Implementation Of Natural Down-Draft Evaporative Cooling Devices In Commercial Buildings: The International Experience

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ABSTRACT

Conventional evaporative coolers are high-pressure high-volume devices that deliver cool air by water evaporation wetted pads. Natural down-draft evaporative coolers, or "Cool Towers", are devices developed at The University of Arizona's Environmental Research Laboratory. Similar to conventional coolers, these devices are equipped with wetted pads and sprays at the top which provide cool air by evaporation but the air is moved by gravity flow saving the energy required by the blower. In arid regions, cool towers are useful for cooling buildings and outdoor private and public areas. This paper focuses on recent implementation of cool towers in two international projects in arid regions. It also demonstrates *CoolT*©, a software developed by the author, which was used for sizing and designing the cool towers used in these projects. The two demonstrated projects are: 1) The Botswana Technology Center (BTC), a Headquarters office building in Botswana, South Africa. The building energy loads were first optimized through energy conservation measures where the heating load, as predicted by computer simulation, was reduced by 89.9% and the cooling load by 24%. The cooling load was further addressed by the use of a series of integrated cool towers. 2) The Ministry of Municipal and Rural Affairs (MOMRA) "Environmental Rowdah" project in Riyadh, Saudi Arabia is the second, recently built, project which demonstrates the use of cool towers in outdoor spaces. The Rowdah is equipped with a 76 feet high cool tower, the biggest in the world, which provides cool air to the surrounding outdoor space. The tower performance, as predicted by the *CoolT* program, demonstrated that on a typical June day in Riyadh, at 3:00 p.m. the ambient air temperature of 107.1°F (41.7°C) will be cooled down to 73.9°F (23.2°C) i.e. 33.2°F (18.4°C) lower, but the 13% relative humidity of air is increased to 75% at the tower discharge.

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 (Thompson 1992).

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, USA (Cunningham & Thompson 1986). The towers are topped with a hydro unit equipped with wetted pads, sprays, gutter and a recycling pump 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 (Figure 1). Water consumed by Cool Towers is almost similar (often less) than that consumed by conventional evaporative coolers. In general, water consumption increases as the volume of cooled air (cfm) produced by either system increases. For example, a 7000 cfm of cooled air produced by a Cool Tower in Tucson, Arizona, consumes about 15 gallons of water per hour (see Table 1 below). A conventional evaporative cooler of the same cfm capacity and the same location and date will consume approximately 18 gallon per hour. Estimating the thermal performance of cool towers is given by Thompson et al (Thompson, Chalfoun & Yoclik, 1994). Additional information on the natural down-draft evaporative cooler design is given by Givoni (Givoni 1991) and Sodha et al (Sodha et al. 1991).

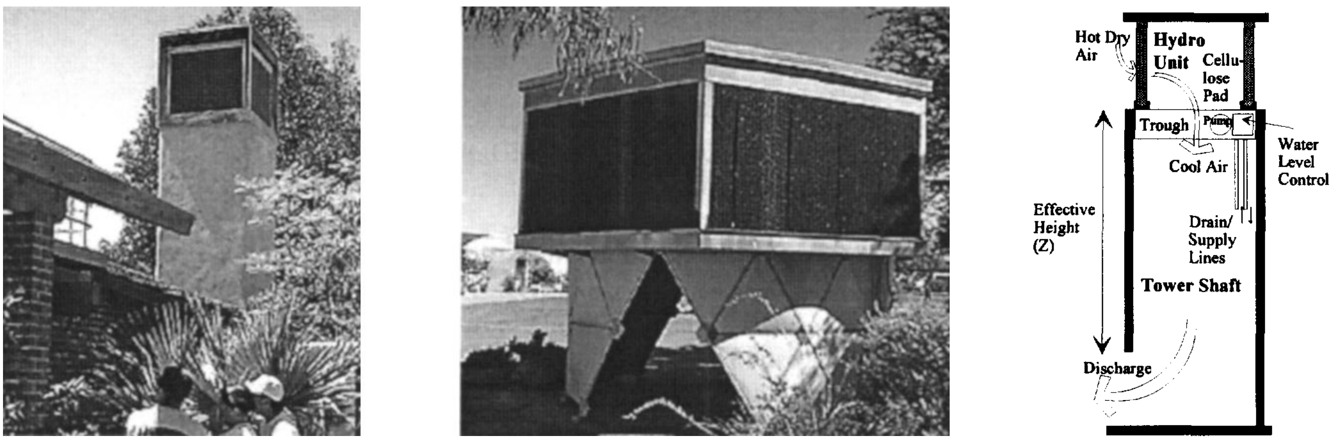

Figure 1. The Hodges Residential Cool Tower in Tucson(left), Hydro Unit Prototype at ERL (middle), and Cool Tower Schematic(right)

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*© (Chalfoun 1992). 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 following equation (Cunningham & Thompson 1986):

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

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 (Watt 1986); 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 uses the no-wind condition to estimate cool tower performance. It has a user interface screen with built-in editor that allow designers to configure the tower by changing different parameters (see Figure 2 below). These parameters are: 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, and 5) 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.

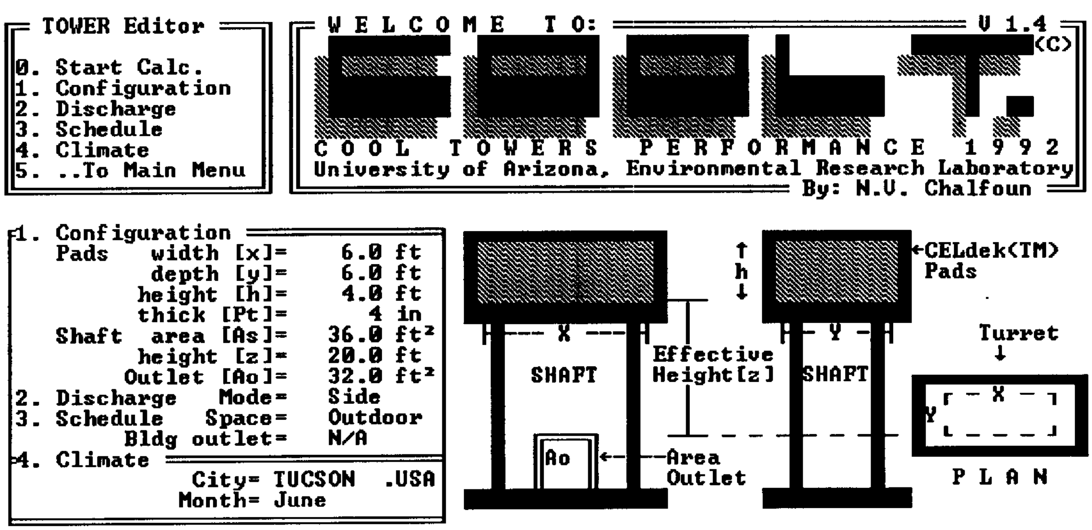

Figure 2: *CoolT*© Interactive Screen and Built-in Editor

After a particular location, month and tower configuration are selected by the user, the program runs and generates results arranged in the form of six sets of hourly output data (See Table 1). These are as follows:

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 (ΔT) between incoming outdoor and delivered air
6. the hourly, average and daily total water consumption.

Table 1. *CoolT*© Output Results for a 32 Feet High Outdoor Tower in Tucson, Arizona.

***CoolT*© RESULTS FILE** Weather File: Tucson.AZ; A CalPas3 "TMY" File Created By: N.V. Chalfoun June, 1992

□ City & Country Name: TUCSON .USA

□ Latitude/Longitude[deg]/Elevation[ft]: 32.20 °North 111.00 °West 2584.00 ft

□ Tower Configuration: Pads width [x]= 6.0 ft depth [y]= 6.0 ft height [h]=4.0 ft thick [Pt]= 4 in

Shaft area [As]= 36.0 ft² height [z]= 20.0 ft Outlet [Ao]= 32.0 ft²

Discharge Mode= Side Schedule Space=Outdoor Bldg outlet=N/A

□ Tower Results for the month of: **June** Atmospheric Pressure: 27.25 in.Hg.

	1. Air Ambient Conditions				2. Air Inside Tower				3. Air at Outlet		4. Evap.	5.	6.
	t-dry °F	t-wet °F	RH %	Density lb/cf	tmp °F	RH %	Density lb/cf	vel fpm	vel fpm	vol cfm	Effec	ΔT °F	Water g/hr
1	81.0	55.0	17.3	0.06684	61.0	70.0	0.06922	201	226	7235	0.77	20.0	16.5
2	78.0	54.0	19.5	0.06721	59.4	71.9	0.06944	194	218	6990	0.77	18.6	14.8
3	76.0	53.0	20.2	0.06746	58.2	72.7	0.06962	191	215	6865	0.78	17.8	14.0
4	74.0	52.0	21.0	0.06772	56.9	73.6	0.06980	187	211	6737	0.78	17.1	13.2
5	72.0	51.0	21.9	0.06798	55.6	74.4	0.06999	183	206	6605	0.78	16.4	12.4
6	70.0	50.0	22.9	0.06824	54.3	75.3	0.07017	180	202	6469	0.78	15.7	11.6
7	74.0	52.0	21.0	0.06772	56.9	73.6	0.06980	187	211	6737	0.78	17.1	13.2
8	78.0	54.0	19.5	0.06721	59.4	71.9	0.06944	194	218	6990	0.77	18.6	14.8
9	82.0	56.0	18.2	0.06670	62.0	70.4	0.06907	201	226	7229	0.77	20.0	16.4
10	87.0	59.0	18.0	0.06606	65.5	69.5	0.06856	207	233	7449	0.77	21.5	18.0
11	93.0	62.0	16.7	0.06532	69.4	67.5	0.06801	216	243	7769	0.76	23.6	20.5
12	98.0	64.0	15.0	0.06472	72.2	65.3	0.06762	224	252	8075	0.76	25.8	23.2
13	99.0	64.0	14.0	0.06461	72.5	64.3	0.06758	227	256	8177	0.76	26.5	24.1
14	101.0	64.0	12.2	0.06440	73.1	62.4	0.06751	233	262	8377	0.75	27.9	25.9
15	102.0	64.0	11.4	0.06429	73.4	61.4	0.06748	235	265	8474	0.75	28.6	26.9
16	102.0	64.0	11.4	0.06429	73.4	61.4	0.06748	235	265	8474	0.75	28.6	26.9
17	102.0	64.0	11.4	0.06429	73.4	61.4	0.06748	235	265	8474	0.75	28.6	26.9
18	102.0	64.0	11.4	0.06429	73.4	61.4	0.06748	235	265	8474	0.75	28.6	26.9
19	100.0	64.0	13.1	0.06451	72.8	63.4	0.06755	230	259	8278	0.75	27.2	25.0
20	98.0	64.0	15.0	0.06472	72.2	65.3	0.06762	224	252	8075	0.76	25.8	23.2
21	96.0	63.0	15.3	0.06496	71.0	65.9	0.06780	222	249	7978	0.76	25.0	22.3
22	94.0	63.0	17.4	0.06518	70.4	68.0	0.06787	216	243	7763	0.76	23.6	20.5
23	91.0	63.0	21.1	0.06551	69.5	71.1	0.06797	206	232	7424	0.77	21.5	17.8
24	89.0	63.0	23.9	0.06573	69.0	73.2	0.06804	200	225	7186	0.77	20.0	16.1
av	89.1	59.4	17.0	0.06583	66.5	68.1	0.06844	211	237	7596	0.77	22.7	19.6

□ Notes: ++ Total Tower Water Consumption = 471.2 Gallons/Day

++ Results are calculated based on "Calm" [No wind] conditions

++ When Schedule=INDOOR, performance is based on windowscreens installed on bldg. outlet area

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Description Of 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 (Chalfoun & Matter 1991). The following two projects are selected to demonstrate the use of cool towers in an indoor space as well as an outdoor space.

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 (Burton et al. 1991).

The climate of Botswana is characterized as dry subtropical. The climate sub-type is classified as semi-desert (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 20"/year (500 mm/year) with the rainfall occurring primarily in the summer or warm season. Warm season temperatures average 79°F (26°C) with high temperatures of 86°F (30°C) not uncommon. Winter, cool season temperatures in Gabarone average 55°F (12.8°C) 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, or cool towers(Yoklic, Chalfoun and Davis 1994).

The 18,000 ft^2 (2000m^2) floor area of this two floor building is arranged in four zones around a 2,300 ft^2 (250m^2) courtyard. The building is divided into four zones as shown in Figure 3 below.

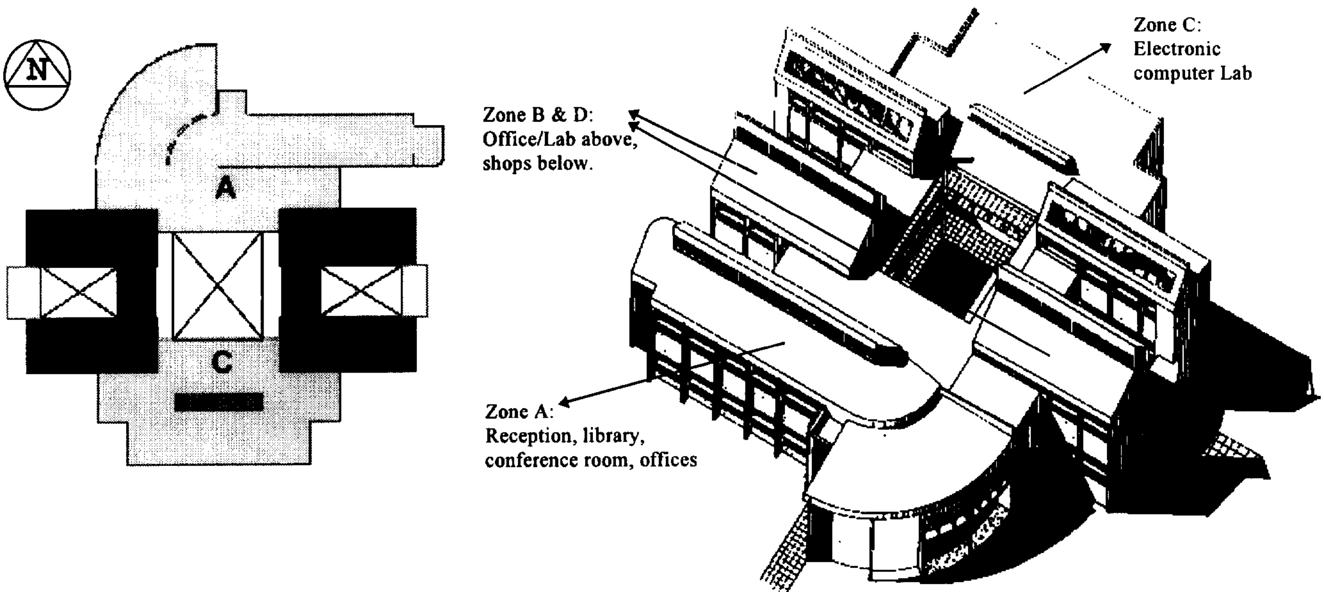

Figure 3. BTC Building Zones
(Note: The sun shines from the north in the southern hemisphere)

To determine the building's thermal performance load profiles and the impact of performance improvement strategies the CalPas3 (CalPas3 1982) 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 3. The passive solar design strategies coupled with effective use of highly insulated, prefabricated building components permitted the predicted heating and cooling loads to be a modest 629.1 MBTU/Yr, or 34.9 KBTU/ft².Yr. This can be compared to estimates for conventional buildings of this type and size of 70.0 KBTU/ft².Yr (DOE 1980; U.S. Energy Information Administration 1981). A parametric study of both standard and specialized conservation and passive solar performance improvement options was undertaken (Chalfoun 1991; Chalfoun et al. 1990). 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 mechanical 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 that zone. 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 4), and their dimensions were made uniform for cost efficiencies.

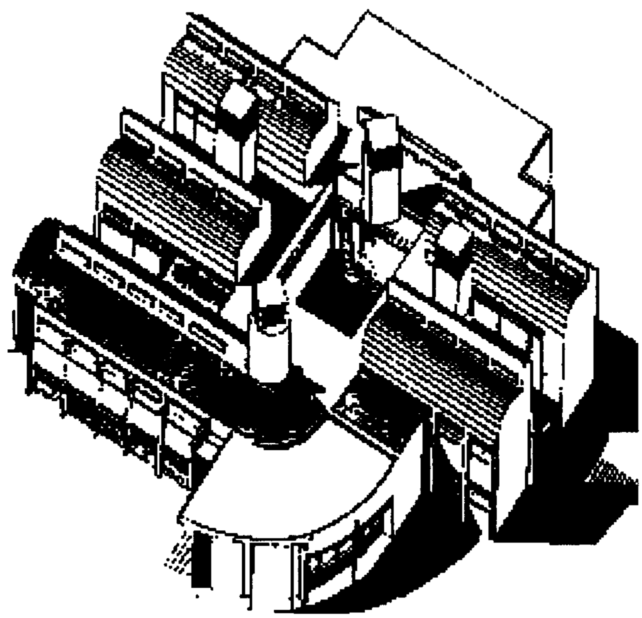

Figure 4. The BTC Building with Four Cool Towers

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 240X240X115 ft (80X80X35 m) 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 5).

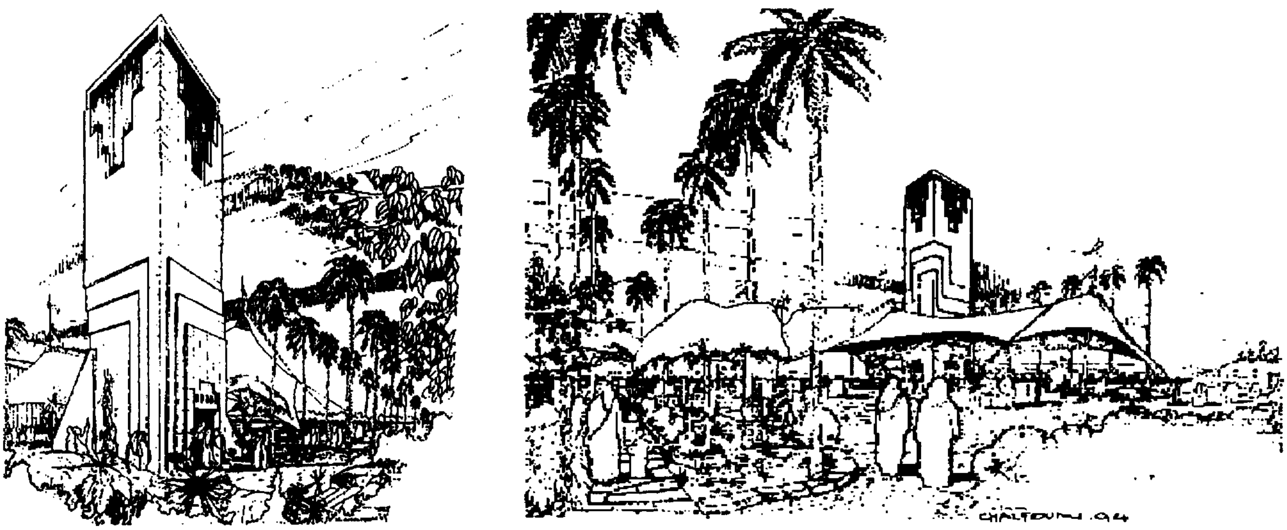

Figure 5. View of the Environmental Rowdah Showing the Climate Control Elements and the Gardens (drawings by the author)

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 76 ft high (25.2 m). The unique indentations which proceed around the tower change its external dimensions from a maximum of 26X26 feet (8X8 m) to a minimum of 21X21 feet (6.5X6.5 m) (Figure 6). The evaporative assembly in the top of the tower (the turret) consists of a series of pads that are constantly kept wet with re-circulating 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.

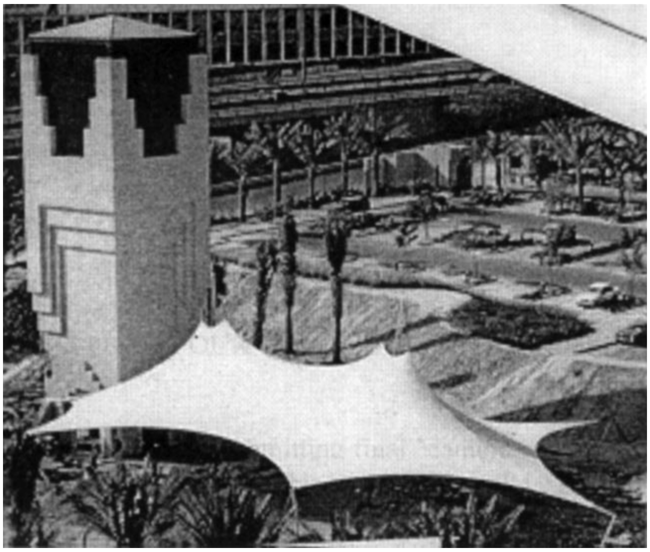

Figure 6. The Cool Tower After Construction (photos courtesy of PDC)

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 107.1°F (41.7°C) will be cooled down to 73.9°F (23.2°C) i.e. 33.2°F (18.4°C) lower, but the 13% relative humidity of air will increase to 75% at the tower discharge. This cooled and moist 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.

Conclusion

In arid regions, natural down-draft evaporative coolers, or "cool towers", are useful devices for cooling buildings and outdoor private and public areas. These tower-like devices cool the air by the water evaporation process and the air is moved by gravity flow saving the energy required by the blower in conventional evaporative coolers. Cool Towers water consumption is also almost similar to that by conventional evaporative coolers. Since there is little moving or mechanical parts, they require simple maintenance. When water evaporates, only pure water is released. The dirt and scale forming minerals are left behind on the pads and on the sump. Quarterly cleaning and flushing of the pads will increase their service life. Cool towers function the best on hot and dry days, exactly those days when optimum performance is desired. They have the capacity of cooling dry air about 25°F to 35°F (14°C to 18 °C). The cooled air is about 60 to 70% higher in moisture content. The *CoolT* program is a useful computer simulation tool and design tool that can help designers integrate and adequately size cool towers for commercial and/or residential use.

Acknowledgment

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