Evaluation of thermal comfort in library buildings in the tropical climate of Ghana

(Case Study of the Balme Library in the University of Ghana, Accra, Ghana)

Double-blind review process

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ABSTRACT: Adaptive thermal comfort plays a crucial role in addressing climate change concerns, especially in Ghana. In this hot and humid region, air-conditioners are identified as one of the main culprits behind the rising trend in electricity demand and greenhouse gas emissions. Additionally, due to the limited prediction accuracy of Fanger's PMV model, there is a need to evaluate adaptive thermal comfort to develop a reliable model for tropical regions. This study evaluates the adaptive thermal comfort in the Balme Library in Accra, Ghana, in both naturally ventilated (NV) and air-conditioned (AC) modes. The presented adaptive model in this study is compared with the current international standards, such as ASHRAE-55 and CEN standards. Based on the linear regression of mean sensation votes (MTSV) and predicted mean votes (PMV) as a function of operative temperature, while the neutral temperature of PMV is 27.8 °C, the linear regression method in NV mode predicts a neutral temperature of 30.3 °C. Consequently, the PMV prediction is 2.5 °C lower than that of the linear regression method. Meanwhile, the current international standards underestimate the ranges of thermal preferences among building occupants, as this proposed model in this study reveals higher slopes in the linear regression model.

1. INTRODUCTION

Thermal comfort is one of the motivations to research climate change-related concerns which cause destructive effects on humans, the environment, and the quality of life. Climate change is a complex environmental issue and presents significant risks to ecological, infrastructure, and economic systems. In current conditions, human-induced climate change is causing dangerous and widespread disruption in nature and affecting the lives of billions of people worldwide, despite efforts to reduce the risks. People and ecosystems least able to cope are being hardest hit. Meanwhile, the potential effects of global climate change on buildings are a growing concern worldwide, as rising temperatures can significantly impact their energy performance and indoor thermal comfort conditions [1]. For instance, heat waves can cause large socioeconomic and environmental impacts. The observed increases in their frequency, intensity and duration are projected to continue with global warming [2].

Additionally, in sub-Saharan African countries, rapid growth of construction has led to the proliferation of low-quality buildings with high energy consumption. This trend has raised environmental concerns regarding their contribution to environmental threats [3,4]. As, buildings can have a great impact on the environment, because buildings are considered one of the most significant sources of energy use and greenhouse gas emissions [5]. Therefore, enhancing the sustainability of the building sector is crucial to combat climate change [6]. To achieve this crucial goal, architects and the other contributors involved in construction are responsible for addressing various concerns when designing buildings, with one of the most significant being ensuring compliance with building codes and standards to evaluate of thermal comfort. While designers and engineers commonly refer to international standards, such as ISO 7730, ASHRAE-55, CEN, and CIBSE for HVAC system sizing and temperature calculations. However, this approach fails to consider the satisfactory performance of buildings and occupants' tolerance levels. Consequently, there is an increasing need in these countries to develop adaptive thermal comfort standards.

2. RESEARCH GAP

There are several justifications to evaluate the thermal comfort of Balme Library, located in Ghana's tropical climate. Increased urbanisation growth and the wasteful use of fossil fuels and non-renewable energy have led to climate change and the production of greenhouse gases. The depletion of fossil fuel resources, low efficiency, and high cost of their environmental impacts have made energy consumption optimisation and the use of renewable energy in construction inevitable [7]. On the other hand, by improving the standard of living, people expect a better level of comfort, which ultimately necessitates the use of heating, ventilation, and air conditioning (HVAC) [8]. Especially, in tropical, hot, and humid regions, such as Ghana, where the straightforward response to discomfort in this climate has been the adoption of air conditioners and mechanical cooling [9]. HVAC systems are crucial for maintaining a consistent temperature and humidity indoors all year long and making it possible to provide pleasant working and living conditions. However, it's important to recognise that the extensive use of HVAC systems can have adverse consequences. This includes an increased demand for electricity and consequently, a contribution to rising greenhouse gas emissions on a global scale [10]. Moreover, the rapid growth of construction in sub-Saharan African countries is characterised by low quality buildings and high energy consumption. This raises concerns about their contribution to environmental threats, especially climate change. This is a disquieting trend, and the initiatives taken to counteract it are few [11]. The progressive urbanisation has significantly impacted energy consumption, resource depletion and pollution and waste production [12]. African cities are outpacing the rest of the world in growth [13]. On the other hand, the comfort zone can differ in size and range within particular geographical areas [14,15] In addition, the necessities of adaptive thermal comfort research can be justified with the following reasons:

- Relying only on international HVAC standards neglects building performance and occupant comfort, causing energy inefficiencies, increased costs, and carbon emissions due to inadequate addressing of overheating and overcooling [16].
- International comfort standards may not be universally applicable to all climates due to variations in comfort preferences among people in different regions and climate zones [17].
- In hot and humid climates like Ghana, prioritise adaptive comfort and passive design over air-conditioning by implementing natural ventilation, shading, and insulation strategies to reduce energy consumption and environmental impact while meeting international standards like ASHRAE -55.

3. THERMAL COMFORT APPROACHES

Thermal comfort models can be used to gain insight into important building design variables and predict whether a given design will provide satisfactory thermal conditions [18]. Some popular thermal comfort models include the Predicted Mean Vote (PMV) model, Griffiths' method, and the adaptive model. The PMV model, introduced by Fanger in the late 1960s as a heat balance model, was developed from Fanger's laboratory and chambers studies [19]. International standards like ASHRAE 55 and CEN recommend using Fanger's model. The PMV model assesses human thermal comfort by considering six key factors: clothing thermal resistance, metabolic rate, air temperature, mean radiant temperature, air velocity, and relative humidity; and it predicts the mean thermal sensation vote of a large group of individuals based on the heat balance of the human body [20,21]. However, its limitations in accurately representing real-world conditions have raised doubts about its accuracy in predicting thermal comfort in actual buildings, including habituation, expectation, behavioural adjustments, and the availability of environmental control options [22,23,24,25]. And the adaptive thermal comfort model considers occupants' ability to adapt to different temperatures based on outdoor climate and seasonal variations, taking into account contextual factors such as access to environmental controls and past thermal experiences [26].

4. METHODOLOGY

4.1 CLIMATE

The climate of Ghana is characteristically tropical and was comparatively stable over recent years [27]. with rainy and dry seasons named Harmattan. According to Köppen & Geiger classification, this climate zone belongs to the Aw climate i.e., the tropical savanna climate characterised by very hot days and colder nights during the dry season [28].

4.2 SITE DESCRIPTION

There are different sections in the Balme library, including the Reference Hall, East Stack, West Stack, Ghana-Korea Information Access Centre on the ground floor, East Mezzanine (above East Stack), West Mezzanine (above West Stack), and Periodical Hall, The Students' Reference Library (SRL), African Library, and Reserved Collections on the first floor. These sections have passive architectural features such as courtyards, outdoor corridors, and high ceilings indoors. Some rooms have been retrofitted with air-conditioning, while others remain naturally ventilated.

4.3 DATA ANALYSIS

To conduct the current research, two types of data analysis have been carried out, including analysing subjective and objective thermal comfort data in naturally ventilated and air-conditioned areas to establish an adaptive thermal comfort model for

Ghana, utilising surveys and data loggers in comparison to the international standards, such as ASHRAE 55. To collect the indoor environmental variables, including air temperature (T_a), globe temperature (T_g), relative humidity (RH), and air velocity (V_a) during the surveys, wet-bulb globe temperature (WBGT) meter data loggers were used. The outdoor temperature and humidity were recorded over two years using Rotronic Instruments Temperature & Humidity data logger. The device was installed on the north-facing wall and a shaded area.

Regarding the subjective data, the questionnaires were distributed among the library users, and 664 individuals completed them, and 655 questionnaires were deemed acceptable for data analysis. This questionnaire involved specifying the location and orientations of the room to categorise the AC and NV modes. Another section collected demographic information of the participants, including gender and age. The third section included thermal comfort questions related to the subject's thermal sensation vote (TSV), thermal preference (TP), thermal acceptance (TA), humidity feeling (HF), airflow movement feeling (AF), and airflow preference (AP). The fourth section pertained to the activity level and clothing insulation, following the guidelines outlined in the standards [29,30].

It should be mentioned that the collected data has been analysed by using Python as the primary software. To conduct this survey, in addition to the aforementioned items, the mean radiant temperature (T_r), and the Operative temperature (T_{op}) were calculated via Equation (1) and (2):

$$Tr = [(T_g + 273)^4 + 1.1 \times 10^8 Va^{0.6} / Ɛ\, D^{0.4} \times (T_g - Ta)]^{1/4} - 273 \quad (1)$$

Where D, is the diameter of the globe is 0.05 mm, and Ɛ, the emissivity of the surface is considered 0.9. Air speed is ranging from 0.2 to 0.8 m/s for lightly clothed (0.5 – 0.7 clo) occupants in sedentary activities. And Va stands for air velocity. And also, to calculate the operative temperature the Equation (2) is used.

$$T_{op} = HT_a + (1 - H)\, T_r \quad (2)$$

Where, $H = h_c / (h_c + h_r)$, and Tr is the mean radiant temperature, hc is the convection heat transfer coefficient, and hr is the radiation heat transfer. The hr is defined as 4.7 W/m^2, and hc is considered for an air velocity of <0.2 m/s, according to the ASHRAE Standard 55. The neutral or comfort temperature (T_{comf}) or comfort zone is the operative temperature at which the average person will be thermally neutral, or the most significant proportion of a group of people will be comfortable [31]. While PMV depends on the six variables of T_a, T_r, RH, V_a, activity, and clothing level, however, it does not consider the expectations and adaptability of users.

4.4 ADAPTIVE MODEL

A regression analysis was carried out to estimate the mean T_{comf} over several days or weeks of the survey period. On the other hand, the Griffiths method suggests calculating the optimal temperature for individual comfort within a specific building and month. Based on the Griffiths method, the neutral temperature can be calculated by the following Equations (3,4) using the relationship from T_{op}, TSV, and G:

$$T_{comf} = T_{op} - (TSV - TSV_n)/G \quad (3)$$

Where the TSV is the thermal sensation vote, the TSV_n represents the neutral thermal feeling, and G is the Griffiths coefficient. For this case study and sensitivity analysis, G was at 0.25, 0.33, and 0.50. These equations mainly consider the weighted running mean temperature (T_{rm}) as an independent variable for outdoor temperature.

$$T_{rm} = \{T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} \ldots\} / \{1 + \alpha + \alpha^2 \ldots\}, \quad (4)$$

Where:

T_{od-1} - daily mean outdoor temperature (°C) for the previous day;

T_{od-2} - daily mean outdoor temperature (°C) for the day before.

The constant α is a unitless constant that shows the time needed for thermal adaptation, and its rate is between 0 and 1. However, ASHRAE 55 recommended considering a range of 0.33 to 0.9 for α. The α = 0.8 is usually taken as a half-life of approximately 3.5 days [32]. The half-life (λ) calculation of an exponentially weighted Trm is given in the following Equation (5).

$$\lambda = 0.69/(1 - \alpha) \quad (5)$$

5. RESULT

5.1 Environmental conditions

Comparisons of the thermal comfort votes, such as subject sample size, indoor thermal conditions, and the PMV for air-conditioned (AC) and naturally ventilated (*NV*) rooms, are presented in Tables 1 and 2.

Table 1: Subject sample size and the survey results in AC rooms

Number of valid surveys	162		55% Male, 45% Female	
Variable	Mean	SD	Max	Min
Respondents age	23.8	6.5	60.0	16.0
Thermal sensation vote	-0.2	1.1	3.0	-3.0
Thermal Preference	-0.5	0.8	1.0	-2.0
Airflow Feeling	-0.4	0.8	2.0	-2.0
Airflow Preference	0.4	0.6	1.0	-1.0
Humidity Feeling	-0.2	0.8	3.0	-2.0
Humidity Preference	-0.5	0.7	1.0	-2.0
Clothing	0.4	0.1	1.1	0.3
PMV	-0.35	0.82	2.47	-2.24

Table 2: Subject sample size and the survey results in NV rooms

Number of valid surveys	429		60% Male, 40% Female	
Variable	Mean	SD	Max	Min
Respondents age	22.4	5.3	60.0	12.0
Thermal sensation vote	0.2	1.0	3.0	-3.0
Thermal Preference	-0.7	0.6	1.0	-2.0
Airflow Feeling	-0.4	0.8	3.0	-2.0
Airflow Preference	0.5	0.5	1.0	-1.0
Humidity Feeling	-0.2	0.8	3.0	-3.0
Humidity Preference	-0.3	0.7	1.0	-2.0
Clothing	0.4	0.2	1.4	0.3
PMVe, e= 0.5	0.48	0.24	0.99	-0.74

In terms of thermal sensation votes, the highest percentage (47.2%) of respondents experienced a comfortable feeling in the naturally-ventilated areas (Fig.1). As for thermal preference, approximately 52% of library users preferred a slightly cooler temperature in the NV mode, while 42.7% preferred the same in the AC spaces (Fig.2).

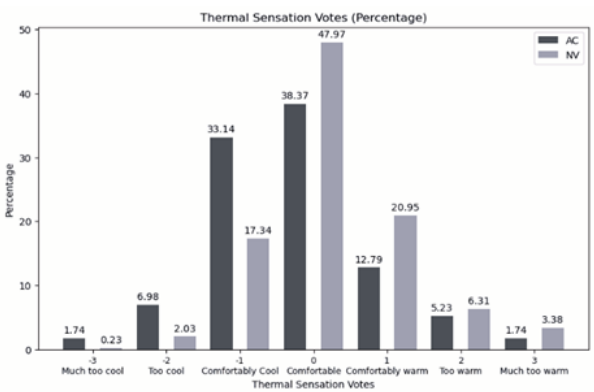

Figure 1: Thermal sensation votes (Percentage)

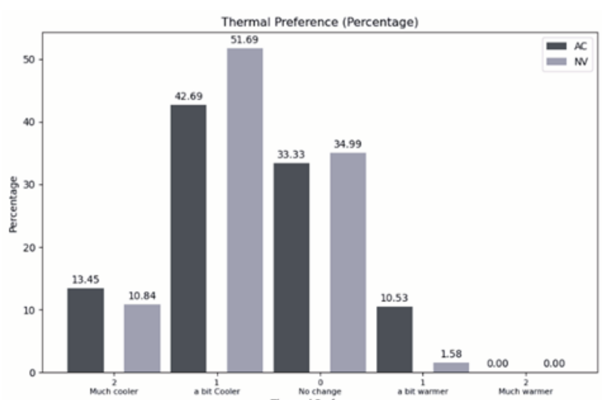

Figure 2: Thermal Preference votes (Percentage)

5.2 Outdoor environmental conditions

The outdoor data has been generated from the on-site data collected between January 2022 and September 2022. This dataset includes outdoor temperature and humidity, which are presented using box plot diagrams (Fig. 3).

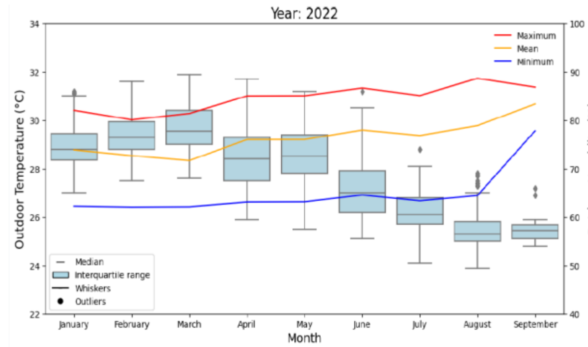

Figure 3: Outdoor weather conditions measured on-site.

Over the study period, the highest temperature belonged to May 2021, 32.95 °C, and the lowest one was in August 2022, 23.9 °C. The highest level of humidity was in September 2021, 90.60%, and the lowest was from January to May 2021, 62%.

5.3 Evaluation by Fanger's PMV

Figure 4 represents the linear regression of the mean sensation votes (MTSV) and predicted mean votes (PMV) as a function of operative temperature in both natural ventilated and air-conditioned modes. The Fanger and Toftum's [33] extended factor of 0.5 and the calculated factor (0.11) were used to compare the TSV with the MV and PMV_e.

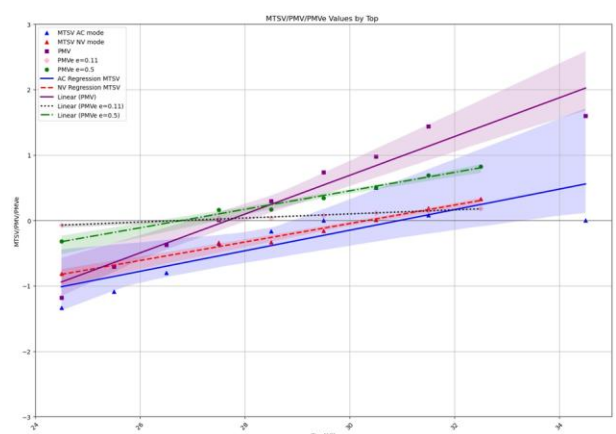

Figure 4: Linear regression of MTSV and the PMV as a function of operative temperature in NV and AC modes.

Based on this figure, the neutral temperature of PMV is 27.8°C, while the linear regression method in NV mode predicts a neutral temperature of 30.3°C. Consequently, the PMV prediction is 2.5°C lower than that of the linear regression method. Meanwhile, the linear regression predicts a comfort temperature of 31°C in the AC mode. Therefore, the discrepancy increases in air-conditioned areas by approximately 3.2 °C. The increase in the slope in AC mode can be observed in the thermal sensation vote bar chart diagram, as 33.14 percent of subjects in the AC mode feeling "comfortably cool". Additionally, in the NV mode, while 47.97 percent of individuals voted for "comfortable" as a neutral feeling, representing half of the subjects, 20.95 percent of them voted for "comfortably warm", or 17.34 percent for "comfortably cool". Therefore, these factors might be the rational explanations for the lower-than- expected slope.

5.4 Comparison with the Standards

ASHRAE-55, as one of the most widely accepted international standards, for naturally-ventilated buildings, is primarily utilised to predict indoor comfort temperature by using the measured outdoor temperature. A comparison of the adaptive comfort temperature and the comfort zone is illustrated using the regression model with ASHRAE-55 (Fig.5).

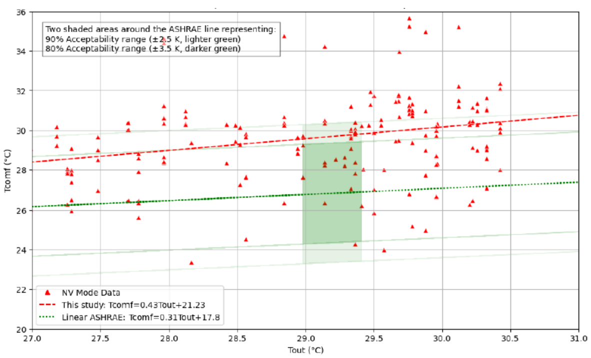

Figure 5: Comparison of the adaptive thermal comfort with the ASHRAE-55 standard

Figure 5 represents that the proposed adaptive model predicts a higher slope than the defined in the ASHRAE-55 standard. It means that this standard predicts a lower comfort range against the achieved results of the current study. And, in NV mode, the majority of the data points and their regression line reside above the standard. Additionally, in comparison with the CEN standard, while the slope of the CEN proposed model is 0.33 K^{-1} in the regression line, this study calculated higher ranges for thermal comfort with the slope of 0.43 K^{-1} for the linear regression as well.

6. CONCLUSION

The main aims of this research were to evaluate the thermal comfort in Balme Library, as a case study in Ghana, and to propose an adaptive thermal comfort model. The results of this research determine that the subjects whose origins were from Ghana, feel neutral or comfortable at different temperatures against the recommendations of the adaptive models of international standards, such as ASHRAE-55. For instance, in the case of NV, when compared to the ASHRAE-55 standard, which has a regression line slope of 0.31 K^{-1}, the slope of 0.43 K^{-1} for this case study suggests that Ghanaians can adapt to the climate faster than predicted by the standards. In AC mode, at the mean temperature of 28.60 °C, 38.37% of the subjects felt comfortable and 41.86% of them felt "comfortably cool", "too cool", and "much too cool". In NV mode, at the mean temperature of 30.24 °C, approximately half of the individuals (47.97%) voted for neutral feeling. Therefore, the current international standards and the HVAC building regulations underestimate the ranges of thermal preferences among the building's occupants.

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