A Multi-Stage Down-Draft Evaporative Cool Tower for Semi-Enclosed Spaces. Part II: Water Spraying System

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ABSTRACT: In a conventional down-draft evaporative cool tower (DECT), dry ambient air is drawn in at the top and cooler moist air is delivered at the bottom. Most of the cooling occurs near the inlet, where water is introduced and air temperature approaches the wet bulb.
A novel DECT was developed which incorporates a secondary air inlet and complex longitudinal section that comprises two partly overlapping cones. The complex section and the addition of a secondary air intake near the middle required a sophisticated water spraying system. In addition to maximizing the cooling potential, the spraying system was designed to limit spray drift beyond the base of the tower, to reduce maintenance costs (especially due to clogging of the sprayers) and to minimize pumping energy.
Analysis shows that maximum cooling may be obtained either by employing a very fine spray, requiring the introduction of a relatively small volume of water, or by spraying a larger volume of coarser drops. However, spraying fine drops requires more pumping power, finer nozzles are more likely to clog and small drops of water aggravate the problem of drift near the tower base. If full evaporation of the water spray is not required and excess water is collected for reuse, the second option is thus preferable.
In addition to the theoretical analysis, the paper presents experimental findings on temperature reduction, water consumption and cooling output of an 8-meter high prototype tower constructed at Sde Boqer, Israel.

Keywords: passive cooling, semi-enclosed spaces, evaporation

1. INTRODUCTION

Down-draft evaporative cool towers (DECTs) have earned attention in recent decades as a low-energy option for the cooling of public open or semi-open spaces.

These systems can be generally divided into two basic types. In the first of these, the ‘mist’ DECT, a very fine water spray is supplied at the top of the tower and droplets evaporate rapidly to cool the air descending through the tower. In the ‘mist’ DECT, all of the water is required to evaporate before reaching ground level, so that the space directly below the tower may be used for pedestrian activity. The towers in the Avenue of Europe at Expo ’92 in Seville are an example of this type of tower [1].

An alternative scheme is known as the ‘shower’ tower, in which larger drops are sprayed at the top of the tower and that water which does not evaporate is collected at the bottom of the tower and recycled. The cool tower installed in a public building complex at Sde-Boqer, Israel, is an example of such a tower [2]. While the surface-to-volume ratio of drops coming in contact with the air is lower in this scheme, a potential advantage is the augmented inertial air flow induced by momentum transfer from the coarse downward water spray to the air [3].

In ‘mist DECTs’ total evaporation can occur only if water supply to the spraying system is adjusted periodically in response to changing environmental conditions [1]. 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 highly pressurized water supply, are less susceptible to clogging than the fine-aperture “micronizers” incorporated in mist DECTs, and are cheaper. On the other hand, recycled water must be filtered to protect the pumping system and the reservoir must be cleaned periodically to remove dust washed out of the air [4].

2. OBJECTIVES

The present study examines the performance of a water spraying system installed in a new experimental tower, designed for improved cooling performance and constructed at the Sde-Boqer campus in Israel.

The design of the water spraying system had a number of objectives relating to the energetic performance of the cooling system, as well as its practical operation:

- *Temperature depression* – Maximizing cooling potential depends first of all on producing the lowest possible air temperature at the outlet of the tower, with the theoretical limit being the wet bulb temperature.

- *Efficiency of evaporation* – Temperature depression is directly related to the efficiency of evaporation, which in turn depends on the total area of contact between water drops and the surrounding air at any given point in time.

- *Water drop area* – To maximize the surface area of water drops, the sprayers may either supply very small droplets in a relatively fine mist (maximum surface/volume ratio), or larger drops of water, in which case a larger volume of water must be supplied to achieve the same total surface area.

- *Suspension and entrainment* – The use of a fine mist can reduce the downward velocity of water droplets and thus increase the length of time that a given droplet is suspended in the air stream, increasing the water-air contact for a given drop density. On the other hand, a coarse spray with large drops descending at high velocity can increase the air flow rate – another essential parameter in overall cooling potential – due to momentum transfer from the drops to the air, or "entrainment."

- *Supply energy* – The energy-efficiency of the water supply system also reflects the supply energy required by the electric pump to generate a specified flow rate and droplet size distribution in the sprayers. In general, a fine spray requires higher pressure and thus is more energy-intensive per unit volume of water supplied.

- *Spray drift* – A significant maintenance concern is minimizing the drift of spray at the outlet of the tower, unless full evaporation is guaranteed. The presence of small water droplets in air supplied by the tower may result 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.

- *Sprayer clogging* – Finally, the design must consider maintenance costs associated with the clogging of sprayers, particularly of 'atomizers' or fine misters – which are particularly susceptible due to their small aperture size.

Despite its theoretical advantage for cooling, then, creating a fine mist has several disadvantages. More energy is required to generate sufficient pressure to operate the sprayers; atomizers are susceptible to clogging; 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 volume, may be done with coarse sprayers and results in less undesirable drift.

3. EXPERIMENTAL SETUP

In a conventional DECT, dry ambient air is drawn in at the top of the tower and cooler moist air is delivered at the bottom. If a substantial supply of water is introduced at the top of a tall tower, than the air may become nearly saturated within a relatively small upper portion of the tower, and its temperature will quickly approach the wet bulb [2].

The design of the new experimental shower-type 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. This 8-meter high tower is composed of two partly overlapping cone-shaped sections (2 meters in diameter at their widest), with a secondary air intake between them, as well as a two-directional wind-capture device at the top inlet and a semi-permeable deflector at the bottom outlet (Fig. 1). It also incorporates a 1.1 kW electric fan that supports operation when environmental wind speed is low. Further details on the tower's physical and aerodynamic design are given in a companion paper.

Although the DECT prototype was not installed in a fully-enclosed space, it was 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 baffle, required only in the test facility, was installed so that airflow through the secondary inlet would be induced entirely by flow through the main section of

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

the tower: wind effects on this inlet could thus be neglected to simulate conditions in an enclosed courtyard.

The complex aerodynamic form of this tower created a unique challenge in the design of the water spraying system. The overall goal was to ensure an 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 [5]. A related concern was to minimize the spray of water onto the skin of the upper, downward-tapering cone of the tower, since the efficiency of evaporation would presumably benefit from droplets remaining in full contact with the air stream. Another challenge was properly distributing water droplets into the fresh air introduced through the lower, secondary inlet.

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. 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 [6]. The first of these is a BETE Spiraljet TF6 nozzle, which has a simple one-piece design that allows a maximum liquid throughput for a given pipe size and minimizes clogging. The spiral nozzle produces a conical spray pattern, with fairly coarse water drops: the Sauter Mean Diameter (SMD) is 138-172 μm at a water pressure of 5 bar and 2 bar, respectively (the SMD 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 5 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 5.6 m above the ground.

The second, finer type of sprayer was a PJ32 atomizer. These are low capacity atomizers that use the liquid pressure alone to produce very fine droplets (SMD of 96-143 μm at a water pressure of 5 bar and 2 bar, respectively), in a full cone spray pattern. It was predicted that atomizers would be effective in saturating the secondary air due to the large surface-to-volume ratio of the droplets, but in practice this potential advantage was outweighed by maintenance problems: the extremely small apertures of these fine sprayers were found to be excessively prone to clogging, and eventually the experiments were carried out with only the coarser spiral nozzles. The number of nozzles activated in each section of the tower was varied in different experimental runs, with a resulting range in the volume of water supplied.

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. Air speed was measured in the secondary inlet only, using a constant temperature LSI hot-wire anemometer. Environmental conditions, including dry bulb temperature, relative humidity, and 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 averaged every 10-minutes.

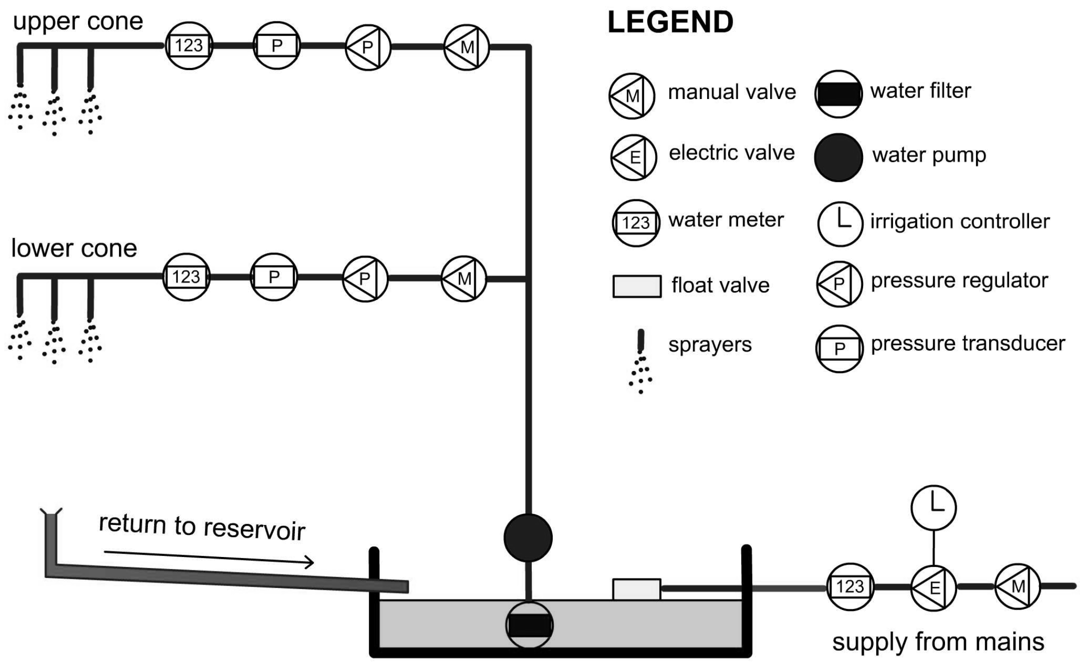

Figure 2: Schematic drawing of water spraying system in the experimental DECT.

4. RESULTS

The following section presents results of a series of measurements carried out after the aerodynamic design of the tower was evaluated in the absence of water spray. Performance tests included variations in the operation of the water spraying system in both fan-assisted and wind-driven modes of operation.

4.1 Measured air temperature at the tower outlet

Fig. 3 shows the daytime evolution of air temperature in the tower under typical summer operating conditions. Temperatures are shown at an intermediate point in the tower, just above the secondary inlet (stage 1) and at the lowest point in the tower (outlet), and compared with the ambient dry bulb and wet bulb temperatures (see also Fig. 7). The spraying system was activated in this case between 10:20 - 16:00 and the fan was operated until 13:30.

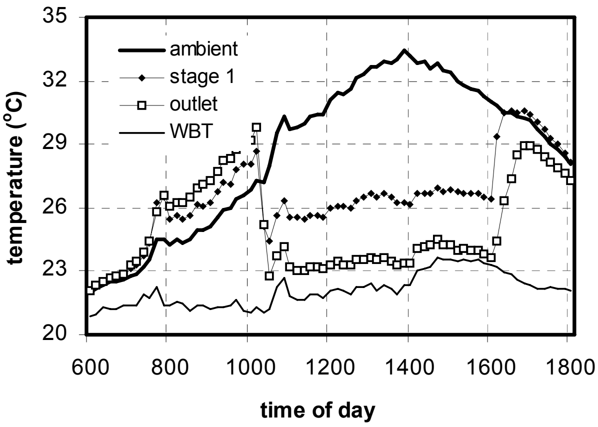

Figure 3: Air temperature above the secondary inlet (stage 1) and at the bottom (outlet) of the tower compared to the ambient dry bulb and wet bulb temperatures. (Data for August 17, 2005)

It may be seen that temperature at the outlet drops abruptly with activation of the sprayers, and is maintained within 1-2^{o}C of the WBT throughout the hours of operation. At mid-day when the ambient temperature peaks around 33^{o}C, the magnitude of the temperature depression exceeds 10^{o}C. This is in contrast to the more modest depression achieved in the upper tower section alone, with temperature at this stage stabilizing about 3^{o}C higher than at the bottom outlet.

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:

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

where P is the nominal cooling power [kJ s^{-1}], A is the area of the horizontal cross-section of the tower where airspeed is measured [m^2], v is the vertical component of the air speed [m s^{-1}], 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 flow in the presence of constant water spray was not. Hot-wire anemometers are unsuitable for use in a wet environment, and even three-dimensional sonic anemometers installed for this purpose did not allow for an accurate assessment of the volumetric flow rate through the overall cross-section. Airflow through the tower was therefore calculated on the basis of correlations obtained during the first phase of the study, when the aerodynamic performance of the tower was evaluated with the sprayers inoperative [5].

The primary indicator of air flow through the tower used in calculation of the cooling output is flow velocity measured by hot-wire anemometer in the secondary air inlet. Volumetric flow through the secondary inlet was found to be between 37-39% of the total flow in the tower for a wide range of velocities, 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 Cooling power comparisons

The cooling output of the prototype DECT during the preliminary experiment, calculated following the procedure outlined in section 4.2 above, reached a total of over 90 kW in the fan assisted mode and up to 60 kW when driven by wind only. As shown in Fig. 4, the cooling power is dictated not only by the air flow generated but also by the prevailing moisture deficit – or the capacity of the air to hold additional water vapour, quantified in grams of water per kg of dry air.

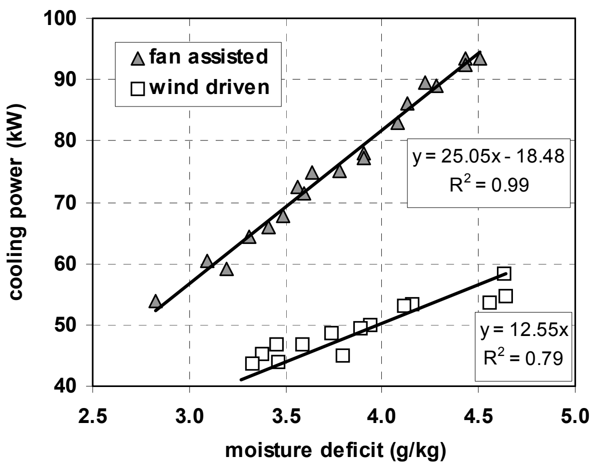

Figure 4: Correlation between cooling output and atmospheric humidity (as expressed by the simultaneous moisture deficit), for tower operation with and without electrical fan. (August 17, 2005)

It should be noted that each of the two water supply 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). An increase in water pressure results not only in more water being delivered by the spraying system, but also in a smaller mean drop size, more efficient contact with the air and hence in more evaporation and greater cooling [7]. Water pressure was therefore kept constant at 2 bar throughout the entire experiment, allowing direct comparison of the effect of changing the water supply.

Fig. 5 shows the cooling output as a function of the moisture deficit, differentiated with respect to the rate at which water was sprayed into the tower. A comparison is made between two spraying regimes, one using a total of seven spiral nozzles and providing on average 26.5 litres per minute, and the other limited to five nozzles and about 20 litres per minute. The larger water supply generates, on the average, a 15% higher cooling output.

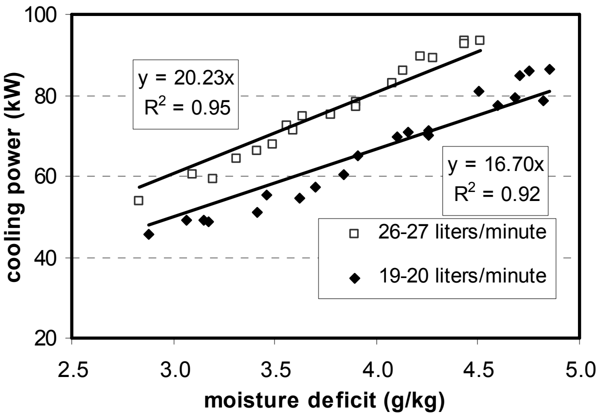

Figure 5: Correlation between cooling power and moisture deficit for different water supply rates. (Data for August 17 and 28, 2005)

The enhancement of cooling by additional water, however, is not just a result of greater evaporation. Figure 6 shows evaporation rates as a function of moisture deficit for different water supply rates and modes of operation (fan assisted and wind driven). It can be seen that while evaporation increases somewhat with water supply, it increases to a much clearer extent with *air* supply: when the air flow is fan-assisted, the evaporation rate increases by some 50%.

Given that the amount of water sprayed was substantially greater than the moisture deficit in all of the sprayer configurations tested, the main contribution of a larger water supply to cooling output was that the spray itself augments the down-draft, generating a volumetric air flow that is some 30% higher whether this flow is fan assisted or not. This result apparently represents a strong inertial air flow due to entrainment, or momentum transfer from the water drops to the air.

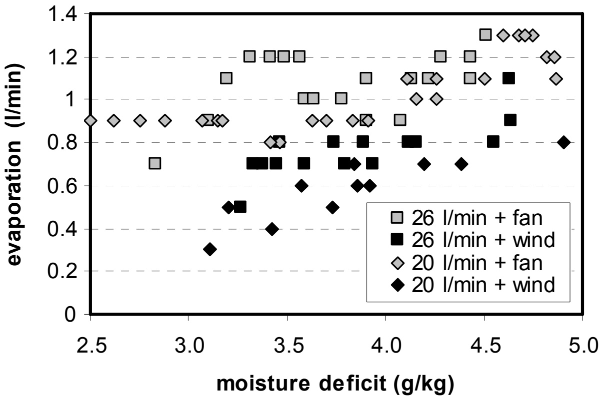

Figure 6: Correlation between evaporation rate and moisture deficit for different water supply rates and modes of operation. (August 17 and 28, 2005)

4.4 Spray drift and deflection

A deflector was installed in the centre of the tower at the level of the bottom outlet (Fig. 7), to improve the transition from vertical downward airflow to horizontally directed outward flow with a minimal loss of momentum. The deflector was made from a semi-permeable mesh, stretched taught in a curved cone-like shape, with the intention of reducing aerodynamic resistance but at the same time absorbing excess water spray (which was collected in a central drain and recycled).

It was found in the aerodynamic analysis of the tower's performance without water spraying (presented in a companion paper) that the deflector cone may amplify air flow substantially – but only on the condition that a substantial initial flow is generated. Thus in fan-assisted operation with wind speeds in excess of 3 m s^{-1}, the volumetric flow rate with the deflector cone installed was commonly 15-25% higher than without it.

As described above, the operation of the water sprayers further augmented the flow of air through the tower, through the mechanism of momentum transfer as well as buoyancy. Given the stronger air flow, the contribution of the deflector cone was expected to be more pronounced in the wet mode as well. However, comparison of the flow rate on similar days with and without the cone showed that its contribution was, if anything, somewhat smaller than its contribution in dry flow. 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.

A possible explanation for this is that while absorption of water by the mesh is advantageous from a practical point of view, it inhibits the inertial air flow by absorbing the water drops' momentum as well. For this reason the effectiveness of the deflector is less pronounced than it otherwise would be at high air flow rates.

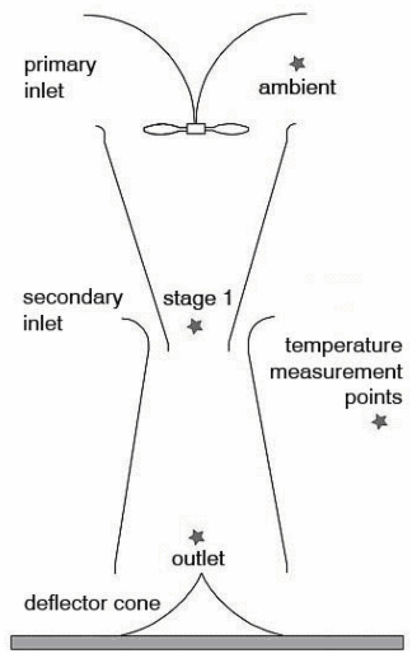

Figure 7: Schematic section of tower showing deflector cone in relation to primary and secondary inlets, and locations of temperature measurement points.

5. CONCLUSIONS

In spite of the technical difficulties involved in measuring air temperature and flow velocity accurately in the presence of water spray, several relationships could be identified in this experimental study that reflect on the cooling potential of the improved down-draft tower.

A nominal cooling output of up to 90 kW was found for typical fan-assisted summer operation, which is substantial given the modest dimensions of the tower. The correlations between cooling power and operational parameters such as water and air supply are fairly clear, and indicate that the water spraying system is capable of producing efficient evaporation as well as a strong inertial air flow.

Clearly under the tested modes of operation, a great deal more water is being sprayed than can be evaporated. Because excess water is collected and re-circulated, however, that water which does evaporate (and which, during most hours, brings the supplied air close to saturation) essentially represents the sole expenditure of water. Since the spray is relatively coarse and produced at relatively low pressure, pumping energy requirements are modest – and the contribution to cooling made by a strong inertial air flow seems to justify this approach.

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. the climate is hot and dry, application of evaporative cool towers may be a practical means of providing low-cost, low-maintenance cooling of large spaces.

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