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Evaluation of Indoor Temperature through Roof and Wall Temperatures - An Experimental Study in Hot and Humid Climate

M.Ponni, Dr.R.Baskar
Research Scholar, Associate professor, Department of Civil and Structural Engineering, Annamalai University, Chidambaram - 608001, Tamil Nadu, India.

Abstract* - The architects, technologists and builders strive to explore energy efficient buildings. The energy efficiency of a building depends on the capability of providing a practicable indoor temperature. The indoor temperature has been predicted by many studies based on the outdoor maximum and minimum temperatures. Few studies consider the weight per unit area of the wall or the weight per unit area of the whole structure. These predictions do not include the material properties which are involved in the construction. The prediction is a common method for all kinds of roof and walls. For different types of roof and walls the prediction does not suit. For a particular region and climate the indoor temperature prediction is the same for all type of buildings. The building envelope possesses the major responsibility in the determination of the indoor temperature of any type of building. Hence the main aim of this study is to find out a method to calculate the indoor temperature of a building through the temperatures of the building elements. For this purpose four experimental modules were constructed with different roofs having different thermal mass and the walls having same thermal mass. This study proposes an equation to calculate the indoor temperature on the basis of the heat transmitted into the module. The measurement of the inside temperature of the walls and roof is taken into account. The result has been compared with other indoor temperature studies. This study has developed a new method of calculating the Indoor Ambient Temperature.

***KEY WORDS*-Indoor Temperature, Thermal mass, IAT Calculated, IAT Measured, Thermal retention.**

I. INTRODUCTION

The Sun is the donor of thermal radiations to the world. The rain is the natural source of water supplier to the earth. The fog, mist and snow are the natural sources of coolers of the earth. Heat and chillness are received without any cost, without our wills and fancies and without any gradation of the society, or nationality. The sun is the primary heat provider to the earth. All the creatures of the world, plants and the human shelters of any type receive heat from the sun impartially. The buildings are the acceptors of heat and chillness and serves as the secondary thermal source. The buildings guard the people from excessive thermal reception or cold reception. The roof and the walls are the building elements which receives the heat or cold. The receiver responds to the outside thermal variations. The behaviour depends on the material with which it is built. Convection takes place with respect to the fluids, conduction and radiation brings out changes in the inside environment of the house with respect to materials used to build. Naturally received energy affects the inside environment of the building according to the region. If the environment outside the building is hot, the building temperature also increases and if it is cold, the building temperature also decreases. If the responses of the building proportionate the outside environment then the building is a poor thermal performer. If the building does not follow the outside thermal variations means the building is a good thermal performer. Everyone wants to have a good thermal performance building but there is a lack of awareness. The electrical energy is utilised to bring a good indoor thermal environment by heating or cooling the indoor, for which the consumer has to spend a large amount. To reduce the energy use, the new technologies have to be applied in construction and maintenance. India is in energy transition. The energy consumption in Indian residential buildings is the highest among all the Asia Pacific Partnership (APP) countries [1] and is increasing at a phenomenal rate. It is well known now that, uncomfortable buildings drive the users towards high energy solutions. A building is said to be energy efficient when it possess a good indoor environment within the comfort level. Roof is the element which directly receives the most of the solar radiation in different angles than the other elements of the building. Inadequate roof insulation results in heat transfer from the roof to indoor. Insulation can be applied between roof rafters or on the rafters. For concrete roofs, outer insulation over the concrete can be applied [2]. Walls are essential in buildings in order to separate spaces into areas of convenient size and also to keep out dust and rain from inside. The most common materials used for walls are stone concrete burnt clay and wood. All the building walls are multi-layered and non- homogeneous and could be non- isotropic. One of the main objectives in building design is reducing the direct heat gain by radiation through openings and reduction of internal surface temperature. In order to achieve this objective, the building should be designed with protected openings and walls [3]. The main factor in choosing wall material regarding energy consumption is the thermal mass of the wall. For different climate conditions, different types of walls are needed. Thermal performance of a wall can

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provide better performance by the addition of air cavities [4]. A building material with high thermal mass and adequate thickness delays the effect of temperature changes from the outside wall on the wall's interior [5]. Construction materials such as concrete, bricks, cement blocks, stones and other solid masonry materials are considered as having high thermal mass. However, high thermal mass materials are considered very effective against rapid heat transfer, which is mainly due to their properties to absorb heat from solar radiation at a much slower rate than lightweight materials with a low thermal mass. Lightweight materials of timber, asbestos sheets, Galvanized sheets and the various building wall materials absorb heat quickly and conversely cool down quickly. A composite construction of roof and wall may be an ideal solution with respect to the local climate conditions. The buildings with different thermal mass levels were monitored under different ventilation and shading conditions during the summer of 1993 in Pala, South California in USA. That study evaluated the effect of mass in lowering the daytime indoor temperatures. It found that night ventilation was very effective in lowering the indoor temperature for a high mass building below the outdoor maximum. It also reported that on an extremely hot day with outdoor maximum of 38 ◦C (100 ◦F), the indoor maximum temperature of the high mass building was only 24.5 ◦C (76 ◦F), which is well within the comfort zone for the humidity level of California [6]. In 1964, six small experimental buildings were built on the grounds of the Cairo Building Research Centre, using different materials. They were used to evaluate cost, local availability, and thermal comfort. Two of these six models represented the extremes. It was identified that the mud-brick had a thermal resistance more than 13 times greater than the prefabricated concrete wall in Egypt [7]. In Egypt mud bricks were used for the rural mass housing. It was observed that even when the local climate was an extreme, the right application of building materials and air movement were able to modify the comfort conditions passively [8]. Several theoretical and experimental methods have been developed to predict the characteristics of internal temperatures. For high mass materials the indoor temperature is closely related to the thickness of the walls and internal partitions. Six test buildings were investigated to test the effect of wall mass on summer space cooling. The buildings were located at the US National Bureau of Standards in Gaithersburg, MD. It was noticed that for indoor temperature set at 24◦C, high mass buildings consumed less cooling energy than similar lightweight buildings that have similar thermal resistance [9]. It was found that thermal mass was more effective when positioned on the interior side of the insulation also studied the effect of thermal mass on night-temperature setback savings and noticed a 40% reduction on sensible heating and cooling loads [10]. Sunaga Tested the role of thermal mass on various passive systems and noted the benefits of adobe buildings [11]. On how best to use thermal mass in residential and small commercial buildings, for south western USA, specific recommendations were presented [12].

II. THE STUDIES OF INDOOR TEMPERATURES AND THE EQUATIONS DEVELOPED

The formula developed by Givoni for the prediction of indoor temperatures for the same type of thermal was as follows:

$$T_{max\text{-}in} = T_{max\text{-}out} - 0.31(T_{max\text{-}out} - T_{min\text{-}out}) + 1.6 \qquad (1)$$

Where Tmax-in is the indoor maximum temperature; Tmax-out is the outdoor maximum temperature; and Tmin-out is the outdoor minimum temperature. The formula "refers to continuously cross-ventilated buildings, where the indoor maximum temperature tends to follow closely the outdoor maximum" [13]. The formula developed by Givoni for the indoor maximum temperature on a particular day for high thermal mass buildings was as follows For high-mass closed buildings, white coloured and shaded, with common infiltration, the formula by Givoni for the indoor maximum temperature on a particular day was as follows:

$$T_{max} = GT_{avg} + 4 + 0.5(T_{avg} - GT_{avg}) \qquad (2)$$

Where T_{max} is the indoor maximum temperature; GT_{avg} the average outdoor temperature of a given period (e.g. 2 weeks); and $T_{avg}$is the average temperature for the given day.

D.M.Ogoli conducted experiments on closed buildings in Nairobi, Kenya, which is an equatorial high altitude region. Precisely, Nairobi is on latitude 1.3˚S with an altitude of 1798m (5900 ft) above sea level. Thermal mass affects the indoor temperatures in buildings. The author developed a formula on the basis of Givoni to predict indoor maximum temperatures for closed high mass buildings at equatorial high altitudes. It is as follows:

$$T_{max\text{-}in} = T_{max\text{-}out} - 0.488(T_{max\text{-}out} - T_{min\text{-}out}) + 2.44 \qquad (3)$$

Where $T_{max\text{-}in}$ is the indoor maximum temperature; $T_{max\text{-}out}$ the outdoor maximum temperature; and $T_{min\text{-}out}$ is the outdoor minimum temperature.

The equation developed by Givoni was used to predict for the same type of thermal mass, used by D M Ogoli in his study and, he found that the patterns look similar, and the differences between the predicted and the observed data were consistently about 2–3 ˚C (4–6 ˚F).

III. EMPIRICAL FORMULA DEVELOPED FOR INDOOR TEMPERATURE IN THIS STUDY

To understand the process of heat conduction, convection and radiation occurring in a building, consider a wall having one surface exposed to solar radiation. The rate of heat transmission through building wall depends on the material density, the size and arrangement of its

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particles or fibres, moisture content, outdoor temperature, and surface characteristics. Of the total solar radiation incident on the outer surface of the wall, a part of it is reflected to the environment. The remaining part is absorbed by the wall and converted into heat energy. The remaining part is conducted into the wall and exists there by raising the wall temperature. The thermal retention by the walls and roof leads to the radiation of heat into the indoor of the building during the hot sunny days. There begins to raise a temperature difference between the outer and inner wall surfaces. The inner surface transfers heat to the air inside the room by convection and radiation and thereby raises its temperature. For this analysis, a steady state heat transfer is assumed to occur.

IV. CONVECTION

The rate of heat transfer (Q_{cv}) by convection from a surface of area (A), can be written as

$Q_{cv} = h\,A\,(T_s - T_f)$ (4)

where,

h = heat transfer coefficient (W/m2-K)

T_s = temperature of the surface

T_f = temperature of the fluid

The numerical value of the heat transfer coefficient depends on the nature of heat flow, velocity of the fluid, physical properties of the fluid, and the surface orientation.

V. RADIATION

Buildings external surfaces such as walls and roofs are always exposed to the atmosphere and therefore subject to a different heat exchange [14]. This is the electro-magnetic heat transfer from warmer surfaces to cooler surfaces. The roof exposed to solar radiation, absorbs or reflects the thermal energy. The roof will also emit long-wave radiation heat, back to the atmosphere. So the radiation exchange (Q_r) between the exposed parts of the building and the atmosphere is an important factor. The heat exchange between the building surface and the sky is given by

$$Q_r = A\varepsilon\sigma\,(T_s^4 - T_{sky}^4) \qquad (5)$$

Where

A = area of the building exposed surface (m^2), ε = emissivity of the building exposed surface, σ = Stefan-Boltzmann constant ($5.67 * 10^{-8}$ W/m^2K^4) T_s = temperature of the building exposed surface (K), T_{sky} = sky temperature (K). T_{sky} represents the temperature of an equivalent atmosphere. It considers the fact that the atmosphere is not at a uniform temperature, and that

VI. CONDUCTION

Energy transfer via conduction can take place in solids, liquids and gases. This process happens when there is a transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles [15]. Or simply, it is the process of heat transfer from one part of a body at a higher temperature to another (or between bodies in direct contact) at a lower temperature [16]. Area of the walls (A), thickness of wall is (L) and the thermal conductivity (k) of the walls is equal for all the considered modules. Considering the heat transfer through building elements, the basic equation of heat conduction is given by:

$$Q_{cd} = k\,A\,(T_o - T_i)/L \qquad (6)$$

Q_{cd} = Quantity of heat flow/ Heat flux due to conduction (w), k= thermal conductivity of the material (w/m/K), A= Surface area (m^2), L= Thickness of the material (m), T_o = temperature of the outside hot surface of the roof or wall, T_i = temperature of the inside surface of the wall or roof. The quantity of heat transmitted inside the building is equal to the heat received by the indoor air. As the roof and walls behave as the secondary sources of heat, the heat conducted to the inner surface of the walls and roof is retained by the elements as long as the solar radiation is received. Hence the temperature of the indoor depends on the temperature of the four walls and the roof. The quantity of heat inside the module is directly proportional to the thermal emissions given out to the inner space by the walls and roof. For a particular roof and wall, the surface area (A), thickness (L) and thermal conductivity (k) are considered to be equal. Hence the quantity of heat conducted depends on the outside and inside temperatures of the walls and roof.

Hence, $Q_{cd} \propto (T_o - T_i)$

$Q_{cd} \propto \Delta T$

$\Delta T = (T_o - T_i)$

ΔT = thermal retention of the roof and walls or the temperature difference between outer and inner surface of the walls. The radiations from the inner side of the walls and roof combine to form the indoor temperature of a building. The inside temperature of the building is proportional to the inside temperature of the roof and walls. Therefore the indoor temperature of the module may be written as

$T_{indoor} \propto (T_{inw} + T_{isw} + T_{iew} + T_{iww} + T_{iroof})$

$$T_{indoor} = C\,(T_{inw} + T_{isw} + T_{iew} + T_{iww} + T_{iroof}) \qquad (7)$$

C is a constant, Where C= 0.196

The above equation (4) calculates the indoor ambient temperature of the room.

T_{inw} - The inside temperature of the north wall

T_{isw} - The inside temperature of the south wall

T_{iew} - The inside temperatures of the east wall

T_{iww} -The inside temperature of the west wall

T_{iroof} - The inside temperature of the roof

VII. RESEARCH DESCRIPTION

This is a study carried out to establish a formula for the calculation of indoor temperatures in closed buildings of same thermal mass. It was conducted in Tropical climate region of Chidambaram, Tamil Nadu, in India. This

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region is the hottest during the months of April to June and coldest during the months of December to January. Chidambaram receives an average annual precipitation of 10 mm (0.39 in), which is lesser than the state average of 1,008 mm (39.7 in). The South west monsoon, with an onset in June and lasting up to August, brings scanty rainfall. Bulk of the rainfall is received during the North East monsoon in the months of October, November and December. The average number of rainy days ranges from 35-40 every year. The elevation above the sea level is 3m. The experiments were carried out exactly in Chidambaram, Tamil Nadu, 11˚24´ N latitude and longitude 79˚44´ E. Previous research efforts have investigated the indoor temperatures using outdoor temperatures. An attempt has been made to calculate the Indoor Ambient Temperature using the inside temperature of walls and roof. Four modules have been constructed for this study. All the modules have same floor, wall area and orientation. The size of the module is 3m x 3m x 3m. The galvanized sheets used in the modules have the same thickness of 0.21 mm. The brick walls plastered on both sides possess a thickness of 230 mm. Two angles are used as purlins in the Module. The slope of the roof is maintained to be 2˚. Walls of the modules were white washed. The floor was cement mortared. Walls of the four modules have the same thermal mass and the other two modules light mass walls and roof. The modules were given a three letter code to describe each of the roofing system:

- Single Decker (SID)
- Poly urethane Decker (PUD)
- Double decker (DOD)
- Reinforced concrete (RCC)

The construction data of the modules used in this study are tabulated in Table 1.

Sl. No	Description	Dimensionin m^2
1	Floor Area	9.29
2	Net Wall Area	35.26
3	Ceiling	11.16
4	Doors	1.76
5	Overhang	2

Table.1 Construction data of the Research Modules

Walls with High Thermal mass and roof with different thermal mass

Thermal mass is a factor which plays an important role in the transmission of solar thermal energy. If the thermal mass is less the transmission of heat is more. If the thermal mass of the walls and roof is high then the heat transmission is delayed.

First Module (SID)

In Single Decker, Galvanized sheets are used as roof element, where the walls are made by bricks. The walls are having high thermal mass. When the solar radiation falls on the roof, the sheets are very easily heated even by early morning due to conduction and it prolongs for the whole day. During the peak hour the amount of transmission of thermal energy into the building is massive.

Second Module (PUD)

Polyurethane panels of length 3660 mm and breadth 1000 mm used as roof for the second module, which is an industrial product. The half white painted reflective steel sheets of thickness 0.47 mm and the poly urethane of thickness 35 mm is used by the industry, to make the panels. One side of the surface of the panel is trapezoidal and the other side is plain so that it sets well during roof making. The roof has a higher thermal mass than the SID module due to its thickness. As the roof panels are possessing insulated material, it helps to reduce the indoor temperature.

Third Module (DOD)

The roof of the second module was newly designed. The design was carried out in four steps. In the first step, first roof was made using galvanised sheets. In the second step wooden reapers of size 3000 mm X 50 mm X 25 mm were arranged over the roof. The spacing between the reapers is 200 mm. In the third step packed mineral wool roll was spread. Thickness of the mineral wool is 50 mm. In the fourth step galvanized sheets were set over it as second roof. The two roofs are separated by 100 mm to 122 mm. Since light roofing system have two light roofs enclosing the wooden reaper and mineral wool, it was named as Double Decker. Since the sheets are trapezoidal, air gap of 11 mm above and below the mineral wool pack and wooden reapers is formed. The air vents created are the passage for the air and takes away the heat produced between the galvanized sheet and the mineral wool bed. Likewise the air vents created between the lower roof sheet, the wooden reaper and the mineral wool bed is also drains away the heat produced by convection. This assembly possesses three insulators namely wooden reapers, mineral wool and air gap. Mineral wool has a low thermal conductivity among the building materials used (k= 0.04 W/m K). The walls of the modules have a high thermal mass and the roof have a medium thermal mass rather higher than the PUD roof.

Fourth Module (RCC)

A room of size 3m x 3m x 3m of a one storey building has been considered as a module for this experiment. The walls and roof are possessing high thermal mass. The roof consists of concrete, weathering course and Mangalore tiles. This module is also an unoccupied closed room. This is a high thermal mass building comparing to the other three structures considered.

VIII. EXPERIMENTAL PROCEDURE

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The modules, used in this study are exactly identical in terms of their geometry, orientation, area and climate conditions. All the modules are fully instrumented. To measure the Indoor Ambient Temperature and Relative Humidity data loggers are used. Infrared thermometer is used for other measurements. In six hours interval (6, 12, 18 hrs.) the roof, walls and floor temperatures were measured. Roof, walls, floor and indoor and outdoor ambient temperature and relative humidity field data have been though catalogued for 12 months for four different roofing systems exposed to weathering on an indoor and outdoor test facility.

Fig -1 Single Decker (SID)

Fig -2 Poly Urethane Decker (PUD)

Fig -3 Double Decker (DOD)

IX. RESULTS AND DISCUSSION

The Indoor Ambient Temperature was measured using digital Hygro- thermometer and the roof and wall temperatures were measured by means of Infrared thermometer. The IAT values are predicted by using the empirical equation formulated. The measured IAT values of SID, PUD, DOD and RCC modules have been considered for the monitoring period from September 2013 to August 2014. For brevity the calculation is taken for 15 days from 16th to 30th of June 2014, since a peak temperature was observed during the summer season. Then the indoor ambient temperature was calculated using the empirical equation for the peak hours of the day. Fig.4 shows the comparison of the measured and calculated vales of the indoor ambient temperature of the SID module along with the outdoor temperature. All the four walls are having the same type of construction with bricks and cement mortar. This is a module which possesses high thermal mass walls and low thermal mass roof. The indoor temperature at the peak summer lies between 35.9˚ C to 40.8˚ C. The calculated and measured values of the indoor temperatures are almost closer. The temperature difference between the calculated and measured values varies from 0.1˚ C to 0.6˚ C.

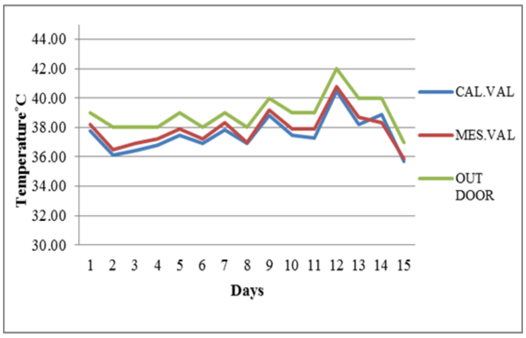

Fig – 4 comparison of the indoor ambient measured and calculated

Fig.5 shows the comparison of the calculated and measured values of the indoor temperature of the PUD module and the prevailing outdoor temperature. From the graph it is obvious that the indoor temperature of the module lies between 32.7˚C to 34.8˚ C. It is very clear that the module provides a low temperature than the outdoor. This module has a high thermal mass walls and a little high thermal mass roof. This roof provides a better indoor temperature than the SID module. Thermal mass has been increased due to the inclusion of insulating material in the roof and the insulator has influenced to the lower the indoor temperature. The variation between the measured and calculated values lies between 0.2 and 0.8˚ C.

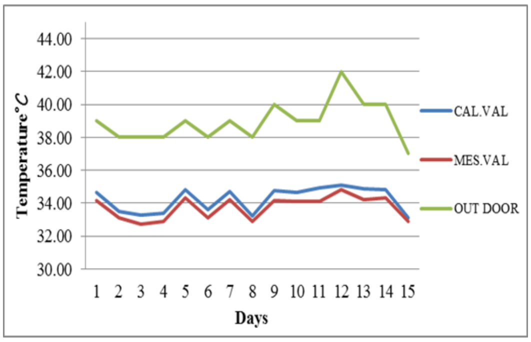

Fig.5 Comparison of measured and calculated indoor temperature and outdoor temperature

Fig.6 shows the comparison of the calculated and measured values of indoor temperature of the DOD module and the existing outdoor temperature. From the graph it is well understood that the indoor temperature

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obtained by both the calculated and measured values are below the outdoor temperature. This module has a high thermal mass walls and a little higher mass roof than the PUD module. The indoor temperature lies between 32.1 and 33.3˚ C. This module provides a low indoor temperature than the other modules. Hybrid thermal insulation and thermal mass increase has made the indoor temperature to a lower value than the other modules. The difference between the measured and calculated values lies between 0.3 and 0.7˚ C.

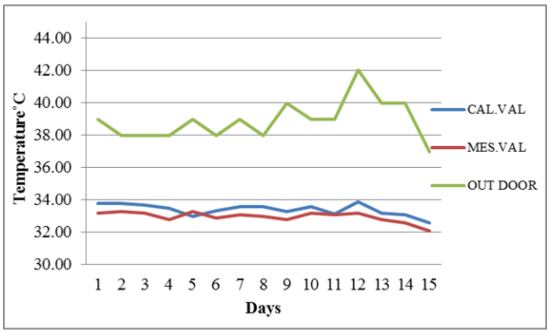

Fig.6 Comparison of measured and calculated indoor temperature and outdoor temperature

Fig.7 shows the comparison of the calculated and measured values of indoor temperature of the RCC module and the existing outdoor temperature. From the graph it is clear that the indoor temperature through the calculated method and measured method are showing that the indoor temperature is always above 34.5 ˚ C and increases up to 37.7 ˚ C during the peak summer. The walls as well as the roof are possessing high thermal mass. Comparing with other modules this module has a high thermal mass. But it provides a higher indoor temperature than the other modules. Walls of all the modules possess equal but high thermal mass. The thermal mass difference arises only due to the roof. Among the four modules insulation is applied only in the PUD and DOD modules. The temperature decrease of the indoor temperature decrease has been caused because of the inclusion of insulation. The difference between the measured and calculated values lies between 0.2 and 0.6 ˚ C.

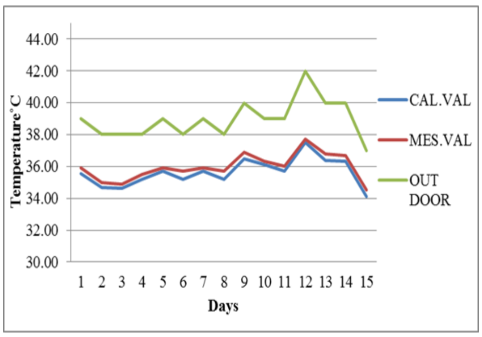

Fig.7 Comparison of measured and calculated indoor temperature and outdoor temperature

X. COMPARISON WITH OTHER STUDIES

The measured and calculated indoor temperature of the modules has been compared with other studies. The indoor temperature prediction equations of Givoniand D.M.Ogoli has been utilised to calculate indoor temperature of this study. The indoor temperature calculated by this study and calculated through other two studies is used to draw the graphs. The calculated and measured values resembles regarding the variations. The indoor temperatures calculated through various studies of the SID module is shown in fig.8. The indoor temperature of the SID module varies from 1.5 to 3.8˚C with the other two studies.

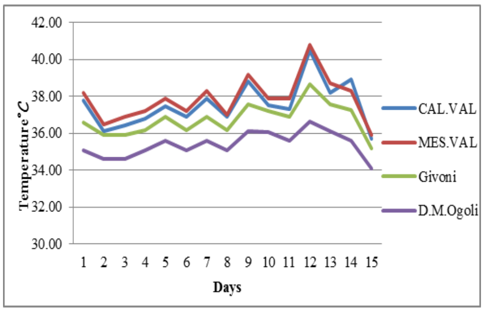

Fig.8 Calculated indoor temperature with other studies – SID

The indoor temperature calculated through various studies of the PUD module is shown in fig.9. The indoor temperature of the PUD module varies from 2.5 to 3.5 ˚C with the other two studies.

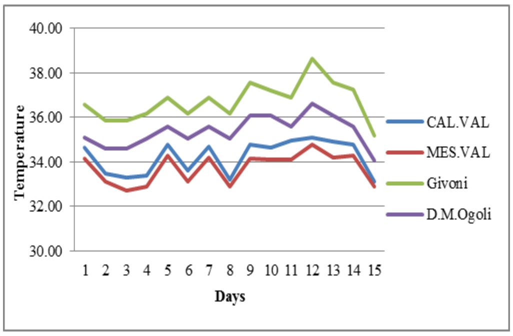

Fig.9 Calculated indoor temperature with other studies – PUD

The indoor temperature calculated through various studies of the DOD module is shown in fig.10. The indoor temperature of the DOD module varies from 2 to 4.7 ˚C with the other two studies.

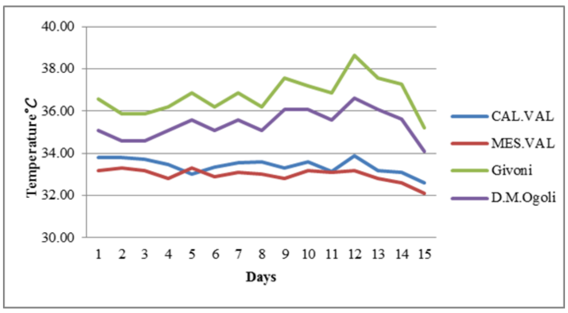

Fig.10 Calculated indoor temperature with other studies – DOD

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The indoor temperature calculated through various studies of the RCC module is shown in fig.11. The indoor temperature of the RCC module varies from 1 to 1.5 ˚C with the other two studies.

The differences between the above relationships can be explained by the fact that 1) the studies were done in different climates 2) the study by Givoni was carried out in open naturally ventilated test chambers 3) the study of D.M.Ogoli was done in closed test chambers in Nairobi 4) the studies are not carried at the same height above the sea level 5) some of the roofs of the modules are insulated in this study.

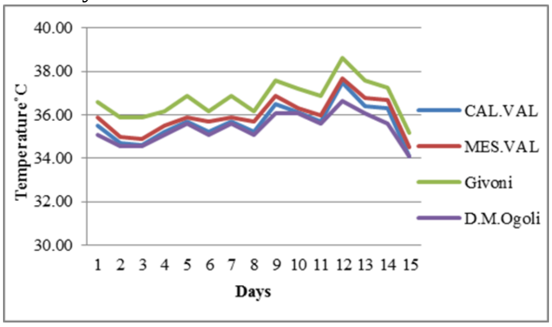

Fig.11 Calculated indoor temperature with other studies – RCC

XI. CONCLUSION

An attempt has been made in this study to investigate a method to calculate the indoor ambient temperature. Since the IAT is considered to rely upon the temperatures of the building elements namely roof, and walls. The IAT of a building is the determiner of the energy efficiency of a building. Among the considered four modules during the monitoring period the measured IAT values show that the SID module has a highest indoor ambient temperature. The PUD module provides a moderate indoor environment. The RCC module is keeping a high indoor ambient temperature at all times of the day in summer. The DOD module provides a best performance than all other modules. The IAT has been calculated by using the predicted empirical equation for all the four modules and the values are compared with the measured values. The proposed equation to calculate the indoor temperature is

$T_{indoor} = 0.196 (T_{inw} + T_{isw} + T_{iew} + T_{iww} + T_{iroof})$

This equation calculates the Indoor Ambient Temperature of medium and high thermal mass buildings and provides best results with the available methods. Thermal mass and roof insulation affects the indoor temperature.

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