ABSTRACT

This study compares the microclimatic performance of courtyards in the single-storey, mid-rise, and high-rise buildings in Nigerian temperate-dry climate by using the field measurement and simulation methods. The field measurement was used to validate the simulation software, while the simulation method was used to perform the experiment. A Hobo Weather Data Logger (HWDL) was used to collect data on air temperature in the courtyard of a building which was used to validate the simulation software. The origin 0.7 software (a spreadsheet) was used to interpret the simulation data obtained. The outcomes show that the microclimate of the courtyard in the high-rise building was best than that of the mid-rise, and the single-storey was the worst. The discrepancies in air temperature were; 1oC, 2oC, and 3oC, while that of relative humidity were: 2%, 4%, and 6% respectively. The paper concludes that the courtyard concept is most suitable in the high-rise buildings, then the mid-rise, and then the single-storey respectively. Finally, further simulation experiments to confirm whether such a result also applies to the indoor-microclimate of such building typologies is required. Furthermore, the impact of air movement and natural lighting were not investigated and such are future areas of inquiry too.

Keywords: Building typologies; Courtyard; Performance; Microclimate.

1. INTRODUCTION

The microclimate of buildings designed by architects is supposed to be conducive due to the fact that such an edifice was conceived by them. The architects’ should understand the passive architectural design strategies and apply such in their architectural vocabularies. By so doing, they can deliver buildings with conducive microclimates. Such buildings may also contribute to the conducive microclimate of the built environment, and that of the urban (Forouzandeh, 2018). The delivery of such buildings is very crucial because it enhances the occupants’ well-being and thereby promoting good health, productivity, and efficiency (Fatma et al., 2016).

The courtyard is one of the most effective passive architectural design strategies that could contribute to the design of buildings with better microclimate because its impact on air temperature is paramount (Markus, 2018a). Muhaisen and Gadi (2006) recommended that the courtyard is a microclimate modifier. Markus, (2018b) suggested that the courtyard is suitable for all typology of buildings in the temperate-dry climatic regions. Even in different climatic regions the savannah, semi-desert, desert, arid-desert and humid areas, the courtyard is used to achieve thermal comfort for occupants (Reynolds, 2002). According to López-Cabeza et al. (2018), the courtyard concept impact microclimate significantly in tropical regions than in the polar regions. Ghaffarianhoseini et al. (2015) argued that the courtyard adds to thermal distress in the humid climatic zones. It could impact the urban microclimate in a significant manner if used appropriately (Taleghani et al., 2014).

Despite the fact that the courtyard is applicable to different typologies of buildings in different climatic regions, its thermal performance may not be the same (Abdulbasit et al., 2015). Hyde (2000) confirmed that the
court yard can improve the indoor-microclimate of all building typologies. However, its microclimatic impact in buildings in the hot/dry, humid and temperate climatic regions is not the same. Their impact may also vary from one building typology to another. For instance, the courtyard performance in the single-storey; mid-rise; and high-rise buildings may be different. Al-Hemidi et al., (2001) concluded that the courtyard is known to be effective in influencing the building microclimatic performance but, a further study towards understanding its performance in buildings is required. According to Tablada et al. (2005), the knowledge of the courtyard thermal performance in different typologies of building height is required, and the application of such knowledge is needed if the courtyard optimum conduciveness is to be realized.

The conduciveness of the courtyard-space in the building is important because of the benefits of the courtyard such as; playing area for children, ceremonial cooking, large family gatherings and dispute settlement (Adeyemi, 2008). Such functions could be performed conveniently if the courtyard has a conducive microclimate. The courtyard is most suitable for residential building purposes, hence, its thermal performance benefits the family units (Fatma et al., 2016). This study has added to the body of knowledge by suggesting the most preferred courtyard building type for a conducive thermal performance in the Nigerian temperate-dry climatic region. The knowledge will assist to deliver the architectural design of courtyard buildings that are passive, conducive and good for the well-being of the end-users. This can become true by advocating the application of the suggestions of this study by the Nigerian Institute of Architects (NIA) and the Architect Registration Council of Nigeria (ARCON) to their membership.

2. AIM AND OBJECTIVES

The aim of this study is to confirm the most conducive courtyard in the courtyard building typologies; single-storey, mid-rise and high-rise within the temperate-dry climatic region of Nigeria. The study achieved its aim through the following objectives:

• The use of field measurement to obtain microclimatic data (air temperature) for the purpose of validating the simulation software.
• Using the Model-It application of the simulation software to develop the simulation models.
• Simulation of the models to obtain their microclimatic performances for the purpose of comparison and analysis.
• Determination of the most conducive courtyard microclimate.

3. LITERATURE REVIEW

The use of the courtyard concept for cooling in buildings has been in existence since the early times (Fahad, 2005). Apart from the other techniques used to achieve conducive indoor-microclimate in buildings, the courtyard has been one of the traditional strategies. Examples of some of the ancient strategies include; the use of high-mass walls, traditional roofs made of local materials, excavated rooms and internal gardens (Adeyemi, 2008). Of all such styles, the courtyard is the only concept that has survived all civilizations (Das, 2006).

The courtyard concept is adaptable to all typologies of buildings such as the traditional, modern and post-modern buildings (Adetokunbo et al., 2013). In all the tropical regions; the hot–arid areas of the Middle East particularly in Saudi Arabia; West African country and Nigeria in particular; the northern part of Africa; and in the western world, the use of the courtyard concept is very common in buildings (Markus, 2016; Fatma et al., 2016). The application of the courtyard in the architectural design of buildings is being motivated due to its numerous benefits which are not limited to obtaining conducive microclimate alone but also, for energy conservation purposes. Energy conservation in a building can be realized when its microclimate is conducive through passive means. The active means require energy to function and have its own demerits due to high cost and environmental pollution. Therefore, a review of the courtyard microclimate is required.

The choice of simulation software used by scholars to study courtyard microclimate depends on the respective aim of their studies. The literature reveals that recent studies that relate the microclimate of the courtyard with that of the urban centers used the ENVI-met simulation software, while the ones which considered the courtyard and the building used IES-VE. For instance, Forouzandeh (2018); Ghaffarianhoseini et al. (2015); Taleghani et al., (2014) and López-Cabeza et al. (2018) used the ENVI-met, while Berkovic et al. (2012); Fahad (2005); Mohammed et al. (2014); Muhaisen and Gabi (2006); and Edward et al. (2005) used the IES-VE. The ENVI-met software is good for outdoor simulation only (Forouzandeh, 2018). On the other hand, the IES-VE software can perform indoor and outdoor simulation provided that the courtyard is fully-enclosed (IES, 2015).

The microclimatic performance of the courtyard has become an area of interest in recent times and scholars have contributed in this regard. They defined the conduciveness of the courtyard in different ways. Forouzandeh (2018) opined that the courtyard is said to be conducive if its microclimatic performance is not worse than that of the building interior. Taleghani et al. (2014) argued that the courtyard of a building can be considered as being conducive when
it is cooler than that of the urban settlement. Meir et al., (1995) asserted that the courtyard becomes conducive provided that human activities can be performed without any kind of thermal stress being experienced by the people performing such activities. With all these definitions, it is obvious that the courtyard is an important concept and the architect should seek to acquire a greater understanding of how it can be conducive rather than using it in buildings and adding thermal stress to its users.

Meir et al., (1995) investigated the microclimatic performance of the semi-enclosed courtyard building typology in Israel. The study confirmed that the courtyard microclimate can be optimized if the appropriate building orientation is applied. Markus et al. (2017a) compared the microclimatic performances of two typologies of courtyard buildings –the fully-enclosed, and the semi-enclosed. The aim of the study was to determine the best option. The study used the field measurement approach to compare the microclimatic performance of the two courtyard building typologies in Kafanchan-Nigeria. It was confirmed that the fully-enclosed is better-off. The conclusion was that for the courtyard to be suitable for habitation, its microclimate should be conducive.

Scholars argued that the courtyard microclimate influences the indoor-microclimate of the entire building in the tropical regions only (Berkovic et al., 2012; Fahad, 2005; Mohammed et al., 2014). To contribute in this regard, Markus et al., (2017b) compared the indoor-microclimatic performances of the semi-enclosed single-storey courtyard residential building with that of the fully-enclosed single-storey courtyard residential building in a temperate-dry climate of Nigeria. The study confirmed that the courtyard microclimate also influences the indoor-microclimate of the building in the temperate hot/dry climates too. The study shows that the fully-enclosed courtyard building had a better indoor-microclimate than the semi-enclosed. It was concluded by suggesting further simulation studies towards the optimization of the semi-enclosed courtyard building typology.

Farzaneh et al., (2016a) studied the performance of the Iranian courtyard house. The study opined that the courtyard could improve thermal comfort if the knowledge of the appropriate dimensions and proportion for its optimum performance are not lacking. Farzaneh et al. (2016b) suggested the application of a water pond in the courtyard to increase the level of humidity in the Iranian courtyard house. The study also recommended further studies towards investigating the effect of building height (storey) on the indoor-microclimatic performance of the courtyard and, thereby, recommending such for future courtyard buildings in the region.

Although Muhaisen and Gabi (2006) and (Edward et al., 2005) studied shading in courtyards, most of the studies conducted by other scholars were carried out in the single-storey courtyard building typology. Also, studies that focused on the microclimatic performance of the mid-rise, and high-rise courtyard buildings are very few, and most especially in Nigeria. Besides, most of the reviewed literature (Meir et al., 1995; Markus, et al., 2017a & b) used the field measurement approach in their studies. But, according to Bagneid, (2006), such a research approach has its own limitations and further simulation method is required to substantiate the findings of such studies.

Therefore, in this study, a combination of both the field measurement and the simulation methods are used. The IES-VE simulation software was used because it is the most suitable for this kind of research endeavor (IES, 2015). This research endeavor has the distinction of extending the frontiers of knowledge by focusing on the single-storey, mid-rise, and high-rise courtyard building typologies. Therefore, the importance and significance of the study cannot be undermined due to its originality.

4. METHODOLOGY

The methodology of this study consists of the field measurement and the simulation approach. The two methods are necessary due to the fact that all simulation studies require validation of the simulation software (Bagneid, 2006). Thus, the field measurement approach was used to validate the Integrated Environment Solution–Virtual Environment (IES-VE) simulation software that was used for the experiment, while the simulation experiment was later conducted to accomplish the study aim. The origin 0.7 software (a spread-sheet) was used for interpretation and analysis. Ibrahim et al. (2019) used it in their study.

4.1 Field measurement

As shown in Figure 1, a single-storey fully-enclosed courtyard residential building located in Sabon Tasha-Kaduna in Nigeria was used for the field measurement. One Hobo Weather Data Logger (HWDL) was used to measure air temperature in the courtyard of the case study building. Only air temperature was measured because one study variable is sufficient for simulation software validation purposes (Leng et al., 2012). The HWDL has accuracy and air temperature range of ± 0.21oC to ±0.36oC and -40oC - 70oC. The tool was preferred because of its capacity and precision in sensing thermal parameters. The HWDL was fixed at the center of the courtyard, at a height of 1.5m above the ground level as shown in Figure 2. It was launched at 30 minutes time intervals, and from 7:00 am to 7:00 pm. Thirty (30) minutes’
time interval was selected because shorter duration provides numerous data, and fluctuations in climatic conditions can be easily dictated (Leng et al., 2012). Night hours were not considered because the previous study revealed that such a period has conducive conditions (Olutoa, 2015).

According to Koppen climate classification, the case study building is located within the warm semi-arid climate with a maximum and minimum air temperature of 21°C and 44°C respectively (Komolafe and Agarwal, 1988). The building is a perfect square with 14m length on all sides and oriented on the North/South direction. Its courtyard aspect ratio is 1:1:1 (3m length, 3m width, and 3m high). It has high albedo because of the building components (wall made of bricks, and roof made of mud-step tiles).

Both the field measurement and the simulation experiment were conducted on the 15th of June, 2019. The weather condition was fair, moderate cloud cover, and no rainfall. Thereafter, the Hobo-Pro software was used to read out the data. The obtained data was later used for the validation of the IES-VE simulation software.

The weather file of Kafanchan was used for the simulation because Kaduna (the study area) has the same weather condition with Kafanchan. Kaduna and Kafanchan fall within the temperate-dry climatic region of Nigeria (Komolafe and Agarwal, 1988). The weather file of a particular city can be used for another city provided that they are all within the same climatic region (Leng et al., 2012). Leng et al. (2012) used the weather file of Singapore to perform a simulation experiment in the state of Johor in Malaysia. Therefore, the use of the Kafanchan weather file for this study is acceptable.

A scaled three-dimensional drawing of the building was developed using the Model-It application of the IES-VE software as illustrated in Figure 3. The base-case model is a prototype of the case study building. The construction and material templates of the software were adjusted and used for assigning both the building components and materials in the base-case model. The simulation was performed using the same date with the field measurement to have the same weather condition. The benchmark used by scholars; Leng, et al. (2012), Prasanthi et al. (2011) and Maameri et al. (2006) was used for the validation.

As shown in Figure 4, the results show that the maximum and minimum discrepancy between the field measurement air temperature in the fully-enclosed courtyard and the IES-VE simulation of the base-case model as 4.5%. The discrepancy is within the accepted benchmark of 0-20% as revealed in the literature (Leng, et al., 2012; Prasanthi et al., 2011; Maameri et al., 2006). The discrepancy may be due to the vegetative nature of the case study built environment which was not captured in the simulation model due to the limitation of the software. However, the validation findings confirmed that the IES-VE software is valid, reliable and suitable to be used for further simulation experiments.
4.3 Simulation Experiments

IES-VE is a complete simulation software often used for simulation experiments in buildings (IES-VE 2010). The microclimatic performance of a courtyard in a building could be experimented via simulation. The IES-VE consists of five (5) applications; Model-It, SUNcast, Apache, Radiance, and Micro-flo (CFD). The Model-It Application was used to model the three simulation models. The Application was set to allow the construction of the models, and the simulation settings followed thereafter. Both the SUNCast and Apache applications of the software were used for the experiment. The former was used for the shading analysis while the latter was used for the thermal simulation.

Courtyard models of 3m, 12m, and 18m heights which represent the single-storey, mid-rise, and high-rise courtyard building typologies were constructed via the Model-It application of the IES-VE software. Such typologies of building height were categorized as the limits for single, mid-rise, and high-rise buildings (Ariga et al., 2006). The courtyard geometry of all the models is squared in form. All their widths were equal to the respective length. Such geometrical forms will behave the same in all orientations, however, the North/South orientation was used (Abdulbasit et al., 2015). The three models were then simulated to compare their microclimatic performances. Previous studies that focused on the courtyard microclimate did not model the entire building because the courtyard-space was their emphasis. (Muhaisen and Gadi, 2006; Muhaisen, 2006; Abdulbasit et al., 2015). Therefore, only the courtyard-space was modeled. Two microclimatic variables such as air temperature and relative humidity were considered for the experiment. The experiment lasted for twenty-four (24) hours, comprising of both the day and night hours. This was required because such can give a complete knowledge of how the different courtyard models behave. Table 1 illustrate the courtyard model scenarios investigated.

<table>
<thead>
<tr>
<th>Courtyard Height</th>
<th>3 Meters</th>
<th>12 Meters</th>
<th>18 Meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Single-storey)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mid-rise)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(High-rise)</td>
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<td></td>
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</tbody>
</table>

5. RESULTS AND DISCUSSION

Two microclimatic parameters; air temperature, and relative humidity were considered during the simulation experiments. This section, therefore, presents and discussed the results.

5.1 The Air Temperature

Figure 5 shows the air temperature performance of the three (3) models. The 18m height model (representing the high-rise courtyard building) had the least air temperature, followed by the 12m height model (which represent the mid-rise courtyard building typology), and the 3m height model (representing the single-storey courtyard building) was the worst scenario.

Figure 5: Effect of Courtyard Height on Air Temperature
Table 2: Courtyard Height and Observed Air Temperature

<table>
<thead>
<tr>
<th>Courtyard Height</th>
<th>Max. Air Temp. (°C)</th>
<th>Time</th>
<th>Min. Air Temp. (°C)</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>18m Height</td>
<td>27.00</td>
<td>1 - 3 pm</td>
<td>18.00</td>
<td>1 - 4 am</td>
</tr>
<tr>
<td>(High-rise)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12m Height</td>
<td>28.01</td>
<td></td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>(Mid-rise)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3m Height</td>
<td>29.02</td>
<td></td>
<td>20.00</td>
<td></td>
</tr>
<tr>
<td>(Single-storey)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The discrepancy between High-rise, Mid-rise & single-storey is (1°C)

A difference of 1oC occurred between the three models. The result connotes that deeper courtyards have a lower air temperature than the shallow ones. These findings concurred with Muhaisen (2006) opinion which emphasized that the effect of shading due to high walls adjacent to the courtyard space could impact the courtyard microclimate significantly. Muhaisen and Gadi (2006) also concluded that the more the courtyard is shaded from direct solar radiation the lower its air temperature will be. The solar radiation which comes directly from the sun heat the courtyard-space, and deeper courtyards will have a shorter duration of exposure to the sunlight and longer duration of shading. The 18meters courtyard height is deeper than the 12 meters, and the 3 meters is the shallower. Consequently, the shading effect will be higher in the 18 meters height courtyard than in the 12 meters height, and the 3 meters height will have the least shade. Therefore, the low air temperature revealed in the respective models is justified. The courtyard concept will be more effective in making the microclimate of the high-rise fully-enclosed courtyard building conducive than that of the mid-rise fully-enclosed courtyard building. The single-storey will be worse. Table 2 shows the detailed analysis of the air temperature results.

5.2 The Relative Humidity

Figure 6 shows the relative humidity performance of the three (3) models. The 3 meters height model (representing the single-storey courtyard building) had the least relative humidity, followed by the 12 meters height model (which represent the mid-rise courtyard building typology), and the 18 meters height model (representing the high-rise courtyard building typology) was the worst scenario. The result suggests that the shallower courtyards have lower relative humidity than the deeper ones. Just as in the air temperature, the relative humidity is considerably influenced by the courtyard height as revealed in Figure 6. A difference of 2%, relative humidity is revealed in the three scenarios.

Table 3 shows a detailed analysis of the relative humidity results. These findings agreed with Farzaneh et al. (2006b) opinion that a rise in air temperature will equal to a fall in relative humidity. Farzaneh et al. (2006) also explained that courtyard buildings in the tropical regions behave in a way such that attainment of air temperature and relative humidity balance may not be achieved due to the inverse relationship that exists between the two microclimatic variables. Most especially in the hot/dry and temperate climatic region, the inverse relationship between the two is very strong (Abdulbasit et al., 2013). Abdulbasit et al. (2013) opined that the most dominant factor for a conducive microclimate among the air temperature and the relative humidity should be considered. Markus (2018b) revealed that Kafanchan and its environs are within the temperate hot/dry climatic region. Since the region is characterized by moderate humidity, and air temperature as the main factor that influences a conducive microclimate, a design strategy that impacts on the air temperature significantly should be given due attention (Markus 2018a).
**Table 3: Minimum and maximum Relative Humidity performances**

<table>
<thead>
<tr>
<th></th>
<th>18m Height (High-rise)</th>
<th>12m Height (Mid-rise)</th>
<th>3m Height (Single-storey)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Relative Humidity (%)</td>
<td>66.00</td>
<td>68.00</td>
<td>70.00</td>
</tr>
<tr>
<td>Min. Relative Humidity (%)</td>
<td>50.00</td>
<td>52.02</td>
<td>54.06</td>
</tr>
<tr>
<td>Time</td>
<td>1 - 4 am</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>1 – 3 pm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The discrepancy between High-rise, Mid-rise & single-storey is (2%)%

### 6. CONCLUSION

Studies on courtyard microclimate of single-storey, mid-rise and high-rise buildings are required, and this study has used both the Field measurement and simulation methods to contribute in this regard. The study has shown that the courtyard concept is suitable in the high-rise fully-enclosed courtyard building typology than in the mid-rise and the single-storey courtyard building typologies. Architects should, therefore, use the courtyard concept in their design proposals of high-rise buildings because such typology of buildings requires the concept of effective shading and thereby, improving their microclimates. Finally, this study made the following recommendations:

i. Further simulation experiments to confirm whether such a result also applies to the indoor microclimate of such building typologies is required.

ii. The impact of air movement and natural lighting were not investigated and such are future areas of inquiry to be considered too.

iii. Further studies towards optimizing the single-storey and mid-rise fully-enclosed courtyard building typologies are required because such is the most common typology in Nigeria.

### REFERENCES


