Simulation of Window-to-Wall Ratio for Thermal Comfort of Fully-Enclosed Courtyard Residential Buildings in Kafanchan

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The literature has revealed that relationship between the courtyard and the window-to-wall ratio (WWR) is paramount to thermal comfort of fully-enclosed courtyard residential buildings. This study, therefore, seeks to determine the optimum WWR for fully-enclosed courtyard residential building typology for Kafanchan and its environs. The Integrated Environment Solution and Virtual Environment (IES-VE) simulation software was used to simulate five typologies of WWRs for four typologies of room area(s) in fully-enclosed courtyard residential buildings in Kafanchan. The IES-VE software was used for the simulation experiment. WWRs were developed into five models which were simulated to determine the optimum. The results revealed that, WWR4 (window size of $1.44m^2$) has better air temperature condition in all the room areas than all the remaining WWRs. This suggests that it is the best, followed by WWR3, 2, 1 and 5 respectively. Conclusively, WWR4 is the optimum. However, further simulation studies are required to understand optimum location of windows for improved airflow in the fully-enclosed courtyard building.

Keywords: Courtyard; window-to-wall ratio; Simulation; Residential buildings; Thermal comfort

INTRODUCTION

The courtyard, especially the fully-enclosed courtyard has been used in buildings, particularly the residential building from ancient civilizations to present civilization (Fatma *et al.,* 2016). This is due to its numerous benefits to the building and its occupants. The fully-enclosed courtyard provides privacy and is suitable for domestic functions such as; cooking, washing, children play ground, family meetings and settling dispute among family household (Adeyemi, 2008). It is also use as a passive design element in architectural design because it enhances day lighting in building interiors, improves wind speed, wind circulation and shading (Berkovic *et al.,* 2012). Due to it passiveness, the fully-enclosed courtyard building is thermally conducive and enhanced the well-being of the end users.

The quest for conducive residential buildings with little or no carbon dioxide emission has been on the rise due to the negative impact of carbon dioxide on climate change. Efforts to mitigate carbon dioxide emission from buildings, the residential building in particular should be the concern of all architects in the building industry. A drastic shift from designing buildings that depends on the active means rather than the passive for thermal comfort is required. According to Kabiru (2011), architects should seek to design buildings that are climate-responsive. He continued that all buildings design by architects in this 21st century should respond to the macroclimate of its surrounding and, should have little or no dependence on any source of energy for a better thermal performance. Olotuah (2015) also concluded that architects should endeavour to contribute positively to the challenge of mitigating carbon dioxide emission from buildings and, thereby, reducing its impact on climate change.

Another dimension to having buildings with higher carbon dioxide emissions to achieve thermal comfort is the high proliferation of buildings designed by architects with little or no awareness on the simulation tool. The passive benefits of the fully-enclosed courtyard may not be achieved if the awareness of simulation is lacking (Markus *et al.,* 2020). For the fully-enclosed courtyard to fully improve wind speed and circulation in a building, its relationship with the WWR is a major factor to be considered. The thermal performance of the courtyard and that of the interiors of the building may not be optimized if the appropriate WWR is not used (Markus & Duniya 2021). The WWR determines the quality and speed of wind that enters into the building and, the simulation approach may be the only suitable option for determining the optimum WWR.

Simulation is an experiment performed with a simulation software to determine the unknown by developing different typologies of simulation models and testing such models (Abdulbasit *et al.,* 2015). It is an expertise that is required for building optimization for better performance. The simulation approach varies from one study to another. The choice of the simulation software to be use in a particular study will depend on the nature of the research question and, the suitability of the simulation software (Markus *et al.,* 2020). All practicing architects should seek to acquire the

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simulation expertise because its benefits are numerous. It enable correct prediction of the design form to be adopted, choice of building material to be specified, suitable headroom, choice of finishes, suitability of passive design elements and approaches (Markus *et al.,* 2020). The simulation provides data that could be compared with the conventional date for a better performance for each simulation. Therefore, through simulation the optimum WWR for conducive thermal comfort in the fully-enclosed courtyard house can be achieved.

Thermal comfort in buildings, mainly the fully-enclosed courtyard residential building is paramount because of its suitability for habitation. The thermal potential of the fully-enclosed courtyard most be harnessed to enable its optimum performance. The simulation tool should be used optimally to obtain the optimum WWR and used at the design stage of the building. Achieving thermal comfort in fully-enclosed courtyard residential buildings in Kafanchan and its environs through determining and recommending the optimum WWR is the aim that this study seeks to achieve.

LITERATURE REVIEW

Simulation is the process of making an intelligent guess based on results obtained from an experiment (Leng *et al.,* 2012). It is an important procedure because of its accuracy and precision. Scholars and professionals have used the approach in recent times to achieve different aims in their respective endeavours (Berkovic *et al.,* 2012; Abdulbasit *et al.,* 2015; Muhaisen, 2006). The simulation process requires software to achieve a desired task and, choice of the simulation software is a major factor to be considered in all simulation experiments (Lim, 2008).

According to Lim *et al.* (2008) the choice of simulation software for any kind of research effort will have to depend on; the research aim, the kind of data required to be imputed into the software, the kind of result expected, and the expertise required to operate the simulation software without error. There are different typologies of simulation software suitable for different simulation task. The software includes; Eco-tect, EnergyPlus, DesignBuilder, Computational Fluid Dynamics, HEEDED, DOE-2, Quest, Energy10, GB/Stu, Envi-met, IES-VE and, and so many others. They have advantages such as; they are fast and reliable for testing multiple study parameters in all optimization related studies, no further validation of the obtained simulation result is required because the simulation software has to be validated prior to the simulation experiment, the software has high percentages of accuracy with low percentages of error, ranging from 0,05 – 0,08% (Leng *et al.,* 2012).

Despite the accuracy of the simulation software, it has challenges such as; expertise and procedure is required, time, resources and energy is required to perform the experiment, validation of the simulation software is required provided that it has not been tested for a particular location and, the validation of the simulation software may be incorrect when the wrong weather file is imputed into the software (Leng *et al.,* 2012). A recent study revealed that some of the simulation software suitable for courtyard building related studies and, courtyard building optimization studies in particular includes; Eco-tect, EnergyPlus, DesignBuilder, Envy-met, Computational Fluid Dynamics and, IES-VE (Antonio & Carvalho, 2015). This study, therefore, uses the IES-VE simulation software to achieve its aim.

Simulation approach to empirical studies and, most especially the courtyard building optimization related studies have been advocate by scholars (Leng *et al.,* 2012, Berkovic *et al.,* 2012; Abdulbasit *et al.,* 2015; Muhaisen 2006). Scholars supported the approach because courtyard building optimization studies cannot be concluded based on respondents' perception only, but, by experiment to determine the thermal performance of the case-study model(s). This study therefore, use IES-VE simulation software to achieve its aim. The simulation software was preferred because it is suitable for courtyard building optimization studies (Markus, 2017).

The fully-enclosed courtyard has been assessed suitable for domestic and household functions due to its privacy, enhanced security and conducive macroclimate (Fatma *et al.,* 2016). According to Muhaisen (2006), the macroclimate of the courtyard-space can be optimized for better thermal comfort. Muhaisen and Gadi (2006) asserted that optimization of the courtyard-space depends on it typology and manipulation of the courtyard design variants. It was concluded that the courtyard-space consist of two typology; the semi-enclosed and, the fully-enclosed. Meir (1995) suggested that the fully-enclosed courtyard-space is better than the semi-enclosed because the former provide privacy and thermal comfort more than the latter. Muhaisen and Gadi (2006) concluded that the relationship between the courtyard-space and the WWR is critical and it is one among the numerous courtyard design variants that requires optimization for enhanced thermal performance of the courtyard-space and the entire courtyard building envelop.

The WWR of an interior space has been defined by scholars in recent studies. It is a percentage of the square of the window-size and the entire gross exterior area of the enclosed space (Huang *et al.,* 2014). It is an important courtyard building design variant because its suitability varies from one building typology to another

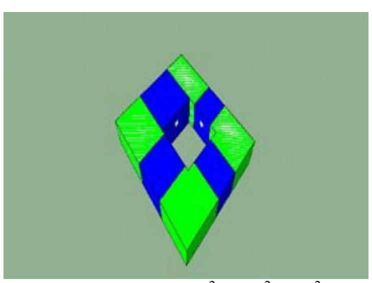
(Yasa, 2010). Yasa (2010) concluded that the optimum WWR of the fully-enclosed courtyard building may be different from that of semi-enclosed courtyard building because they both have different thermal behaviour due to the variability in form. To determine the optimum WWR for a fully-enclosed courtyard building is critical due to the fact that additional expertise is required (Berkovik *et al.,* 2012). Chan (1995) concurred that the architect should seek additional knowledge to understanding the importance of optimization of architectural building design through the aid of software applications. It was concluded that such knowledge is important because it cannot be acquire in school of architecture but, rather as additional expertise seeing that it is not enshrine in the curriculum that birth architects in most of the schools of architecture in Nigeria.

Therefore, to determine the optimum WWR for a fully-enclosed courtyard building is a noble task that this study seeks to achieve. It is noble because the optimum for buildings varies from one climatic region to another (Ogunsote, 1993). According to Ogunsote (1993), the thermal comfort and design requirements for buildings varies from one climatic zone to another, therefore, the design requirement for a building in the temperate-dry climatic region of Nigeria (the case-study for this study) may be different with that of hot-dry climatic zone. Consequently, the optimum WWR for the fully-enclosed courtyard building may also differ except proven not to be so through further simulation studies. Conclusively, using the different typologies of WWRs with different typologies of room area(s) as obtained in as built fully-enclosed courtyard buildings in Kafanchan from a recent study, to simulate and to determine the optimum WWR for Kafanchan and its environs will add significantly to the literature.

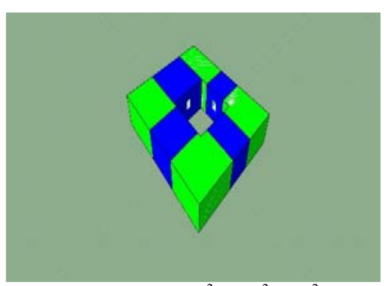
METHODOLOGY

The IES-VE software was used for the simulation experiment. The validation procedure for simulation software may not be repeated for the same location if it has been validated (Leng *et al.,* 2012). Consequently, Markus (2017), Markus (2018) and Markus *et al,* (2020) concluded that the software is suitable for further courtyard building simulation studies within the temperate-dry climatic zone of Nigerian because the discrepancy of the field measurement via the HWDL with that of the simulated case study building falls within the acceptable range of 0 – 20%.

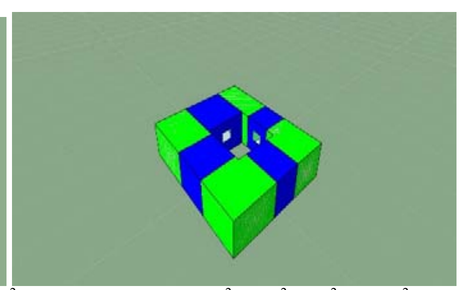
For the simulation procedure, five typologies of WWRs for four typologies of room area(s) were developed and tested. The WWRs are: WWR1 for $9m^2$, $12m^2$,$16m^2$, $20m^2$; WWR2 for $9m^2$, $12m^2$,$16m^2$, $20m^2$; WWR3 for $9m^2$, $12m^2$,$16m^2$, $20m^2$; WWR4 for $9m^2$, $12m^2$,$16m^2$, $20m^2$ and WWR5 for $9m^2$, $12m^2$,$16m^2$, $20m^2$. The models tested are shown in Figure 1. These models were considered because they reflect the typologies of WWRs and room area(s) commonly used in fully-enclosed courtyard residential buildings in Kafanchan. A total of twenty simulation experiments were performed at time intervals of one hour each, starting from 6am – 6pm. The experiment was conducted on the 21st of March because it is the hottest day in a year (equinox) for locations within the tropical regions. The obtained data were extracted from the IES-VE software and imported to Microsoft Excel Sheet (MES) for interpretation. Thereafter, the optimum WWR was determined and the results discussed.



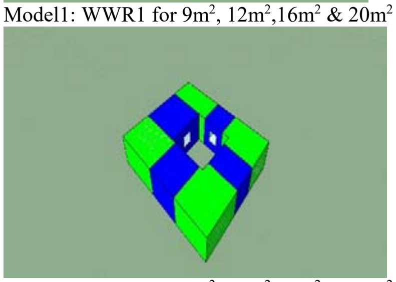
Model1: WWR1 for $9m^2$, $12m^2$,$16m^2$ & $20m^2$



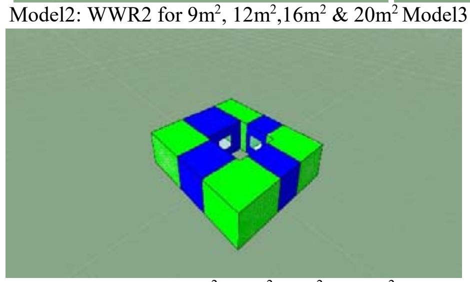
Model2: WWR2 for $9m^2$, $12m^2$,$16m^2$ & $20m^2$



Model3: WWR3 for $9m^2$, $12m^2$,$16m^2$ & $20m^2$



Model4: WWR4 for $9m^2$, $12m^2$,$16m^2$ & $20m^2$

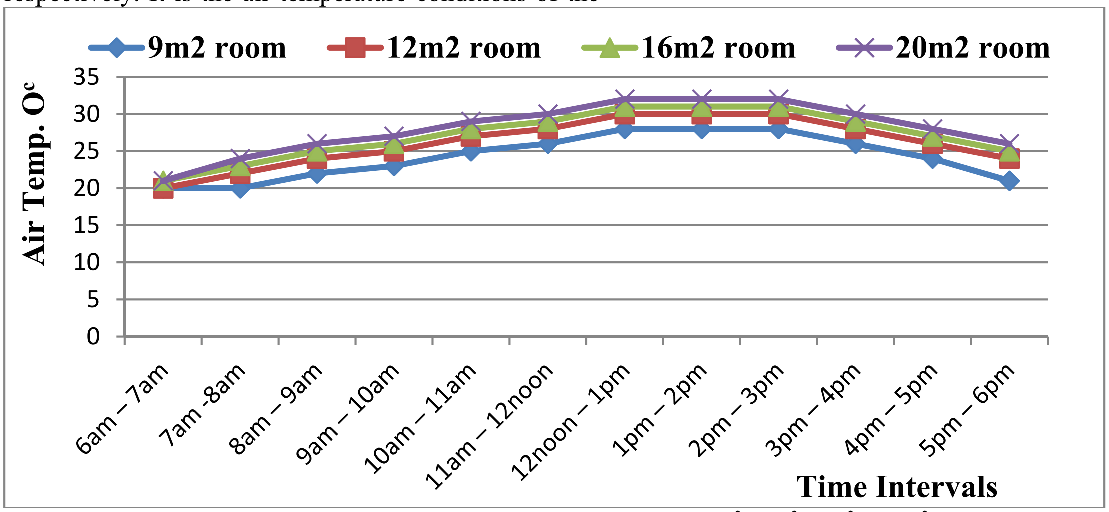


Model5: WWR5 for $9m^2$, $12m^2$,$16m^2$ & $20m^2$

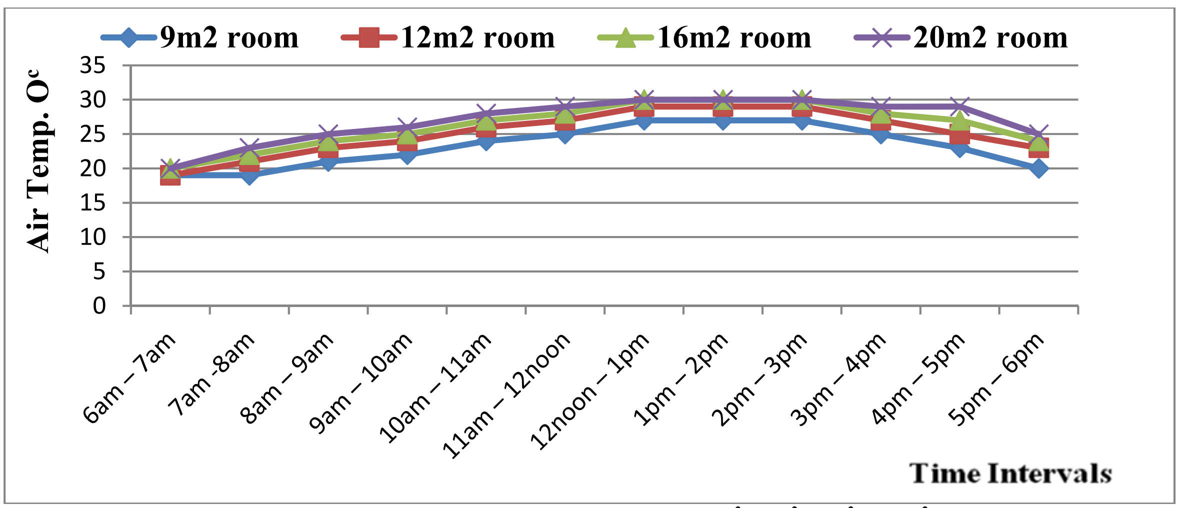
NOTE: WWR1 = window-size $0.36m^2$, WWR2 = window-size $0.675m^2$, WWR3 = window-size $1.08m^2$, WWR4 = window-size $1.44m^2$ & WWR5 = window-size $2.16m^2$ respectively. **Figure 1: Showing Typology of Simulation Models**

RESULTS

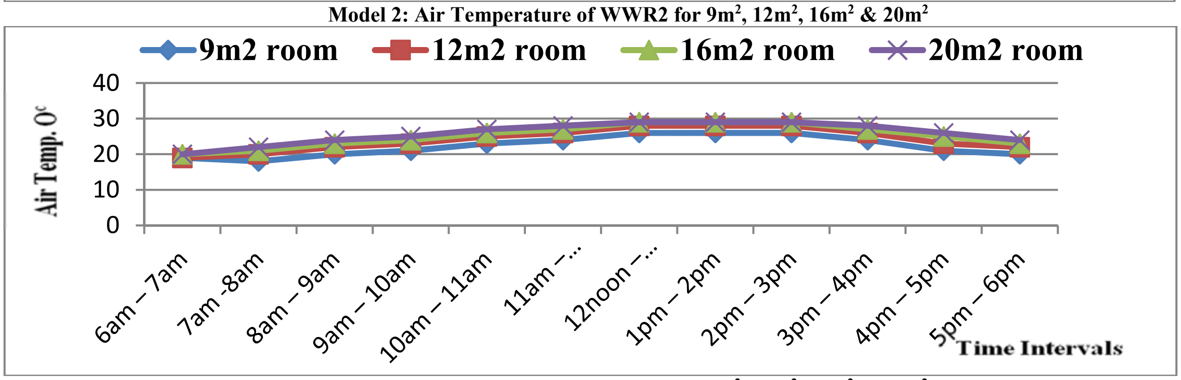
Results of the study are as presented in Fig 1, 2, 3, 4 and 5 respectively. Fig1, 2, 3, 4 and 5 represents model 1, 2, 3 and 4 WWR for 9m^2, 12m^2, 16m^2 and 20m^2 respectively. It is the air temperature conditions of the models tested. Air temperature is the only studied variable because it the most effective thermal comfort parameter for buildings in tropical regions (Muhaisen, 2006).



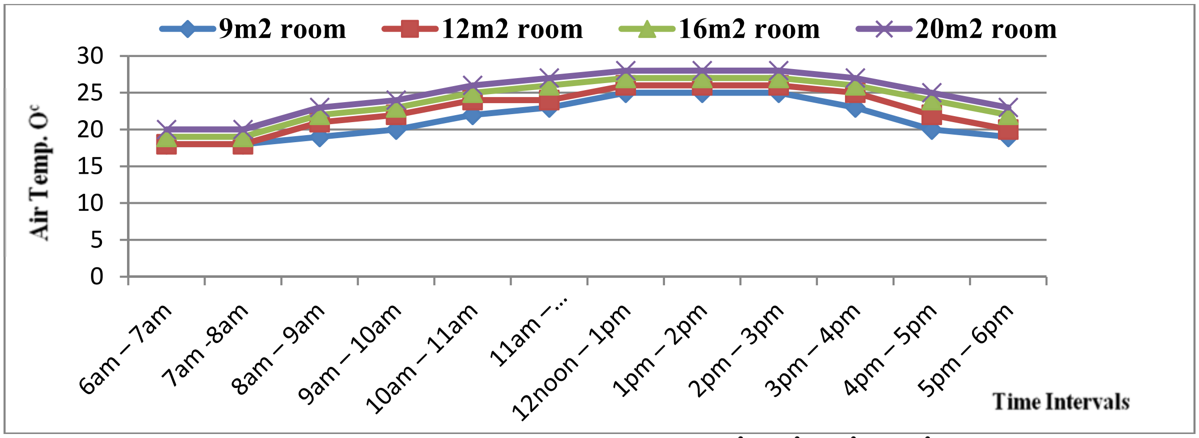
Model 1: Air Temperature of WWR1 for 9m^2, 12m^2, 16m^2 & 20m^2



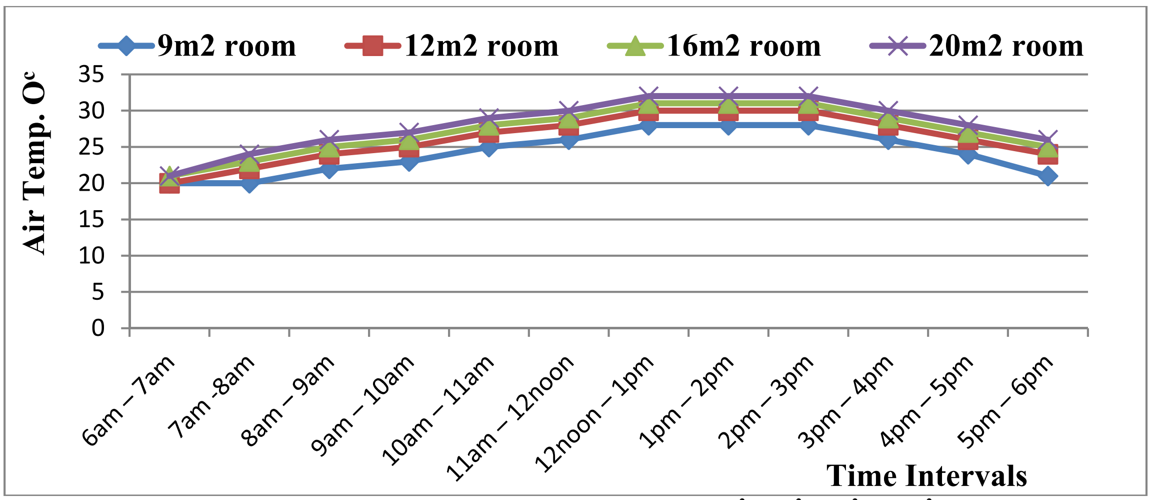
Model 2: Air Temperature of WWR2 for 9m^2, 12m^2, 16m^2 & 20m^2



Model 3: Air Tempereture of WWR3 for 9m^2, 12m^2, 16m^2 & 20m^2



Model 4: Air Temperature of WWR 4 for 9m², 12m², 16m² & 20m²



Model 5: Air Temperature of WWR5s for 9m², 12m², 16m² & 20m²

DISCUSSION

The results of this study as presented in the previous section shows a similar pattern of air temperature conditions in all the tested models. The air temperature conditions are almost the same all through the early morning hours of 6am – 7am. This suggest that WWRs of the fully-enclosed courtyard house have insignificant impact on indoor thermal comfort because the air temperature discrepancies is between 0.5 – 1 0^c in all the models. The air temperature behaviour of the simulation models agrees with Ogunsote (1993) opinion that, indoor thermal comfort of all buildings are within the comfort range of 16 – 18 O^c during the early morning hours irrespective of application of passive design strategy to enhance thermal performance. According to Ogunsote (1993), the conduciveness of buildings within the early morning hours may be due to the long hours of non-solar radiation emission falling on the entire building.

From 7am – 12noon, there is a significant raise in air temperature as shown in Fig 1, 2, 3, 4 & 5. The raise in air temperature was symmetrical. This behaviour connotes that the impact of solar radiation emissions affected all the models tested symmetrically. The result concurred with that of Muhaisen (2006). In his effort to determine the effect of solar radiation emissions through shading, five typologies of courtyard building forms were simulated for different climatic regions. It was revealed that the impact is high in the tropical regions and the indoor thermal comfort of all the tested models rises progressively. In this study, however, the air temperature conditions in the models experimented were not the same because of the impact of the room sizes and the WWRs.

Furthermore, commencing from 12noon – 3pm the air temperature condition in all the experimented models was steady. This behaviour means that the intensity of solar radiation due to location of the sun as relating to the sunpath is the same for a given period of time (Olotuah, 2015). Olotuah (2015) asserted that, the location of the sun on the sun path determines the intensity of solar radiation emitted by the sun at any giving time. Consequently, any passive design strategy for conducive thermal comfort of buildings may be insignificant to mitigating the intensity of solar radiation, but, could enhance thermal performance. The decline in air temperature condition starting from 3pm – 6pm as shown in all results may be due to the same sun path effect because the sun is setting down and its intensity reduces.

Generally, a comparison of the air temperature condition of all the models as shown in Fig 1, 2, 3, 4 and 5 revealed that WWR1, WWR2, WWR3 WWR4 and WWR5 (window size of $0.36m^2$, $0.675m^2$, $1.08m^2$, $1.44m^2$ and $2.16m^2$) decreases progressively in all the typologies of room areas as the WWRs increases, but, increases astronomically in WWR5. These suggest that thermal comfort condition becomes more conducive as the WWR increases in all the room area, however, a worse scenario was observed with WWR 5 ($2.16M^2$). As shown in the results, Model 4 (window size of $1.44m^2$) has better air temperature condition in all the room areas than all the remaining models. It shows that, model 4 is the best, followed by model 3, 2, 1 and 5 respectively.

The results suggest that the impact of ventilation (air speed) on air temperature is much because the bigger the WWR the better the thermal comfort condition in all the room areas. However, at a greater WWR the thermal comfort becomes bad. This finding concurred with Berkovic *et al.* (2012) that larger WWRs could increase the influx of hot air provided that the appropriate room area is not exceeded. However, further simulation studies are required to reveal the range of room area(s) for optimum thermal comfort.

CONCLUSION

Conclusively, the results of this study have shown that WWRs have significant impact on air temperature and thermal comfort. It has also revealed that WWR4 (window size of $1.44m^2$) is the optimum due to the fact that it has a better thermal condition in all the models experimented. But further experiments are require to understand the optimum location for windows for improve airflow pattern in the fully-enclosed courtyard building. Also, more simulation studies are required to make known the range of room area(s) for the most favourable thermal comfort condition. The implication of the study is that achieving thermal comfort in courtyard buildings through effective use WWR is attainable when the architect can perform simulation experiment to generate date to support his design idea.

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