International Journal of Students' Research in Technology & Management
Vol 2 (05), August-September 2014, ISSN 2321-2543, pg 172-177

Using a New Programme to Predict Thermal Comfort as a Base to Design Energy Efficient Buildings

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***Abstract*---- A strong relationship relates the thermal comfort and the consumption of energy, especially in the hot arid climate where the installation of HVAC systems is unavoidable. In fact, it has been reported that the HVAC systems are responsible for consuming huge amounts of the total energy used by the buildings that can globally reach up to 40% of the total primary energy requirement. The future estimations indicate that the energy consumption is likely to continue growing in the developed economies to exceed that of the developed countries in 2020. Under these situations, it seems that the shift towards more energy efficient buildings is not an option. Because part of any successful environmental design is to understand the potentials of the site, the proposed programme (THERCOM) assists in weighing the indoor and outdoor thermal comfort in different climates in order to provide better understanding of the site environment as well as testing the thermal comfort chances of the initial concepts.**

Keywords---- energy efficient buildings, indoor thermal comfort, outdoor thermal comfort, passive design, arid climate, equatorial climate, warm temperate climate

I. INTRODUCTION

The current records indicate that the buildings sector is responsible for consuming 40% approximately of the total primary energy requirements [1]. For any typical building, around 80% of this amount is consumed as an operational energy from which huge amounts are consumed for the HVAC systems alone [2]. This pattern of consumption is forecasted to grow as the future estimations predict that in 2020, the energy consumption of the developed economies are likely to exceed that of the developed countries [1].

The associated negative influences for these consumption patterns on the ecological systems of the planet impose their regulation. Hence, the concept of the energy efficient buildings is an attractive option. The energy efficient buildings can be characterised by their ability to satisfy both the proposed design requirements and the operational demands using the possible minimum energy compared with other buildings in the same design category [3]. This is mainly attained via applying the passive environmental design strategies in addition to utilising the renewable energy technologies.

In this regard, it may worth mentioning that the thermal comfort opportunities are defined to a large extent by the passive design strategies which in turn are mostly defined by the early design decisions. Thus, it is crucial to analyse and appreciate the thermal comfort demands in the early stages of the design in order to satisfy them passively as much as possible. Under the unavoidable conditions when the HVAC systems are required to modify the thermal conditions, the analysis of the thermal demands is still of benefit as it can be related to control the set points in order to achieve the optimal efficiency which will be reflected in potential savings.

However, in constructing such buildings, it is crucial to ensure that the proposed efficiency during the design stages is reflected in the operational stages as well. In fact, it has been reported that some of the energy efficient buildings tend to consume huge amounts of energy in order to keep them running properly, regardless of the apparent efficiency in the design stage [3].

The excess consumption of the operational energy may be partially due to the nature of the method by which the performance of these buildings is assessed. Frequently, a simulation approach is implemented to compare the intended scenario of the energy consumption with an ideal one. Although the patterns of the occupants' behaviour are often included, it is difficult to predict the actual patterns.

Therefore, and taking into consideration that most of the operational energy is consumed to achieve the thermal comfort, it may be advantageous to view the thermal comfort demands from the approach of the adaptive models instead of applying the analytical ones. The former models are tailored towards specific groups of people in harmony with certain types of climates and they intensively consider the behavioural adaptations patterns [4]. As a result, most likely their predictions will resemble the actual patterns of consuming the energy in order to achieve the required thermal comfort.

Additionally and based on the characteristics of the energy efficient buildings, it can be understood that, at least in certain periods of the year, these buildings encompass the concept of the free running buildings that satisfy the heating and cooling demands passively. In a comparison with the buildings that depend on the HVAC systems, the free running buildings reduce the operational energy by around 50% [5]. However, in the attempt to use less energy, the risk of achieving poor quality of the indoor environment is obvious. This situation can partially be avoided by the comprehensive analysis of both the buildings thermal demands and the site potentials which leads to defining the periods at which the buildings can be operated on the free running mode. Inversely, in the situations of the uncomfortable conditions, the results of this analysis can be utilized to define adaptive set points that achieve the maximum potential savings.

II. THERCOM PROGRAMME

Based on the Visual Basic programming language, the proposed programme (Thermal Comfort in Different Climates - THERCOM) has been developed to measure and predict the thermal comfort in the free running buildings (to download a trial version of the programme, kindly visit: http://www.nottingham.ac.uk/~lazmbg/MScREA/). It does so by means of measuring the wet bulb globe temperature index, the adaptive model for thermal comfort, and the tropical summer index. In addition, it assess the thermal comfort in the outdoor environments by means of measuring the wet bulb globe temperature index, the wind chill index, the discomfort index, and the heat index.

THERCOM can measure the thermal comfort in twelve different cities located in three climates based on the Koppen-Geiger climate classification. Based on the integrated data, the predictions can be calculated for 24 hours in each month for all the integrated indices, except those of the adaptive model for thermal comfort. This exception was due to the nature of the integrated formula which is based on the outdoor monthly mean temperature. The integrated climates are: the equatorial, arid, and warm temperate climates. The exclusion of the remaining two climates, i.e. snow and polar, was due to the relatively low populations in regions where these climates are dominant [6]. More details about the programme can be obtained from [7].

By predicting the interior thermal conditions, THERCOM assists in facilitating the selection of the most optimum design among the different design alternatives through comparing the thermal performance [5], [8]. In addition, by defining the periods at which the interior thermal conditions are comfortable, the programme in fact defines the periods at which the HVAC system can be switched off in the examined building. On the other hand, predicting the outdoor thermal conditions is crucial in order to design the exterior environments properly as they affect the indoor environments [9].

III. METHODOLOGY

The concept of the energy efficient buildings implies the good matching between the site environment and the used materials and equipment [3]. Based on this, and for the purpose of the study at hand, four mock-up models were constructed with different construction materials for the roof. The thermal performance of these models was investigated based on the effectiveness of the roof materials in contributing towards providing the comfortable thermal conditions.

A. Constructional Details

Despite the construction of the roof, the four models share identical dimensions, properties, and construction materials of the other parts of the models. They are basically a 3 m x 3 m x 3 m models with one 40 mm foam core plywood door (1 m x 2.2 m) located at the east facade and a single pane of glass with aluminium frame window (1.5 m x 1.5 m) located at the west facade. Brick concrete blocks with total thickness of 340 mm were used for the walls and a 100 mm concrete slab placed on the ground for the floor. The construction of these elements is detailed in Table 1.

For the roof, the investigated four construction systems are:

- Cinder concrete with insulation
- Hardboard slab with insulation
- Timber slab without insulation
- Concrete roof with asphalt cover

The detailed components and their properties are displayed in Table 2.

The models are assumed to be located in Colombo city. It has been found that the west wind is dominant according to a previous analysis study of the city climate.

Therefore, the window was positioned on the west facade in order to encourage the natural ventilation. The wind velocity was modified based on the wind power low and based on Melaragno method to account for the changes in the wind velocity inside the buildings [10].

TABLE 1
CONSTRUCTIONAL DETAILS OF THE MODELS ELEMENTS EXCEPT THE ROOF

Layer	Width (mm)	Density (kg/m³)	Specific heat (J/kg.°C)	Conductivity (W/m.°C)
Wall				
Brick Masonry Medium	110	2000	836.8	0.711
Concrete Cinder	220	1600	656.9	0.335
Plaster Building (Molded Dry)	10	1250	1088	0.431
Floor				
Concrete	100	3800	656.9	0.837
Door				
Plywood	3	530	1400	0.140
Polystyrene Foam	34	46	1130	0.008
Plywood	3	530	1400	0.140
Window				
Glass Standard	6	2300	836	1.046

B. Selected Thermal Index

THERCOM programme was used to compute the thermal comfort for the explored models by means of calculating the Tropical Summer Index. This model was selected for the study at hand based on the coincidence of its climatic boundaries and the climatic conditions of the chosen city [7]. The investigated period includes 288 hours distributed as 24 hours from each month.

IV. RESULTS AND DISCUSSION

A. Periods of Switching-off HVAC

For each model, the dominant thermal conditions over the examined period are presented in their percentages of thermal sensation as depicted in Figure 1. As can be noted from the pie chart of the first model, a comfortable thermal sensation was dominant in 83% of the investigated hours followed by slightly warm sensation with a percentage of 16%. In 1% of the investigated hours, the dominant sensation was slightly cool.

For the second model, the pie chart indicates that in 78% of the examined hours, the thermal conditions were considered as comfortable. In 21% and 1% of the investigated hours, slightly warm and slightly cool sensations were presented respectively. For the third model, the thermal sensation of 76% of the tested hours was comfortable. In the remaining hours, a slightly cool sensation was present.

TABLE 2
DETAILS OF THE ROOF CONSTRUCTION

Layer	Width (mm)	Density (kg/m³)	Specific heat (J/kg.°C)	Conductivity (W/m.°C)
Case 1: Cinder concrete with insulation				
Aggregate	10	2240	840	1.8
Rubber natural	2	930	2092	0.138
Polystyrene foam	50	46	1130	0.008
Polyethylene	1	950	2301	0.502
Concrete cinder	100	1600	656.9	0.335
Plaster ceiling tiles	10	1120	840	0.38
Case 2: Hardboard slab with insulation				
Aggregate	10	2240	920	1.3
Rubber Polyurethane elastomer	2	1250	1674	0.293
Hardboard slab	10	1000	1680	0.29
Wool, fibrous	10	96	840	0.043
Board	10	160	1890	0.04
Coat	10	2300	1700	1.2
Case 3: Timber slab without insulation				
Sand	10	2240	840	1.74
Rubber	2	1100	2092	0.293
Slab	10	300	960	0.055
Plaster Board	10	1250	1088	0.431
Case 4: Concrete roof with asphalt cover				
Asphalt cover	6	900	1966	0.088
Concrete lightweight	150	950	656.9	0.209
Plaster	10	1250	1088	0.431

The fourth model has a different thermal scenario as demonstrated from the Figure. The comfortable conditions were dominant in only 52% of the examined hours, with the slightly warm and warm sensations forming the remaining percentages as 42% and 6% respectively.

Based on these percentages, it can be concluded that the longest period in which the mechanical ventilation systems can be switched off is of the first model followed by the second, third, and fourth with percentages of 83%, 78%, 76%, and 52% respectively.

For the rest of the investigated hours, it may be necessary to use the HVAC systems to achieve the required comfortable thermal conditions with an obvious need for cooling in the four cases.

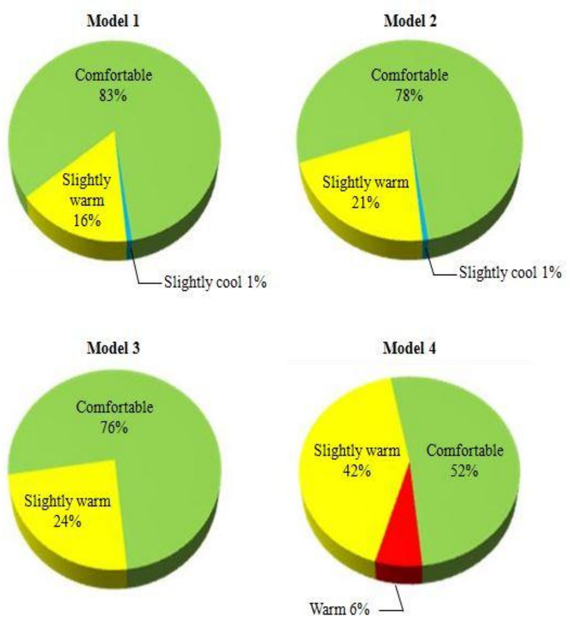

Fig. 1 Percentages of the thermal sensations of the examined models

A detailed examination of the thermal conditions distributions as depicted in Figure 2 shows that for the first model, the mechanical ventilation can be switched off in about 14 hours from 20 to 10. Although an identical scenario is applicable for models 2 and 3 as can be noted from the Figure, the scope of switching off the HVAC systems in the hours from 10 to 20 is greater for the first model in comparison with the other models. In the fourth model, the hours at which the HVAC system can be switched off are limited to around 9 hours in each of January and February, 6 hours in each of May, June, November, and December, and the maximum is 13 hours in each of the months from July to October including both.

Nevertheless, it should not be forgotten that it is possible to expand the comfortable thermal conditions through the implementation of the passive design strategies. These strategies include the proper selection of the materials of the building envelope, the proper proportion of the openings to the solid area of the envelope, the orientation, the aspect ratio,

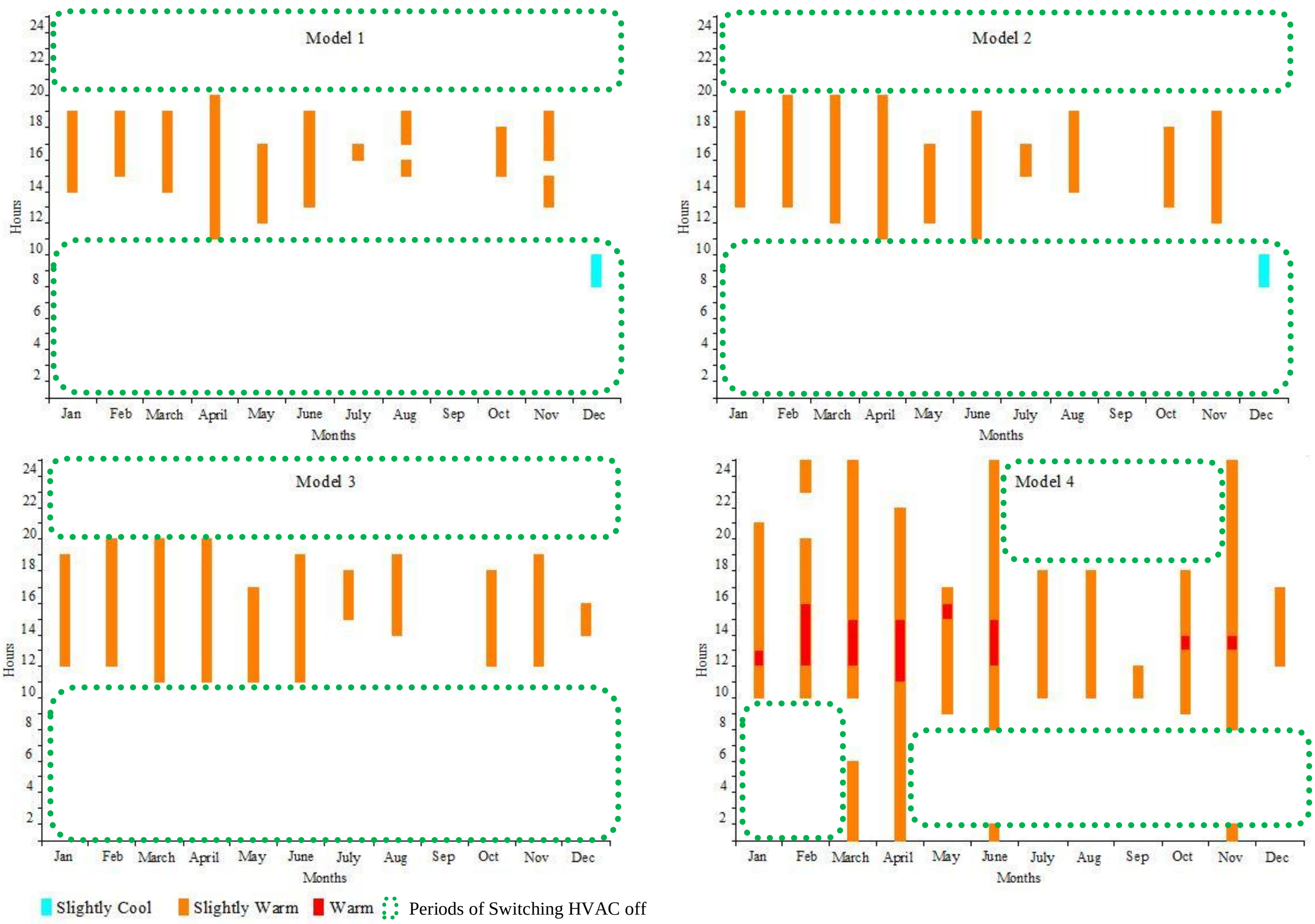

Fig. 2 Hours distribution of thermal sensations of the examined models

the integration of the shading devices, etc. Additionally, it should be mentioned that the use of the fans is permitted [12] as they consume negligible amount of energy compared with the HVAC systems to achieve an identical extension of the comfortable conditions.

B. Selecting the Optimum Roof System

From other perspective, the statistical variance of the tropical summer index temperatures was calculated for the four models to show values of 1.92, 2.54, 3.11, and 3.89, where the means of the index temperatures were 28.59 ºC, 28.69 ºC, 28.91 ºC, and 30.29 ºC in sequence.

The narrowest spread of the index temperatures of the first model from its mean value, in addition to its longest comfortable period and consequently shortest uncomfortable periods especially those with slightly warm conditions in comparison with other models, indicate that the first model may be considered as the optimum option within the investigated alternatives.

Table 3 shows the thermal resistance of the four examined roofs. It is clear from the table that the first model has the best thermal performance as it has the highest thermal resistance. A closer look clarifies that this resistance is mainly due to the presence of the thick insulation layer (layer 3: Polystyrene foam) which alone contributes of about 95% of the total roof resistance.

TABLE 3
DETAILS OF THE ROOF CONSTRUCTION

Resistance of	Model 1	Model 2	Model 3	Model 4
Layer 1	0.006	0.008	0.006	0.068
Layer 2	0.014	0.007	0.007	0.718
Layer 3	6.250	0.034	0.182	0.023
Layer 4	0.002	0.233	0.023	-
Layer 5	0.299	0.250	-	-
Layer 6	0.026	0.008	-	-
Total	6.597	0.532	0.218	0.809

Nonetheless, the relatively good thermal performance of the first model may additionally be partially due to the combined effect of the high thermal mass of the concrete deck in addition to the position of the insulation layer where it was located above the structural deck close to the outer surface. This according to [11] is the optimum position for the insulation to insure the most comfortable thermal conditions in the hot periods. For the first model, the order of the construction materials with the insulation closer to the outer surface insures that most of the heat is being prevented from passing through conduction to the interior layers of the roof. The permitted amount is absorbed and stored in the thermal mass of the concrete and thus delayed from affecting the interior conditions.

Although a fibrous wool thermal insulation was used in the second model, its thinness and position towards the inner side of the roof, in addition to the low thermal mass of the hard board deck, might contributed towards the lower thermal performance of this model in comparison with the first model.

Moreover, the lack of the insulation layer had an influence on the much lower thermal performance of the remaining models. However, the lower thermal mass of the timber slab of the third model had a relatively positive impact on the interior thermal conditions as it has a shorter time lag. This insures that the indoor temperature follows the exterior temperature. On the other hand, the high thermal mass of the concrete deck had contributed in the continuous heat stress during the night period as it can be noted from Figure 2.

IV. CONCLUSION

Under the current rates of energy consumption, it is important to consider the occupants' behaviour from the early stages of design as most of the operational energy is consumed to achieve the thermal comfort. This consideration is crucial for the energy efficient buildings as the risk of having poor quality of indoor environment is possible under the attempts to reduce the consumption of the operational energy.

Although calculating the thermal resistance may give an impression about the thermal performance of the examined roofs, the effect of the different construction systems and materials on the actual thermal conditions remains unclear. Hence, it is important to consult tools such as THERCOM to understand the predicted thermal comfort experience of the users by means of computing the thermal comfort indices suitable for the cases under consideration.

THERCOM is of great importance as it helps in better understanding and good appreciation of the available thermal comfort opportunities and the deviation from the required conditions. This understanding helps in making decisions about selecting the appropriate equipment, materials, amenities and possibly adjusting the operating patterns which eventually will increase the efficiency of the buildings.

In the study at hand, four mock-up models were tested to explore the thermal performance of the roof construction system and materials. The thermal comfort conditions were investigated using the tropical summer index. The aim of this examination was to define the periods at which the HVAC systems can be switched off and to select the most optimum construction system among the explored roofs. The first model, cinder concrete with insulation, had the optimum thermal performance. Possible factors incorporated to achieve this performance include the position of the insulation layer, its high thermal resistance, and the high thermal mass of the concrete deck.

Furthermore, and in order to extent the comfortable conditions of the first model further, it is recommended to select the construction systems of the other parts of the building envelope based on their thermal properties, in particular the thermal mass. However, careful planning of the buildings layouts should be maintained to ensure the continuity of the natural ventilation.

Finally, it is recommended to perform further investigations to explore the extent at which the comfortable thermal conditions may be extended by means of using fans as a step before the unavoidable use of the HVAC systems.

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