

## OVERVIEW AND ANALYSIS OF THE OVERHEATING EFFECT IN MODERN SUDANESE BUILDINGS

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**Abstract:** Sudan is suffering from harsh summers, but most of the modern buildings in urban areas are not compatible with the recent and future climate phenomena. Application of cooling devices is relatively expensive and therefore beyond reach. The main objective of this research is to give an overview on the overheating problem and the thermal comfort in buildings. A dynamic energy simulation has been performed for a selected case study using Design Builder Code. The results show that the share of discomfort hours for a typical modern building is 78% and 33% above 26 °C and 32 °C per year, respectively, but after using a combination of different ventilation, shading and building materials options the discomfort hours can be reduced to 77% and 26%, respectively.

**Keywords:** Climate change, Overheating, Thermal comfort, Dynamic energy simulation, Sudan

### 1. Introduction

With climate change, overheating is likely to occur more frequently [1]. According to the Stern Report on climate change, overheating problems need to be highlighted and tackled now [2]. The primary function of buildings and building services engineering is to create and maintain a comfortable environment for people. Overheating is increasing during warm weather in buildings without air-conditioning, especially in homes in temperate climates where the retention of winter heat has been the major focus of thermal design [3]-[5].

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Thermal comfort is the point of satisfaction with the thermal environment, i.e. when the great majority of people are not feeling either too hot or too cold. Thermal discomfort is where people start to feel uncomfortable, i.e. they are feeling hot or cold, but they are not experiencing any health effects [6]. There are many factors that affect thermal comfort. For overheating discomfort, temperature is probably the primary factor but there are other factors that affect the feeling of comfort or discomfort in both hot and cold conditions. The other factors are humidity, air movement, radiation and radiation asymmetry [7], [8].

There is no internationally accepted definition of 'overheating' because it depends on local climatic conditions. The WHO guidance on thermal comfort states that temperatures above 24 °C cause discomfort in temperate zones [9]. Factors like the rate of increase in temperature, the temperature reached, the length of time for which the temperature stays high and individual tolerance are all important factors [10].

As a result of climate change, the summer overheating phenomenon occurs in different climate zones. The effect is the worst in the hot arid climate zone because it is very far from the comfort zone on the psychrometric chart [11] and it is difficult to achieve the comfort level by applying simple solutions [12], [13]. Also, there are gaps in the knowledge on the thermal performance of buildings in developing countries. The main objective of this paper is to analyze the overheating level in modern Sudanese buildings and study the effect of applying passive techniques, such as shading, ventilation and choice of building materials using dynamic building energy simulation.

## 2. Methodology

The thermal performance of a building and the internal comfort can be assessed using dynamic building simulation. For dynamic simulation, a lot of data are required as location, weather, building geometry and building materials, etc., which are described in the following sections.

### 2.1 Description of the case study

A first building typology matrix for Sudan has been compiled by Ali and Szalay [14]. In this paper, one type from the typology is selected, which is representative of modern buildings in a warm semi-arid climate zone. The building is a single-family house with a floor area of 96 m<sup>2</sup> (*Fig. 1*). There were no architectural plans available, but a common arrangement and typical dimensions were assumed based on expert estimations. The building has a single floor with two bedrooms, kitchen, living area, toilet and bathroom. There is a wall made out of bricks surrounding the building, which is very typical due to security and privacy reasons.

### 2.2. Location and weather file (Sudan, Khartoum)

Sudan is located in North-East Africa. Sudan is classified into three climatic zones (Zone I: warm desert climate, Zone II: warm semi-arid climate and Zone III: tropical savanna climate) as it is shown in *Fig. 2* [15], [16]. Sudan's weather is characterized by

three seasons: the hot season from March-May (summer), the wet rainy season between June and October (autumn) and the dry season from November until February (winter).

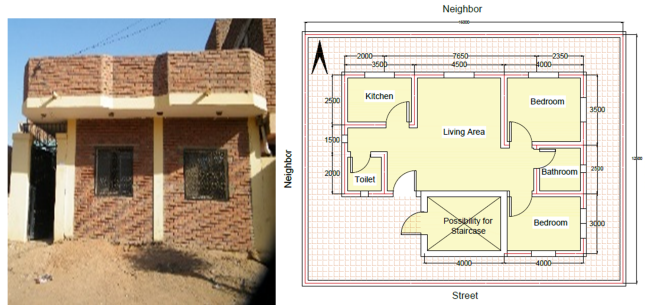


Fig. 1. Plan and photo of the building

The northern part of Sudan (zone I) has a harsh climate compared to the other regions. Here summer temperatures exceed  $43.3\text{ }^{\circ}\text{C}$  in the desert zones and rainfall is negligible, except in the center, where rainfall is common between June and September. Zone II has moderate summer and winter temperatures, high rainfall and relative humidity values, because it is close to the tropical savannah region [17], [18].

The greatest amount of solar radiation in Sudan is between  $15$  and  $35$  latitude north. Wind speed and direction vary with seasons. In winter, the wind speed ranges between  $0.54\text{ m/s}$  to  $1.54\text{ m/s}$  in N and NW direction, while in the summer season winds are in the direction of NW to SW.

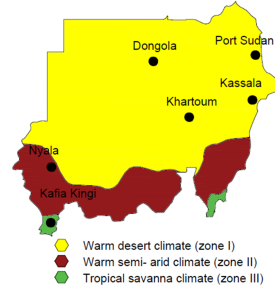


Fig. 2. Sudan climate zones (Source: S. I. A. Ali on the basis of Koppen, and Sudan Meteorological Authority (SMA) [16], [15])

The case study is located in the capital city Khartoum, with latitude  $N15.550^{\circ}$ , longitude  $E32.530^{\circ}$ , altitude  $366\text{ m}$  and climate zone 1 B according to the Meteonorm database [18]. In Khartoum, the average annual temperature is about  $26.7\text{ }^{\circ}\text{C}$ ; and the annual rainfall is about  $254\text{ mm}$ . Energy simulation tools need hourly ambient conditions (temperature, humidity, wind velocity, solar radiation, etc.) at the building location. This information is available in weather files. For this simulation, the weather file from Meteonorm was used [18].

### 2.3. Building energy simulation tool

The simulation was performed with Design Builder Code, v6. Design Builder provides a range of environmental performance data like energy consumption, comfort conditions, maximum summertime temperatures and Heating, Ventilation and Air Conditioning (HVAC) component sizes [19].

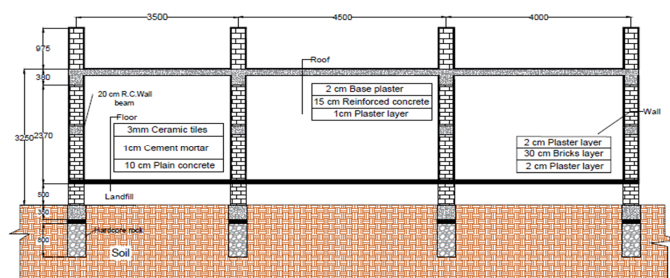
### 2.4. Base case model

As the first step for the simulation process, a base case model was created that is typical for Sudanese buildings and can be compared with different design alternatives. The base case has solid brick walls with concrete slab, natural ventilation and no shading system.

**Orientation.** The typical orientation of the building allowing maximum natural ventilation and daylight is shown in *Fig. 1*. In selecting suitable building orientation in hot dry regions, reduction of the internal daytime temperatures must be the main objective, and thus minimization of solar load is a primary concern [20].

**Zoning.** Zones are used in thermal simulations to divide the building into separate areas with different energy/thermal characteristics [19]. As the selected case study is a small single-storey building where internal doors would be frequently left open, a single zone is used in the calculations. Additional thermal mass was included in the simulation using hanging partitions.

**Building components.** It is necessary to have construction details, for instance the thickness and thermo-physical properties of materials used in each layer of the building envelope (*Table I*). The floor consists of 4 layers, which are plain concrete, sand layer, cement mortar and ceramic tiles. External walls are 0.3 m solid brick walls with mortar and plaster layer inside and outside the wall, while internal walls and partitions are 20 cm thick and have a loadbearing function with a similar composition to external walls. The flat roof is most common in the urban parts of Sudan. Usually a mixture of crush bricks, sand and stabilizer is applied on the top of the flat roof as a kind of waterproofing, and this was modeled as a lightweight plaster material in Design Builder. This case study has a reinforced concrete flat roof with a 2 cm plaster layer in the top and 1 cm base plaster on the bottom of the roof (*Fig. 3*). The thermal properties were taken from the database of Design Builder. Thermal bridges were neglected in this study.

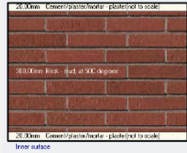

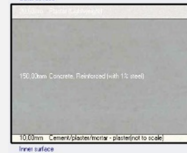
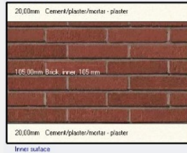



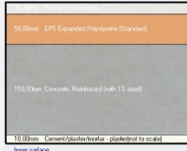



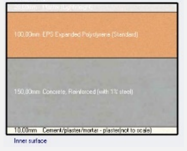


*Fig. 3.* Construction details (cross-section)



Table I

Description of the wall and roof buildings materials options

Wall		Roof	
 <p><b>Solid Bricks</b> (base case) 2 cm plaster 30 cm red bricks 2 cm plaster <math>U=1.729 \text{ W/m}^2\text{K}</math></p>	 <p><b>Lightweight Conc. B.</b> 2 cm plaster 30 cm concrete block 2 cm plaster <math>U=0.537 \text{ W/m}^2\text{K}</math></p>	 <p><b>R.C. Slab (base case)</b> 2 cm L.W plaster 15 cm R.C Slab 1 cm plaster <math>U=2.787 \text{ W/m}^2\text{K}</math></p>	 <p><b>Jack Arch Roof</b> 2 cm plaster 10 cm inner brick 2 cm plaster <math>U=2.264 \text{ W/m}^2\text{K}</math></p>
 <p><b>Hollow R Bricks</b> 2 cm plaster 30 cm hollow bricks 2 cm plaster <math>U=0.779 \text{ W/m}^2\text{K}</math></p>	 <p><b>Solid Bricks+ 5cm Ins.</b> 1 cm plaster 5 cm EPS 30 cm red bricks 2 cm plaster <math>U=0.547 \text{ W/m}^2\text{K}</math></p>	 <p><b>CISs + Air gap</b> 3 mm metal sheet 20 cm air gap 1.5 cm gypsum board <math>U=2.156 \text{ W/m}^2\text{K}</math></p>	 <p><b>R.C. Slab+ 5cm Ins.</b> 2 cm light W. plaster 5 cm EPS 15 cm R.C Slab 1 cm plaster <math>U=0.622 \text{ W/m}^2\text{K}</math></p>
 <p><b>Cement Block</b> 2 cm plaster 30 cm cement blocks 2 cm plaster <math>U=0.838 \text{ W/m}^2\text{K}</math></p>	 <p><b>Solid Bricks+ 10 cm Ins.</b> 1 cm plaster 10 cm EPS 30 cm red bricks 2 cm plaster <math>U=0.325 \text{ W/m}^2\text{K}</math></p>	 <p><b>CISs + EPS Roof</b> 3 mm metal sheet 5 cm EPS 1.5 cm gypsum board <math>U=0.674 \text{ W/m}^2\text{K}</math></p>	 <p><b>R.C. Slab+ 10cm Ins.</b> 2 cm light W. plaster 5 cm EPS 15 cm R.C Slab 1 cm plaster <math>U=0.35 \text{ W/m}^2\text{K}</math></p>

*Openings (Doors and Windows)* Doors are usually made of wood or aluminum, while windows have single glazing with a wooden, aluminum or metallic frame.

*Shading.* In Sudan, usually there are two types of shading: a permanent one, which is aluminum fencing for windows (mostly for security purposes) and curtains. Due to the high solar altitude, roofs with an overhang also shade the windows. For the base case, no shading was applied.

*Usage of building.* The hourly schedules of occupancy, lighting, equipment, thermostat set-point, and HVAC operation are required for the simulation. Internal gains

are calculated according to the occupants' density, activity, and equipment. Sudanese single family houses are normally occupied by an average of 5 persons [21], so the occupant density is 0.05 person/m<sup>2</sup>. Metabolic activity is assumed as light manual work, 150 W household equipment is calculated as the absolute zone power and 24 °C is the indoor temperature ventilation set-point.

*Ventilation and infiltration.* There are two general approaches to model natural ventilation and infiltration in Design Builder: 'scheduled', where fixed air change rates are set manually by users or 'calculated', where natural ventilation and infiltration rates are modeled based on window opening, cracks, buoyancy and wind-driven pressure differences. In the case study, the calculated model option is used for more accuracy. For infiltration, 'poor airtightness' from the crack template of Design Builder was assumed according to Sudanese building envelope characteristics. Due to the high cost of mechanical ventilation installations, natural ventilation is mainly used in Sudanese buildings. Simple fans are used in some parts of the buildings. Windows were assumed to be open if the internal temperature is above 24 °C and the external temperature is lower than the internal temperature. External doors were assumed to be closed 24 hours a day.

*Cooling system.* In Sudan, mechanical cooling is usually not applied due to the high cost. Sometimes simple air conditioners are used. Here, no cooling system was assumed.

### 2.5 Applied options

In order to analyze the effect of certain parameters on the thermal comfort, different options for ventilation, shading and building materials were examined. For natural ventilation, the different tested options are temperature controlled ventilation, no ventilation and constant ventilation option (*Table II*). For shading, closed weave inside and outside, and cantilever of 0.5 m and 1 m from the flat slab have been applied (*Table II*). The options for the wall are solid bricks, hollow red bricks, cement block, lightweight concrete block and solid bricks + 5 or 10 cm polystyrene insulation. The options for roof are concrete slab, jack arch roof, corrugated iron sheets with or without insulation and concrete slab with 5 or 10 cm polystyrene insulation (*Table I*).

## 3. Results and discussion

### 3.1. Base case results

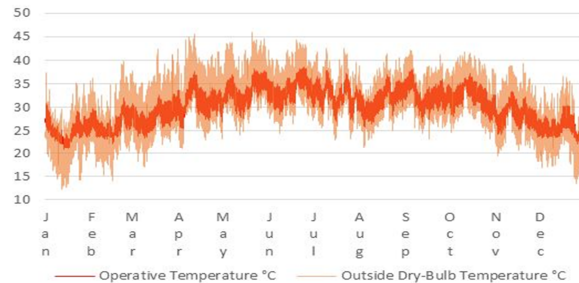
The annual, seasonal and weekly temperatures have been extracted and compared for the base case and the different options. *Fig. 4* shows the annual internal Operative (Op) and the Outside Dry-Bulb (ODB) temperatures for the base case. Generally, there is a big difference between the day and night temperatures. During the summer hot season, the maximum ODB temperature difference between day and night is 16 °C, while the minimum is 7 °C. The maximum range for the ODB and Op temperatures are between 34-46 and 26- 38 °C during the daytime, and 17-24 and 23-30 °C during the night, respectively.

Table II

Description of the ventilation and shading options

Ventilation			Shading		
<i>Control Mode</i>	<u>Temperature (base case)</u> Windows and doors are opened if $T_{zone} > T_{out}$ and $T_{zone} > T_{set}$ $T_{set} = 24\text{ }^{\circ}\text{C}$	<u>Constant</u> Windows and doors are open all the time.	<i>Control Mode</i>	<u>Drapes- close weave light inside:</u> Outdoor air temperature + Horizontal solar Solar setpoint= $150\text{ (W/m}^2\text{)}$ $T_{set} = 24\text{ }^{\circ}\text{C}$	<u>Overhang</u> 0.5 m
		<u>No Ventilation</u> Windows and doors are closed at all times.		<u>Drapes- close weave light outside</u> Outdoor air temperature + Horizontal solar Solar setpoint= $150\text{ (W/m}^2\text{)}$ Outside air temperature setpoint = $24\text{ }^{\circ}\text{C}$	<u>Overhang</u> 1.0 m

In the wet autumn, the maximum difference between day and night ODB temperatures is  $13\text{ }^{\circ}\text{C}$ , while the minimum is  $3\text{ }^{\circ}\text{C}$ . The maximum range for the ODB and Op temperatures are between  $35\text{--}44$  and  $29\text{--}38\text{ }^{\circ}\text{C}$  during the daytime, and  $21\text{--}26$  and  $26\text{--}30\text{ }^{\circ}\text{C}$  during the night. In the dry winter season, the maximum ODB temperature difference between day and night is  $15\text{ }^{\circ}\text{C}$ , while the minimum is  $10\text{ }^{\circ}\text{C}$ . The maximum range for the ODB and Op temperatures are between  $30\text{--}39$  and  $24\text{--}33\text{ }^{\circ}\text{C}$  during the daytime and  $24\text{--}14$  and  $22\text{--}32\text{ }^{\circ}\text{C}$  during the night.

Fig. 4. Annual operative and outside dry-bulb temperatures ( $^{\circ}\text{C}$ ) for the base case

In order to compare the total discomfort hours between the different seasons, the hottest week in the hot, wet and dry season was selected. As of now there is no standard discomfort level for the hot arid climate or especially for Sudan. According to the discomfort baseline, the number of Discomfort Hours (DH) above  $26\text{ }^{\circ}\text{C}$ , which is a standard value in Europe was counted, and also  $28$ ,  $30$  and  $32\text{ }^{\circ}\text{C}$  Op and ODB temperatures. Fig. 5 illustrates the indoor and outdoor total DH percentage for the hottest week in the summer, autumn and winter seasons. In the summer week, the operative temperature is always above  $32\text{ }^{\circ}\text{C}$ , while for the ODB all the hours are above

28 °C, and 95 and 81% of the hours are above 30 and 32 °C, respectively. The autumn week is even hotter, 89% of the hours are above 32 °C for the ODB. In the winter season, the percentage of discomfort hours is much lower than in the summer and autumn, only 13% of the hours are above 26 °C for the operative temperature.

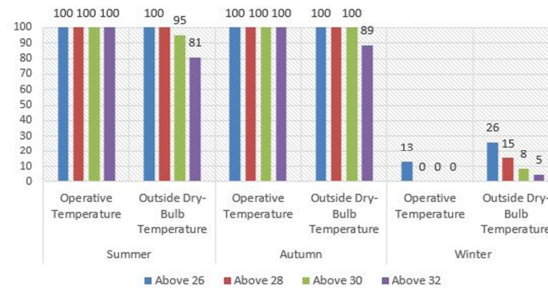


Fig. 5. Percent of hours above a certain temperature limit for the summer, autumn and winter design week

### 3.2. Different options results

As it is shown in Fig. 6 and Table III the annual discomfort hours (above 26, 28, 30 and 32 °C) are calculated for the different ventilation, shading, and material options. In the calculations, only one parameter was changed at a time compared to the base case.

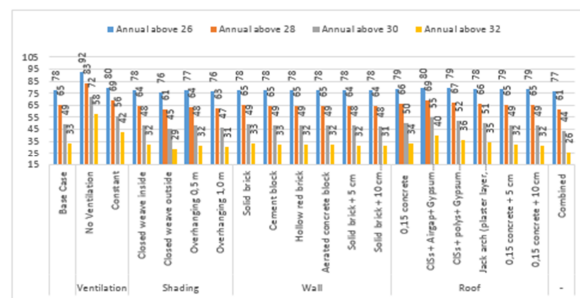


Fig. 6. Percent of the annual discomfort hours for the different selected options compared to the total hours of the year

In the ventilation options, the lowest discomfort hours are registered for the temperature control model option, which represents the base case, with 6806 hours above 26 °C, while both the no ventilation option and the constant ventilation have higher values. For the shading options, DH results for the closed weave outside are better than the other shading options, but applying an overhang shading has the benefit of allowing more daylight into the room.

Regarding the applied material options, there is no big change in the discomfort values for the walling and roofing material. Applying an insulation layer of 10 cm to the

base case wall and roof showed discomfort hours of about 5609 and 5696 above 30 °C and 6798 and 6892 above 26 °C, respectively.

Table III

Total discomfort hours per year for the different studied options

Options		Annual (hours)			
		Above 26 °C	Above 28 °C	Above 30 °C	Above 32 °C
Base case (temperature controlled ventilation, no shading, solid brick wall, concrete roof)		6806	5686	4314	2903
Vent.	No Ventilation	8082	7307	6281	5085
	Constant ventilation	6976	6083	4931	3721
Shading	Closed weave inside	6811	5641	4213	2799
	Closed weave outside	6622	5384	3976	2510
	Overhang 0,5 m	6761	5598	4208	2784
	Overhang 1,0 m	6685	5490	4093	2690
Materials (Wall)	Cement block	6808	5667	4278	2848
	Hollow red brick	6803	5663	4272	2844
	Aerated concrete block	6797	5653	4256	2830
	Solid brick + 5 cm insulation	6802	5631	4219	2787
	Solid brick + 10 cm insulation	6798	5609	4188	2759
Materials (Roof)	CISs + Airgap+ Gypsum board	6969	6017	4805	3517
	CISs + polys+ Gypsum board	6953	5908	4554	3154
	Jack arch (plaster, bricks, plaster)	6864	5791	4440	3028
	Concrete + 5 cm ins.	6881	5692	4261	2795
	Concrete + 10 cm ins.	6892	5696	4260	2788
Combined case (temperature controlled ventilation, overhang 1.0 m, solid brick wall + 5 cm insulation, reinf. concrete roof +10 cm insulation)		6734	5355	3868	2243

Finally, in order to decrease the discomfort hour values, a combination of different options is used (Table III). The combined model uses the temperature control ventilation option with a 1 m overhang for shading and an insulation layer of 5 cm for the solid brick wall and 10 cm for the concrete roof slab. After applying these, the annual discomfort hours decreased by 660 hours above 32 °C, that represent 23% improvement compared to the base case (Fig. 6).

### 3.3. Temperature in the different seasons

For more details through the different seasons, a temperature comparison between the base case and the combined model was added. In the summer, there is some difference for the operative temperature between the base case and the modified combined case, the highest temperature for the base case is 40.3 °C while for the combined case 37.04 °C (Fig. 7a).

During the autumn, a reduction in operative temperature can be observed throughout the whole week period. The highest temperature registered for the base case is 38.35 °C

and 36.07 °C for the combined case (Fig. 7b). In the winter season, there is no big difference in the operative temperatures between the base and combined case, so the highest operative temperature was 27.83 °C for the base case and 26.32 °C for the combined case (Fig. 7c).

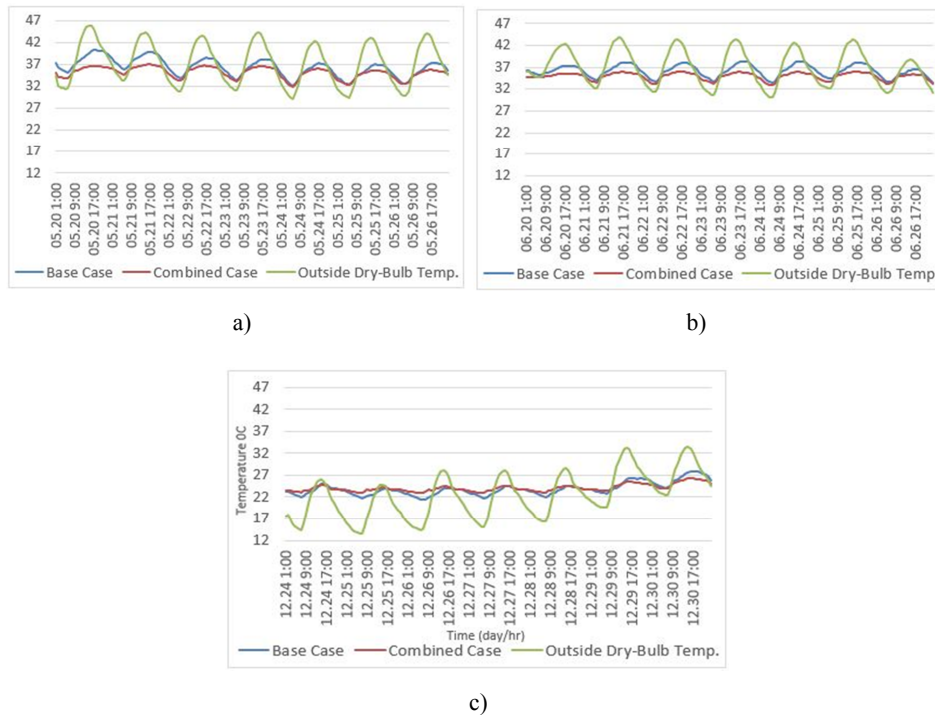


Fig. 7. Hourly (design week) operative temperatures for the base case and combined case during a) summer b) autumn c) winter

Fig. 8 illustrates the difference in temperatures between the base case and the combined case during the summer, autumn and winter seasons. The maximum temperature decrease occurs during the summer by 3.66 °C, followed by the autumn season where the difference in the operative temperature for the combined case was 2.53 °C. In the winter season, the difference is less and temperatures in the combined case are slightly higher than in the base case but still in the comfort range.

#### 4. Conclusion

In this paper, the internal temperatures in a typical modern Sudanese building were analyzed. Based on the dynamic simulation modeling the following can be concluded:

- In the base case the simulation results showed that 78% and 33% of the year is above 26 °C and 32 °C, respectively;

- Most of the comfort period is in the winter dry season (Nov to Feb), while the rest of the year (March to Oct) was in the discomfort level;
- If no natural ventilation is applied when the outside temperatures are lower than inside, the annual discomfort hours increase by 14% and 25% above 26 °C and 32 °C over the year, respectively;
- It is difficult to achieve 100% comfort level for the base case without using a mechanical ventilation or cooling system, but by using a combination of different passive solutions, an improvement of 10% above 30 °C and 23% above 32 °C compared to the base case can be achieved;
- There is no specific benchmark for the discomfort level in the hot arid climate zone. In this research the temperatures above 26, 28, 30 and 32 °C were checked;
- Only the internal operative temperatures were analyzed as a first indicator of overheating. As thermal comfort is a function of various parameters, further research will focus on complex thermal indices.

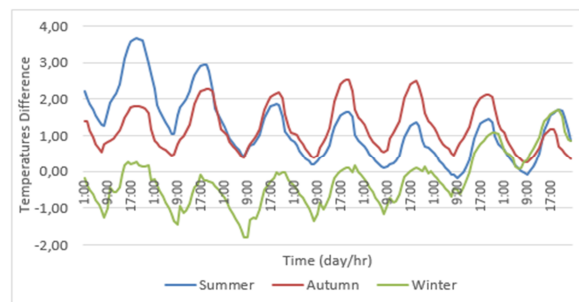


Fig. 8. Difference in the internal operative temperatures between the combined and the base case for the summer, autumn and winter design week

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