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Establishing Indoor Thermal Comfort Range for Office Buildings in Jos Nigeria Using the Adaptive Psychrometric Chart

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Abstract: A psychrometric chart is a web-based graphical user interface that allows for the prediction of thermal comfort and the visualization of comfort boundaries within predefined atmospheric qualities. Based on ASHRAE 55 adaptive method, this chart was used to analyse 10 administrative office buildings, with occupant-controlled natural conditioned spaces, located within Jos urban conurbation in Nigeria. This tool revealed that with an outdoor temperature of 32.0°C, indoor thermal comfort range for 80% and 90% acceptability corresponds to 24.2°C to 31.2°C and 25.2°C to 30.2°C respectively. It also established a neutral operative temperature of 29.0°C on the Adaptive Psychrometric Chart. The neutral operative temperature of 29.0°C is at slight variance with other research indicating a Neutral Temperature of 29.4°C. However, this established neutral temperatures fall within 80% and 90% of acceptability thermal comfort range. This authenticates the validity of Psychometric Chart and the Neutral Temperature Analysis techniques as viable tools in thermal comfort studies in this research environment and conditions. This also indicates that most of the office buildings examined can operate fairly effectively without mechanical ventilation thereby providing savings in energy use and ensuring environmental sustainability.

Keywords: Adaptive Model, Neutral Temperature, Thermal Comfort, Indoor Air Quality (IAQ), Psychrometric Chart, ASHRAE 55

1. Introduction

In the life cycle of a building, the design and pre-occupancy stages provides a great opportunity for energy savings through thermal comfort analysis. In other to obtain optimum interior thermal comfort, attempts are made to maintain a narrow and highly optimized temperature band. This often requires a high level of expertise and specialized equipment which, in turn, can also be energy intensive thereby defeating the raison d'etre of the exercise. A system that obtains a wider temperature band for thermal comfort studies will be obviously more appreciable. This also implies that the system will be easily deployable in diverse conditions of technical abilities and economy thereby becoming holistically more successful in thermal comfort applications. The Pyschrometric Chart provides this opportunity by presenting a graphical analysis output of varying potential solutions without having to carry out long and laborious mathematical calculations. These predictions are executed according to ASHRAE Standard 55 [1, 2, 15].

The principle guiding the assessment of indoor thermal environment is hinged on the theoretical analysis of the interrelationship between human (physiological) heat exchanges with his environment [7, 11, 15]. This has led to the development of Indices or standards based on 'rational' or 'empirical' method or adaptive thermal comfort standards. In naturally ventilated buildings, the *adaptive comfort model* is required. All the buildings analyzed in this research are naturally ventilated (See Figures 2, 3 and 4). This adaptive model is based on the concept that outdoor climate has effect on indoor thermal comfort. This adaptive hypothesis predicts that contextual factors, such as having access to environmental controls, and past physiological memory of thermal history of that environment influences building occupants' thermal expectations and preferences. This fact is incorporated into ASHRAE 55-2004 standard as the adaptive comfort model. This adaptive Psychometric Chart relates indoor comfort temperature to prevailing outdoor temperature and defines zones of 80% and 90% satisfaction.

Previous thermal studies, using the Psychrometric Chart, mostly have been executed in the northern hemisphere, in developed regions, with the subjects mainly being adults occupying offices and similar public spaces [4, 5, 8, 10]. However, the thermal research by Ogbonna, & Harris (2007) was executed in Sub-Saharan Africa. Here, the Fanger's method was used. The subjects were mainly teenagers in higher institutions in Jos-Nigeria. The study indicated a comfort range of 24.88°C to 27.88°C for the persons under study and a neutral temperature of 26.27°C. Other research indicated a Neutral Temperature of 29.4°C for adults in naturally ventilated office building in Jos Nigeria [6, 7]. Here, the subjects were adults occupying Administrative offices in Jos Nigeria. The movement from the thermal studies of teenagers in higher institution to adults in administrative offices completes the possible spectrum of thermal studies in Sub-Saharan Africa. This research seeks to validate the above-mentioned findings using the Psychrometric Chart in Sub-Saharan Africa to determine indoor thermal comfort range for office buildings in Jos, Nigeria.

2. Methodology of Study

10 administrative office buildings were studied using established methodologies [1-3, 5, 13]. (See Table 3). Measurements were taken at intervals of 8.00hrs, 12.00hrs and 15.00hrs. These conveniently represent opening hours, mid-day break and closing hours of the offices under study. Other data obtained includes; Volume of air/space (Length x Breadth x height), Air temperature (°C) (average at 2 heights and multiple locations in the room), Air velocity (m/s) (average at multiple locations in the room), Meant Radiant temperature (°C) (average of room surfaces), Relative Humidity (%) (Average across multiple locations in the room), Activity Rate (met) (See Table 1) and Clothing Level (clo). (See Figure 1) Below are the methodologies and equipment used for the above-mentioned data acquisition.

2.1. Outdoor Weather Conditions

Outdoor meteorological observations were carried out on location using an Oregon scientific wireless weather station Model WMR928NX. The weather station includes a wind gauge, an outdoor thermo-hygrometer, a rain gauge and an indoor Thermos-Hygrometer and Barometer. Data derived from these measurements are compared and combined with data from the local weather station to calculate derived indices as may be needed for the research.

2.2. Temperature Measurements

In order to take into account the impact of horizontal and vertical variations in temperature within the room, air temperature readings were taken at three different locations in each space and at two different levels corresponding to the body level and the ankle level in the offices corresponding to approximately 0.1m and 1.2m above floor levels respectively. An RS 1364 Humidity Temperature Meter with a thermostat sensor of measuring range: -20 to 60°C; 0.1°C resolution and sampling rate of 2 times per second was used.

2.3. Relative Humidity

The same RS 1364 humidity temperature meter with a precision capacitance sensor was used to determine the relative humidity levels at body level in all cases. The hygrometer has a measuring range of 10 to 95% RH, Accuracy:±3%RH at 25°C, Resolution of 0.1%RH and Operating temperature of 0 - 50°C.

2.4. Mean Radiant Temperature

The measurement of the mean radiant temperature was obtained from the readings of a Cyclops Compac 3 Infrared Thermometer. The infrared System recorded radiant temperatures on the different room surfaces; walls, floor, ceiling as well as the furniture immediately around the respondents. A simple average of the readings was adopted as the mean radiant temperature.

2.5. Operative Temperature

Operative temperatures were obtained for the different rooms using the equation to=Ata + (1-A) tr (ISO 7730: 1995) (ASHRAE 55-2004). Where A is assumed to be 0.5 where the difference between ta and tr is < 4°C and for air velocity <0.2m/s. ta is the air temperature and tr is the mean radiant temperature.

2.6. Indoor/Outdoor Air Velocity

A Pyle PMA90 Digital Thermo-Anemometer was used to measure air movement indoor and outdoor. This meter was place to take readings at body level at the different room locations indoors. The windows in all the rooms were left in their usual open positions during the survey as is the case during working hours. For outdoor readings, the device was located away from any large object that could cause local interference in wind speed dynamics. This device has a range of 0.20 - 30m/s and an accuracy level of±3% for readings greater than 0.20m/s. The average of these readings for each office was used as the air velocity of the room.

2.7. Global Positioning System

A Cobra GPS 100 global Positioning System receiver was used to obtained global location of buildings of interest. This device provided accurate positioning to within 3 meters, if held in any position open to the sky. It offers information as to current positioning, altitude above sea level, bearing and time of the day.

Table 1. *Metabolic Rate for Different Activities.*

S. No.	Activity	Metabolic Rate	
		W/m^2	Met
01	Reclining	46	0.8
02	Seated, Relaxed	58	1.0
03	Sedentary Activity (Office, Dwelling, School, Laboratory).	70	1.2
04	Standing, Light Activity (Shopping, Laboratory, Light Industry)	93	1.6
05	Standing, Medium Activity (Shop Assistant, Domestic Work, Machine Work)	116	2.0
	Walking On Level Ground:		
	2km/h	110	1.9
06	3km/h	140	2.4
	4km/h	165	2.8
	5km/h	200	3.4

Source: ISO 8996

Table 2. *Garment Insulation Values.*

Clothing Description	Garments Included	(clo)
Trousers	1) Trousers, short-sleeve shirt	0.57
	2) Trousers, long-sleeve shirt	0.61
	3) #2 plus suit jacket	0.96
	4) #2 plus suit jacket, vest, T-shirt	1.14
	5) #2 plus long-sleeve sweater, T-shirt	1.01
	6) #5 plus suit jacket, long underwear bottoms	1.30
Skirts/Dresses	7) Knee-length skirt, short-sleeve shirt (sandals)	0.54
	8) Knee-length skirt, long-sleeve shirt, full slip	0.67
	9) Knee-length skirt, long-sleeve shirt, half slip	1.10
	10) Knee-length skirt, long-sleeve shirt, suit jacket	1.04
	11) Ankle-length skirt, long-sleeve shirt, suit jacket	1.10
Shorts	12) Walking shorts, short-sleeve shirt	0.36
Overalls/Coveralls	13) Long-sleeve coveralls, T-shirt	0.72
	14) Overalls, long-sleeve shirt, T-shirt	0.89
	15) Insulated coveralls, long-sleeve thermal underwear tops and bottoms	1.37
Athletic	16) Sweat pants, long-sleeve sweatshirt	0.74
Sleepwear	17) Long-sleeve pajama tops, long pajama trousers, short 3/4 length robe	0.96

Source: ASHRAE Handbook (2005) Atlanta, pp 8.9

2.8. Methods of Objective Data Analysis

For objective data obtained from measurement instruments described above, this was inputted into the web-based Pyschrometric Chart (See Figure 2). The University of California at Berkeley developed a Web-based tool for this purpose. It was obtained from http://smap.cbe.berkeley.edu/comforttool (Tyler et al. 2019). Relevant data from Table 3 were imputed, which consist of the average of all environmental inputs required by the web-based tool. The figures and the graphical output obtained were thus analyzed.

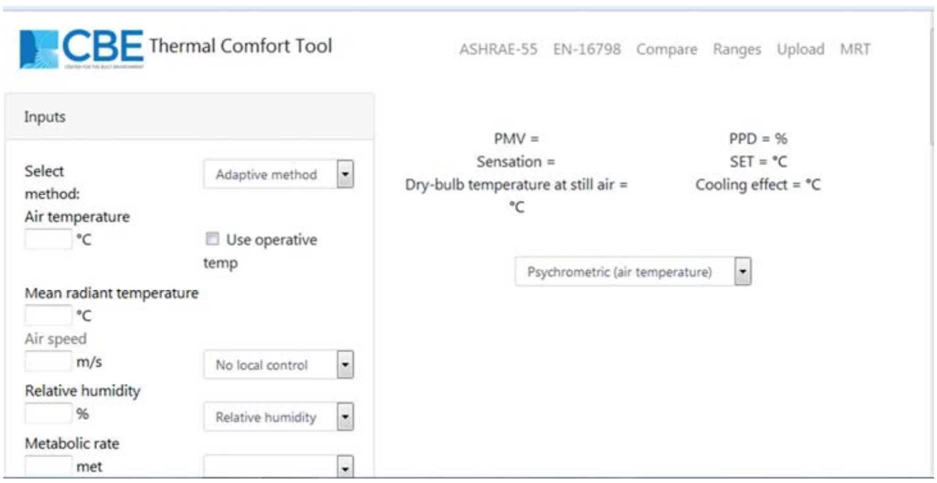

Figure 1. *Screen-shot of the web-based Adaptive Psychometric Chart Based on ASHRAE Standard 55-2010 Indicating Predicted Zone of Thermal Comfortability (Tyler et al. 2019).*

3. Sample Area Characteristics

Jos, Plateau State characterized by rocky terrain (topography) giving rise to plateaus and plains, hills and valleys and it enjoys a unique climate (temperate climate) than much of the rest of Nigeria. It is on the average located at an altitude of 1,217m (3,993ft) above sea level. The wet season starts from April – October and the dry season starts from November- March. The mean annual rainfall here is about 320mm in the month of August with an average monthly temperatures ranging 21°C-38°C (69.8°F-100.4°F), and from mid-November to late January, night time temperatures can drop as low as 11°C (52°F). Daily solar radiation average of over 4300wh/m2 per annum is recorded.

3.1. Population and Sampling

The subjects under research are Administrative Office Buildings of federal and state government institutions and establishments. This constitutes the accessible population. However, the Administrative Office Buildings of Federal and State government institutions and establishment located within Jos urban conurbation here in Nigeria constitute the target population. By random sampling within the accessible population, a sample for the purpose of this research was obtained (See Table 3). Here, Administrative building are described as a building purpose built or modified for the function of carrying out activities such social and financial planning, record keeping and personnel management within working days and hours (See Figures 2, 3 and 4).

Table 3. *Office Buildings Sampled.*

S/N	Administrative Buildings	Building ID	Location (GPS)	Elevation (m)
01	Ministry for Local Government and Chieftaincy Affairs	MIN/LGCA	NO9°53.207 E08°52.075	1224
02	Ministry of Housing and Urban Development	MIN/URBAN	NO9°53.727 E08°52.791	1221
03	Ministry of Lands, Survey and Town Planning	MIN/LSTP	NO9°54.982 E08°53.242	1232
04	National Film Institute Jos Administrative Building	NFI/ADM	NO9°53.880 E08°53.625	1254
05	NIPSS Jos Administrative Building	NIPSS/ADM	NO9°44.726 E08° 49.084	1263
06	Plateau Publishing Company	PLSPC	NO9°54.538 E08°53.660	1235
07	Plateau Specialist Hospital Administrative Building	PLSH/ADM	NO9°53.961 E08°53.185	1246
08	Plateau State Board of Internal Revenue	PLSBIR	NO9°54.584 E08°53.434	1233
09	Plateau State Polytechnic Administrative Building	PLSP/ADM	NO9°52.916 E08°52.339	1250
10	University of Jos Administrative Building	UJ/ADM	NO9°57.187 E08°52.263	1286

3.2. Architecture Features of Building Under Study

Figure 2. *Showing Typical Examples of Office Building Studied.*

Figure 3. *Showing Typical Examples of Office Interior.*

Figure 4. *Showing Typical Examples of Office Corridor.*

4. Fieldwork

4.1. Recorded Environmental Variables

The field work consists of obtaining objective data for the purpose of analysis. This objective data was obtained from measurement instruments as earlier enumerated. The procedure for data collection in this thermal comfort survey is based on the thermal comfort experiment framework equivalent to the Class II Field experiment protocols for thermal comfort and consistent with ISO 7726 and ASHRAE standard 55- 1992 and ASHRAE fundamentals (2005). Also, works by Nicol & Humphreys (2002), which postulated that the range of thermal conditions considered comfortable by occupants is often affected by the climate, the characteristics of the building and the opportunities for individual adaptation by the occupants (acclimatization) formed a background for this research.

Table 4. *Summary of Indoor Climatic, Metabolic and Clothing Variables.*

BUILDING ID	AREA. (M^3)	Ta (indoor) (°C)	Ta (outdoor) (°C)	Vel. (M/S)	Tr (°C)	RH (%)	Ar (met)	Cl (clo)
UJ/ADMIN	40.32	32.3	32.41	0.3	30.87	38.2	1.2	0.57
NIPSS/ADMIN	50.24	28.6	31.71	0.5	29.37	43.9	1.2	0.57
PLASBIR	324	27.76	32.53	0.5	27.52	61.2	1.2	0.57
PLSPC	45.61	29.62	33.47	0.5	28.61	30.5	1.2	0.57
MIN/LGCA	74.3	28.1	34.38	0.5	27.47	72.5	1.2	0.57
MIN/URBAN	109.13	27.52	31.21	0.5	28.62	41.9	1.2	0.57
MIN/LSTP	53.14	31.2	32.5	0.3	29.54	63.4	1.2	0.57
NFI/ADMIN	120	28.4	33.71	0.5	27.52	62.7	1.2	0.57
PLSP/ADMIN	62.42	29.7	29.4	0.3	29.2	65.5	1.2	0.57
PLSH/ADMIN	75.61	31.45	35.23	0.2	28.76	42.3	1.2	0.57
AVERAGE READING	95.477	29.45	32.66	0.3	28.76	52.21	1.2	0.57

Where:
Vol: Volume of air/space (Length x Breadth x height)
Ta: Air temperature (°C) (average at 2 heights and multiple locations in the room)
Vel: Air velocity (m/s) (average at multiple locations in the room)
Tr: Meant Radiant temperature (°C) (average of room surfaces)
RH: Relative Humidity (%) (Average across multiple locations in the room)
Ar: Activity Rate (met)
Cl: Clothing Level (clo): (See Figure 1)

4.2. Graphical Representation of Environmental Variables

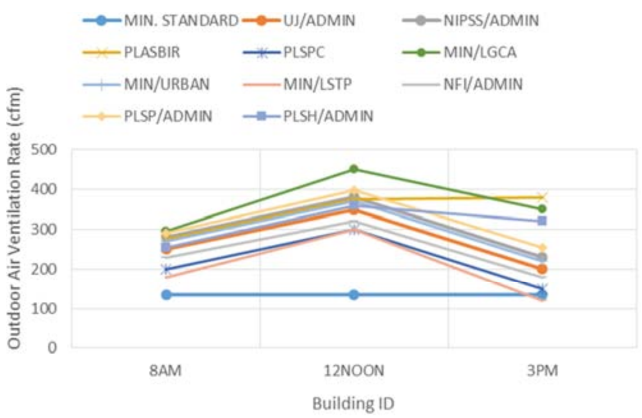

Figure 5. *Outdoor Air Ventilation Rate.*

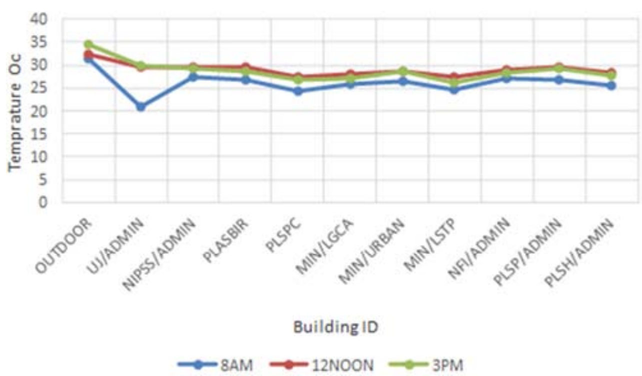

Figure 6. *Outdoor Air-Temperature Recordings.*

5. Analysis of Findings

5.1. Outdoor Air Ventilation Rate

The ASHRAE Standard 62.1-2013 recommends a minimum steady state of outdoor air ventilation rate of about 7.5 L/s/person or 15 cfm/person in other to achieve a comfortable indoor level of thermal comfort. This showed that measured outdoor ventilation rates were higher than minimum acceptable outdoor rate all through the working hours of the day. Outdoor air velocity was lowest at 8am with a reading of 180cfm. A 450cfm maximum outdoor air velocity was obtained at midday (See Figures 5 & 6). Indoor air velocity was mostly minimal. This is due to the fact that the predominant design-type for the offices studied adopted a double-loaded corridor office design principle leading to no or very little cross ventilation within the offices (See Figures 5 & 6).

5.2. Air-Temperature Recordings (Outdoor and Indoor)

Ambient air temperature (Ta) was taken at two (2) heights; 0.1m and 1.2m representing ankle and mid body levels respectively). The measurements in Offices were taken as close to the respondents' workstation as feasible. It was taken at resumption of work (8am), midday (12noon) and at close of work (3pm). The mean ambient temperature (Ta) in all buildings studied is 27.16°C (See Table 4). Temperatures taken at 8am were the lowest at between 20.8°C to 27.5°C for all the buildings examined. This increased to between 27.3°C to 29.7°C at midday and there was a slight increase at closing hour to between 26.2°C to 29.8°C (See Figure 6).

The mean temperature at 8am, midday and at closing is given as 25.6°C, 28.71°C and 28.18°C. The corresponding ambient outdoor temperature at 8am, midday and at closing was 31.1°C, 32.4°C and 34.5°C. These outdoor readings are higher than that of the interior. Lower indoor ambient temperature is explained by the mass content and U-Values of enveloping materials. A higher mass content produces a lower interior temperature [9].

5.3. Mean Radiant Temperature

The mean radiant temperature (Tr) represents the average radiant temperature readings across the various room surfaces (ceiling, floor, walls and furniture). This involves taking temperature of surface of floors, ceiling and furniture in a particular room and obtaining an average reading. This is done using an infra-red device so as to reduce local interference as a result of touch or surface uniqueness. The mean radiant temperature at 8am is 27.7°C, at midday the readings indicated 27.5°C and 28.02°C at the close of day for all offices studied. The mean radiant temperature for all surfaces cumulatively is 28.76°C (See figure 7). Therefore, the cumulative difference in surface temperature from 8am to 3pm is less than 1°C.

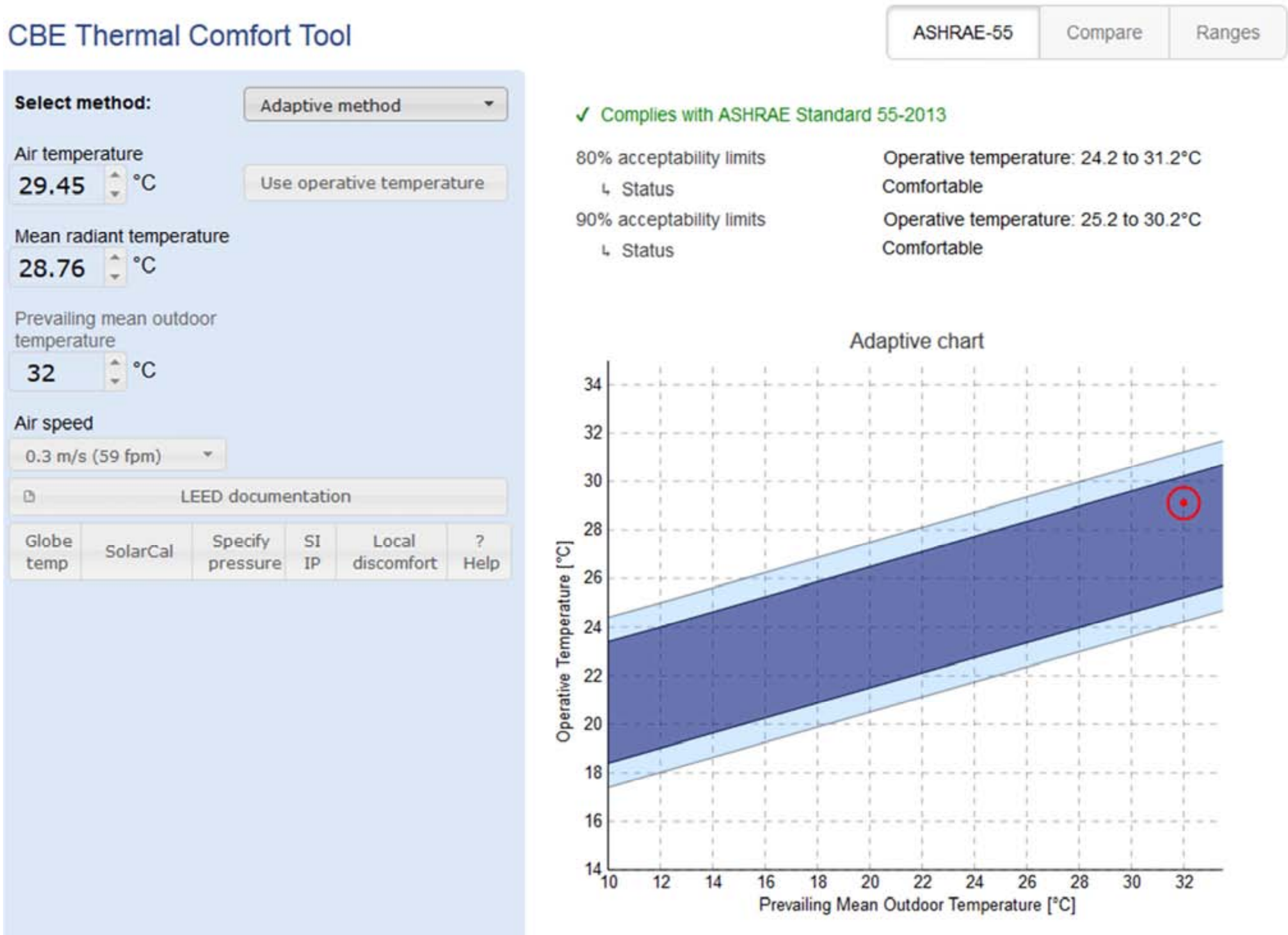

Figure 7. *Result of Adaptive Psychrometric Chart Simulation Based on ASHRAE 55.*

5.4. Adaptive Psychometric Chart

This tool revealed that with an average outdoor temperature of 32.0°C, indoor thermal comfort range for 80% and 90% acceptability corresponds to 24.2°C to 31.2°C and 25.2°C to 30.2°C respectively. It also established a neutral operative temperature of 29°C on the Adaptive Psychrometric Chart (See figure 7). The neutral operative temperature of 29°C is at slight variance with other research indicating a Neutral Temperature of 29.4°C [7] and 26.27°C [12]. However, this established neutral temperatures fall within 80% and 90% of acceptability thermal comfort range.

6. Conclusion and Recommendations

This research establishes the effectiveness of Psychometric Chart and the Neutral Temperature Analysis, using the ASHRAE 55 adaptive method techniques, as a viable instrument in thermal comfort studies under the earlier defined research conditions. This also indicates that most of the office buildings examined can operate fairly effectively without mechanical ventilation thereby providing savings in energy use and ensuring environmental sustainability. The recommendations are as follows:

1) Climate and weather conditions differ from place to

place even within the sub-saharan region. Weather components are a large determining factor in thermal studies. There will therefore be need for similar research to be carried out in regions with differing weather characteristics, garment and activity type (See Tables 1 & 2).

2) With the mean indoor air temperature in all buildings studied at 29.45°C, indoor thermal comfort range for 80% and 90% acceptability corresponds to 24.2°C to 31.2°C and 25.2°C to 30.2°C respectively. The research therefore recommends less reliance on energy consuming mechanical ventilation for the offices covered by this research, as the ambient temperature and Neutral Temperature falls within the established comfort range. This would translate into great savings in energy consumption and thus improved sustainability [14].
3) This research was conducted in the month of June 2018 in Jos, Nigeria. It coincides with rainy season in the sub-Saharan region. There would be the need for similar research to be conducted in other seasons and other location within this geographic zone, thereby exposing the research framework and associate tools to further use and thus granting validity to these tools. This would enable a complete and comprehensive picture of energy performance assessment for administrative buildings in sub-Saharan region of Africa using the Psychrometric Chart.

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