**Benchmarking Indoor Headroom Heights of Residential Buildings Based on ASHRAE Standard 55**

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**ABSTRACT**

The continuous design of residential buildings without comprehensive attention to the vital form and envelope related decision-making steps has necessitated this study. The research aims to uncover the impact of headroom heights of different residential buildings on indoor operative temperature (Top), influenced by mean radiant temperature (MRT). Based on an adaptive approach, we conducted field measurements of indoor headroom heights, thermal comfort variables and interview surveys in 200 households around Kebbi, Nigeria. We used CFD simulations to estimate MRT and Top for a wide range of base-case headroom models. We finally used ASHRAE Standard 55 thermal comfort tool to evaluate comfort levelin each model. Using the measured variables, results show that Top of occupants in models with headrooms between 2.2m-2.75m fell outside the comfort zone and Top of occupants in models with headrooms between 3.25m-3.75m are within acceptable limits.

**Keywords:** Residential buildings; Indoor headrooms; MRT; CFD; Thermal comfort; ASHRAE Standard 55; Adaptive Approach

**1.0 Introduction**

All bodies exchange thermal radiation with their surroundings, depending on the differences in their surface temperatures and their emissivity. This radiant exchange is an essential component of the thermal comfort that will be experienced by a person, particularly in places where there may be significant differences in radiant and air temperatures (Designing Buildings 2020). The significance of understanding such relationships is further highlighted by (Simberloof 2014) and (Ammannn, Dietler and Winker 2021). The studies looked at the impact of climate change on human health, especially in extremely hot climates such as Africa. Furthermore, users’ thermal comfort constitutes almost 40% of energy and process-related emissions (Global Alliance for Buildings and Construction 2019). Energy process-related emissions have also led to the implementation of speciﬁc policies, such as the Energy Performance of Buildings Directive in Europe (European Parliament 2018).

Mean Radiant Temperature (MRT) in thermal comfort is one of the most critical parameters governing human energy balance and the thermal comfort of man. The MRT sums up all short and long-wave radiation ﬂuxes, to which the human body is exposed (Thorsson et al. 2007). MRT is the uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body equals the radiant heat transfer in the actual non-uniform enclosure (ASHRAE 2001). In buildings where radiant cooling systems are rarely adopted, the temperature of surfaces makes the MRT of indoor spaces greater than surrounding air temperature and air temperature cannot be an estimate for MRT except vice-versa (Dawe and Bauman 2020).

Several studies reported different methods for estimating MRT, for example, using field measurements and computer simulations to identify the relationships between outdoor environmental factors and indoor physical conditions relative to occupants’ thermal comfort (Kantor and Unger 2011; Lindberg, Holmer, and Thorsson 2008; Micko et al. 2021). Yoo (2018) studied and estimated the impact of room shape and different surface temperatures (MRT derivatives) on thermal comfort for the human body. Prek (2002) determined the radiant heat exchange for a complex surface and concluded that the surface temperatures and the angle factor between the body and the wall surface are crucial parameters for thermal balance. Gennusa et al. (2008) evaluated thermal comfort for people living and working in confined spaces. Their studies create a foundation for a more advanced thermal comfort analysis in complex architectural forms. Godbole (2018) found that a rise in MRT could lead to a rise in the predicted mean vote (PMV) value and discomfort vote amongst occupants seated near a glazed façade in an educational building. There have been many more studies estimating MRT to improve the thermal comfort of an environment, however, only very few cover the impact of MRT as a deciding variable while emphasising thermal adaptability indices to contextualise an early decision-making process of thermal comfort based on occupants’ different physiological and social behavioural conditions. Putting in mind the occupants’ thermal adaptability indices, the impact of headroom heights on thermal comfort variables (MRT and operative temperature) is the innovation in this study. This innovation became necessary considering the fact that residential houses (especially) in most West African countries, lack any early-decision underlying guidelines on indoor headroom heights targeted at occupants’ indoor comfort.

It is not possible to mention MRT without giving references to operative temperature (Top) and predicted mean vote (PMV). Top is a more functional measure of thermal comfort in buildings, calculated from air temperature, MRT, air speed, air humidity, and the thermal sensation of a body as a whole can be predicted by calculating the PMV (ISO 77320 2005). A balance between the operative temperature and MRT can create a more comfortable space (Matzarakis 2000). ASHRAE Standard 55(2017) developed analytical psychrometric comfort zones for different metabolic rates, clothing insulations, and air speeds with operative temperature as the measure of thermal comfort zones.

Standard Effective Temperature (SET) is also an index commonly used for indoor environmental standardization, its recognition in the field of research is gradually increasing, mainly because of two reasons: 1) SET is suitable for dynamic conditions, whereas PMV is suitable for a steady-state environment; and 2) SET predicts skin’s temperature and skin moisture, as against PMV that cannot predict the body’s physiological response (Zhang and Lin 2020).

**1.1 Overview of ASHRAE Standard 55**

In this paper, ASHRAE Standard 55 was the benchmarking tool for comfort zones; therefore, it is essential to note the overview of its evolution up to date. ASHRAE Standard 55 (2004) incorporates the relevant experiences gained since the ASHRAE 1992 revision, such as the addition of PMV/PPD calculation methods and thermal adaptation. It is the standard where the comfort zones concept was first proposed, along with the applicable air temperature, MRT, humidity, airspeed, clothing insulation, and metabolic rate to create the graphical and analytical (computer model) methods. The graphical method (Fig. 1) showed a typical sedentary activity where occupants have activity levels of 1.0, and 1.3 metabolic rates, clothing insulation between 0.5, and 1.0, and the comfort zone and for spaces where air speeds are not greater than 0.2ms-1. Although while there was no precise relationship between an increase in airspeed and improved comfort, the 2004 Standard gave allowance to increase in air speed above 0.2ms-1. Linear interpolation of range is used to determine the comfort zone of Top using the following equations:

Tmin, Icl = [(Icl – 0.5 clo) Tmin, 1.0 clo + (1.0 clo – Icl) Tmin, 0.5clo] / 0.5 clo (1)

Tmax, Icl = [(Icl – 0.5 clo) Tmax, 1.0 clo + (1.0 clo – Icl) Tmax, 0.5clo] / 0.5 clo (2)

Where:

Tmax, Icl = upper Top limit for clothing insulation Icl, Tmin, Icl = lower Top limit for clothing insulation Icl, and Icl = thermal insulation of the clothing in question (clo)

**[Figure 1 here]**

Since 2004, the standards have had the following updates in table 1:

**[Table 1 here]**

**2.0 Overview of Indoor Comfort in Residential Buildings**

Thermal comfort indoor calculation in a residential building is far from being a steady state, as nearly all forms of adaptations apply to the case of residential buildings. Amongst many reasons, for example, both the activity level and clothing insulation can vary within a short period of time (Peeters et al. 2009). Adunlola and Ajibola (2016) confirmed the adaptive movement from space to space due to variation in spatial comfort in residential buildings; in their study, indoor comfort assessments varied according to different building design typologies and the thermal assessment of respondents for different spaces in their respective buildings also varied. Akande and Adebamowo (2010) found a temperature range of 27.10C-29.30C as acceptable in residential buildings in a hot and dry climates. The study concluded that some obstacles to comfortable indoor temperature are types of clothing used, the openings that can provide adequate ventilation, and low-level ceiling height. Similarly, Maeyens et al. (2001) suggested a comfort temperature of 26.40C with a maximum of 27.50C (PMV +0.5) for a bedroom thermal zone in a residential building. The summer comfort temperature in their research is close to the maximum temperature suggested by (CIBSE 2006). More researches have estimated the indoor comfort level of residential buildings based on adaptive approaches, but no comprehensive research yet exists on MRT variations and its influence on the Top index when headrooms of residential environments are varied.

**3.0 Methodology**

The importance of this article is that it contextually applied MRT and the adaptive parameters based on subjects to find optimum indoor headroom heights using computational fluid dynamics (CFD). In this investigation, we used the SET and Top in the ASHRAE thermal comfort tool (Tartarini et al. 2020) to benchmark the different indoor headrooms of thermal zones for residential buildings in a hot-dry climate.

**3.1 Study Location**

The study location is Kebbi, Nigeria, a tropical hot-dry climate in Sub-Saharan Africa, between latitude 12.260 north and longitude 4.130 east. Kebbi is characterised as one of the warmest regions in Nigeria, with an average daily temperature above 360C, with low humidity. The hottest season lasts beyond two months, from March until late May. The hottest month of the year is April, with an average temperature as high as 380C and a low temperature of 300C. During the hot periods when the rainy season is at its peak from July to August, the mean relative humidity falls between 20% and 70%.

**3.2 Field Measurements and Survey**

The field study was conducted in Birnin-Kebbi, as shown in figure 3. We carried out measurements on 200 households throughout April, representing the hottest period. In order to satisfy the aim this study, the households were carefully chosen purposively based on the following three (3) criteria :(i) evidently having different headrooms, (ii) were within the same neighbourhood at approximately within 5-10 meters apart, as well as, (iii) most having almost similar construction methods and building envelope. It is important to note that other households, aside the 200 chosen within the neighbourhood may also be qualified for the assessment. However, as a result of some unavoidable circumstances, i.e., restrictions to full access into some households, forcing them to be screened out and not considered. In the first instance, we measured the headroom heights in each of these households (ceiling-to-floor heights). We grouped the households into the following: 2.2m≤H≤2.5m, 2.5m≤H≤2.75m, 2.75m≤H≤3m, 3m≤H≤3.25m, 3.25m≤H≤3.5m and 3.5m≤H<3.75m as shown in Table 3. Secondly, we measured thermal comfort variables – air temperature, air velocity, and relative humidity – with a multi-function digital handheld thermal comfort data logger (figure. 2 and table 2) to calculate the MRT of the environment. The air temperature and air velocity measurements followed the ‘modify section 7.3.2’ of the ASHRAE Standard 55-2017, where data are taken at 1.0m inward from the center of each room’s wall; measurements for seated occupants were taken at 0.1m,0.6m and, 1.1m and for standing occupants were taken at 0.1m, 1.1m and, 1.7m heights above floor level (ASHRAE Standard 55 2017). We controlled the natural ventilation by adjusting window openings, and data were taken with the logger after 10 minutes into each space. A fair control of air allowed into the spaces (figure 3 shows some examples of the interior spaces). To simplify measurements, we only considered the comfort variables and headroom heights in the living rooms. We noticed a wide variation of air velocity ranging between 0.02-0.5ms-1across the households, due to different orientations of buildings and window sizes. The average airspeed recorded is shown in table 3. Lastly, we used the results of the interview from respondents to calculate the clothing insulation and activity level of the occupants, complying with (IS0 7726 1998) and (Engineering toolbox 2004).

**[table 2 here]**

**[figure 2 here]**

**[figure 3 here]**

**[table 3 here]**

**3.3 CFD Simulation**

In this section, we used Autodesk CFD for pre-processing, where we prepared computational meshing and boundary conditions (table 5). Computational mesh settings are necessary for CFD, as learned from past studies, to enhance the accuracy of the results ( Lee et al. 2020; John et al. 2022; and Tacutu et al. 2021). In this study, we provided the settings in Table 4. We performed diagnoses the on models for good mesh quality before further analyses. In the simulations, we assigned the same envelope material and boundary conditions to each model. We based the boundary conditions on the assumption of the meteorological data and locations coordinate of Birnin-Kebbi (figure 4). We set and ran the simulations to allow for heat transfer mechanisms between surfaces in a steady-state solution mode for 100-300 iterations. After that, we used the information gathered from field surveys (table 3) to calculate the MRT and Top of the indoor headroom heights, using the CFD in a Finite Element Method (FEM). The FEM discretizes large systems into smaller finite elements for easier and faster computation. We used Revit software to model a 5m x 5m square floor area (base case models) against various headrooms, representing typical average sizes of the living rooms of the occupants. Then, each model was imported separately into the CFD through the CFD plug in in Revit. A human model was assumed in each of the base case models to display the thermal sensation of the human body in the spaces by temperature stratification.

**[table 4 here]**

**[figure 4 here]**

**[table 5 here]**

**3.4 Mesh Independence Test**

Both resolution and refinement influence the mesh quality. Mesh quality is thecomponent that affects the accuracy of the CFD solution and calculation time. Mesh or Grid independence test simply implies that the outcome of the CFD results is independent of the mesh resolution, i.e., irrespective of being fine or coarse, rather is dependent on the boundary conditions and physics employed. We expect that when one performs the mesh independence test, the model with accurate mesh settings should give almost exact results. Where one observes results with far margin after the mesh independence test, one will need to refine the mesh more until the results are independent of the mesh for an improved confidence and accuracy. We tested the automatic mesh setting of the model, two different fine mesh models and a coarse mesh model (table 6). In figure 5 and 6, after several mesh refinement, we observed that the discrepancies in the results for the two fine meshes and the medium mesh are almost negligible. The output bar of the CFD reported 99.9% and 96.5% accuracy on the temperature test and velocity magnitude. Beyond the further mesh refinements, the non-complex nature of the models, as mentioned earlier, also added to the quality and simplification of mesh sizing. To save computational cost, we adopted the medium mesh size for calculations in the following sections, and we repeated the same procedure for the remaining headroom models.

**[table 6 here]**

**[figure 5]**

**[figure 6]**

**3.5 Field Experimental for CFD Validation**

To validate the post-processing process, we compared the field measurements of temperature and air velocity with those in the post-processing. We once again used the values of the 3m headroom model for validation, like in the section above. As earlier mentioned, the modified section 7.3.2 of (ASHRAE Standard 55 2017) provides guidelines for indoor environmental field measurements, and we adopted these during the field survey, where we took data at 1.0m inward from the center of each room’s wall; measurements for seated subjects at 0.1m, 0.6m, and, 1.1m; for standing subjects at 0.1m, 1.1m and, 1.7m heights above floor level. Both the sitting and standing measurements were plotted at 0.1m, 0.6m, 1.1m and, 1.7m. In this study, we assumed and designated these strategic measurements as areas of interest (AOI). figures 7 and 8 show the comparison of the air temperature and velocity in the field survey against the CFD. Although while CFD approximates the AOI positions from settings, it also interestingly mapped many other parametric measurements automatically (figure 7 and 8).

**[figure 7 here]**

**[figure 8 here]**

**3.6 Validation Error**

In order to place a confidence on the validation of CFD and the field measurements (air temperature and velocity), it was necessary to provide the error analyses in order to know the possible deviations that occurred. In this study, the authors used the percent-dependent evaluation metric, i.e., the Symmetric Mean Absolute Percentage Error (SMAPE) and Mean Absolute Percentage Error (MAPE). Both SMAPE and MAPE measure the errors in percentages and provide interpretable thinking on account of the quality of the prediction, and they also help especially if the reviewer or the audience does not know the scale of the data (Flores 1986). Although, MAPE has the disadvantage of penalising positive errors more deeply than negative errors, and is also very scale-sensitve by providing extreme errors if the actual value is small (Hyndman 2006), and (Armstrong and Callopy 1992). As a result of this, the SMAPE metric was chosen, since it is a modified version of MAPE which takes care of this disadvantage. MAPE and SMAPE can be interpreted by the following equations (Sanders 1997):

Where the simulation values, = the field experimental measurements, = the number of data points under regard.

The number of data points for the air temperature and velocity in the field measurements, which fell in the AOI as mentioned above, were only considered. These data points together with their corresponding values in the CFD simulations were used for calculating the errors. The values are presented on table (7).

(table 7 here)

By using the SMAPE metric and the data points on table 7, the error found for the air temperature is 4.2% and the velocity is 11%. This is quite reasonable based on the basic rule that the closer a percentage approaches 0%, the better the accuracy (Jierula et al. 2021).

**4.0 Results and Discussion**

CFD has an apparent visual graphics of results, displaying the thermal stratification of models (figure 9). In this study, for simplification, we simulated seven models, with, each having a headroom height of 2.2m, 2.5m, 2.75m, 3.0m, .25m, 3.5m, and 3.75m. Each model represents the category to which the measured spaces fell during the survey. Although, from the survey measurements, none of the 200 households have a headroom height up to 3.75m, we still simulated it with the same variables used in the simulation of the 3.5m headroom, which is a closer measurement to it. This is an essential step to observe and compare the likely differences of thermal zones across allthe measured heights, to predict their impact on MRT.

**[figure 9]**

From the CFD results of the thermal stratification, it can be clearly seen that overall temperature profile of the headroom heights decreases with increase in the headrooms. A similar scenario was noted in the study by Farooq, Zubair and Arif (2020), where the evaluation of ventilation effectiveness with ventilators was based on the temperature magnitude of some houses’ ceiling height. They study found that the average temperature of the low ceiling houses is15.310C and that of the high ceiling houses was 13.880C. It also follows the outcome of the study where a reduction in the ceiling height was noted causing a slight increase in temperature for hot climate regions, such as tropical countries (Guimaraes et al. 2013).

**4.1 MRT and Top Estimation**

We made estimations within 2.0m height at 0.5m intervals, corresponding to an approximate human height. For the 2.2m headroom (figure 10a), the maximum value of MRT occurred at 0.6m, corresponding to 33.40C with a minimum value occurring at 0.25m height, corresponding to 29.30C, and the mean average of 31.60C. Similarly, table 10 shows the summary of the MRT values for the charts in figure 10(b-g). Again, important to note is that the maximum MRT values for all the charts in figure 10 occur at an approximate distance between 0.6m-1.5m, mainly because positions of windows are placed within this range, allowing for CFD to estimate higher values for regions exposed to more radiant heat. This similar trend was noted in the study conducted by Walikewitz etal. (2014),where the positioning of windows and their sizes, as well as the direction of the solar intensity being the factors which cause variations in temperature between the MRT and air temperature. This also agrees with the common physical condition where only the short wave radiation from the sun enters the indoor space through the window and the long wave absorbed by the outside of the window (Frieß 2002).

**[figure 10 here]**

As mentioned earlier above, for climate regions like hot-dry where residential buildings do not incorporate radiant cooling systems, air temperature is not equivalent to MRT. In this study, there is a fluctuation between the average air temperature measured in the survey (table 3) and the estimated MRT values. Also, the slight effect of radiant heat is evident in some of the estimated values of MRT on indoor air temperature (table 8). This follows almost the same trend in the study by Lindberg et al. (2014). Although in the study, it is an opposite case, where no autochthonal weather conditions were recorded during the measurements due to cloud cover. This causes the absence of the slight effect of radiant heat, allowing air temperature to equaled MRT.

Top depends on MRT, as seen from the charts in figure 11 and table 8. It can be observed that there was a direct consequence of MRT on Top, as increase in MRT values led to a slight increase in Top.With the values of MRT computed, it was possible to set CFD to use a similar algorithm to estimate and compute Top values. Like in the case of MRT, table 8 summarises the maximum, minimum and, the mean average Top.

**[figure 11 here]**

**[table 8]**

**4.2 Thermal Comfort Tool Method (ASHRAE Standard 55)**

Now, the Top for the headrooms is benchmarked using the SET contour curves in the comfort zone of the ASHRAE Standard 55 thermal comfort tool. The standard interpolates the air speeds on the y-axis against the Top on the x-axis within the contour range of SET values. With these values, the thermal comfort tool benchmarked the comfort zones depending on clothing level and metabolic values. According to ASHRAE Standard 55, it was possible to adjust the clothing and metabolic values by the following set rules: An increase of 0.1 clo or 0.1 met corresponds approximately to a 0.8°C (1.4°F) or 0.5°C (0.9°F) reduction in operative temperature (Top); a decrease of 0.1 clo or 0.1 met corresponds approximately to a 0.8°C (1.4°F) or 0.5°C (0.9°F) increase in operative (Top). For thermal adaptability, it is essential to discuss the clothing and metabolic values for the evaluation. During the survey, the interview outcomes of the respondents of most households in terms of their activities and clothing styles during hot periods are within 1.2≤met≤1.7 and 0.4≤clo≤0.5. For worst-case scenarios, we adopted 1.7 met and 0.5 clo for evaluations in this study. 0.4 clo was applied in some instances to allow the Top to likely shift into the comfort zone (figures 12b, 13b, and 14b).

Figures 12-14 describe the comfort zone of the Top in 2.2m, 2.5m, and 2.75m headroom. In figure 16, one can observe that the average air speed of 0.22ms-1 fails to place the average Top within the acceptable comfort zone limit, indicating a vast margin of about 30C with 0.5clo. With this margin, it means that during hot periods, irrespective of adjustment of wearable clothing level, it is impossible to attain the minimum comfort except for more supply of airspeed. Likewise, in figure 17, the Top was outside the margin with about 1.50C, and with a clothing level of 0.4 clo, a slight shift occurred, yet outside the comfort zone. In figure 18, the Top still did not fall in the comfort zone with 0.5clo, but with a clothing of 0.4 clo, it fell slightly within.

**[figure 12a here]**

**[figure 12b here]**

**[figure 13a here]**

**[figure 13b here]**

**[figure 14a here]**

**[figure 14b here]**

Figure 15-18 describes the comfort zone of the Top in 3m-3.75m headrooms. It was noticed that the Top in figure 15 is slightly into the comfort zone; this implies that 0.4 clo will fall into a better margin of the comfort zone, being a lighter clothing insulation like in figure (12-14) above. In instances where there is a fluctuation in airspeed, for example, slightly lower than 0.22ms-1, 27.30C Top  (Fig.15) with a 0.5 clo – corresponding to 3.0m headroom – is an unlikely desirable range for a comfort zone. Top in figure 16-18 are more reliable for a comfort zone as both 0.5 clo and 0.4 clo fit rightly in the comfort zone. It is important to note that ASHRAE Standard 55 provides upper limits where occupants do not have control over the airspeed, for Top  > 25.50C, the upper limit is 0.8ms-1. This upper limit may affect comfort zones in figure 16-18 due to a possibility of a draft as 0.22 ms-1 appears to be within optimum, although air speed up to 0.3-0.4 ms-1 is allowed. However, this is different for Top in figure 12-14, where occupants struggle to fit in the comfort zones in respect of 0.22ms-1 airspeed. An upper limit of 0.8ms-1 may offset temperature and place Top in the comfort zones (figure12-14).

**[figure 15 here]**

**[figure 16 here]**

**[figure 17 here]**

**[figure 18 here]**

**5.0 Conclusion**

MRT is an essential variable of thermal comfort that affects the Top of spaces, yet is mostly assumed to be an estimate of air temperature in past research, especially in Africa, where radiant cooling systems which mitigate the influence of MRT are not well adopted, making MRT estimation a necessity. In this study, the aim was to develop a method that could be used for evaluating and predicting the thermal comfort level of various headroom heights. This was possible through the estimation of the MRT of residential environments, coupled with emphases onthe basic social lifestyles of occupants. Such lifestyles are the most frequent activity levels and clothing insulations, to allow for an adaptive approach. . From the results in this study, one can gather that most occupants are not comfortable with their indoor spaces in hot periods in environments with lower headroom heights, which traditional construction practices in regions like Kebbi in Nigeria. This study provides underlying guidelines to professionals in the building industries to understand the necessity of headroom heights and their impact on the thermal comfort of an environment, with emphasis on residential buildings where low air speeds are most common with non-sedentary activities at most times. In the future, researchers may check the impacts of other early-decision-making processes in the design stage like window-to- wall ratio and plenum space above ceiling level, on MRT variations with air temperature.

The following are necessary takeaways from this study:

1. By using ASHRAE Standard 55 thermal comfort tool, this study once again proved that thermal adaptive indices(i.e., clothing insulation and activity level) are essential for the evaluation of occupants’comfort levels. This aligned with the study by (Yon et al. 2022) and (Jiao et al. 2017), where adaptive indices for comfort played a significant role, and also having the potential to accommodate feedbacks from adaptive actions.
2. The CFD simulation of the MRT in this study lends a credence to the experimental studies by (Walikewitz etal. 2014), which gathered that a slight deviation exist between the air temperature and the MRT. This is specifically in warmer periods where outdoor temperature is significantly high, thus leading to radiant heat transfer.
3. According to evaluations with ASHRAE Standard 55, indoor headrooms below 3.25m are not recommended for typical hot periods in the study area, where occupants’ clothing insulations are generally between 0.4 clo-0.5 clo.

Air speeds above 0.3 ms-1 up to the 0.8 ms-1 upper limits recommended by ASHRAE Standard 55 for elevated air speed zones may or may not offset high temperatures for occupants in environments with lower headroooms below 3.25m, as a result of the (iii) above.

**Acknowledgements**

The authors thank the households who participated and granted supports during the survey. We also thank Sufiyanu Karaye of the Department of Architecture, Kebbi State University of Science and Technology, for organising a team for the field survey data collection.

**Conflict of Interest**

The authors declare none.

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