A Multi-Stage Down-Draft Evaporative Cool Tower for Semi-Enclosed Spaces. Part I: Aerodynamic Design

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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 reports on the results of experiments conducted to establish the aerodynamic performance of the design prior to installation of a water spraying system. Design of the water spraying system and experiments on cooling performance are discussed in a companion paper.

Keywords: evaporative cooling, cool towers, airflow

1. INTRODUCTION

Evaporative cooling is possibly the only economically viable solution for cooling large, semi-open spaces such as atria and internal courtyards in arid climates [1] [2]. The down-draft evaporative cool towers (DECT) constructed in the 1992 World Exposition in Seville, Spain, to cool the public space between the pavilions [3] are a well-known implementation of the technique

The main forces that move the air through a DECT are a) the wind pressure at its top inlet; and b) the increase in the specific weight of the cooled air in the upper section of the tower, which is slightly heavier than its surroundings and thus descends, generating air movement through the full height of the tower [4]. If large drops of water are sprayed that are not fully evaporated in the tower, momentum transfer from the water to the air also contributes to the airflow.

The potential for pure thermodynamic convection in a tower is related to its height and to the difference in temperature [5]. Vertical airspeed due to negative buoyancy (alone) may be calculated as follows, assuming adiabatic conditions below the point at which water is introduced and neglecting friction:

$$w = -\sqrt{2gz\frac{T_e - T_p}{T_e}} \qquad (1)$$

where w is velocity (ms^{-1}), g is acceleration due to gravity (ms^{-2}), z is the height difference between the point where water is introduced and the bottom of the tower (m), T_e is the temperature of the environment (K) and T_p is the temperature of the air parcel cooled by evaporation (K). The negative sign indicates downward motion.

However, flow in real cool towers cannot be fully predicted from Equation 1 alone because it does not include the effects of aerodynamic drag. Data published by Cunningham and Thompson [6] illustrate this point. In the cool tower they tested, air was introduced through 10 cm thick vertical cellulose pads installed at the top of all four sides of a 5-metre high tower, which were kept wet by a small pump. Although a plywood “X” baffle was installed inside the tower to catch the wind, measured data showed no correlation between wind speed and airflow in the tower: air speed in the tower was almost exactly 1/3 of the magnitude predicted for negative buoyancy alone (Equation 1). The loss of airspeed is due to the aerodynamic drag created by the wet pads and by friction with the walls of the tower.

The cooling output of a DECT is proportional not only to the temperature of the air supplied but also to its volume, so effective design of such a device should seek to maximize airflow. Since the height and cross-section of a DECT may be limited by cost, space or structural considerations, it may be beneficial to optimise the aerodynamic design to promote airflow through a relatively small tower.

Airflow in a DECT may be augmented by making use of wind. Wind catchers, only some of which incorporate evaporative cooling, have been used extensively in traditional architecture throughout the hot arid countries of the Middle East. They are known variously as the *malqaf* in Egypt or as the *badgir* in Iraq and Iran, and are found as far east as Pakistan and Afghanistan. There are many varieties of wind catchers, which may be classified according to flow concept, cross-sectional shape, orientation with respect to the prevailing wind, geometry of the inlet and total height [7]. Wind induced flow into a cool tower may also be controlled by means of gravity-shut dampers designed to prevent air escaping on the lee side [8].

If the height of a tower built for space cooling is insufficient to generate a strong thermal flow, it may harness wind or employ an electric fan to generate airflow through it. The design of the air inlet in such a tower should therefore be optimised to allow effective operation in all three modes: pure buoyancy, wind assisted and fan-assisted. An experimental evaluation of several intake geometries for such a tower was undertaken at Sde Boqer, Israel, using a reduced scale model [9]. The optimal configuration was found to be a fixed deflector with a curved section. In the case of Sde Boqer, where the prevailing winds blow from either of two diametrically opposed directions, the wind catcher could be constructed symmetrically to allow air intake from these directions only.

A full-scaled evaporative cool tower incorporating this wind catcher was installed in the atrium of a multi-purpose building [10]. Monitoring of the tower showed that about 85% of the cooling effect was achieved in the uppermost two meters of the tower, and that outlet temperatures were only about 3°C above the ambient wet bulb temperature. Since a further significant reduction in air temperature is not possible, the performance of such a tower can be improved only by increasing the volume of the air drawn through it and by reducing the amount of water evaporated to supply cooled air at the lowest temperature consistent with the environmental conditions. The current paper reports on an experimental design that seeks to do just this.

2. EXPERIMENT

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

The design of the new DECT was required to be compatible with fan-assisted operation when wind speed is low, in addition to pure wind-driven flow when environmental conditions are suitable. Several geometric configurations for a multi-stage tower were analysed in detail by CFD (FLUENT) simulation, and in scale-model wind tunnel experiments.

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

The final design 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. An electric fan supports operation when environmental wind speed is low.

A prototype tower conforming to this design (Fig. 1) was constructed at Sde-Boqer, Israel. The tower is 8 meters high and 2.25 meters in diameter at its widest point.

Fig. 2 shows a schematic representation of the airflow measurement set-up in dry operation. Speed and direction of the free, unobstructed wind (V_∞) were measured throughout the experiment near the primary inlet by means of a cup anemometer (Met One 010B) and wind vane (Met One). Measurement of airspeed at the bottom of the upper cone (V_2 in Fig. 2), the secondary inlet (V_3) and horizontal and vertical cross-sections of the airflow (V_{4-7} and V_{8-10}, respectively) were made with LSI constant temperature hot-wire anemometers (threshold

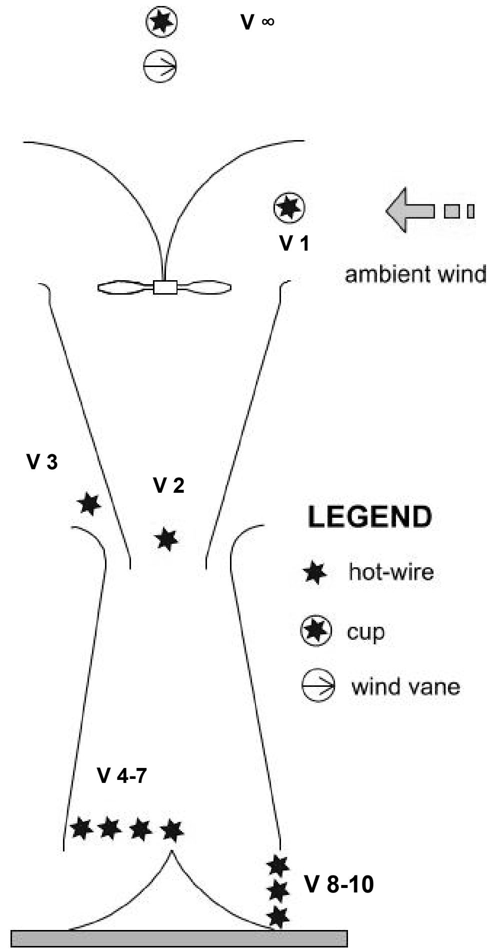

Figure 2: Monitoring air speed in the tower in ‘dry’ operation (water spray inoperative).

velocity: 0.01 m s^{-1}; accuracy 4% or +/-0.04 m s^{-1} at 1 m s^{-1}; thermal drift of 0.14% $^oC^{-1}$). In wet operation (sprayers operating), hot-wire anemometers V_2 and V_{4-10} were removed, since they cannot be exposed to water. Two 3-D ultrasonic anemometers (Young 81000) were installed in place of sensors V_4, near the tower envelope and V_7, at the tower centre just above the outlet cone. Data were logged on Campbell 21X and 23X loggers at 10-second intervals, and 10-minute averages were retrieved for further processing.

3. RESULTS

Airflow in the tower was monitored in two separate phases:

First, detailed measurements were made of airflow prior to operation of the sprayers, to evaluate the effect of specific features of the aerodynamic design, such as the wind catcher above the primary inlet, the secondary inlet and the deflector cone at the outlet. The data obtained in this phase of the experiment were used to obtain parameterisations of the total volumetric flow rate in the tower in terms of flow through the secondary inlet and with respect to wind speed, for both fan-assisted and wind driven operation. Measurements in this phase were carried out by an array of hot-wire anemometers.

In the second phase, water spray was introduced. In addition to monitoring the effects of evaporation on air temperature, airflow was measured by means of two 3-D sonic anemometers installed in the tower interior.

3.1 Effect of axial symmetry in the wind catcher on airflow in the tower

Previous experiments with different designs for a wind catcher above the primary inlet of the tower [9] showed that at Sde-Boqer, where wind direction in the cooling season is generally very stable, axial symmetry is enough to ensure optimum flow into the top of the tower. With airflow deflected into the tower from one direction only, it was necessary to establish whether air in the prototype tower had become fully mixed by the time it had travelled through the entire height to the outlet, for two reasons. First, full mixing of the water spray with the incoming air is required to achieve maximum cooling output; second, measurement of airspeed in the monitoring experiment must take into account any lack of homogeneity in the flow when sensor locations are established. Detailed measurements of airspeed at the bottom of the tower were therefore made in two cross-sections: parallel to the main (horizontal) axis of the wind catcher and perpendicular to it [11]. Although fan-assisted flow differed from wind-driven flow (see below), measurements made in each of the two modes gave consistent results, irrespective of the orientation of the section - parallel or perpendicular to the main axis of the wind catcher.

3.2 Estimating total flow through the tower

Calculation of the cooling output of the tower requires both the temperature depression resulting from evaporation of water and of the rate of airflow through the tower. Measuring this airflow correctly was one of the main aims of the first phase of the project. Empirical correlations were obtained between total airflow and free wind speed, and between total flow and flow through the secondary inlet.

Total airflow through the tower is the sum of the flows through the primary and secondary inlets. Experiments made with the sprayers inoperative showed that the correlation between wind speed, measured near the primary inlet, and total flow, is very high in the wind-driven mode, as might be expected [11]. However, it was also quite high in the fan-assisted mode. Without the contribution of the sprayers, flow was sustained by the intake fan at a minimum rate of approximately 3 $m^3 s^{-1}$ in the absence of wind; in the presence of wind, the flow rate shows a linear increase that reflects the contribution of the wind catcher.

Flow through the secondary inlet may be measured directly using hot-wire anemometers even when the water spraying system is in operation, since flow through this inlet is consistent in its direction and there is no risk of spray damaging the sensors. A correlation between flow through this inlet and total flow through the tower may therefore provide a means of estimating total flow in the absence of direct measurements in the tower interior, which is saturated with water droplets.

CFD simulation studies indicated that with respect to maximizing airflow in the secondary inlet, the optimum configuration of the tower was one in which there was an overlap of about 0.4 meters between the upper cone and the lower one. In this configuration, flow through the secondary inlet was predicted to be approximately 40% of total flow through the tower.

The tower prototype was built precisely according to the findings of this optimisation study. As Fig. 3 shows, the measured contribution of the secondary inlet was found to be about 39% of the total airflow through the tower. This percentage was quite stable, irrespective of whether flow in the tower was generated by the intake fan or by wind alone, for all airspeeds measured.

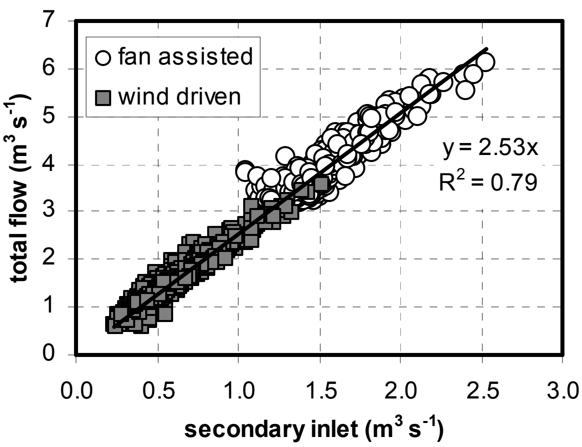

Figure 3: The correlation between airflow in the secondary inlet and total flow through the tower, in the *wind-driven mode* and *fan-assisted operation*. (Data are for one representative day in each mode – June 21 and June 22, 2004, respectively.)

Confidence in this method is further justified by the close agreement between the numerical simulation and the measured data. All subsequent calculations of total airflow through the tower are based on this relationship.

3.3 Contribution of wind to airflow through the upper part of the tower

Airflow through the upper part of the tower was calculated from measured airspeed at the bottom of this section, signified by V_2 in Fig. 2 above. Unlike measurements taken at alternative points closer to the primary inlet, which may be affected by reverse (outward) flow near the inlet, measurement at this point gives the actual flow through the upper part of the tower: The decreasing cross-section created by the conical form, coupled with the fact that there are no substantial forces acting upward at this point, mean that flow will consistently be directed downward.

The contribution of wind to flow in the upper section was assessed by measurements carried out when the intake fan was not operating, and the flow was therefore due entirely to the wind. Since the inlet does not have full circular symmetry, the component normal to the axis of the wind catcher was calculated from wind speed and direction data. A high correlation (r^2=0.92) was found between this component and wind-generated airflow through the upper section of the tower [11].

3.4 Differences between fan-assisted and wind-driven flow

Simulation studies and flow visualization with smoke indicated that the difference between fan-assisted and wind-driven flow is not only one of magnitude – fan assisted flow is substantially higher in most conditions - but is also manifested in a different flow pattern. The action of the fan introduces a strong centrifugal component to the flow: air is deflected towards the fabric skin of the tower and is forced downward in a spiral. This pattern is preserved during the transition from the upper cone to the lower one, in spite of the substantial variations in the longitudinal section of the tower and the introduction of additional external air through the secondary inlet.

In dry operation (sprayers inactive), the maximum air speed in the wind-driven mode, recorded about 30 cm from the middle of the tower, was 1.3-1.4 m s^{-1} on average, while substantially lower air speed, averaging about 0.5 m s^{-1}, was recorded near the fabric skin [11]. The flow near the sides of the tower in this mode was not only slower, on average, than flow in the middle, but it was also much more stable. In fan-assisted operation, air speed was relatively slow near the middle of the tower – only 0.6-0.7 m s^{-1} on average, about the same as the slowest part of the flow in the wind-driven mode. Air speed increased with distance from the centre, however, and reached a maximum of about 2.1-2.5 m s^{-1} adjacent to the fabric skin of the tower. In addition to being faster, the flow near the skin of the tower was also much more turbulent, with speeds fluctuating from less than 1 m s^{-1} to more than 3 m s^{-1}.

With the sprayers operating, airspeed was measured at only two points in the main section: Near the centre of the tower, just above the deflector cone, and about 30 cm from the perimeter. Airspeed was also measured in the secondary inlet. As Fig. 4 shows, when the fan is in operation (between 08:00-13:40) flow is directed downwards near the perimeter of the tower. However, there appears to be a weak upwards directed flow near the middle, indicating that the turbulence created by the fan generated a counter-rotating vortex. When flow is generated by wind and the action of the sprayers, the pattern is reversed: the main downwards flow occurred near the middle of the tower.

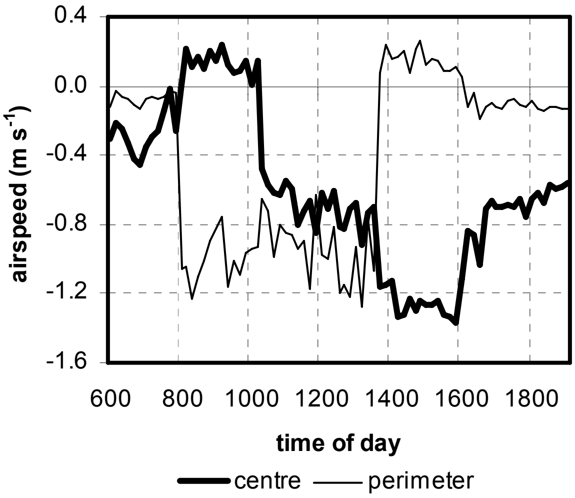

Figure 4: Vertical component of flow at the bottom of the tower. The intake fan was in operation from 08:00-13:30. Water sprayers were operated from about 10:10 to 16:00. Negative values indicate flow is directed downwards. (Data for August 17, 2005)

3.5 Effect of the deflector cone at the tower outlet

If the tower outlet is close to ground level, a deflector cone may improve the transition in the direction of airflow from vertical (downwards) to horizontal (outwards), with a minimal loss of momentum. The effect of such a cone on airflow was assessed without sprayers by conducting a series of measurements of airspeed prior to its installation, and then repeating the same sequence once it was in place. With the sprayers operating, the process was reversed and airflow was measured for several days after the cone was removed.

In the *wind driven* mode, the expected increase in airflow through the tower due to the introduction of the deflector did not materialize: the relationship between ambient wind speed and flow through the tower is substantially the same in both configurations. This behaviour may be attributed to the fact that air reaches the bottom of the tower in this mode at a relatively low velocity, typically under 1.0 m s^{-1} (though varying with ambient wind speed). At such low airspeed, loss of momentum at the bottom of the tower is in any case small, so a deflector cone may be unnecessary.

In the *fan-assisted mode*, airflow is directed mainly towards the side of the tower due to the centrifugal force of the fan. The deflector cone has little effect on this flow, which has a large horizontal component. When wind speed is low, airflow through the tower is maintained mainly through the action of the intake fan, and the minimum flow rate is about 3 $m^3 s^{-1}$. However, when ambient wind speed is higher than about 3 m s^{-1}, wind induced flow is added to the fan-generated flow, and airspeed near the centre of the tower is higher. The outlet cone helps to deflect this component of the flow outwards: the flow rate increases from a maximum of about 4 $m^3 s^{-1}$ to as much as 6 $m^3 s^{-1}$ (Fig. 5).

With the sprayers operating, the total flow rate was higher than in dry operation (see section 3.6), both in wind-assisted and fan-assisted operation. The contribution of the deflector cone was therefore expected to be higher, too. However, comparison of the flow rate on similar days with and without the cone showed that its contribution was, if anything, somewhat smaller. The sustained flow rate in fan-assisted operation was about 8.5 $m^3 s^{-1}$ with the cone and about 7.5 $m^3 s^{-1}$ without it.

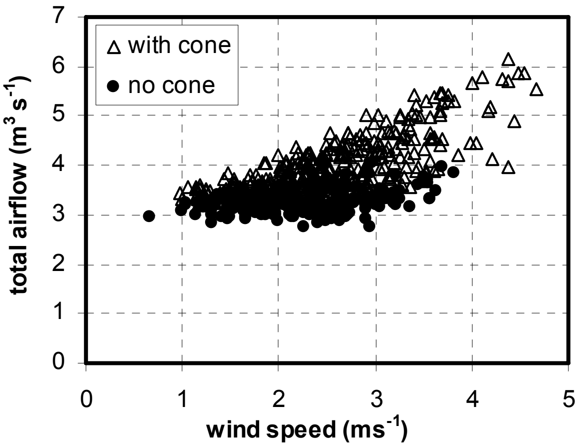

Figure 5: Effect of deflector cone on airflow in the tower, in the fan-assisted mode. (Data for one day in each configuration - June 12 and June 21, 2004.)

3.6 Contribution of the sprayers to the airflow

The contribution of the sprayers to airflow in the tower has two components: buoyancy flow created as dense air cooled by evaporation of water sprayed at the top of the tower subsides, and momentum transferred from drops of water falling through its entire height.

Buoyancy flow in an open space may be calculated from the temperature difference measured at two separate heights. However, in a restricted space such as the tower, actual airflow is reduced by the drag resulting from inlet and outlet losses, by friction with the fabric envelope of the tower and by the change in the cross sectional area along its height.

When water is introduced into the airflow by means of atomizers, total evaporation occurs within a relatively short time. If the height of the tower is large, momentum transfer may then be much smaller than the buoyancy force. However, when the initial radius of the drops is sizeable, momentum transfer may be responsible for a substantial proportion of the airflow generated by the sprayers.

Assessing the relative contribution of buoyancy and momentum transfer to the total airflow in the tower cannot be done on the basis of the experimental data alone. It requires mathematical modelling supported by empirical estimates of the aerodynamic drag created by each of the tower's components. The development of such models is beyond the scope of this paper.

The overall contribution of the water sprayers to airflow is easily discernable from the experimental data. Total airflow in the tower presents a step pattern that corresponds to changes in the operating schedule (Fig. 6). Operation of the intake fan was initiated at about 08:00, and created a flow rate of about 5-5.5 $m^3 s^{-1}$. Since ambient wind speed at this time was negligible, the flow is attributed entirely to the fan. Sprayer operation commenced at about 10:10, increasing the flow rate to about 8.5 $m^3 s^{-1}$. When the fan was stopped at about 13:30, total flow dropped to about 4.5 $m^3 s^{-1}$, due to the combined effect of the sprayers and of the wind, which averaged about 1 ms^{-1}. After 16:00, when water spraying stopped, the wind-generated airflow was about 2-2.5 $m^3 s^{-1}$.

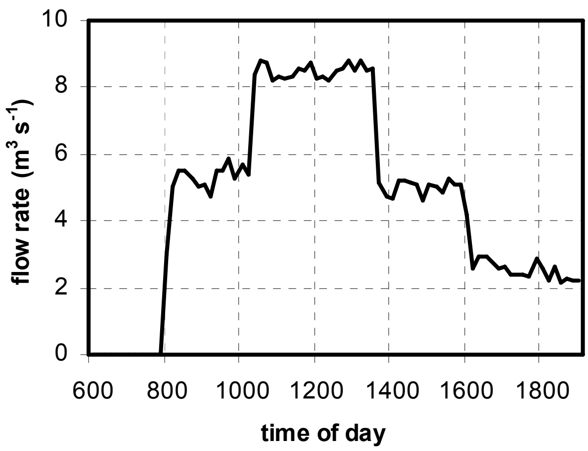

Figure 6: Total airflow through the tower, illustrating the contribution of the fan, water sprayers and wind: Fan operation was initiated at 08:00. At about 10:10, water sprayers were activated. At about 13:30, the fan was turned off, and at 16:00 the water sprayers were shut down. Flow after 16:00 is due to wind only. (Data for August 17, 2005)

4. DISCUSSION

Much of the existing research on cool towers has concentrated on buoyancy-generated airflow, and there has been little research on the contribution of wind, either alone or in combination with an electric fan. The experiment described here suggests that in a "shower tower" with a well-designed wind catcher, although total flow may vary in response to changing environmental conditions, the contribution of these forces is substantial.

The effects of the secondary inlet and of the deflector cone at the outlet were established in quantitative terms. It was demonstrated that flow in the secondary inlet was directly proportional to flow in the main section of the tower for all airspeeds: Even when flow through the upper (inverted) cone of the tower was as slow as $0.5\ m^3\ s^{-1}$, the flow convergence created by the conical section resulted in a sufficiently high airspeed at its narrowest point to generate stable flow through the secondary inlet. In contrast, the effect of the deflector cone on airflow, and hence on tower performance, was noticeable only in relatively high airspeeds. The increase in fan-assisted airflow resulting from addition of the deflector cone averaged just over 5% when the total flow through the tower was $3\ m^3\ s^{-1}$, but was about 15% when total flow was $4\ m^3\ s^{-1}$ and over 23% when flow was $5\ m^3\ s^{-1}$.

There are substantial differences between flow patterns in the tower in the wind-driven and fan-assisted modes. The strong centrifugal component imparted to the flow in the upper cone through the action of the fan was simulated correctly in CFD studies. However, the fact that it is preserved even after flow converges in the narrow section at the bottom of the upper cone and after the introduction of substantial inflow through the secondary inlet is nevertheless somewhat unexpected. The lack of homogeneity in the flow and the differences between the two operating modes poses difficulties with respect to optimising the location of water sprayers. Introduction of a fixed diffuser below the intake fan may be the only means of generating a uniform flow pattern in the tower.

It should be noted that while the actual empirical relations observed may be specific to this tower, the fact that robust relationships can be derived is important in the wider context of designing multi-inlet DECTs in general.

In particular, the fact that flow generated through the secondary inlet comprises a substantial and almost constant proportion of the total flow has great significance. It means that in order to supply a given volume of cool air to the space in which the DECT is installed, interior air may be circulated through the tower and re-cooled, saving a substantial amount of water compared to cooling much hotter and drier ambient air to the same temperature.

5. CONCLUSION

The cooling output of a DECT is determined by the reduction in air temperature and by the rate of airflow through it. Experiments with a novel tower design showed that substantial airflow could be generated through a secondary air inlet, and that additional features such as a deflector cone at the outlet of the tower could increase flow rate in certain conditions. Quantitative relationships among several operating parameters were derived from experimental data, and these can be used in the evaluation of cooling output resulting from the operation of a water spraying system. Results of this evaluation, which comprises the second part of the experiment, are given in a companion paper.

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