A novel multi-stage down-draft evaporative cool tower for space cooling. Part 1: 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.

1. BACKGROUND

Evaporative cooling is possibly the only economically viable solution for cooling large, semi-open spaces such as atria and internal courtyards in arid climates (Fathy, 1986; Yellot, 1989; Givoni, 1993). Down-draft evaporative cool towers (DECT) were constructed in the 1992 World Exposition in Seville, Spain, to cool the public space between the pavilions (Alvarez et al., 1991). Current state-of-the-art, though, does not yet enable full exploitation of the potential of such towers. Their widespread adoption depends not only on their acceptance by designers and the public, but also on improvements in performance and the installation of demonstration projects.

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 (Rodriguez et al., 1991). 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.

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. Al-Megren (1987) classified wind catchers according to the following characteristics:

- *Flow concept*: A wind catcher may be either uni-directional, if wind enters through the top and air is allowed to escape the house at ground level; or it may be bi-directional, if the tower is divided along its vertical axis so that air enters through an opening on the windward side, travels down to ground level in one passage and then up again through a second passage to be exhausted through an opening on the lee side of the tower.
- *Cross-sectional shape*: Traditional wind towers are constructed of brick, and are generally either square or rectangular.
- *Orientation with respect to wind*: Rectangular wind catchers generally have their long axis normal to the prevailing winds. Bi-

directional towers are usually oriented diagonally with respect to the prevailing wind, and have a square section.

- *Shape of the top end of the catcher*: Uni-directional catchers have an inclined roof with a slope of 30-45 degrees. Bi-directional towers may have either flat tops or inclined ones (a 'butterfly' configuration).
- *Height*: Traditional wind towers range in height from about 5 to 15 meters, and generally project at least one story above roof height.

Renewed interest in passive cooling in the 1980s led to the development of a number of cool towers, in which air was drawn into the tower through gravity-shut dampers designed to prevent air escaping on the lee side (Bahadori, 1985) or through wetted pads similar to those used in desert coolers (Cunningham and Thompson, 1986).

The potential for pure thermodynamic convection in a tower is directly related to its height (Guetta, 1993). However, the height of a tower built for space cooling is limited by considerations of structural strength, expense or architectural form, and is usually insufficient to generate a strong thermal flow. An evaporative cool tower for space cooling must therefore harness wind or employ an electric fan to generate flow through it.

Based on these theoretical considerations, a fan-assisted evaporative cool tower was installed in the atrium of a multi-purpose building at Sde-Boqer, Israel (Etzion et al., 1997). 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. An experimental evaluation of several generic designs for a wind catcher suitable for both wind-driven and fan-assisted flow recommended the use of a fixed curved deflector (Pearlmutter et al., 1996), which was subsequently installed to improve airflow in the tower.

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 analyzed in detail by CFD (FLUENT) simulation, and in scale-model wind tunnel experiments.

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, and was monitored for several weeks in dry operation, prior to installation of the water

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

spraying system. The tower is 8 meters high and 2.25 meters in diameter at its widest point.

Detailed airspeed measurements were carried out in the tower in wind-driven and fan-assisted operation. Data were logged on Campbell 21X and 23X loggers at 10-second intervals, and 10-minute averages were retrieved for further processing.

Figure 2 shows a schematic representation of the airflow measurement setup. 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 ($V_{4\text{-}7}$ and $V_{8\text{-}10}$, respectively) were made with LSI constant temperature hot-wire anemometers (threshold velocity: 0.01 m s^{-1}; accuracy 4% or +/-0.04 m s^{-1} at 1 m s^{-1}; thermal drift of 0.14% $^{o}C^{-1}$).

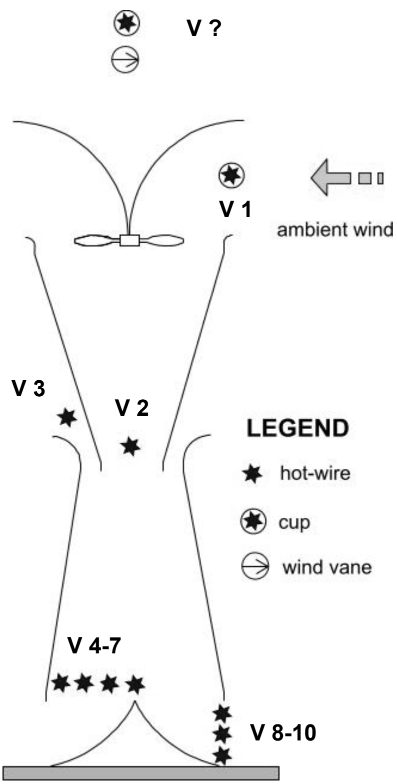


Figure 2: Monitoring air speed in the tower in 'dry' operation (water spray inoperative).

3. RESULTS

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 (Pearlmutter et al., 1996) 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 wind flow 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 traveled through the entire height to the outlet, for two reasons. First, full mixing of 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 cross-sectional measurements of airspeed at the bottom of the tower were therefore made in two configurations: parallel to the main (horizontal) axis of the wind catcher and perpendicular to it.

Although fan-assisted flow differed from wind-driven flow (see Section 3.4 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 Airflow in the secondary inlet

Although the DECT prototype is not installed in a fully-enclosed space, it is surrounded by a fabric baffle designed to shield it from the direct impact of the wind while allowing unobstructed flow into the primary inlet and through the outlet at the bottom. The intention was that airflow through the secondary inlet would be induced entirely by flow through the main section of the tower, and that the effects of wind could be neglected, to simulate conditions in an enclosed courtyard.

To test this assumption, concurrent measurements were made of airflow at four different locations in the secondary inlet, corresponding to the four quadrants of the compass. This inlet is symmetrical with respect to the longitudinal axis of the tower, and flow in the upper cone of the tower in the fan-assisted mode is also assumed to be symmetrical. The airspeed at all

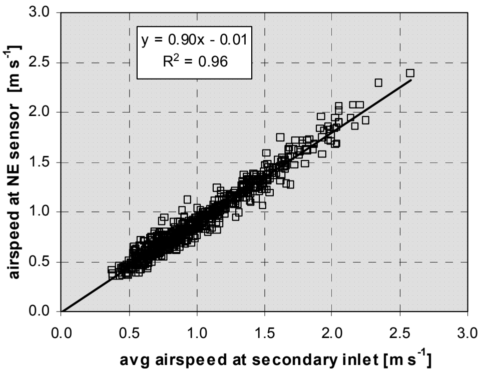


Figure 3: Homogeneity of flow in secondary inlet, as indicated by correlation between airspeed measured by hot-wire in NE quadrant and average of all four hot wires, in wind driven mode. Results for fan-assisted operation were nearly identical.

four locations could therefore be expected to be the same in the absence of wind, whereas wind-generated airflow inside the sheltered volume of air created by the fabric baffle would result in different air velocities being recorded on the windward side and on the lee side of the tower.

Observations showed that there was in fact a certain amount of asymmetry in the flow through the secondary inlet, in both the fan-assisted and wind driven modes. However, as Figure 3 shows, the correlation between the average airspeed (for all four sensors) and the airspeed measured by the sensor in the northeast quadrant was very high, for all directions of ambient wind. Since there were insufficient hot wire anemometers for continuous monitoring at 4 points, this sensor alone was used to measure airspeed in this inlet. The readings of this sensor were then adjusted on the basis of the empirical correlation to give an estimate of the average air speed for the inlet as a whole.

The 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 m between the upper cone and the lower one. The 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. (See also Section 3.6 and Figure 8 below.)

3.3 Effect of the deflector cone at the tower outlet

A deflector cone at the bottom of the tower is necessary to make a smooth transition in the direction of airflow at the outlet from vertical (downwards) to horizontal (outwards) with a minimal loss of momentum. The effect of this cone on airflow was assessed by conducting a series of measurements of airspeed prior to its installation, and then repeating the same sequence once it was in place.

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 behavior 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*, the contribution of the deflector cone is manifested mainly when airspeed at the bottom of the tower is high. As Figure 4 shows, when ambient 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 3-4 m^3 s^{-1}. When ambient wind speed is higher than about 2.5-3 m s^{-1}, flow through the tower derives substantial contributions from both the intake fan and the wind. Under these conditions, the flow rate increases from about 4-5 m^3 s^{-1} to as much as 6 m^3 s^{-1} due to the deflector cone - and the performance of the tower is enhanced significantly.

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 the typical 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

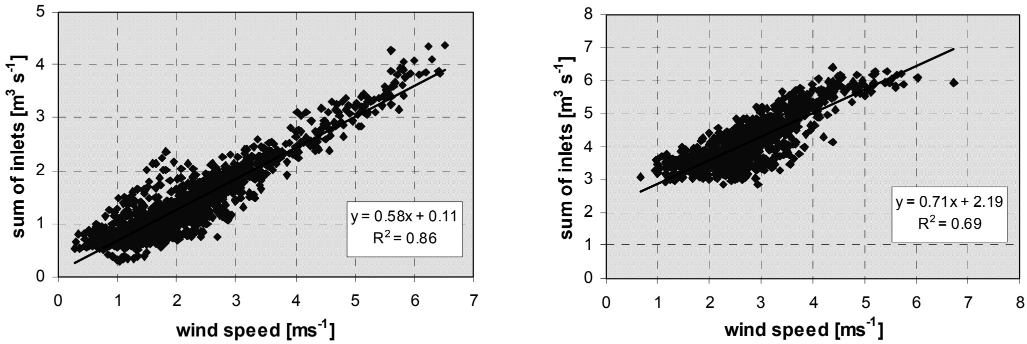


Figure 4: Effect of the deflector cone, illustrated by the correlation between the ambient wind speed (measured near the primary inlet) and the rate of airflow through the tower in the *fan-assisted mode*. Graphs show ensemble data for periods of three days before installation of the deflector cone, left, and afterward, right.

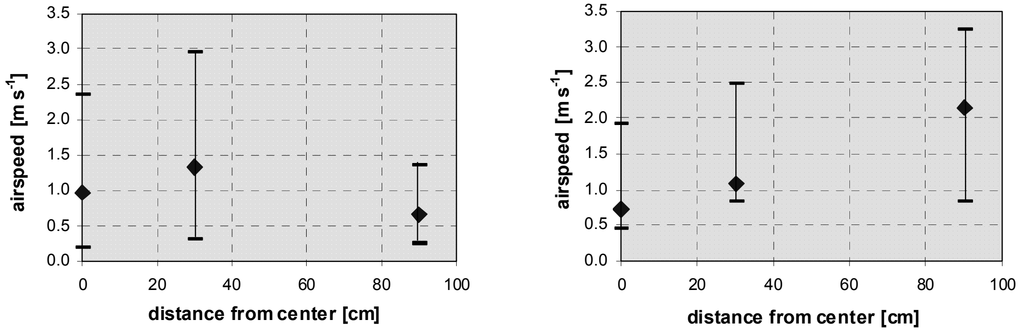


Figure 5: Airspeed in a horizontal cross-section at the outlet of the tower (90 cm above the ground), measured perpendicular to the axis of the wind-catcher. Data were recorded on two separate days in the *wind-driven mode* (left) and *fan-assisted mode* (right), after installation of the deflector cone. Filled diamonds indicate mean values for the period; horizontal bars indicate minimum and maximum values.

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.

As Figure 5 (left) shows, 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. 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 is 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 increases with distance from the center, however, and reaches 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 is also much more turbulent, with speeds fluctuating from less than 1 m s^{-1} to more than 3 m s^{-1}.

3.5 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 Figure 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

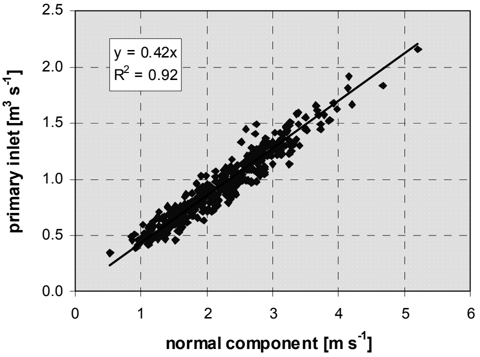


Figure 6: Correlation between the normal component of the wind and airflow through the upper part of the tower.

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. Figure 6 shows a high correlation between this normal wind speed component and the volumetric airflow through the upper part of the tower.

3.6 Estimating total flow through the tower

Since the cooling output of the tower is a product of the temperature depression resulting from evaporation of water and the rate of air flow through the tower, measuring this airflow correctly was one of the main aims of this phase of the project. Empirical correlations were obtained between total airflow and environmental wind speed, and between total flow and flow through the secondary inlet. Each of these correlations will be discussed in turn in the following paragraphs.

3.6.1 Correlation between total airflow and wind

Total airflow through the tower is calculated as the sum of the flows through the primary and secondary inlets. 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. However, it is also quite high in the fan-assisted mode (Fig. 7). In this mode, flow is 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.

3.6.2 Correlation between total airflow and flow through the secondary inlet

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.

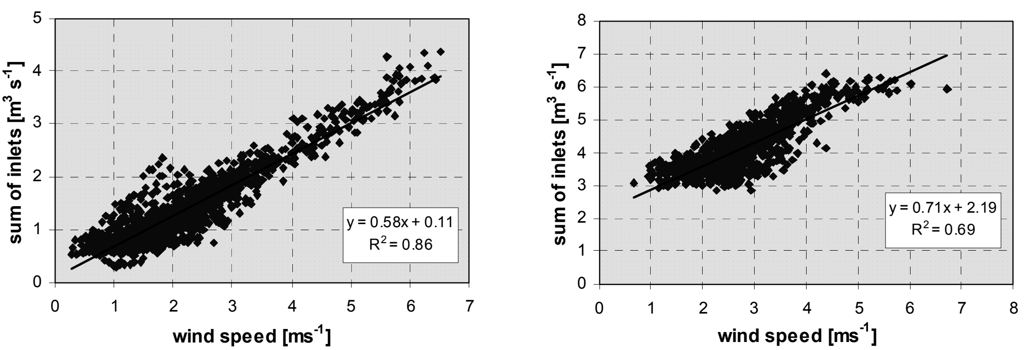
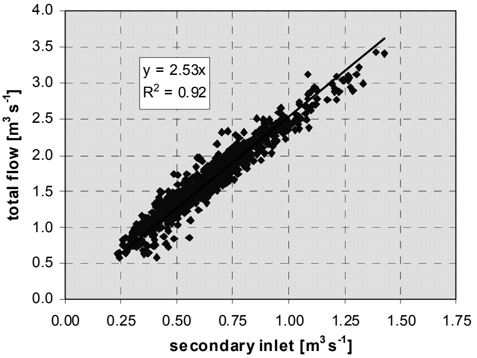


Figure 7: Correlation between total airflow through the tower and environmental wind speed, in the *wind-driven mode* (left) and *fan-assisted mode* (right). Data were recorded at 1-minute intervals during June 18-19 (wind-driven) and June 13, 16 and 23 (fan-assisted) modes.



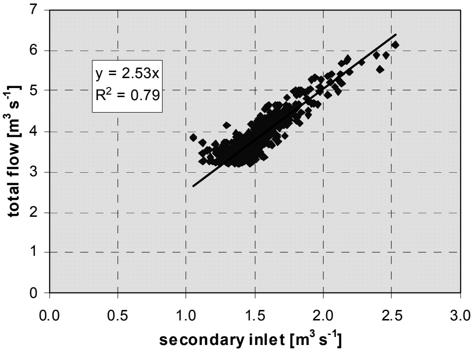


Figure 8: The correlation between airflow in the secondary inlet and total flow through the tower, in the *wind-driven mode* (left) and *fan-assisted operation* (right). Data are for one representative day in each mode – June 21 and June 22, 2004, respectively.

Figure 8 shows that flow through the secondary inlet may in fact be used to estimate total flow fairly accurately, as indicated by the high coefficient of correlation ($R^2 = 0.92$ in the wind driven mode and 0.79 in the fan-assisted mode). Confidence in this method is further justified by the fact that the ratio between the two flows is identical in both modes.

4. DISCUSSION

Direct measurement of airflow is difficult to carry out in the presence of water spray, especially in relatively confined spaces or where the size of the gradient requires adjacent instruments to be placed very closely together. The strategy employed in this experiment was therefore two-fold: Direct measurement of the relevant airspeed profiles were carried out in the absence of water spray to describe the detailed structure of the flow in the tower. Empirical correlations between different components of the flow and with environmental variables could then be generated to allow quantitative analysis of cooling once the sprayers were added.

Results of this stage of the monitoring program have several implications:

First, total airflow in the tower can be estimated with sufficient accuracy from measurements of environmental wind speed and of airspeed in the secondary inlet to allow calculation of the cooling output once the spraying system is installed and direct measurements of airflow in the primary section of the tower are not possible. Different empirical correlations were found to predict total airflow in the tower in wind-driven or fan-assisted operation, a crucial outcome that underpins the second stage of the experiment.

Second, 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 $m^3 s^{-1}$.

Finally, it was demonstrated that the airflow patterns in the wind-driven mode and in the fan-assisted mode are different, and that this difference is displayed not only in the upper cone, as may be expected, but also in the lower cone. Any scheme for the distribution and layout of the water sprayers must take into account these flow patterns in order to optimize the cooling performance of 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 warmer ambient air to the same temperature.

The final important result from airflow monitoring is the observation that 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 optimizing 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.

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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