DESIGN AND APPLICATION OF NATURAL DOWN-DRAFT EVAPORATIVE COOLING DEVICES.

Nader V. Chalfoun, Ph.D.
Associate Professor of Architecture, University of Arizona
Director: The House Energy Doctor (HED) program
Tucson, AZ 85712
e-mail Chalfoun@ccit.arizona.edu

ABSTRACT

Natural down-draft evaporative coolers are devices recently developed at the University of Arizona's Environmental Research Laboratory (ERL). These towers-like devices are equipped with wetted pads and sprays at the top which provide cool air by gravity flow. In arid regions, these devices can be used for cooling residential and commercial buildings, as well as outdoor private and public areas. This paper focuses on some recent developments and applications of the towers in arid regions internationally and nationally. The paper also demonstrates *CoolT*Error! Switch argument not specified.©, a computer program developed by the author that has been used for cool tower sizing and performance prediction. Recent examples include the Botswana Technology Center, a Headquarters office building in South Africa currently under construction. This building is cooled by a series of cool towers, and the MOMRA "Environmental Rowdah" project in Riyadh, Saudi Arabia another recently built project which demonstrates the use of cool towers for cooling outdoor spaces.

1. INTRODUCTION

Forced draft or "swamp" coolers have been used for many years in the desert southwest of the United States and require energy for a blower to force air through wetted pads and the structure to be cooled, plus a small pump for re-circulating water over the pads. Natural down-draft evaporative coolers do not need the blower and require only the re-circulating pump; some designs eliminate the re-circulation pump and utilize the pressure in the supply water line to periodically surge water over the pads, eliminating the requirement for any electrical energy input [1].

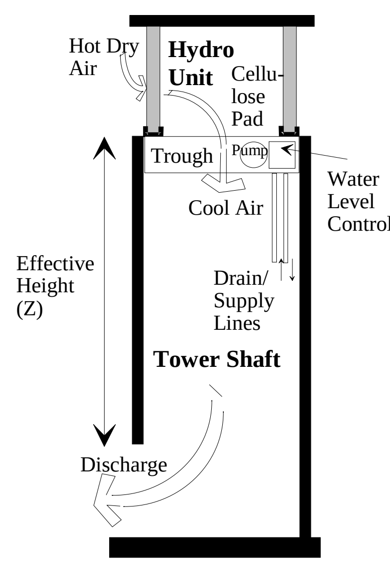

Fig. 1: Cool Tower Schematic

Natural down-draft evaporative coolers , or *Cool Towers*, were originally designed and developed by scientists and engineers at the University of Arizona's Environmental Research Laboratory in Tucson Arizona, U.S.A.[2]. The towers are equipped with wetted pads, sprays, or other evaporative cooling devices at the top which provide cool air by gravity flow. These towers are often described as reverse chimneys; just as the column of warm air in a chimney rises, the column of cool air, in this instance, falls. The air flow rate depends on the efficiency of the evaporative cooling device, tower height and cross section, as well as the resistance to air flow in the cooling device, tower and structure (if any) into which it discharges (see Figure 1). Estimating the thermal performance of cool towers is given by Thompson et al [3]. Additional information on the natural down-draft evaporative cooler design is given by Givoni [4] and Sodha et al [5].

2. *COOLT*©; THE SOFTWARE

In order to predict cool towers performance the author, in collaboration with scientists at the ERL has developed a computer program called *CoolT*© [6]. The program runs on IBM or compatible computers under DOS operating system. The air flow rate provided by a cool tower is determined by the equation [2]:

$$\left(\frac{\rho_t V_t^2}{2g_c}\right)\sum K=\left(\frac{g}{g_c}\right)Z\Delta\rho+\Delta C_{wp}\left(\frac{\rho_a V_w^2}{2g_c}\right) \qquad (1)$$

That is, the air flow rate is determined by the sum of the density of the air and wind forces; where ρ is air density (lb/ft^3), ρ_t being the average density in the tower, ρ_a the outdoor air density, and $\Delta\rho$ the difference between the tower and ambient air densities. V_t and V_w are velocities of the tower air and wind, respectively (ft/s); $\sum K$ is the sum of pressure loss coefficients for the tower; g_c is Newton's law conversion factor (32.2 lb_m-ft/$lb_f s^2$); g is acceleration due to gravity (ft/s^2); Z is the effective tower height, or the distance from the bottom of the pads to the uppermost point of the tower outlet (ft) as shown in figure 1; ΔC_{wp} is the difference between the wind pressure coefficients at the tower inlet and outlet. C_{wp} is positive on windward surfaces and negative on leeward surfaces [7]; in some instances, the ΔC_{wp} term may become negative, and the wind may cause cool air flow down the tower to cease or reverse.

In the absence of wind, equation (1) can be simplified to:

$$V_t = \sqrt{\left(\frac{2gZ}{\Sigma K}\right)\left(1-\frac{\rho_a}{\rho_t}\right)} \qquad (2)$$

The density of air inside the tower is determined largely by the properties of the outside air, i.e. temperature, humidity and barometric pressure; and the performance of the evaporative cooling pads at the top of the tower. The pad efficiency (ε) is defined as the ratio of the drop in dry-bulb temperature of the air passing through the pad (Δt) to the wet-bulb depression (Δt_w), or the difference between the dry (t_a) and wet-bulb (t_{wb}) air temperatures:

$$\varepsilon = \frac{t_a - t_t}{t_a - t_{wb}} = \frac{\Delta t}{\Delta t_w} \qquad (3)$$

The *CoolT*© software allows the user to select from a variety of weather files based on Typical Meteorological Year (TMY) data. Additional data such as latitude, longitude and elevation above sea level are also built into the weather file. The tower can be configured in terms of 1) pads width, depth, height and thickness, 2) shaft area, height, and area of outlet, 3) side discharge mode or bottom discharge mode, and 4) tower schedule i.e. serving an indoor space or an outdoor space. The program calculates cool tower performance under no wind conditions only.

When a particular month is selected by the user, the program runs and generates six sets of hourly output data: 1) Ambient conditions; dry-bulb, wet-bulb, relative humidity and air density. 2) data inside the tower such as: air temperature, relative humidity air density and air velocity. 3) data at the outlet of the tower such as: air velocity and air volume. 4) evaporative effectiveness of the pads. 5) temperature drop between incoming outdoor air dry-bulb temperature and delivered air temperatures. 6) the hourly water consumption. A monthly average of water consumption is also reported as well as the total daily water consumption of the cool tower.

3. RECENT PROJECTS

During the last few years, the author and a research team from the ERL have helped in the design development of several projects nationally and internationally. Advanced energy-saving construction techniques have been introduced as well as innovative passive cooling devices, such as cool towers[8]. The following two projects are selected to emphasize the use of cool towers in indoor spaces as well as outdoor spaces.

3.1. The Botswana Technology Center

The Botswana Technology Center (BTC), a research and technology institute located in Gabarone, Botswana, has finalized designs for a new headquarters building which will fulfill all its current and projected office and laboratory space needs. The new building is designed to demonstrate technologies supportive of BTC's philosophy and mission; that is, to demonstrate, test and transfer sustainable technologies for the benefit of the regional community [9].

The climate of Botswana is characterized as dry subtropical. The climate sub-type is classified as semidesert (Steppe-desert transition) in the region of Gabarone. Rainfall is small and unreliable as Botswana is part of the greater Kalahari desert. Average rainfall in Gabarone is 500 mm/year with the rainfall occurring primarily in the summer or warm season. Warm season temperatures average 26°C (79°F) with high temperatures of 30°C (86°F) not uncommon. Winter, cool season temperatures in Gabarone average 12.8°C (55°F) in June with occasional frost.

The role of the author was to work in collaboration with the BTC's design review committee and the local project architect and engineering team to optimize the thermal performance of the new headquarters building and to provide most of the cooling through the integration of natural down-draft evaporative coolers (cool towers)[10].

The 2000 m² (18,000 ft²) floor area of this two floor building is arranged in four zones around a 250 m² (2,300 ft²) courtyard. The building is divided into four zones as shown in Figure 2 below. Zone A includes reception, library, conference room, director's office and open visual access to the courtyard. Zones B and D have office/lab space above and shop space below with small enclosed courts with loading areas. Zone C has an electronic/computer lab on the first floor with offices above. The courtyard serves as pedestrian circulation, meeting and demonstration space.

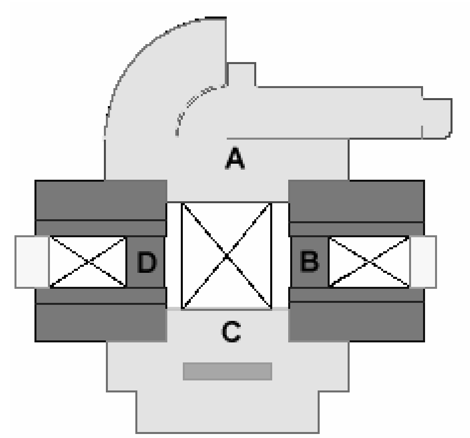

Fig. 2: BTC building zones

To determine the building's thermal performance load profiles and the impact of performance improvement strategies the CalPas3 [11]

computer program was chosen over other energy simulation models because of its flexibility in modeling innovations in building envelope design.
The building was modeled by zones as described in Figure 2. The passive solar design strategies coupled with effective use of highly insulated, prefabricated building components permitted the predicted basecase heating and cooling to be a modest 629.1 MBTU/Yr, or 34.9 KBTU/ft^2.Yr. This can be compared to estimates for conventional buildings of this type and size of 70.0 KBTU/ft^2.Yr [12] [13]. A parametric study of both standard and specialized conservation and passive solar performance improvement options was undertaken [14] [15].

This study examined the effects of double glazing, slab insulation, reflective roof coating, overhang shading, inside venetian blinds, exposed interior mass, and nighttime thermostat setbacks. The predicted result was a 89.9% reduction in the heating load and a 24% reduction in cooling load.

The parametric study was based on the use of a heat pump. Since evaporative cooling has been shown to be an effective means for cooling in arid regions mitigating the remaining cooling load was addressed through the use of cool towers. The evaporative cooling requirements for each zone were provided by sizing cool towers to an equivalent output in cubic feet per minute using the *CoolT*© software.

Initially, a total of seven cool towers were recommended for the cooling requirements of the four zones. For each zone one or more cool towers were sized to provide the equivalent output determined by the simulation, and designed to provide for desired airflow through the zones. Three modestly sized cool towers were included for Zone D (west) due to its sizable cooling requirement. One additional cool tower was also included to provide climate control for the courtyard and the offices that open onto it. As a result of design reviews the number of towers was reduced to four (Figure 3), and their dimensions were made uniform for cost efficiencies.

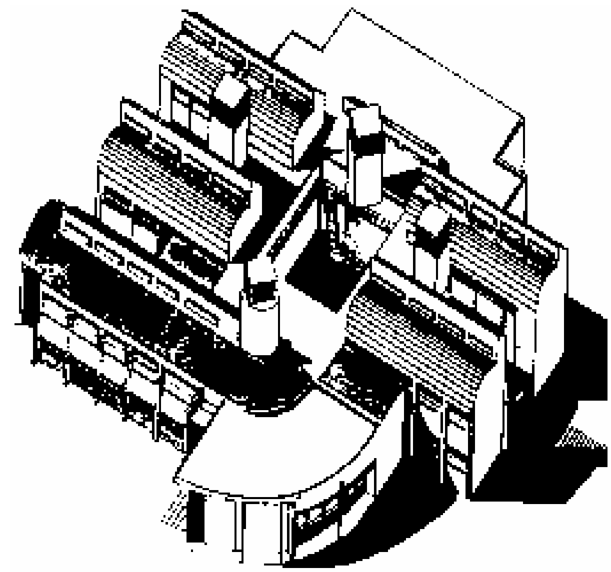

Fig. 3: The BTC building with four Cool towers

3.2. The MOMRA Environmental Rowdah

The new building of the Ministry of Municipal and Rural Affairs (MOMRA) is considered an important addition to the architecture wealth of the city of Riyadh in Saudi Arabia. The building is located on prominent site on one of Riyadh's most important streets, the King Fahd Road. The project is characterized by its simplicity in form, clarity of structure and most importantly its successful integration of indoor and outdoor spaces.

The new MOMRA building is in the shape of a large cube 80X80X35 m (240X240X115 ft) planted amidst a palm grove of 1000 trees and a wide variety of other trees and shrubs. Within the grove are 4 landscaped gardens defined by natural stone boundaries. The north west quarter of the grove is designated for the placement of the environmental rowdah. Through the Planetary Design Corporation (PDC) the author was appointed as the principal architect working on the design of the Environmental Rowdah. The Rowdah is designed as a demonstration project to illustrate state-of-the-art environmental control strategies and human thermal comfort techniques for outdoor spaces. Strategies incorporated into the Rowdah are a Cool Tower, a Cool pit, a tent, herbal, halophyte, vegetable, and medicinal gardens, fish and water ponds, a Root Room, and water fountains (Figure 4).

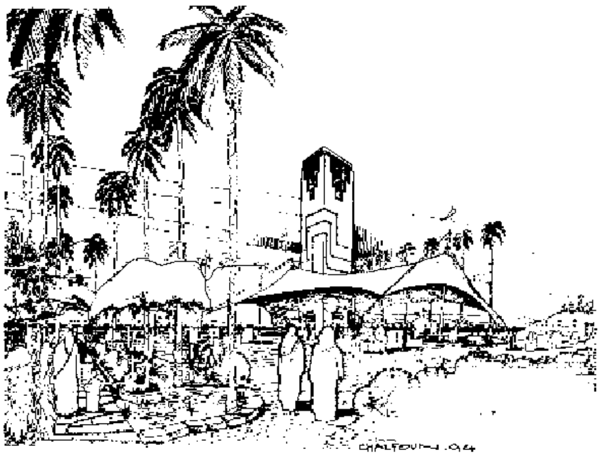

Fig. 4: View of the Environmental Rowdah Showing the Climate Control Elements and the Gardens (drawings by the author)

The cool tower is designed as an architectural compliment to the new headquarters building. It incorporates the wisdom of the Arabian wind towers and modern evaporative cooling technology. The visitor's eye is drawn from the building to the tower across to the slopping lines of the connecting tensile structure. Like the headquarters, the tower is clad in Riyadh limestone but with the smaller module size of stone veneer.

The cool tower is 25.2 meters high (76 ft). The unique indentations which proceed around the tower change its external dimensions from a maximum of 8X8 meters to a minimum of 6.5X6.5 meters (Figure 5). The evaporative assembly in the top of the tower (the turret) consists of a series of pads that are constantly kept wet with recirculating water from a reservoir in the turret. The tower cools the air through the process of evaporation. As the dry air contacts the saturated pads a percentage of the water on the pads evaporates. This process consumes energy and the air is cooled. This now cooler air begins to fall as it is heavier than the surrounding hotter air. As this "packet" of air falls down the tower it creates a vacuum behind it drawing more outside hot air in through the pads. The result is a continuous flow of cooled air down the shaft of the tower and into the cool air lake. No fans are required to draw the air into the tower or force it out into the rowdah.

Fig. 5: The Cool Tower after construction

The performance of the tower was optimized through the *CoolT*© software. The tower performance as calculated by the program predicts a "typical" June day as follows: At 3:00 p.m. the ambient air temperature of 41.7°C (107.1 °F) will be cooled 18.4°C (65.2 °F) to 23.3°C (73.9°F). This cooled air will mix with the surrounding air as it moves away from the base of the tower creating a perceptible temperature gradient. The results of the model demonstrate the range of performance and its association with the variables of temperature and relative humidity. The system functions the best on hot dry days, exactly those days when optimum performance is desired.

4. Acknowledgment

The author would like to acknowledge: Mr. Carl Hodges, chief executive officer of Planetary Design Corporation (PDC), an international technology transfer company, for hiring him as a principal architect on the MOMRA project; also, Mr. Roy Hodges the project manager and Martin Yoklic the principal Landscape architect for their help and support; and Eng. Lew Thompson for his help in the development of the COOLT program. The author also thanks Greg Davis and Martin Yoklic as project managers on the Botswana Technology Center project.

5. REFRENCES

(1) Thompson, T., Hydraulically controlled valve for a cool tower and the like. *U.S. Pat*. 5,121,770 1992.

(2) Cunningham, W., and Thompson, T. "Passive Cooling with Natural Draft Cooling Towers in Combination with Solar Chimneys", Proc. of PLEA '86, Passive and Low Energy Architecture. Pecs, Hungary. Sept. 1-5 1986.

(3) Thompson, T., Chalfoun, N., & Yoklic, M., Estimating the Thermal Performance of Natural Down-draft evaporative coolers, Energy Convers. Mgmt. Vol. 35, No.11, pp. 909-915, El Sevier Science Ltd, Pergamon (1994)

(4) Givoni, B., Modeling a passive evaporative cooling tower. Proceedings of the 1991 Solar World Congress, Denver Colorado, U.S.A., pp. 3067-3071 (1991).

(5) Sodha, M., et. Al. Thermal Performance of a room coupled to an evaporative cooling tower. Proceedings of the 1991 Solar World Congress, Denver, Colorado, U.S.A., pp. 3095-3100 (1991).

(6) Chalfoun, N., CoolT, V. 1.4, Copyright Cool Tower Performance Program, Environmental Research Laboratory, University of Arizona, Tucson, Arizona (1992).

(7) Watt, R., Evaporative Cooling Handbook, 2nd edn, pp. 107-114, 185. Chapman & Hall, New York (1986).

(8) Chalfoun, N., and Matter, F., "Advanced Low-cost Residential Energy Analysis Techniques Performed by the House Energy Doctor Team at the College of Architecture, U. of Arizona, Tucson. Proceedings of IDEEA one, the 1st International Design for Extreme Environments Assembly, Houston TX, U.S.A. 1991

(9) Burton, R., et. al, The role of Botswana Technology Center in addressing future technology. In Which Way Botswana's Environment? Kalahari Conservation Society, Botswana, 1992.

(10) Yoklic, M., Chalfoun, N., and G. L. Davis. The Botswana Technology Center: Energy Performance Modeling to Assist in the Development of an Innovative Passive Commercial Building in Southern Africa. Proceedings of the 11th Passive and Low Energy Architecture (PLEA) International Conference. Dead Sea, Israel, 1994.

(11) CalPas3. Users Manual. Berkeley Solar Group. Berkeley, CA. U.S.A. 1982

(12) DOE. Economic Analysis, Energy Performance Standards for New Buildings. United States Department of Energy. DOE/CS-0129, Jan. pp. D57, 1980.

(13) U.S. DOE/Energy Information Administration. Residential energy consumption survey, Part 1: National data (DOE/EIA-0262/1). Washington, D.C.: U.S. Government Printing Office, U.S.A., 1981

(14) Chalfoun, N., The "House Energy Doctor©"; An Educational, Research and Community Service Program at the College of Architecture, The University of Arizona. Proceedings of the Design for Desert Living Symposium, Jul. 21-26, Tucson, AZ, U.S.A.,1991.

(15) Chalfoun, N., et al Planning & Architectural Criteria with Respect to Climate: Thermal Behavior of Building Envelope. Egyptian

Academy of Scientific Research and Technology,
Cairo, Egypt, 1990.