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Investigation into Human Thermal Comfortability under used Tyre-Roof

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Abstract: *This research work investigated how used tyre can be employed for roofing houses, and evaluated the thermal comfort of the house. A house with dimensions 3 x 3 x 6 (m) was constructed with concrete blocks and roofed with sliced worn tyres. It was partitioned into two and one-half (1.5 x 3 x 6 m) was evaluated for human comfort. Four radiant temperatures were measured at the inside and outside East and West walls of the building with thermocouples. The air velocity and relative humidity were respectively measured with anemometer and hygrometer. All the measuring instruments were connected to a data logger pre-set for hourly readings.Fanger's Predicted Mean Vote model was used to evaluate the human thermal comfortability. The results showed that air speed was in the range of 0 – 2.5 ms^{-1}, mean radiant temperature was in the range of 0 – 34.35^{o}C, relative humidity was in the range of 70.4% - 100% and air temperature was in the range of 31.36^{o}C, with -2.50 to +2.51 Predicted Mean Vote (cold to warm scale). A linear average of 0.72 Predicted Mean Vote was obtained. The results of the work are in close range with Fanger Comfort Model and ISO 7730:2005. It was concluded that houses roofed with used tyres are comfortable for human beings.*

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I. Introduction

The increasing industrialization and the attendant usage of automobile cars and trucks globally have led to a steep rise in the number of waste tyres generated around the world. This waste tyres present complex disposal problem as they are non-biodegradable. The negative environmental impact caused by disposal of used automobile tyre in landfills or by incineration is of great concern. This challenge can therefore be reduced or mitigated by turning used tyres into useful purpose which include roofing houses, shoe-making and heating purposes[1].

The utilization of solid wastes for useful purposes has become a global phenomenon. Used tyres represent a major part of such wastes. The disposal of solid tyre wastes from human activity is a growing environmental problem for the modern society, especially in developing countries. Car tyres, a major polymer solid waste, is non-biodegradable because of its complex mixture of very different materials, which include several rubbers, carbon black, steel cord and other organic and inorganic components[2]. Williams[3] noted that the production of waste tyres throughout the world is estimated to be one billion tons per year. One common way of disposal of car tyres is land filling, but land filling of used tyres needs a large space because the volume of tyres cannot be compacted[2]. Satope[4], reported that about 33.5 million tyres were rethreaded and an estimated 10 million were reused each year as second-hand tyres. It was estimated that 7% of the discarded tyres are currently being recycled into new products and 11 per cent are converted to energy. Nearly 78% are being landfilled, stockpiled, or illegally dumped, with the remainder being exported to developing countries for second hand use. Nigeria is not left out in its share of the global menace of poor solid waste management, especially discarded automobile tyres. The country is littered with a lot of them from the vastly imported used tyres[1, 4].

The need for affordable, durable and fashionable roofing material is of great importance to homeowners. These characteristics are not only enough for the selection of the material; the human comforts needed to be considered and known to make it adaptable for man. The aim of this work is to adapt used tyres for roofing purposesand evaluate it for human thermal comfortability.

II. Material And Methods

Materials

The materials used for the construction of the house are concrete blocks, sand, cement, wood, nails, used tyre, flash band and water. The used tyres were sourced locally from individual and roadside vulcanizers after which the sidewall of the tyres were cut out with the use of hand cutting machine and cutlass. The equipment used for recording parameters needed in evaluating thermal comfort are FG275 relative humidity and temperature sensor which measured the relative humidity and air temperature, temperature sensors which measured radiant temperature, anemometer which measured the air velocity, data logger which recorded the values of the parameters every minute, solar panel which powered the data logger, temperature sensors, chair, table and clothes.

Method
Experimental set up

A house of dimension of 3 x 3 x 3.16 (m) was built and roofed with used tyres. It was constructed at the back of Engineering Central Workshop at the Federal University of Technology, Akure on Latitude 7.25^o. It was partitioned at the middle into two; one side was used for storage of grains while the thermal comfort of the other side was evaluated. The dimension of the structure used for evaluation of thermal comfort was 1.50 x 3 x 3 (m) room built with concrete blocks of 0.15 m thickness with a door of 0.87 x 2.14 (m) at one end, and window of 1.04 x 1.2 (m) placed at the middle of the side wall. Asbestos ceiling was used to cover the inside of the roof. The sliced tyres were nailed to the roof in form of roofing shingles. Flash band (an adhesive material made of bitumen) was used on the adjoining part of the tyres on the roof to prevent leakages. The roof type was gable roof with planks in between to hold the shingles firmly. Plates 1 to 3 are pictures of the tyre roof and built house.

Plate1: The Constructed Tyre Roof

Plate 2: Tyre Roof with Flash Band Adhesive to Prevent Leakages

Plate 3: The house roofed with used tyres

Four temperature sensors were used to measure the radiant temperatures at the East and West sides of the building. One sensor was respectively placed on the outer east side and the outer west side of the building, while one sensor each was placed inside the building at the east and west sides directly opposite the external sensors.

Air velocity was measured at two points with anemometers. One was used to measure air velocity at the window level (1.2 m from ground level), while the other anemometer was placed 0.25 m from ground level.

Thermal anemometer and hygrometer were attached to the data logger at 0.7 m from ground level for 8 days. Two solar panels of 12 V each were connected in parallel outside the building to provide power that would charge the battery of the data logger. The recording started at 1700 hours on 30th October 2018. Chair and office wears were placed in the room throughout the period of the experiment. The windows and door were opened at 0800 hours and closed at 1700 hours throughout the period of the experiment.The experimental set up is as depicted in Plate 4.

Plate 4: Experimental Set Up

Evaluation for Thermal Comfortability of the Structure

The thermal comfort was evaluated using Fanger's Predicted Mean Vote (PMV) model as given in equation (1). The parameters used to calculate the PMV are the air temperature, the mean radiant temperature, the air velocity, the relative humidity and two subjective parameters of human metabolism rate and the clothing insulation of the person[5].

$$\mathrm{PMV} = (0.303e^{-0.036M} + 0.028)[(M - W) - H - E_c - C_{res} - E_{res})] \qquad (1)$$

where,

PMV is the Predicted Mean Vote
C_{res} is the Respiratory convective heat exchange [W/m^2]
W is the Effective mechanical power
E_c is the Evaporative heat exchange at the skin [W/m^2]
E_{res} is the Respiratory evaporative heat exchange [W/m^2]
M is the Metabolic rate [W/m^2]
H is the Dry Heat Loss [W/m^2]

The thermal balance of the body for comfort is expressed in simple terms by equations (2) – (10)

$$M - W = H + C_{res} + E_{res} + E_c \qquad (2)$$

$$E_c = 3.05 * 10^{-3}[5733 - 6.99(M - W - P_a)] + 0.42(M - W - 58.15) \qquad (3)$$

$$C_{res} = 0.0014M(34 - t_a) \qquad (4)$$

$$E_{res} = 1.72 * 10^{-5}M(5867 - P_a) \qquad (5)$$

$$\mathrm{H} = 3.96 * 10^{-8}f_{cl}[(t_{cl} + 273)^4 - (t_f + 273)^4] + f_{cl}h_c(t_{cl} - t_a) \qquad (6)$$

$$t_{cl} = t_{sk} - 3.96 * 10^{-8}I_{cl}f_{cl}[(t_{cl} + 273)^4 - (t_f + 273)^4] - I_{cl}f_{cl}h_c(t_{cl} - t_a) \qquad (7)$$

$$t_{sk} = 35.7 - 0.028(M - W) \qquad (8)$$

$$h_c = \begin{cases} 2.38|t_{cl} - t_a|^{0.25} & for\ \ 2.38|t_{cl} - t_a|^{0.25} > 12.1\sqrt{v_a} \\ 12.1\sqrt{v_a} & for\ \ 2.38|t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_a} \end{cases} \qquad (9)$$

$$f_{cl} = \begin{cases} 1.00 + 1.29I_{cl} & for\ \ I_{cl} \leq 0.078m^2KW^{-1} \\ 1.05 + 0.645I_{cl} & for\ \ I_{cl} > 0.078m^2KW^{-1} \end{cases} \qquad (10)$$

$f_{cl}$is the clothing area factor. The ratio of the surface area of the clothed body to the surface area of the naked body.
$h_c$is the convective heat transfer coefficient. [W/m^2/°C]
t_{cl} is the clothing temperature [^{o}C]
$t_a$is the Air temperature [^{o}C]
$t_r$is the Mean Radiant Temperature [^{o}C]
t_{sk} is the skin temperature [^{o}C]
I_{cl} is the clothing insulation [m^{2}KW^{-1}]
$v_a$is the Air Velocity [ms^{-1}]
p_a is the Humidity [Pa]

In this experiment, $I_{cl}$for the cloth used during the time when the door and windows were opened (0800 – 1700 hrs.) was 0.10 m^{2}KW^{-1}. I_{cl} at the closing of the door was taken to be 0.11 m^{2}KW^{-1}

Predicted Mean Vote

The Predicted Mean Vote is an index that predicts the mean value of the votes of a large group of persons on the 7-point thermal sensation scale (Table 1), based on the heat balance of the human body. The thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate temperate environment, the human thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance (ISO 7730, 2005).

Table 1: Seven Point Thermal Sensation Scale

+3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The thirty-minute and hourly average of the parameter were calculated and inputted into Spreadsheet for the Calculation of Thermal Indices. The software calculates clothing temperature based on iterative process, Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD). The various heat fluxes were calculated using the hourly average of parameters measured. The software was designed using Microsoft Excel. Plate 5 shows the graphic interface of the software used.

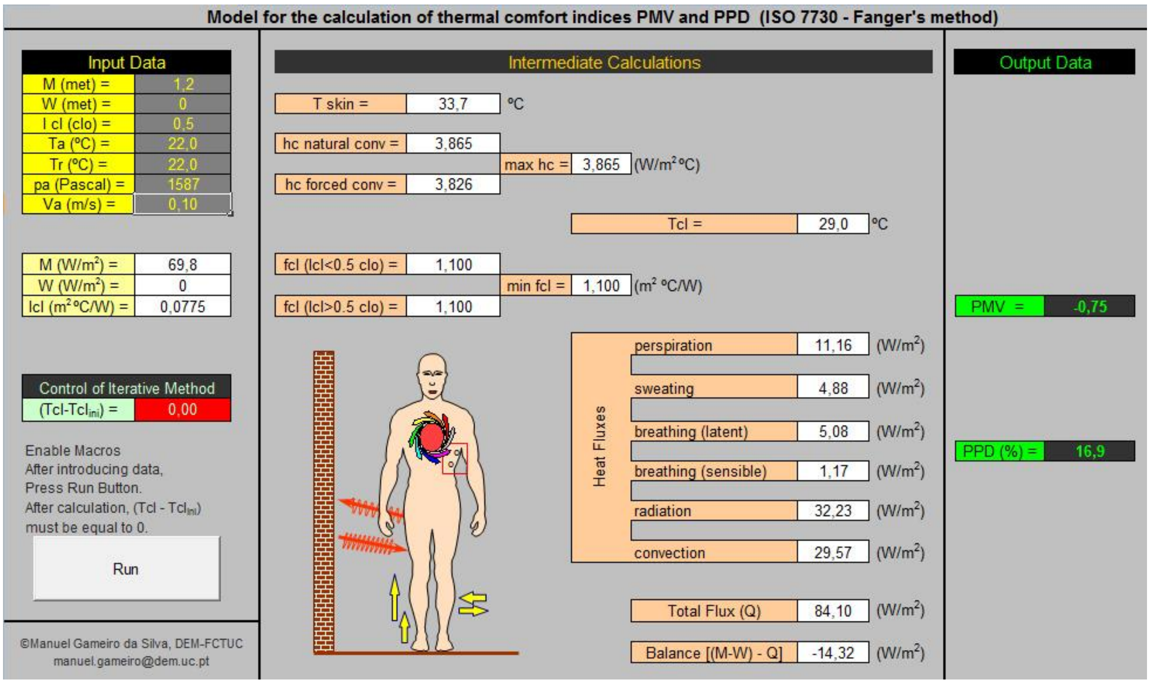

Plate 5: Graphic Interface of Software Used

III. Result and Discussions

Air Temperature

The measured air temperature for every hour is graphically presented in Figure 1. From the graph, it can be seen that on the first day, the air temperature decreased from 30.21°C to 25.43°C at 0800 on the second day although the door and windows were closed. Relative humidity at this time also increased from 74.02% to 99.14%. At 0900 hours, there were increase in air temperature and relative humidity. This could be due to opening of the door and windows, which also led to increase in air speed during this period. It was discovered that air temperature was at its peak between the hours of 1500-1600 hours for five (5) consecutive days except for the seventh day that it occurred at 1900. There were also peak period at 1600 hours on sixth and eighth days. Also, at the closing of the door and windows at 1700, reduction in air temperature was observed. The least air temperature was 22.78°C at 1800 on the fifth day. The linear average of air temperature was 26.53°C.

The result agrees with the general statement that most people will feel comfortable at room temperature, varying greatly between individuals and depending on factors such as activity level, clothing, humidity and location[10].

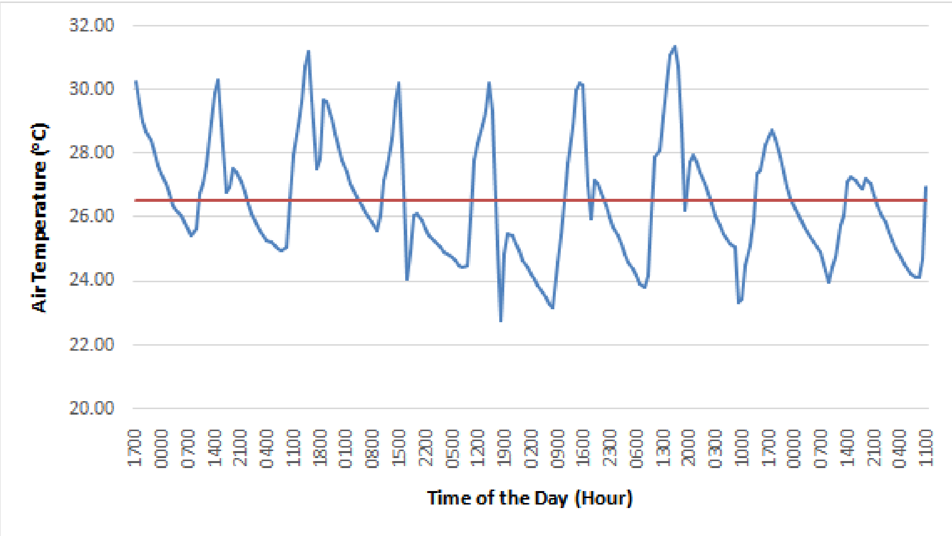

Figure 1: Graph of Air Temperature against Time

Relative Humidity

Relative humidity increased gradually from the beginning of the experiment and was at the highest at 0800 with a value of 99.14%. The value then decreased until 1600 after which it started increasing at 1700 and got to maximum on the third day at 0900. This trend was repeated throughout the experiment in which relative humidity was highest between 0800 and 0900 and lowest between 1600 and 1700. The highest relative humidity recorded was 100% while the lowest was 70.4%. The linear average of the relative humidity was 91.11%. This is shown in Figure 2.

This could be as a result of the fact that the building was closed at night, and the air velocity in the room was low. The relative humidity of the space was high. But the building was opened during the day and there was cross ventilation which led to the redistribution of air, and hence, the fall in the relative humidity.

The lower range of the result of 70.4% agrees with work of Simion *et. al.*[11], that relative humidity in the range of 30% - 70% is suitable for thermal comfort, but will prevent sweat evaporation and cause sultry weather that make occupants feel discomfort when greater than 70%.

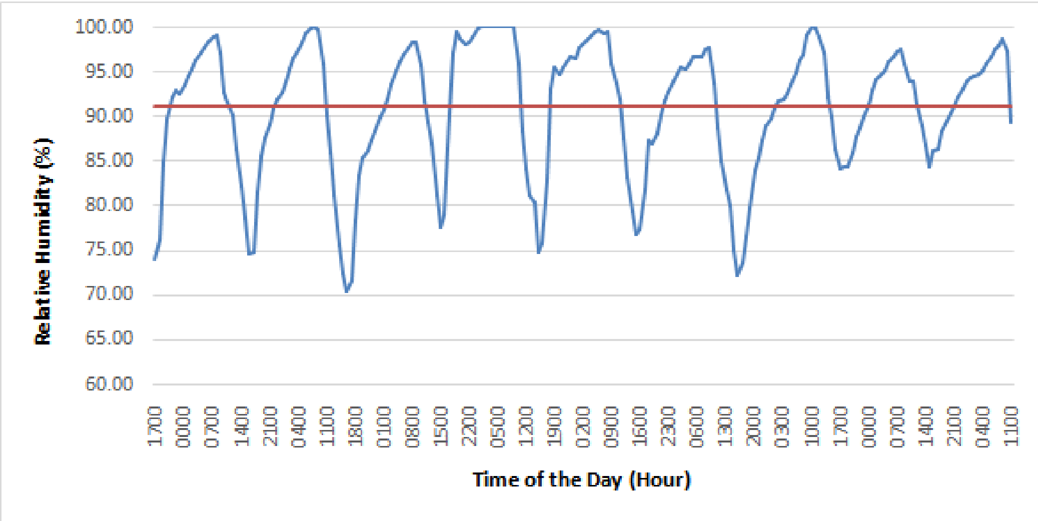

Figure 2: Graph of Relative Humidity against Time

Mean Radiant Temperature

The mean radiant temperature decreased from 32.71^{o}C to 27.55^{o}C first day to the beginning of the second day at 1700 to 0800 hours in which the door and windows were closed. It was observed that when the door was open at 0800 hours, its value increased steadily and reached its peak at 1500 hours with a value of 32.56^{o}C and dropped to 26.93^{o}C on the third day at 0800 hours. On the same day, the peak value was reached at 1900. On the fourth day, temperature was lowest at 0900 hours with 27.81^{0}C and highest at 1500 hours with 32.2^{o}C. The fifth day was not different as the radiant temperature had the lowest value at 0800 hours and highest value at 1600 hours. Same thing occurred on sixth day at 0800 hours with a value of 24.92^{o}C and at 1600 hours with a value of 32.4^{o}C but the seventh day was a different case with the highest value recorded at 1700. Least radiant temperature value for the eighth day occurred at 0900 hours with a value of 26.52^{o}C and highest value of 32.29^{o}C was recorded at 1800 hours. Same trend was observed on the ninth day at 0900 hours having least value of 26.48^{o}C and highest value of 30.91 ^{o}C at 1800 hours. The highest radiant temperature recorded during sun set shows that the heat trapped during sunrise was radiated into the house. The linear average of the mean radiant temperature was 29.13^{o}C In the course of this research work, the least air temperature recorded in the morning was 23.3^{o}C and the lowest mean radiant temperature was 24.9^{o}C. This is in close agreement with the result of Kalu*et al.*[12], in which they compared inner temperature of mud block house with thatched roof and mud block house with corrugated sheet; they recorded lowest inner temperature of 20^{o}C for thatched roof and 26^{o}C for corrugated sheet in the morning. Figure 3 depicts the graph of mean radiant temperature against time of the day.

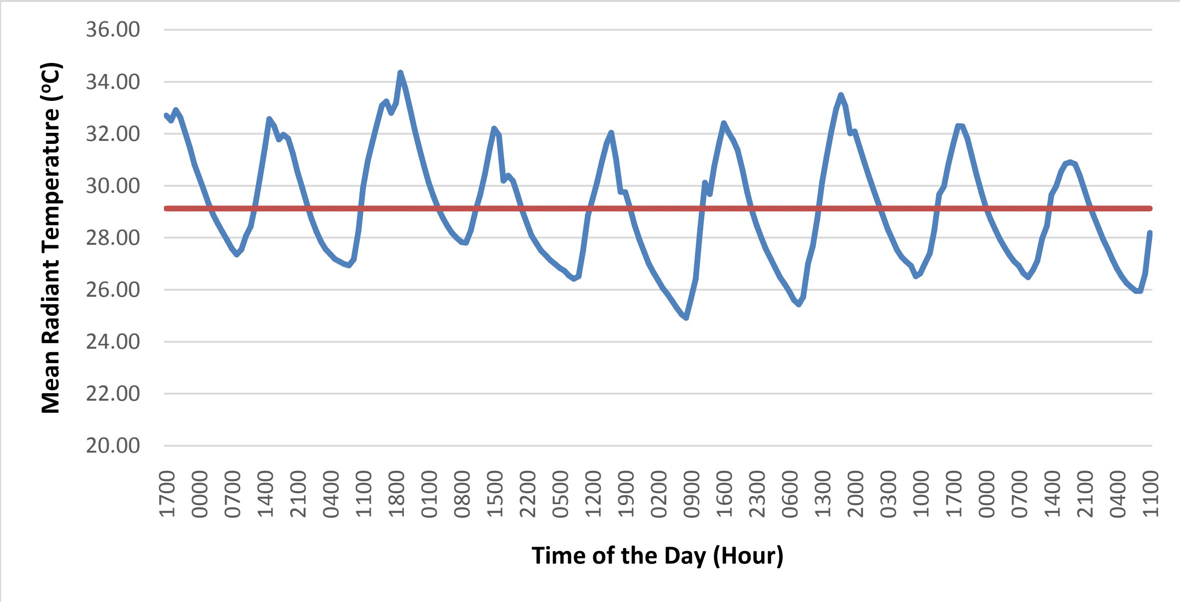

Figure 3: Graph of Mean Radiant temperature against Time

3.4 Mean Air Velocity

It was observed that when the doors and windows were closed between 1700 – 0800 hours of the following day, air velocity was always zero. On the second day, maximum air speed was 1.18 ms^{-1} at 1000 hours, on the third day maximum air velocity was 2.05 ms^{-1} at 1200 hours, on the fourth day maximum air velocity was 2.39 ms^{-1} at 1600 hours and on the fifth day maximum air velocity was 2.49 ms^{-1} at 1700 hours. On the sixth day maximum air velocity recorded was 1.46 ms^{-1} at 1500 hours, on the seventh day maximum air velocity was 1.36 ms^{-1} at 1300 hours, on the eighth day it was 0.95 ms^{-1} at 1600 hours, on the ninth day maximum value was 2.34 ms^{-1} at 1500 hours. These are depicted in Figure 4.

On the average (1.78 m/s), the air velocity in the room was comfortable, and agreed with the work of Roghanchi*et al.*[13], that beyond 2 m/s, increasing air velocity would negatively affect thermal comfort.

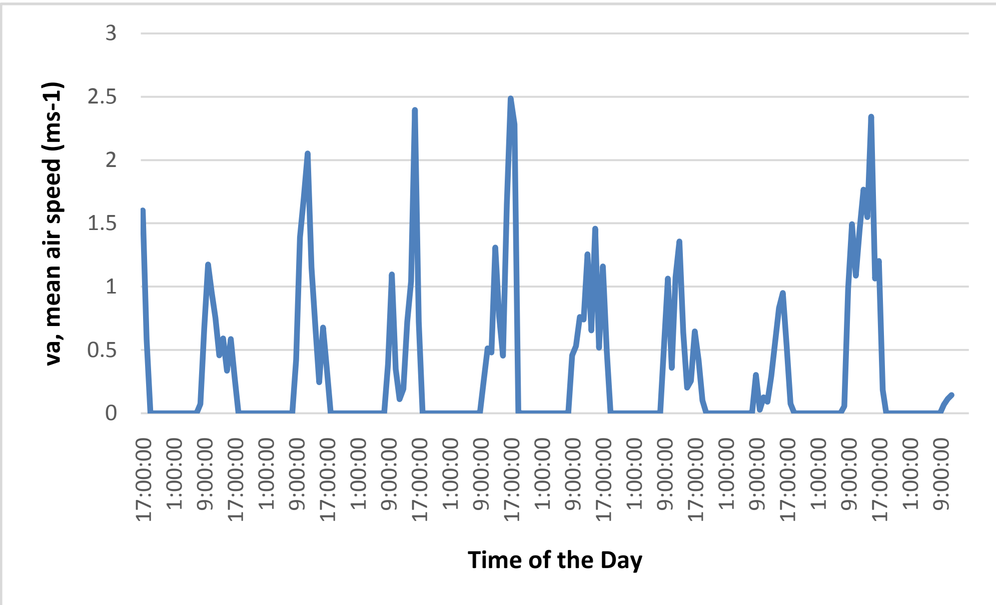

Figure 4: Graph of Mean Air Velocity against Time

Predicted Mean Vote

The Predicted Mean Vote (PMV) results are depicted in Figure 5.

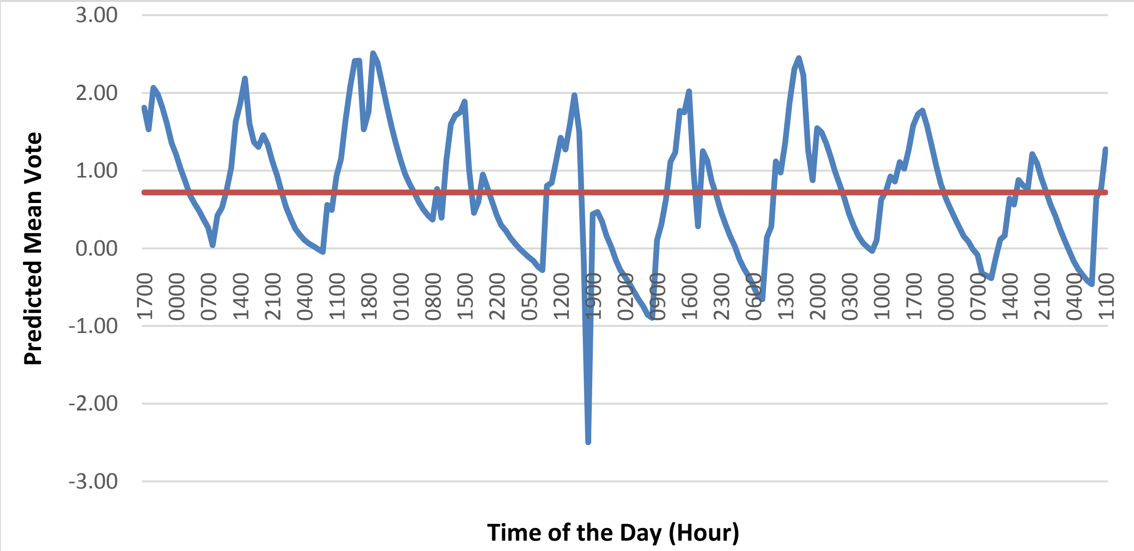

Figure 5: Graph of Predicted Mean Vote against Time

Result obtained gave a comfort range of -2.5 to +2.51 (cold to warm scale), with a linear average of 0.72. As shown in Figure 5, the tyre roofed house was most comfortable at 0500-0900 hours on the second day, 0100-0800 hours and 1000 hours on the third day, 0600-0800, 1000, 1700 and 2300 hours on the fourth day. Also, at 0000-0800,1700 and 2100-2359 hours on the fifth day, 0000-0400, 0900-1000, 18:00 and 2300 hours on the sixth day, 0000-0600, 0900-1000, 1800 and 2300 hours on the seventh day, 0000-0600 and 0900-1000 hours on the eighth day, 0300-0900 hours on the ninth day. Thus tyre house was most comfortable at night and very early in the morning. The results of this research work are in close range with Fanger[14] Comfort Model that suggested a Predicted Mean Vote within the range 0.5 to -0.5 within a scale of -3 to +3 thermal sensation scale.

IV. Conclusion

A house of 3 x 3 x 6 (m) was built and roofed with used tyre. It was partitioned into two portions. The thermal comfort of a side having a dimension of 1.5 x 3 x 6 (m) was evaluated. Air velocity was in the range of 0 – 2.5 ms^{-1}, mean radiant temperature was in the range of 0 – 34.35°C, relative humidity was in the range of 70.4% - 100%, air temperature was in the range of 0 – 31.36°C and Predicted Mean Vote was in the range of -2.50 to +2.51. A linear average of 0.72 Predicted Mean Vote was obtained. It was observed that air velocity was in the range of 0 – 2.5 ms^{-1}, mean radiant temperature was within the range of 0 – 34.35°C, relative humidity was in the range of 70.4% - 100% and air temperature was in the range of 0 – 31.36°C. These values are in close range of Fanger condition for evaluation of thermal comfort, that air velocity should be in the range of 0 - 1 ms^{-1}, mean radiant temperature should be in the range of 10°C - 40°C, relative humidity should be in the range of 0 – 50% and temperature should be in the range of 10°C - 30°C. However, the difference in the value of air velocity and humidity is because the humidity and air velocity in an open environment cannot be controlled except for a closed area. It can be concluded that tyre-roofed house is habitable for human being since thermal sensation scale is within the range of cold to warm.

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