PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING:
The Applicability for residential space cooling in Riyadh, Saudi Arabia

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ABSTRACT: The climate in Saudi Arabia is characterised by low relative humidity and very high summer ambient temperatures. Space cooling is therefore required to achieve internal thermal comfort. Air-conditioning is the typical cooling solution, and accounts for about 65% of energy use in buildings in this region. This is a notable source of greenhouse gas emissions and coupled with their high energy demand, alternative means of achieving space cooling would prove invaluable. This paper investigated the applicability of Passive Downdraught Evaporative Cooling (PDEC) in residential buildings in this region by using a proposed PDEC system for a prototype house as a research vehicle. "Downdraught cooling is an energy efficient, and cost effective alternative to conventional air-conditioning for new and existing buildings" [2]. It is a well-tested system and the climatic conditions of Riyadh favour its application. This study was carried out in three phases; the first phase involved reducing the building cooling loads by appropriate solar control and improving the building envelope; the second phase was an evaluation and optimisation of the proposed PDEC system; the third phase involved future-proofing the building by evaluating the performance of the system in the year 2100 using interpolated weather data. Internal comfort conditions were determined based on the adaptive comfort principle and the efficacy of the system was assessed by the percentage of resultant hourly internal temperatures achieved within the target comfort range when the PDEC system was in operation. The thermal simulation was done using Bentley TAS and the results showed the proposed PDEC system fulfilled the cooling requirements for more than 75% of the required periods (both for present-day and future climatic conditions). The study therefore lends credence to the applicability of PDEC as a viable cooling solution for residential buildings in Riyadh and other regions with similar climatic conditions.
Keywords: Passive Downdraught Evaporative cooling; Residential buildings; Adaptive thermal comfort; Riyadh; Bentley TAS

INTRODUCTION
Riyadh, the capital city of Saudi Arabia is located at Latitude 24.7°N and Longitude 46.8°E. In summer, ambient temperatures often soar above 46.1°C, with mean monthly temperatures varying from of 27.3 – 37.1°C.

The extremely high summer ambient temperatures require appropriate cooling systems to ensure thermal comfort for occupants in buildings.

Passive Downdraught Evaporative Cooling (PDEC) is one of the proven alternatives to conventional cooling as its operation requires low amounts of energy with significant reduction in CO2 emissions when compared with conventional Air-conditioners [2].

This study focuses on thermal comfort of the building occupants. Other related factors like lifecycle cost analysis, amount and sourcing of water required for the PDEC system, and energy consumption figures are not covered within the scope of this paper.

CONTEXT AND CIMATE
The weather data used for this study was obtained from the Meteonorm software. Historic data was based on actual readings from weather stations in Riyadh, while future weather data was generated based on the Intergovernmental Panel on Climate Change (IPCC) B1 climate change scenario. This is explained in more detail in the literature review section.

The key climatic observations relevant to this study are as follows:

i. From April-October, ambient temperatures are very high and relative humidity is consistently low. This is the fundamental principle on which PDEC operates (see fig. 1 and fig. 2). July and August are the hottest months of the year.

ii. Wind speeds vary throughout the year but usually occur at an average of about 7m/s with the prevailing wind direction being north. This is advantageous in terms of exploiting natural ventilation, and assisting air flow rates while using the PDEC system.

iii. Due to its proximity to the equator (Latitude 24.7°N), the sun maintains a high altitude as it traverses its daily path. Roofs of buildings (especially flat ones) are therefore exposed to the sun's direct radiation for most times of the day, and hence could be major sources of heat gains to the buildings.

iv. Night time convective cooling, coupled with the thermal mass provided by the building envelope would be useful in the mid-season and summer months.

Annual temperature and relative humidity profiles for Riyadh are shown in fig. 1 and fig. 2 below.

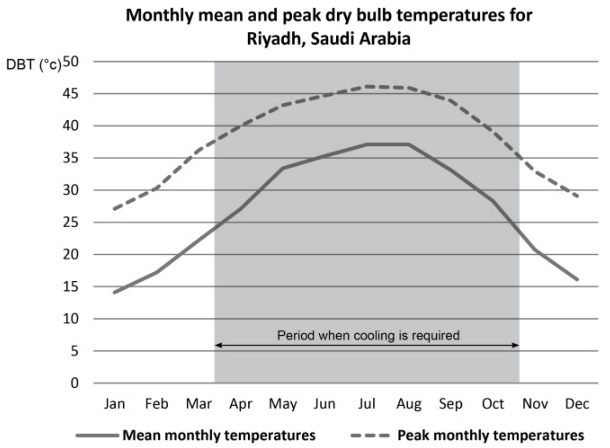

Figure 1: Annual temperature profile for Riyadh showing period when cooling is required.

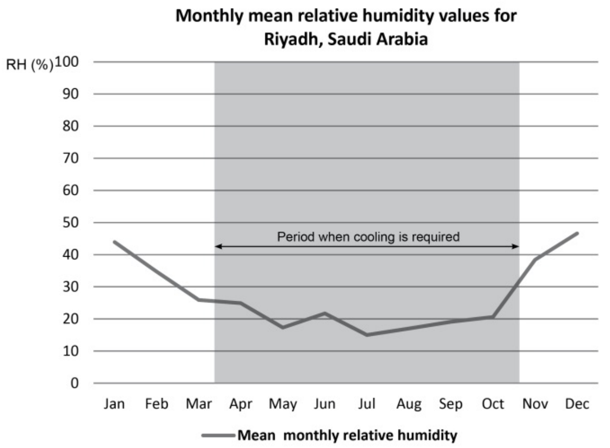

Figure 2: Annual relative humidity profile for Riyadh.

PROTOTYPE HOUSE

The prototype house was designed for a large family of 8 – 11 occupants and has a total floor area of about $154M^2$. Fig. 3 shows the floor plans of the building; the spaces to be cooled by the PDEC system are the Lounges, dining area, and the bedrooms (highlighted on the plan). The PDEC system is positioned at the top of a 1 x 1.5m shaft (hereafter referred to as 'cooling tower' or 'misting tower'). Openings in the tower were provided on the first level for distribution of the cool air from the tower to the adjacent spaces. The location and size of the cooling tower were evaluated during the performative studies.

Figure 3: Floor plan of the prototype house (the spaces to be cooled by the PDEC system are highlighted).

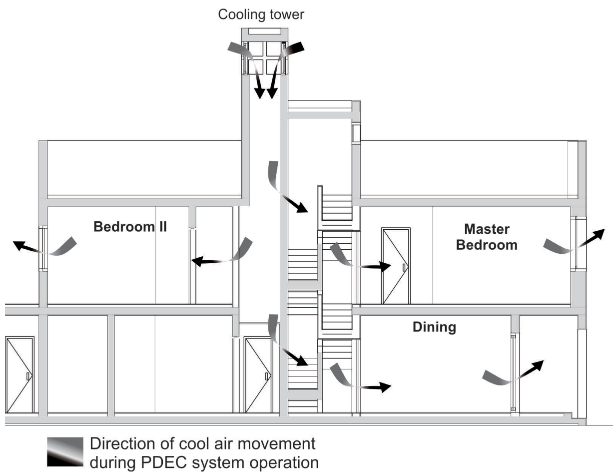

Figure 4: Section through the proposed prototype house showing the direction of air flow when the PDEC system is in operation.

Fig. 4 is a section through the north – south axis of the prototype house. Evaporation of water droplets at the top of the cooling tower leads to a reduction in air temperature; the cool air falls under gravity and is distributed via windows / doors to the adjacent spaces in the building. The reverse is the case at night, when ambient temperatures are more favourable; the perimeter windows act as air inlets, while stale air is exhausted from the top of the tower by buoyancy.

The building envelope was made up of an EVG 3D Panel construction: *3D panels consisting of a three-dimensional welded wire space frame provided with a polystyrene insulation core. The panel is placed in position and is 'sandwiched' by concrete (see* *www.evg.com for full specifications)*. Based on the construction method used, the U-values of the walls, floors and roof were 0.6W/M^{2}K. Windows were double glazed (U-value: 1.8W/M^{2}K). Fig. 5 is an illustration of the EVG 3D panel construction system.

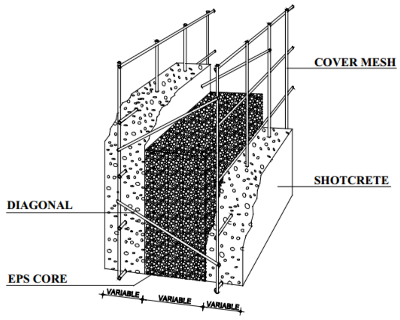

Figure 5: EVG 3D construction system used in the prototype house. (Source: www.evg.com)

LITERATURE REVIEW

Designing for hot and dry climates

"Sustainable architecture and developments are in the process of creating new forms of climate-sensitive vernacular for the 21st century. The future of architecture will not depend on styles and fashion promoted by consumerism and media. It will depend on sincere application of sustainable strategies and the achievement of successful regional environmental solutions. We will be able to appreciate and enjoy diversity instead of being contained in monotony and uniformity." [4]

Traditional building design and construction methods are usually highly influenced by local accumulated building experiences and cleverly adapted to the climatic conditions. For instance, the use of courtyards and reduced opening sizes of spaces are characteristic architectural features found in hot climates. Some pronounced building features in the form of wind-catchers are commonly observed in vernacular buildings in Egypt and the Middle East.

Insulation also plays a key role in enhancing the thermal performance of building envelopes. Traditionally in Saudi Arabia, capacitive insulation has been used as shown by the thick walls of old buildings. With the development of building technology however, a combination of thinner walls and resistive insulation can be used to achieve thermal comfort. [1]

Passive Downdraught Evaporative cooling (PDEC)

Origin:

Evaporative cooling has been applied in various forms for several centuries in different parts of the world, particularly in the Middle East where various techniques have been employed over time to encourage air movement and cooling in buildings. These methods include the use of wind catchers, wet woven 'Khus' mats hung over openings, as well as the use of scented water jars located in specially designed openings. These are designed strategically in such a way that they cool the air passing over them into the adjacent spaces. It is important to note that these traditional methods are still being used in some parts of the world to achieve cooling and they have worked satisfactorily [2].

Cooling Principle:

Evaporative cooling relies on the principle that evaporation of water in an air stream leads to a reduction in the air temperature. This is due to the transfer of energy (required to induce evaporation) in the form of heat from the air to the water. Studies have shown that the cooling potential of a PDEC system is such that a temperature reduction of up to 80% of the difference between the Dry-bulb and Wet-bulb temperatures is achievable [2]. This is shown in equation (1):

$$T_T = T_{DB} - 0.8(T_{DB} - T_{WB}) \quad (1)$$

Where:
T_T = Tower supply air temperature
T_{DB} = Ambient dry-bulb temperature
T_{WB}= Ambient wet-bulb temperature

Downdraught cooling systems can generally be classified based on the method of generating the cool air. These include cooling towers, shower towers, porous media and misting towers [2].

The misting tower system was proposed in the prototype house. It uses misting nozzles fitted at the top of the tower which spray water in the form of very tiny droplets. The small size of the water droplets sprayed greatly enhances the evaporation process. This is an efficient system as the amount of cooling achieved through evaporation generally increases with a decrease in the droplet size of water. "Recent developments in misting nozzle technology now allow evaporation at low pressure, making this the most efficient and cost effective system of downdraught evaporative cooling [2].

Applicability:

The applicability of a PDEC system in a building / region can be evaluated at an early stage in the design process based on a number of parameters [2]. These are as follows:

• *Dry bulb temperature and relative humidity*: For evaporative cooling to be utilised successfully, an appropriate wet-bulb depression (of at least 8°C) should be achieved. This is achievable in conditions of high ambient temperatures and low relative humidity. From the microclimate analysis, this condition generally exists in Riyadh from Mid-march through October. Hence, this criterion is satisfied.

• *Void to floor ratio*: Another parameter is the void (tower cross sectional area) / floor ratio. From the study of precedents and technical literature, a generalised benchmark ratio of 5% can be used for the evaluation. Initial calculations from the proposed system in the prototype house show a void / floor ratio of about 2.2%, and this was identified as a potential problem.
• *Tower position*: The optimum location for the misting tower should be somewhere that is accessible to the spaces where cooling is required to ensure minimal resistance to the flow of air. In the proposed design, the tower location is almost central within the building; the tower position can however be optimized by making minor changes to the internal layout which would not affect the architectural space and form. This is explored in the analysis.
• *Inlets and outlets for air movement*: Inlets are required for delivering air from the misting towers to the spaces, as well as outlets for exhausting air from the spaces.

Adaptive thermal comfort

"The fundamental assumption of the adaptive approach is expressed by the adaptive principle: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" [4].

The adaptive comfort model as discussed by Humphreys and Nicol [4] was used to determine the comfort zone for occupants of the building. This meant that the comfort zone varied based on the mean monthly external temperatures. Whilst an argument could be made for an alternative comfort model, this model has been used due to its relationship with external ambient temperatures, and importantly, adaptive opportunities exist for the building occupants. The monthly comfort temperatures were calculated based on equation (2), with an allowance of ±2°C for the comfort band as shown in equation (3).

$$Tc = 13.5 + 0.54To \quad (2)$$

$$Tcz = Tc \pm 2°C \quad (3)$$

Where:
Tc = Comfort temperature
To = monthly mean of ambient dry bulb temperatures
Tcz = Comfort zone

ANALYSIS

Research methodology:

The building analysis was based on dynamic thermal simulation using the Bentley TAS software. The building properties such as orientation, construction materials, opening sizes and locations, and internal conditions were represented and modelled as accurately as possible.

The study was carried out in three phases; the first phase involved reducing the building cooling loads by appropriate solar control and improving the building envelope; the second phase was an evaluation and optimisation of the proposed PDEC system for a present day scenario; the third phase involved future-proofing the building by evaluating the performance of the system in the year 2100 using interpolated weather data. The phases are hereafter referred to as 'cases'.
• *Case 1 (base case):* The building was modelled with the proposed construction materials and was simulated as a 'free running' building which was assumed to be naturally ventilated for the entire year.
• *Case 2 (Solar control / cooling load reduction):* As earlier stated, the u-value of the roof and external walls was calculated as $0.6W/M^2k$. A building with such a high u-value will transmit a significant proportion of solar radiation. Hence the in-fill insulation was increased from 50mm to 100mm and this reduced the u-value to $0.22W/M^2k$. Furthermore, roof and window shading were introduced to reduce solar gains.
• *Case 3 (PDEC system – present day scenario):* The PDEC system was introduced based on the design parameters in the original proposal. A few changes were proposed to the cooling tower to optimise the performance and distribution of the system. The weather data used for this stage was for the present day climate scenario.
• *Case 4 (PDEC system – Future scenario)* - The final step involved testing the optimised PDEC system with interpolated weather data for the year 2100 based on the IPCC B1 climate change scenario.

Assumptions / Input parameters for TAS simulation software:

• *Cooling tower:* Supply temperatures for the tower were computed based on the formula in equation (1). Air flow rates and distribution were computed by the TAS simulation engine.
• *Internal conditions:* Internal gains from occupants, lighting and equipment were accounted for. Occupancy patterns and user behaviour were assumed based on the Authors' discretion.
• *Calendar:* The PDEC system was set to operate during the months when cooling was required as indicated in fig 1.
• *Weather data:* Weather data was obtained from the Meteonorm software. Historic data from a weather station in Riyadh was used for the present day scenario. This data was 'morphed' based on the IPCC climate change scenario B1 for the year 2100.

The IPCC has developed long-term emissions scenarios which have been used to analyse possible climate change and its impacts, as well as options to mitigate climate change.

"The B1 scenario describes a convergent world with a global population that peaks in mid-century and declines thereafter, but with rapid changes in economic

structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies” [3].

RESULTS

The study undertaken for the ground floor lounge has been chosen as the representative case for presenting the results. A tabular summary of the results of the entire house is however presented at the end of the analysis section. The sequence of ‘cases’ described in the methodology is also used here to present the results.

Case 1 (Base case): The building was modelled with all the proposed construction materials and was left free running with natural ventilation as the only cooling mechanism. As expected, resultant internal temperatures exceeded the comfort set-point for a significant period of time; the results showed that the resultant temperatures of the representative space fell within the comfort zone for only 41% of the occupied hours. Natural ventilation alone was insufficient in meeting the cooling demand of the space.

Case 2 (Solar control / cooling load reduction): The next step involved reducing the cooling load by shading the roof and windows, and improving the thermal properties of the building envelope. The results showed an improvement in the internal conditions; the resultant temperatures of the representative space fell within the comfort zone for 52% of the occupied hours. This is shown in fig. 6 below; the lower and upper boundaries of the comfort set points used are indicated by the dotted lines on the graph.

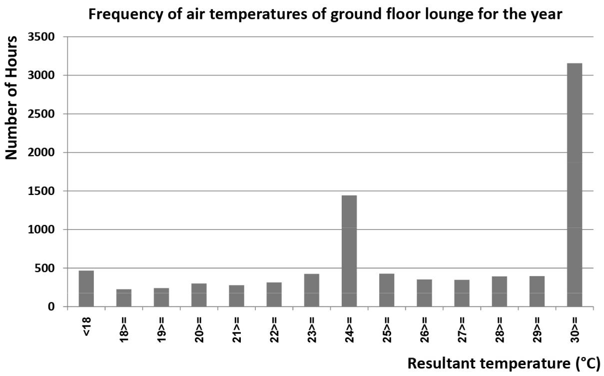

Figure 6: Frequency of air temperatures of ground floor lounge space for the year (Case 2)

Case 3 (PDEC system – present day scenario): At this stage, the PDEC system was introduced based on the proposed design. The percentage of hours that fell within the comfort zone increased significantly to 74%. A few design modifications were made to the tower proportion and location in order to further enhance the cooling potential and more importantly, distribution of the cool air to the relevant spaces. The main design alterations are shown in the fig. 7 below. As a result of this alteration, the percentage of hours that fell within the comfort zone as shown in fig. 8, increased to 81%.

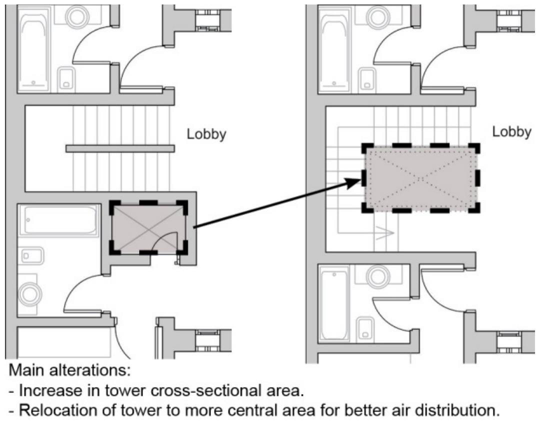

Figure 8: Internal design alteration to tower area to improve efficacy of PDEC system

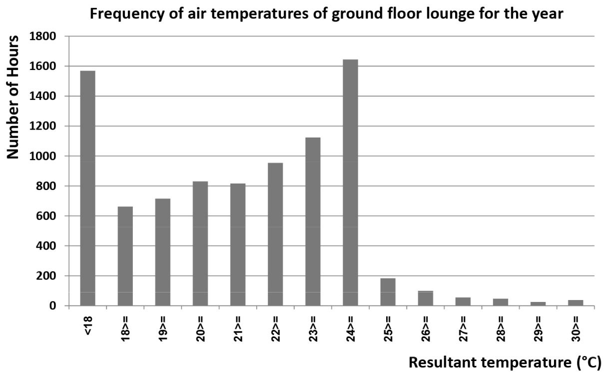

Figure 9: Frequency of air temperatures of ground floor lounge for the year (Case 3)

Case 4 (PDEC system – future scenario): The final step involved future-proofing the proposed design against the possible effects of climate change. Hence, the interpolated weather data for the year 2100 was substituted for the historic weather data used in the previous simulations. The results showed that the percentage of hours within the comfort zone reduced to 77%. This however was expected based on the increased temperatures in the weather data. Fig. 10 below shows the results.

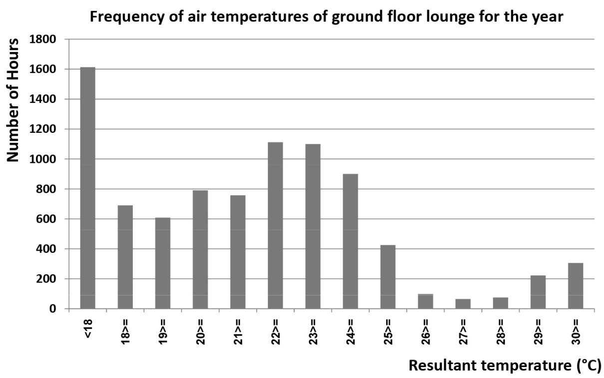

Figure 10: Frequency of air temperatures of ground floor lounge space for the year (case 4)

SUMMARY

A comparison of the results obtained shows first of all, the environmental benefit of incorporating adequate solar control measures while designing in a climate of this nature. More importantly, the potential of PDEC as an alternative cooling solution has been demonstrated.

It should be noted that the relative improvement observed due to the modification of the PDEC system is marginal as observed in the case of the ground floor lounge (i.e. 74% - 81%). This is because in both cases, distribution of cool air from the tower at this level is unhindered. However, the relative improvement is higher in the other spaces within the building. The results for the building are summarised in Table 1 and Fig. 11 below.

*Table 1: Summary of comfort conditions achieved across the different cases**

	(% hours in comfort zone)			
	Case 1: Base case with natural ventilation	**Case 2:** Solar control and building envelope enhancement	**Case 3:** PDEC in operation (present)	**Case 4:** PDEC in operation (future)
G.F lounge	41	52	81	77
Dining	38	50	80	76
F.F lounge	39	49	88	85
Bedroom 1	36	48	89	84
Bedroom 2	39	47	86	81
Bedroom 3	36	46	83	79
Average**	38	49	84	80

** Values are rounded up to the nearest whole numbers to aid readability*

***Average is used as a means of evaluating the overall thermal performance of the building taking into account the conditions in ALL the spaces. The bar chart that follows is generated based on this average.*

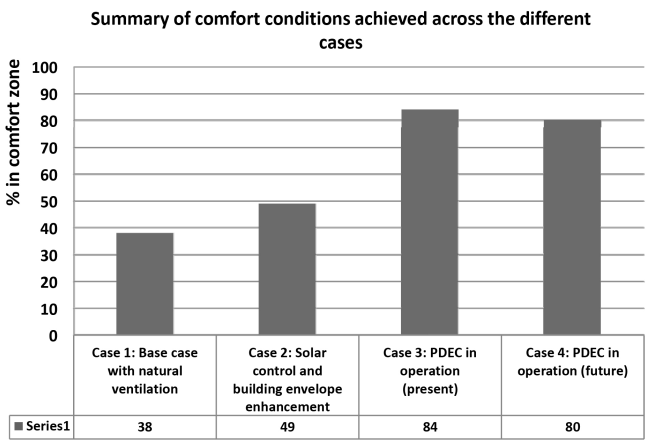

Figure 11: Summary of comfort conditions achieved across the different cases

Table 1 and Fig. 11 both show the percentage of occupied hours during which the internal temperatures within the spaces fell within the comfort zone. It should be noted that some of the discomfort hours were actually below the lower set-point and hence should not be interpreted as periods of overheating.

CONCLUSION

The results from this study have shown that the space cooling requirements for the prototype house were met by using PDEC system. Based on the results obtained from the comparative analysis, it can be concluded that PDEC is a viable solution for residential space cooling in Riyadh, taking into consideration all the parameters required for a proper functioning of the system as stated in this paper. Apart from the cooling potential demonstrated in this study, it has the added benefit of a significant reduction in the overall building energy consumption as well as CO2 emissions.

This limited study has opened up immense opportunities for further research on this subject and the authors have identified the following areas for further investigation:

- The simulation results will perhaps be better represented using computational fluid dynamics (CFD) software, as aspects of the results like air distribution and flow rates can be investigated in more detail.
- Also, a post occupancy survey would be very useful in confirming the theoretical findings presented in this paper.

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