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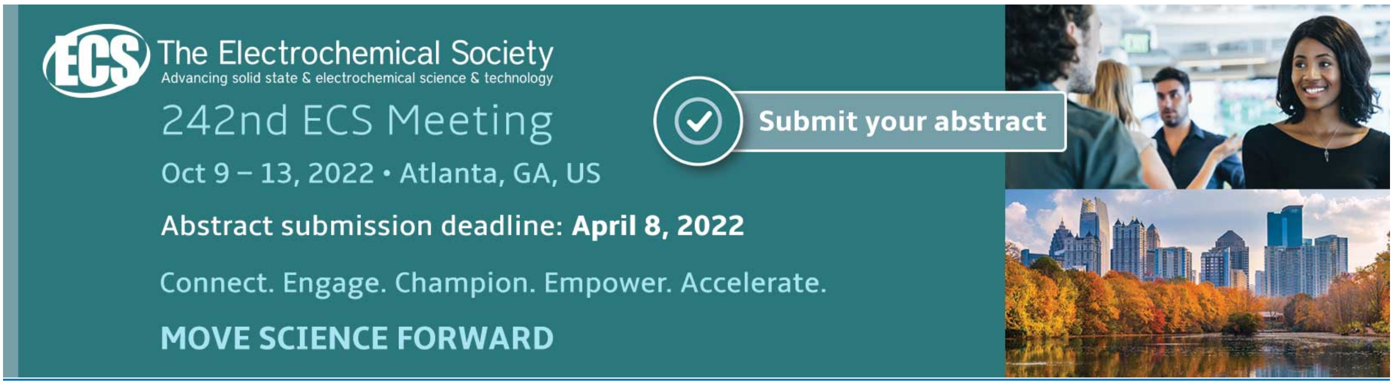

Improving the energy efficiency of an office building by applying a thermal comfort model

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Abstract

The building represents one of the main actors of global warming of the planet because of the significant amounts of energy consumed. In Benin, 44,38% of electrical energy is consumed by office and service buildings. This is explained by the excessive use of air conditioning systems due to the lack of a thermal comfort index specific to the region. This work therefore focuses on assessing the impact of the choice of a thermal comfort model on the energy efficiency of buildings. For this purpose, an office building was chosen in the south of Benin and comfort surveys were conducted among the occupants. The model selected for this purpose is the adaptive model developed by López-Pérez and al. for air-conditioned buildings in humid tropical regions. Subsequently, a monitoring campaign of meteorological, hygrothermal and energetic data of the building was carried out during six months. The results obtained show that the average temperature of the offices ($T_f \approx 24°C$) during the hours of occupancy is relatively lower than the comfort temperature determined with the model ($T_c = 26.2°C$). Moreover, the different simulations carried out under TRNSYS by substituting the office temperatures by the comfort temperature show a reduction of about 20% of the building's energy consumption. This shows the importance of the comfort model of López-Pérez and al. in improving the energy efficiency of the building.

Key words: energy efficiency, thermal comfort, adaptive model, tropical region

1. Introduction

Energy is at the heart of the development of any nation. At the same time, its production actively contributes to global warming. In addition, the buildings sector consumes about 30 to 40% of the world's energy production and accounts for about 40 to 50% of greenhouse gas emissions into the atmosphere [1]. H. Hafeznia and al. [2] associate such consumption with population growth and the search for well-being. The life cycle energy analysis of some buildings by Ramesh and al. revealed that 80 to 90% of the energy consumption of buildings is carried out during their use phase [3]. At the same time, Shamsi and al. [4] argue that HVAC systems consume the largest share of the energy used by buildings to meet the comfort requirements of the occupants. However, this consumption can be reduced by adjusting setpoint temperatures to the actual needs of the occupants.

In Benin, the energy (electricity) share of the office and service building sector is about 45% [5]. This is due to overuse of air-conditioning systems. Indeed, the country's energy efficiency code imposes thermal conditions in the order of $24°C$ to $27°C$ inside offices [6]. A comfort survey carried out by Kiki and al. [7] on an office building in the city of Cotonou revealed that most of the monitored offices operate at a temperature of $24°C$. This statement is confirmed by the present study where the monitoring campaign carried out over 6 months in the same building showed that 85% of the monitored offices are at a temperature of about $24°C$ as opposed to 15% with operating temperatures not exceeding $26°C$. However, these temperatures can be considered relatively low for a population living in a hot and humid region such as Cotonou. As evidence, Mina and al. assert that people living in hot regions tolerate relatively high comfort temperatures [8]. Furthermore, [8] estimated, based solely on the results of the comfort survey, that the comfort temperature of the occupants is $26.1°C$. This value is in agreement with the comfort temperature obtained by the authors by applying the model of López-Pérez and al. [9] (i.e. $26.1°C$). This thus testifies to the effectiveness of this model in determining the comfort conditions in the building. However, no evaluation of the energy gains resulting from the adoption of such a model was carried out by the authors. The present study is therefore devoted to evaluating the impact of the use of the adaptive comfort model of López-Pérez and al. on the energy consumption of the building.

2. Material and method

2.1. Material

Presentation of the study building

The building selected for this study is an office building located in the city of Cotonou in southern Benin. It consists of an 8-storey circular tower and two 7-storey wings (A and B) with a rounded shape. With the exception of the first floor, which includes a large entrance hall, two offices, a conference room and a canteen, the architecture of the upper levels (+1 to +7) is identical. Each floor consists mainly of twelve (12) offices, a meeting room and a small hall located in the tower. On the other hand, the 8th floor covers only the circular tower and includes two (2) offices and a waiting room. The floor area of the building is $6098\ m^2$ and the annual consumption is estimated at $125\ kWh/m^2$.

All the offices in wings A and B each have at least one air conditioning unit (split) with variable power depending on the occupancy mode (one split of $1.2\ kW$ per individual office and 2 splits with a nominal power of $1.9\ kW$ each per landscape office). As for the rooms in the circular tower, they are conditioned by a central air conditioning unit with a capacity of $55\ kW$ installed on each floor.

Thermal comfort survey

An environment is considered thermally comfortable when the occupants express their satisfaction with the thermal conditions. Such a feeling is subjective and depends not only on the hygrothermal conditions of the considered environment, but also on the metabolism, the thermal history and the social cultural factors of the occupants. Moreover, as these factors are difficult to quantify, several studies suggest comfort surveys in order to collect the real feeling of the occupants. Thus, a comfort survey was conducted among the occupants of the study building [7]. A questionnaire was thus set up in reference to the one carried out by Moujalled [10]. Through it, the participants expressed their thermal feelings and preferences according to the ASHRAE scale $[-3;\ +3]$. Information such as the type of clothing, health status, etc., were also provided. A total of 14 women and 15 men took part in the survey and 205 correctly filled in questionnaires were collected over a period of about one month. At the same time, measurements of temperature, humidity and air velocity in the surveyed offices were carried out according to the recommendations of ISO 7726 [11].

Monitoring Campaign

In order to have real data to enter into the simulations, a six-month monitoring campaign was initiated. This consisted of collecting hygrothermal and energy data for the building. Thus, the temperature, humidity and air speed of the offices were recorded as well as the power and hourly consumption of certain appliances. The characteristics of the temperature and humidity sensors (Figure 1b) used for this purpose are given in Table 1. As for the energy data, a power recorder (Figure 1d) and a consumption hour recorder (Figure 1c) were installed. Finally, a mini-station placed on the roof of the building (Figure 1a) was used to measure temperature, humidity and overall solar radiation from the outside environment.

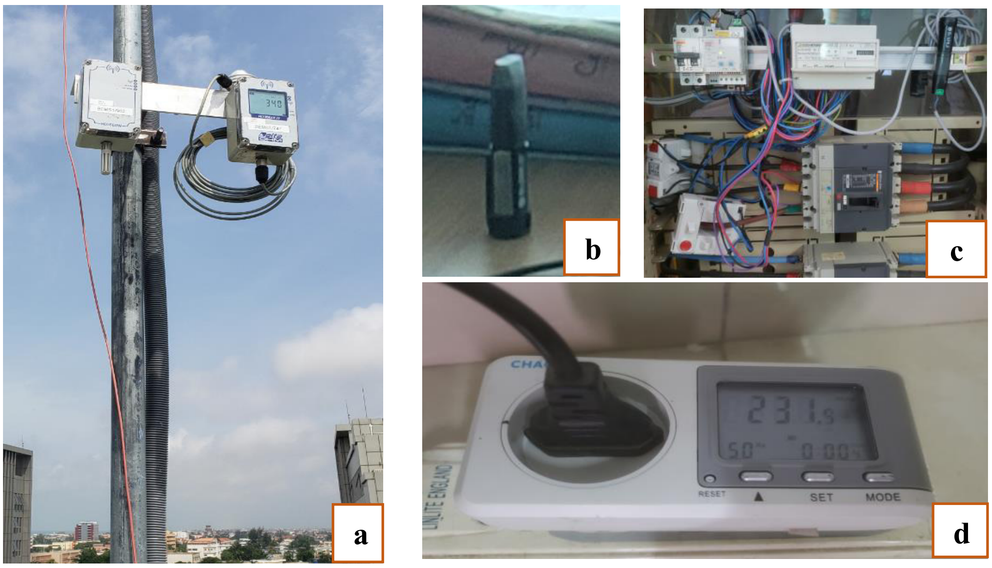

Figure 1: Equipment for recording hygrothermal and energy data of the building

Table 1
Specifications of the instruments.

Parameter measured	Instrument	Quantity	Accuracy	Internal resolution	Tolerance
Indoor air temperature ($°C$)	EasyLog USB 2+	10	$\pm 0.55°C$	$0.5°C$	$[-35°C;\ +80°C]$
Indoor relative humidity (%)	EasyLog USB 2+	10	$\pm 0.5\%RH$	0.5%	$[0\%;\ 100\%]$
Indoor air velocity (m/s)	Delta OHM HD4V3TS	3	$\pm 0.5\%$	$0.005m/s$	$[0.1\ m/s;\ 5\ m/s]$
Outside air temperature ($°C$)	Delta OHM HD35EDW	1	$\pm 0.1°C$	$0.1°C$	$[-20°C;\ +70°C]$
Outside relative humidity (%)	Delta OHM HD35EDW	1	$\pm 1.8\%RH$	0.1%	$[0\%;\ 100\%]$
Global solar radiation (W/m^2)	Delta OHM HD35EDLW	1	–	$1W/m^2$	$[0\ ; 2000W/m^2]$
Power of office appliances (W)	CHACON 54357	3	$\pm 0.5\%$	$0.1W$	$[0W;\ 3500W]$
Hourly power consumption (kWh)	GOSSEN METRAWATT U389B	1	–	–	$[0\ ; 1000 Imp./kWh]$

Simulation tool

In order to disaggregate the energy consumption of the building and to evaluate energy saving opportunities, the simulation software TRNSYS 18 was chosen. It is a complete and extensible simulation environment intended, among other things, for the thermal and energy simulation of buildings and their component systems. In this study, the software was used in particular to distribute the overall energy consumption of the building according to the various consumption items, namely air conditioning, lighting and office equipment. It was also used to estimate the energy gains resulting from the adoption of the comfort model of López-Pérez and al.

2.2. Methodology

Determination of the comfort temperature

The present work is based on the results of the comfort study carried out by Kiki and al. [7] in the same building. Following a comfort survey of the occupants, the authors recommend the use of the adaptive comfort model of López-Pérez and al. [9] for the evaluation of thermal comfort in the building. Thus, equation (1) is used to determine the comfort temperature in the building.

$$T_c = 0.13T_{rm} + 22.7 \quad (1)$$

Where T_{rm} is the running mean outdoor temperature.

$$T_{rm} = (1 - \alpha)(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \cdots) \quad (2)$$

Where α is the Griffiths coefficient whose value varies between 0.6 and 0.9; T_{od-1}, T_{od-2}… are the average daily temperatures of the days successively preceding the survey ($°C$).
In addition to the above-mentioned study, a monitoring campaign of energy and hygrothermal data took place from June 26 to December 31, 2020. On the basis of the meteorological data collected on site, the comfort temperature was therefore calculated. As the building is located in a humid tropical region, $\alpha = 0.9$ [12].

Energy simulation of the building
Simulating a building in TRNSYS 18 means modeling the building in 3D in Google SketchUp, defining the characteristics of the building envelope, the mode of operation and occupancy of the building in TRNBuild before proceeding to the settings of the simulation parameters in TRNSYS Studio. Due to the similarity between the different floors of the building in terms of architecture, occupancy and operation mode, the simulations were performed on only one level (the 7th floor). The data entered in the simulations are those resulting from the monitoring campaign. Thus, the temperature, humidity and air speed data collected in the offices made it possible to define the hygrothermal conditions of each zone. As a result, the heat gains related to office equipment (computers, printers, etc...) and occupants were informed thanks to the energy data provided by the electrical recorders and on the basis of a survey conducted among the occupants during the monitoring campaign. As for the hourly meteorological data of the site, including temperature, humidity and global solar radiation, they were used to correct the data proposed by the software. However, it should be noted that the simplified Watanabe method [13] was sused to split the recorded global radiation into incident and diffuse radiation.

The first phase of the simulation consisted in determining the consumption of the building by maintaining the thermal conditions observed in the offices during the monitoring campaign ($T_f = 24°C$). Consumption was divided into three different items: air conditioning, lighting and office equipment. In the second phase, the operating temperature of the offices was replaced by the comfort temperature determined with the López-Pérez and al. model (equation 1). The energy consumption was simulated again and compared with the previously obtained consumption.

3. Results and discussion

Based on the ASHRAE scale $[-3; +3]$, 58.52% of the respondents expressed their feeling of thermal neutrality (0) towards their environment against 23.5% who feel a slightly cold thermal sensation (-1) and 15.12% a slight heat $(+1)$; the remaining 2.86% express cool (-2) and warm $(+2)$ sensations. The average temperatures recorded during the survey phase are equal to $24.6°C$ for zero thermal sensation votes ($TSV = 0$); $23.2°C$ for $TSV = -1$ and $27.4°C$ for $TSV = +1$.

The average clothing levels associated with these operating temperatures are $0.79\ clo$, $0.82\ clo$ and $0.74\ clo$, respectively. Given that the participants are engaged in office activity, the metabolic value is estimated to be $1.2\ met$. Analysis of these results reveals a relatively low neutral temperature and a high average clothing level for people living in a warm region. In other words, occupants adapt to their environment by increasing their clothing level whose maximum value for office activities in such a region can be estimated at $0.75\ clo$ according to ISO 7730. Looking at the thermal preference vote, the desired comfort temperature the occupants are estimated to be $26.1°C$ [7]. Figure 2 shows the hygrothermal data recorded during the monitoring campaign.

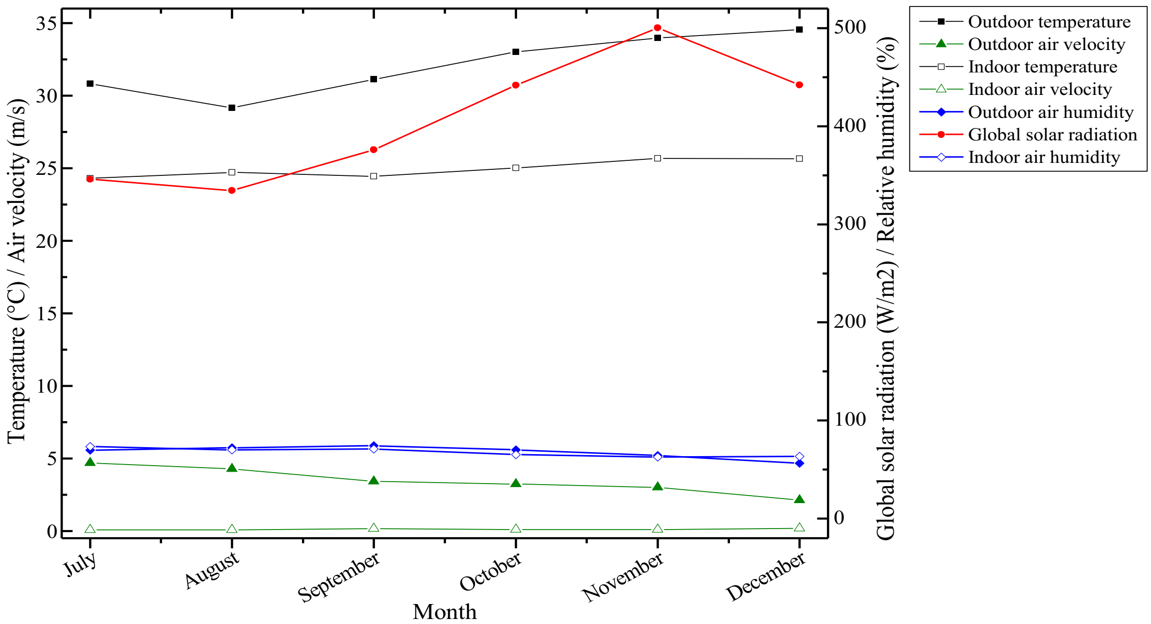

Figure 2: Hygrothermal and aeraulic data of the monitored offices and meteorological conditions of the site during the hours of occupation

The disaggregation of the energy consumption performed under TRNSYS following the actual operating conditions of the building is presented in Figure 3a. It is clear that air conditioning consumes the largest share of the building's energy (64%), followed by office equipment, which consumes 23.7%. Lighting consumes only 7.75% of the building's annual energy consumption. The rest of the consumption is mainly attributed to the two elevators that the building has and the booster pumps that send water to the floors. A recording of the hourly consumption of the elevators during one month allowed to estimate the real consumption of the elevators at 3.71%. The simulation values therefore seem to be in adequacy with the data collected in the field, particularly with regard to lighting, elevators and office equipment, for which the real consumption is estimated at 8.6%, 3.7% and 18.9% respectively. The largest discrepancy is observed in the consumption of office equipment. This is justified by the sanitary measures related to covid-19 and implemented by the management from March to June 2020, obliging the occupants of the landscaped offices to work alternately. With regard to the actual consumption of air conditioning systems, no measurement could be made due to the lack of suitable equipment for the installation.

By replacing the actual operating temperature of the offices ($T_f \approx 24°C$) by the comfort temperature calculated using equation (1) ($T_c = 26.2°C$), the energy share of the air conditioning systems previously estimated at 64% decreased to 45.27%. The energy shares of the other consumption items having hardly changed, an energy gain of 18.73% can therefore be observed. The real and simulated monthly consumption for operating temperatures of $24°C$ and $26.2°C$ are shown in figure 3b. The uncertainties associated with the simulated consumption are relative to the global uncertainties related to the simulation temperatures. The evaluated uncertainties on these temperatures are composed of the standard uncertainties A and B defined in the Guide to Measurement Uncertainties (GUM) [14]. The first type A uncertainty is obtained through the values recorded in-situ, while the second depends on the accuracy of the measurement devices. Thus, the uncertainties related to operating and comfort temperatures are ± 0.6 and ± 0.5 respectively. Taking into account these uncertainties on the simulation results allows to obtain energy gains varying in the range $[17.4\% \,;\, 20\%]$.

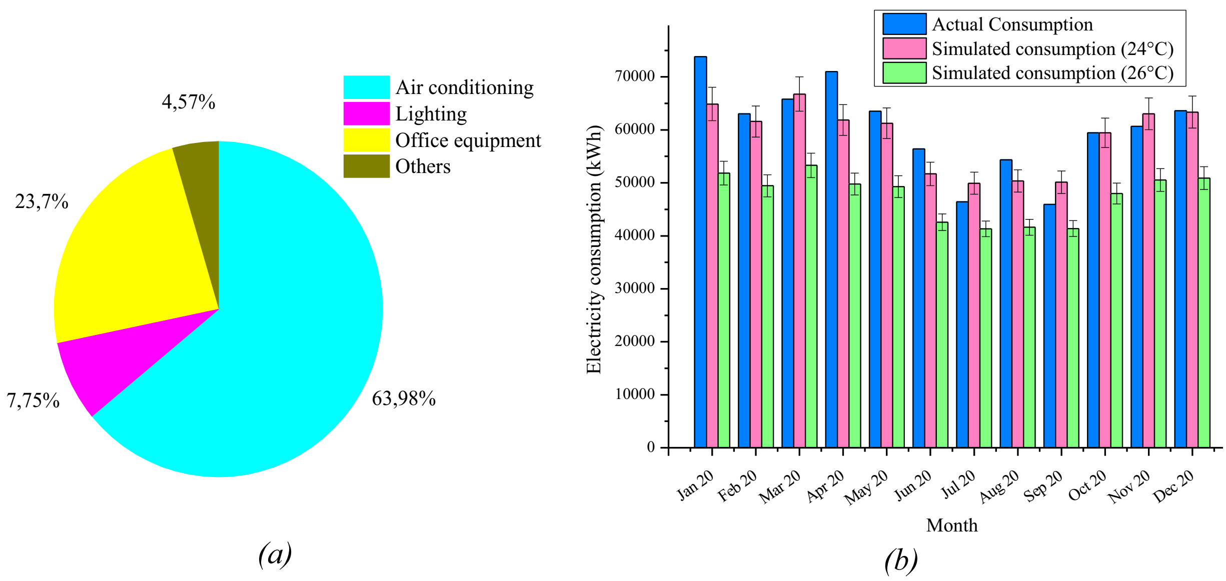

Figure 3: *(a)* Disaggregation profile of the building's energy consumption; *(b)* Actual and simulated monthly consumption of the building.

Conclusion

Taking into account the thermal history and the ability of people to adapt to their environment is an essential factor in determining the target temperatures of the rooms they occupy. This contributes not only to the well-being and productivity of the individual, but also to improving the energy efficiency of buildings. Thus, the adoption of the adaptive comfort model of López-Pérez and al. developed for air-conditioned buildings in humid tropical regions has reduced the energy consumption of the building under study by about 20% without compromising the well-being of its occupants. The change from an operating temperature of $24°C$ to $26.2°C$ responds well to the comfort aspirations of the occupants.

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