

# **PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING IN OFFICE BUILDING- JORDAN**

by

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## ABSTRACT

Wind driven ventilation presented in wind tower finds its roots in the Middle East vernacular architecture; it catches the upper air stream cools and channelled it down to the occupied spaces.

This paper explores the cooling potential of passive downdraught evaporative cooling wind catcher to ventilate an office building in Amman/Jordan.

Summer comfort zone for Amman is developed to present a thermal assessment tool for the results.

Study case of an office building in Amman is introduced based on the regulations.

Theoretical model is initiated to establish the measurements for wind tower based on the accepted internal conditions. The later assumption is based on the required cooling load, tower height and the condition of air leaving the evaporative column.

The assumption is tested using TAS software. The results are promising as temperature and humidity results were within  $\pm 1^\circ\text{C}$  and  $\pm 5\%$  from the calculated values. Although further work is needed to improve the performance of the upper floor.

The results demonstrates that as the tower height increases the water consumption steadily increases until 6m-tower height is reached, the increment becomes less progressive. The average internal temperature is gradually decreases as tower height increases till 7m-tower height is reached, then higher tower is not notably improve the internal temperature.

Dehumidification is needed to bring the internal conditions over the cooling season into comfort zone.

Comparison of air outlet velocity as a function of tower height between the assumption charts and TAS results illustrates contradictions in air flow regimes.

It was concluded that PDEC is viable method for passive ventilation in office building, it managed to bring the internal conditions into the thermal comfort zone with minor energy demand.

### *Keywords*

Mulqaf; Badgir; Baud Geer; Wind tower; Wind catcher; Cool tower; Passive ventilation; stack ventilation, Natural ventilation, Natural cooling; Passive cooling; Downdraught evaporative cooling; Design tools; Hot dry climate; Jordan.

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# 1 CHAPTER 1: BACKGROUND

## 1.1 WHY REVISITING OLD ISSUES?

“Why Worry? As the world becomes ecologically overloaded, conventional economic development becomes self- destructive and impoverishing and puts human survival at risk” (Wackernagel and Rees, 1996).

The rising demands for food, shelter and services associated with ever-increasing population places economic growth as a top priority on the political agenda.

The accelerating industrial development, which uses the natural resources to form the stock of wealth, speeded up the depletion of soil, diminution of resources, waste accumulation, greenhouse gases emissions, damage of ozone layer, air pollution and global warming. In addition, this climate change brought about new problems like the seasonal changes, water scarcity, rising sea levels, flooding, water quality, etc...

This degradation of the natural environment, stepping up since the industrial revolution, reaches unprecedented levels, which pose critical challenges to planner and policy makers in achieving the sustainable development as defined in “Brundtland Report” “development that meets the needs of this generation without jeopardising the ability of future generations to meet their own needs” (WCED, 1987).

It seems that everybody is agreed on the concept of sustainable development, yet not decided on the interpretation of what should be passed to future generations, which is reflected on the extent and level of integration between people activities and the ecological system which hosts them. Colby (1990, p.1-30) classified the environmental management in development into five paradigms<sup>1</sup> as they move from weak towards strong sustainability; *Frontier economics*: which considers that man-made stock of wealth is the primary elements of development and that damage to

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<sup>1</sup> Paradigm: (1) a criterion for choosing problems.. that can be assumed to have solutions. Other problems are rejected as metaphysical, as the concern of another discipline, or sometimes as just too problematic to be worth the time; (2) the entire constellation of beliefs, values, techniques, and so on shared by members of a given community, or one element in that constellation, the concrete puzzle-solutions which, employed as models or examples, can replace explicit rules as a basis for the solution of the remaining puzzles of normal science (Kuhn, 1970 in Colby, 1990). (3) a worldview or mode of perception; a model around which reality is organized (Berman, 1981 in Colby, 1990).

nature could be mitigated by advanced technology, secondly, *Environmental protection*: this paradigm focuses on the control of damage resulted from development rather than improving the ecological performance of the development. Then, *Resource management*: This considers the mutual effect of the natural, capital and labour resources for development and investment planning, decreasing the consumption of energy and the implementing energy efficiency and resource conservation. Next, *Eco-development* which takes into account the global carrying capacity when designing for development, based on renewable energy and information intensiveness rather than on increased material energy intensiveness and expands sustainability to include social, ecological and economic criteria, incorporates social equity and communities sharing resources for development and use of technology. Finally, *Deep ecology*: this approach imposes reversing the current lifestyle and minimising the causes of environment depletion, i.e. human population and related activities.

As it happens in the different communities at diverse levels, scientist should also be open to paradigm shift. Though planners set the subjective goals for sustainable development; science sets the objective goals. Designers can attend to be sustainable when designing especially that buildings produce half of climate change-greenhouse gases emissions. That implies, when designing taking into account the environmental management in the (built-environment design).

Proper today-design for tomorrow needs will save today resources (fuel consumption) and can be transfer to the next generation and save tomorrow resources (new building embodied energy), climate change is what is meant here by tomorrow's needs, i.e. to stretch the thermal comfort zone within buildings to accommodate warmer climate with the less impact on energy consumption for active cooling.

Paradigm shift is taking place because people needs have been changed, so what have been changed?

### 1.1.1 THE WIDER CONTEXT;

The wider context for the need of effective natural ventilation and passive downdraught evaporative cooling can be summarized as shown in Figure 4 and as described below.

*For the rich* in hot countries, thermal comfort is achieved in summer by using air conditioning regardless of the building's capacity for passive cooling. The more air conditioning used, the more fossil fuel is burnt, more fossil fuel use leads to extra air pollutants, additional greenhouse gases emitted and accumulated in the atmosphere forming a dense layer which prevent the heat absorbed by the ground from radiating back to the outer space, further warming up the earth. This in turn requires more air conditioning.

*For the poor* in hot climates, who can not afford air conditioning or move to new building, a warming climate will push the internal temperature more beyond the thermal comfort threshold, consequently,

- the most vulnerable members of society, the old and infirm will die prematurely as climate warms.
- people will look forward to change their situation as suggested by Roaf et al (2005, p.48); migrate to other places in which the temperature is mild and no need for air conditioning, or where they can work and come up with the money for the AC. This doesn't look sustainable solution, as it is not on hand of the vulnerable sector of society, like aged, unhealthy, women and children who might find it difficult to leave their habitat or to manage new jobs in new places. On the other hand, group migration will not solve the problem but rather mitigate it for a while. It will bring social problems to the new areas, i.e. unemployment, cultural conflicts, services crisis, crime percentage increase, etc. Moreover, migration will lead to more urbanization density in the new areas which increases the effect of the urban heat islands where the city is 6-8°F hotter than its surrounding. This hotness, according to (Heat Island Group), contributes to the cities-build up warming where it was estimated that 1°F per decade is the rising in temperature in some cities, Figure 1 and Figure 2. Figure 3 Subsequently, higher ambient temperatures bring about increases of the need for air conditioning, and the cycle continues.

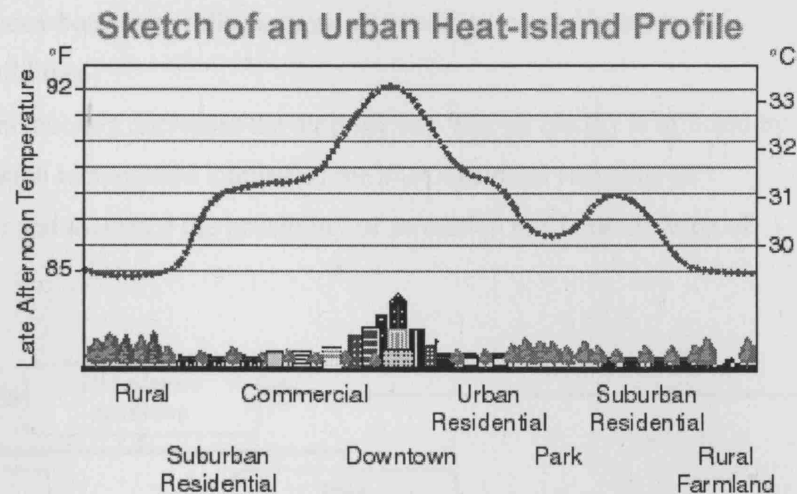


Figure 1, Source Heat Island Group, <http://eetd.lbl.gov/HeatIsland/HighTemps/>. Retrieved: 14.06.2005.

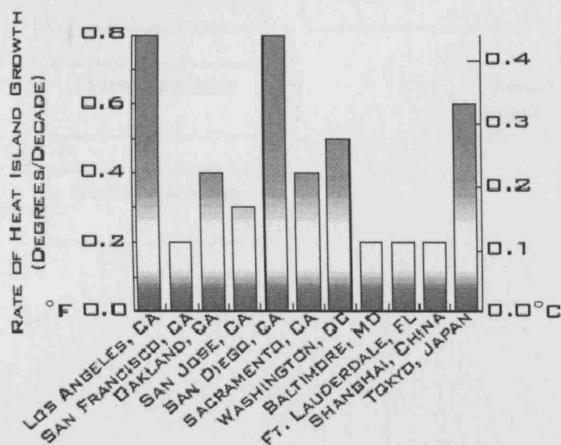


Figure 2, Data from these cities indicates increases in urban temperatures ranging from 0.2 to 0.8°F per decade. Source: Heat Island Group, <http://eetd.lbl.gov/HeatIsland/HighTemps/IncreasingTemps.html>. Retrieved: 14.06.2005.

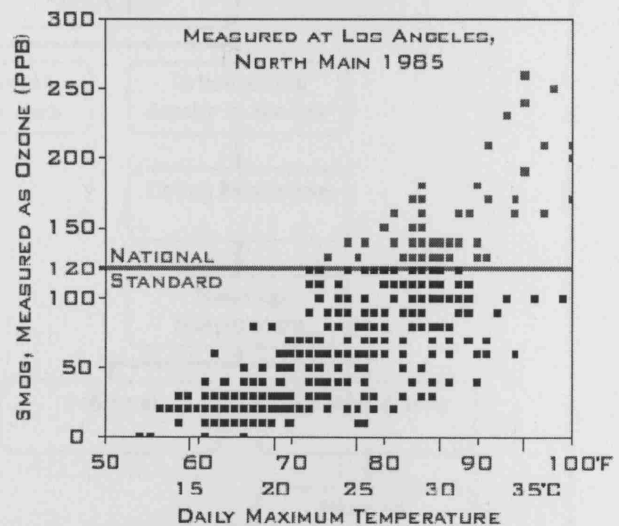
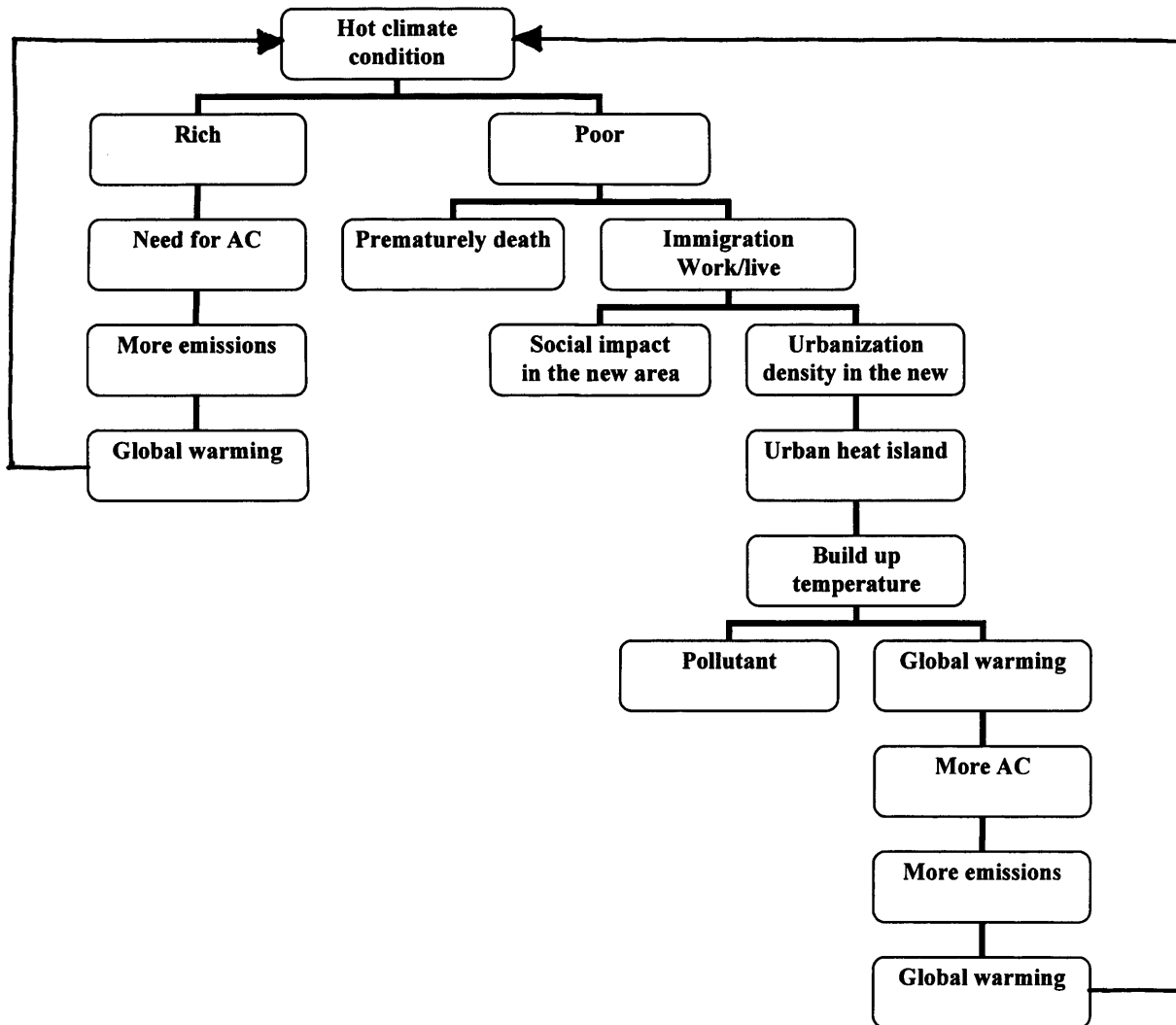


Figure 3, Smog formation and concentration is direct proportional to the temperature rising. Source: Heat Island Group, <http://eetd.lbl.gov/HeatIsland/AirQuality/>. Retrieved: 14.06.2005.

Alternatively, intelligent building which passively ventilate and condition the space utilizing free energy offered by nature expands the ambient thermal threshold for the expected temperature rise, at least, for the coming 50 years, the expected life of the building. Subsequently it will minimize the reliance on non renewable energy and reduce the greenhouse gases which are believed to be the main reason for the global warming. In addition, passive cooling in buildings reduces the emissions of ozone-

depleting chlorofluocarbons from refrigeration, air conditioning and heat pump systems used in buildings.

Furthermore, natural cooling decreases the air pollutant. The air quality is affected by the warmth as the high temperature intensifies the photochemical reactions of pollutants in the air and increases the possibility of formation and concentration of smog, (Figure 3).



**Figure 4, The wider context of the mutual effects between poor designs (depend on active cooling) and environmental and social impact.**

### 1.1.2 THE NARROW CONTEXT; OFFICES

Building consumes 50% of fossil fuel use in developed countries (Figure 5). Office buildings in particular are characterized by high internal gain due to office equipments and high occupancy level for long time attendance, lead to strong need for ventilation and conditioning, consequently, more consumption of energy and more emissions to atmosphere than residential building.

On the other hand, the health and comfort of staff is an important issue because it is connected to their productivity, and productivity of the staff versus the initial and operating cost justifies the existence of an office building.

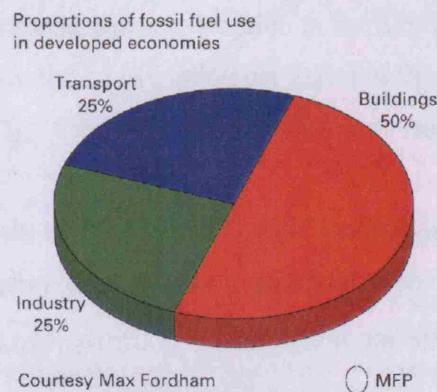


Figure 5, Source: Roaf et al, 2005.

Studies showed direct relation between unhealthy building environment and medical conditions represented by sore throats, eye irritation, headaches and lethargy.

CIBSE Application Manual (1997, p.8) demonstrates that office staff related many health problems to air conditioning, preferring natural ventilated building as long it provided the comfort conditions. In addition, it links between productivity and natural ventilation, provided user control and comfort are not compromised.

In Jordan people are not yet keen to air conditioning because of its high expenses, but with the trend of global warming and the use of imported modern design and construction materials, air conditioning becomes an inevitable option. For this reason, this paper is will investigate the mixed mode ventilation of an office building located in Amman-Jordan.



### 1.1.3 JORDAN IN CONTEXT;

Jordan's consumption of energy per capita is a little when comparing to the world consumption as shown in Figure 12 and Figure 13.

Figure 9 and Figure 11 illustrate respectively, almost constant levels of carbon dioxide emissions and energy consumption per capita in Jordan over the years 1985-2002/ 2001, while Figure 8 illustrates the increase in carbon dioxide emissions in Jordan over the years, this is because the increase in emissions is parallel with the growing population.

Table 1 demonstrate that the energy consumed by the country is increasing along with the population growth, which is estimated to be 2.8% (Chedid et al). It also shows the constant rise in energy demand and consumption in the future which necessitates finding solutions to reduce the consumption per capita as the population is in constant rise. In this case, the energy consumption could be steady rather than increasing.

Reducing the energy likely to be consumed by air conditioning in offices becomes an important issue for the greenhouse gases emissions because:

- Most of the energy consumed in Jordan is from the use from fossil fuels, Figure 14.
- Though Jordan's energy consumption and gasses emission are small compared to the world's, it has a impact on the country, as it has a large desert area, negligible green area and limited water resources which may mitigate the impact of degradation of nature, all this make the country ecologically fragile region. Figure 6 and Figure 7 show the two scenarios of human-impact on the ecosystem in Jordan on 2002 and the expected one in 2050. They reflect the high impact around the major cities due to human construction and activities. On the other hand, they show the ecologically fragile region which lacks water and green areas.

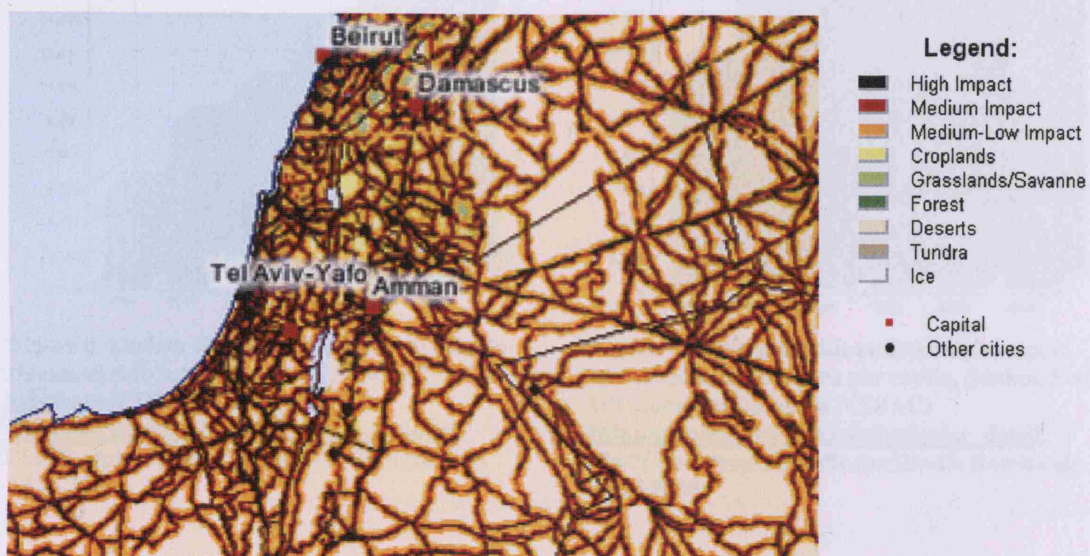


Figure 6, human impact on land, Jordan, 2002.

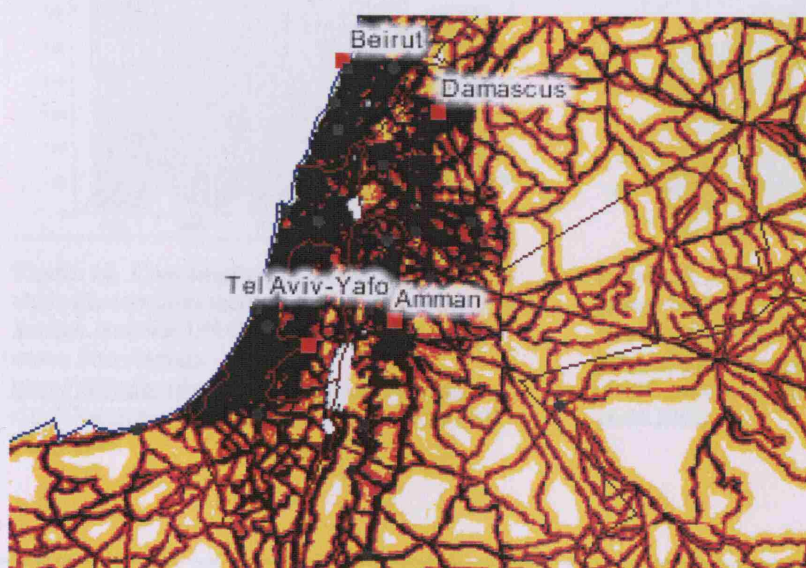


Figure 7, human impact on land, Jordan, 2050.

Pictures above source: <http://globalis.gvu.unu.edu/?841>. Retrieved 16.06.2005.

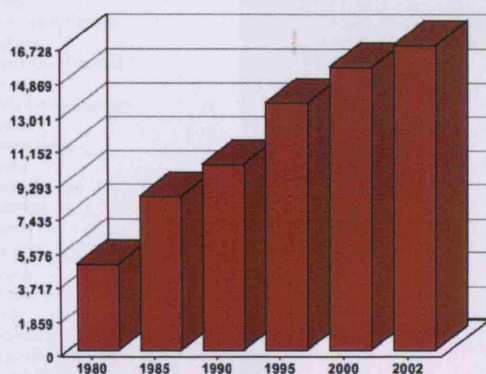


Figure 8, Carbon dioxide emissions measured in thousand metric tons, Jordan. Source: UN Common Database (CDIAC).  
[http://globalis.gvu.unu.edu/indicator\\_detail.cfm?Country=JO&IndicatorID=48](http://globalis.gvu.unu.edu/indicator_detail.cfm?Country=JO&IndicatorID=48). Retrieved 16.06.2005.

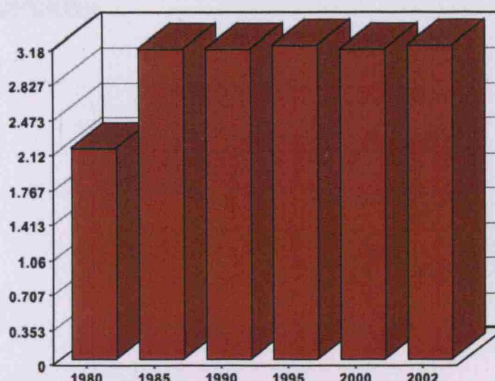


Figure 9, Carbon dioxide emissions per capita measured in metric tons per capita, Jordan. Source: UN Common Database (CDIAC).  
[http://globalis.gvu.unu.edu/indicator\\_detail.cfm?Country=JO&IndicatorID=47](http://globalis.gvu.unu.edu/indicator_detail.cfm?Country=JO&IndicatorID=47). Retrieved: 16.06.2005.

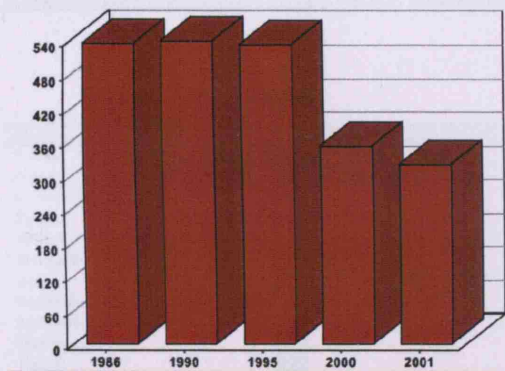


Figure 10, Consumption of ozone-depleting chlorofluorocarbons measured in ODP metric tons, Jordan. Source: UN Common Database (UNEP-ozone Secretariat).  
[http://globalis.gvu.unu.edu/indicator\\_detail.cfm?Country=JO&IndicatorID=82](http://globalis.gvu.unu.edu/indicator_detail.cfm?Country=JO&IndicatorID=82). Retrieved 16.06.2005.

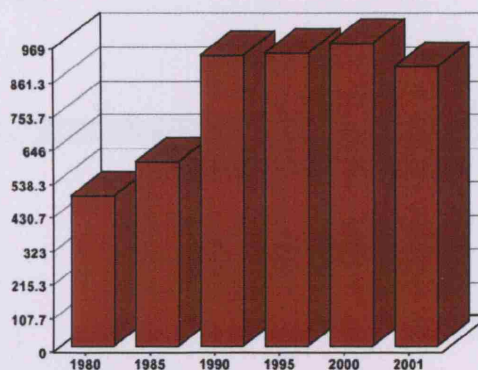
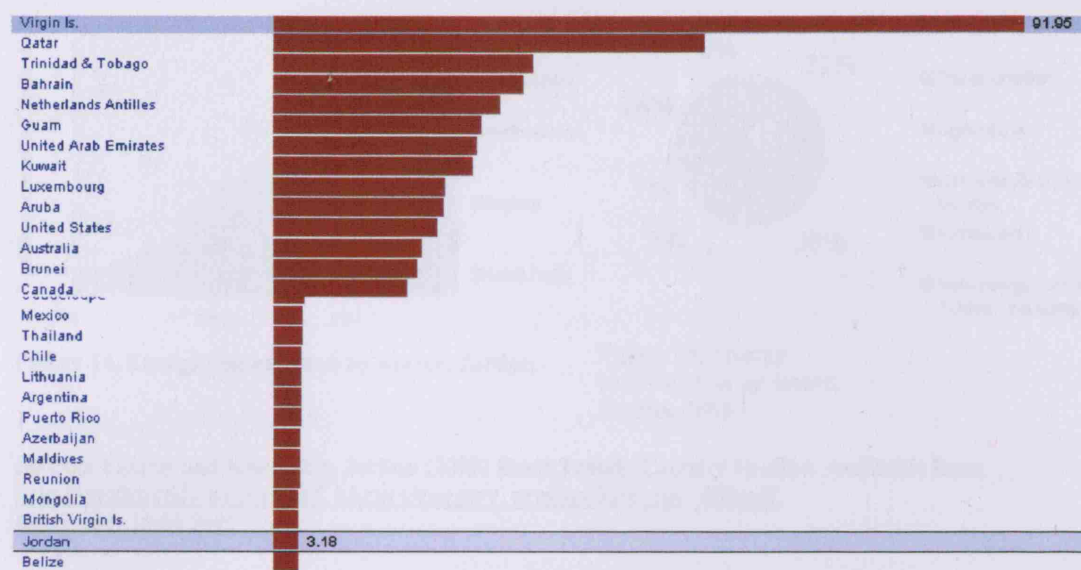


Figure 11, Energy consumption per capita measured in tones of oil equivalents pr capita, Jordan. Source: UN Common Database.  
[http://globalis.gvu.unu.edu/indicator\\_detail.cfm?Country=JO&IndicatorID=146](http://globalis.gvu.unu.edu/indicator_detail.cfm?Country=JO&IndicatorID=146). Retrieved 16.06.2005.

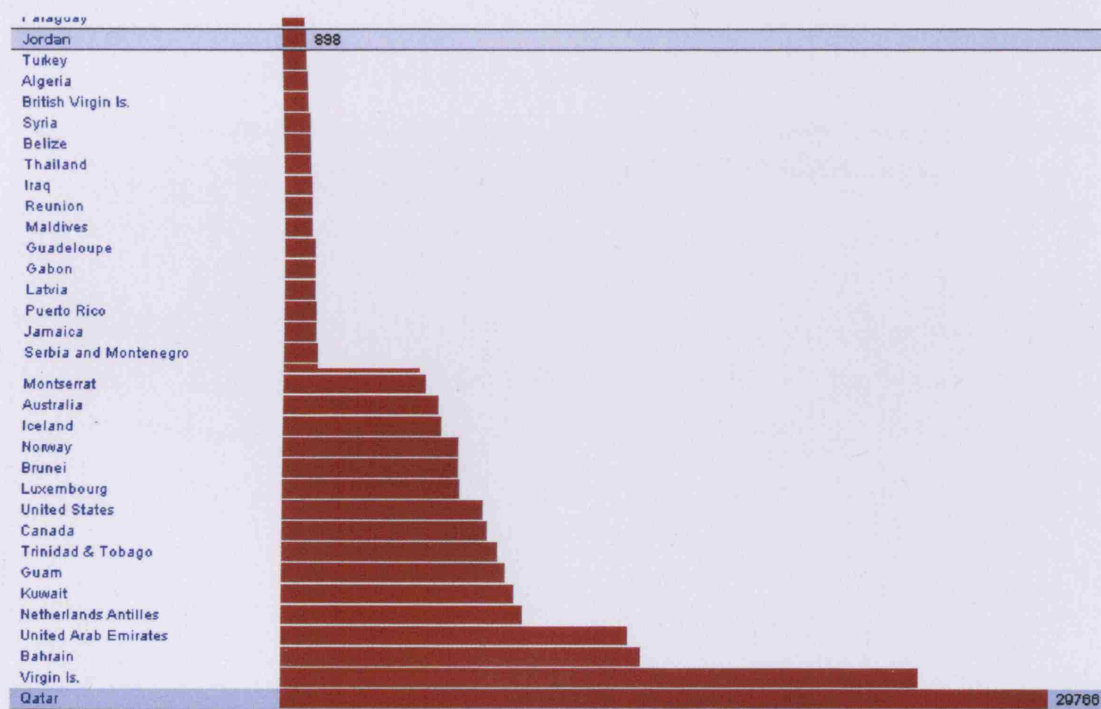
Country	Energy consumption (GWh)		Avg. growth rate %	Project demand (GWh)		
	1995	2000		2005	2010	2015
Jordan	4778	5810	5	7596	8849	10159

Table 1, Total energy consumption and predicted demand in Jordan. Source: Chedid et al.





**Figure 12, Ranking of Jordan to World for carbon dioxide emissions per capita shown as percentage %, 2002. Source: UN Common Database (CDIAC). <http://globalis.gvu.unu.edu/indicator.cfm?IndicatorID=47&country=JO#rowJO>. Retrieved 27.06.2005.**



**Figure 13, Ranking of Jordan to World for the annual primary energy consumption per capita shown as tons of oil equivalents pr capita, 2001. Source: UN Common Database. <http://globalis.gvu.unu.edu/indicator.cfm?IndicatorID=146&country=JO#rowJO>. Retrieved 27.06.2005.**

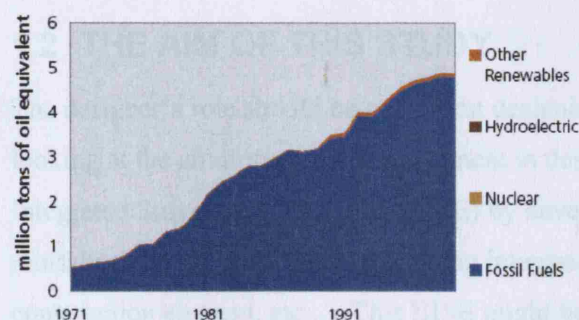


Figure 14, Energy consumption by source, Jordan

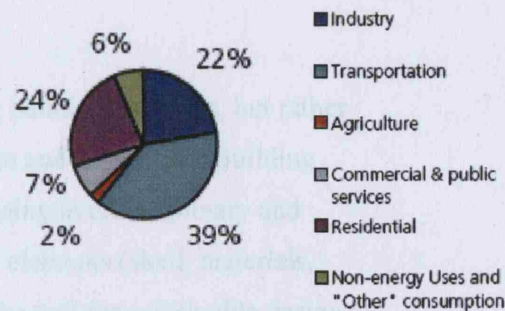


Figure 15, Energy consumption by sector, Jordan, 1999

Source: Energy and Resources, Jordan (2003) EarthTrends Country Profiles. Available from [http://earthtrends.wri.org/pdf\\_library/country\\_profiles/Ene\\_cou\\_400.pdf](http://earthtrends.wri.org/pdf_library/country_profiles/Ene_cou_400.pdf). Retrieved: 16.06.2005

## 1.2 THE AIM OF THIS STUDY

The designer's role should be more than designing building elements, but rather looking at the environmental management in design and developing Building Integrated Sustainable Elements (BISE) by developing interdisciplinary and multidisciplinary criteria using building integrated elements (shell, materials, construction element, etc...). This BISE might be the tool for sustainable design. This report considers the role of the wind catcher or Mulqaf as a promising BISE. The wind catcher tackles both ecological and social aspects of sustainability.

- Ecological sustainability; it utilizes renewable energy of wind to trim down the energy demands for ventilation and air conditioning, subsequently, reducing fuel consumption, greenhouse gases emissions, air pollution, global warming while improving air quality by reducing the pollutant problem associated with air conditioning; it can also provides better indoor air quality than window-ventilation, as air is drawn from high level above the road pollution level.
- Social sustainability; it addresses the social equity, i.e. it promotes the equal rights for rich and poor to have thermal comfort. Once the wind catcher is built it doesn't need running cost. The conventional rights of thermal comfort used to be for rich since they can afford building services.

The aim of this paper is to investigate the cooling potential of evaporative cooling wind catcher in office building in Amman/Jordan, and to improve its performance to save the expensive and unnecessary energy wastage of air conditioning.

## 2 CHAPTER 2: LITERATURE REVIEW

### 2.1 EVAPORATIVE COOLING

Evaporative cooling is a cooling technique used to elevate the thermal comfort in hot dry areas, where the convective cooling is not enough due to high temperature at night time which hinders the thermal mass cooling and wind temperature during day is high and need high ventilation rate to expand the body comfort zone which causes unwanted draught.

Evaporative cooling occurs when the water changes from liquid to gas taking some of the sensible heat and transfers it to latent heat, this technique is accompanied by temperature reduction and humidity increment.

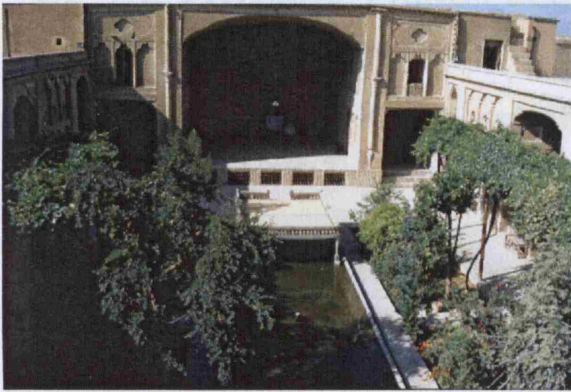
Buildings can be evaporative cooled either directly or indirectly as explained by Aboul Naga (1990):

- Direct evaporative cooling is the effect of direct cooling to the air in the occupied spaces when air bypass over the water and evaporates, in this technique the indoor humidity is more than the external's, Figure 19.
- Indirect evaporative cooling is the effect of cooling the air surrounding the building, the air supplied to the occupied spaces is cooled without excessive humidity.

Historically, evaporative cooling has been used in hot-dry climate utilizing fountains and vegetation in courtyards to improve their ambient conditions as the courts act like pre conditioning spaces which supply the modified air to internal occupied spaces, Figure 16 and Figure 17. Green-covered alleys, water in wind towers, water jars behind windows, wetted matting in front of windows, damping the floors and walls are old techniques used by people all over the world to improve their environmental conditions.

Architectural designs incorporate apertures around the evaporative cooled place to encourage air movement thus increase the evaporative process and carrying the conditioned air to the surrounding areas.



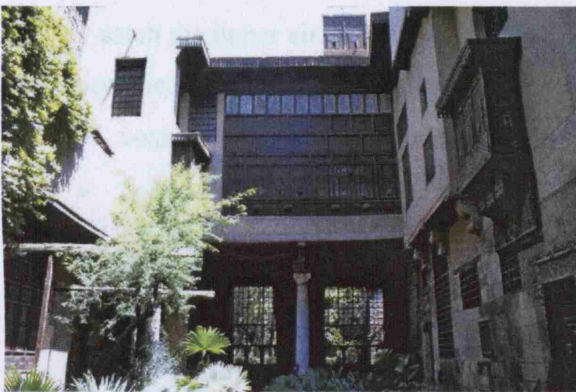


**Figure 16, Evaporative cooling by water element and vegetation in the courtyard.**



**Figure 17, Evaporative cooling and Rewaq (alley) shaded by greenery in the court yard.**

Pictures above source: Lari house, Yazd, Iran, Aga Khan Trust for culture, [http://archnet.org/library/images/one-image.tcl?location\\_id=5992&image\\_id=18933](http://archnet.org/library/images/one-image.tcl?location_id=5992&image_id=18933), Retrieved 7.08.2005.



**Figure 18, Courtyard façade, Al Mashrabeyh 'window's lattice wooden screen' is a passive cooling technique reduces glare and sun and allows air.**



**Figure 19, South Iwan in the reception hall, evaporative cooling by indoor fountain.**

Pictures above source: Al Suhaymi, Cairo- Egypt. Aga Khan visual archive. [http://archnet.org/library/images/one-image.tcl?location\\_id=4723&image\\_id=15936](http://archnet.org/library/images/one-image.tcl?location_id=4723&image_id=15936), Retrieved 7.08.2005.



## 2.2 THE PHYSICAL PRINCIPLES OF WIND CATCHER COOLING TECHNIQUES.

The wind catcher (Mulqaf) has been used in hot dry climate in the Middle East for years, Figure 20, Figure 21, Figure 22 and Figure 23. They provided sensible cooling and/or evaporative cooling.

Water is introduced to the system in many ways, ground water leaks through basement walls, pools, fountain or underground streams or by covering the tower inlet by wet pads. In his designs, the Egyptian architect Hasan Fathy used clay vessel filled with water in the bottom of the tower. In advanced studies, water has been sprinkled from the top of tower; the water drops push a volume of air and create a flow of evaporatively cooled air down the shaft

Sometimes wind catcher is used with dome or curved roof to make use of the stratification of the heated air at high level, (Billington, 1982, p.285).

They catch the upper air stream and conduit it down to passively ventilate and cool the occupied spaces in three ways as described by Roaf et al (2005, p.46):

- ventilate the deep parts which do not have enough windows,
- cool people by convective cooling if the ambient air is below skin temperature (32,35°C) and evaporative cooling if higher ambient temperature, and finally,
- remove the excessive heat from the structure by night ventilation to remove the heat collected in those walls, which also helps in reducing the mean radiant temperature of the building.

The driving force for air flow in wind tower is achieved by the power of air moving between the inlets and outlets due to density and pressure differences surrounding the building. It is important to discharge a sufficient amount of air as the inflow air is equivalent to the outflow air.

The wind speed increases with height, that means the pressure of wind at the wind catcher inlet at the top is larger than the outlet at the bottom, thus, creating positive pressure through the building.

Besides, air movement within the tower accrues in terms of buoyancy; the temperature of the air entering the tower is reduced by convective and conductive heat transfer with the structure or by evaporation when structure is moisturized. Cooler air

inside has higher density than the air outside, which creates a downdraught air stream into the tower to the occupied spaces.

Night ventilation is essential to cool the structure of the tower and the building to store the coolness for the next day which helps to cool and channel down the air in the tower, provide thermal comfort inside the building by coolness stored in the internal surfaces which provides radiant coolth and by the thermal mass effect of the structure which stabilises the temperature and dampens the effect of short term fluctuations in heat gain.

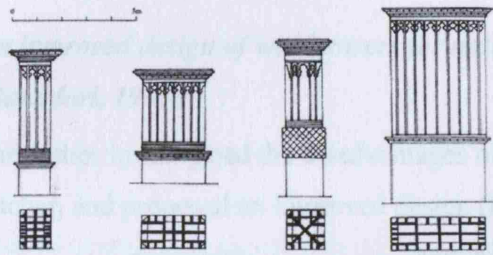


Figure 20, Different shapes of traditional Mulqaf (wind catcher).

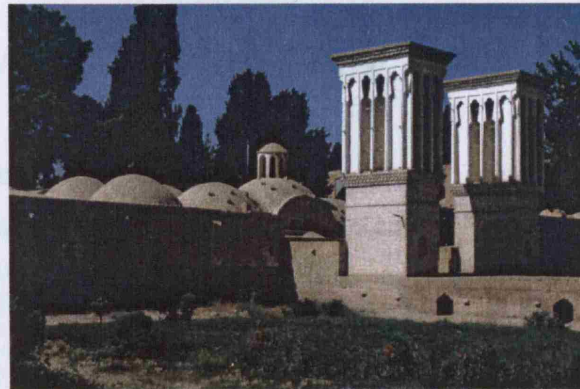


Figure 21, Ground level badgir (wind catcher) at Shrine of Shah Nur ad-Din Ni'matullah Vali, Mahan, Iran.

Pictures source: [http://archnet.org/library/dictionary/entry.tcl?entry\\_id=DIA0483#](http://archnet.org/library/dictionary/entry.tcl?entry_id=DIA0483#).  
[http://archnet.org/library/images/one-image/tcl?image\\_id=11970](http://archnet.org/library/images/one-image/tcl?image_id=11970). Retrieved 7.08.2005.

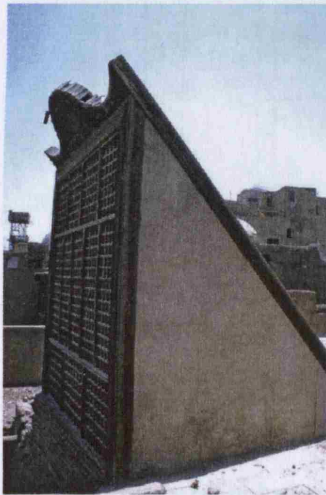


Figure 22, Mulqaf at Al Suhaymi house- Cairo, Egypt. Source Aga Khan visual archive, MIT, [http://archnet.org/library/images/one-image.tcl?image\\_id=15938](http://archnet.org/library/images/one-image.tcl?image_id=15938). Retrieved 7.08.2005.



Figure 23, Badgir (wind tower) at Aqazadeh's house- Abarghu, Yazd. Source: <http://www.yazd.com/album/017.htm>. Retrieved 7.08.2005.

## 2.3 BRIEF REVIEW OF OTHER RELATED WORKS

### 2.3.1 TRADITIONAL APPLICATION OF WINDCATCHER PREREVIEW

The following discusses two major papers in the area of study; they dealt with the traditional design of evaporative cooling wind catchers, and established a method for determining the tower cross-section area and height according to the needed air flow, cooling loads and ambient conditions. The results of these studies will be used to estimate the tower cross section of the study case.

#### *An improved design of wind towers for natural ventilation and passive cooling, (Bahadori, 1985):*

The author investigated the disadvantages of the conventional design of the wind catcher, and proposed an improved design (Figure 25) to reduce these weaknesses.

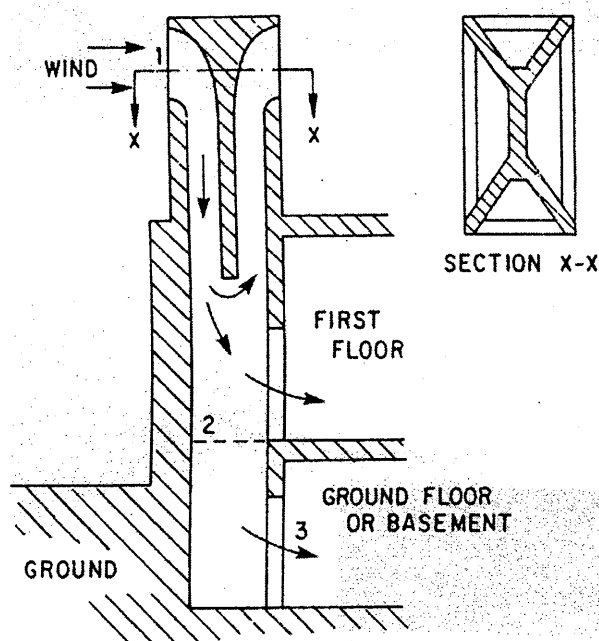


Figure 24, Air flow pattern in a conventional wind tower. Source: Bahadori, 1984.

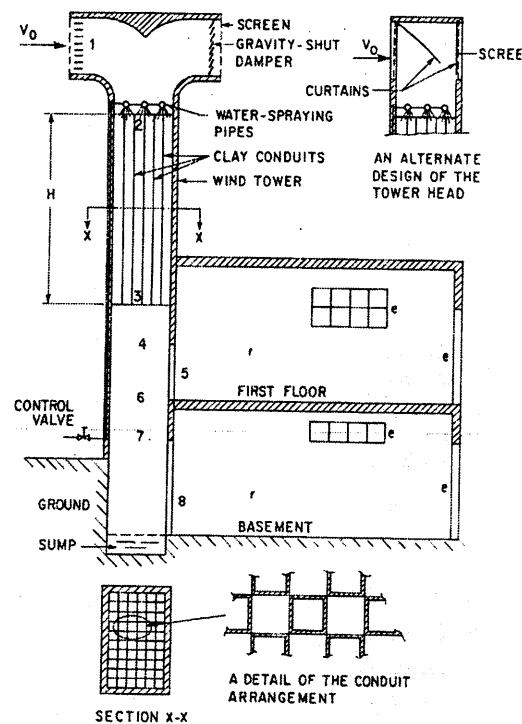


Figure 25, Details of the improved design of wind tower by Bahadori. Source: Bahadori, 1984.

The improvement included tower head modification to allow the wind from any direction and prevent it from escaping from other openings with negative pressure coefficient. This is to be achieved by using dampers or durable curtain material hung behind large opening screen. The latter stops birds and large insects from entering.

In addition, designing energy storing system which maximizes the heat transfer surface area using 10mm thick, baked, unglazed clay conduits of 100mm outside dimension could be rectangular or circular, total number of conduits is  $50/\text{m}^2$  of the tower cross-section.

Finally, utilizing evaporative cooling by spraying water over the clay conduits.

The proposed design was theoretically analysed by manual calculations under different hot arid climate conditions in which Jordan/ Amman climate was included assumed to have  $36^\circ\text{C}$  dry bulb temperature,  $21^\circ\text{C}$  wet bulb temperature and  $5\text{m/s}$  wind speed. The analysis included fluid flow, heat transfer, energy storage, mass transfer and evaporative cooling.

The researcher comes to the conclusion that the design managed to bring about higher air flow and less dust into the building using the evaporative cooling, Figure 26.

While the energy storage system coped to produce a very little improvement to the thermal conditions, (Figure 27). These conclusions based on metabolic rate of 1 Met and clothing level of 0.5 clo.

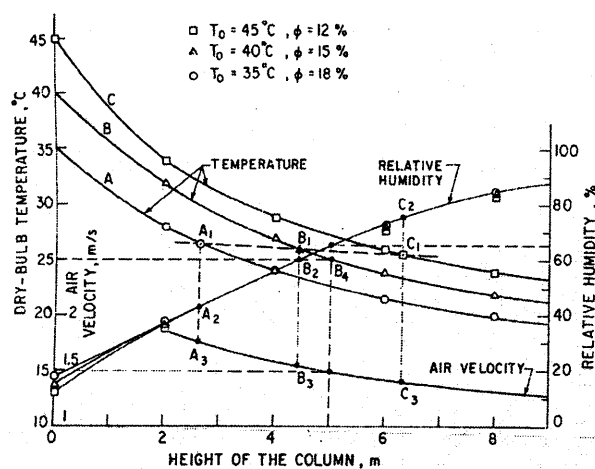


Figure 26, Dry bulb temperature of air leaving the evaporative cooling column as a function of column height, ambient temperature and humidity for a wind velocity of  $5\text{ m/s}$ .  $T_0, \phi_0$  indicates the ambient air temperature and humidity. Source: Bahadori, 1984.

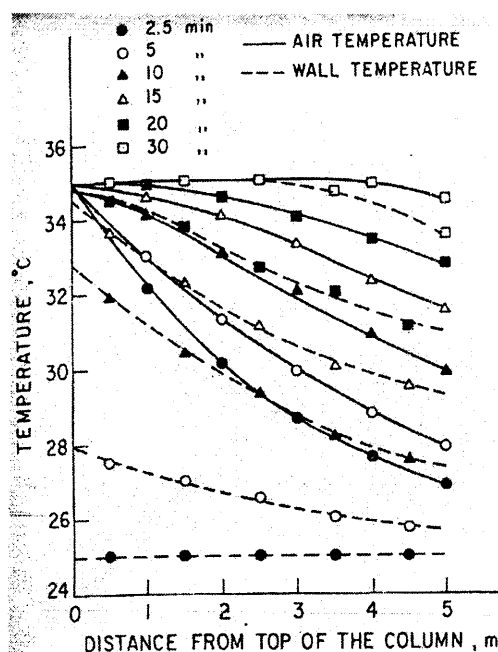


Figure 27, Variation of air and wall temperatures in the non wetted column as a function of time and column height for a wind velocity of  $5\text{ m/s}$ . Source: Bahadori, 1984.

The points A1, B1 and C1 Figure 26 indicate the minimum tower height which maintain the thermal comfort of occupant, these points were determined by using the comfort chart and by trial and error.

The author drew attention to system control:

- controlling the evaporative cooling by changing the rate of water sprayed on the clay conduits, and
- controlling the airflow when partial or no cooling loads demand like in winter seasons by controlling the amount of water sprayed which causes downdraught, then by closing the opening between the tower and the occupied spaces.

The author represented solved example to estimate the size of the tower in accordance to air flow needed and using the psychometric chart, this example will be followed literally to estimate the study case tower dimensions.

***Performance of cool towers under various climates in Jordan, (Badran, 2003):***

Badran studied the performance of the improved cool tower model developed by Bahadori (1985) under the different climatic region in Jordan, i.e. hilly areas, desert areas, Jordan valley (Ghor) and Aqaba gulf. The author used four openings cool tower of  $(1 \times 1) \text{m}^2$  cross-section, filled with conduits of circular cross-section and made of 10mm thick, baked, unglazed clay of 100mm outside diameter, total number of conduits is  $50/\text{m}^2$  of the tower cross-section, Figure 28.

The paper theoretically analyzed the fluid flow, heat transfer, energy storage, mass transfer and evaporative cooling of the tower by manual calculations.

It concluded that as the tower height increases the relative humidity increases while both of the air velocity and dry bulb temperature decreases at the outlet of the tower until the 9m height, where tower height H is the part of the tower filled with clay conduits, Figure 29 illustrates this conclusion in hilly climate condition of  $32^\circ\text{C}$  dry-bulb temperature, 39% relative humidity and 4m/s wind speed. The same conclusion is applied to the different climate regions in Jordan. The paper suggested that it is feasible to reduce the height less than 9m without obvious fall in the physical performance of the tower.

The researcher suggested that as the tower height increases beyond 4m, the reduction in the dry bulb temperature at the outlet is small, and proposed that tower height of 4m can perform rather acceptable performance and save extra cost for the higher tower.

The tower cross section was taken  $1 \times 1 \text{m}$  as a unit area, based on that the designer can figure out the needed tower cross section for the required flow rate of air. The unit flow rate of air ( $\text{m}^3/\text{s}$ ) for a certain tower height is the product of the outlet velocity of air taken from the related graph by the unit cross section ( $1 \text{m}^2$ ). Thus, the required cross sectional area for the same tower height equals the required flow rate divided by the unit flow rate. (Badran, Ali [badran@ju.edu.jo](mailto:badran@ju.edu.jo), 03 July 2005, RE: Tower cross section calculations. e-mail to Al Asir, R [r\\_alasir@yahoo.co.uk](mailto:r_alasir@yahoo.co.uk)).

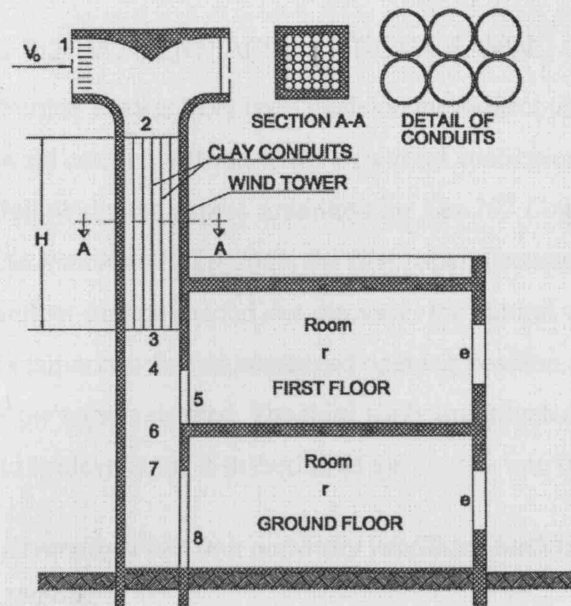


Figure 28, Cross section of a typical cool tower. Source of both figures: Badran (2003).

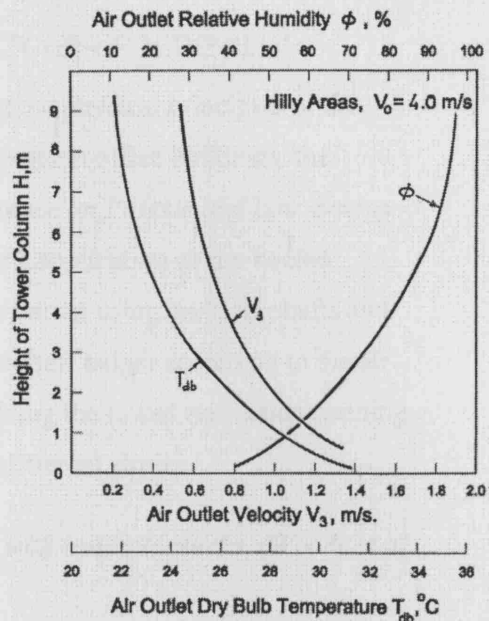


Figure 29, Air outlet velocity, dry-bulb temperature and relative humidity in relation to the height of tower column for hilly climate.

Givoni (1997), developed shower tower passive cooling system and test it by experiments under different climates, the cooling system he used consists of an open shaft with showers at the top and a collecting the extra water in at pond in the bottom and re-pump it from the bottom.

The performance of the system was examined in Los Angeles/ mild climate, Yokohama-Japan/hot humid climate, Riyadh-Saudi Arabia/ hot dry climate.

The performance was analysed by the temperature drop of the air exiting from the shaft relative to the ambient WBT depression, and the generated air flow rate

The researcher pointed to the insulation of the shaft; when the shaft located within the cooled area or outside but with good insulation the heat gain could be neglected, but when the outside shaft is un-insulated the height of the tower should be increased to neutralize the effect of the heat gain.

The test show similar results using portable, sea or brackish water.

The relative temperature drop increased when shower height increased. In Riyadh, the shower was tested on an elongated building consists of five rooms (3.6x3.6x3) m of high mass and insulated walls, shower height of 4 m (above pond's water) resulted in and indoor temperature of 28°C while the external temperature is 40°C

### 2.3.2 MODERN APPLICATION OF WIND CATCHER PREREVIEW

Further studies have been made on the subject using the physical principles of the wind catcher with stack driven natural ventilation shafts in office buildings, the following two papers submitted for *The 20<sup>th</sup> Conference on Passive and Low Energy Architecture-PELA 2003*, the first paper discusses the application of pre-cooled inflow-air, the second one discusses the natural ventilation using multiple shafts and summarizes the recommended opening position and shaft height according to the air flow regime desired. The third study investigated sizing the tower ventilation opening to achieve equal distribution of air flow-in into the different stories.

***Reversing Flow in a naturally ventilated building with multiple stacks, (Woods et al 2003-b):***

This paper studied the air flow of natural ventilation of office building when air is pre-cooled and supplied from central atrium, which creates enough pressure to drive air into the floor space, then the air is heated up and the exhausted through stack shafts at the outskirts of the building. The researchers investigated the possibility of using pre-cooled air while using natural ventilation to reduce the energy cost in summer and in spring-autumn. The study was carried out by simplified quantitative modelling and laboratory experiments.

The paper analysed the pressure profiles in the building compared to the outside, it consider the flow through a single floor as U-tube, and examine the pressure differences in the case of mild and hot climates. Figure 30 and Figure 32 illustrate the mild climate where the out flowing air is warmer than the exterior and the heating load in the occupied spaces is greater than the pre-cooling load; the pressure differences between the atrium inflow and the air in the out flowing stack is greater than the pressure between the atrium inflow and the exterior. This pressure difference enhances the natural ventilation by the up-stream of warm air through the outflow stack, Figure 32 also shows that the pressure difference is greater when the inflow atrium height is smaller than the out flow stack.

Figure 31 and Figure 33 illustrates the case when the temperature of the out flow stack is less than the temperature outside, in the case of hot weather or when pre-cooling load is greater than the heating load, then the air flow in the stack shaft will restrain the ventilation as the pressure in the outflow column is greater than the



pressure in the ambient air temperature. Consequently, the ventilation will be reduced comparing to that in the case of natural ventilation through opening in the base of the building. In this case if the height of the atrium is smaller than the out flow stack, this will suppress the ventilation as the air goes up against the gravity.

Figure 34 and Figure 35 demonstrated that the ratio of inflow conditioning air to the volume flux if there is no cooling and temperature of the space depend on the rate of pre-cooling to the heat gain, as this ratio increased the ventilation stops, the space becomes inadequately ventilated and cold,

The researchers concluded that the U-shape air flow path is powerful mean of ventilation as long the exterior temperature is lower than the out flow air.

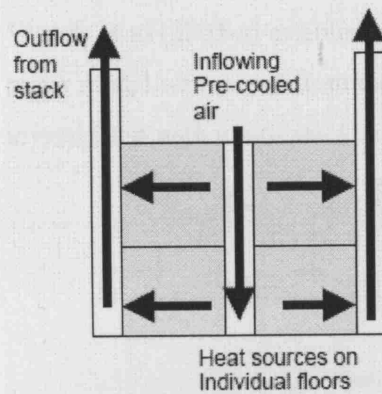


Figure 30, Building form for conditions where external temperature is close to the comfort conditions.

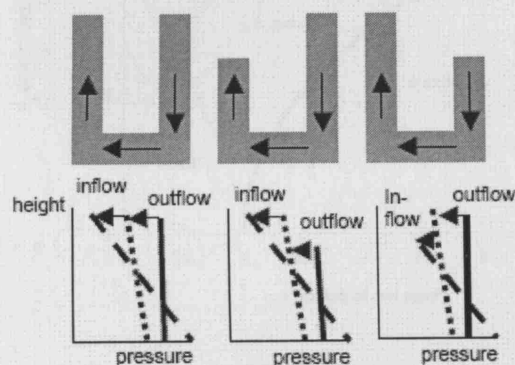


Figure 32, Heat load in occupied spaces is greater than the pre-cooling loads.

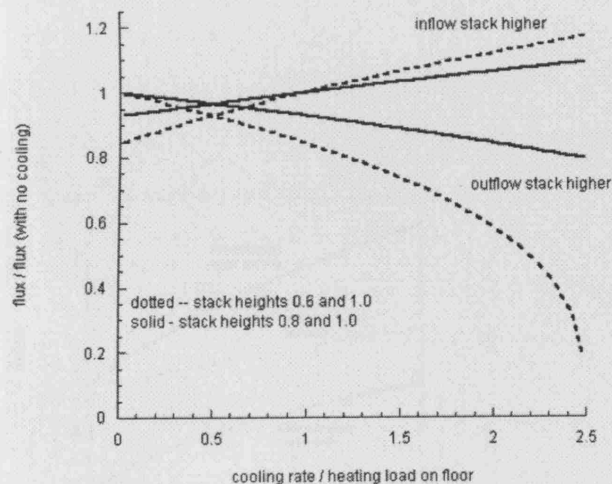


Figure 34, ventilation flow volume flux compared to the volume flux when there is no pre-cooling as a function of the degree of pre-cooling, shown as a fraction of the degree of pre heating / the different curves correspond to stacks which are high than or lower than the atrium, as labelled on the figure.

All above figures source: Woods, A (2003-b).

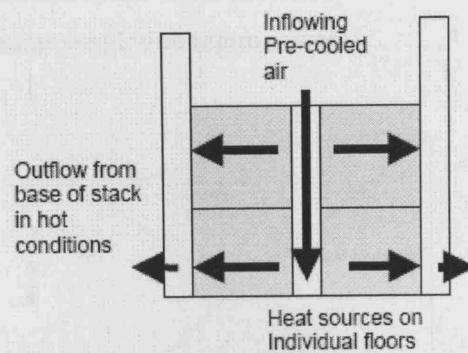


Figure 31, Ventilation strategies for hot external conditions with pre-cooling in top of stack.

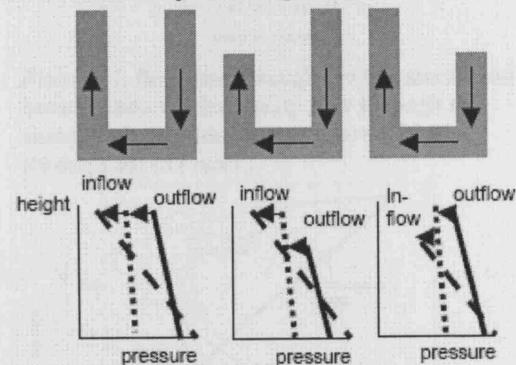


Figure 33, Heat load in occupied spaces is smaller than pre-cooling loads.

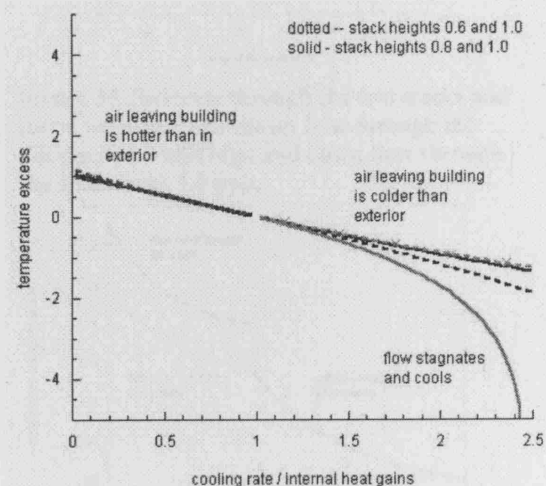


Figure 35, Temperature of out flowing air relative to the exterior temperature shown as a function of the cooling rate as a fraction of the heating rate.

Woods et al (2003-a) established further studies, the atrium space in the previous paper model was closed from the top and different natural ventilation regimes were investigated with multi- stack and lower opening.

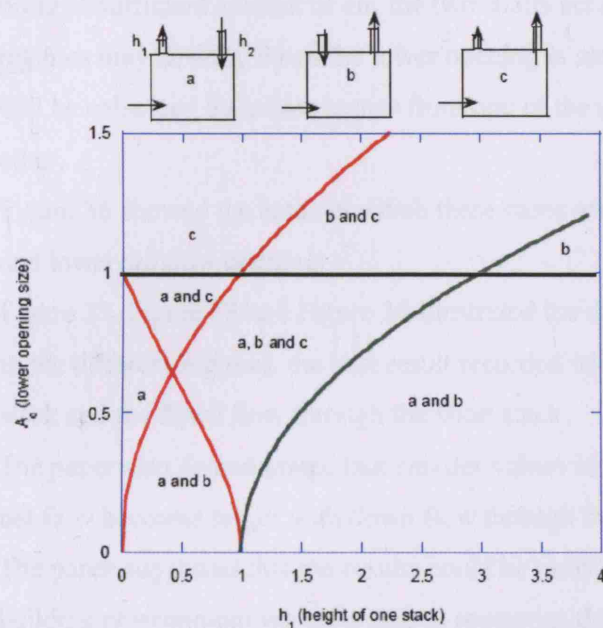


Figure 36, Diagram illustrating the different flow regimes which could be applied according to different lower opening area  $A_0$ , and the height one of the stacks  $h_1$ .

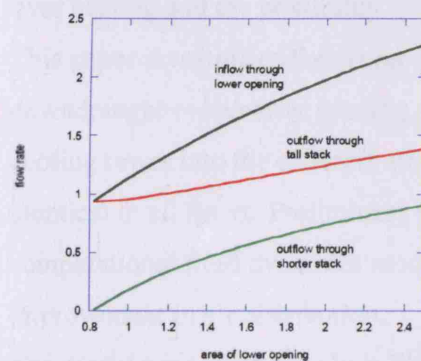


Figure 39, flow rate through the two stacks and lower window when the up flow both stacks, the transitions in regimes occur when the flow through one of the stacks falls to zero.

All above figures source: Woods, A (2003-a).

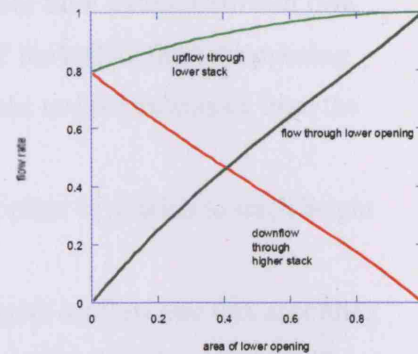


Figure 37, flow rate through the two stacks and lower window when the up flow through the short stack, 1.0 unit high and down flow through the tall stack.

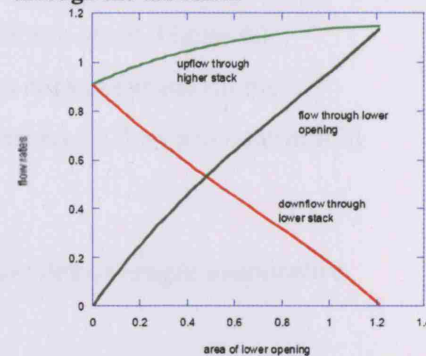


Figure 38, flow rate through the two stacks and lower window when the up flow through the tall stack, 1.5 unit high and down flow through the short stack 1.0 unit.

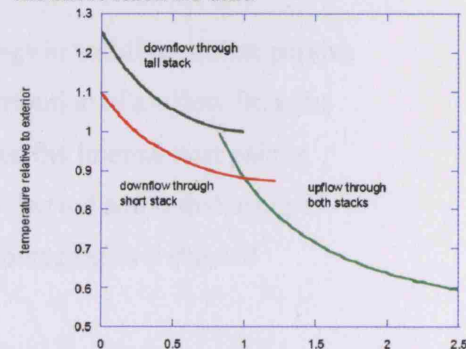


Figure 40, Temperature relative to exterior as function of the area of lower opening for the three flow regimes.

The study was carried out by simplified quantitative modelling and laboratory experiments.

The results of the experiments showed that when the lower window is big enough to bring in sufficient amount of air, the two shafts act as out flow stacks. Different flow regimes may develop when the lower opening is small; the inflow from the opening will be enhanced by inflow comes from one of the stacks and the exhausted from the other.

Figure 36 showed the areas in which these cases are applied in relation to stack height and lower window opening.

Figure 37, Figure 38 and Figure 39 illustrated the different air flow and flux according to the different regimes, the best result recorded when the up flow through the tall stack and the down flow through the short stack.

The paper also demonstrated that smaller values of the area of the lower opening, the net flow becomes larger with down flow through the shorter stack, Figure 40.

The paper suggested that the results could be used for a control system for the building environment which is able to recognize the desired air flow and control it by opening or closing the stacks.

***Sizing of ventilation openings in buildings with passive downdraught evaporative cooling, (Cook et al 2000):***

As the evaporatively-cooled air flows down the cooling tower, it drives more air flow into the lower openings leaving the upper ones with the risk of poor ventilation and over heating and the possibility.

This paper investigates the sizing of ventilation openings in buildings utilize passive downdraught evaporative cooling, to ensure equal distribution of air flow from the cooling tower into the different storeys, especially when the internal heat gain is identical in all floors. Preliminary sizing equation was derived and tested using a computational fluid dynamics model; results were encouraging as it showed improvement in air distribution.

The model used for the study is illustrated in Figure 41.

The equation could be used when there is no air flow through the top of the exhaust stack.

$$\text{Sizing equation: } \frac{\frac{1}{A_{in(i)}^2} + \frac{1}{A_{out(i)}^2} + \delta}{\frac{1}{A_{in(n)}^2} + \frac{1}{A_{out(n)}^2} + \delta} = \frac{[M - (i-1)H] + \lambda(i-1)H}{[M - (n-1)H] + \lambda(n-1)H}$$

Where:  $\delta$  represents the effective opening area of the inlet opening at the top of the capture zone and the outlet from the exhaust stack,

$$\lambda = \frac{T_{occ} - T_{amb}}{T_{PDEC} - T_{amb}} \text{ where } T \text{ stands for temperature and the subscripts occ: for occupied space, PDEC for capture zone and amb for the ambient temperature,}$$

$i$  is storey code number,  $n$  is number of floors,

$A_{in(i)}$  is the effective inlet opening area into the  $i$ th storey from the capture zone,

$A_{out(i)}$  is the effective opening area of the outlet from the  $i$ th storey (includes perimeter space and bulkhead duct),

$M$  is height of the PDEC capture zone and  $H$  is height of each storey.

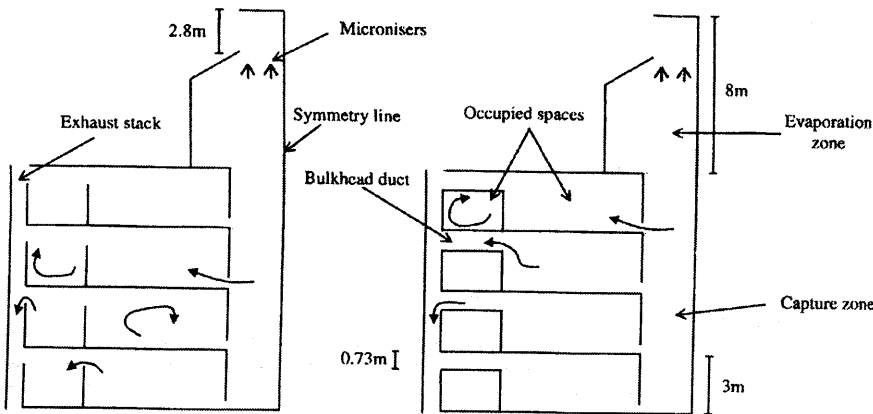


Figure 41, Sections through the PDEC building used for the study.

#### *As a conclusion from these papers;*

In hot countries, higher out flow stack will stall the ventilation while increase the height of the inflow shaft will increase the cold dense air driven down, and the flow will enhanced by making the outflow at the base of the floor. The area of this low outflow opening should be studied carefully as big outflow could stall the down flow through the intake shaft. At last, the size of tower ventilation openings should be calculated to ensure adequate ventilation for all floors.

### 3 CHAPTER 3: THE METHODOLOGY

In order to have thermal assessment tool, summer-Jordan comfort zone is produced and plotted on spreadsheet.

The passive cooling techniques are plotted on spreadsheet to investigate the potential strategies for Jordan summer ambient conditions.

Weather Tool software of Square One is used to analyse the prevailing wind pattern according to Amman weather file-1995.

The building regulation is reviewed to set the design parameters for the study case.

The thermal performance of the base case is simulated using TAS software to estimate the rate of cooling and the cooling peak load required to achieve 27°C internal temperature.

Rate of cooling is used to estimate the air flow required to bring the pre-cooled air from the tower into the spaces using the equation:  $\text{Rate of Cooling} = \rho V C_p \Delta T$

The graphs produced by Badran and Bahadori based on the weather condition are used to approximate the condition of air leaving the evaporative column for a certain tower height then using the psychrometric chart to calculate and corresponding air density and enthalpy. Using the peak cooling load from TAS-base model and the air flow calculated above; the enthalpy of the internal spaces is calculated from the equation:

$$Q = \rho_e V_e (h_i - h_e)$$

Then using the sensible ratio to set an assumption of the *expected internal conditions*.

Afterwards, plotting the internal conditions for different tower height on Jordan-summer comfort zone to determine *tower height* which achieves the appropriate conditions. 6m tower high is believed to bring about acceptable internal conditions.

Using the velocity of air leaving the evaporative column for the selected tower height and air flow needed, with the assumption that the velocity of air leaving the evaporative column will be the same in case of different tower section and different air flow, *tower cross section* is calculated using the equation  $V = v \times A$

Then, using the equation  $V=v \times A$ , the air flow required for all floors and the wind speed to determine the *tower inlet size*.

Using the air flow required for single floor and the velocity of air leaving the evaporative column to calculate the *tower outlet size* of the third floor.

Using the sizing equation with some assumption to adjust the equation to the study case for the purpose of lower opening sizes estimation.

An assumption is made that the tower outlet size is equal to the floor discharge opening (high window).

The thermal performance of the office building with PDEC tower is simulated by TAS software for equal ventilation opening, sizing ventilation opening and better roof insulation for 6m tower high. The evaporative cooling is simulated by assuming air conditioned zone in the tower with temperature and humidity as extracted from the chart for the relevant tower height.

The best model results are compared with the calculated internal conditions and plotted on summer comfort zone of Amman, dehumidification is suggested to bring the conditions to the thermal zone.

Adopting the best model (3), further TAS simulation is run using different evaporation tower heights (2→9) and the corresponding parameters for the air condition space representing the evaporative column. Using air flow-in from TAS and the psychrometric chart to calculate moisture added to the ambient air, the water consumption per hour is calculated and plotted with the internal temperature as a function of tower height.

At last, comparison of air outlet velocity as a function of tower height is made between TAS results and the graphs used in the calculations.

Thermal comfort assessment tools		
Amman summer comfort zone is produced to assess the internal thermal conditions.	Passive cooling strategies and Amman comfort zone are plotted on spreadsheet to investigate the possible passive strategies	Wind analysis using the Weather Tool software of Square One Amman weather file-1995

Study case design parameters		
Building regulation review	Base case design hypothesis based on regulations and construction method likely to be used.	PDEC model assumption based on previous researches.

Evaporative column hypothesis/ trial and error		
Expected internal conditions: -TAS base-case simulation -Badran & Bahadori graphs -psychrometric chart	Evaluation of the expected internal conditions using summer comfort zone-Amman	Determining tower height and the parameter represents the condition of air leaving evaporative column to be used in TAS

TAS simulation		
Model 1: equal ventilation opening	Model 2: sizing ventilation opening	Model 3: sizing & improved roof insulation
Comparing the TAS internal results with the assumption made by calculation.		
Plotting the best results (model-3) on summer comfort zone-Amman		
TAS simulation for evaporative tower height 2→9		
TAS & psychrometric chart to calculate water consumption		



## 4 CHAPTER 4: THERMAL COMFORT

### 4.1 REGULATIONS:

CIBSE Manual (1997, p.17) summarizes the variables determining thermal comfort by the physical parameters; air temperature, mean radiant temperature, humidity and air speed, besides the behavioural parameters such as clothing level and metabolic rate. Air movement, at high indoor temperatures, generates better feeling of thermal comfort and better satisfaction with the internal conditions, the cooling potential for natural ventilation per floor area for different temperature differences between inside and outside and according to flow rate per person is illustrated in Figure 42 provided that occupant density is  $1 / 10\text{m}^2$ . It shows that the ventilation rate needed for cooling is much more than that needed for fresh air control of 8 l/s to control body odour according to CIBSE.

Figure 43 shows the resultant temperature as a function of air temperatures, mean radiant temperature and air speed. The resultant temperature takes into account the effect of radiant heat exchange with the surroundings, and gives better perception of body comfort “since radiant temperature counts for approximately half of the body’s heat exchange”, CIBSE TM4: 1990. For this reason the resultant temperature will be considered in the analysis of the results.

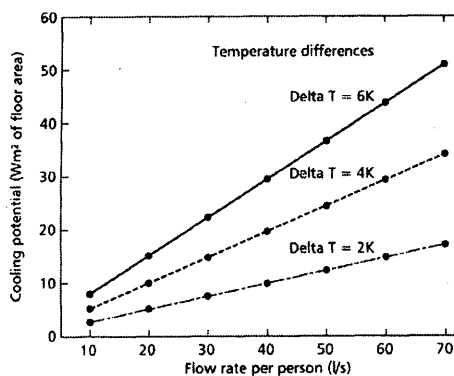


Figure 42, The cooling potential of ventilation.  
Source: CIBSE Application Manual 1997.

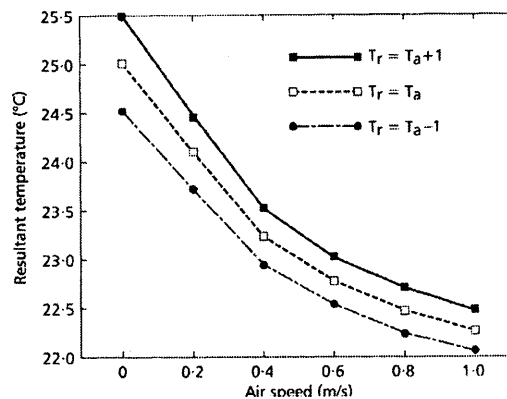


Figure 43, Resultant temperature in relation to air temperature, mean radiant temperature and air speed where  $T_r$  is radiant temp,  $T_a$  is air temp. Source: CIBSE Application Manual 1997.

## 4.2 THERMAL COMFORT CHART:

In this chapter, summer comfort zone for Jordan is produced; then, passive cooling strategies are plotted with the comfort zone in spreadsheet in order to prepare a thermal assessment tool. Afterwards, summer weather data is plotted on the chart to investigate the possible passive solutions.

### 4.2.1 JORDAN-HOTTEST MONTH COMFORT ZONE:

The comfort zone is effected by three variables as defined by Szokolay (2004),

Environmental, personal, and contributing factors,

The environmental includes air temperature, air movement, humidity and radiation.

The personal includes metabolic rate, clothing, state of health and acclimatisation.

While contributing factors include food and drink, body shape, subcutaneous fat, age and gender.

As human body is active component in the environment, the neutrality temperature (the norm of peoples' votes) changes with the mean temperature, consequently, the comfort zone changes.

Summer month	June	July	August	September
Monthly mean temperature °C	22.35	24.11	24.18	22.61

Table 2, Jordan weather data 1995.

August has the highest mean temperature value, therefore, August is chosen to represent the warmest month, and its comfort zone was drawn according to Szokolay (2004) equations:

August outdoor average temperature  $T_{o,ave} = 24.18$  °C.

Thermal neutrality  $T_n = 17.6 + \{0.31 \times T_{o,ave}\}$

$T_n = 17.6 + 0.31 \times 24.18 = 25.1$  °C

The upper and lower comfort limits  $T_U$  and  $T_L = T_n \pm 2.5$ °C.

$T_L = 25.1 - 2.5 = 22.6$  °C

$T_U = 25.1 + 2.5 = 27.6$  °C

To define the side boundaries of the comfort zone, these temperatures have been marked on 50% RH curve, and the side boundaries have been drawn corresponding to SET lines.

SET lines, defined as the Standard Effective Temperature, combined the effect of temperature and humidity; i.e. the higher the humidity is the lower temperature is acceptable, and the lower the humidity is the higher temperature is tolerable.

Then, the top and bottom limits of the comfort zones are defined by the humidity limits of 12 and 4 g/kg respectively. Figure 45 illustrates August comfort zone in Amman plotted on the psychrometric chart of Szokolay (2004, fig.1.14)

However, August comfort zone was plotted again on the psychrometric chart of Amman (Alsaad and Hammad 2001, fig.A-1). This chart takes into account the air pressure of the city (city elevation 980m). The following steps were followed to set the SET-lines as described in Szokolay (2004, p:278)

Knowing,

$$T_{o,ave} = 24.18 \text{ }^{\circ}\text{C}.$$

$$T_n = 25.1 \text{ }^{\circ}\text{C}$$

$$T_L = 22.6 \text{ }^{\circ}\text{C}$$

$$T_U = 27.6 \text{ }^{\circ}\text{C}$$

Next, to define the side boundaries of the comfort zone, the SET line slopes was constructed:

- Using the chart; the absolute humidity  $AH_{50}(T_L) = 9.5\text{g/kg}$  and  $AH_{50}(T_U) = 12.5\text{g/kg}$
- Determining the x-axis intercept points

$$T_{Umax} = T_U + \{0.023 \times (T_U - 14) \times AH_{50}\}$$

$$T_{Lmax} = 27.6 + \{0.023 \times (27.6 - 14) \times 12.5\} = 31.51^{\circ}\text{C}$$

$$T_{Lmax} = T_L + \{0.023 \times (T_L - 14) \times AH_{50}\}$$

$$T_{Lmax} = 22.6 + 0.023 \times (22.6 - 14) \times 9.5 = 24.5 \text{ }^{\circ}\text{C}$$

The lines connecting  $T_{Umax}$ ,  $T_U$  and  $T_{Lmax}$ ,  $T_L$  define the side boundaries of the comfort zone,

Then, the upper and lower boundaries are defined by the 12 and 4 g/kg absolute humidity, refer to Figure 46.

When comparing the two comfort zones, the second one, which is plotted on the Amman psychrometric chart, is slightly shifted down and covers less humid areas with almost the same temperatures when compared to the first chart. The second chart will be adopted for thermal conditions assessment.

#### 4.2.2 PASSIVE COOLING STRATEGIES

In order to have general guidance for the adaptive cooling strategies necessary to accommodate Jordan climate envelope, Givoni's building bioclimatic chart is used. The chart shows the relationship of the various physical conditions that manipulate human comfort; i.e. air temperature, mean radiant temperature, humidity and air speed, by which most of the people feel comfortable.

Milne and Givoni (1979) incorporated strategies to expand the accepted thermal conditions through the difficult ambient conditions.

For the purpose of the study, the cooling strategies; i.e. thermal mass, evaporative cooling, night, natural and mechanical ventilation are considered and plotted with Jordan summer comfort zone using spreadsheet.

Weather data, dry bulb temperature and relative humidity were taken from Jordan weather data 1995 available in Meteoronorm program files.

Then, plotting summer season, i.e. June, July, August and September, on the psychrometric charts to visualize the climate condition for each month and to show the appropriate technique to bring the ambient conditions to the comfort threshold.

The strategies were drawn with the guidance of the charts of Milne and Givoni (1979) and Bio-Climatic Design Central website.

Figure 44 shows the fluctuation in the external temperatures and relative humidity between day and night in typical hot day in August. The high thermal mass of building can take the advantage of the night breeze to cool the structure and dampen the fluctuation of temperature.

Figure 47 shows that most of the ambient conditions are located within the passive cooling strategies, natural and mechanical ventilation expand the comfort zone in the hot season, while thermal mass and night ventilation accommodates further extreme conditions.

The plot shows that the weather circumstances contained within evaporative cooling strategy could be substituted by natural and mechanical ventilation or high thermal mass cooling; this is an advantage when taking into account water shortage in Jordan. Some extreme conditions in July, August and September are behind all strategies. Other conditions in the early day and late night are within passive solar heating.

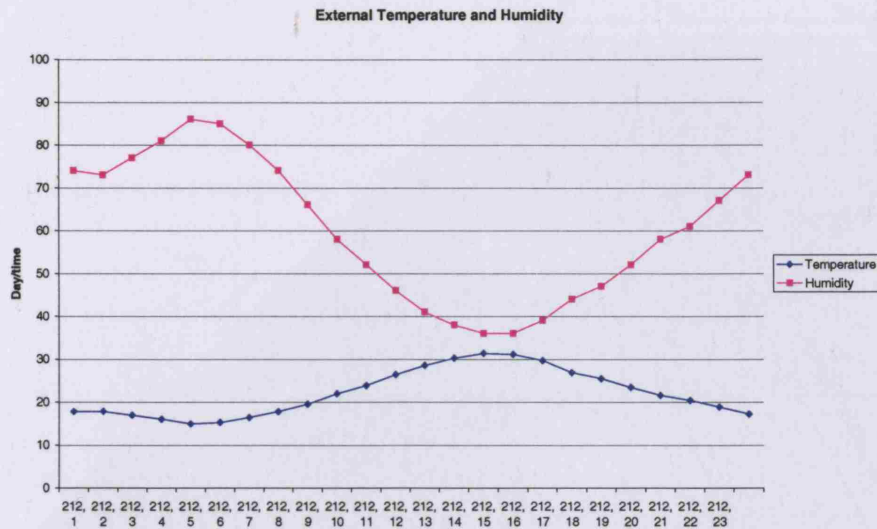


Figure 44, External temperature and humidity in typical August day-day 202.

#### 4.2.3 EVAPORATIVE COOLING PSYCHROMENTRIC CHART:

When air is evaporatively cooled, the energy needed to change the water into vapor is taken from the ambient temperature, so the surrounding air temperature is reduced.

The cooled air is generally close to 100% saturation.

The energy is constant as the heat is changed from sensible into latent, consequently, the evaporative cooling comfort zone moves along constant enthalpy, provided that sufficient amount of water is available, “the boundary is defined by the capacity of the volume of air that can be comfortably moved through the interior of the building” (Bio-Climatic Design Central). 13.88°C is the limit of the reduction in the ambient temperature which could be achieved with acceptable indoor air speed.

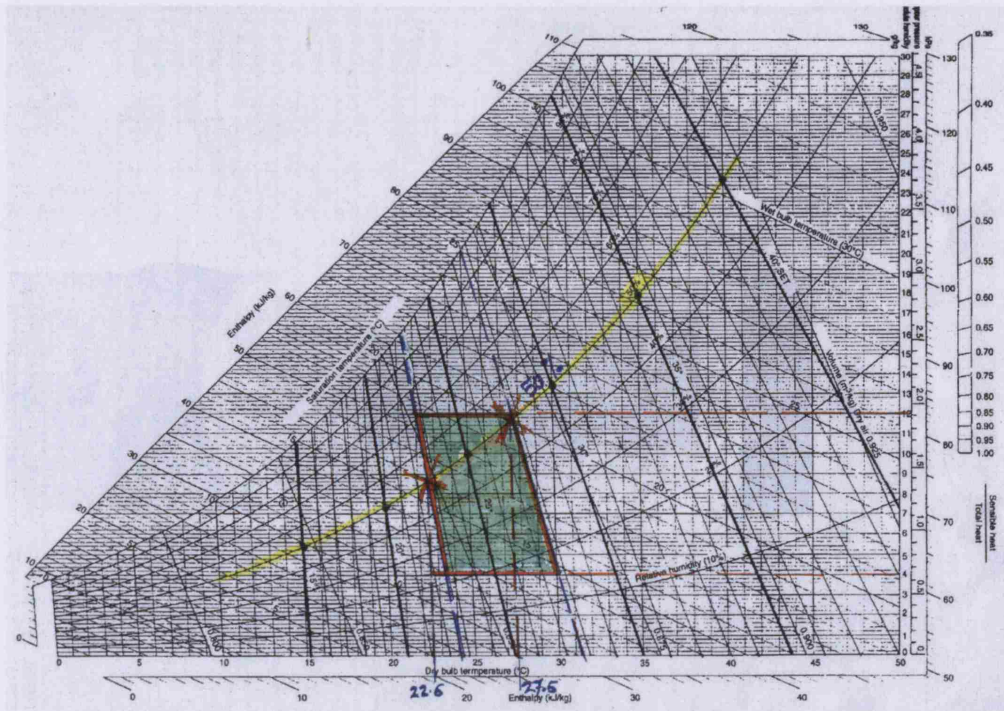


Figure 45, August comfort zone-Jordan plotted on Szokolay (2004) psychrometric chart.

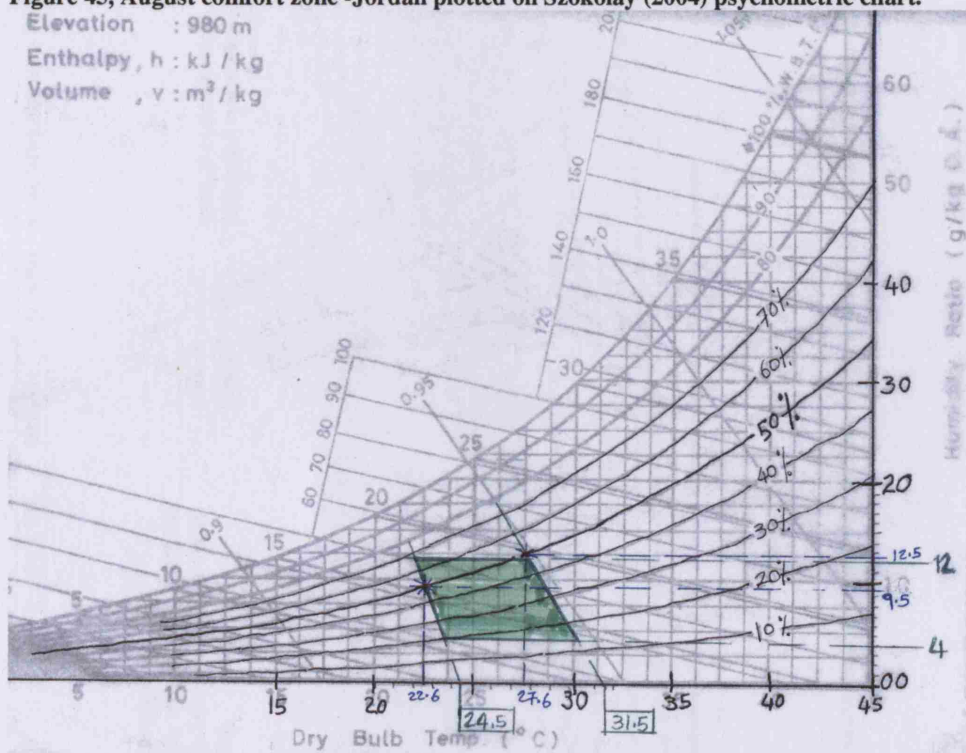


Figure 46, August comfort zone-Jordan, plotted on Alsaad and Hammad 2001 psychrometric chart.



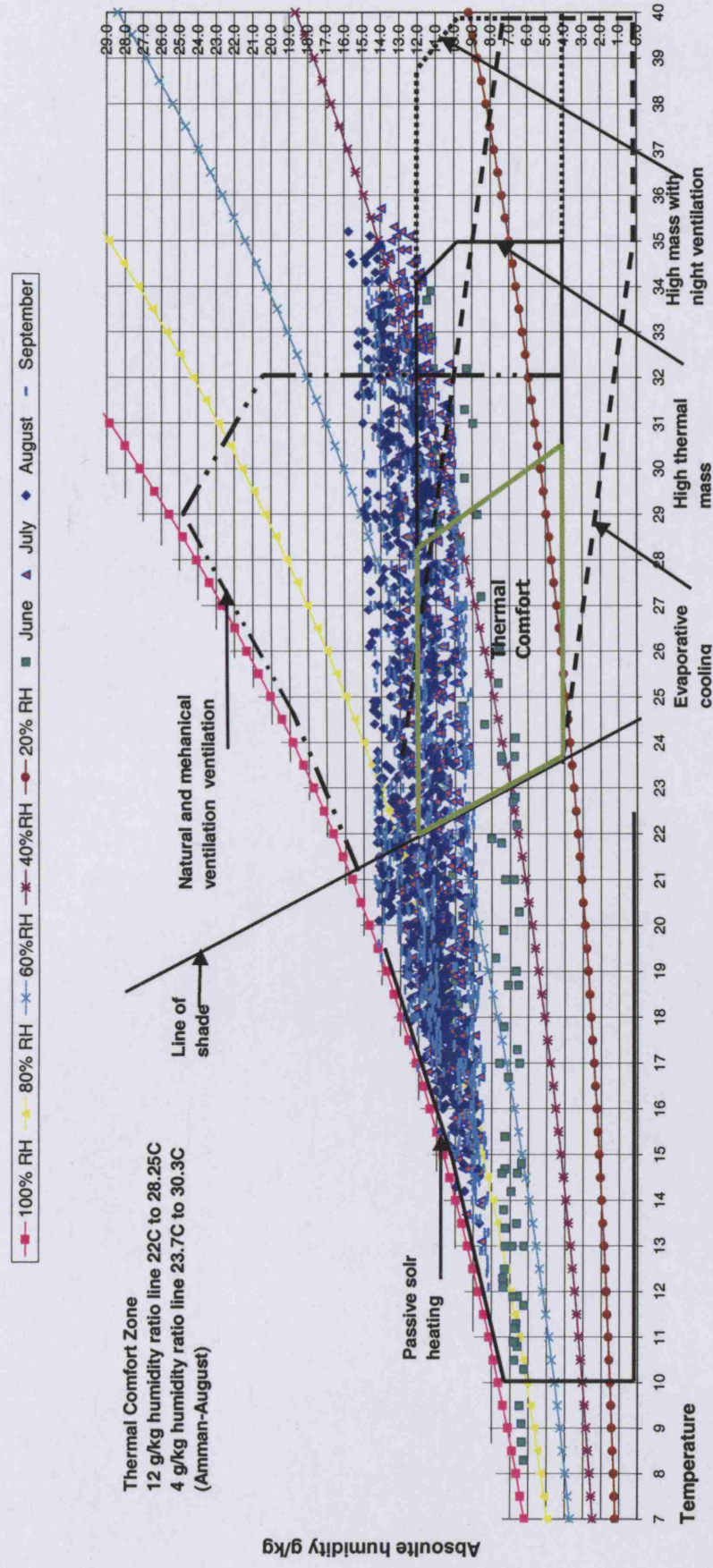


Figure 47, Jordan-summer weather condition plotted on Jordan summer comfort zone, cooling strategies have been added as suggested by Milne and Givoni.

### 4.3 WIND ANALYSIS

For general guidance, the Weather Tool of Square One website was used to analyse prevailing winds from Amman Weather file 1995.

Figure 48 summarizes the prevailing winds during the year; it shows that the higher intensity of the wind blows from the west, the rest comes from the south-west. This is applied for morning and afternoon wind.

Figure 49, demonstrates the frequency of the wind during the year measured in hours, the most frequent wind is between 10 and 15 km/h, that is 3-4 m/s.

The higher wind temperature, as shown in Figure 50, is from the west with small angle towards the north, while the cold wind from the south-west. The monthly analysis of the wind in Figure 51 shows that, summer wind of June, July, August and September is blown from the west with slight angle towards the north.

The weekly summary of wind performance is demonstrated in Figure 52; the x-axis presents the hours of the day, y-axis presents the weeks of the year while z-axis stands for wind speed measured in km/h. it shows that speed of the wind reaches its maximum during the day, around the afternoon, that means wind can be utilized for wind driven ventilation during the office working hours, while in the late/very early hours the heat can be flushed out through the shaft by the stack effect.



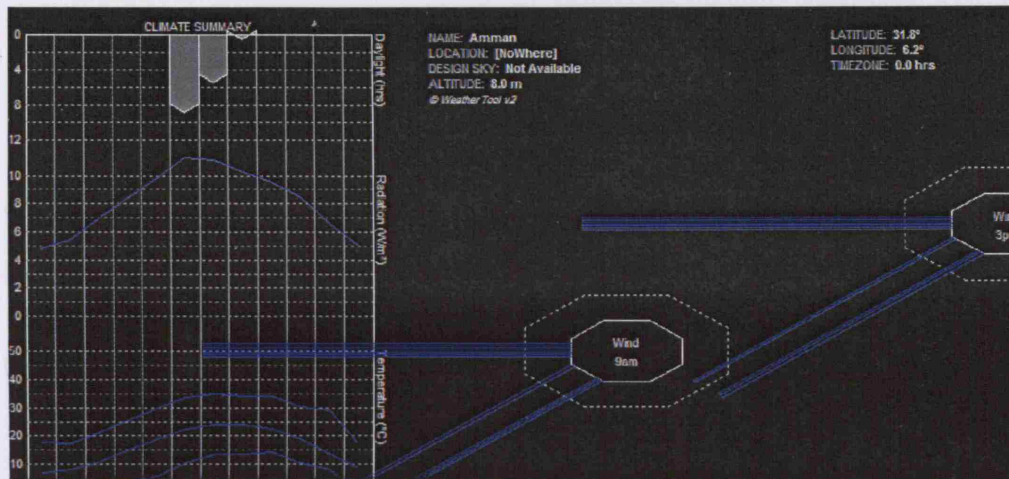


Figure 48, Prevailing winds summary for Amman-1995 year.

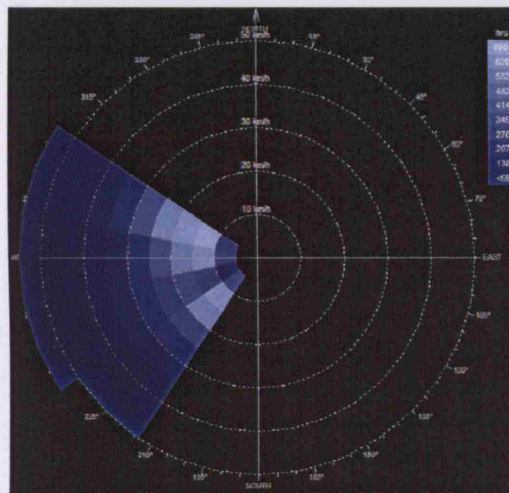


Figure 49, Prevailing winds, wind frequency/hours.

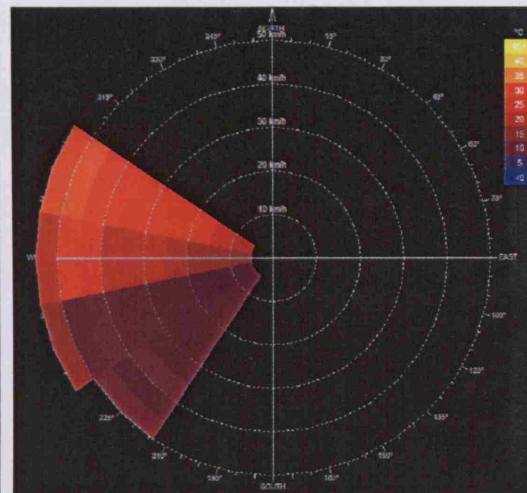


Figure 50, Prevailing winds, average wind temperatures.

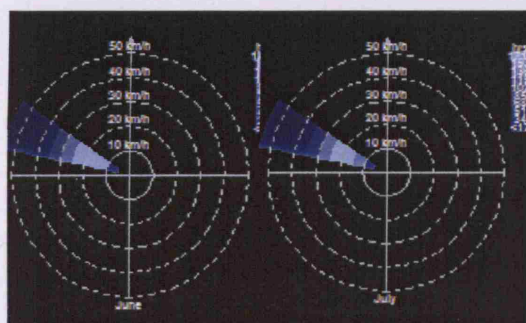
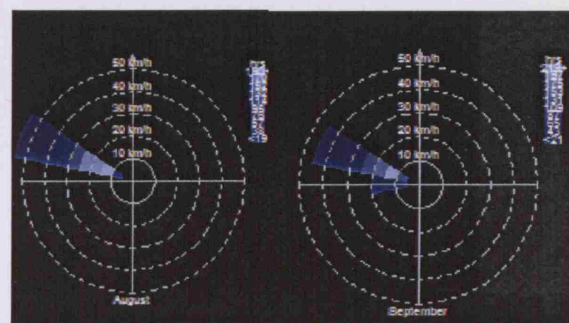


Figure 51, Wind frequency/hours, monthly analysis.



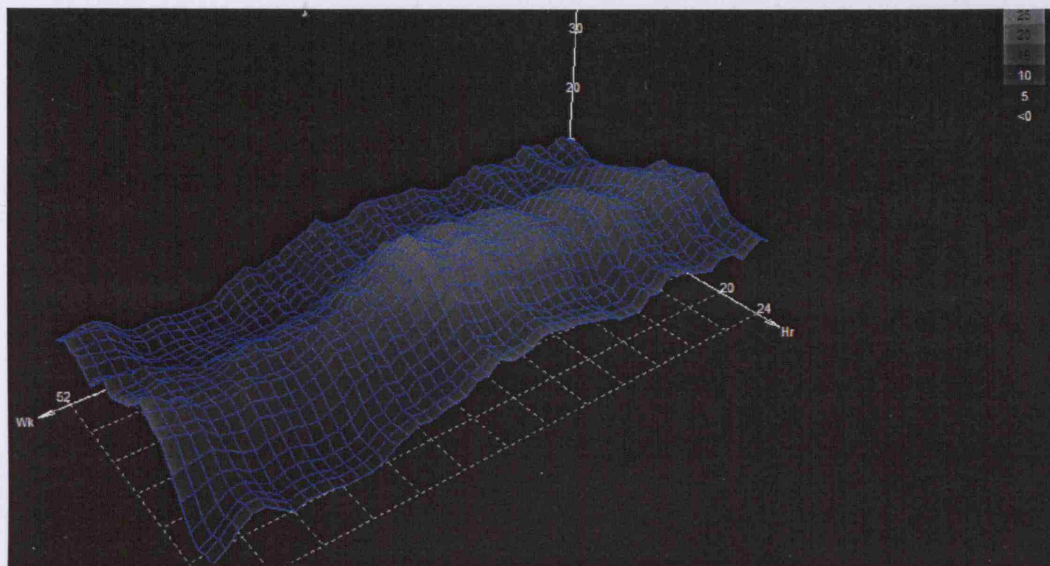


Figure 52, Prevailing winds weekly summery, average wind speed km/h.

The above images are obtained from the Weather Tool of Square One website, loading Amman weather file for the year 1995, <http://www.squ1.com/index.php?http://www.squ1.com/downloads/index.html#weath>

## 5 CHAPTER 5: STUDY CASE DESIGN PARAMETER FOR OFFICE BUILDING- JORDAN

This chapter presents the methodology of selecting the study case design parameters according to building regulations applied in Amman/Jordan.

The general regulation is reviewed, after that, rough design parameters are hypothesized according to assumptions based on building regulations of the municipality of greater Amman city. This includes the suggested plot area, percentage of allowed footprint, and number of floors ....etc.

Building element materials and construction method assumed are based on the vernacular methods for construction and the method likely to be used in modern office building construction.

Next, selecting the appropriate method of applying the wind tower to the base case building, taking into account the recommendation of the previous studies.

### 5.1 BUILDING REGULATION IN JORDAN

According to Legislation and Building Regulations for the Municipality of Greater Amman, the land usage within the regulated area is specified as follows<sup>2</sup>:

- a. Residential area, divided to sectors A, B, C and D.
- b. Green residence area
- c. Popular residence area
- d. Rural residence area
- e. Agricultural residence area
- f. Central commercial area
- g. Normal commercial area
- h. Local commercial area
- i. Industry area
- j. Light industry area
- k. Offices area. (Clause 27, Legislation no 67, 1979<sup>3</sup>)

---

<sup>2</sup> The following is literal translation of the regulations from Arabic,

These areas differ in land usage, plot area, the length of the plot side facing the street, the land regulations like the setbacks, building height, building percentage, number of car park needed...etc.

The 'offices area' follows the regulations of the residential sector of which the land follows. (Ibid, Clause 35(b)<sup>3</sup>).

That means the regulated plot (by municipality) as office area can be within residential or local commercial areas and then will follow the regulation of that area. Residential sector A regulation will be considered for the plot, Table 3 summarises the applicable regulations.

Regulations of sector A		
Item	Clause	Regulation
Max ground floor concrete level	2 <sup>3</sup>	1.25m from road level
Max roof floor area, excluding elevator and staircase areas	15(a-2) <sup>3</sup>	50m <sup>2</sup>
Roof floor highest point	15(a-1)	3.25m above lower floor
Last floor parapet height	15(c) <sup>3</sup>	$1 \leq h \leq 1.5$
Car parking	16(b)	Car per 100m <sup>2</sup>
Area per car- (way inclusive)	17	$\geq 25\text{m}^2$
Front setback	29(b-1)	5m
Side setback	29(b-1)	5m
Rear setback	29(b-1)	7m
Building percentage <sup>4</sup>	29(b-2)	%39 of plot area
Max number of floors	29(f)	4
Max bldg height from ground floor <sup>5</sup>	29(f)	15m
Min plot area	45(b-2)	1000m <sup>2</sup>
Min length of plot facing street side	45(b-2)	25m
Min clear head	57(a)	2.4m

**Table 3: Building regulation summary for residential sector A.**

<sup>3</sup> Modified according to Legislation no (21), issued on 21.03. 2005, index 4700, Revision Legislation for *Building Legislation and Regulations for Amman City*,

<sup>4</sup> Building percentage: the percentage of the building plan area to the plot area in which this building will be constructed on.

<sup>5</sup> Roof floor is excluded from the building height, according to the legislation definitions.

## 5.2 SUGGESTED ROUGH DESIGN PARAMETERS

### 5.2.1 THE GENERAL LAYOUT:

According to Table 3, a proposed sector A regulated area of  $25 \times 40 = 1000 \text{ m}^2$  plot's areas with 25m plot length facing the street was considered.

For the office,  $40 \times 40 = 1600 \text{ m}^2$  plot area was assumed, refer to Figure 53.

The allowed built area according to building percentage is  $1600 \times \%39 = 624 \text{ m}^2$ , while the allowed built area for the office plot according to the setbacks is  $30 \times 28 = 840 \text{ m}^2$ .

For that, the proposed building plan area will consider  $30 \times 20.8 = 624 \text{ m}^2$  and the rear setback will be increased, refer to

Figure 55.

The surrounding built areas are proposed according to the regulation stated in Table 1, which is the allowed building percentage compared to plot area and setbacks for each plot for the purpose of simulation.

Figure 54 shows the built area for each plot, the height of the building is considered 14.5m for computer simulation purposes.

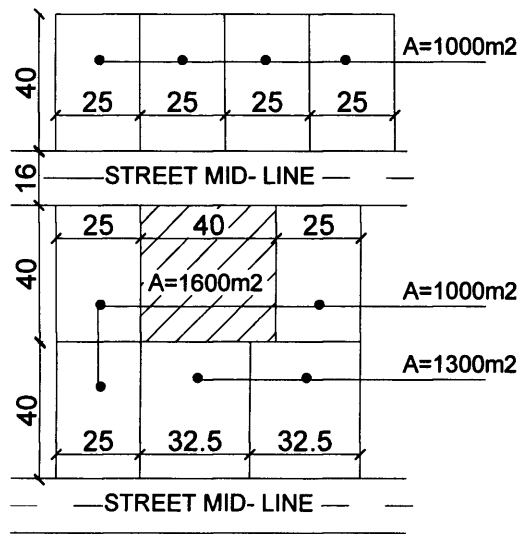


Figure 53, Proposed regulated land plots in Residential Sector A, plot areas are shown, the hatch indicates office plot, dimensions in meters.

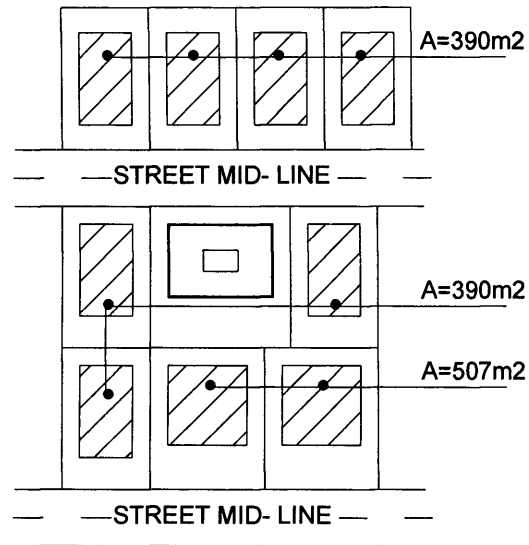


Figure 54, The surrounding building layout according to the maximum of the regulations; the hatch indicates the built areas.

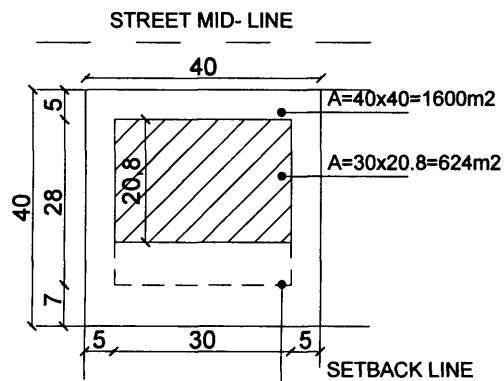


Figure 55, Setbacks of office building in Residential Sector A, dimensions in meters.

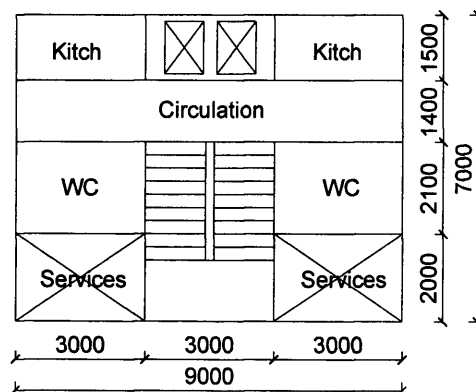


Figure 56, Estimation of the area needed for services.<sup>6</sup>

<sup>6</sup> All dimensions are in millimetres unless mentioned otherwise.

### 5.2.2 OFFICE BUILDING LAYOUT:

Floor plan area is  $30 \times 20.8 = 624 \text{ m}^2$ , each floor has service area located in the middle of the space to keep free elevations and to ensure equal distribution of facilities with less distances.

The service area is estimated to be around  $63 \text{ m}^2$ , as shown in Figure 56, almost 10% of the office area, Figure 56 is drawn for the purpose of estimating the needed area which could be designed in different dimensions.

Figure 57 shows the proposed base plan for simulation.

The proposed building consists of four floors and basement to be used as car parking; each is 3300mm height measured from slab to slab level. In addition, there is a roof floor for general building services, 3000mm high to top of slab, refer to Figure 58.

The proposed external wall construction, as shown in Figure 60, consists of stone cladding, concrete block cavity wall filled with thermal insulation (extruded polystyrene), paint and plaster finish for interior surfaces. For stone fixing, semi wet method is used; steel mesh with ties is used to hang the stone then mortar is cast behind.

Figure 61 and Figure 62 illustrates the proposed construction details for roof slab and slab on grade.

Slabs are 250mm reinforced concrete; floors are 150mm raised floor, refer to Figure 59. False ceiling is avoided to benefit from the thermal massive structure.

Open office plan layout is adopted.

Glazing ratio of 40% of the façade is considered; refer to App-A 2 for glazing calculations.

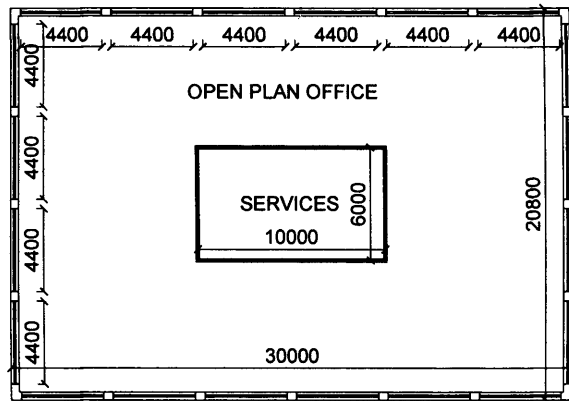


Figure 57, Proposed base plan for study case office building.

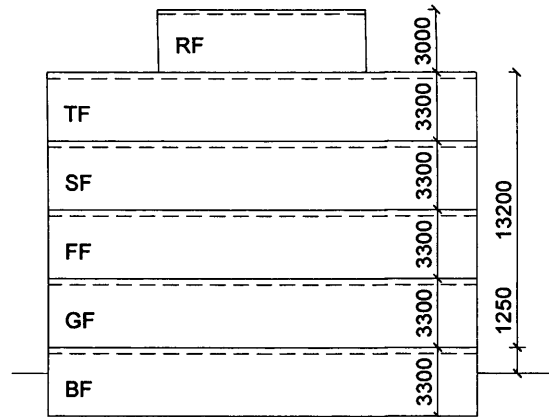


Figure 58, Section through the proposed office building.

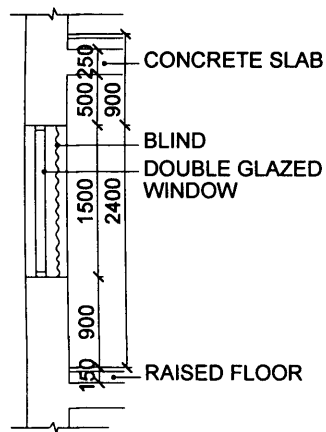


Figure 59, Section through typical floor.

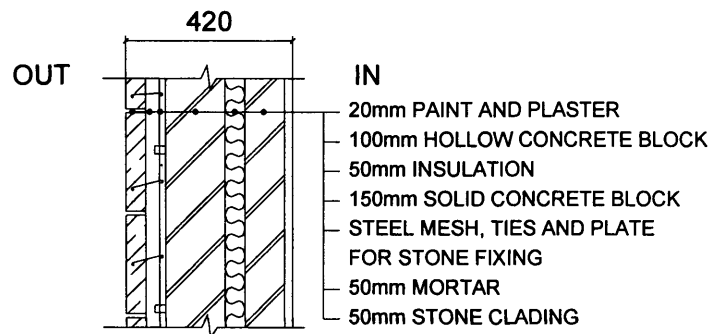


Figure 60, Proposed external wall construction.

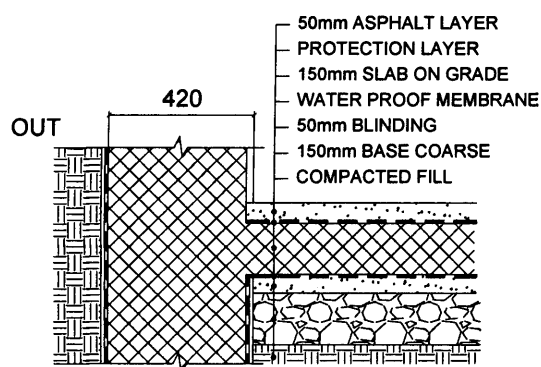


Figure 61, Slab on grade construction detail.

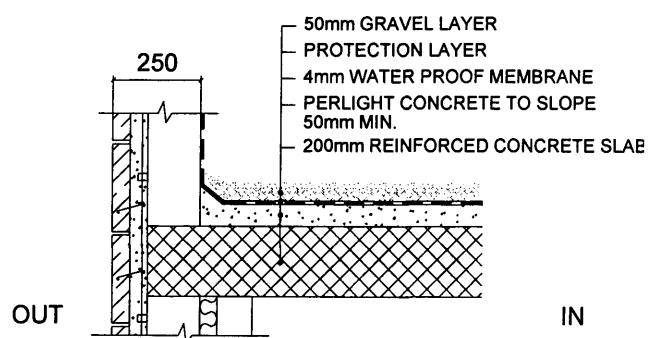


Figure 62, Roof slab detail.



### 5.3 SUGGESTED ROUGH DESIGN FOR THE TOWER

#### *Air flow regime:*

The exterior air is assumed to be greater than the out flowing air; according to Woods et al experiment, tower shaft for air intake and outflow-opening in each floor will be considered. For better distribution of air two intake shafts are proposed, each shaft has one opening in each floor. Each floor has two outlets to exhaust the air to outside.

#### *The tower model*

Suggested for this paper is the improved wind catcher model suggested by Bahadori; Even though the dominant wind direction, as shown in wind analysis, is from the west, the wind direction could be effected by the physical obstruction in the city, which changes the direction of the wind in the level of the wind tower inlet, for that four inlets model is adopted to catch the wind from any direction, the openings to be supplied with dampers to allow the wind in when pressure coefficient is positive at a certain opening and prevent wind escaping through the others. Alternatively, separate between openings by intersecting low-height walls, which prevent wind from escaping from the opposite opening and lead wind downwards toward the evaporative column.

Evaporative column is made of clay conduits. Water spraying pipes, located on top of the clay conduits, keeps the surfaces of the clay wet. The height of the evaporative column to be determined later using Badran (2003) and Bahadori (1985) and by trial and error, to achieve internal conditions located in the summer comfort zone of Amman.

#### *Tower volume:*

Taken into account the conclusion charts of the study of Badran (2003) and Bahadori (1985), calculation were made to estimate the tower cross section needed (refer to section 6.2.1), based on the needed cooling loads calculated by simulating a conditioned office building (without wind catcher) to the desired internal temperatures.

The suggested tower form is square to minimize the surface area and consequently minimize air flow resistance through the shaft.

***Tower location:***

Two shafts, located at the perimeter of the service core, are suggested to enhance the distribution of air and to ensure equal distribution of air to the internal spaces.

## **6 CHAPTER 6: COMPUTER MODELLING**

### **6.1 BASE CASE**

The base case was simulated for the purpose of estimating the cooling loads needed to keep the internal temperature at 27°C.

The base case is the above described building without wind catcher tower.

The thermal performance of the building-base case was simulated using TAS-software.

Amman weather data file for the year 1995, was obtained from Meteonorm programme and used for weather data base.

Mixed mode approach to ventilate the offices is adopted, natural ventilation and air conditioning.

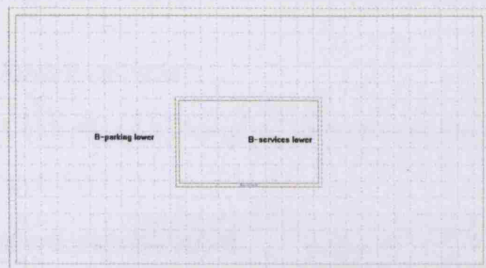
The apertures open as a function of temperature and start to close as the internal temperature reaches 23°C, the aperture are fully opened during the night hours for night ventilation, cooling the exposed thermally massive structure.

The plant is assumed to be operated from 8am to 18pm; cooling starts at 27°C.

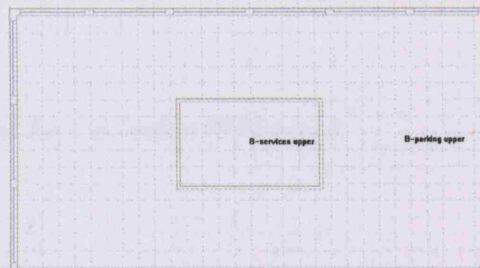
The building was zoned in the bases of open plan layout for offices in addition to the service core.

The simulation was run for the cooling season; June, July, August and September, i.e. from day 151 to 273.

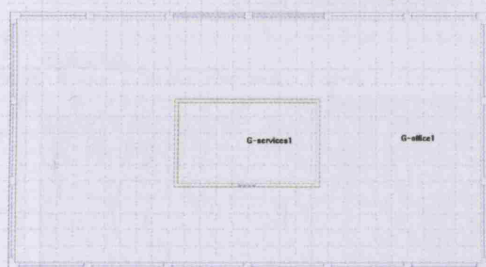
### 6.1.1 BASE MODEL DESCRIPTION



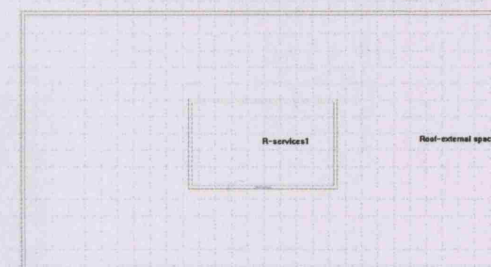
Basement; the zone under natural ground level



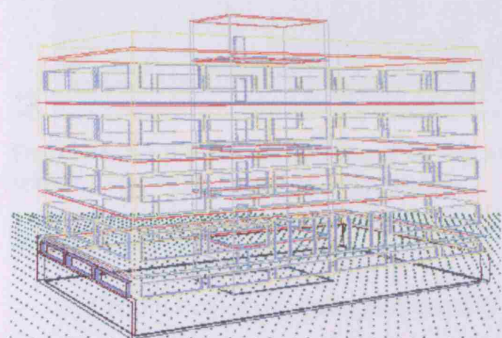
Basement; the zone above natural ground level



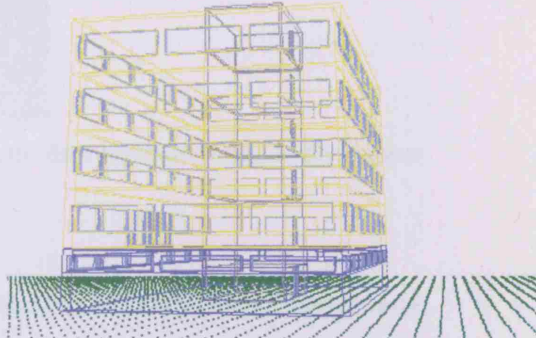
Typical floor



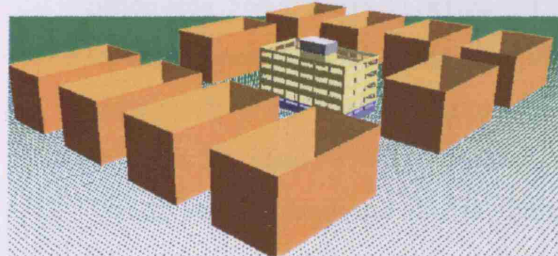
Roof floor



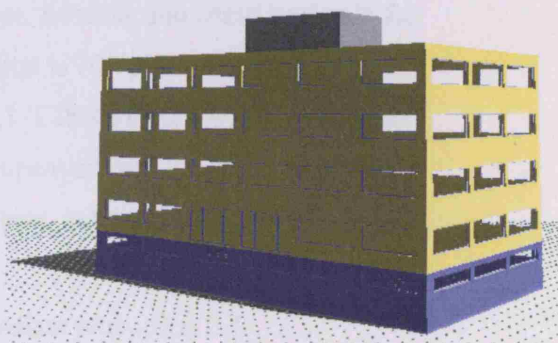
3D model front view



3D model side view.



The office in the urban context.



3D model with sun shade display

### 6.1.2 BASE MODEL SPECIFICATION AND ASSUMPTION

The following specification and assumptions were considered:

#### *Jordan calendar:*

A calendar was assigned to represent the weekend days in Jordan (Friday and Saturday).

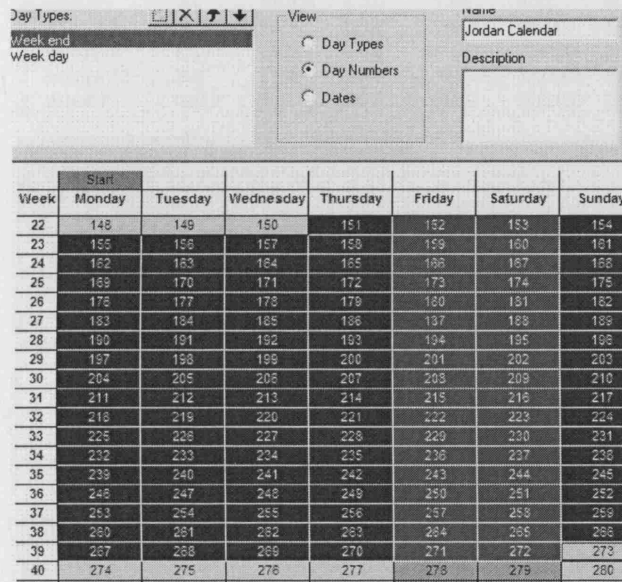


Figure 63, Jordan calendar displayed by day numbers, the days highlighted represents summer season; June, July, August and September.

#### *Internal heat gain;*

- People heat gain: occupant density is assumed to be person/10m<sup>2</sup>. Given; total assumed floor area is 30x20.8=624m<sup>2</sup>, service area 60 m<sup>2</sup>, leaves 564 m<sup>2</sup> open office area, 564 x %10= 57 person per floor. Sensible and latent heat gain for seated to moderate work in office application is 70/70 W per person respectively in 26 °C according to table 6.1 (CIBSE Guide A, please refer to appendix B). Thus 70W/ 10 m<sup>2</sup> -since occupant density is person/10 m<sup>2</sup> -or 7W/ m<sup>2</sup> sensible heat, and 7W/ m<sup>2</sup>, latent heat, radiant proportion assumed is 0.2.
- Equipment heat gain assumed 15W/ m<sup>2</sup>, radiant proportion 0.1.
- Lighting power heat gain assumed 12W/ m<sup>2</sup>, radiant proportion 0.3.

Person required 8 litter/second x 57person x 3600 second /1000 x (564x2.9) m<sup>3</sup>

(volume of office space in the single floor) = 1641600/ 1635600=1 ach.

**Building elements construction:**

The materials described in section 5.2 were used.

Opaque Construction		Name		Basement retaining		Description		Retaining wall part of the basement wall	
Solar Absorptance		Emissivity		Conductance (W/m2 C)		Time Constant (hours)			
ext. surf.	int. surf.	External	Internal						
0.760	0.360	0.910	0.920	0.276		177.934			

M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\38	10.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1concd\1	400.0	1.400	0.000	34.000	2360.000	1030.000	CONCRETE 1:2:4 *3
am1asph\12	20.0	0.500	0.000	10000.0...	1700.000	1000.000	1-3 FELT + 2-3 LAYERS HOT BITUMEN *2
am1soil\7	1000.0	0.329	0.000	99.000	1515.000	796.000	SAND, DRY *2

Opaque Construction		Name		External wall		Description		Stone clad cavity wall	
Solar Absorptance		Emissivity		Conductance (W/m2 C)		Time Constant (hours)			
ext. surf.	int. surf.	External	Internal						
0.900	0.360	0.900	0.920	0.418		12.217			

M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\38	10.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1block\1	100.0	0.317	0.000	14.800	1040.000	1050.000	FOAMED SLAG CONC. PARTITION BLOCK *1
am1ins\11	50.0	0.040	0.000	21.000	16.000	1210.000	POLYSTYRENE EXPANDED SHEET CLOSED
am1block\1	150.0	0.317	0.000	14.800	1040.000	1050.000	FOAMED SLAG CONC. PARTITION BLOCK *1
am1plast\19	50.0	0.700	0.000	11.000	1600.000	837.000	LIME PLASTER *4
am1stone\5	50.0	1.900	0.000	48.000	2700.000	770.000	SLATE *4

Opaque Construction		Name		Services wall		Description		Plastered concrete wall	
Solar Absorptance		Emissivity		Conductance (W/m2 C)		Time Constant (hours)			
ext. surf.	int. surf.	External	Internal						
0.360	0.360	0.920	0.920	1.565		11.630			

M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\38	3.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1concd\6	150.0	1.130	0.000	34.000	2000.000	1000.000	DENSITY 1 CONCRETE *4
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1s\38	3.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3

Opaque Construction		Name		Ground floor		Description		Slab on grade construction	
Solar Absorptance		Emissivity		Conductance (W/m2 C)		Time Constant (hours)			
ext. surf.	int. surf.	External	Internal						
0.820	0.900	0.910	0.950	0.426		301.200			

M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1asph\6	50.0	1.150	0.000	1000.000	2320.000	840.000	ASPHALT, HEAVY, 20% GRIT 2 *3
am1concd\1	150.0	0.870	0.000	14.800	1800.000	920.000	CONCRETE 3/4 m.c. 8 *3
am1asph\12	4.0	0.500	0.000	10000.0...	1700.000	1000.000	1-3 FELT + 2-3 LAYERS HOT BITUMEN *2
am1concd\9	50.0	1.280	0.000	34.000	2100.000	1000.000	CONCRETE SCREED *3
am1aggr\29	150.0	0.920	0.000	14.800	1840.000	1054.000	NO FINES HAM RIVER GRAVEL 1:6 *2
am1soil\3	1000.0	0.520	0.000	99.000	2050.000	1824.000	EARTH COARSE GRAVELLY *3

Opaque Construction		Name		Ceiling	Description		External roof ceiling
Solar Absorptance		Emissivity		Conductance (W/m2 C)	Time Constant (hours)		
ext. surf.	int. surf.	External	Internal				
0.650	0.920	0.900	0.900	0.316	13.054		

M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\28	3.0	999.999	0.000	5.565	0.000	0.000	BLUE PAINT (DARK) *2
am1plast\10	20.0	0.300	0.000	11.000	960.000	837.000	LIGHTWEIGHT PLASTER 10 *3
am1concd\1	200.0	0.870	0.000	14.800	1800.000	920.000	CONCRETE 3/4 m.c. 8 *3
am1ins\11	100.0	0.040	0.000	21.000	16.000	1210.000	POLYSTYRENE EXPANDED SHEET CLOS.
am1ins\31	70.0	0.216	0.000	6.800	800.000	1063.000	PERLITE 3 *2
am1asph\9	4.0	0.410	0.000	1300.000	960.000	1000.000	ROOFING FELT 1 *2
am1aggr\5	50.0	1.500	0.000	38.400	2130.000	1052.000	GRAVEL AGGREGATE *3

Opaque Construction		Name		Upper Ceiling	Description		Typical ceiling
Solar Absorbtance		Emissivity		Conductance (W/m2 C)	Time Constant (hours)		
ext. surf.	int. surf.	External	Internal				
0.500	0.360	0.900	0.920	0.992	23.795		

M-Code	Width ...	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\38	3.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1concd\1	200.0	0.870	0.000	14.800	1800.000	920.000	CONCRETE 3/4 m.c. 8 *3
am1concd\9	50.0	1.280	0.000	34.000	2100.000	1000.000	CONCRETE SCREED *3
am1cav\7	100.0	0.000	0.960	1.000	0.000	0.000	100MM AIR (HORIZONTAL FLOW)
am1metal\4	40.0	43.000	0.000	99999.0...	7800.000	500.000	STEEL *3
am1tile\9	10.0	0.310	0.000	20000.0...	1600.000	1381.000	RUBBER *1

Opaque Construction		Name		Upp ceiling-service		Description		Typical services ceiling	
Solar Absorptance		Emissivity		Conductance (W/m2 C)	Time Constant (hours)				
ext. surf.	int. surf.	External	Internal						
0.650	0.360	0.900	0.920	1.822	8.504				

M-Code	Width [...]	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1s\38	3.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3
am1plast\1	20.0	0.079	0.000	11.000	400.000	837.000	LIGHTWEIGHT PLASTER 1 *4
am1concd\1	200.0	0.870	0.000	14.800	1800.000	920.000	CONCRETE 3/4 m.c. 8 *3
am1aggr\17	70.0	1.440	0.000	34.000	2480.000	1090.000	1:2:4 SAND FINE & WHINSTONE COARSE
am1tile\13	30.0	1.750	0.000	48.000	2400.000	850.000	TERRAZZO *4

Transparent Construction		Name		Typ window pane		Description		Double glazing, low E suncool glass.			
Solar Transmittance	External Solar Absorptance		Internal Solar Absorptance		Light Transmittance	Emissivity		Conductance (W/m2 C)	Time Constant (hours)	External Blind	Internal Blind
	ext. surf.	int. surf.	int. surf.	ext. surf.		External	Internal				
0.006	0.746	0.037	0.421	0.069	0.011	0.845	0.850	2.421	0.000	NO	YES

M-Code	Widt...	Solar...	Ext S...	Int S...	Ext E...	Int E...	Cond...	Conv...	Vapo...	Description
blind\16	1.0	0.110	0.500	0.500	0.850	0.850	1.000	0.000	1.000	opaque white, 45 angle
am1cav\2	12.0	0.000	0.000	0.000	0.000	0.000	0.000	2.080	1.000	12MM AIR (HORIZONTAL FLOW)
am1pik\2	6.0	0.780	0.070	0.070	0.845	0.845	1.000	0.000	9999...	6MM CLEAR FLOAT
am1cav\2	12.0	0.000	0.000	0.000	0.000	0.000	0.000	2.080	1.000	12MM AIR (HORIZONTAL FLOW)
am1pik\21	6.0	0.060	0.210	0.370	0.845	0.410	1.000	0.000	9999...	6MM SUNCOOL 10/24 (BRONZE)

Opaque Construction		Name	Window frame		Description	Aluminum	
Solar Absorptance		Emissivity		Conductance (W/m2 C)	Time Constant (hours)		
ext. surf.	int. surf.	External	Internal				
0.500	0.500	0.216	0.216	999.999	0.000		

M-Code	Width [...]	Conduc...	Convec...	Vapour ...	Density	Specific...	Description
am1metal\1	3.0	204.000	0.000	99999.0...	2700.000	896.000	ALUMINIUM *3

Opaque Construction		Name	Description																					
<table border="1"> <thead> <tr> <th colspan="2">Solar Absorptance</th> <th colspan="2">Emissivity</th> <th rowspan="2">Conductance (W/m<sup>2</sup> C)</th> <th rowspan="2">Time Constant (hours)</th> </tr> <tr> <th>ext. surf.</th> <th>int. surf.</th> <th>External</th> <th>Internal</th> </tr> </thead> <tbody> <tr> <td>0.600</td> <td>0.600</td> <td>0.920</td> <td>0.920</td> <td>3.975</td> <td>0.000</td> </tr> </tbody> </table>		Solar Absorptance		Emissivity		Conductance (W/m <sup>2</sup> C)	Time Constant (hours)	ext. surf.	int. surf.	External	Internal	0.600	0.600	0.920	0.920	3.975	0.000	Internal door pane						
Solar Absorptance		Emissivity		Conductance (W/m <sup>2</sup> C)	Time Constant (hours)																			
ext. surf.	int. surf.	External	Internal																					
0.600	0.600	0.920	0.920	3.975	0.000																			
M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description																	
am1wood\26	40.0	0.159	0.000	11.420	770.000	2390.000	OAK, ACROSS GRAIN 14% m.c. *2																	

Opaque Construction		Name	Description																					
<table border="1"> <thead> <tr> <th colspan="2">Solar Absorptance</th> <th colspan="2">Emissivity</th> <th rowspan="2">Conductance (W/m<sup>2</sup> C)</th> <th rowspan="2">Time Constant (hours)</th> </tr> <tr> <th>ext. surf.</th> <th>int. surf.</th> <th>External</th> <th>Internal</th> </tr> </thead> <tbody> <tr> <td>0.600</td> <td>0.600</td> <td>0.920</td> <td>0.920</td> <td>1.060</td> <td>7.329</td> </tr> </tbody> </table>		Solar Absorptance		Emissivity		Conductance (W/m <sup>2</sup> C)	Time Constant (hours)	ext. surf.	int. surf.	External	Internal	0.600	0.600	0.920	0.920	1.060	7.329	Internal door frame						
Solar Absorptance		Emissivity		Conductance (W/m <sup>2</sup> C)	Time Constant (hours)																			
ext. surf.	int. surf.	External	Internal																					
0.600	0.600	0.920	0.920	1.060	7.329																			
M-Code	Width (...)	Conduc...	Convec...	Vapour ...	Density	Specific...	Description																	
am1wood\26	150.0	0.159	0.000	11.420	770.000	2390.000	OAK, ACROSS GRAIN 14% m.c. *2																	



## 6.2 BASE CASE WITH WIND CATCHER

### 6.2.1 CALCULATIONS

#### *Calculations of pre-cooled air flow needed to be driven by the tower:*

Typical August hot day temperature is around 33°C. An assumption is made that an indoor temperature of around 27°C is the target to be achieved by natural ventilation. From the base model simulation results, the hourly average cooling load needed over summer season during the office hours (the summation of total cooling loads divided by the number of office hours) is 71.6 W/m<sup>2</sup>, to keep office temperature within 27°C.

$$\text{Rate of cooling} = \rho V C_p \Delta T$$

This figure is for the calculations of needed air flow for natural ventilation when outdoor temperature is lower than indoor temperature.

Considering the pre-cooled air in the tower as the lower outdoor temperature, we need to calculate the flow needed to be driven from the cooling tower into the occupied spaces for natural ventilation.

The cooling at this stage is convective cooling as the air is already cooled by evaporative cooling in the tower and should enter the offices.

Assuming the desired internal temperature is 27°C, and that the inflow air from the tower is pre-cooled to 21°C that gives  $\Delta T = 6$ ,

$$C_p = 1026 \text{ kJ/kg, office volume} = 1635.6 \text{ m}^3$$

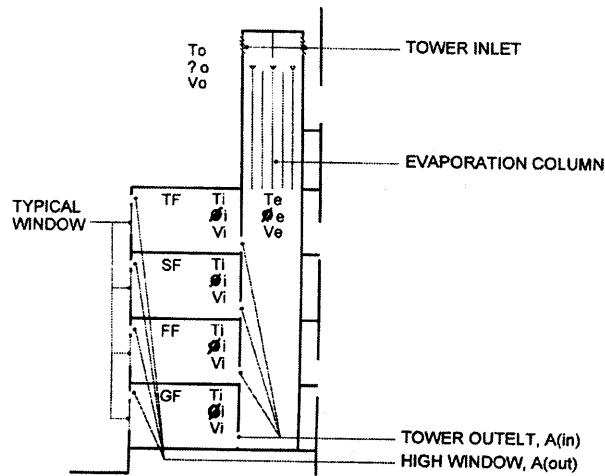
Assuming that the internal humidity becomes 70% due to the evaporative cooling and occupant latent heat  $\rightarrow \rho = 1.145 \text{ kg/m}^3$ .

$$\therefore 71.6 = 1.145 \times v \times 1026 \times 6 \rightarrow v = 0.010158 \text{ V/m}^2.$$

$$\text{ach} = (0.010158 \times 3600 \times A) / (A \times 2.9) = 12.6$$

$$(12.6 \text{ ach} \times 1635.6 \text{ m}^3) / 3600 \text{ s} = 5.7 \text{ m}^3/\text{s}.$$

This result is very close to notice made by Golneshan and Yagoubé “a ventilation rate of 12 air change per hour will achieve comfort if a wind tower is used (convective cooling)” Golneshan and Yagoubé (1984): Aboul Naga, 1990.

***Tower cross-section area calculations:*****Figure 64,**

Given; the needed air flow to be delivered by the tower for each floor is  $5.75 \text{ m}^3/\text{s} = 12.6 \text{ ach}$ .

Total sensible heat; lighting, occupancy and equipment (12,7,15 respectively) =  $34 \text{ W}/\text{m}^2$ , total latent heat (occupancy) is  $7 \text{ W}/\text{m}^2$ , gives sensible heat factor (sensible/total heat ration) = 0.83.

Peak of total cooling demand (from TAS results of the base case, the maximum hourly cooling demand)  $Q = 86.7 \text{ kW}$ .

Assuming that the air reaching the occupants have been heated (through the building heat gains), as an average, by about  $\frac{1}{2}$  of the cooling load; and its velocity  $v_e = 0.1 \text{ m/s}$ .  $T_o$ : Dry bulb temperature, the subscripts refer to the zone area; subscript (0) refers to outdoor ambient air, (e) refers to the air leaving the evaporative column and (i) stands for the internal spaces (offices).

$\Phi$ : relative humidity, h: enthalpy, v: air velocity, V: volumetric air flow per second.

- Based on Bahadori (1985) graphs:

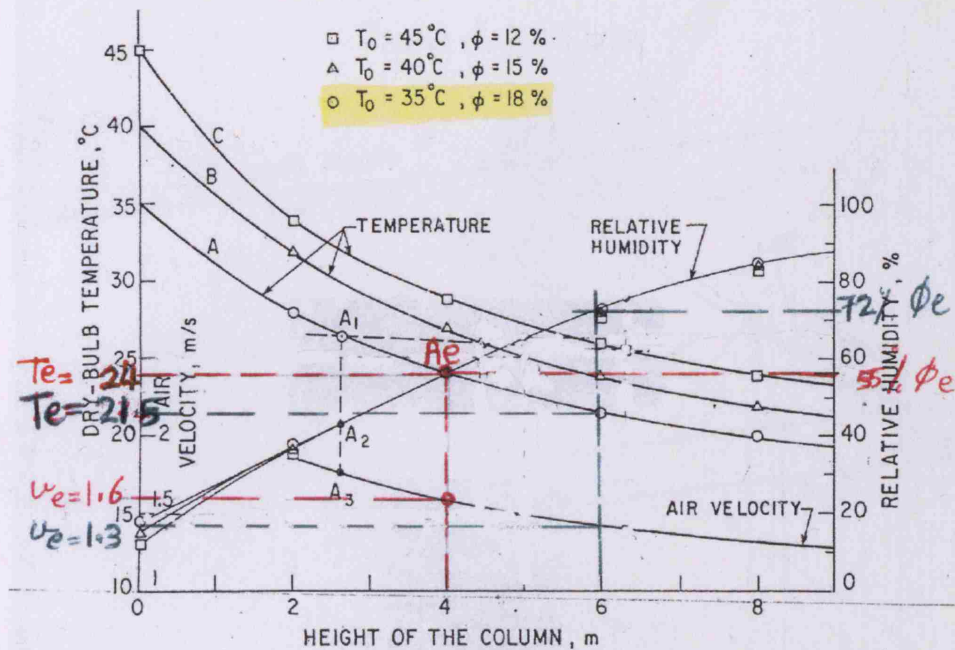


Figure 65, Condition of air leaving the evaporative cooling plotted on the chart of Bahadori (1985, fig.6).

Following the same procedure of the example given by the author,

Assuming the curve labelled A in Figure 65 (for  $T_0 = 35^\circ\text{C}$ ,  $\Phi = 18\%$ ,  $v_0 = 5\text{m/s}$ ) can represent the design conditions for Amman. Assume tower height is 4m, the point  $A_e$  is indicated to represent the conditions of air leaving the evaporative column (and it is located in the right of  $A_1$ ) which is at  $T_e = 24^\circ\text{C}$ ,  $\Phi_e = 55\%$ ,  $v_e = 1.6\text{m/s}$ , and from psychrometric chart we obtain enthalpy and density of this air to be about  $h_e = 50.5\text{kJ/kg C}$  and specific volume  $= 0.885\text{m}^3/\text{kg} \rightarrow \rho_e = 1.169\text{kg/m}^3$ .

The condition of air reaching the occupants can be determined from:

$$\frac{1}{2} Q = \rho_e V_e (h_i - h_e) \rightarrow \frac{1}{2} 86.7 = 1.169 \times 5.75 (h_i - 50.5)$$

$h_i = 57\text{ kJ/kg}$ , from the psychrometric chart and using sensible heat factor  $= 0.83$ ,  $T_i = 29.2^\circ\text{C}$ ,  $\Phi_i = 42\%$ , These conditions, under the assumptions made, are not within the comfort zone when plotting on Amman-summer comfort chart (Figure 46).

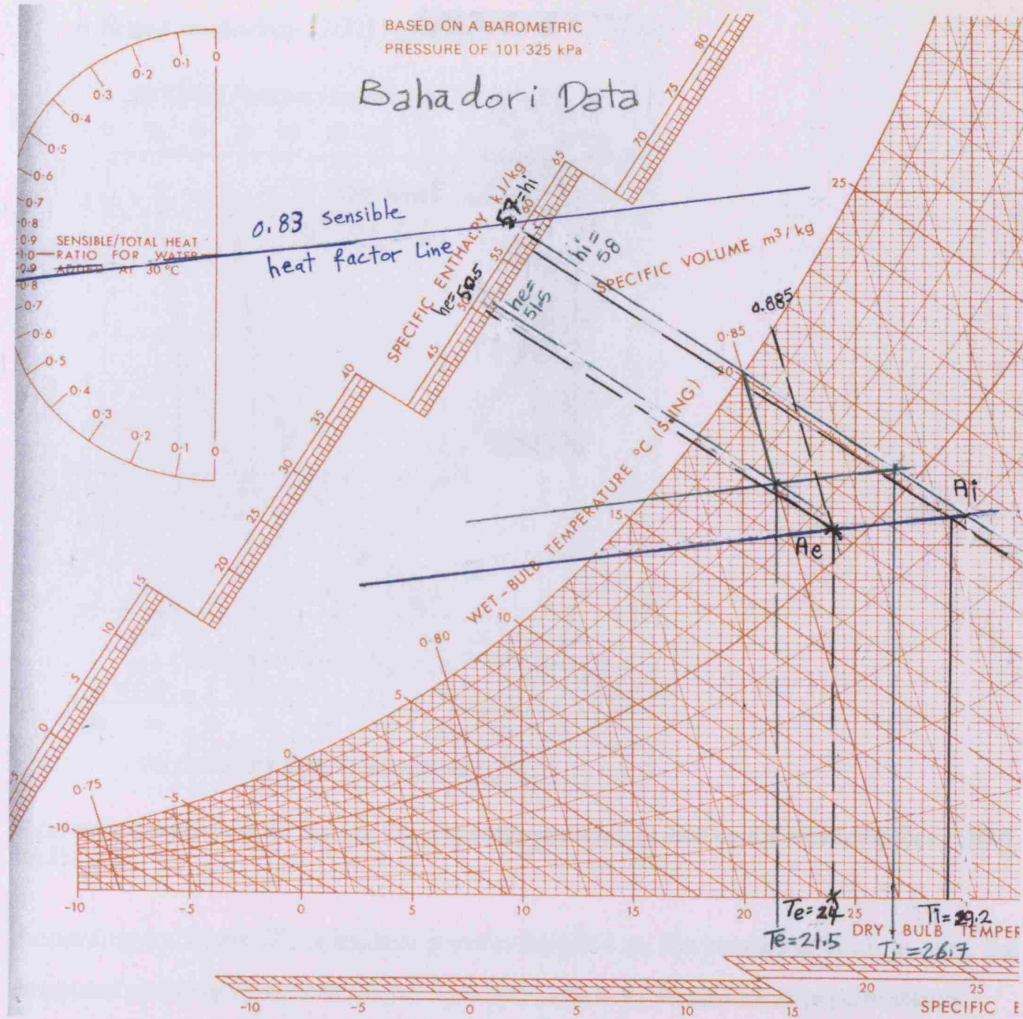


Figure 66, The condition of air (based on Bahadori chart) analysis according to CIBSE psychrometric chart.

Trial 2: considering tower height 6 m, the condition of air leaving the evaporative tower is:  $v_e = 1.3 \text{ m/s}$ ,  $T_e = 21.5^\circ\text{C}$ ,  $\Phi_e = 72\%$ , and from psychrometric chart we obtain enthalpy and density of this air to be about  $h_e = 51.5 \text{ kJ/kg C}$  and specific volume =  $0.85 \text{ m}^3/\text{kg} \rightarrow \rho_e = 1.176 \text{ kg/m}^3$ .

The condition of air reaching the occupants:

$$\frac{1}{2} Q = \rho_e V_e (h_i - h_e) \rightarrow \frac{1}{2} 86.7 = 1.176 \times 5.75 (h_i - 51.5)$$

$h_i = 57.9 \text{ kJ/kg}$ , from the psychrometric chart and using sensible heat factor = 0.83,  $T_i = 26.7^\circ\text{C}$ ,  $\Phi_i = 54\%$ . These conditions are hardly above the comfort zone when plotting on Amman-summer comfort chart (Figure 46).

As a result from Bahadori chart: the tower height of 6m has the potential to achieve the required internal conditions.



- Based on Badran (2003) graphs:

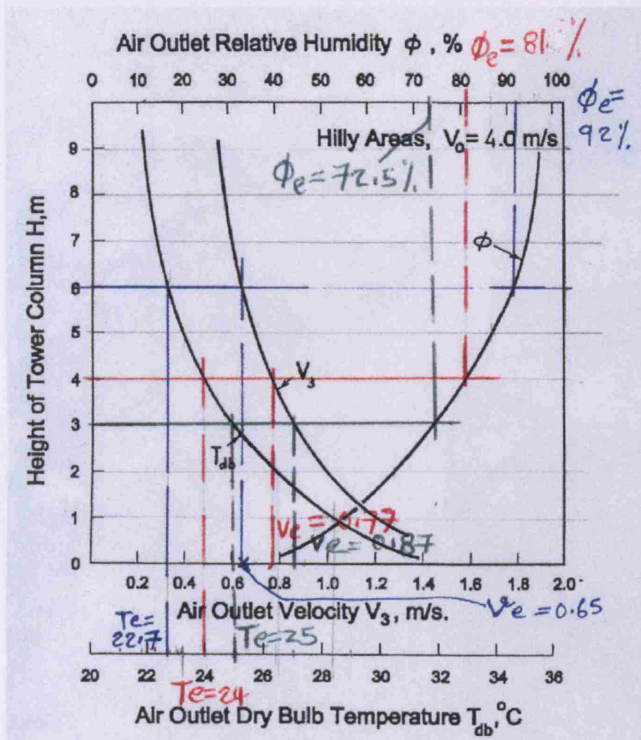


Figure 67, Condition of air leaving the evaporative column, plotted on the chart of Badran (2003, fig.2).

According to Figure 67; considering tower height 4 m, the condition of air leaving the evaporative tower is:  $v_e = 0.77 \text{ m/s}$ ,  $T_e = 24^\circ\text{C}$ ,  $\Phi_e = 81\%$ , and from psychrometric chart we obtain enthalpy and density of this air to be about  $h_e = 63.25 \text{ kJ/kg C}$  and specific volume  $= 0.862 \text{ m}^3/\text{kg} \rightarrow \rho_e = 1.16 \text{ kg/m}^3$ .

The condition of air reaching the occupants:

$$\frac{1}{2} Q = \rho_e V_e (h_i - h_e) \rightarrow \frac{1}{2} 86.7 = 1.16 \times 5.75 (h_i - 63.25)$$

$h_i = 69.7 \text{ kJ/kg}$ , from the psychrometric chart and using sensible heat factor  $= 0.83$ ,  $T_i = 29^\circ\text{C}$ ,  $\Phi_i = 62\%$ . These conditions are not within the comfort zone when plotting on Amman-summer comfort chart (Figure 46).

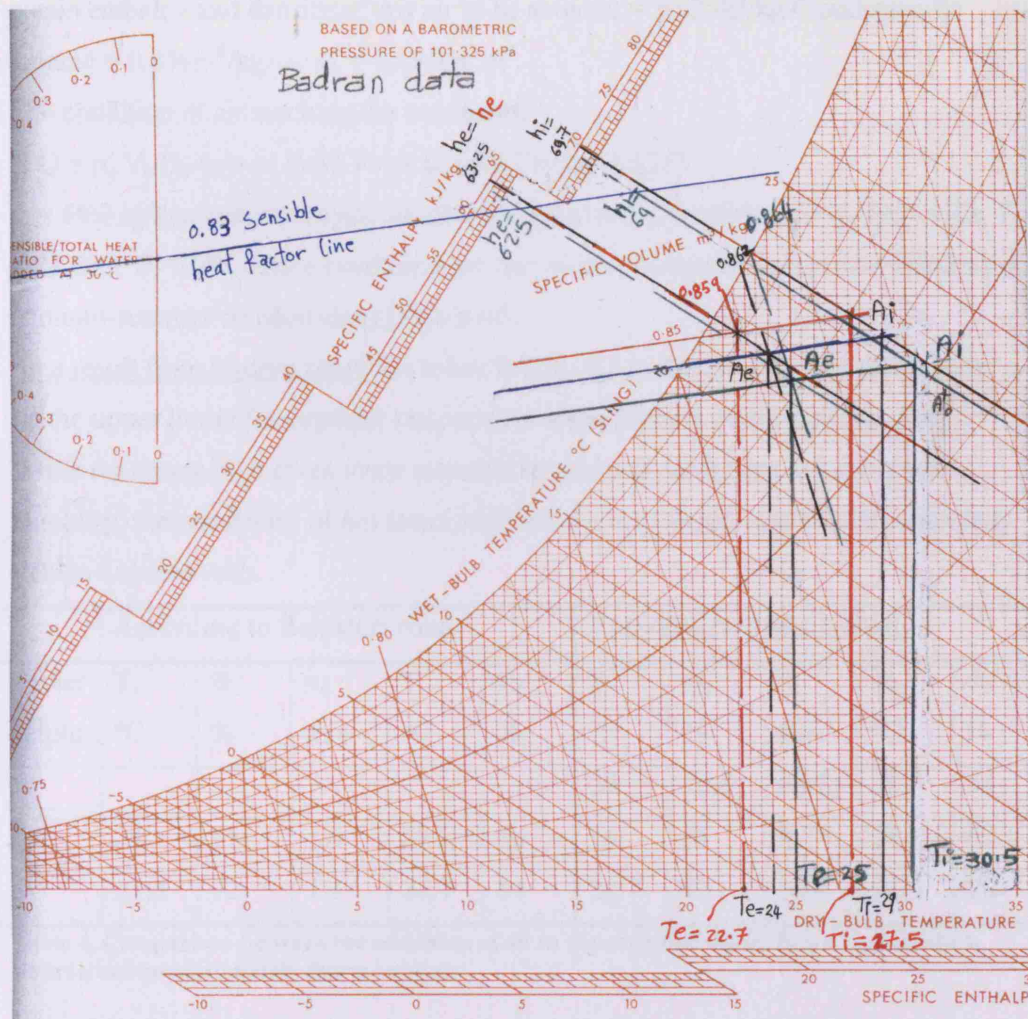


Figure 68, The condition of air (based on Badran chart) analysis according to CIBSE psychrometric chart. The black lines represent 4m-tower high, the green lines represent 3m-tower high.

Trial 2: to reduce the humidity, 3m tower high was considered, the condition of air leaving the evaporative tower is:  $v_e = 0.87 \text{ m/s}$ ,  $T_e = 25^\circ\text{C}$ ,  $\Phi_e = 72.5\%$ , and from psychrometric chart we obtain enthalpy and density of this air to be about  $h_e = 62.5 \text{ kJ/kg}$  and specific volume  $= 0.864 \text{ m}^3/\text{kg} \rightarrow \rho_e = 1.157 \text{ kg/m}^3$ .

The condition of air reaching the occupants:

$$\frac{1}{2} Q = \rho_e V_e (h_i - h_e) \rightarrow \frac{1}{2} 86.7 = 1.157 \times 5.75 (h_i - 62.5)$$

$h_i = 69 \text{ kJ/kg}$ , from the psychrometric chart and using sensible heat factor  $= 0.83$ ,  $T_i = 30.5^\circ\text{C}$ ,  $\Phi_i = 54\%$ . These conditions are not within the comfort zone when plotting on Amman-summer comfort chart (Figure 46).

Trial 3: considering tower height 6 m, the condition of air leaving the evaporative tower is:  $v_e = 0.65 \text{ m/s}$ ,  $T_e = 22.7^\circ\text{C}$ ,  $\Phi_e = 92\%$ , and from psychrometric chart we

obtain enthalpy and density of this air to be about  $h_e = 63.25 \text{ kJ/kg C}$  and specific volume  $= 0.859 \text{ m}^3/\text{kg} \rightarrow \rho_e = 1.164 \text{ kg/m}^3$ .

The condition of air reaching the occupants:

$$\frac{1}{2} Q = \rho_e V_e (h_i - h_e) \rightarrow \frac{1}{2} 86.7 = 1.164 \times 5.75 (h_i - 63.25)$$

$h_i = 69.7 \text{ kJ/kg}$ , from the psychrometric chart and using sensible heat factor  $= 0.83$ ,  $T_i = 27.5^\circ\text{C}$ ,  $\Phi_i = 70\%$ . These conditions are not within the comfort zone when plotting on Amman-summer comfort chart (Figure 46).

As a result from Badran chart: the tower height of 3 and 4 gives indoor temperature on the upper limit of acceptable temperature when plotting on the comfort zone. While 6m tower high gives more tolerable temperature accompanied with high humidity, the conditions of 6m tower high will be considered, and the extra humidity will be handled with.

Tower height	According to Bahadori chart					According to Badran chart				
	$T_e$ °C	$\Phi_e$ %	$v_e$ m/s	$T_i$ °C	$\Phi_i$ %	$T_e$ °C	$\Phi_e$ %	$v_e$ m/s	$T_i$ °C	$\Phi_i$ %
3						25	72.5	0.87	30.5	54
4	24	55	1.6	29.2	42	24	81	0.77	29	62
6	21.5	72	1.3	26.7	54	22.7	92	0.65	27.5	70

**Table 4, Comparison between the condition of air in the occupied spaces based on Bahadori, Badran and psychrometric charts analysis.**

As a conclusion:

The external conditions considered by Bahadori, i.e. temperature humidity and wind velocity, are not exactly like Amman conditions, as the humidity corresponding to  $35^\circ\text{C}$  is around 38% not 18% as considered in Bahadori study. This may explain the differences between the humidity values when comparing the two results.

The differences between the values of air speed leaving the evaporative column could be explained by the differences in wind speed considered when conducting these studies; Bahadori research considered external wind speed of 5m/s, while Badran considered 4 m/s according to Jordan Department of meteorology.

According to the weather file 1995 used in this paper; the average wind speed in summer season is 4m/s, Typical August hot day temperature is around  $33^\circ\text{C}$  and relative humidity corresponding to this temperature is 37% (Figure 44), which is more



close to the climate condition used by Badran, (2003, table:1) hilly areas- which represents Amman city.

The results obtained using Badran chart for 6m column height will be considered, i.e. temperature and relative humidity, However, the velocity of the air leaving the evaporative cooling will be considered from the Bahadori chart for 6m column height; because wind analysis shows that the higher wind speed is recorded during the office hours, particularly, in the afternoon. In addition, both studies considered the same physical assumption for evaporative column, tower unit area and method of analysis.

6m tower height		
External conditions	Evaporative column conditions	Internal conditions
$T_o = 33^\circ\text{C}$	$T_e = 22.7^\circ\text{C}$	$T_i = 27.5^\circ\text{C}$
$\Phi_i = 39\%$	$\Phi_e = 92\%$	$\Phi_i = 70\%$
$v_o = 5\text{m/s.}$	$v_e = 1.3\text{m/s.}$	

**Table 5, Data considered for 6m tower height**

The air velocity of the air leaving the evaporative tower, for  $1\text{m}^2$  unit tower areas, is  $v_e 1.3\text{m/s}$ , Figure 65. This velocity gives an air flow equals  $v \times A = 1.3 \times 1 = 1.3 \text{ m}^3/\text{s}$ . The needed tower cross section area to achieve  $5.75\text{m}^3/\text{s}$  is  $5.75 / 1.3 = 4.4\text{m}^2$ . The needed tower cross section area to supply  $5.75\text{m}^3/\text{s}$  (per floor) for four floors =  $4.4 \times 4 = 17.6 \text{ m}^2$ .

Two shafts will be considered, for better distribution of air, of each  $8.8\text{m}^2$ .

*Tower cross section area considered for the study:  $3 \times 3 = 9\text{m}^2$*

***Tower inlet size (opening between the tower and outside):***

The tower should supply  $5.75 \times 4 = 23 \text{ m}^3/\text{s}$ , average wind velocity during office hours (when the evaporative cooling is on)  $v_o = 5\text{m/s}$ ,  $\rightarrow A_{\text{tot}} = 4.6 \text{ m}^2$ , though four inlet model is suggested, only one inlet per shaft will be considered in the calculations to admit air (as wind will not blew from all directions at the same time),  $\rightarrow A = 4.6/2 = 2.3 \text{ m}^2$  each,

*Tower inlet size considered:  $2.3 \times 1 = 2.3 \text{ m}^2$*

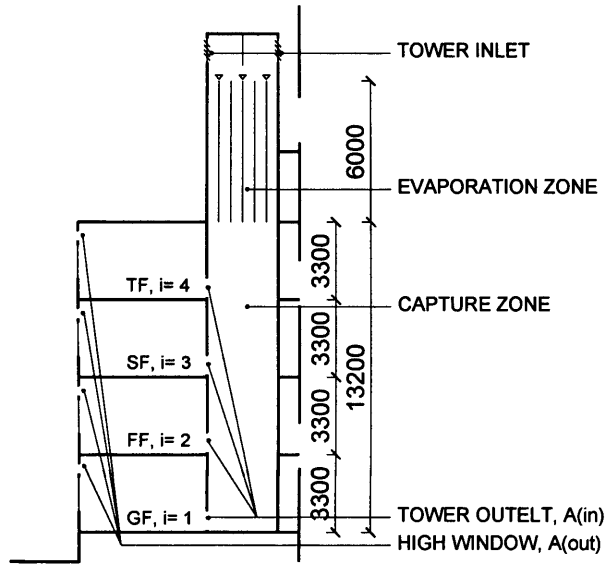
***Tower outlets sizes (opening between the tower and offices-inlet into the storey):***

Assumption is made that the area of the tower outlet (inflow air from tower to inside) is equal to the area of the high window (outflow air from floor to outside).

Tower outlet to be long horizontal windows, located at low level (0.10m above finish floor level), to avoid any potential draught at desk top level.

High windows to be long horizontal windows, located at high level (2.5m above finish floor level), to exhaust the heat and contaminants stratified at high level above the occupied zone.

The dimensions of the windows will be rounded off, to examine the method stated.



**Figure 69, Partial section of PEDC office building.**

***Third floor openings:***

Each floor needs  $5.75 \text{ m}^3/\text{s}$ ,  $v_e 1.3 \text{ m/s}$ ,  $\rightarrow A_{\text{tot}} = 4.4 \text{ m}^2$ , using two shafts and one outlet per shaft  $\rightarrow A = 4.4/2 = 2.2 \text{ m}^2$  each, at low level (10cm above floor level),

3<sup>rd</sup> floor tower outlet area =  $2.75 \times 0.8 = 2.2 \text{ m}^2$ ,

high window area =  $4.4 \times 0.5 = 2.2 \text{ m}^2$ ,

The column of cool air drives more air flow into the lower floors, which leaves the upper floors with less ventilation rate, for that Cook et al (2000) sizing equation was followed for lower floors.

$$\frac{\frac{1}{A_{in(i)}^2} + \frac{1}{A_{out(i)}^2} + \delta}{\frac{1}{A_{in(n)}^2} + \frac{1}{A_{out(n)}^2} + \delta} = \frac{[M - (i-1)H] + \lambda(i-1)H}{[M - (n-1)H] + \lambda(n-1)H}$$

In this case there is no exhaust stack, air flow out directly from storey outlet (the high window)

$$\delta = 2.3 \text{ m}^2$$

$$T_{\text{occ}} = T_i = 27.5^\circ\text{C},$$

$$T_{\text{PDEC}} = T_e = 22.7^\circ\text{C},$$

$$T_{\text{amb}} = T_o = 33^\circ\text{C},$$

$$\lambda = \frac{T_{\text{occ}} - T_{\text{amb}}}{T_{\text{PDEC}} - T_{\text{amb}}}$$

$$\lambda = \frac{27.5 - 33}{22.7 - 33} = \frac{5.5}{10.3} = 0.53$$

$i$  = storey code number; ground floor = 1, 1<sup>st</sup> floor = 2, 2<sup>nd</sup> floor = 3, 3<sup>rd</sup> floor = 4.

$$n = 4$$

$A_{\text{in}}$  = tower outlet into the  $i$ th storey

$A_{\text{out}}$  = high window in the  $i$ th storey

$$A_{\text{in}(i)} = A_{\text{out}(i)}$$

$$A_{\text{in}(n)} = A_{\text{out}(n)} = 2.2 \text{ m}^2.$$

$$M = 13.2 \text{ m}, H = 3.3 \text{ m},$$

Second floor openings: ( $i = 3$ )

$$\frac{\frac{1}{A^2} + \frac{1}{A^2} + 0.53}{\frac{1}{(2.2)^2} + \frac{1}{(2.2)^2} + 0.53} = \frac{[13.2 - (3-1)3.3] + 0.53(3-1)3.3}{[13.2 - (4-1)3.3] + 0.53(4-1)3.3}$$

$$\frac{\frac{2}{A^2} + 0.53}{\frac{2}{(4.84)} + 0.53} = \frac{6.6 + 3.498}{3.3 + 5.247} = \frac{\frac{2}{A^2} + 0.53}{0.94} = \frac{10.098}{8.547} = 1.182$$

$$\frac{2}{A^2} + 0.53 = 1.182 \times 0.94 = 1.11 \rightarrow \frac{2}{A^2} = 0.58 \rightarrow A^2 = \frac{2}{0.58} = 3.5 \rightarrow A = 1.87 \text{ m}^2$$

$$2^{\text{nd}} \text{ floor tower outlet area} = 2.75 \times 0.68 = 1.87 \text{ m}^2,$$

$$\text{high window area} = 4.4 \times 0.425 = 1.87 \text{ m}^2,$$

First floor openings: ( $i = 2$ )

$$\frac{\frac{2}{A^2} + 0.53}{\frac{2}{(2.2)^2} + 0.53} = \frac{[13.2 - (2-1)3.3] + 0.53(2-1)3.3}{[13.2 - (4-1)3.3] + 0.53(4-1)3.3}$$

$$\frac{\frac{2}{A^2} + 0.53}{0.41 + 0.53} = \frac{9.9 + 1.749}{3.3 + 5.247} = \frac{2}{A^2} + 0.53 = \frac{11.649 \times 0.94}{8.547} = 1.28$$

$$\frac{2}{A^2} = 0.75 \rightarrow A^2 = 2.67 \rightarrow A = 1.63 \text{ m}^2$$

1<sup>st</sup> floor tower outlet area =  $2.75 \times 0.593 = 1.63 \text{ m}^2$ ,  
 high window area =  $4.4 \times 0.371 = 1.63 \text{ m}^2$ ,

Ground floor openings: ( $i = 1$ )

$$\frac{\frac{2}{A^2} + 0.53}{\frac{2}{(2.2)^2} + 0.53} = \frac{[13.2 - (1-1)3.3] + 0.53(1-1)3.3}{[13.2 - (4-1)3.3] + 0.53(4-1)3.3}$$

$$\frac{2}{A^2} + 0.53 = \frac{0.94 \times 13.2}{8.547} = 1.45$$

$$\frac{2}{A^2} = 0.92 \rightarrow A^2 = 2.174 \rightarrow A = 1.5 \text{ m}^2$$

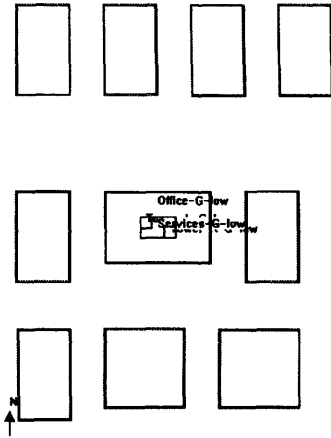
Ground floor tower outlet area =  $2.75 \times 0.546 = 1.5 \text{ m}^2$ ,  
 high window area =  $4.4 \times 0.341 = 1.5 \text{ m}^2$ ,

Western elevation was avoided when allocating high windows, as the dominant wind direction is west, to avoid positive wind coefficient on the windows which drive air flow out.

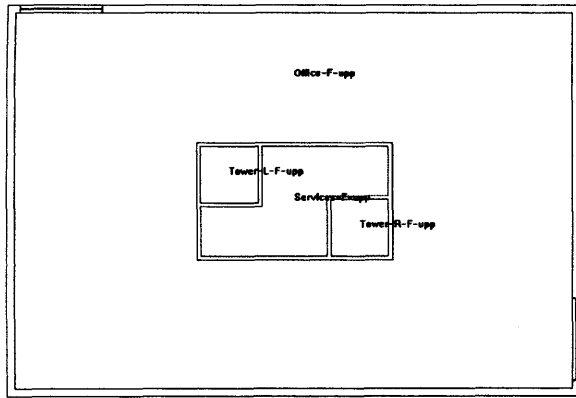
***Typical perimeter windows;***

Glazing ratio to perimeters window is specified to be 40% of the exposed wall, refer to App-A 2 for window area calculations. However, window's height was reduced from 1.5m to 1.4m to keep the 40% ratio after adding two high windows per floor.

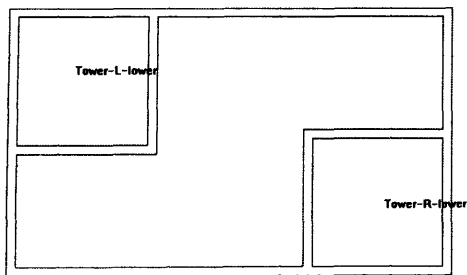
## 6.2.2 WIND CATCHER MODEL DESCRIPTION



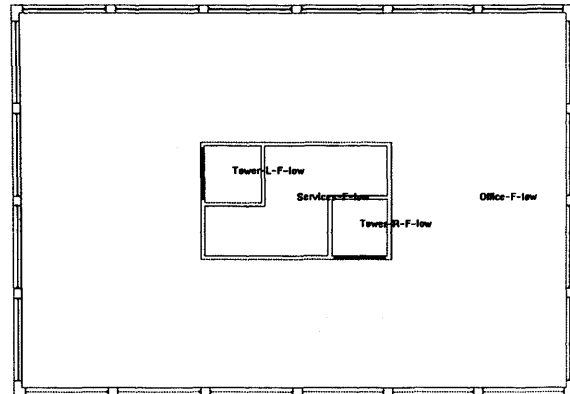
**Figure 70, Ground floor-lower the office bldg surrounded by buildings.**



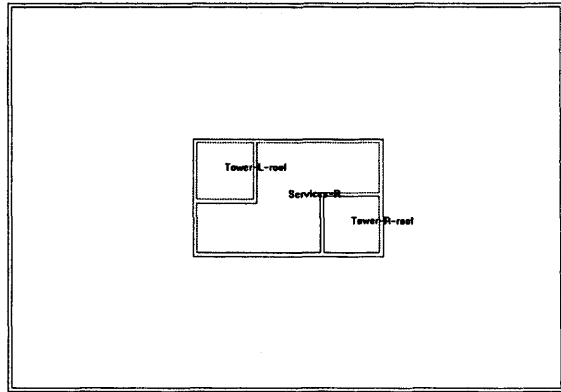
**Figure 72, Typical floor upper level, above occupant zone, contains high windows to discharge the exhausted air, no internal gains assigned to this zone.**



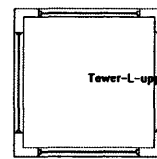
**Figure 74, Tower lower level, contains the rest of the evaporative column as applicable; the area in the middle is external space.**



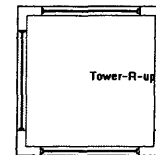
**Figure 71, Typical floor lower level, contains all the internal heat gains, tower outlets, and the typical perimeter windows used for night ventilation.**

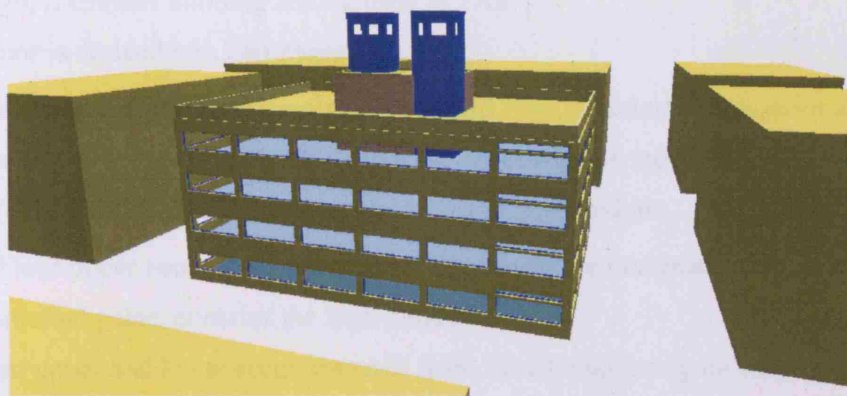


**Figure 73, Roof floor level, the surrounding area is external space, the evaporative column starts here.**

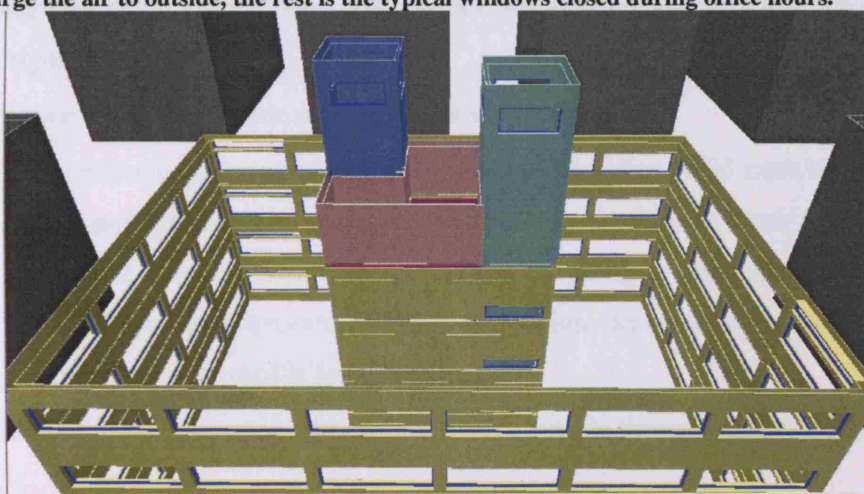


**Figure 75, Tower upper level, contains the tower inlets.**

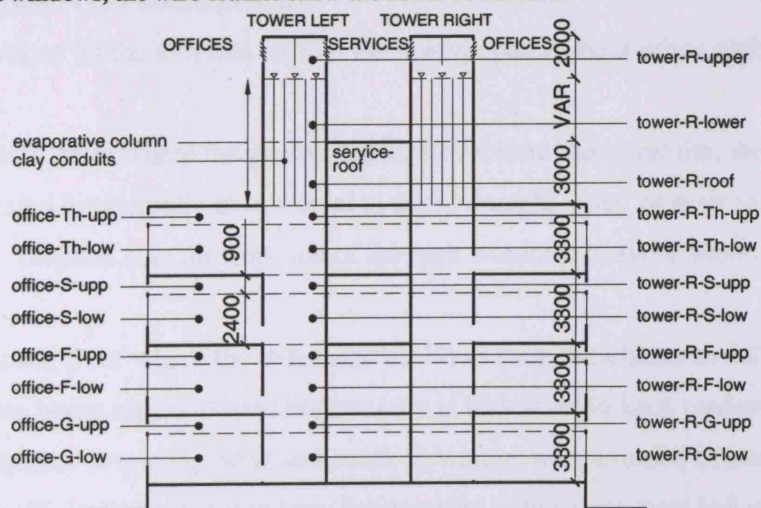




**Figure 76, Wind catcher office within the urban context, the horizontal high windows to discharge the air to outside, the rest is the typical windows closed during office hours.**



**Figure 77, The floors are removed to show the distribution of tower inlets, tower outlets, high and typical windows, the wire-frames show the zones boundaries.**



**Figure 78, Section through the building explains the zoning criterion; dashed lines indicate the boundaries between zones.**

***Zoning criterion:***

Figure 78, illustrates building zoning used in TAS.

Each floor is divided into two zones;

- Floor lower zone; represents the occupied zone, all internal heat gains are assigned to this level, air flow in from tower into the space from this level (tower outlets), in addition to typical perimeter windows.
- Floor upper zone; represents the volume above the occupied space, free of internal gains, contains the high windows.

Services; upper and lower zones for each floor, no internal heat gain was assigned for all floors services as the ventilation of these areas would be arranged separately from the office ventilation system, thus, they are not part of the study.

Tower right and Tower left;

- Tower lower and upper zones throughout the floors,
- Evaporative column; starts at the level of tower-roof to avoid extra tower height, and the rest of evaporative column is included in the tower lower zone. The height of tower lower zone is variable according to the evaporative column height, e.g. when evaporative column is 5m high, the tower lower is 2m because the tower roof is 3m (fixed height).
- Tower upper; this zone admits the air from outside through tower inlets.

***Aperture types:***

Aperture sizes as calculated in 6.2.1.

Tower inlets; to let the external air into the tower, open 24 hour allow night ventilation.

Tower outlets; from where the pre-cooled air flows from the tower into the occupied spaces, located horizontally at low level to avoid draught, open 24 hour to allow night ventilation. Located is in the opposite of the high windows to avoid short circuits ventilation.

High windows; from where the exhausted air flows from the offices to outside, open during office hours only. Located horizontally at high level to keep contaminated air above occupancy level. The west and south elevations were avoided to keep negative pressure coefficient on these windows (as the wind blows from west and west/south



directions), to improve air movement by increasing the pressure difference between air inlet and outlet.

Typical windows; closed during office hours and fully opened for night ventilation.<sup>7</sup>

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<sup>7</sup> Time schedule as shown in Figure 79.

### 6.2.3 WIND CATCHER MODEL SPECIFICATION AND ASSUMPTION

The same calendar, weather file and building elements applied to the base model were assigned to this model, in addition to the new specifications for new elements added to this model:

Transparent Construction		Name		Tower outlet		Description		single glazed window		
Solar Transmittance	External Solar Absorptance		Internal Solar Absorptance		Light Transmittance	Emissivity		Conductance (W/m2 C)	Time Constant (hours)	Extern Blin
	ext. surf.	int. surf.	int. surf.	ext. surf.		External	Internal			
0.780	0.075	0.075	0.075	0.075	0.870	0.845	0.845	166.667	0.000	NO
M-Code	Widk...	Solar...	Ext S...	Int S...	Ext E...	Int E...	Cond...	Conv...	Vapo...	Description
am1pilk\2	6.0	0.780	0.070	0.070	0.845	0.845	1.000	0.000	9999...	6MM CLEAR FLO/

Opaque Construction		Name		Tower wall		Description		Insulated shaft wall		
Solar Absorptance		Emissivity		Conductance (W/m2 C)	Time Constant (hours)					
ext. surf.	int. surf.	External	Internal							
0.360	0.650	0.920	0.900	0.594	5.989					
M-Code	Width [...]	Conduc...	Convec...	Vapour ...	Density	Specific...	Description			
am1conc\6	150.0	0.380	0.000	14.800	1200.000	920.000	CONCRETE 3/ m.c. 5 *3			
am1ins\11	50.0	0.040	0.000	21.000	16.000	1210.000	POLYSTRENE EXPANDED SHEET CLOSED			
am1plast\23	20.0	0.500	0.000	19.200	1300.000	769.000	CEMENT RENDERING 1 *3			
am1s\38	3.0	999.999	0.000	5.565	0.000	0.000	WHITE PAINT *3			

#### Internal conditions:

schedule		schedule		schedule	
Name		Name		Name	
24 hours		Night ventilation		Office 8am to 6pm Week	
Description		Description		Description	
				Basic office hours	
Hour	0/1	Hour	0/1	Hour	0/1
0-1	1	0-1	1	0-1	0
1-2	1	1-2	1	1-2	0
2-3	1	2-3	1	2-3	0
3-4	1	3-4	1	3-4	0
4-5	1	4-5	1	4-5	0
5-6	1	5-6	1	5-6	0
6-7	1	6-7	1	6-7	0
7-8	1	7-8	0	7-8	0
8-9	1	8-9	0	8-9	1
9-10	1	9-10	0	9-10	1
10-11	1	10-11	0	10-11	1
11-12	1	11-12	0	11-12	1
12-13	1	12-13	0	12-13	1
13-14	1	13-14	0	13-14	1
14-15	1	14-15	0	14-15	1
15-16	1	15-16	0	15-16	1
16-17	1	16-17	0	16-17	1
17-18	1	17-18	0	17-18	1
18-19	1	18-19	0	18-19	0
19-20	1	19-20	0	19-20	0
20-21	1	20-21	0	20-21	0
21-22	1	21-22	0	21-22	0
22-23	1	22-23	1	22-23	0
23-0	1	23-0	1	23-0	0

Figure 79, Schedules applied to TAS.

Internal heat gain is the same as the base model, Figure 80 and Figure 81 shows the internal gain assigned to the naturally ventilated office lower zones during office hours and weekend.

Figure 82 shows the internal gain in the always unoccupied zones, i.e. upper zones, tower zones and services.

The temperature and humidity thermostat is always off in the above mentioned conditions.

*Simulating the evaporative column;*

However, a separate internal conditions is assigned to tower-roof, with no internal heat gain and temperature and humidity thermostat control. Thermostat temperature and humidity are based on the data extracted from Badran chart (Figure 67), i.e. the conditions of air leaving evaporative column, as this zone represents the condition of the air leaving the evaporative column.

Name: Basic office gains 41W/m2 total

Description: Basic office weekdays only

Radiant Proportion		View Coefficient	
Lighting	0.30	Lighting	0.49
Occupant	0.20	Occupant	0.23
Equipment	0.10	Equipment	0.37

Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.50	1.00	0.00	24 hours
Ventilation	ach	0.00	1.00	0.00	24 hours
Lighting Gain	w/...	12.00	1.00	0.00	Office 8am to 6p...
Occupancy Sens...	w/...	7.00	1.00	0.00	Office 8am to 6p...
Occupancy Late...	w/...	7.00	1.00	0.00	Office 8am to 6p...
Equipment Sensi...	w/...	15.00	1.00	5.00	Office 8am to 6p...
Equipment Laten...	w/...	0.00	1.00	0.00	24 hours

Figure 80, Internal heat gain in offices during working hours

Name: Office no gains

Description: Office weekend only

Radiant Proportion		View Coefficient	
Lighting	0.48	Lighting	0.49
Occupant	0.20	Occupant	0.23
Equipment	0.10	Equipment	0.37

Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.50	1.00	0.00	24 hours
Ventilation	ach	0.00	1.00	0.00	24 hours
Lighting Gain	w/...	0.00	1.00	0.00	24 hours
Occupancy Sens...	w/...	0.00	1.00	0.00	24 hours
Occupancy Late...	w/...	0.00	1.00	0.00	24 hours
Equipment Sensi...	w/...	0.00	1.00	0.00	24 hours
Equipment Laten...	w/...	0.00	1.00	0.00	24 hours

Figure 81, Internal conditions in offices during weekend.

Name: Always unoccupied, No internal gain

Description: weekend and weekday

Radiant Proportion		View Coefficient	
Lighting	0.48	Lighting	0.49
Occupant	0.20	Occupant	0.23
Equipment	0.10	Equipment	0.37

Gain	Units	Value	Factor	Setback Value	Schedule
Infiltration	ach	0.50	1.00	0.00	24 hours
Ventilation	ach	0.00	1.00	0.00	24 hours
Lighting Gain	w/...	0.00	1.00	0.00	24 hours
Occupancy Sens...	w/...	0.00	1.00	0.00	24 hours
Occupancy Late...	w/...	0.00	1.00	0.00	24 hours
Equipment Sensi...	w/...	0.00	1.00	0.00	24 hours
Equipment Laten...	w/...	0.00	1.00	0.00	24 hours

Figure 82, Internal gain applied to towers and services.

Name: New Thermostat

Description: Evaporative tower-roof

Proportional Control: ☐

Control Range: 0.00

Gain	Units	Value	Factor	Setback Value	Schedule
Upper Limit	oC	22.70	1.00	100.00	Office 8am to 6pm Weekday
Lower Limit	oC	-50.00	1.00	-50.00	24 hours
Humidity Upper ...	%	100.00	1.00	100.00	24 hours
Humidity Lower ...	%	92.00	1.00	0.00	Office 8am to 6pm Weekday

Figure 83, Thermostat control applied to tower-roof zone in the case of 6m tower height.

## 7 CHAPTER 7: DISCUSSION

### 7.1 ANALYSIS OF FINDING

#### 7.1.1 CONDITION OF AIR LEAVING 6M HIGH- EVAPORATIVE COLUMN

First TAS simulation runs using equal tower outlets in all floors (2.75x0.8)m and equal high windows in all floors (4.4x0.5)m.

Second TAS simulation runs using different tower outlet and high window sizes in all floors according to sizing equation results.

Third TAS simulation runs using better insulation for roof (100 mm extruded polystyrene layer was added) and sizing outlets.

Table 6, represents the results of these three models, day 200, represents the hottest day in this weather file, is selected for the comparison. Hour 18 is selected because it is within office hours and the external temperature at this hour is close to the assumption made during the calculations.

TAS model	Day/hour	Ext-tem°C	Ext-RH%	G-tem°C	F-tem°C	S-tem°C	Th-tem°C	G-RH%	F-RH%	S-RH%	Th-RH%
Equal outlet	200/18	32.4	45	26.19	27.27	28.35	30.53	73.27	69.64	64.99	57.22
Sizing outlet	200/18	32.4	45	26.96	27.82	28.38	30.01	69.17	67.04	64.96	59.36
Better Insulation	200/18	32.4	45	26.95	27.79	28.27	29.34	69.25	67.13	65.32	61.48

Table 6, TAS results (temperature and relative humidity) in the offices for the three models.

The temperature is the resultant temperature as it gives more realistic evaluation of perceived thermal comfort because it takes into account the radiant heat exchange.

Figure 84 shows that the resultant temperature is lower than dry bulb temperature during the day due to the radiative coolth of the thermal mass, while it is higher during the night when the structure releases its content of temperature.

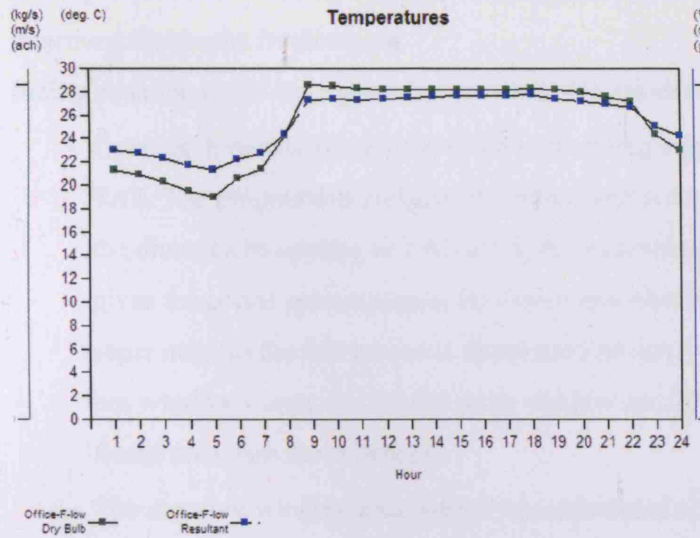


Figure 84, Resultant and dry bulb temperatures in first floor office day 200.

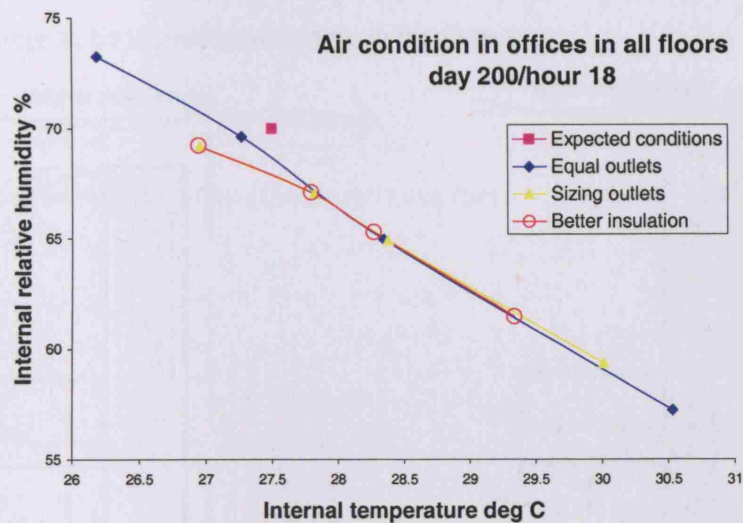


Figure 85, Comparison between the results of computer simulation and expected conditions based on numerical calculation for the offices, nodes on the lines indicate different floors.

Figure 85 compares the condition of air in offices in all floors in the three models described above with the expected condition which was numerically calculated (Table 5).

It illustrates that Ground, first and second floor offices are within  $\pm 1^\circ\text{C}$  from the anticipated temperature. While the relative humidity in the same floors is within  $\pm 5\%$  from the anticipated one. It shows also, that sizing the outlets reduces the differences

in temperature and humidity between different floors. Better insulation for the roof improved the results furthermore.

Sizing equation could have given better results if considering the following points:

- Opening dimensions, calculated from the sizing equation, were assigned to TAS. The programme excludes the frame area from the opening, this implies the dimensions applied to TAS are frame inclusive, while the sizing equation gives the actual opening sizes, the frame area should be calculated in each case separately, as the frame area is direct proportional to the window's perimeter not window's area, i.e. for the same window area, the square shape has less frame area than the rectangle.
- The required window area, which was calculated according the needed air flow, was assigned to the third floor. The lower openings were calculated by the sizing equation accordingly. Probably, this area should be assigned to the ground floor as this floor receives the direct amount of air, and the upper openings to be increased according to the formula.

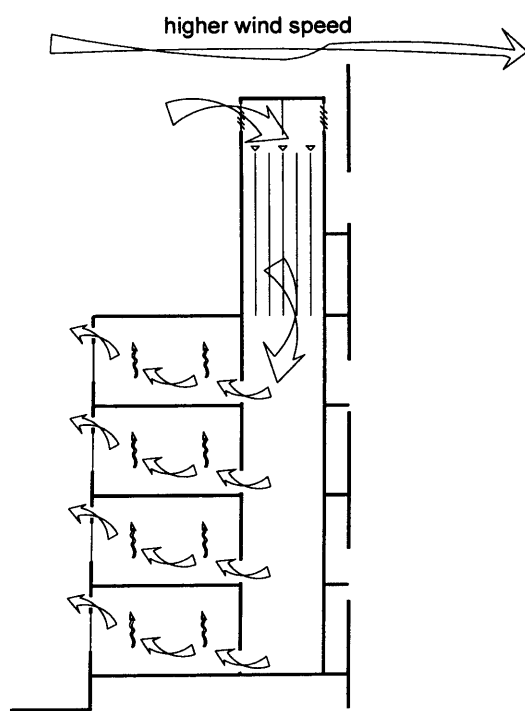


Figure 86, Day time ventilation regime.

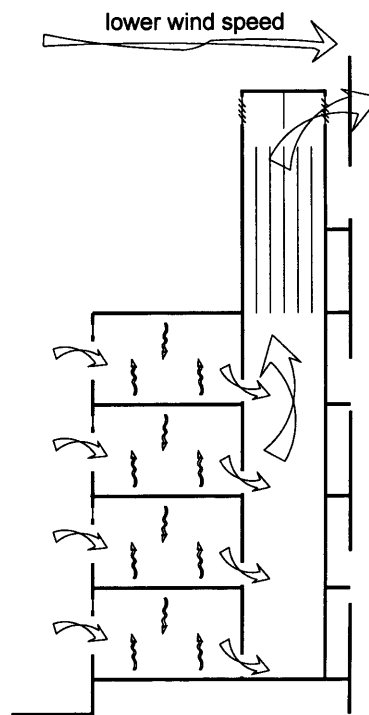


Figure 87, Night ventilation regime.

TAS model 3 results during day 200 showed two ventilation regimes,



- Daytime ventilation; during office hours air flows from tower lower in average of 8.628 kg/s. Then, stream from the floor of tower-roof, i.e. evaporative column in average of 8.628kg/s and enters the offices from tower outlets (of all floors) in average of 8.546 kg/s. Afterwards, air flows outside offices via high window in average of 8.416 kg/s, as illustrated in Figure 86.
- Night ventilation; air flows from outside into the offices through the perimeter typical windows (of all floors) in average of 67.489 kg/s, 64.37 kg/s in average leaves out through adjacent perimeter windows (cross ventilation) and 3.253 kg/s flows out through tower outlets. Then, 3.2kg/s leaves the tower lower, this regime is illustrated in Figure 87.

Figure 88 shows TAS results (temperature and humidity) for model 3 for all offices over summer season plotted on Jordan comfort zone for summer season. It demonstrates that the indoor conditions are outside the comfort zone because of the extra humidity, which is expected as the evaporative cooling reduces sensible heat and increases the latent heat, in addition to the latent gain by office occupants. According to Figure 84, the internal relative humidity should be reduced to 50% to accommodate the internal temperature within the comfort zone.

To simulate the dehumidification plant, the humidity upper limit was set to 50% in the thermostat assigned to offices-low. The building average removal load due to dehumidification (measured over summer season) was 80672.21 Wh, the offices area in all floors is  $564 \times 4 = 2256 \text{ m}^2$ , considering 95% treated % of gross (Energy consumption Guide 19)  $\rightarrow$  treated floor area =  $2143.2 \text{ m}^2 \rightarrow$  average removal load to keep the offices within the comfort zone (23 to 28°C & 50%) is  $37.64 \text{ Wh/ m}^2 = 0.0037 \text{ kWh/ m}^2$ .

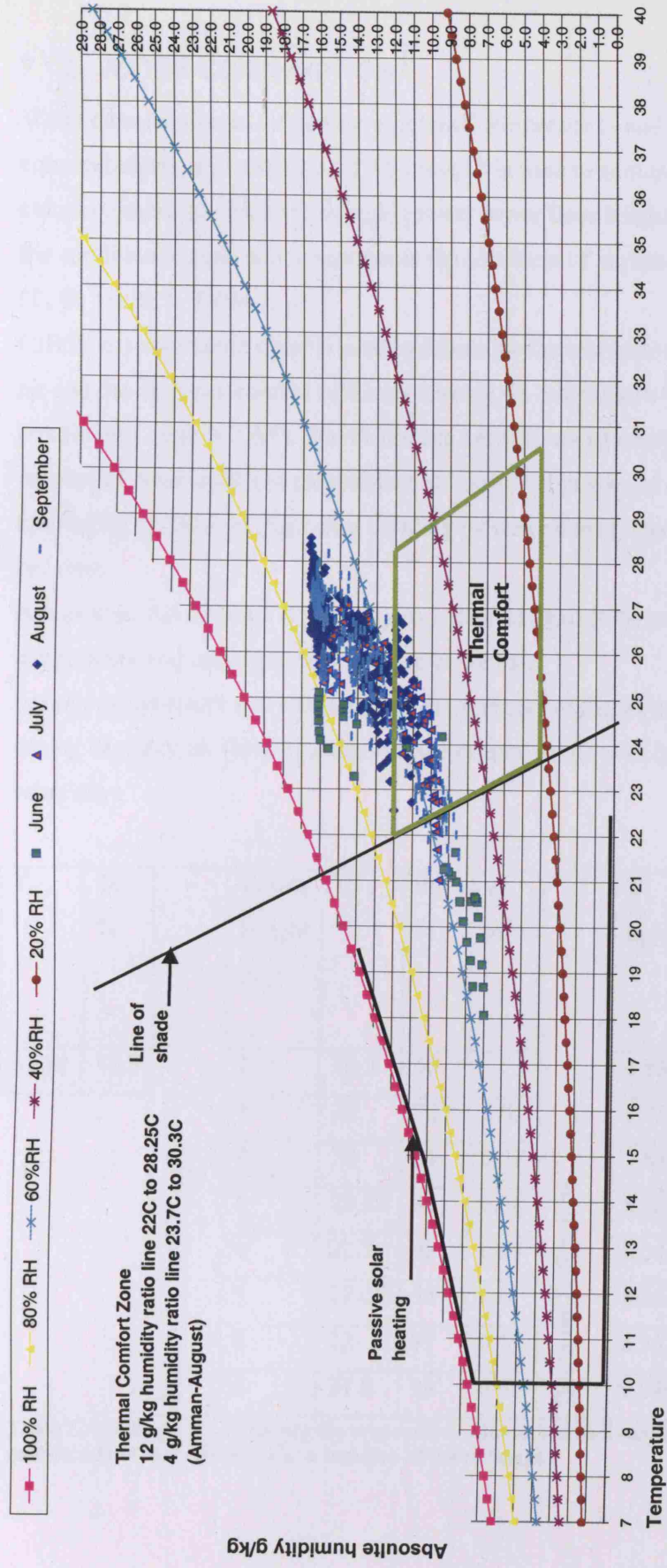


Figure 88, TAS results; condition of air in all offices over summer season plotted on Jordan comfort zone for summer season.

### 7.1.2 WATER CONSUMPTION

Water consumption as a function of internal temperatures and different evaporative column heights is investigated. TAS model 3 is used to simulate different evaporative column heights (2→9)m by changing tower lower floor height and the thermostat of the conditioned zone which represents the condition of air leaving evaporative column ( $T_e, \Phi_e$ ) refer to Table 7.

CIBSE psychrometric chart is used to determine the moisture content of the ambient air and the moisture content of the air leaving the evaporative column (the air conditioned zone in TAS). The difference between moisture contents indicates the amount of water added to the ambient air measured in g/kg of dry air. Multiplying this number by air flow-in (kg/s) and dividing by water density gives the amount of water per time.

Afterwards, the different tower heights is plotted against the amount of water, internal temperature and temperature of the pre-cooled air.

Internal temperature and humidity are the averages of the all offices over office hours during day 200; air flow-in is the average of total air flow-in into all floors in the same day.

$T_o$ °C	$\Phi_o$ %	Based on Badram chart	Tower Height m	$T_e$ °C	$\Phi_e$ %	$v_e$ m/s	Based on TAS results	$V_i$ kg/s	$T_i$ °C	$\Phi_i$ %	Based CIBSE psychrometric chart	Additional Moisture content g/kg
31.81	46.9		2	26.5	65	1		6.861	29.42	52.26		0.3
			3	25	72.5	0.87		7.75	28.73	55.91		0.5
			4	24	81	0.77		7.885	28.33	60.07		1.3
			5	23.25	86	0.68		8.282	27.94	62.66		1.6
			6	22.7	92	0.65		8.546	27.77	65.58		2.1
			7	22.25	95	0.6		8.843	27.34	66.59		2.1
			8	22	97	0.57		8.957	27.19	68.89		2.2
			9	21.8	98	0.53		9.049	27.07	69.4		2.3

**Table 7, Condition of air leaving the evaporative column, internal conditions and the moisture content added to ambient air as a function of tower height.**

*Two meter tower high:*

total air flow-in in all floors 6.861 kg/s, additional moisture 0.3 g/kg

$$\rightarrow 6.861 \times 0.3 = 2.058 \text{ g(water) / s}$$

$$\rho_{\text{water}} = 1000 \frac{\text{kg}}{\text{m}^3} = 1 \frac{\text{kg}}{\text{liter}} = 1000 \frac{\text{g}}{\text{liter}}$$

$$\therefore \frac{2.058 \frac{\text{g}}{\text{s}}}{1000 \frac{\text{g}}{\text{liter}}} = 0.002058 \frac{\text{liter}}{\text{s}} \times 3600 \text{ s} = 7.41 \frac{\text{liter}}{\text{hour}}$$

*Three meter tower high:*

$$7.75 \times 0.5 = 3.875 \frac{\text{g}}{\text{s}} \rightarrow \frac{3.875}{1000} \times 3600 = 13.95 \frac{\text{liter}}{\text{hour}}$$

*Four meter tower high:*

$$7.885 \times 1.3 = 10.2505 \frac{\text{g}}{\text{s}} \rightarrow \frac{10.2505}{1000} \times 3600 = 36.90 \frac{\text{liter}}{\text{hour}}$$

*Five meter tower high:*

$$8.282 \times 1.6 = 13.2512 \frac{\text{g}}{\text{s}} \rightarrow \frac{13.2512}{1000} \times 3600 = 47.7 \frac{\text{liter}}{\text{hour}}$$

*Six meter tower high:*

$$8.546 \times 2.1 = 17.9466 \frac{\text{g}}{\text{s}} \rightarrow \frac{17.9466}{1000} \times 3600 = 64.61 \frac{\text{liter}}{\text{hour}}$$

*Seven meter tower high:*

$$\frac{8.843 \times 2.1}{1000} \times 3600 = 66.85 \frac{\text{liter}}{\text{hour}}$$

*Eight meter tower high:*

$$\frac{8.957 \times 2.2}{1000} \times 3600 = 70.94 \frac{\text{liter}}{\text{hour}}$$

*Nine meter tower high:*

$$\frac{9.049 \times 2.3}{1000} \times 3600 = 74.93 \frac{\text{liter}}{\text{hour}}$$

Figure 89 illustrates water consumption, average internal temperature (in all floors) and temperature of air leaving the evaporative column as a function of evaporative column height.

As the tower height increases the internal temperature steadily decreases, until tower height of 7m is reached. Then, higher tower is not significantly decreases the internal temperature. It shows also, bigger reduction in the temperature of the air leaving evaporative column is required to decrease the internal temperature.

Water consumption progressively increases along with tower height until tower height of 6m, the slope becomes more flattened.

The internal temperature curve, which is all floors temperatures averages, is affected by the third floor temperature which is 1 degree higher than the lower floor. This curve could be improved by proper window sizing to enhance the air flow in and by further improving of roof insulation.

Figure 90, compares the velocity of air leaving the evaporative column as a function of tower height between data obtained from TAS with those obtained from Badran chart for day 200.

Average air flow out from tower-roof (evaporative column) measured in kg/s was divided by the density of air at ( $T_e = 22.7^\circ\text{C}$ ,  $\Phi_e = 92\%$ );  $\rho = 1.164 \text{ kg/m}^3$  multiplied by tower cross section.

While Badran and Bahadori graphs illustrate inverse proportional between tower height and outlet velocity; TAS result shows direct proportion. In addition, the velocities value according to TAS are much less than those from Badran and Bahadori.

It seems that the air flow tends to change its regime when water is introduced to the system and the tower temperature is reduced. The column of cool air drives larger air velocities as the tower height increases. While equation used in the manual calculations depends on the external wind velocity and pressure drop through the column.

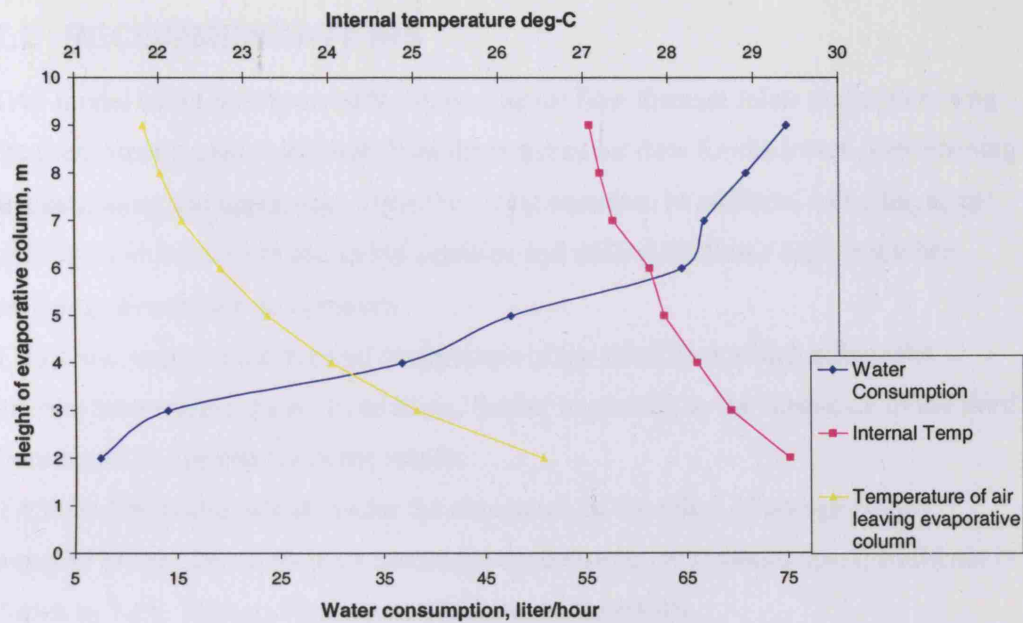


Figure 89, Water consumption, average internal temperature over all floors and temperature of air leaving the evaporative column as a function of evaporative column height.

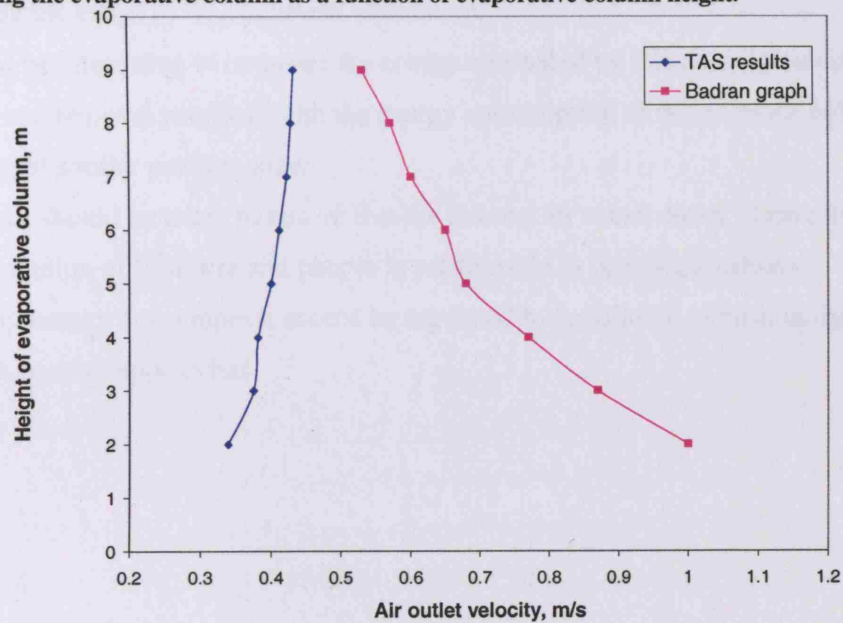


Figure 90, Comparison between TAS data and Badran chart for the velocity of air leaving the evaporative column as a function of tower height in day 200.

## 7.2 RECOMMENDATIONS

TAS model could be improved by improving air flow through inlets and outlet using the (benchmark) area calculated from the required air flow for the lower floor opening and increasing the upper ones using the sizing equation. In addition, using the actual opening calculated from the sizing equation and adding the frame area to it when assigning dimensions to apertures.

This could improve the internal temperature of the third floor which affects the internal temperature curve. In addition, further improving to the insulation of the third floor could be applied for better results.

TAS has limitations which hinder the simulation of the effect of energy storing material of the clay conduit, as such adjacent construction (100mm apart) could not be drawn in TAS. This could obstruct obtaining better results.

High-level tower outlet location could be simulated instead of low-level windows to stimulate the effect of displacement ventilation.

It would be interesting to compare the energy consumed by this model (humidity adding and removal profiles) with the energy consumption of mixed mode office building of similar performance.

Measures should be taken to ensure that the internal air speed doesn't cause draught, by distribution of furniture and people in relationship to opening locations

Building energy consumption should be regulated by legislation to push designs towards passive approaches.



## 8 CHAPTER 8: CONCLUSION

The purpose of this paper is to investigate the cooling potential of evaporative cooling wind catcher in office building in Amman/Jordan.

Psychrometric chart was developed to represent the summer comfort zone in Amman. This chart was used to estimate the loads needed to bring internal conditions into comfort threshold.

The graphs developed by Badran(2003) and Bahadori(1985) for traditional windcatcher evaporative model based on weather data are used to establish the measurements of the wind tower and to investigate the possibilities of applying traditional PDEC tower to office building in similar weather conditions.

The outcome is promising as TAS temperature and humidity results were within  $\pm 1^\circ\text{C}$  and  $\pm 5\%$  from the calculated values.

The results demonstrates that as the tower height increases the water consumption steadily increases until 6m-tower height is reached, the increment becomes less progressive.

The average internal temperature is gradually decreases as tower height increases till 7m-tower height is reached, then higher tower is not notably improve the internal temperature.

The model of 6m-evaporative column high, managed to drop the external temperature in day 200 (hottest day) from  $31.81^\circ\text{C}$  (average over working hours) to average of  $27.7^\circ\text{C}$  in gross area of  $2256\text{m}^2$  using 64.6 litre of water/ hour.

Dehumidification needed to bring the internal conditions over the cooling season into comfort zone is  $80672.21 \text{ Wh} = 0.0037 \text{ kWh/ m}^2$  treated area.

Comparison of air outlet velocity as a function of tower height between the assumption charts and TAS results illustrates differences in air flow regimes; while assumption charts shows inverse proportional between tower height and outlet velocity; TAS result shows direct proportion.

To conclude, evaporative cooling via windcatcher in an office building is a promising means of passive ventilation, it managed to bring the internal conditions into the thermal comfort zone with minor energy demand.

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## Appendices

### APPENDIX A:

#### Abbreviation:

GF: Ground floor

FF: First floor

SF: Second floor

TF: Third floor

RF: Roof floor

CL: Concrete level

A: area

T<sub>n</sub>: Neutrality temperature

T<sub>L</sub>: Temperature lower limit

T<sub>U</sub>: Temperature upper limit

#### **App-A 1, Abbreviations and technical terms.**

#### Windows area calculations:

The long-elevation area floor = elevation length x floor height	$30 \times 3.3 = 99 \text{ m}^2$
Glazing area per floor	$99 \times \% 40 = 39.6 \text{ m}^2$
Window's area, provided that the number of windows are 6	$39.6 / 6 = 6.6 \text{ m}^2$
Window's width, provided that window's height is 1.5m	$6.6 / 1.5 = 4.4 \text{ m}$

**App-A 2, Windows dimensions calculations provided that glazing ration is %40 of the exposed wall.**

**APPENDIX B:**

Elevation : 980 m

Enthalpy,  $h$  : kJ / kg

Volume,  $v$  : m<sup>3</sup> / kg

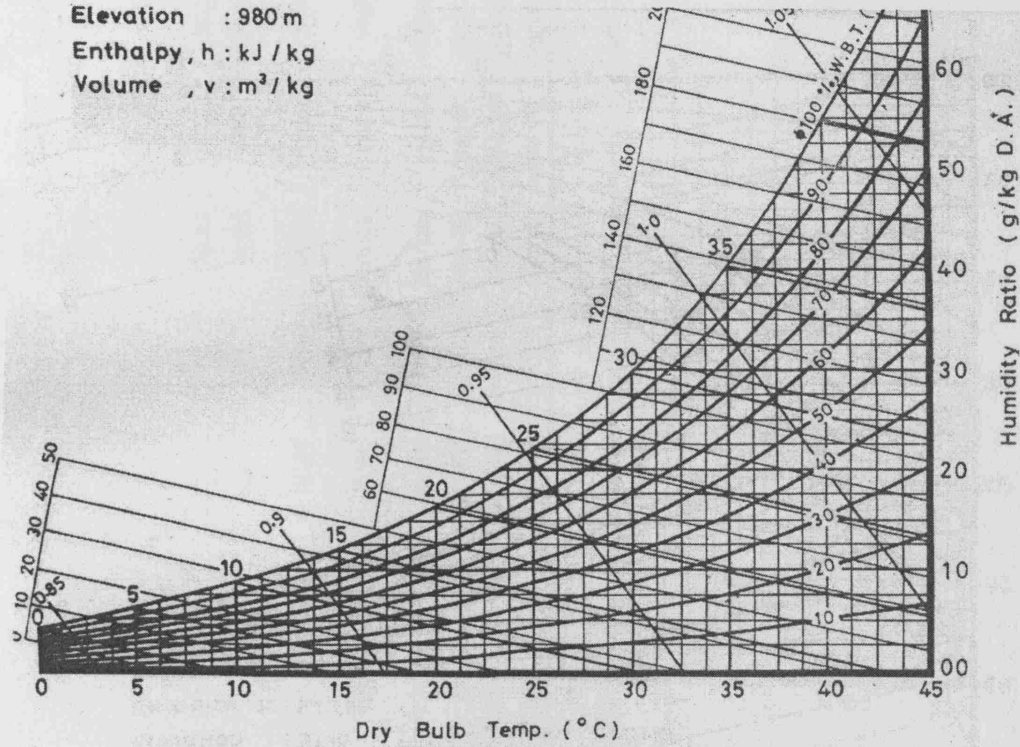


Figure A-1 Psychrometric chart for the city of Amman.

App-B 1, Source: Alsaad, M and Hammad, M (2001) *Heating and Air-Conditioning*. 3<sup>rd</sup> edition, Amman-Jordan, privately published.



Table 6.1 Heat emission (W) from an adult male body (of surface area 2 m<sup>2</sup>) and average heat emission per person for a mixture of men, women and children typical of the stated application

Activity	Typical application	Occupancy density (m <sup>2</sup> /person)	Total, sensible and latent heat emission (W) for stated application and dry bulb temperature (C) for adult male (and average for mixture of men, women and children)									
			15		20		22		24		26	
			Sensible	Latent	Sensible	Latent	Sensible	Latent	Sensible	Latent	Sensible	Latent
Seated, inactive	Theatre, cinema matinee	0.75–1.0 <sup>(2,3)</sup>	115 (100)	100 (87)	15 (13)	90 (78)	25 (22)	80 (70)	35 (30)	75 (65)	40 (35)	65 (57)
Seated, inactive	Theatre, cinema evening	0.75–1.0 <sup>(2,3)</sup>	115 (105)	100 (91)	15 (14)	90 (82)	25 (23)	80 (73)	35 (32)	75 (68)	40 (37)	65 (59)
Seated, light work	Restaurant	1.0–2.0 <sup>(2,3)</sup>	140 (126)	110 (99)	30 (27)	100 (90)	40 (36)	90 (81)	50 (45)	80 (72)	60 (54)	70 (63)
Seated, moderate work	Office	8–39 <sup>(4-6)</sup> , 14 <sup>(4,7)*</sup>	140 (130)	110 (102)	30 (28)	100 (93)	40 (37)	90 (84)	50 (46)	80 (74)	60 (56)	70 (65)
Standing, light work, walking	Department store	1.7–4.3 <sup>(2,3)</sup>	160 (141)	120 (106)	40 (35)	110 (97)	50 (44)	100 (88)	60 (53)	85 (75)	75 (66)	85 (75)
Standing, light work, walking	Bank	—	160 (142)	120 (107)	40 (35)	110 (98)	50 (44)	100 (89)	60 (53)	85 (76)	75 (66)	85 (76)
Light bench work	Factory	—	235 (209)	150 (133)	85 (76)	130 (116)	105 (93)	115 (102)	120 (107)	100 (89)	135 (121)	80 (71)
Medium bench work	Factory	—	265 (249)	160 (150)	105 (99)	140 (132)	125 (117)	125 (117)	140 (132)	105 (99)	160 (150)	90 (85)
Heavy work	Factory	—	440 (440)	220 (220)	220 (220)	190 (190)	250 (250)	165 (165)	275 (275)	135 (135)	305 (305)	105 (105)
Moderate dancing	Dance hall	0.5–1.0	265 (249)	160 (150)	105 (99)	140 (132)	125 (117)	125 (117)	140 (132)	105 (99)	160 (150)	90 (85)

\* Recommended

Notes:

(1) Figures in parenthesis are adjusted heat gains based on normal percentage of men, women and children for the applications listed. This is based on the heat gain for women and children of 85% and 75% respectively of that of an adult male.

(2) For restaurant serving hot meals add 10 W sensible and 10 W latent for food per individual.