A novel multi-stage down-draft evaporative cool tower for space cooling. Part 2: Preliminary experiments with a water spraying system

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ABSTRACT

A multi-stage down-draft evaporative cool tower (DECT) was developed as an improvement to an existing single-stage design. The new tower incorporates a secondary air inlet, added to increase the cooling output and reduce the water consumption in a tower of given cross-section and primary inlet geometry. The secondary air, which may be drawn from the interior space being cooled, is cooled by evaporation in the lower section of the tower.

This paper focuses on the design of the water spraying system installed in the tower, and presents a preliminary assessment of the system's cooling efficiency. Performance of the novel aerodynamic design of the tower is discussed in a companion paper.

1. BACKGROUND

There are two basic types of downdraft evaporative cool towers (DECTs):

1. The 'Mist DECT', in which a very fine mist of water is generated at the top of the tower, and which evaporates very rapidly and cools the air around it. In the 'mist DECT', all water drops are evaporated before reaching ground level, so the space directly below it is suitable for pedestrian activity. The towers in the Avenue of Europe at Expo '92 in Seville are an example of this type of tower (Alvarez et al., 1991).
2. The 'Shower DECT', in which large drops of water are sprayed at the top of the tower and are not fully evaporated by the time they reach ground level. The cool tower at Sde-Boqer, Israel, is an example of such a tower (Pearlmutter et al., 1996). Because the volume of water introduced is larger than the potential for evaporation, a shower DECT produces chilled water in addition to cooling the air in the tower (Rodriguez et al., 1991). The excess water is collected into an operational reservoir beneath the tower, and may be circulated through heat exchangers to cool non-adjacent spaces.

In 'mist DECTs' total evaporation can occur only if water supply to the spraying system is adjusted periodically in response to changing environmental conditions (Alvarez et al., 1991). Alternatively, a conservative approach may be adopted where water supply is restricted to a rate that ensures full evaporation at all times. This strategy results in sub-optimal performance in hot dry conditions, where the potential for evaporation in the tower exceeds the water supply to the sprayers. In 'shower DECTs', where total evaporation of water spray is not required, spraying excess water effectively ensures that the rate of evaporation will always be the maximum possible in the given environmental conditions.

The water spraying system in shower DECTs is usually simpler and more reliable than that in mist DECTs: The spray heads do not require a pressurized water supply, are less susceptible to clogging than the micronizers incorporated in mist DECTs and are cheaper. On the other hand, the operation and maintenance of the operational reservoir incorporated in shower DECTs requires care: Recycled water must be filtered to protect the pumping system and the reservoir itself must be cleaned periodically to remove dust particles washed out of the air by the water drops (Etzion et al., 1997).

2. OBJECTIVES

The design of the water spraying system had the following objectives:

- to maximize cooling performance, by obtaining the lowest possible air temperature at the outlet of the tower.
- to minimize drift of spray at the outlet of the tower. The presence of small water droplets in air supplied by the tower results in constant wetting of adjacent surfaces, creating safety issues in pedestrian areas and maintenance problems due to deposition of soluble salts and increased risk of corrosion.
- to maximize the energy efficiency of the water supply system. The supply energy reflects the water pressure required to generate a specified flow rate and droplet size distribution in the sprayers.
- to minimize the maintenance costs associated with clogging of atomizers, etc.

To maximize evaporation in a given volume of air, the water spraying system must generate water drops with the largest possible surface area. This objective may be achieved by either of two opposite strategies: The sprayers may supply very small droplets of water, in which case only a small volume of water is required; Or they may supply large drops of water, in which case more water is required to achieve the same total surface area.

Creating a fine mist has several disadvantages: More energy is required to generate sufficient pressure to operate the sprayers; atomizers are susceptible to clogging because of the small orifice diameter; and any small droplets not evaporated are more likely to drift beyond the tower and into the space being cooled. Supplying large drops of water with an equal surface area, in contrast, requires less energy per unit area, may be done with coarse sprayers and results in less undesirable drift.

Efficient distribution of water in the interior of the tower should also guarantee the maximum time of residence for individual drops of water, and should supply water to the entire volume of air without creating over-supply in some regions.

3. EXPERIMENT

In a conventional down-draft evaporative cool tower (DECT), dry ambient air is drawn in at the top of the tower and cooler moist air is delivered at the bottom. If water is introduced at the top of a tall tower, then most of the cooling occurs near the inlet and air temperature approaches the wet bulb.

The design of the experimental DECT at Sde- Boqer differs from conventional designs in that it has two air inlets at different levels, rather than just one inlet at the top. It comprises a primary section incorporating two partly overlapping cones, of which the upper is inverted, in addition to a two-directional inlet and a semi-permeable deflector at the outlet (Fig. 1). It also incorporates a 1.1 kW electric fan that supports operation when environmental wind speed is low. (A detailed description of the tower is given in Erell et al., 2005.)

The complex aerodynamic form of this tower created unique challenges in the design of the water spraying system:

- Ensuring optimal distribution of water drops in both wind-driven and fan-assisted operation, which were found to have substantially different airflow patterns inside the tower.
- Avoiding excess water on the skin of the upper (inverted) cone of the tower, in spite of its tapering section.
- Distributing water droplets into the fresh air

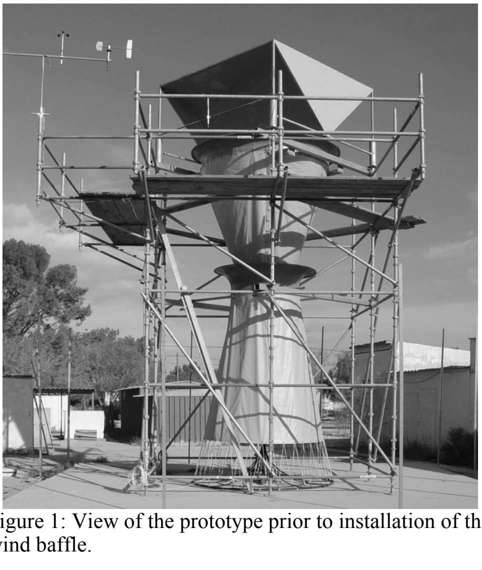

Figure 1: View of the prototype prior to installation of the wind baffle.

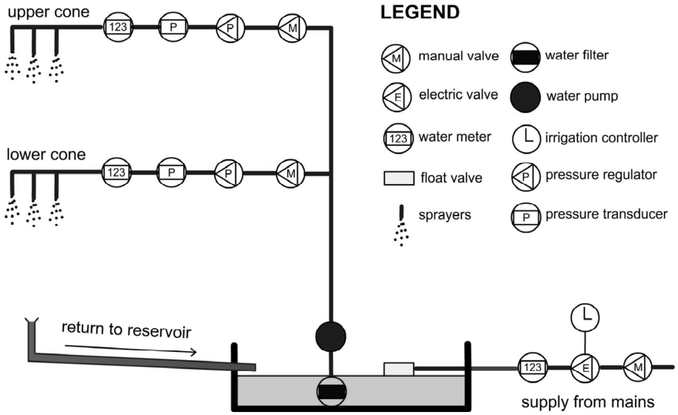

Figure 2: Schematic drawing of water spraying system in the experimental DECT.

introduced through the secondary inlet.

The water spraying system designed for the preliminary experiments on the prototype tower draws water from the main operational reservoir by means of a single 750 W pump. It allows individual control of two separate circuits leading to sprayers located below the primary air inlet and below the secondary inlet (Fig. 2). Each circuit comprises a control valve, pressure regulator, pressure transducer, water meter and sprayers located inside the tower.

Two types of sprayers were installed in the tower:

A ring of 5 BETE Spiraljet TF6 nozzles approximately 50 cm apart and 50 cm from the envelope of the tower was attached about 20 cm below the intake fan, or about 5.60 above the ground. The spiral nozzle has a simple one-piece design that allows a maximum liquid throughput for a given pipe size and minimizes clogging. It produces a conical spray pattern, with fairly coarse water drops: The Sauter Mean Diameter is 138-172 μm at a water pressure of 5 bar and 2 bar, respectively. (The Sauter Mean Diameter is the diameter of a drop having the same volume-to-surface area ratio as the ratio of the total volume of all the drops to the total surface area of all the drops.)

A ring of six PJ32 atomizers approximately 50cm apart was attached about 50 cm below the secondary intake, or about 250 cm above the ground. These are low capacity atomizers that use the liquid pressure alone to produce very finely atomized drops (SMD of 96-143 μm at a water pressure of 5 bar and 2 bar, respectively), in a full cone spray pattern. Atomizers were preferred in this instance because of the desire to saturate the secondary air in spite of the shorter time of residence of the drops.

Air temperature in the tower was measured with copper-constantan thermocouples in specially designed screens to protect the sensors from contact with the water spray. Airspeed was measured in the secondary inlet only, using a constant temperature LSI hotwire anemometer. Environmental conditions, including dry bulb temperature, relative humidity, wind speed and direction were monitored near the primary inlet. All data were logged on Campbell 21X and 23X loggers at 10-second intervals, and 10-minute averages were retrieved for further processing.

4. RESULTS AND DISCUSSION

The following section presents results of a preliminary series of measurements carried out after the aerodynamic design of the tower was evaluated in the absence of water spray (Erell et al., 2005). The configuration of the tower was unchanged during this phase, and performance tests were limited to variations in the operation of the water spraying system in both fan-assisted and purely wind-driven modes of operation.

4.1 Measured air temperature at the tower outlet

There are several measures for atmospheric humidity, but the wet bulb temperature is used in this case because it provides a simple visual representation of the potential for evaporative cooling: The wet bulb temperature depression is the difference between the dry bulb temperature of the air and the wet bulb temperature.

Figure 3 shows time series of the evolution of air temperature at the lowest point in the tower (‘tower low’ in Fig. 3) on two separate days, compared with the environmental dry bulb and wet bulb temperatures. Data are shown only for periods during which the spraying system was active. However, during each of the days shown here, operation of the sprayers was varied to evaluate the effect of different operating parameters on cooling performance. The output temperature is therefore not necessarily an indicator of the maximum cooling effect possible for the given environmental conditions. Abrupt changes in temperature are the result of changes in the spraying mode.

The primary environmental factor affecting the potential for evaporative cooling is atmospheric moisture. Large reductions in the temperature of air as it passes through the tower are possible only if there is a substantial wet bulb temperature depression, as illustrated in Figure 4. In the conditions tested, the cooling effect observed varied between a minimum of under 4°C to a maximum of over 10°C.

4.2 Calculating cooling output

Nominal cooling output was calculated on the basis of the air flow rate through the tower and the temperature differential between ambient air and air at the outlet of the tower, as follows:

$$P = Av\rho c_p \Delta T \qquad (1)$$

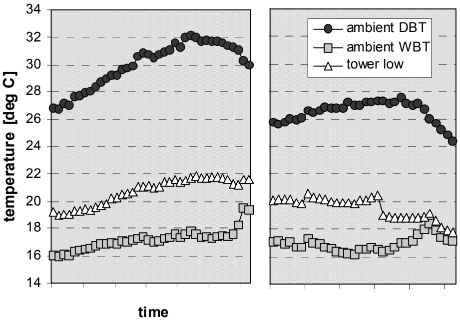

Figure 3: Air temperature at the bottom of the tower compared to the environmental dry bulb and wet bulb temperatures. Data for t*wo* separate days (October 26 and 27, 2004).

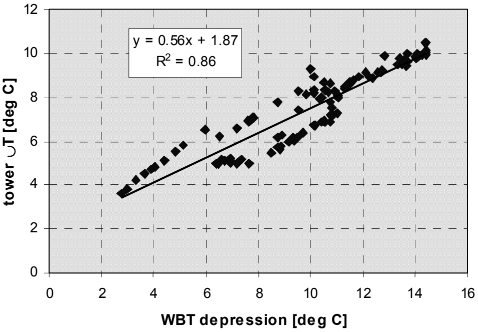

Figure 4: Correlation between the reduction in dry bulb temperature of air passing through the tower and atmospheric humidity, represented by the wet bulb temperature depression.

where P is the nominal cooling power [kJ s^{-1}], v is the vertical component of the air speed [m s^{-1}], A is the area of the horizontal cross-section of the tower where airspeed is measured [m^2], ρ is the density of the air [kg m^{-3}], c_p the specific heat of air [kJ kg^{-1} K^{-1}], and ΔT the temperature differential [K]. The specific heat of air is assumed constant, and equal to 1.005 kJ kg^{-1}. Air density is corrected for changes in ambient air temperature.

It should be noted that this procedure calculates only cooling resulting from the drop in air temperature, and does not account for the cooling output obtained as a result of the drop in the temperature of the water.

While calculation of the cross-sectional area of the tower at any given location was straightforward, measurement of air speed in the presence of constant water spray was not. Three-dimensional sonic anemometers purchased for this purpose gave faulty readings, and hot-wire anemometers are unsuitable for use in a wet environment. Airflow through the tower was therefore calculated on the basis of measurements of the unobstructed free wind above the primary inlet and of airspeed in the secondary inlet, using empirical correlations obtained during the first phase, when aerodynamic performance of the tower was evaluated with the sprayers inoperative.

The primary indicator of airflow through the tower used in calculation of the cooling output is airflow in the secondary air inlet. This was found to be between 37-39% of the total airflow in the tower in the dry mode for a wide range of airspeeds, and since it is nearly constant it provides a fairly robust estimate of total flow in the tower in the absence of direct measurements.

4.3 Gross cooling power of air

The cooling output of the prototype DECT during the preliminary experiment, calculated following the procedure outlined in section 4.2 above, ranged from a low of only 22kW to a maximum of 69 kW. These values should be considered only as an indication of the order of magnitude of the cooling output of air flowing through the tower, since they are based on a small sample of data obtained when the DECT was operating in marginal environmental conditions. They do not account for the cooling effect of evaporation on water drops that were not fully evaporated and were collected in the operational reservoir. They also do not take into account the power requirements of the intake fan and of the pump providing water to the spraying system.

It should also be noted at this point that in the current configuration of the water supply system, each of the two circuits could be controlled separately to modify the water pressure delivered to the sprayers by means of both a shut-off valve and a pressure regulator (see Fig. 2 above). However, an increase in water pressure results not only in more water delivered by the spraying system, but also in a smaller mean drop size. While smaller drop sizes result in more efficient contact with the air and hence in more evaporation and greater cooling (Guetta, 1993), the relative contribution of each of the above parameters to changes in the cooling output in the prototype DECT could not be quantified. In the following discussion, the operation of the water spraying system is therefore described by means of the water mass ratio only for the sake of convenience, although variations in cooling output may be due at least in part to changes in droplet size.

Figure 5 below shows the gross raw cooling output as a function of the moisture deficit, differentiated with respect to the rate at which water was sprayed into the tower. (The moisture deficit is the difference between the moisture content of a volume of air brought to saturation adiabatically by evaporation of water, and the actual moisture content of the air, in grams of water per kilogram of dry air).

As expected, atmospheric humidity appears to be the dominant factor affecting cooling output. However, the effect of the rate at which water was sprayed into the tower on cooling output cannot be established with confidence from the graph: Although cooling appears to be highest for any given value of the moisture deficit when water supply was at a maximum (25-27 l min^{-1}), the number of data points is still too small to be confident of this conclusion.

To account for the effect on cooling output of changes in the volumetric airflow rate through the tower (in addition to changes resulting from variations in the rate of water supply), the cooling output was again plotted against the moisture deficit, but this time differentiating the results with respect to the ratio between the mass of water sprayed and the mass of air passing through the tower, in grams of water per kilogram of air (Fig. 6).

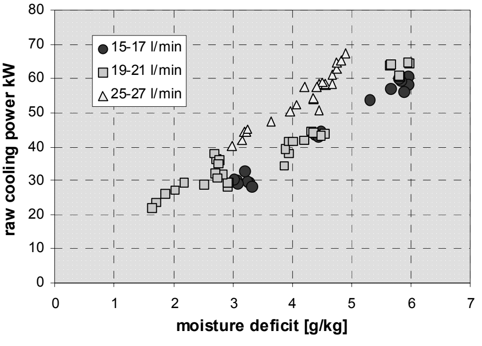

Figure 5: Correlation between the gross cooling output of the tower and atmospheric humidity, represented by the moisture deficit, for different water supply rates.

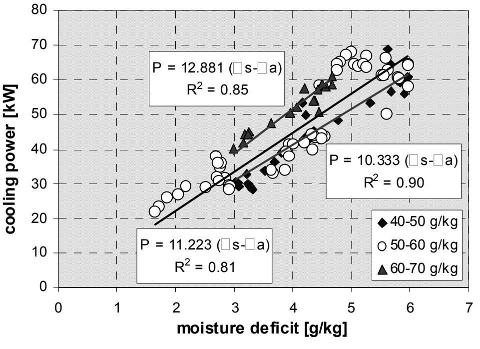

Figure 6: Correlation between the gross cooling output of the tower and atmospheric humidity (represented by the moisture deficit) for different water mass ratios (in g of water per kg of air).

Table 1: Values of the coefficient of evaporation calculated for different water mass ratios on the basis of raw cooling output in the prototype DECT.

ratio of water sprayed to airflow in the tower [g kg^{-1}]	coefficient of evaporation [W kg g^{-1}]
40-45	10.299
45-50	10.351
50-55	10.786
55-60	12.224
60-65	12.748
65-70	13.057

The lines of best fit obtained by linear regression are of the form

$$P = K(\omega_s - \omega_a) \tag{2}$$

where P is cooling output in kW and (ω_s-ω_a) is the moisture deficit of the air in g kg^{-1}. K is a coefficient of evaporation having units of kW kg g^{-1}.

As the graph shows, values of the coefficient of evaporation tend to increase with the water mass sprayed into the air, although the increase is rather modest.

Table 1 shows the results of a similar analysis in which experimental data were differentiated by smaller increments of the water mass ratio. Although the changes in water mass ratio were small, the table nonetheless supports the findings illustrated in Figure 6.

In an ideal system designed to cool air by evaporation, the mass of water sprayed exactly equals the moisture deficit of the incoming air. In real systems, it is impossible to guarantee a perfect distribution of water drops, so to obtain maximum cooling power an excess amount of water must be sprayed. If in addition the intention is to cool water, the mass of water sprayed must be greater still. However, while increasing the water mass ratio requires more pumping power, it also has diminishing returns with respect to the cooling output obtained (Gueta, 1993).

The design of the water supply system for the experimental DECT assumed a higher airflow than was observed in the preliminary experiments. As a result, the actual water mass ratio during the preliminary experiments, which varied between 40-70 grams of water sprayed for every kilogram of air flowing through the tower, was much higher than the moisture deficit of the air, which varied between 2-6 g kg^{-1}. In other words, the amount of water sprayed was excessive with respect to energy-efficient operation of the water spraying system. While both Figure 6 and Table 1 suggest that higher water mass ratios result in greater cooling output, changes in the coefficient of evaporation resulting from reduction of the water mass ratio should become progressively larger as the amount of water sprayed is reduced and approaches the moisture deficit of the air.

4.4 Normalizing cooling output for varying environmental conditions

As Figures 4-6 illustrate, monitoring of the cooling performance of the tower was carried out in a variety of (changing) environmental conditions. The figures also show that as expected, atmospheric moisture content has a marked effect on evaporation in the tower, and hence on cooling output. The empirical relationships derived for different water mass ratios also suggest that cooling output may be predicted reasonably accurately if in addition to this parameter the atmospheric humidity is known.

An alternative, complementary, approach towards comparing the effect of different operating strategies is to normalize the cooling power with respect to the relevant environmental parameters. In the following discussion, the nominal cooling power P is normalized to account for changes in atmospheric moisture content and for variations in the rate of airflow through the tower. The result is plotted against the rate at which water is sprayed, which is one of the main controls on DECT operation. As noted above, the operation of the water spraying system is described by means of the water flow rate only for the sake of convenience, although variations in cooling output may be due at least in part to changes in droplet size.

The nominal cooling output was first normalized for differences in *atmospheric moisture*. For a given volume of air, the potential for evaporative cooling is the difference between its moisture content when brought to saturation adiabatically, ω_s, and its actual moisture content ω_a. The evaporative cooling potential can then be employed to normalize the nominal cooling output of the tower with reference to an (arbitrary) reference atmospheric humidity of 25% relative humidity at 30°C:

$$P_{norm} = P\frac{(\omega_s - \omega_\alpha)_{ref}}{(\omega_s - \omega_\alpha)} \qquad (3)$$

As Figure 7 shows, the correlation between water flow rate and normalized cooling output is fairly modest. The magnitude of the offset is also a source of some concern, since it implies that cooling is possible with no water sprayed at all – which is patently impossible.

The effect of varying *volumetric airflow* was then accounted for by normalizing cooling output with respect to a reference airflow rate. In the absence of any preferred benchmark flow, the nominal cooling output was normalized by the ratio between the total flow through the tower at a given time to the average total flow for the entire period:

$$P_{norm} = P\frac{dV/dt}{d\overline{V}/dt} \qquad (4)$$

where *dV/dt* is the total volumetric air flow rate through the tower and the overbar signifies the mean value for the period.

Due to limitations of the airflow sensors available for the experiment, the volumetric airflow through the tower could not be measured directly while the sprayers were operating. However, empirical correlations are available between the total flow in the tower and measured quantities, such as wind speed near the primary inlet or airspeed in the secondary inlet. (For a detailed discussion of airflow in the tower, see Erell et al., 2005). The use of measured airspeed in the secondary inlet to assess total airflow in the tower in the wet mode is somewhat problematic from a conceptual point of view, since airflow in the secondary inlet results from flow in the main section of the tower, and thus incorporates the effects of the cooling system itself on the flow. However, the quality of the correlation, which was substantially higher than the one between wind speed and total airflow, and the fact that there is a uniform relationship between measured airspeed in the secondary inlet and total flow in the tower irrespective of whether the intake fan is operating or not, nevertheless favored this approach.

Figure 8 illustrates the effect of normalizing the nominal cooling output with respect to both atmospheric moisture and total airflow, the latter estimated empirically from measured airspeed in the secondary inlet. As the figure shows, the coefficient of correlation obtained when normalizing cooling output for both atmospheric moisture and airflow in the DECT is substantially higher than that obtained from an estimate based on atmospheric moisture alone (Fig. 7). The lower value of the offset in this case is also intuitively sounder, since in the absence of spraying (indicated by a water flow rate equal to zero), the cooling output should also be zero.

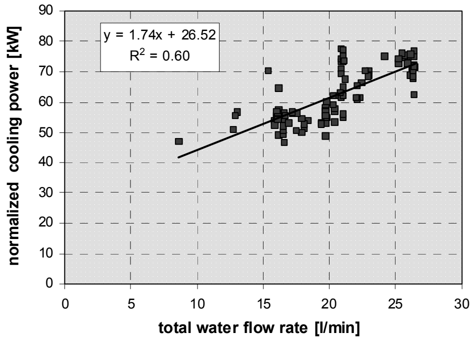

Figure 7: Relationship between total water flow rate through the spraying system and cooling output normalized for differences in atmospheric humidity. Ensemble data for three days (October 21, 26 and 27, 2004), showing performance in all spraying modes in a variety of environmental conditions.

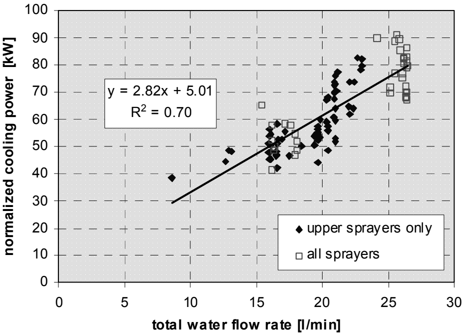

Figure 8: Relationship between total water flow rate through the spraying system and cooling output normalized for differences in atmospheric humidity and airflow rate predicted from airspeed in the secondary inlet. Ensemble data for three days (October 21, 26 and 27, 2004), showing performance in all spraying modes in a variety of environmental conditions.

5. CONCLUSIONS

The results reported upon in this paper are based on preliminary measurements carried out over a short period only. Any conclusions based on such limited data should therefore be treated with caution. The relationships between water flow rate and cooling output should be further qualified by noting that the experiments did not allow differentiation between the effects of increased water flow rate and the effects of reduced droplet diameter. A series of experiments is planned to provide a sufficiently large database for a sound statistical evaluation of the effects of both water mass ratio and drop diameter in a variety of environmental conditions.

Nevertheless, there are several aspects of the preliminary experiment that are encouraging:

- In spite of the technical difficulties involved in measuring air temperature and airspeed accurately in the presence of water spray, the correlations between the cooling output and operational parameters such as the water mass ratio and water supply are fairly high.
- In spite of marginal environmental conditions during the preliminary test and the fact that the water supply system had not yet been optimized, the nominal cooling output of up to 70 kW is quite promising.
- The simplicity of operation of the basic components of the DECT system throughout the tests and the apparent reliability of the various components suggest that where environmental conditions are suitable, i.e. weather is dry and warm, application of evaporative cool towers may be a practical means of providing low-cost, low-maintenance cooling of large spaces.

ACKNOWLEDGEMENTS

This research was supported by a grant from the Israel Ministry of Science, Culture and Sport and Forschungszentrum Juelich GmbH, Germany, within the Joint German-Israeli Research Program.

Installation of the equipment and supervision of the monitoring program were carried out by Mr. Wolfgang Motzafi-Haller.

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