Analysis and Evaluation of a Passive Evaporative Cool Tower in conjunction with a Solar Chimney

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ABSTRACT: Passive Evaporative Cooling is one of the most efficient and long recognized ways of inducing thermal comfort in predominantly hot and arid climates. In order to extend the use of evaporative cooling, a downdraft evaporative 'cool tower' was integrated at the Solar Lab at the School of Architecture and Landscape Architecture, Arizona State University. The model explains how elevated temperature and pressure differences can increase the efficiency of a cooling tower, and how adding a Solar Chimney can create that elevated pressure difference. The synergy created by the cooler incoming air through the cool tower (positive pressure) and the hot air exiting through the solar chimney (negative pressure) will definitely alter the air movement and therefore the fluid dynamics. Our objective is to analyze the indoor air velocity increment and the indoor air movement, as well as the possible heat gains through convection and conduction due to increased air circulation. To accomplish our research, a scaled model has been built at the Solar Laboratory of the College of Architecture and Environmental Design where we will be executing, monitoring and collecting data for a period from 25th April to 5th June, 2005. The time for data under consideration for the paper is 24 hours from 9:17 AM, 31st May to 9:17 AM, 1st June.

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Keywords: Down-draft cool tower, Passive Evaporative Cooling, Buoyancy Ventilation, Thermal comfort

INTRODUCTION

A Cool Tower is one of the most efficient ways of inducing passive evaporative cooling in buildings located in predominantly hot and arid climates. It does not require any blowers or fans to move the cool air. The only power required is for a small DC pump to circulate water over the cooler pads or a mister. A cool tower is a perfect answer for cooling a Renewable Energy powered dwelling.

Cool towers use gravity to move cool air without any fans, although fans might be used in order to reduce the size of the towers. The most common cool towers do this by having a wet pad medium in the top of the tower. Since cool air is heavier than warm air, it moves down, creating its own airflow. Wind is not required, but will improve the airflow in a cool tower.

Passive ventilation systems rely on the movement of air through buildings to equalize pressure. The pressure difference can be caused by Wind or the Buoyancy effect created by stratified warm air. In either case, the amount of ventilation will depend critically on the size and placement of openings in the building. The maximum the pressure difference, the greater will be the efficiency of a Cool Tower.

2. TWO RELATED TERMS

2.1 Buoyancy Ventilation

Buoyancy ventilation, which is more commonly known as temperature-induced or stack ventilation, results from differences in air density. The density of air depends on temperature and humidity. Cool air is heavier than warm air at the same humidity.

Thus, the dropping of heavier air, forcing lighter air to exhaust, generates airflow. Tower height, or the distance from the air intake (top of tower) to the air outlet (bottom of tower), will determine the velocity or pressure of the air. The greater this distance the more air pressure created, similar to a water column. The tower uses a column of cool moist air (compared to the hot dry air outside) to create this pressure.

Wind causes a positive pressure on the windward side and a negative pressure on the leeward side of buildings. To equalize pressure, fresh air will enter any windward opening and be exhausted from any leeward opening.

Cooler pads or misters sit at the top of a tower with pump re-circulating water over them. As hot air passes through the pads or misters it is cooled by the evaporation of the water. Cool moist air is heavier than hot dry air and drops down the tower and into your house. In order for the cool air to flow in, hot air must be exhausted.

2.2 Solar Chimney

A solar chimney is another ingredient for providing naturally drafted ventilation and thermal comfort inside living spaces. It generates air movement by buoyancy forces, in which hot air rises and exits from the top of the chimney, drawing air through the building core in a continuous cycle. The driving force on the air column in the chimney is the difference in the density of the air inside and outside the chimney. If the height of the chimney is such that the normal variation of pressure and temperature in the atmosphere can be neglected, together with temperature changes within the Chimney due to adiabatic expansion, the pressure difference $\bullet P$ can be given by:

$$\bullet P = 11.67\ (1- T_a / T_c)\ h$$

Where h is height of chimney, T_a is ambient air temperature and T_c is temperature inside the chimney. Neglecting losses in the chimney (a reasonable assumption for a chimney of diameter greater than 1/10 of its height), the air velocity at the top of the chimney can be given by:

$$V = \bullet\ (2 \bullet P \bullet \bullet_1)$$

Where "$\bullet_1$" is the density of air at chimney temperature.

Thus, the effort in this experiment will be prove that a combination of both these strategies which work on the same principle can bring about a much higher degree of comfort which will be directly proportional to the outside dry bulb temperature. Alternatively, the building can be aerodynamically shaped to encourage an increased velocity air stream over the building. This improves the 'draw' and therefore the performance of the wind tower.

3. THE EXPERIMENT

3.1 Set up

The experimental evaluation for evaluating the efficiency of a Down Draft Evaporative Cool Tower (DECT) was performed at the Solar lab at the School of Architecture & Landscape Architecture, ASU, from the 25th April to the 5th June 2005. The experiment required setting up a scaled model of a cool tower having tower dimensions of 25 X 30 X 244 (l X b X h) Cu.Cms. The tower is made of single ply board. The tower is attached to a box made up of Styrofoam as seen in Fig 5 & Fig 6. An opening is made at the plane of attachment to provide the cool air inlet. There is also another opening in the northern side, which is provided with a single glass cover as shown in Fig 6. A solar chimney of diameter 10cms and height of 1mt. is then attached and is colored pitch black in order to increase the negative pressure to scoop out the hot air from inside the box. The sizes we came up with for the cool tower and the chimney at this scale were too small to be calculated in the "COOL T" program which is a simple DOS tool developed by N.V. Chalfoun, at the University of Arizona, Tucson for calculating sizes of cool towers and their corresponding air velocities. So, the sizes of the tower and the chimney we came up with were actually averaged out from the Thomson & Cunnigham cool tower dimensions built in Tucson, Arizona.

Thermocouples were then attached to each surface as tabled in Fig 1 to take down the temperatures. A total of 15 thermocouples are then attached in the order shown in the table above. All the thermocouples are then connected to an AGILENT BENCHLINK ® data logger which collects all the temperatures at an interval of 10 seconds. Two MRT (Fig 1 & 3 below)

Component	Thermocouple
North Glass Window	1
Ceiling	2
East wall	3
Wind tower up	4
Inlet cool air	5
Upper MRT	6
North wall	7
West wall	8
Lower MRT	9
Floor	10
Inlet solar chimney	11
Air near water	12
South Wall	13
Water	14
Chimney up	15

Fig 1. Position of the 15 thermocouples attached to the various Cool Tower components.

balls are kept inside the box to collect mean radiant temperatures. One is placed near the cool air inlet of the box and the other one is placed near the solar chimney opening to ascertain exit air temperature and also of the surroundings. The wind tower is provided with a conical scoop at the top. The scoop is provided with a mister (Fig 8) to provide with a supply of water to cool off the air comes down from the scoop, and thus it becomes heavier and moves down the tower and inside the box through the opening for the cool air inlet. Water to the mister is pumped from a pump and a valve from lower level as shown below in Fig 9.

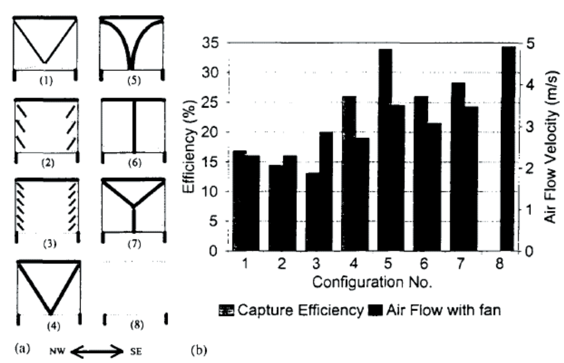


Fig 2. A comparative study and chart of different scoop design done by Prof. Yair Etzion et al. for cool tower performance enhancement.

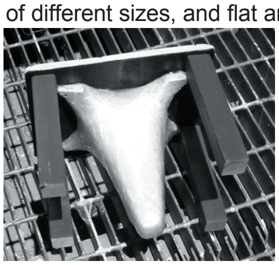
3.2 Design of the scoop for air intake

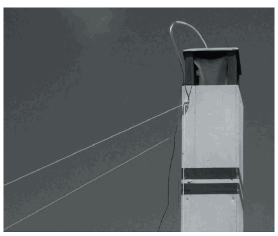
The utilization of wind capture has been investigated as a potential improvement to the above said configuration, which helps in:

(i) Saving on the need for a mechanical fan, and thereby increasing potential energy savings accordingly, and

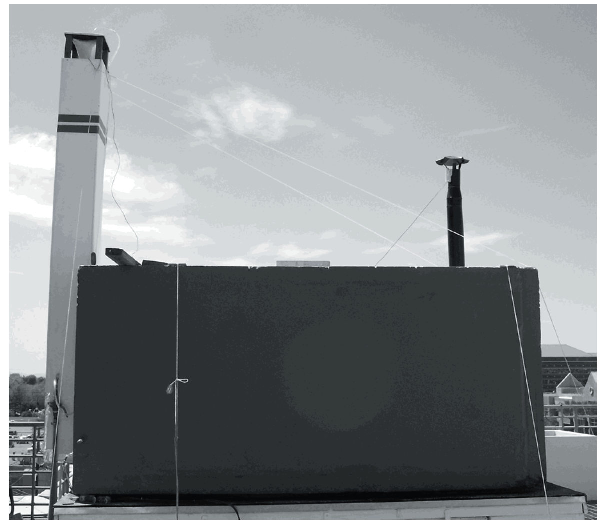
(ii) Enlarging the potential for overall airflow, and in turn the cooling capability of the tower. Since the supply of wind energy is not constant throughout the desired hours of operation, an optimal configuration should be sought which would exploit positive wind pressure when available and minimize resistance to airflow when the tower is fan-assisted.

After a thorough research done for appropriate designs for wind scoop, the research done by Prof. Yair Etzion et al. (Fig 2) was carefully studied and so, the conical scoop was chosen appropriate for the project. The variations of wind catcher designs done by Prof. Etzion et al. included louver-panel entrances of different sizes, and flat and curved deflectors inside the capture unit of both fixed and dynamic configuration as shown in the figure below. All configurations made use of the same symmetrical superstructure, which admitted wind. The three initial designs (configurations 1-3, fig 2) employed inwardly swinging louvers of different sizes installed in each of the two openings, with the intention of reducing energy losses due to outflow on the leeward side of the wind catcher. Such flows appeared to be relatively weak, and the expenditure of kinetic energy on opening the louvers against the force of gravity apparently factored heavily in the low wind capture efficiency of these configurations, which failed to rise above 20% regardless of specific louver size or density (see graph in Fig.2). The resistance of these louvers also led to below average flows when forced air from a mechanical fan was used. Configurations 4 and 5 (Fig 2) employed fixed deflectors to channel wind flow into the tower. This approach led to an increased efficiency of over 25% in the case of flat deflectors, and nearly 35% in the case of curved deflectors. The latter also provided the least resistance to forced airflow, allowing an average velocity of 3.5 m/s. Two additional configurations (6 and 7, Fig 2) were also investigated by them, with swinging panels centred in the capture unit, both alone and in combination with a fixed deflector. While these yielded better results than the initial louvered openings, they did not surpass the performance of the curved fixed deflector, which was seen to provide the greatest overall wind capture. All these factors led us to come up with a conical scoop design for the experimental set up under consideration here, which can be seen in Fig 3 and Fig 4.





Figures 3 & 4: Conical scoop design for the cool



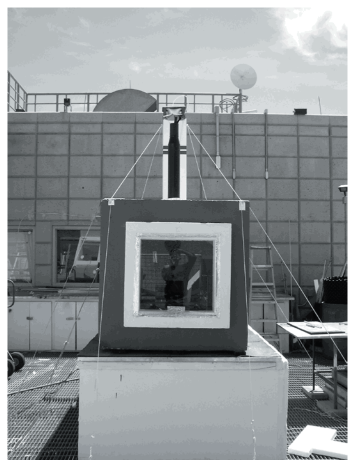


Fig 5 (Top): The cool tower along with the solar chimney – side elevation

Fig 6 (left): Front/ north elevation.

Fig 7 (Top Right): Placing the upper MRT ball in the enclosed space.

Fig 8 (Bottom Right): View of the Tower from top showing the mister in action.

Fig 9 (Bottom Left): Control Valve for the water supply to the misters.

4. ANALYSIS OF EXPERIMENTAL DATA

Looking at the theory, it can be assumed that the WBT depression (DBT - WBT); the ambient wind speed; the tower's height and cross section and the solar chimney can affect the performance of a passive evaporative cool tower to a large extent. The expected effects of the WBT depression, the ambient wind speed, and the solar chimney on the diurnal patterns of the flow rate through the cool tower are all in the same direction and thus enhance the airflow. There is a strong correlation between the diurnal patterns of the WBT depression, the wind speed, and the solar chimney temperature: all of them reach their maximum in the early afternoon and a minimum during the night. To distinguish between the separate effects of these correlated factors on the performance of the cool tower, the analysis of the individual effects was applied in sequence: starting with the factor considered to be the major one, and then observing the deviations of computed data from measured values as functions of the other factors.

The data under analysis is for a 24 hour long period from 9:17 AM on the 31st May to 9:17 AM, 1st June 2005. The first graph (Graph 1) shows efficiency of the misters that has been installed at the top of the cool tower just below the scoop. Though in that period the dry bulb temperature or the air temperature above the wind tower soared as high as 100.58°F at 5:17 pm and the average being 86.5°F, the average inlet air temperature remained as low as 67.8°F on an average. The inlet air temperature was 74.1°F at 5:17 pm when the highest temperature of the day was recorded. So, it can be said that the misters, though they need to be operated through out the entire length of the day, (night time temperatures after 9 pm are quite comfortable and so, water supply may be stopped at that time) proves to be effective in dropping down the temperature to a great extent.

Now looking at the temperature recorded (Graph 2) by the MRT ball placed at a lower level at some distance to the air inlet, shows a little increase in temperature which is nothing but the cumulative effect of the internal heat gain as well as the cool air entry. The temperature record thus is a step ahead towards attaining the comfort level inside the box. It can be seen from the graph below that the MRT is also well below the air temperature outside, the average being 74.7°F in the peak hours that is between 9:17 AM and 9:17 pm, which is pretty much satisfactory. The maximum delta T however was actually on 5:17 pm when the outdoor temp. reached 100.5°F whereas the indoor temperature as taken from the Lower MRT ball was 77.7°F which is well within the comfort zone. Looking at this value, it can be said that the cool tower design is efficient to a greater extent.

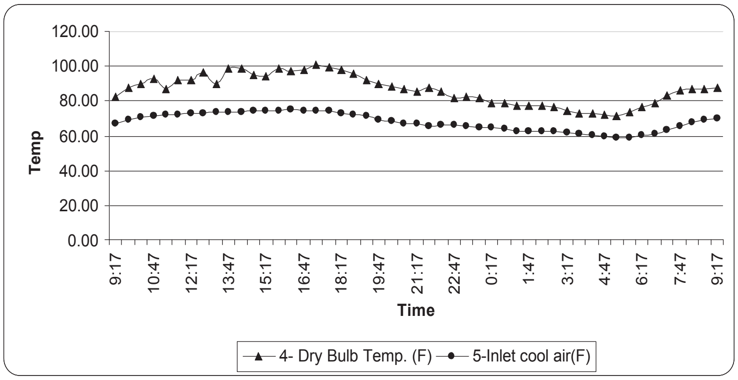
Now, looking at the temperature recorded by the upper MRT ball near the solar chimney, (Graph 3) it can be seen from the graph below that since the cool air becomes hot as it moves towards the chimney. It is mainly due to internal heat gains by the surface and also by the uninsulated glass surface on the other side of the set up. Thus the average temperature recorded by the upper MRT ball during the peak hours (9:17AM – 9:17PM) is 80.69°F. Now the mean of both the MRT readings will give the operative indoor temperature of the set up which is 77.7°F at the peak hours. And this temperature is well within the comfort zone.

The next set of results as shown in Graph 4 shows comparison of the Dry Bulb Temperature to the temperature at the Inlet of the solar chimney and also to the temperature at the top of the solar chimney or the exit air temperature. The temperature readings seem to be satisfactory in the sense that air is being heated up by the chimney that creates a negative pressure through out the length of the chimney. This negative pressure then scoops out the air inside the set up thereby maintaining the air circulation cycle inside the experimental box. Thus looking at the data, it can be seen that the maximum temperature at the top of the chimney is 88.17°F where as at the bottom of the chimney at the inlet is 80.60°F. During daytime, this difference is higher than nights. This differential heat inside the chimney creates the negative pressure. In the next phase of the experimentation, evaluation of the pressure difference and wind flow will be ascertained.

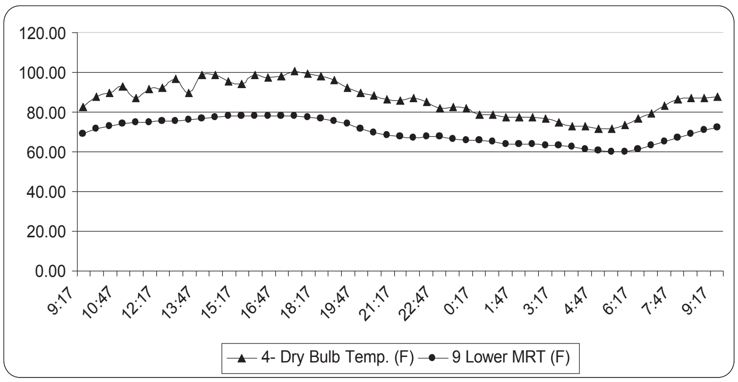
Finally, the last set of numbers make a graph (Graph 5) which shows the comparison between the pressure difference and wind velocity inside the chimney to the operative temperature inside. Although the maximum pressure difference took place at 9:47 pm and that was around 9.53 inches but the delta T was near 19°F the maximum being 19.72°F. The maximum air velocity inside the chimney was also recorded at the same time and the velocity was 11.50 mph. The graph thus succeeds in proving that not only elevated temperatures but higher pressure difference and wind velocities can increase the efficiency and performance of a passive evaporative cool tower. Future research in this experimentation will include an extensive research of water consumption and diurnal frequencies when the cool tower should be kept on along with the effects of the internal heat gains to the cooling process.

CONCLUSION

A simple model of a passive evaporative cool tower, as developed and tested in the Solar Lab of the School Of Architecture, Arizona State University has been described. Taking temperature readings through thermocouples attached at different parts of the set up did validation of the model. Based on the performance of the solar chimney and the ambient wind speed on the flow rate, demonstrated in the experimental study, the expected performance of an evaporative cool tower can be expressed as a function of the delta T, the pressure difference as well as the details of the tower and the main thermal properties of the building cooled by it. The model calculates the hourly values of the tower air entry temperatures, the chimney exit air temperatures, the temperatures of all the surfaces of the box, and two MRT balls for a day between the 31st May and 1st June 2005 and the results were satisfactory.



Graph 1 showing comparison of the external air temperature to the Inlet cool air



Graph 2 showing comparison of the external air temperature to the Lower MRT.

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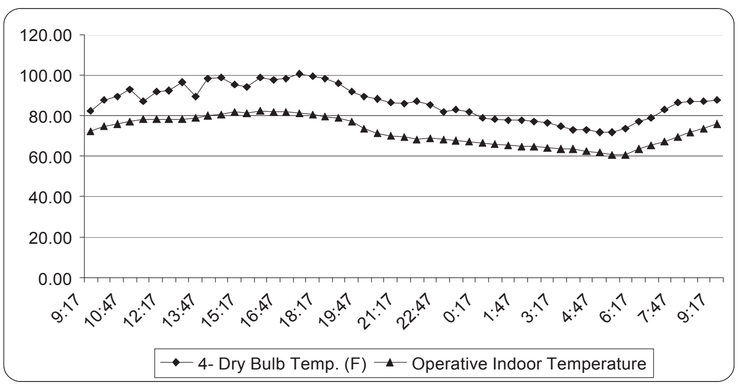
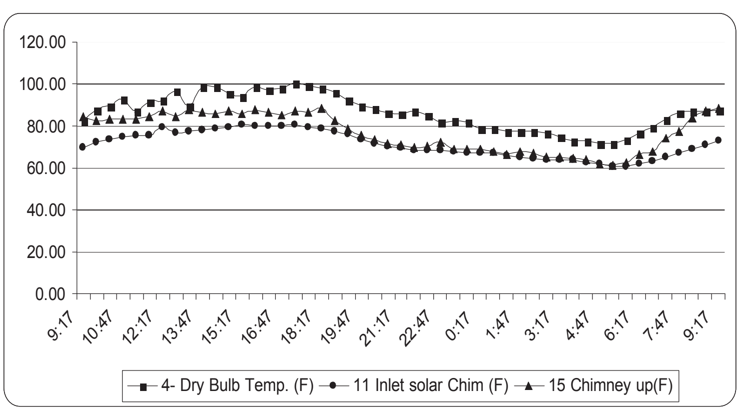
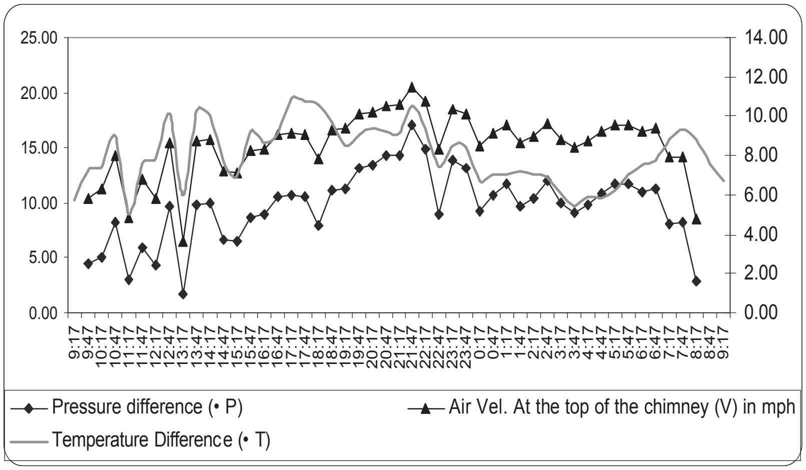


Graph 3 showing comparison of the external air temperature to the Operative Indoor temperature



Graph 4 showing comparison of the external air temperature to the temperature at the Inlet of the solar chimney and the temperature at the top of the solar chimney or the exit air temperature



Graph 5 (below) showing comparison between the pressure difference, temp. difference and the air velocities at different times inside the cool tower

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Image Citation:

[1] Figure 2: " A comparative study and chart of different scoop design done by Prof. Yair Etzion et al. for cool tower performance enhancement" cited from Pearlmutter D., Etzion Y., Erell E., Meir I.A., Di H., "Refining the use of evaporation in an experimental down-draft cool tower", *Energy and Buildings,* Vol. 23, No. 3, pp. 191-197, 1996.