ambient air (g/kg dry air), W_s the moisure content of ambient air at saturation (g/kg dry air), and $(W_s - W)_1$ the difference between W_s and W at the given hour for the reference configuration.

From analysis of the above parameters, the following conclusions may be obtained:

(i) The cooling system is capable of decreasing air temperatures by 10-15°C at the peak of its performance, depending on configuration and ambient conditions. The majority of this reduction (8-12°C) is achieved within the top two meters of the tower, even when sprayers are spaced evenly throughout its height. The maximum reduction is achieved with the mixed system of both fine and coarse sprayers (Fig.2).

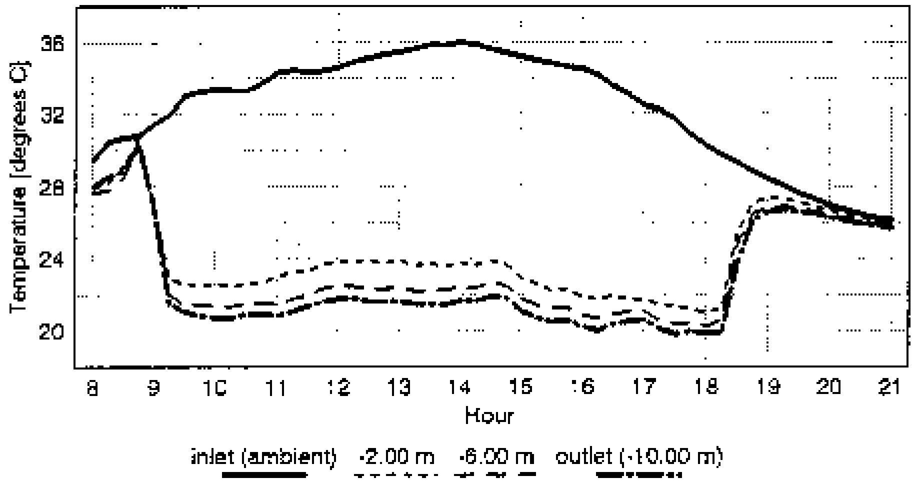

Fig. 2. Dry bulb temperature depression during hours of cooling operation: Typical daily curve for reference configuration.(-)inlet (ambient): (---)2.00m; (- - -) 6.00 m, and (-.-.-) outlet 10.00m.

ii) Cooling efficiency, as determined by the relative wet-bulb temperature depression, is highly variable depending on ambient humidity. Under typical summer conditions, each of the different configurations is capable of achieving a maximum cooling efficiency of 90-95% (Fig. 3).

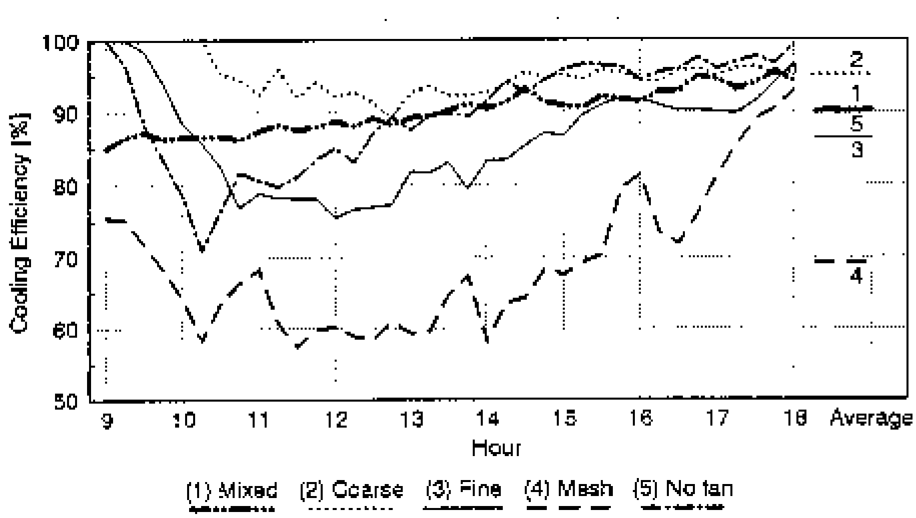

Fig. 3. Hourly and daily cooling efficiency for different system configurations: (1) mixed; (2) coarse; (3) fine; (4) mesh, and (5) no fan.

Water consumption likewise varies widely with ambient conditions, ranging from approximately 0.5 to 2.0m³/day. It may be seen that under the conditions monitored, the efficiency of a relatively fine-spray system is not greater than that of a coarse spray system. Thus while theoretically the evaporative process should be facilitated by smaller water droplets with a larger relative surface area, no evidence of this relationship has been found in the actual tower thus far. While it may be surmised that this is due to either (a) inconsistencies in actual water flow rates, or (b) insufficient differentials between 'fine' and 'coarse' drop sizes, a more detailed analysis of the relationship between drop diameter and cooling efficiency remains the subject of future study.

iii) Comparison of the different systems' cooling capacities when normalized for ambient conditions reveals that the most effective cooling is provided by the configuration of mixed sprayers (Fig. 4).

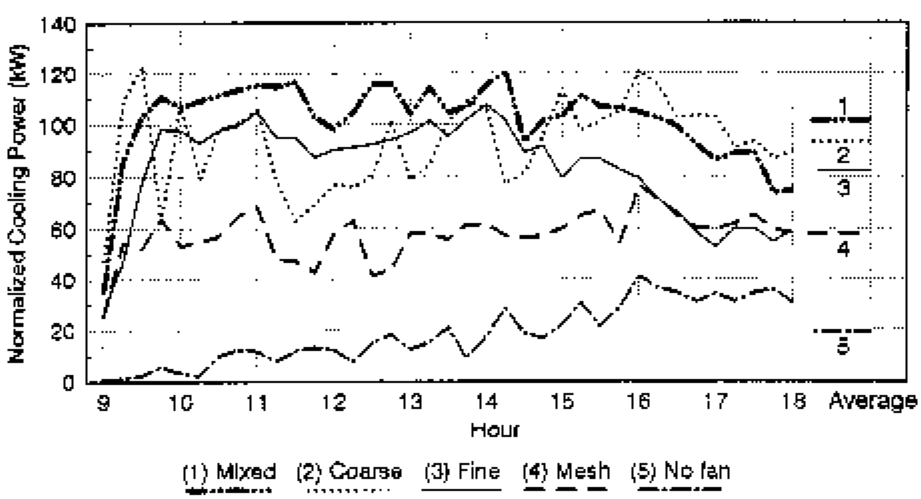

Fig. 4. Hourly and average daily cooling power output for different system confiurations, normalized for varying ambient conditions: (1) mixed; (2) coarse; (3) fine; (4) mesh, and (5) no fan.

The cooling power of this system reached 100-120 kW under ambient conditions of 36°C and 22% relative humidity. Only slightly less effective, however, is the system with coarse spray only, followed by that with fine spray only. In this case it appears likely that the more massive droplets produced by the coarse water stream are able to increase airflow, and in turn cooling, by facilitating a greater transfer of momentum, although the evidence to this effect is inconclusive. It is also clear that the performance of the system with no fan, and to a lesser degree that with the mesh filler, are impaired by a low air speed. (Fig. 5).

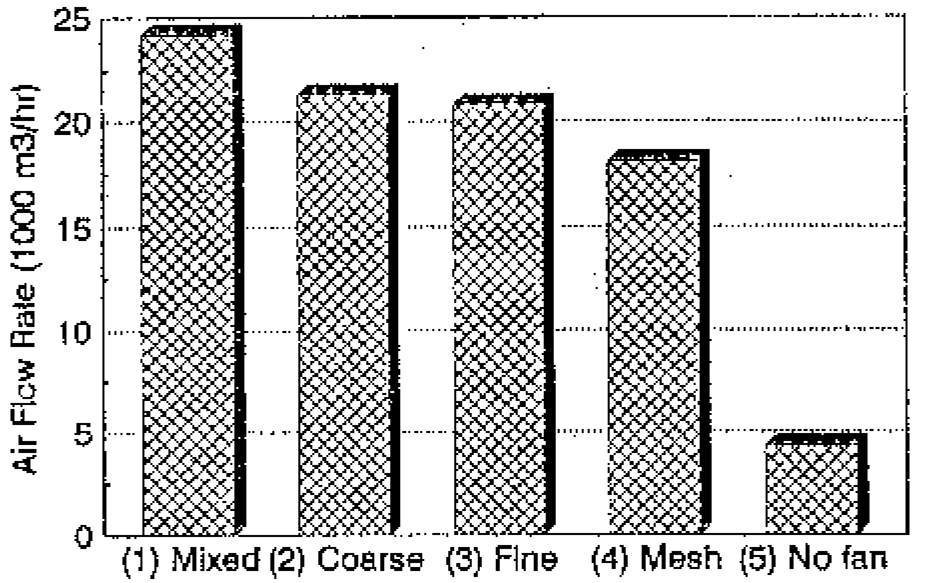

Fig.5. Comparison of average airflow rates for different system configurations.

It should be noted that the cooling output compared reflects the cooling of air only; a substantial portion of the latent heat absorbed in the evaporation of water drops is removed from the water itself. Excess water collected in the pool beneath the tower is thus cooled considerably and, if more efficiently utilized, could potentially increase the system's effectiveness.

iv) The rate of airflow appears to be the limiting factor to cooling regardless of specific configuration, since the cooling efficiency achieved is not far from maximum potential, and monitoring showed the effect of the cooling to be largely concentrated in the near vicinity of the tower entrance. It is predicted that this flow may be enhanced by means of wind capture, either in addition to or instead of a mechanical fan.

4. Wind capture studies

The utilization of wind capture was investigated as a potential improvement to the previous configuration, with the intent of i) reducing or eliminating the need for a mechanical fan, and increasing potential energy savings accordingly, and/or ii) enlarging the potential for overall air flow, and in turn the cooling capability of the tower. Since the supply of wind energy is not constant throughout the desired hours of operation, an optimal configuration was sought which would exploit positive wind pressure when available and minimize resistance to airflow when the tower is fan-assisted.

The model tower used in the first stage, approximately one-third scale of the actual system, was fitted with a wind-catcher mechanism in which various configurations of openings and deflectors could be tested. Airflow in the tower was evaluated for each configuration with respect to the wind speed and attack angle at the entrance: the wind capture 'efficiency' was calculated as the ratio between tower flow velocity and that of the wind component normal to the opening. In addition, the velocity for each configuration was measured in the presence of mechanically forced draft. The variations of wind-catcher designs included louver-panel entrances of different sizes, and flat and curved deflectors inside the capture unit of both fixed and dynamic configuration (Fig. 6a).

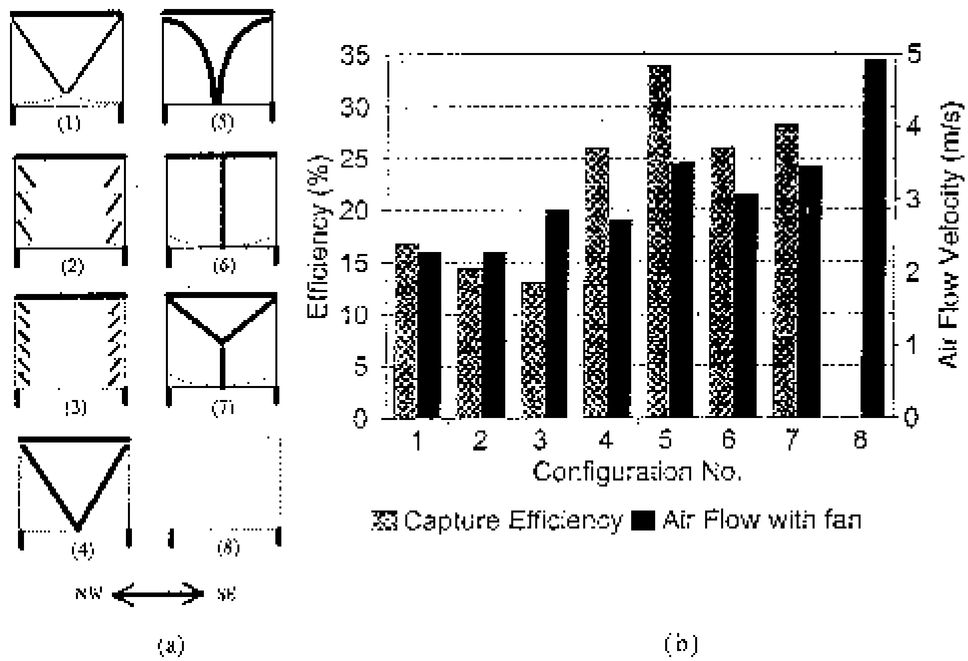

Fig. 6. (a) Cross-sectional configurations of the experimental wind catchers.
(b) Performance comparison: wind-capture eficiency without mechanical assistance,
and airflow velocity with forced draft.

All configurations made use of the same symmetrical superstructure, which admitted wind from the northwest sector (the prevailing direction during the summer months), and the southeast sector (the most common direction during the periodic heat waves of the spring season.)

The three initial designs (configurations 1-3) employed inwardly swinging louvers of different sizes installed in each of the two openings, with the intention of reducing energy losses due to outflow on the leeward side of the wind catcher. Such flows appeared to be relatively weak, however, and the expenditure of kinetic energy on opening the louvers against the force of gravity apparently factored heavily in the low wind capture efficiency of these configurations, which failed to rise above 20% regardless of specific louver size or density (Fig. 6b). The resistance of these louvers also led to below average flows when forced air from a mechanical fan was used.

Configurations 4 and 5 employed fixed deflectors to channel wind flow into the tower. This approach led to an increased efficiency of over 25% in the case of flat deflectors, and nearly 35% in the case of curved deflectors. The latter also provided the least resistance to forced airflow, allowing an average velocity of 3.5 m/sec. Two additional configurations (6 and 7) were investigated, with swinging panels centered in the capture unit, both alone and in combination with a fixed deflector. While these yielded better results than the initial louvered openings, they did not surpass the performance of the curved fixed deflector, which was seen to provide the greatest overall wind capture.

5. Conclusions

From observations made in the three phases of development carried out thus far, it may be concluded that an evaporative cooling tower such as that built at Sede-Boqer holds the potential for substantial cooling of semi-enclosed spaces in arid regions, with a modest consumption of water and energy. In light of the facts that i) extremely high cooling effeciencies were obtained with relative ease, and ii) the down draft effect based on thermal convection was seen to be relatively weak, a crucial parameter in determining the system's effectiveness is the generation of air flow from the tower into the space. The most effective natural means found for achieving this purpose is a wind scoop employing a fixed curved deflector, which provides a minimum resistance to flow generated either by wind pressure or mechanical means.

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