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Modelling the effect of tree-shading on summer indoor and outdoor thermal condition of two similar buildings in a Nigerian university

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ABSTRACT

Using field measurement and numerical simulation techniques, this study assessed the impact of tree-shading on indoor and outdoor summer thermal conditions of two similar buildings at the Federal University of Technology Akure (FUTA), Nigeria. One of the buildings was shaded by trees, while the other was unshaded. For the numerical simulation, outdoor micro-climate model, ENVI-met and Building Energy Simulation (BES) program, EnergyPlus were integrated. This modelling approach was validated using simultaneously observed air temperature and relative humidity data inside and outside both buildings during the summer period (September–November) of year 2010. Model performance statistics results indicate reasonable agreement between simulated and observed micro-climatic data at the indoor and outdoor of both buildings. The integrated models captured the evolution and magnitude of a warm-humid micro-climate of West Africa sub-region and impact of tree-shades on local thermal comfort. Furthermore, micro-scale relationship between non-radiation based thermal comfort indices (Temperature-Humidity Index, THI and Wet Bulb Globe Temperature, WBGT) and Physiological Equivalent Temperature, PET at the interior and exterior of both buildings was investigated. Result suggests preference of WBGT to THI for the assessment of local thermal condition where technical instrumentation (required for PET estimation) and/or model capability is lacking irrespective of shading condition and environment (indoor or outdoor).

1. Introduction

There is a growing concern on global warming and its associated consequences because it is happening faster than previously envisaged [1]. Global mean surface temperature is projected to increase from 0.3–0.7 °C (based on 1985–2010 baselines) to 2.6–4.8 °C by 2100 [2]. Cities whose temperature are above 35 °C have already recorded 1–2 °C increase in average temperature from 1980, with additional 2–4 °C increase predicted [2]. These increases have led to and will result in temperature extremes and more frequent intense heat waves in the urban environment. Life-consuming episodes of heat waves were recently reported in parts of Asia, Middle-east and Europe [3–5]. Although, no death has been attributed to heat-wave in Nigeria in recent times, the Intergovernmental Panel on Climate Change's (IPCC) climate projection for the country and the West African subcontinent at large suggests a significantly warmer condition – indicating the necessity to advocate, create and maintain more thermally comfortable indoor and outdoor urban environments. To dampen the effects of this current and projected temperature increase on the built environment, some mitigation and adaptation technical solutions have been suggested. This include but not limited to modifications of building/surface materials and urban morphology, insulation of buildings, installation of irrigation systems and urban greening [6–10]. More recently, advocacy for greening urban areas, especially at the heat island hotspots has increased [10–13]. This is simply because urban greenery (e.g. trees) help impede direct solar insolation thereby decreasing surface and air temperature [8,14–16] and energy demand [17,18]. Internal spaces of tree-shaded buildings have also been found to be often cooler than their unshaded counterparts with lower rate and quantity of heat transmission, cooling energy demand and expenditure [19–24].

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Thermally comfortable indoor and outdoor environment is usually accomplished with the help of mechanical cooling or heating for indoor environments [25] and passive cooling achievable by building shades, trees shades (focus in this study) and water bodies for outdoor environments [15,26–30]. Assessment of the role of trees in thermal control/comfort is generally done through four main methods, namely satellite remote sensing, perception study, field measurements, and/or micro-climate (numerical) modelling [10–13,31–36]. Studies utilizing these methods show varying degree of temperature and energy demand reduction as well as improved thermal comfort by trees depending on several factors such as land surface characteristics, location and configuration of the considered trees, prevailing meteorological conditions and location/settings of the study (e.g. street canyon or open–environment).

This study adopts field measurement and micro-climate modelling to investigate the effect of tree-shading on two institutional buildings. Numerical simulations using integrated Building Energy Simulation (BES) program, EnergyPlus and outdoor micro-climate model, ENVI-met was used to simulate both the indoor and outdoor micro-climate of/around the two similar buildings. Although widely adopted, the public version of ENVI-met does not have the ability to simulate indoor thermal condition [37] which is one of the strengths of EnergyPlus. On the other hand, EnergyPlus only models trees as conventional shading elements but unable to simulate the thermal impacts created by such vegetation in the immediate environment while ENVI-met includes a realistic vegetation module where models vegetation and its interaction with surface and atmosphere. A detailed description of our modelling and measurement techniques is presented in later section of this paper.

The study aims to evaluate the ability of the integrated models to capture the micro-climate pattern and magnitude of a warm-humid climate of West Africa sub-region and impact of tree-shades on local thermal comfort. Our literature search revealed these models (especially ENVI-met) has not been validated for use in this region. Meanwhile modeling of urban micro-climate is an unlimited method to understand the present and future micro-climate dynamics of built environment. Furthermore, we investigated the micro-scale relationship between non-radiation based thermal comfort indices (Temperature-Humidity Index, THI and Wet Bulb Globe Temperature, WBGT) and Physiological Equivalent Temperature, PET at interior and exterior of both buildings. The role of tree-shades on the relationship was also studied. Such information could help in estimating PET where technical instrumentation is lacking and/or choosing the best representative non-radiation based index for thermal condition assessment. This study can be regarded as a follow up to our previously published papers on the same location [15,16,18].

2. Methodology

2.1. Site descriptions and climate

Two buildings situated ~60 m apart but of similar architectural design, building materials and geographical orientation on the campus of the Federal University of Technology Akure, (FUTA) Nigeria were selected for this study. One of the buildings (also referred to as Building A) is the University's School of Agriculture and Agricultural Technology (SAAT) while the other building (also referred to as Building B) is the School of Engineering and Engineering Technology (SEET). On the south-east façade of Building A are high-dense trees while Building B is un-shaded as shown in Fig. 1. The micro-climate conditions of the outdoor spaces of these building were studied. For indoor thermal comfort study, we selected similar internal spaces of the same perimeter, floor area, volume and having the same position (to the south-eastern side) in both buildings. These internal spaces have a dimension (Length × Breadth × Headroom height) of 17 m × 10 m × 10 m. As at the time of this study, the space in building A was used as a students' computer laboratory where six (6) air conditioner and four (4) fans are usually operated during especially laboratory sessions. On the other hand, the internal space of Building B was used as the University's goods acquisition office/store (see Fig. S1).

The city of Akure (where the university is located) is positioned on Latitude 7°17′N and Longitude 5°18′E. It is a rapidly growing medium-sized urban centre in Nigeria with the university's campus located to its north-western side. The City's climate is classified as warm humid: average rainfall of about 1500 mm per annum, annual average temperature ranges between 21.4 °C and 31.1 °C while the mean annual relative humidity is about 77.1% [38].

2.2. Field measurement, instrumentation and data filtering

Three consecutive summer months (September–November, 2010) data of air temperature and relative humidity have been simultaneously collected at the outdoor and indoor environment of Buildings A and B using EL-USB2 temperature-humidity sensor/logger. This instrument has the capability to record precise air temperature measurements between −35 °C and 80 °C with an accuracy of ±0.5 °C and relative humidity between 0% and 100% with an accuracy of ±3% for a long period of time due to its high storage capacity and long-life lithium battery. More importantly, the instrument is suitable for our study location's climate (warm-humid) as it was protected against ingress of water and dust to IP67 standard with the fitted plastic cap and seal. At the outdoor of Building A and B, the instrument was fastened to a tree trunk and standing pole at ~3 m height above ground level, respectively to reduce the influence of thermal radiative fluxes i.e., reflected shortwave and long-wave radiation emitted from the human (students and staff) bodies on the temperature measurement since this effect cannot be accounted for in the outdoor modelling system (ENVI-met model). Both the tree and pole (where instruments were hanged) are situated 8 m from the building's south-east external wall. In additional to this, prevailing wind speed and direction data were obtained from the nearby FUTA's meteorological station (see Fig. 1).

It is important to mention that the period of measurements covered the second peak of the rainy and summer season in Nigeria. During this period, the south-westerly maritime wind dominantly brings in moisture over the heated West Africa sub-region. Hence, different levels of cloudiness were observed during the measurement period. In our earlier study [15], we have investigated the influence of difference level of cloudiness (i.e. cloudy, near-clear and clear days) on air temperature and the corresponding influence of trees. We found slight difference in the magnitude of air temperature change at different cloudiness levels. For the present study, data corresponding to clear days in the months under consideration were selected. Additionally, during the measurement period, there were days and times when indoor air temperature in Building A became unusually higher when compared with Building B's data despite the cooling system in use. This resulted from overcrowding and prolonged use of the space during some week days and weekends. For unbiased comparison and to avoid an exaggerative influence of the observed temperature spikes on further analysis and results, temperature data for such days were filtered out of the dataset [15,16,18].

2.3. Model coupling procedure

One-way integration of outdoor micro-climate model, ENVI-met and Building Energy Simulation (BES) program, EnergyPlus was