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Sustainable Solutions for Cooling Systems in Residential Buildings Case Study in the Western Cape Province, South Africa

Intended category: Evolutions in Technology

Abstract

The energy demand in building sectors for summer air-conditioning is growing exponentially due to thermal loads, increased living standards and occupant comfort demands throughout the last decades. This increasing consumption of primary energy is contributing significantly to emission of greenhouse gases and therefore to global warming. Moreover, fossil fuels, current main sources of energy used for electricity generation, are being depleted at an alarming rate despite continued warning. In addition, most air-conditioning equipment still utilise CFC's, promoting further destruction of our planet's protective ozone layer. Concerns over these environmental changes, have begun shifting the emphasis from current cooling methods, to 'sustainable strategies' of achieving equally comfortable conditions in building interiors. Study of ancient strategies applied by vernacular architecture shows how the indigenously clean energies to satisfy the cooling need were used. One of the most important influences on vernacular architecture is the macro-climate of the area in which the building is constructed. Mediterranean vernacular architecture, as well as that of much of the Middle East, often includes a courtyard with a fountain or pond; air cooled by water mist and evaporation is drawn through the building by the natural ventilation set up by the building form, and in many cases also includes wind-catchers to draw air through the internal spaces. Similarly, Northern African vernacular designs often have very high thermal mass and small windows to keep the occupants cool. Not only vernacular structure but also the recent development in solar and geothermal cooling technologies could be used to the needs for environmental control. Intelligent coupling of these methods as alternative design strategies could help developing countries such as South Africa toward sustainable development in air-conditioning of building. In this paper, the possible strategies for sustainable cooling in residential buildings of Western Cape, South Africa are discussed.

Keywords: cooling systems; passive energy; residential buildings; South Africa; sustainability; vernacular architecture.

1. Introduction

In industrial countries, buildings account for 25-40% of total energy consumption in society. The most of this portion is consumed during the building's operational phase, for heating, cooling and lighting purposes which is contributing to significant amount of carbon dioxide (CO_2) emission (UNEP, 2007). If developing countries such as South Africa, one of the highest emitters of the Greenhouse gases per capita (UNEP/GRID-Arendal, 2002) (Fig. 1), follow the same unsustainable consumption path as developed countries, the consequences will be significant (UNEP, 2007) (Fig. 2).

In South Africa, air conditioning accounts for a significant portion of the electricity in most offices, hotels, hospitals and other facilities. In some cases air conditioning accounts for almost 50% of the monthly electricity bill (Energy Reduction, n. d.). Department of Minerals and Energy studies indicate that in the Cape Town summer, air-conditioning accounts for up to 74% of electricity consumption in office buildings. Eskom (the national electricity provider) has called upon all consumers to use electrical equipment specifically air-conditioners more efficiently (Eskom, n. d.). Although the main focuses is still on office building in South Africa, but cooling demand in houses due to thermal loads, increasing living standards and occupant comfort demands, is increasingly growing. In addition, air conditioning equipments still utilize CFC's, promoting continued destruction of our protective ozone layer.

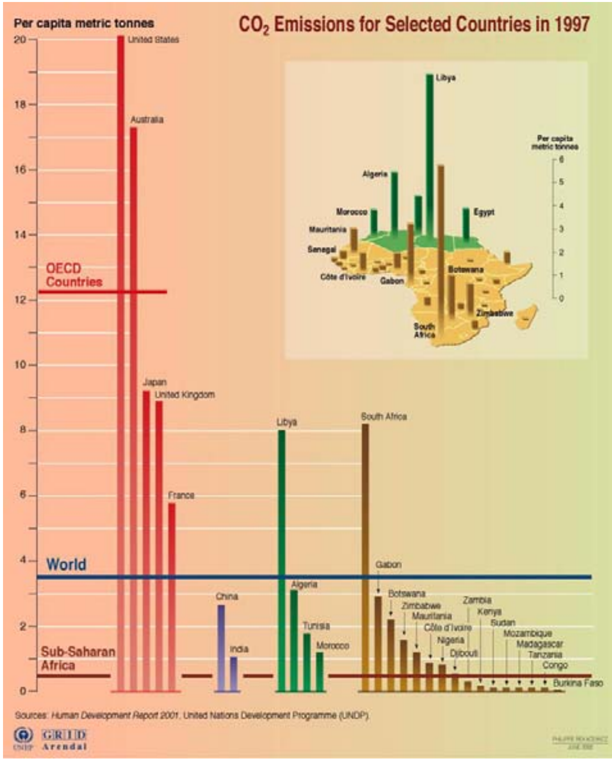

Fig. 1: Carbon Dioxide (CO2) emissions for selected African countries in 1997 (UNEP/GRID-Arendal, 2002)

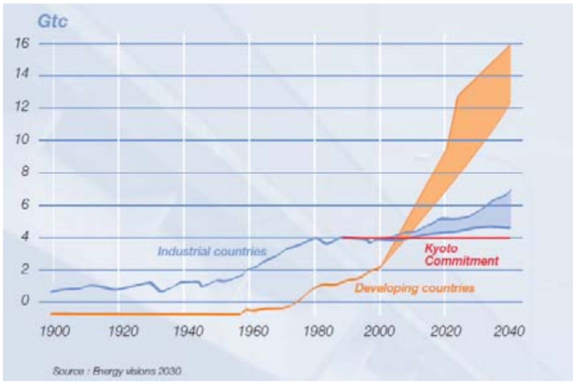

Fig. 2: After 2020 major parts of CO_2 emission will come from developing countries (UNEP, 2007)

Beyond the environmental implications, the human cost of over-conditioned spaces is considerable. In today's technological society, the main activities of living and working take place in an enclosed space in which people spend more than 90% of their time (Jenkins et al., 1990), and in more than 40% of the enclosed space, people suffer from health-, comfort- and safety related complaints and illnesses (Dorgan Associated, 1993) as a result of the 'sick building syndrome'. The emergence of the building-related sickness among building occupants can significantly reduce comfort and productivity (Dorgan Associated, 1993; Bonnefoy et al., 2004). South Africa as a developing country with about HIV positive population trying to improve health and living standards of population needs more consideration over these problems.

Since South Africa has signed the UNFCCC and the Kyoto Protocol Mid 2002 (UNIDO, 2003), it needs to take into consideration the promoting sustainable development by implementing policies and measures to, among others, enhance energy efficiency, protect and enhance sinks and reservoirs of greenhouse gases, increase the usage of new and renewable forms of energy and of advanced and innovative environmentally sound technologies. Applying renewable energy sources as an alternative for summer air-conditioning not only has an extensive potential for South Africa to meet its commitments but also it will have a significant contribution to improve living standards of its population.

Useful ancient energy strategies for natural cooling of buildings during summer that have been used for centuries in various parts of the world are now being re-examined and re-engineered in developed countries to fit within modern building forms and materials. By modifying and applying of these strategies compatible with weather condition of South Africa, people were able to live in comfort with less electricity consumption for air-conditioning systems.

In this paper, on the basis of Western Cape climate, ancient cooling strategies as well as new sustainable technologies applied for similar conditions will be reviewed. Finally, we will explore proper strategies for Western Cape as a case study.

2. Climate condition of Western Cape

Western Cape climate conditions generally range from Mediterranean in south-western corner to moderate coast in southeast and semi arid plateau in north and northeast. Overall, its summer climate is warm and dry with low rainfall prevail (Fig. 3). Near the coast, average summer temperature during the day is 27°C which can exceed up to 37°C. Inland temperatures are some 3-5°C higher (South Africa climate and weather, n.d.). Moreover, it should be noted that according to IPCC Fourth Assessment Report, world temperatures could rise by 1.1 to 6.4 °C during the 21st century (Solomon et al., 2007). In our study, we will consider on two general climate of this area here are mostly populated; warm and dry summer along the coast and warm to hot with dry summer at inland area.

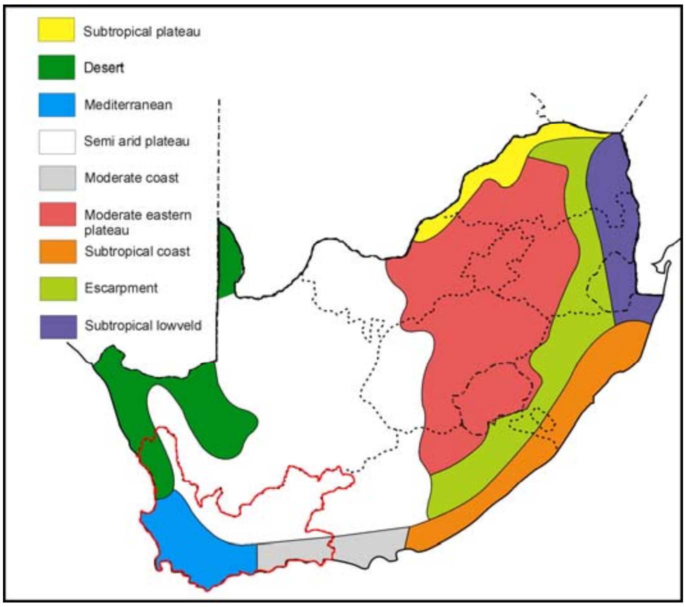

Fig. 3: Western Cape is distinguished by red boundary in South Africa map. Different colours represent different type of climates as shown in legend.

3. Ancient cooling strategies

Since antiquity, mankind reacted to his environment and used his faculties to develop strategies for obtaining thermal comfort in house. In that era, vernacular architectures were forced to devise ways to create comfortable internal conditions in summer time with only natural sources of energies and physical phenomena. The strategies relied on utilising energy from the sun and wind by the innovative architectural structures (Fathy, 1986). Since these solutions depended on the climate they were quite different from one another. To simplify the study, the various features and elements of buildings which devised as a useful cooling strategies, were divided into three major groups: basic design, construction materials, and architectural elements.

3.1. The basic design

3.1.1. The inner courts and summer quarters

The common feature of houses built in hot and arid climate such as Middle East was their inward orientation (Golany, 1980). Components of building were properly located relative to the Inner courts (Fig. 4). The main summer sitting-room opening directly faced onto the court through the porches. The south rooms were suitable for summer use since they faced the northern cool breeze and had also less exposure to the direct sun rays in summer (Fig. 5). The self shading courts and its component- pound, fountains, vegetations, porches- played an important role in keeping cool and ventilating of the summer quarters (Safarzadeh, 2005). It should be noted an unshaded court has higher temperatures than out door environment, especially where the width of the court is large relative to the building height (Givoni, 1986). However, studies (Rajapaksha, 2003, Safarzadeh, 2005) have shown potential of natural ventilation of building by court yards.

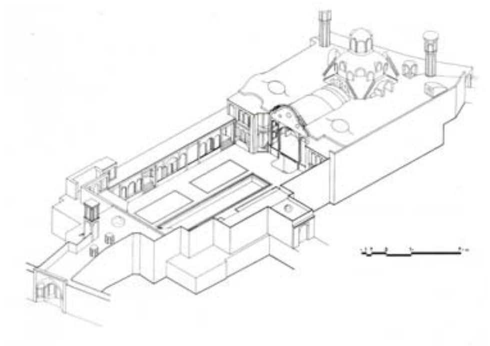

Fig. 4: Inward orientation of house, no windows onto out side

Fig. 5: The main summer room, Iran

3.1.2. High ceilings and the use of doomed roofs

Meeting and sitting rooms at the summer quarters had higher ceilings, in some cases equivalent to two regular floors than winter quarters (Golany, 1980) (Fig. 6). In ancient time due to the structural restrictions, domed shape roof was developed in Middle East, Africa as well as some Mediterranean villages. This type of roof supplied better thermal comfort due to the higher ceiling. High ceilings provide more spaces where stratification of air allows the occupants to inhabit the cooler lower levels (Lechner, 1991) (Fig. 7).

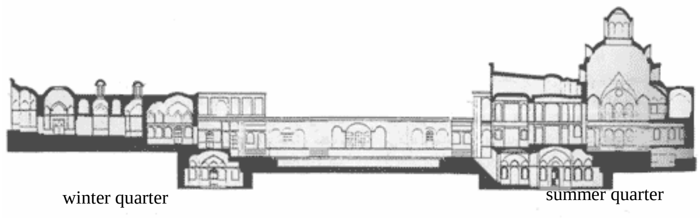

Fig. 6: Difference in the height of ceilings for thermal comfort at the summer and winter quarter, Kashan, Iran

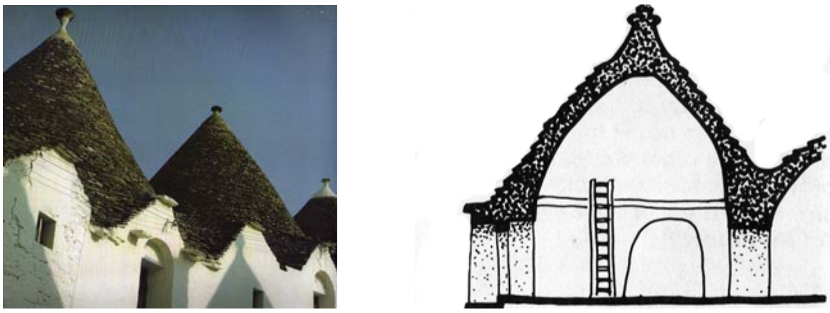

Fig. 7: Large mass and high ceilings houses, Apulia, Italy

Sometimes vents were located at the top to improve ventilation. When out side wind flows over a curved surface, its velocity increases and its pressure decreases at the top of the surface. The decrease in pressure at the top of the domed roof induces the hot air under the roof to flow out through the vent (Bahadori, 1978) (Fig. 8).

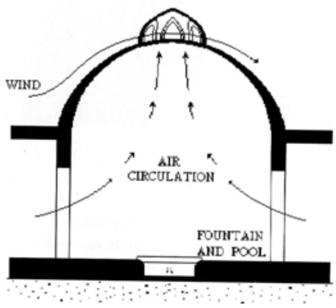

Fig. 8: Airflow patterns through a doomed roof air vent

The most dramatic example of this kind of dome is the Borujerdi houses, in Iran (Fig. 9). The beautiful and specific design of dome and its vents not only improve air circulation but also provided proper light without direct penetration of sun rays. The other benefit of domed roof is that during the day it received less solar radiation than flat roof based on the unit areas, while radiation cooling of dome at night was more than flat ones since the full hemisphere, wider area, saw the night sky. Thus, radiant heating is minimized while radiant cooling is maximized (Lechner, 1991).

Fig. 9: Specific design of domed roof with vents, Broujerdi house, Kashan

3.2. Construction materials and techniques

In hot-dry and Mediterranean climates, buildings usually constructed in light surface colours and massive construction, such as adobe, brick, or stone (Lechner, 1991). These massive materials not only retarded and delayed the progress of heat through the walls and roof but also acted as a heat sink during the hot summer days. the mass cooled at night and then acted as a heat sink the next day. Although wood did not use as a basic material in construction but it was utilised for doors, windows, decorated screens and furniture. In Iran, Windows usually were decorated with colour glasses which not only used as statistic aspect but also minimized solar penetration and heat gain through the windows (Fig. 10). Usually, retractable bamboo shades which could be adjusted to either exclude or admit solar radiation hanged outside windows (Fig. 11).

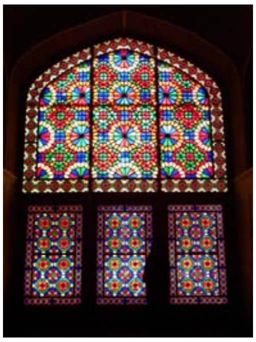

Fig. 10: Colure glasses windows

Fig. 11: Retractable bamboo shades

Earth sheltered building was another technique which was an effective barrier to the extreme temperatures (Fig. 12). The deep earth is usually near the mean annual temperature of a region, which in many cases is cool enough to act as a heat sink during summer days (House & House, 2004).

Fig. 12: Earth sheltered houses, Setenil, Spain (House & House, 2004)

3.3. Architectural elements

3.3.1. Evaporative cooling elements

To cool the dry and hot breeze, vernacular architectures utilised the basic principle that contact between cool water and hot dry air produces evaporations and results in a heat loss to surrounding areas. Thus, they located devices such as fountains (Fig. 13) and Selsebils in courts and summer quarters. Selsebil is a slanted slab on the wall upon whose surface the water gurgles down and terminating in a small pool underneath (Fig. 14). While the water slides down, it evaporates and helps the room to cool down. Early examples of selsebils were traced back to the thirteenth century in the old city of Diyarbakir, Turkey (Golany, 1980).

Effective Evaporation requires a continuous flow of air which was easily available in open courts over the central pool and fountains. However, in covered halls the circulation of air had to be enhanced through the use of wind trap elements.

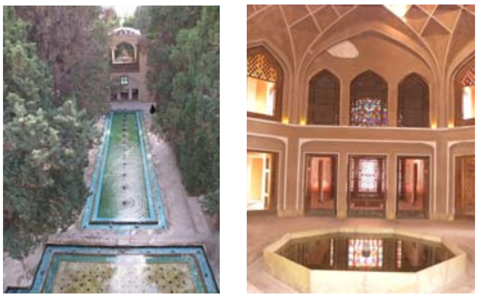

Fig. 13: Fountains and pound at the court and in the main sitting room

Fig. 14: Selsebil in sitting room

3.3.2. Wind traps elements

To maximize cooling ventilation through the air movement in hot and arid zones ingenious devices for catching the wind were designed. Dependent on wind direction and site, these devices are strikingly different in appearance. When there was strong prevailing wind direction, different types of wind scoops which all aimed in the same direction were designed (Lechner, 1991). These devices are open shad facing cool breeze and located at a high point in the house. The roof of shad is inclined at an angle designed to divert the wind downward toward the air shaft and directly to the rooms and corridors. As seen In Fig. 15, 16 the different design of wind scoops in Egypt and Pakistan were devised to catching prevailing winds.

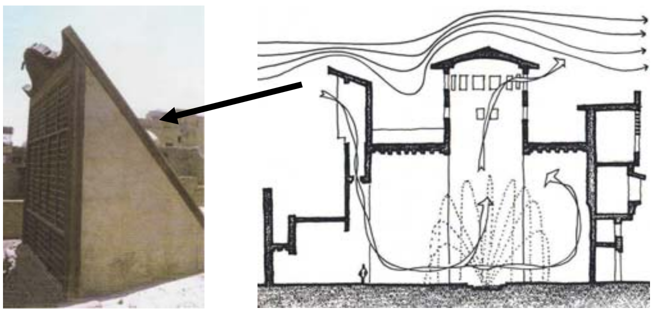

Fig. 15: Malqaf, a Cairane house, Egypt (Fathy, 1986)

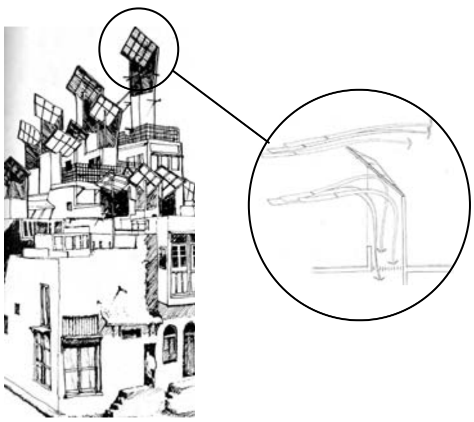

Fig. 16: The wind scoops in Hyderabad, Pakistan

When there was no prevailing wind direction, wind-catchers with many openings were used as in Persia and other Persian Gulf countries (Battle McCarthy Consulting Engineers, 1999). These towers rise above the roof and are divided by internal blades, which create separate air ducts (Fig. 17).

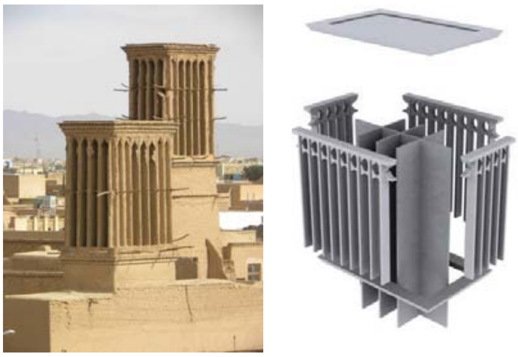

Fig. 17: An example of wind-catcher and internal blades wind-catchers

At the windward side, air is leaded through the channels to the interior space of building. At the leeward side, warmed interior air will be sucked out (Fig. 18). In the absence of wind, the towers continue to ventilate rooms through stack effect (A'zami, 2005) (Fig. 19).

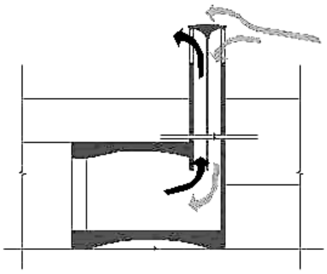

Fig.18: Traction and suction in wind-catcher

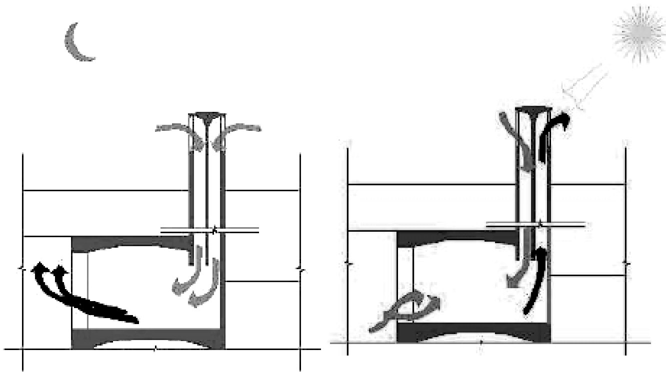

Fig. 19: Air movement during the day and night by stack effect

The smart combination of domed roof, wind-catcher and fountain in some cases in Iran which back about 900_{AD} (Bahadori, 1978), were instrumental use to create better thermal comfort for occupants of building (Fig. 20). In some cases architectures used their talent and experience to create a unique shape (Fig. 21).

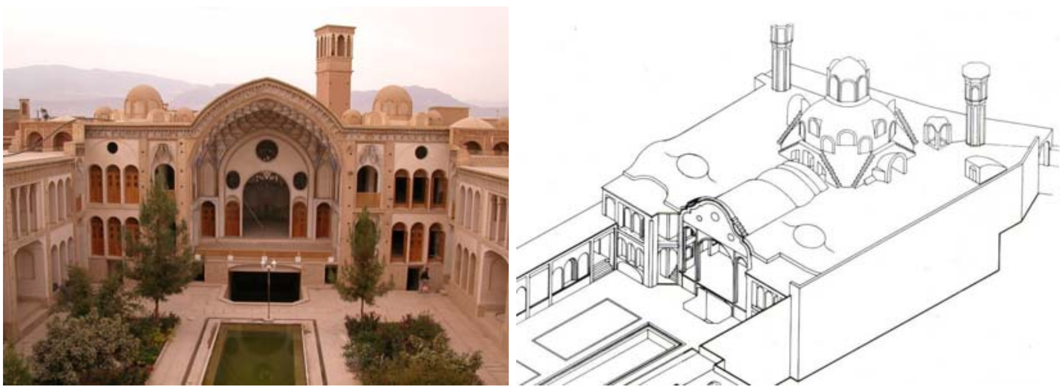

Fig. 20: Emrani House (left), Borujerdi House (right)

Fig. 21: Some unique design of wind-catcher in Iran

The Mashrabiya was another popular wind trap feature in Arabic Middle East homes. These bay windows were used as a sitting place where the users would get maximum exposure to the cool breeze while the delicate wood screen kept most of the sun out (Fig. 22).

Fig. 22: Mashrabiya screen over a window in Coptic Cairo, side view (Golany, 1980)

4. Modern eco-air-conditioning systems

4.1. Modern wind traps

Bansel et al. (1994) and Bahadori (1994) describe modern designs of ancient wind catchers which use control dampers to control volumetric flow rate and solar collectors to enhance the stack effect for exhausts at purposefully designed exits (Fig. 23). A study (Bahadori, 1994) investigated a wind catcher coupled with evaporative cooling columns which can increase the cooling potential (Fig. 24). They also provide detailed methodology for designing and sitting it.

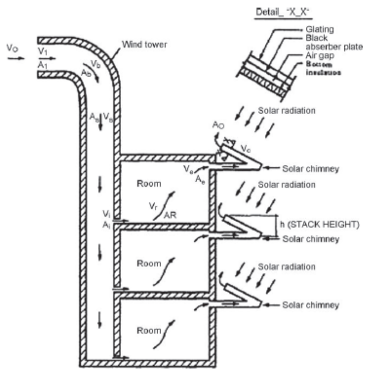

Fig. 23: Wind-catcher with solar collector

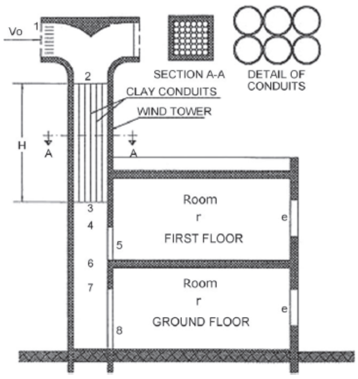

Fig. 24:Wind-catcher with cooling columns

Monodraught wind-catcher was launched in 1990. Fig. 25 shows the basic operational principles of its system. The system is normally divided into four quarters which run the full length of the body and become air intakes or extractors depending on wind direction thus making it less vulnerable to periodic wind changes and negating the need for any possible rotation to face the wind. It has also weatherproof louvers protect the interior of the building and volume control dampers to moderate flow (Khan et al., 2008). A recent improvement in the this windcatcher design is the Monodraught SolaBoost seen in Fig. 26 when the solar panel reaches 14 V an intelligent power control device will boost the power to the fan to 25V resulting in a 250 % increase in the speed of the fan and hence the flow rate (Monodraught, n.d.)

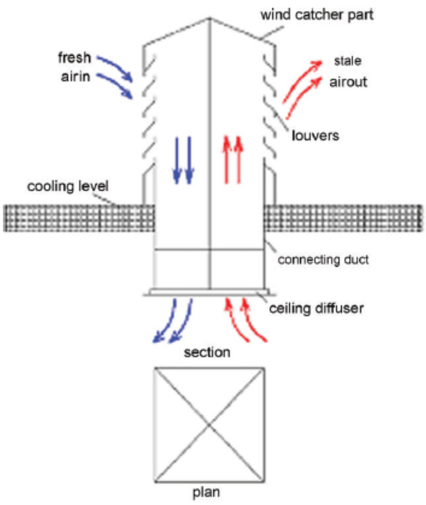

Fig. 25: Operating principle of Monodraught

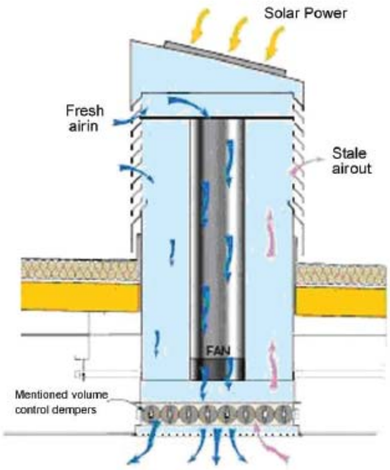

Fig. 26: Recent design of Monodraught, SolaBoost

The new design of wind scoops can rotate about an axis so as to always have the opening facing the incident wind. These types significantly were found to be better at producing positive pressure than suction cowls which back the wind and develop negative pressures for air extraction (Adekoya, 1994).A good example of a rotating wind scoops used for natural air conditioning is at the ICI chemicals visitor centre in Runcorn, UK (Khan et al., 2008) (Fig. 27).

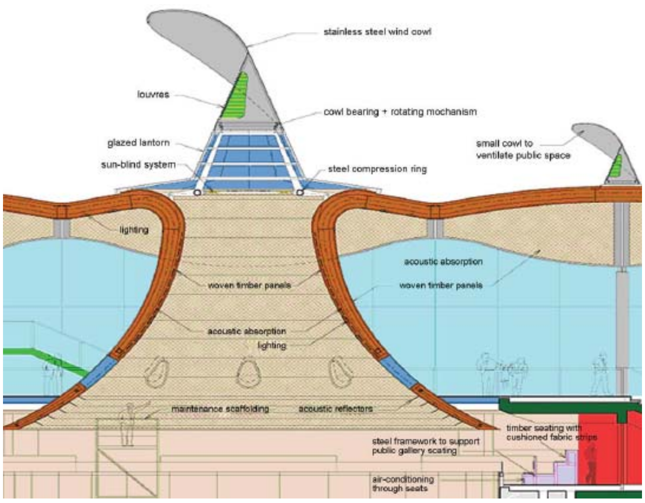

Fig. 27: Public sector building in Wales

4.2. Geothermal cooling systems

Geothermal cooling is a process by which shallow ground is utilized within a system to regulate temperature. The upper 10 feet of the earth's surface holds a stable temperature between 10° to 16°C. This stable temperature is harnessed, using a geothermal device, to draw heat energy out of a system and thus transfer the cool temperatures into a warmer area. This device is connected to a loop of copper tubing or high-density polyethylene, which is literally buried underneath the earth's surface. This loop contains a refrigerant that is pumped through the tubing, exchanging the warm energy in the building with cooler energy in the ground and acting almost like a heat sink. This process is known as direct exchange and is very effective at keeping a location at a stable cool temperature (Earth to Air, n.d.).

4.3. Deep sea water cooling

On 2006, the world’s first commercial deep seawater air-conditioning system opened for hotel business at the Intercontinental Resort and Thalasso Spa Bora-Bora, French Polynesia. The designer of this project was Makai Ocean Engineering, Inc. of Hawaii (Makai Ocean Engineering, n.d.).

The new hotel’s air-conditioning pipeline supplies seawater with 5°C temperature from 900m sea depth to eliminate typical air conditioner machinery driven by large electric motors. The seawater passes through a heat exchanger to cool the hotel-wide freshwater cooling network. By using the naturally cold water, the hotel’s 15 kilowatt seawater pump provides cooling that would otherwise consume 300 kilowatts of electricity. It is claimed that this strategy results in 90% saving of annual electrical savings. (Intercontinental Bora Bora resort and thalasso, n.d.)

A similar project has been done in Maldive on 2008 to replace the electrical air-conditioner with deap sea water cooling systems. This plant is expected to reduce 20% of power consumption in Sovena Fushi resort (Maldives Resort Spa and Accommodation, n.d.). The lower saving in power consumption in this case compared to Bora-Bora resort could be due to higher temperature of deep sea water of 11°C. It is obvious that deep sea water is a commercial scale strategy that is difficult to be employed for individual residential buildings.

5. Proposal strategies and concluding remarks for Western Cape

Although each site needs to be analyzed in terms of its micro-climatic features, a general rule for energy efficient building in Western Cape as follows:

- Since the case study is located in the southern hemisphere, the best orientation of the building is along an east west axis where the predominant façade faces north, maximizing the potential natural lighting and thermal regulation.
- The east and west facades should be smaller to minimize the associated heat gains from the low angle morning and afternoon sun, whilst the north and south facades are elongated to ensure adequate day lighting and natural ventilation.
- Building openings should be of suitable size and should be orientated to enable natural airflow from the windward to the leeward side. A building should not have too deep a plan and should be relatively free of major obstructions within the interior.
- Heat exhausted systems, such as solar chimneys and roof ventilators, allow internal heat to rise and escape from the building. At the same time fresh air is drawn into the building

through openings in the building envelope. This modern strategy is more efficient than ancient domed roof shape and high ceiling.

- Wind catcher or wind scoop can drawn fresh air into the building and provide comfort thermal for occupants of building, especially in the case of keeping close windows at night because of safety issues in SA.
- Windows can be coated with sun control film to reflect incoming sunlight.
- Retractable awnings or fixed overhangs over north-facing windows can provide complete shading from the direct sun during summer, and still enable solar penetration in winter.
- Operable shutters which can be adjusted at will, to either exclude or admit solar radiation, can intercept solar radiation reflected from the ground, in addition to intercepting the direct sun radiation.
- shrubs on the sunny side of the house elevate humidity level as wall as deciduous shade trees close the windows prevent solar penetration at summer while enable solar penetration in winter.
- Geothermal cooling systems for the residential building with big yard can be used in combination with wind catcher
- Since the Atlantic Ocean has a great potential for deep sea water cooling due to its low temperature, big hotels and malls close to this ocean could utilize a central deep sea water cooling system with bearing in mind to not disturb the tourism face of the city.

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