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Optimization of Thermal Comfort Indices using Passive Design Strategies for an Office Room in Delhi

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Abstract—*A building which is energy efficient can be called effectual only when its occupants remain at thermal ease, in the absence of which, not only would they be at greater health risks, it would also lead to a decrease in their productivity. To maintain a thermally comfortable environment, the occupants would opt for alternate methods for space heating and cooling, which would thus, lead to increased energy consumption, a major share of which lies in maintaining thermal comfort. Hence, as far as possible, passive design methods should be adopted for lowering the energy expenditure and for sustaining the required thermal comfort. If the desired comfort is not met even after this, then artificial methods need to be adopted, such as Heating, Ventilation, and Air Conditioning systems.*

Study of thermal comfort precisely represents the indoor air quality of a building and generalizes the distribution of the most prominent comfort zones by considering prime variables including humidity, air velocity, metabolic rate, temperature of the air, clothing insulation and average radiant temperature. In the present study a small office room in Delhi has been selected for carrying out the thermal comfort study. Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD) models, being the most accepted models for determining thermal comfort index, have been used. Parameters like air temperature, mean radiant temperature, relative humidity have been measured for a designated period and the values thus obtained have been used for finding out the PMV and PPD analytically. These results were then compared with the simulation results obtained from IDA ICE 4.7 Beta software and were found to be in agreement. The influence of various passive parameters on the thermal comfort indices was also analyzed, which included the provision of wall insulation and provision of roof insulation, with varying thicknesses.

Keywords*: Predicted Mean Vote (PMV), Mean Radiant Temperature, Thermal comfort, Percentage People Dissatisfied (PPD).*

1. INTRODUCTION

Thermal comfort, as expressed by ASHRAE Standard 55 [1], is a state of contentment of the human minds with their surrounding thermal environment, which can be assessed by subjective evaluation. In a physical way, it is an equilibrium condition between the humans and their surroundings, which is established when the generated heat by the metabolism of the humans is allowed to be dissipated into the environment. In absence of thermal comfort for the occupants, their health may decline and their productivity is reduced as well. According to ASHRAE Standard 55 [1] and ISO 7730:2006 Standard [2], at least 80% of the occupants need to feel thermally comfortable. Thermal comfort conditions may vary from one individual to another.

A building which is energy efficient can be called effectual only when its occupants remain at thermal ease. If the occupants of the building are not feeling comfortable, not only would they be at greater health risks, it would also lead to a decrease in their productivity.

There are various methods to assess the thermal comfort of an occupant and various models have been devised which give the mathematical relationship between the thermal comfort values and the various factors affecting it. The most widely accepted models for determining thermally comfortable environment are the Predicted Mean Vote (PMV) model and the Percentage People Dissatisfied (PPD) model, which are also accepted as the standard model for finding thermal comfort by ASHRAE Standard 55 [1], as well as by ISO 7730:2006 Standard [2].

Various researches have been done on thermal comfort using the PMV and PPD models. One such study was conducted by Pourshaghaghy and Omidvari [3], wherein, the performance of air conditioning system and the level of thermal comfort have been determined in a state hospital in the west of Iran in winter and summer using the PMV model. In another study by Ravikumar and Prakash [4], dimensions of the openings of an office room were varied to analyze thermal comfort using the CFD approach. Natural ventilation and building orientation were kept as the prime parameters for the study of their potential in achieving the optimum thermally comfortable environment in warm and humid climates, by Haase and Amato [5].

A prototype thermal EM system was developed by Kumar et al. [6], which measured parameters affecting thermal comfort, using which PMV was found out. The effect of building envelope on thermal comfort and on the energy-saving potential has also been studied by Hwang and Shu [7] for PMV-based comfort control in glass facade buildings.

The PMV model has certain limitations, due to which, it is not suitable to be used everywhere, thus, certain modifications have been made in the model to provide the best results in each fitting case. In a study by Humphreys and Nicol [8], the possible origins of the biasedness in the values of PMV, both for air conditioned as well as non-air conditioned, based on its affecting parameters have been discussed, along with suggesting ways to modify PMV value to reduce the difference between the PMV value and the actual mean vote. An extension of PMV model was proposed by Fanger and Toftum [9] by introducing an expectancy factor, for non- air conditioned buildings in warm climates. From the literature survey, it can be concluded that it is important to study the conditions in which the PMV model is valid and gives the best results, and also to provide a better prospective to increase the thermal comfort along with the indoor air quality.

The objective of this study is to analyze the thermal comfort conditions in a building both by measurements and using an analysis led design and to study the effects of various parameters on the thermal comfort. This is followed by an optimum solution proposition for maintaining the thermal comfort of the occupants of the office room.

1.1 Predicted Mean Vote (PMV) Model

The PMV refers to a scale of the thermal sensation, the value of which lies between -3.0 (Cold) to 3.0 (Hot). ASHRAE Standard 55 [1] and ISO Standard 7730:2005 [2] recommend the tolerable PMV range for thermal comfort condition to be -0.5 to +0.5 for an indoor space.

For describing the thermal comfort conditions, there are six primary variables that must be addressed which are the rate of metabolism (M), clothing, insulation (f_{cl}), the air temperature (t_a), mean radiant temperature (t_r), air velocity (v_{ar}) and humidity (RH). Basically, PMV model is calculated using these primary variables only. Out of these, the rate of metabolism and insulation of clothing are derived parameters and the remaining are measurable quantities.

1.2 Percentage People Dissatisfied (PPD) Model

Although a measure of thermal perception is an important parameter to assess the thermal environment of an area, it is also crucial to examine whether the people occupying the indoor space would be satisfied with their thermal environment or not. To estimate this parameter, another index was developed by P. Ole Fanger, known as the Predicted Mean Vote Model, which relates the satisfaction of the occupants with the predicted mean vote values obtained. This model has also been adopted by ASHRAE Standard 55 [1] and ISO Standard 7720:2005 [2], and mentions that the acceptable value of PPD should be ≤20%.

A curve has also been developed to analyze the relationship between the percentage of people discontented with their environment and the PMV values, which is represented in Fig. 1.

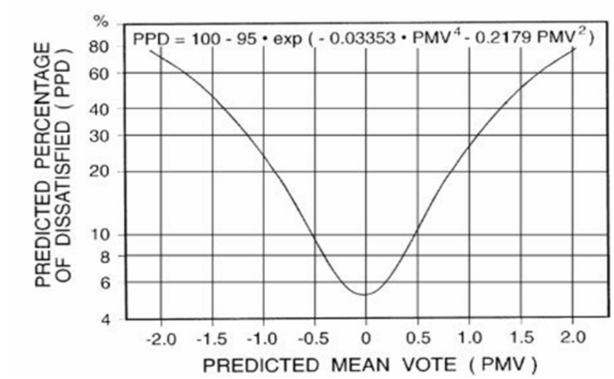

Fig. 1: Empirical relationship between PMV and PPD

2. MATHEMATICAL MODEL AND METHODOLOGY

2.1 Predicted Mean Vote (PMV) Model

The equation for the PMV value of a zone is based on the heat transfer balance equations and has been used for finding out the results.

$PMV = (0.303e^{-0.036M} + 0.028) \times L$ …......……….... (1)

Where, L represents the thermal load on the body of an occupant

$L = (M - W) - H - E_c - C_{res} - E_{res}$ ………….……... (2)

Where, M – Metabolic Rate (W/m^2)

W – Effective Mechanical Power (W/m^2)

H – Sensitive Heat Losses (W/m^2)

E_c – Heat exchange by evaporation on skin (W/m^2)

C_{res} – Heat exchange by convection in breathing (W/m^2)

E_{res} – Evaporative Heat exchange in breathing (W/m^2)

2.2 Percentage People Dissatisfied (PPD) Model

The equation for finding PPD depends upon the PMV value and is given by the following equation-

$PPD = 100 - 95 \times e^{[-(0.3353PMV^4 + 0.2179PMV^2)]}$ ... (3)

Where, PPD – Percentage People Dissatisfied (%)

PMV – Predicted Mean Vote

2.3 Experimental Work

For carrying out the experimentation work and for performing the analysis led design a small office room of "Global Evolutionary Energy Design" has been selected. The location of the building chosen is in Delhi, the time zone of which is GMT +5.5 hours. Fig. 2 gives the plan and dimensions of the office room considered for study.

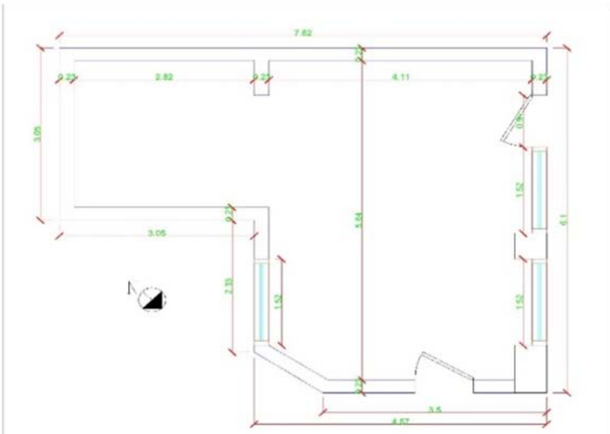

Fig. 2: Plan of the Office Room

In the office room, Active Space Indoor Environmental Quality Sensor was installed. The sensors in the device continuously measured the air temperature, mean radiant temperature, relative humidity, etc., and stored it into the workstation connected to the IEQ sensor. The experiment was performed for two months, starting from the 5th of December till 5th of February. The data so collected was filtered on the basis of the occupancy days of the office, i.e., on all weekdays, and on the basis of the occupancy hours, i.e., from 10:00 A.M. to 6:30 P.M, and was used to find out the thermal comfort indices.

2.4 Analysis led design studies

For the purpose of analyzing the influence of various parameters on the existing office room, a simulation study has been carried out in the IDA ICE 4.7 Beta software to model the same office room. The plan of the office room located on the first floor of a building has been prepared in the AutoCAD software, outer dimensions of which are 7.62 × 6.1 m^2, with each surface having a thickness of 0.23 m. The construction details and the material properties [10] are then defined for the building, which are as shown in table 1 and table 2.

Table 1: Construction Details of the Office Room

	Layers	Thickness (mm)	Density (kg/m^3)	Thermal Conductivity (W/m K)	Specific Heat Capacity (J/kg K)
Walls	Gypsum Plaster	12	970	0.22	1090
	Bricks	228.6	1500	0.58	840
	Gypsum Plaster	12	970	0.22	1090
Floor	Concrete Slab	127	2300	1.70	880
	Gypsum Plaster	12	970	0.22	1090
	Marble Tiles	38.1	2300	3.00	880
Roof	Gypsum Plaster	12	970	0.22	1090
	Concrete Slab	127	2300	1.70	880
	Cement Mortar Slurry	100	1648	0.72	920
	Mud Phuska	101.6	1622	0.52	880
	Brick Tiles	38.1	1892	0.79	880
Door	Wood	38.1	2300	0.14	500

Table 2: Properties of Windows of the Office Room

Thickness (mm)	12
Solar Heat Gain Coefficient (SHGC)	0.68
Solar Transmittance	0.60
Visible Transmittance	0.74
Glazing U-Value (W/m^2 K)	1.90
Internal Emissivity	0.84
External Emissivity	0.84

Since the office consisted of a large single room, so only one zone was created, for which, number of occupants, their schedule, along with the equipment and lighting schedule needed to be provided to the software for the simulation run. Number of occupants of the office were 7, present in the weekdays, from 10:00 A.M. to 6:30 P.M., which have been provided as an input to the software. 11 PC's were present in the office, while 3 tube-lights and 4 bulbs were present as equipment and lighting respectively. Several other system settings needed to be given as an input to the software, such as infiltration of the office room, thermal bridging, location setting of the office, along with the number and the list of holidays. Since the experimental work has been carried out for the period of two months, so the same time period has been provided as an input to the software to carry out the simulations for the desired results.

3. RESULTS & DISCUSSION

3.1 Validation of Base Case

From the experimental measurements, PMV has been calculated through measurements of the instantaneous values of measured primary variables. The PMV values were observed to be ranging from -1.21 to 1.08, with the average PMV value obtained as -0.15, which is within the acceptable range of ideal thermal comfort conditions, (-0.5 to +0.5). The PPD values have also been found out for the same, which are ranging from 5% to 36.01%, while the average PPD value obtained during the study period is 11.72%, which means that only on an average, 88.28% of the occupants are satisfied with their thermal environment. This value is well within the acceptable value given in ASHRAE Standard 55 [1] and in ISO Standard 7730:2005 [2], in which it is mentioned that at least 80% of the occupants need to be satisfied with their thermal environment.

A simulation study was also conducted, and it was observed that the value of PMV for the study period is ranging from -1.22 to 1.11, while the average PMV value obtained during the study period is -0.17. Similarly, PPD values were also found out, which ranged from 5.00% to 36.61%, while the average PPD value obtained during the study period is 11.63%, which means that only on an average, 88.37% of the occupants are satisfied with their thermal environment.

The graph between PMV and PPD obtained experimentally was then compared with the graph plotted between PMV and PPD obtained using simulation results, and it was observed that the curve formed using the simulated values matched exactly with the curve obtained experimentally were well within 15% of error. This validated the simulation results with the actual environment and the software can thus be used to study the influence of various parameters on the thermal comfort indices. Fig. 3 shows the PMV-PPD values obtained experimentally as well as using simulation-based results.

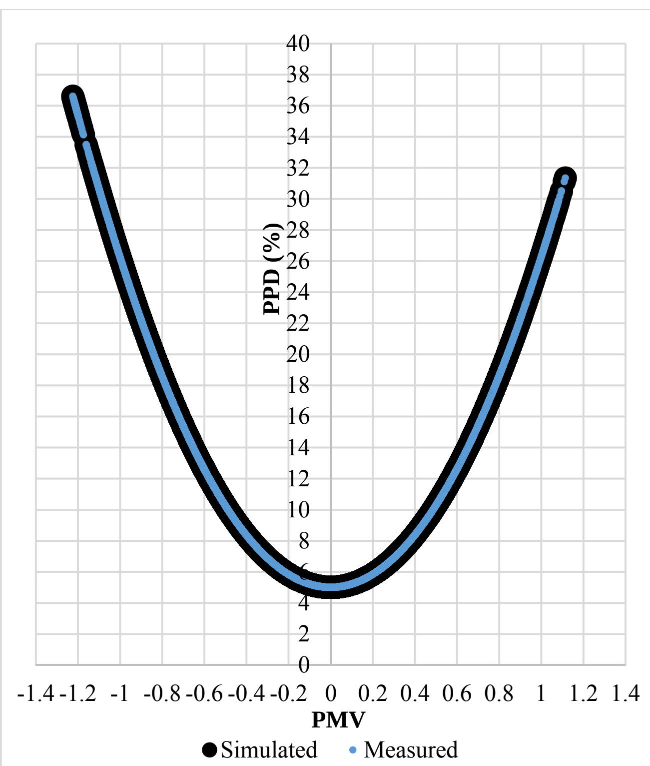

Fig. 3: Validation Graph of Simulation Results with Experimental Results

3.2 Influence of Different Parameters on Thermal Comfort

3.2.1. Provision of Wall Insulations. One of the most common types of insulation material used nowadays is the mineral wool insulation, which consists of glass wool, produced from recycled glass, rock wool, produced from basalt and slag wool, made from the slag obtained from the steel mills. It is moisture-resistant, sound proof and acts as a fire barrier. Table 3 enlists the properties of mineral wool external wall insulation [11].

Table 3: Thermal Properties of Mineral Wool Insulation

Density (ρ) (kg/m^3)	40
Specific Heat (C_p) (J/kg-K)	840
Thermal Conductivity (W/m-K)	0.038

In the existing construction of the office exterior walls, a layer of mineral wool with different thicknesses of 0.02 m, 0.04 m, 0.06 m, 0.08 m and 0.10 m has been used to check its effect on the variation in the thermal comfort indices. With increasing thickness, it was observed that the average value of PMV is increasing towards a slightly warmer side, but is within the ideal thermal comfort range.

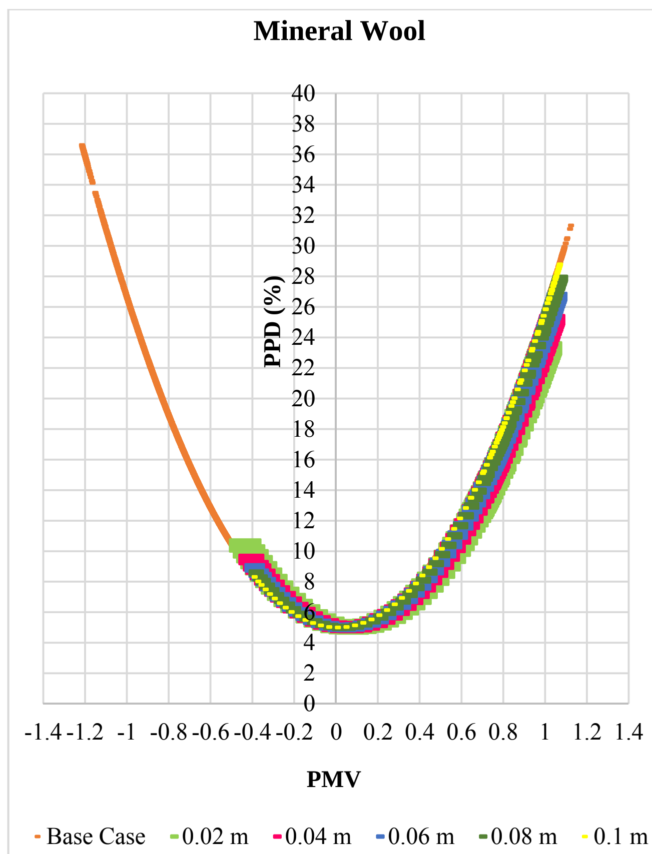

Fig. 4: Graph between PMV and PPD with application of mineral wool wall insulation

It was also observed that the maximum PMV is constantly increasing with increasing thickness, thus, moving away from the ideal thermal comfort range, while the minimum PMV value is constantly decreasing throughout the range of thicknesses considered for study, and thus, suggesting that the provision of this insulation is reducing the slight coldness in the thermal environment, and is tending towards the ideal thermal comfort range. Similarly, it was observed that the average PPD is constantly increasing with increasing thickness, indicating that more percentage of people would start to feel discomfort. The maximum PPD value showed an increasing trend with increasing thickness, while the minimum PPD value remained the same. Fig. 4 shows the results of providing mineral wool wall insulation with varying thicknesses.

3.2.2. **Provision of Roof Insulations.** In the existing construction of the office roof, a layer of mineral wool with different thicknesses of 0.02 m, 0.04 m, 0.06 m, 0.08 m and 0.10 m has been used to examine its effect on the variation in the thermal comfort indices from the simulation of the base case results. With increasing thickness, it was observed that the average value of PMV is almost constant and is within the ideal thermal comfort range. It was also observed that the maximum, as well as minimum values of PMV, are constantly decreasing with increasing thickness, thus, moving towards the ideal thermal comfort range.

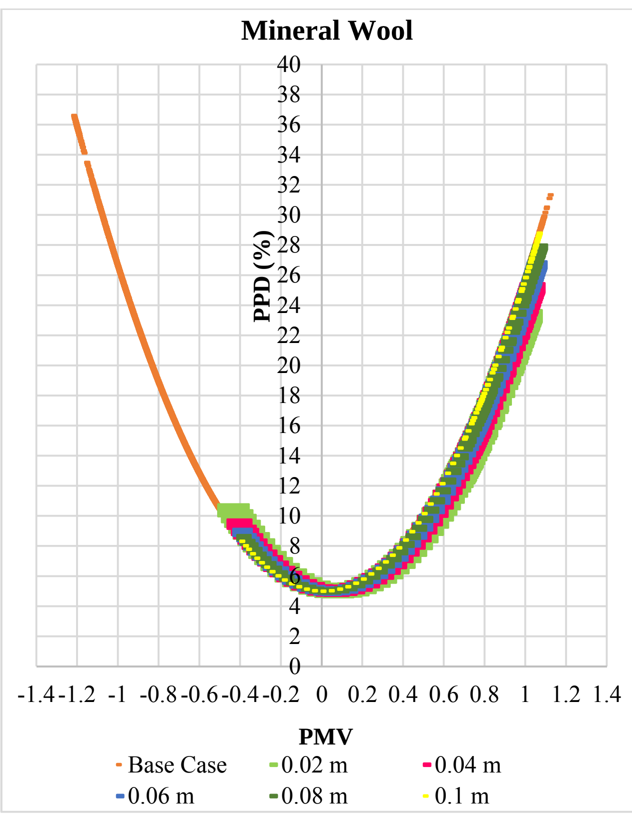

Fig. 5: Graph between PMV and PPD with application of mineral wool roof insulation

This suggests that the provision of this insulation is reducing the slight coldness and slight warmness in the thermal environment, and is tending towards the ideal thermal comfort range. Similarly, it was observed that the average and maximum values of PPD followed the same trend, indicating that lesser percentage of people would start to feel discomfort, while the minimum PPD value remained the same. Fig. 5 shows the results of providing mineral wool roof insulation with varying thicknesses.

4. CONCLUSIONS

PMV and PPD models, being the most widely accepted models by ASHRAE Standard 55 [1] and ISO Standard 7730:2005 [2], have been used to carry out the present study of finding out thermal comfort indices within an office room in Delhi, both by measurements and using software. The effects of various parameters on the thermal comfort were also studied, and hence, an optimum solution for maintaining the thermal comfort of the occupants of the office room has also been proposed. The following inferences can be drawn from the present work:

- PMV within the office room is lying in the range of -1.22 to 1.11, with an average value being -0.17, signifying a slightly cold environment for most of the instances.
- PPD values are ranging from 5% to 36.61%, depicting that at some instances more than 20% of the people are dissatisfied with their thermal environment.
- Experimental results are in agreement with the simulation results, with errors of 0.83% and 2.78% on the cold sides and the warm sides respectively.
- The influence of various passive parameters on the thermal comfort indices was also analyzed, which showed that those parameters either improved the overall thermal environment very slightly, or improved the thermal environment on one side of the scale, while degrading the thermal environment on the other side of the scale.
- Out of all the parameters studied, maximum improvement in thermal comfort has been observed in the case when mineral wool wall insulation has been used of thickness 20 mm. This optimum solution resulted in the PMV range of -0.54 to 1.06, with percentage improvements of 55.73% on the colder side, but only 4.50% on the warmer side respectively. The PPD value also drastically reduced from 36.61% to 31.20%, leading to a percentage improvement of 14.78% in the values of PPD. This indicates that this solution would result in a larger percentage of people being satisfied with their thermal environment.

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