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The thermal performance of an educational office building in Ghana

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ABSTRACT

The thermal performance of an educational office building which exhibits sustainable design principles of passive architecture (emphasis on the use of natural ventilation) was studied. The main aim of the study was to investigate the thermal conditions, ventilation possibilities and preference for office type in the building. The building has individual cell and open-plan office spaces with different orientation and ventilation possibilities (cross, one-sided and borrowed ventilation). Data loggers were installed to monitor the environmental conditions existing in the building during the rainy season. The evaluated data showed that the indoor temperatures were comfortable (mean of 25°C), the relative humidity values were mostly high (80 - 85%) and the dew point temperature (22°C) was found to be close to the recommended minimum comfort temperature. Moreover, the enclosed corridor space was found to be warmer than the adjacent office spaces during the day time. The use of cool night air as a passive cooling strategy is recommended. Preference for office types with ventilation possibilities could not be statistically recommended since all the evaluated thermal values showed insignificant deviations.

Keywords: Natural ventilation; thermal; environment; relative humidity.

INTRODUCTION

A building which is able to provide comfort and satisfaction to its occupants with minimum use of energy is said to be efficient. The prime aim of current research has centred on energy efficiency, user behaviour and thermal comfort [1].

The human body has a constant temperature of about 37°C and through the processes of physiological and behavioural strategies, tolerance to a range of thermal conditions is improved [2]. A variation of the body temperature by less than or more than 2°C leads to either hypothermia (35°C) or hyperthermia (39°C) with the possibility of death at a reduction of about 10°C or an elevation of 5°C [3]. In Ghana, where outdoor temperatures can reach as high as 37°C, designers must make sure that buildings are comfortable, especially in naturally ventilated types, where the indoor and outdoor temperatures tend to balance each other. With the adoption of sustainable design recommendations for passive architecture, a good indoor thermal condition and air quality can be achieved [4]. The attainment of a good indoor climate is paramount since people spend about 80% of their time in homes or offices [5]. Generally, naturally ventilated and mixed-mode thermal control buildings have a high user acceptance and use less energy, but their effectiveness depends on prevailing outdoor conditions (wind velocity and temperature). In favorable climates, the application of natural ventilation has led to a low total energy use of 10 – 30% when compared to air-conditioned buildings [6].

Ghana is characterized by a favorable climate during the rainy season (June – September). During this period, the mean outdoor temperature is about 26°C but relative humidity values are rather high (above 80%). Generally, for thermal comfort in spaces, an acceptable range of temperature and relative humidity values needs to be achieved. Ferstl [7] suggests 22 – 26°C and 30 - 80% relative humidity values. The standard of building biology testing methods [8] suggests 30 to 70% relative humidity to be comfortable. Koranteng and Mahdavi [9] advocate 23 – 29°C for 90% acceptability based on calculations of a long term study on thermal comfort and an approach after [1]. Further, a relative humidity of 30 – 80% is recommended. Fischer *et al.* [10] suggest a range of 50 – 70% of relative humidity to be comfortable. The danger of higher humidities in Ghana is the condensation on and in building materials which serves as a source of germs and odour. Generally, the growth of mould is accelerated when humidity increases [10]. According to [11], high humidities restrict evaporation from the skin and in respiration, and thus kerb the dissipation mechanism as experienced in Ghana, especially during the rainy season where humidity values of above 90% are recorded.

The human perception with regard to air velocity has been summarized [1]. An air velocity of less than 0.1 $m.s^{-1}$ is perceived as stuffy, 0.1 – 0.2 $m.s^{-1}$ as unnoticed, 0.2 – 0.5 $m.s^{-1}$ as pleasant, 0.5 – 1.0 $m.s^{-1}$ as awareness, 1 – 1.5 $m.s^{-1}$ as draughty and over 1.5 $m.s^{-1}$ as annoying. The influence of high air velocities in humid conditions can be welcoming since it plays an important role in the evaporative cooling potential of the skin. Moreover, sustainable design principles of orientation, building form, window sizes, air change rates and shading cannot be over-emphasised, especially in naturally ventilated buildings.

The present paper investigates the temperature, dew point and relative humidity values in an educational office building during the moderate period (rainy season) of the year in Ghana. Here, lessons on preference, based on the thermal conditions of the different office spaces (individual cell, open-plan) and on the ventilation possibilities (cross, one-sided and borrowed) are the focus of the study. Indoor sensors were used to record the thermal conditions and an evaluation exercise was conducted afterwards.

MATERIALS AND METHODS

To effectively study the thermal performance of naturally ventilated office buildings during the rainy season, the thermal conditions existing in an educational office building with characteristics of sustainable design principles were observed. The chosen building is the newly constructed studio (architectural students drawing spaces and offices) block of the College of Architecture and Planning, KNUST, Kumasi, capital of the Ashanti Region in Ghana. It is representative of low-rise educational buildings being constructed in Ghana (see Fig 1 and 2). Moreover, aspects of sustainable design principles (which are often neglected) of orientation, form, ventilation and shading have been employed, which makes the building worthy of studying.

Fig 1 View of the building at CAP, KNUST

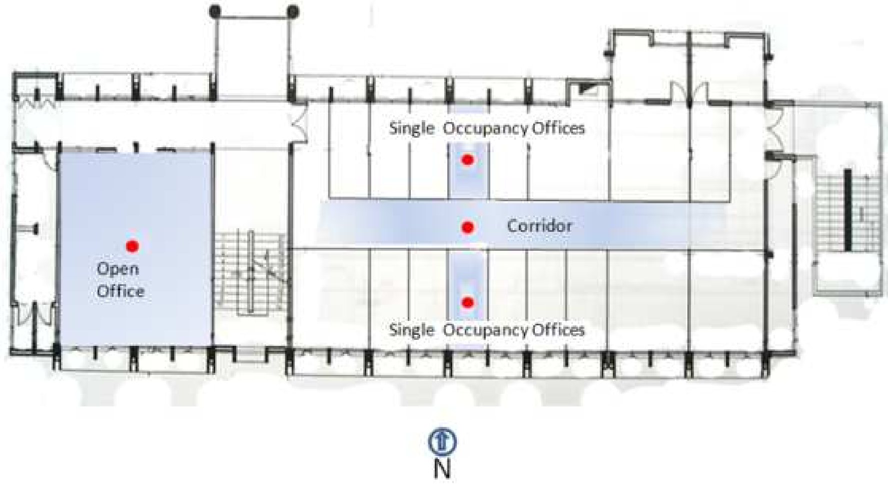

Fig 2 Schematic floor plan of the building with monitored spaces

The naturally ventilated building with an area of 2500m² is oriented towards the north, has three floors and a sub basement. The offices are mostly of a single occupancy type with few open plan and multiple occupancy spaces on the third and fourth floors. The ground floor and sub basement are used by students as studio spaces. The windows have been recessed on the main facades whereas only few are located on the east and west sides, serving the utility spaces. The corridor type of arrangement of the single cell offices means that the corridor needs artificial lighting and cross ventilation cannot be fully utilised (see Fig 3). High level louvre blade windows are used on both sides of the office walls to support privacy and comfort. The window to wall ratio on the main facade is 0.40 and the rectangular building form has an aspect ratio of 1:3.20.

Fig 3 Corridor showing high level windows of the building

Indoor temperature, relative humidity and dew point sensors (hobos) were installed in a number of offices (single and open plan, see Fig. 2). Further, outdoor data loggers with a cover protecting them from rain were used to record the external environmental conditions (temperature, relative humidity and dew point). Since the building is naturally ventilated, the need to monitor the prevailing outdoor conditions was paramount. The data was recorded every 10 minutes during the rainy season (July to September). Table 1 shows the accuracy of the sensors. The measured data were analysed in spread sheets and the various mean monthly values evaluated and graphed.

Table 1- Accuracy of the hobo sensors

Sensor	Range	Error
Air temperature	-20 to 70 ^{o}C	± 0.4 ^{o}C
Relative humidity	5 to 95 %	± 3%

Furthermore, to evaluate the window to wall ratios, air velocities and volumetric flow rates, recommended values and equations were used. Equation 1 shows the calculation of the air change rates (ACH) with minimum recommendations of 30m³/h. person and 50m³/h. person for individual cell and open-plan office spaces [11].

$$ACH = Ų/V\ [h^{-1}] \qquad (1)$$

Where *ACH* is number of air change rates, *Ų* is volumetric air flow rate [m³/h. person] and *V* is volume of space in m³.

The estimation of the air velocities for cross ventilated spaces was based on [12] (Equation 2). The assessment of the room depth for naturally ventilated buildings (for one-sided ventilation, Equation 3 and for cross ventilated spaces, Equation 4) was based on [11].

$$V = (ACH + 3.43)/63.1\ [ms.^{-1}] \qquad (2)$$

Where *V* is air velocity and *ACH* is air change rate.

$$D = 2.50.\ h\ [m],\ \text{(one-sided ventilation)} \qquad (3)$$

$$D = 5.0.\ h\ [m],\ \text{(cross ventilation)} \qquad (4)$$

Here, *D* implies the room depth and *h* is the floor height.

Recommendation on the form aspect ratio (rectangular buildings to be 1:1.75) was based on previous work of [13]. Finally, a general value for window to wall ratio (0.5) for appreciable ventilation was applied. The employed equations are general recommendations without correction factors for the Ghanaian context. There is the need for research in Ghana to proof the relevance and effectiveness of architectural design recommendations. The air change rates, air velocities in the spaces, assessment of room depth and form aspect ratios of the buildings were tabulated and compared with the design recommendations.

RESULTS

The mean monthly hourly values recorded from the offices, namely, individual cells oriented towards the north and south (named north or south), the corridor, the open-plan (named open) spaces and the outdoor values are illustrated.

Fig 4 shows the mean monthly hourly temperature values during the working hours (8-17 hours) and Fig 5 illustrates the mean monthly temperature values for the evening and night time.

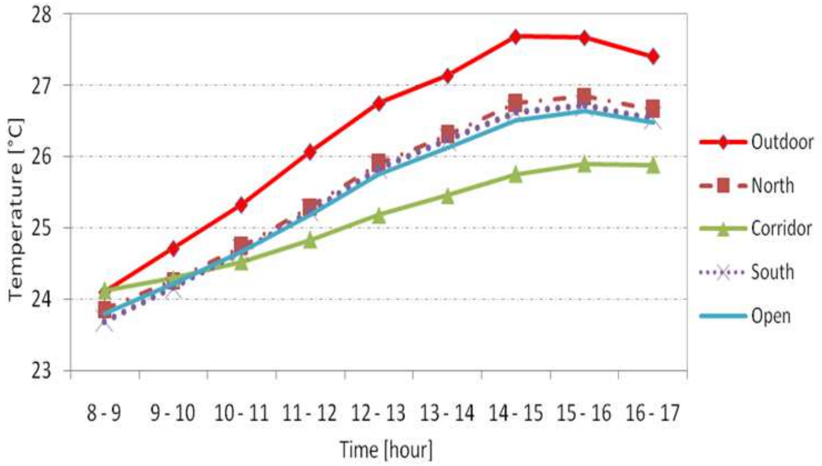

Fig.4: Mean monthly hourly temperature values during the working hours of individual cells (north and south orientation) and open-plan offices

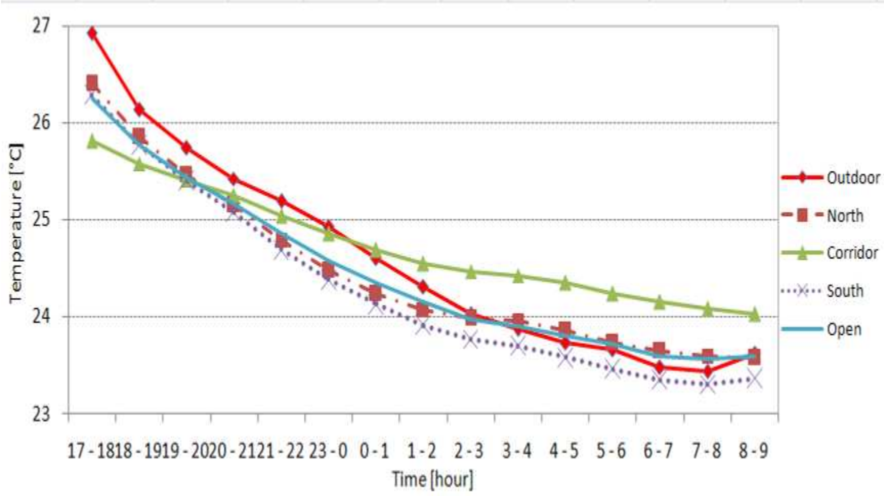

Fig.5: Mean monthly hourly temperature values during the evening and night hours of individual cells (north and south orientation) and open-plan offices

The mean monthly hourly relative humidity values during and after the working time is demonstrated in Fig 6 and 7. Furthermore, Fig 8 and 9 show the dew point values (mean monthly) during the working hours and for the evening and night time.

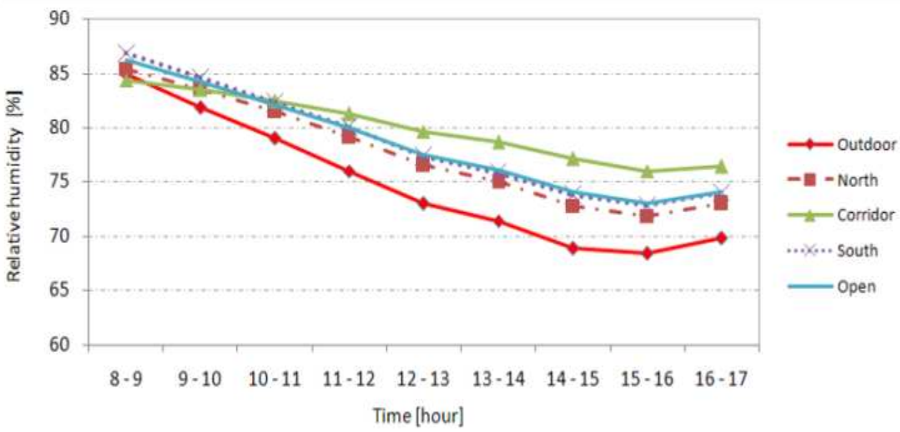

Fig.6: Mean monthly hourly relative humidity values during the working hours of individual cells (north and south orientation) and open-plan offices

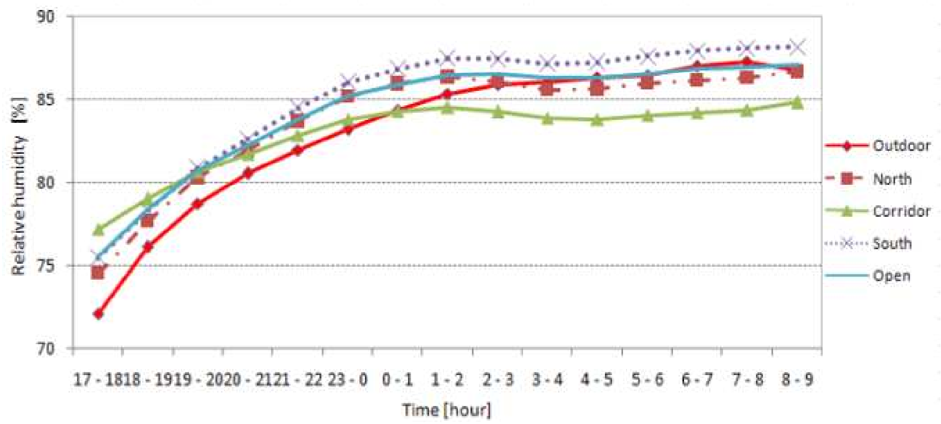

Fig.7: Mean monthly hourly relative humidity values during the evening and night hours of individual cells (north and south orientation) and open-plan offices

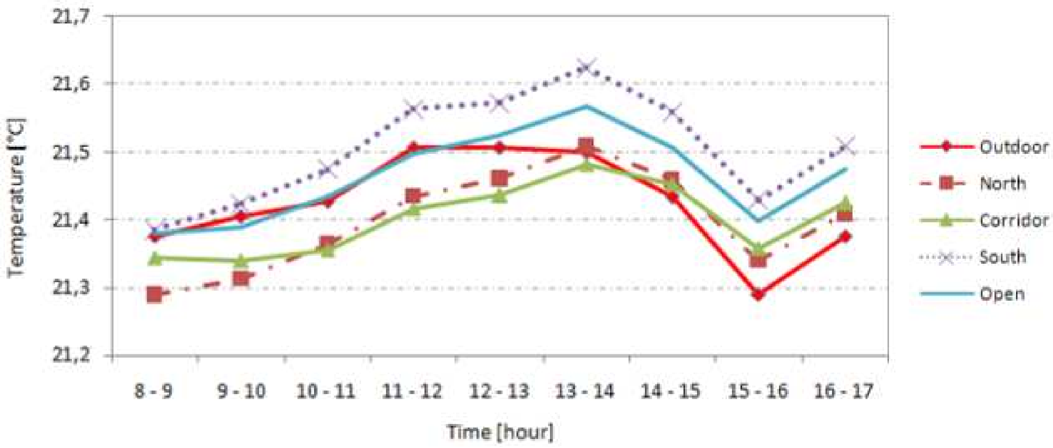

Fig.8: Mean monthly hourly dew point values during the working hours of individual cells (north and south orientation) and open-plan offices

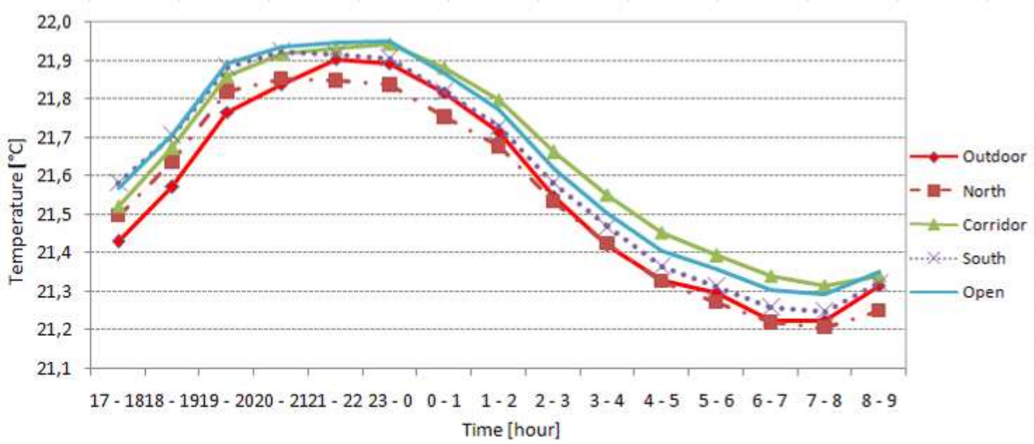

Fig.9: Mean monthly hourly dew point values during the evening and night hours of individual cells (north and south orientation) and open-plan offices

The mean monthly thermal values (temperature, relative humidity and dew point) for the individual cell offices oriented towards the north are illustrated in Fig 10. The same thermal values for the corridor, individual cells oriented towards the south, and the open-plan offices are shown in Fig 11, 12 and 13.

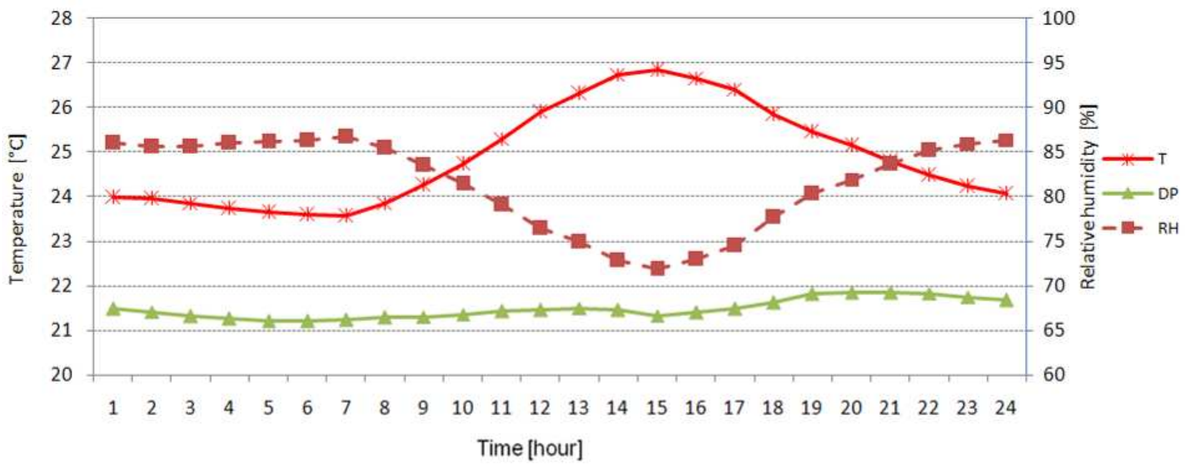

Fig.10: Mean monthly hourly thermal values of an individual cell office oriented towards the north (T: Temperature, DP: Dew point and RH: Relative humidity)

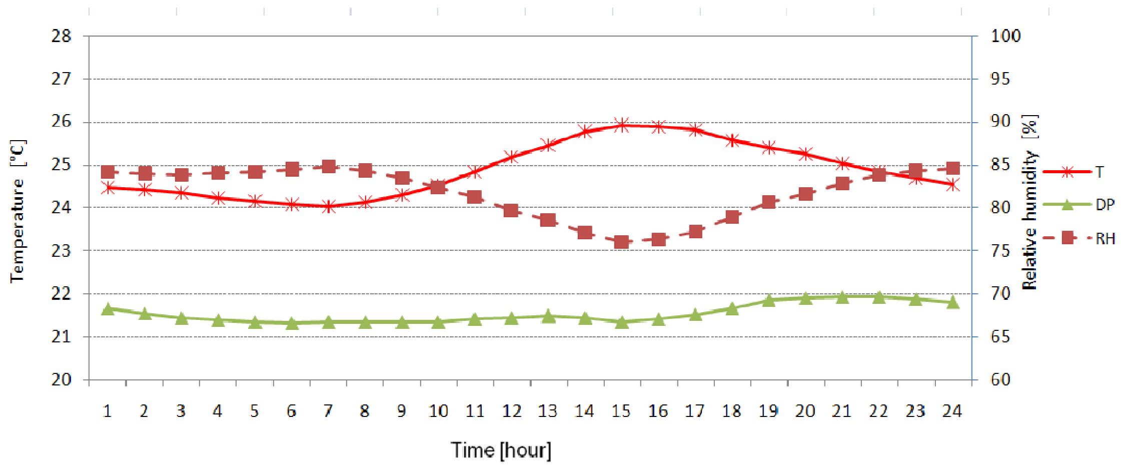

Fig.11: Mean monthly hourly thermal values of the corridor (T: Temperature, DP: Dew point and RH: Relative humidity)

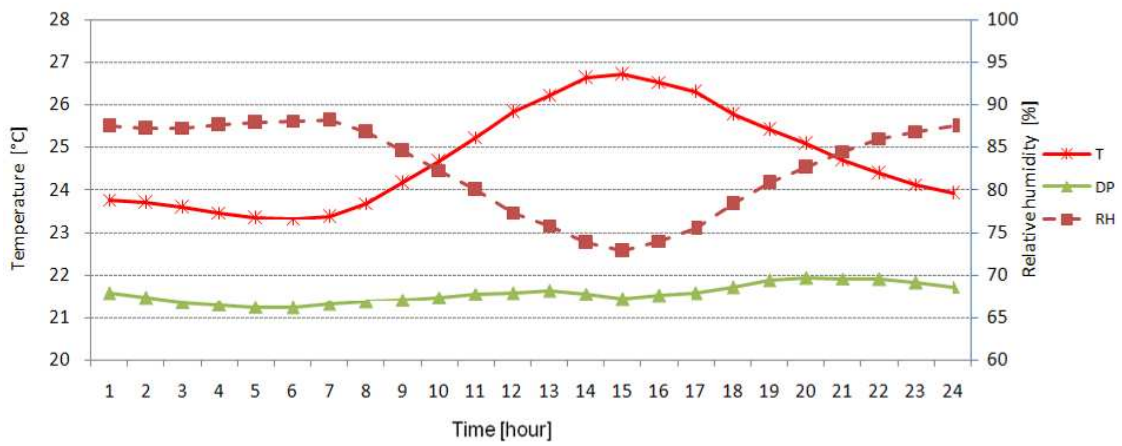

Fig.12: Mean monthly hourly thermal values of an individual cell office oriented towards the south (T: Temperature, DP: Dew point and RH: Relative humidity)

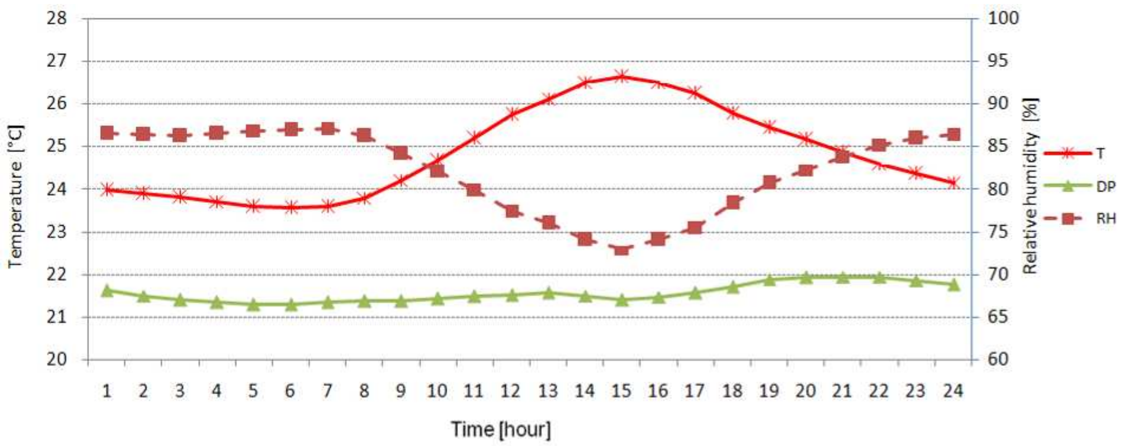

Fig.13: Mean monthly hourly thermal values of the open-plan office (T: Temperature, DP: Dew point and RH: Relative humidity)

Table 2 shows the results of the evaluation of air flow rates and window area per office space.

Table 2- Output data on air flow rates and window area

Parameter	Individual cell office (area = 5 m²)	Open-plan office (area = 80 m²)
Air change rate, ACH [h^{-1}]	2.40	2.50
Air velocity, V [$m.s^{-1}$]	0.10	0.10
Air velocity, V (pleasant) [$m.s^{-1}$]	0.50	0.50
Air change rate, ACH (pleasant) [h^{-1}]	0.4	4
Volumetric air flow rate, Ų [m³.h. person^{-1}]	30.0	50.0
Occupancy	1.00	10.0
Window area, north façade [m²]	2.20	8.00
Window area per façade required [m²]	2.75	10.0
Window area, corridor-walls [m²]	1.10	8.00

The building depth of 12.50m and depth of individual cell offices (2.50m) fulfils the recommended values for cross and one-sided ventilation buildings (Equations 3 and 4). However, the aspect ratio of 1:3.20 is more than the recommended value of 1:1.75 for rectangular buildings [13].

DISCUSSION

The outdoor mean monthly hourly temperature value rises from 24 °C in the morning to a peak of about 28 °C during the working hours (Fig 4). At 8 in the morning, all the temperature values of the monitored spaces are nearly the same (24 °C). As the outdoor temperature rises with increasing solar radiation, the indoor temperature also increases. The individual office cells show a slightly higher temperature (northern and southern oriented) than the open-plan space (Fig 2) but with a standard deviation of 0.07. Here, preference of office and ventilation type over each other cannot be recommended. The maximum indoor temperature of about 27 °C could be said to be comfortable for all the spaces [9] (studies based on Fanger's percentage of dissatisfied persons). Interestingly, the corridor shows a lower temperature value between the hours of 10 am and 5 pm. The cool air at the enclosed corridor resulted from the low air change rates. This characteristic has also been observed in compact buildings [14]. The advantage in compact building forms is that they gain less heat during the day but loose less heat at night. To make good use of the cool air in the corridor, workspace could be located away from the external facades. However, corridors could be noisy and impair concentration of workers in office buildings.

In Fig 5, a fall in all the temperature values (evening and night hours) is demonstrated. The outdoor temperature reduces, reaching the corridor levels around midnight and continues to fall to about 23.5 °C. At this level, the outdoor air is cooler than that of the corridor (ca. 1 °C temperature difference), northern and open office spaces, but slightly warmer than the individual cell offices oriented towards the south. The high temperature in the southern individual cells could be linked to the exposed external walls, absorbing much solar radiation during the day. The standard deviation of the cool to the warm offices is low (0.02) and the prevailing indoor temperatures are all in the recommended thermal comfort range. The cooler outdoor air from 2 am onwards has a passive cooling potential when effectively used. This could be combined with thermal mass to improve the thermal performance and energy use of buildings [15 and 16].

The plotted relative humidity values during the working hours (8 am to 5 pm) showed lower outdoor values than the indoor spaces (Fig 6). During the mornings, the relative humidity difference was about 2 %, which increased to about 7 % at 3 pm. High values (above 70 %) are recorded for the corridor, followed by the open-plan and the individual cells (southern and northern) but with a difference of less than 3 %. Moreover, the values exceed 80 % from 8 am to 12 noon. These values raise severe concerns, since high humidity levels result in inefficient evaporative cooling of the skin which leads to discomfort. In addition, odours and ill-health symptoms are part of the concern with high humidity values [8]. However, values of 70 to 80 % fall within the recommendations on relative humidity [7 and 9]. Furthermore, monitoring of high humidity values above 75 % is recommended, since latent loads of occupants could result in an increase in relative humidity (58 – 85 $g.h^{-1}$ per person at temperatures of 24 to 28 °C), [10].

The demonstration of the relative humidity values during the evening and night hours (Fig 7) raises extreme concern. The degree of the concern (humidity and temperature discomfort) is based on the standard of building biology [8]. After 19 hours, the recorded relative humidity data exceed the boundary of the recommendation value of 80 %. From midnight to 9 am, values of 85 to 88 % were recorded (mean corridor value of 84 %). The most important factor accompanying high relative humidity values is the dew point temperature. Moisture will be visible when indoor temperature falls below the dew point. In Fig 8, the highest dew point temperature was recorded in the individual cell office towards the south, which was followed by the open-plan space and the individual cell towards the north, and the corridor space. The standard deviation ranges from 0.05 to 0.08 which illustrates the closeness of the values. Besides, the mean dew point temperature of 21.4 °C is just below the minimum recommended temperature for comfort (23 °C) [9]. The pattern of the dew point temperature was similar during the evening and the night hours (Fig 9). A mean temperature value of 21.5 °C and a standard deviation of 0.20 to 0.21was recorded.

This clearly shows the difficulty involved (moisture control) in designing healthy and efficient buildings in warm and humid environments. Further, at a temperature range of 0 to 50 °C, an accelerated growth rate of 15 to 30 % of fungal spores (weekly growth rate of 10^3 - 10^6 of spores/m^3 air) has been observed [10]. The proliferation of microorganisms in buildings affects indoor air quality, creates hazardous health conditions for the occupants and contributes to the deterioration of building components [17].

In Fig 10 – 13, the thermal conditions in the spaces have been demonstrated. The mean temperature (24.7 to 24.9 °C), relative humidity (81.5 to 82.2 %) and dew point (21.5 to 21.6 °C) values calculated showed insignificant differences and therefore no preference of office space and ventilation type over the other was given. The maximum temperature values recorded ranged from 25.9 to 26.8 °C. Also, the maximum relative humidity values ranged from 85 to 88 %. The dew point temperature had a peak of 21.9 °C. The maximum temperatures were recorded at 3 pm, this time of day also showed the minimum relative humidity values (Fig 10 – 13). The main concern are definitely the high relative humidity levels and the dew points leading to problems associated with mould. Persistent moisture leads to rot, corrosion, and other forms of deterioration. Also, the reduction of thermal resistance and a decrease in the strength and or stiffness of materials have been observed. Furthermore, insect infestation through invisible mites, cockroaches and ants are a result of moisture related issues [17].

The evaluation of the air flow rates (Table 2) showed that due to the high relative humidity values, a high air change rate would be needed to achieve a pleasant (air velocity of 0.5 $m.s^{-1}$) indoor climate. Whilst the window area required per office space was 0.55 m^2 and 2 m^2 less on the main facades for the individual cell and open-plan office spaces, that of the corridor would need to be increased by 1.65 m^2 (individual cell offices), (Table 2). A minimum window to wall ratio of 0.5 is recommended in passive designs to assist in the effective use of natural ventilation, which would help to avoid mildew. To control and avoid mildew, the use of non-porous building materials and sustainable design principles are recommended. The installation and use of fans would help to promote evaporative cooling of the skin and should be a priority in all office buildings, especially in naturally ventilated types, since the effect would be thermal sensation reduction of air temperature values of 2 – 3 °C [18].

CONCLUSION

To effectively study the building performance of naturally ventilated office buildings during the rainy season, the thermal environment prevailing in an educational office building with attributes of sustainable design was monitored. The results pertaining to the different office types, ventilation possibilities and orientation showed that whilst the temperature values (mean of ca. 25 °C) were in the recommended comfort range, the relative humidity levels were rather high (above 80%). The associated dew point temperatures were also high (very close to the minimum comfort temperature of 23 °C). The danger is the growth of mildew, damage to building construction and health problems. Further, the thermal conditions could not justify one office type over the other since the recorded values showed minor deviations. However, the corridor space was found to be cooler during the day time hours but warmer at night. The consequent use of sustainable building design principles could lead to a better thermal environment.

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