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DEVELOPEMENT OF MODIFIED THERMAL COMFORT EQUATION FOR A ROOM WITH WINDOW OPENINGS AT ADJACENT WALLS

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Abstract

Thermal comfort in a residential building is an important factors that determines the human comfort and productivity .The thermal comfort depends on many personal and environmental factors. Thermal comfort is predicted through thermal comfort sensation index developed by Fanger's equation. In this paper, a modified equation for the determination of Predicted Mean vote (PMV) is developed from Fanger's equation. This modified Predicted mean vote equation is the function of humans metabolic rate, human's work activity, insulation value of clothing's, indoor temperature. Also a detailed indoor air flow simulation was conducted for a room with window openings at the adjacent wall under the generalized window opening area and its position by computational fluid dynamic (CFD) technique. Three dimensional model was created and standard k-ε turbulence model was employed. The CFD simulation was checked for grid independency and the simulated results were checked with network model. From the CFD simulated cases, the average temperature at various planes are predicted. Finally, the regression analysis on the predicted average indoor temperature is performed. The developed modified equation of PMV and the regression models for the average indoor temperature are found to have close agreement with Fanger's equation and CFD simulation respectively.

Index Terms: *Thermal comfort, Predicted mean vote, Computational fluid dynamics, Regression model..*

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1. INTRODUCTION

Thermal comfort is defined as the state in which there are no driving impulse to correct the environment by the behaviour. As per the ASHRAE standard 55 (2004) it is the condition of mind that expresses the satisfaction with the thermal environment . From the above definition it is identified that thermal comfort is not a state of condition however it is the state of mind. Many factors such as physical, physiological and psychological affects the thermal comfort. Thermal comfort varies person to person even if they are in the same environment. Satisfaction with the thermal environment is a complex subjective response to several interacting and less tangible variables (Ogbonna and Harris 2008). However, the comfort occurs when the body temperature are held within narrow ranges, skin moisture is low and the physiological effort of regulation is minimized. Macpherson narrated the six factors namely air temperature, air velocity, relative humidity, mean radiant temperature and two personal factors (metabolic rate and clothing insulation) that affects the thermal comfort (Lin and Deng 2008). Determination of thermal comfort is very important for the building because this is the key parameter for a healthy and productive work place (Taylor et al, 2008 and Wagner et al 2007).

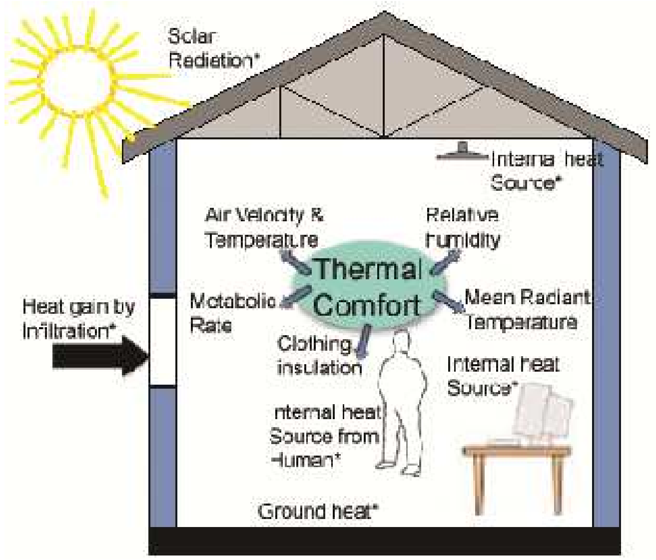

Fig-1: Thermal comfort of a human being in a building

Many building related health problems like sick building syndrome, and building related sickness due to poor thermal comfort encourages the researchers to develop a thermal comfort model (Fanger 1970), predicting correlation for thermal comfort criteria on health issues like SBS (Wagner et al 2007), to establish thermal comfort standards and evaluation method (Olesen and Parsons 2002).

2.THERMAL COMFORT MODELS

2.1Fanger's model

Fanger's approach combines the theories of heat balance with the physiology of thermoregulation to determine the range of comfort temperature at which the building occupant feels the comfort. Fanger conducted the experimental test in a climate chamber with occupants whose sweat rate and skin temperature were measured. The relation between the sweat rate and skin temperature as a function of metabolic rate was predicted through regression analysis. The resulting equation is an imbalance of actual heat flow from the body in the given thermal environment and the heat flow required for the heat flow requirement for the optimum comfort for the given activity and it is referred as Predicted Mean Vote (PMV) given in equation 1. This approach is the path breaking contribution to the theory of thermal comfort and it is widely used and accepted for design and field assessment of thermal comfort (Lin and Deng 2008).

$$PMV = (0.303e^{-0.036M} + 0.028)\{(M - W) - 3.05\times10^{-3} [5733 - 6.99(M - W) - p_a] - 0.42[(M - W) - 58.15] - 1.7\times10^{-5} M(5867 - p_a) - 0.0014M(34 - T_a) - 3.96\times10^{-8} f_{cl}[(T_{cl} + 273)^4 - (T_r + 273)^4] - f_{cl} h_c (T_{cl} - T_a)\} \quad (1)$$

where M = Metabolic rate, W = Work done, pa is the vapor pressure of the surrounding air, f_{cl} = factor of clothing, T_{cl} = clothing surface temperature, T_r = mean radiant temperature, h_C = convective heat transfer coefficient.

2.2 Operative temperature model

According to the ASHRAE, temperature can be obtained on the basis of activity and clothing is shown in the Equation 2.

$$toac = tosed - 3(1+ clo)(met - 1.2) \quad (2)$$

The equation is valid between 1.2 and 3 met with a minimum toac acceptable value of 15ºC.The operative temperature conditions for a sedentary activity in summer or winter are:

Terms of summer: $t\,osed = 24.5 \pm 1.6$ºC (3)

Terms of winter: $t\,osed = 21.8 \pm 1.8$ºC (4)

The ASHRAE recommends an office building activity level between 1.1 and 1.3 met. ASHRAE also provides the values of the clo as clothing for each season. In this way, typical **2.3 Adaptive models** Spanish clo values chosen for each season of the year were 0.5 in summer and 1.0 in winter.

Over the last few years, adaptive models are applied to define the neutral temperature as a function of outdoor, indoor or both temperatures. Some of them present a higher accuracy in certain conditions. Nicol and Roaf (1996) recommended the model of equation 5 for occupants of natural ventilation buildings. Many other adaptive models have also been proposed. For example, Humphreys (1976) developed two models for neutral temperature, as given in Equation 6 and 7, and Auliciems and de Dear developed the relations for predicting group neutralities based on mean indoor and outdoor temperatures, as given in equations 8, 9 and 10, which was employed by the ASHRAE in Equation 11.

$T_{n,o} = 17+0.38T_o$ (5)

$T_{n,1} = 2.6 + 0.831T_i$ (6)

$T_{n,o} = 11.9 + 0.534T_o$ (7)

$T_{n,i} =5.41 + 0.73T_i$ (8)

$T_{n,o} = 17.56 + 0.31T_o$ (9)

$T_{n,i,o} = 9.22 + 0.48T_i + 0.14T_o$ (10)

ASHRAE:

$T_c = 17.8 + 0.31T_o$ (11)

Where Tc is the comfort temperature, To is the outdoor air temperature, Ti is the mean indoor air temperature, Tn,i is neutral temperature based on mean indoor air temperature and Tn,o is neutral temperature based on mean outdoor air temperature. These models will fit well for the occupants at near sedentary activity (1-1.3 met) and must be able to freely adapt their clothing. Furthermore, neither a heating system nor a mechanical cooling system can be in operation, although non-conditioned mechanical ventilation can be present. Despite this, windows must be the principal way of controlling the thermal conditions.

3. VENTILATION IN BUILDING THERMAL COMFORT

Ventilation is the key factor that determines and improves the thermal comfort in building. Ventilation is the process of supplying fresh air from outside and allow them to distribute and circulate inside the space and removing it from enclosures. Ventilation is very much essential for meeting the metabolic needs of the occupants and for diluting and removing the pollutants emitted in the indoor sources. Thus ventilation has become a key factor in providing good thermal comfort for the occupants. Building ventilation can be made by natural means and by mechanical systems. In natural ventilated building, the indoor air flow was due to wind force and buoyancy effect, where as in mechanically ventilated building uses electrically powered fans, exhaust units and air conditioning systems.

Even though the mechanical ventilation is having high capability to control the indoor space at the required temperature, it was prone to the cause of sick building syndrome and building related sickness. The thermal comfort survey conducted in Bangkok by Busch (1992) suggests that people can tolerate even higher temperature in a naturally ventilated buildings than in a mechanically ventilated buildings. Also the symptom rate in mechanically ventilated buildings is much higher than the naturally ventilated buildings (Muji et al 1998). Hence, natural ventilation is identified as a promising solution for providing good thermal comfort and also it is an important sustainable strategy in building design because of its energy saving capability.

2. TEST CASE ROOM WITH ADJACENT WINDOW OPENINGS

The test case room of size (5m x 5m x 5m) was modelled with two window openings(1m x 1m) at the adjacent sides of the building wall. The position of the window openings was changed in the vertical (Y axis), longitudinal (Z axis) and lateral direction (X axis).The test case room model along with the nomenclature was shown in figure 2. The importance of investigating the room with window openings at their adjacent walls were discussed by Ravikumar and Prakash (2009).

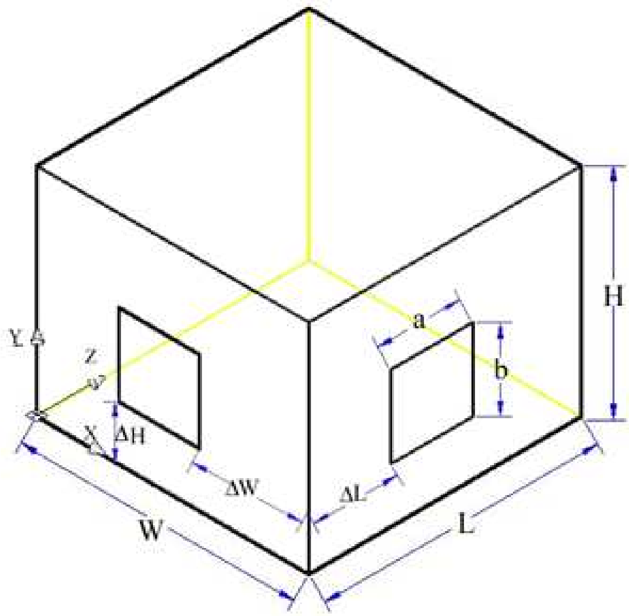

Fig-2: Test case room with windows at adjacent walls

In this paper, the window opening area and its location are generalized with building dimension as a non dimensional equation and are defined in the table 1.

Sl.No	Test case Details	Equations	Values
1	Window open area- a non dimensional number	$a* = \frac{(a \times b)}{(W \times H)}$	0.01, 0.0225, 0.04, 0.0625, 0.09, 0.125, 0.16, 0.2025 & 0.25
2	Changing the position of window in y direction	$h* = \Delta H/H$	0.1, 0.2, 0.3, 0.4, 0.5, 0.6 & 0.7
3	Changing the position of window in x and z direction at same height	$x* = \Delta W/W$ $z* = \Delta L/L$ $s*=x*=z*$	0.1, 0.2, 0.3, 0.4, 0.5, 0.6 & 0.7

Table- 1: Details of analyzed cases

3.CFD SIMULATION AND ITS BOUNDARY CONDITIONS

In general, velocity of air flow varies with respect to building height. This variation is specified either by logarithmic profile (Evalo and Popov, 2006) or by dividing the velocity inlet into a number of sub inlet zones (Asfour and Gadi, 2007). In this paper, the wind entering zone is divided in to 4 sub zones and their respective velocity is predicted form equation 12.

$$V = V_r c H^a \qquad (12)$$

where, V is the wind speed at ground level. (m/s), V_r is the reference wind speed, H is the height of the building, c is the parameter relating wind speed to terrain nature (0.68 in the open country terrain), and a is the exponent relating wind speed to the height above the ground (0.17 in the open county terrain). Ambient temperature is specified as 306 K. Free slip boundary conditions are employed to the wall surfaces. The temperature value at the side walls, floor and roof are specified as 312K, 303K and 325 K respectively. These values are based on midday measurements conducted in an actual building during the summer. Some electrical appliances used by the employees are considered and their heat generation value is assumed to be 25 W/m^2. This generated heat is uniformly applied to the floor as a boundary condition. T grid scheme of meshing is employed and this scheme uses tetrahedral shaped element for meshing the flow domain. Mesh size of 0.6m was used which identified as result independent grid size. Double- precision, segregated solver is used to solve the flow domain with standard k-ε turbulence and standard wall function (Launder and Spalding, 1974). In the solution control, second order upwind method is specified. All the cases are iterated up to the convergence level of 10^{-6}.

The above cases are simulated in FLUENT software and the mass flow rate at the windward side opening was compared with the network model and found that the CFD simulation is having a good agreement with Network model (Ravikumar and Prakash , 2009).

From the simulated cases, the average temperature at the XZ plane at various distance from the ground surface was predicted. The predicted indoor temperature was converted to a non dimensional number with reference to atmospheric temperature as T^*_{avg} .

$$T^*_{avg} = T_{in}/T_{amb} \tag{13}$$

where T_{in} is the average indoor temperature and T_{amb} is the atmospheric temperature. The T^*_{avg} for the analyzed a*, h* and s* cases are predicted at the XZ plane and are shown in figure 3 to 5 . In the figure 3, T^*_{avg} value decreases by increasing the a* value. Also, the T^*_{avg} is maximum near the Y = 4.5m and reduces gradually towards Y=2.5m and below 2.5 m a slight rise in T^*_{avg} value is identified. This variation in T^*_{avg} is common to all a* values.

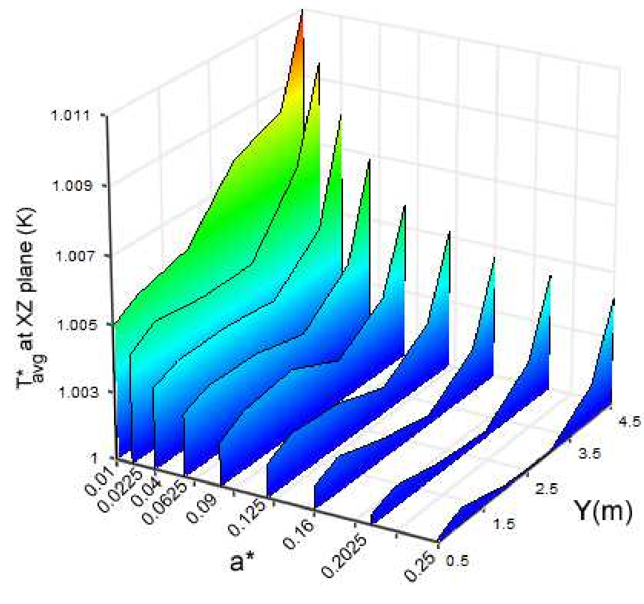

Fig-3: T^*_{avg} plot for various a* values

For the figure 4, T^*_{avg} is maximum near the Y= 4.5m and decreases suddenly towards Y=3m. However the minimum value for T^*_{avg} is obtained at different height from the ground surface. Also this minimum value occurs at the level of window opening.

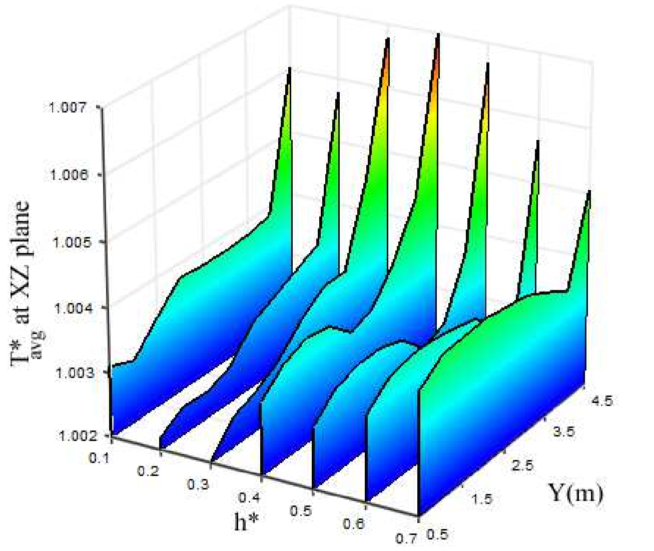

Fig-4: T^*_{avg} plot for various h* values

From figure 5, the T^*_{avg} is maximum for s*=0.1, 0.2, 0.6 and 0.7. The T^*_{avg} is minimum between s*= 0.3 to 0.5. In this case also, the T^*_{avg} value is high near Y = 4.5 m and reduces gradually towards Y=0.5m.

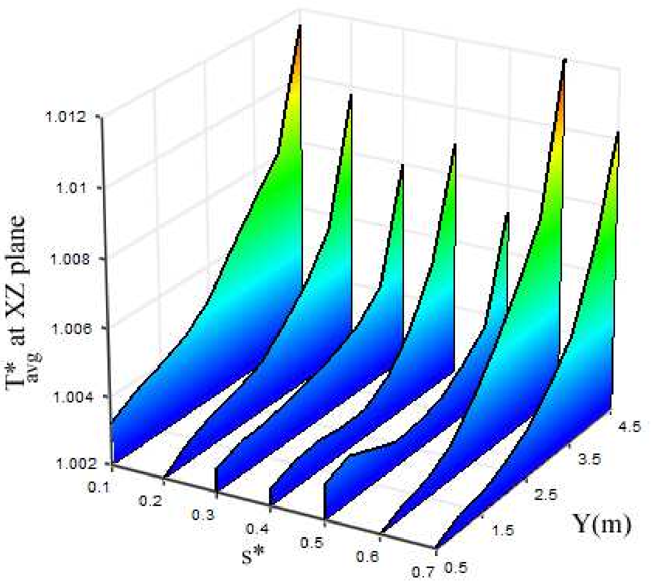

Fig-5: T^*_{avg} plot for various s* values

4. REGRESSION ANALYSIS FOR AVERAGE INDOOR TEMPERATURE

The regression analysis is conducted for the analyzed cases a*, h* and s* and their corresponding regression equations are determined. These regression equations are very much useful to predict the T^*_{avg} at various level from the ground surface. After predicting the T^*_{avg}, the indoor temperature (T_{in}) is predicted for the respective atmospheric temperature.

$$T^*_{avg\ a^*=0.1} = 0.0002\ y^5 - 0.0025\ y^4 + 0.0106 y^3 - 0.0199\ y^2 + 0.0164\ y + 1.0002 \quad (14)$$

$$T^*_{avg\ a^*=0.0225} = 2\times10^{-5}\ y^5 - 0.0003\ y^4 + 0.0015 y^3 - 0.0043\ y^2 + 0.0053\ y + 1.0021 \quad (15)$$

$$T^*_{avg\ a^*=0.04} = 4\times10^{-5}\ y^5 - 0.0004\ y^4 + 0.0016 y^3 - 0.0032\ y^2 + 0.0034\ y + 1.002 \quad (16)$$

$$T^*_{avg\ a^*=0.0625} = 3\times10^{-5}\ y^5 - 0.0002\ y^4 + 0.0007 y^3 - 0.0017\ y^2 + 0.0023\ y + 1.0016 \quad (17)$$

$$T^*_{avg\ a^*=0.09} = -2\times10^{-5}\ y^5 + 0.0003\ y^4 - 0.0016 y^3 + 0.0028\ y^2 - 0.001\ y + 1.0019 \quad (18)$$

$$T^*_{avg\ a^*=0.125} = 1.74\times10^{-5}\ y^5 - 0.000136\ y^4 + 0.000562 y^3 - 0.00176\ y^2 + 0.00273\ y + 1.00055 \quad (19)$$

$$T^*_{avg\ a^*=0.16} = 5\times10^{-5}\ y^5 - 0.0006\ y^4 + 0.0028 y^3 - 0.0063\ y^2 + 0.0065\ y + 0.9993 \quad (20)$$

$$T^*_{avg\ a^*=0.2025} = 4.11\times10^{-5}\ y^5 - 0.000459\ y^4 + 0.0021 y^3 - 0.00477\ y^2 + 0.00483\ y + 0.99939 \quad (21)$$

$$T^*_{avg\ a^*=0.25} = 5.23\times10^{-5}\ y^5 - 0.000607\ y^4 + 0.00282 y^3 - 0.00632\ y^2 + 0.0063\ y + 0.99873 \quad (22)$$

$$T^*_{avg\ h^*=0.1} = 3\times10^{-5}\ y^5 - 0.0002\ y^4 + 3\times10^{-3} y^3 + 0.0016\ y^2 - 0.0023\ y + 1.0037 \quad (23)$$

$$T^*_{avg\ h^*=0.2} = 0.0001\ y^5 - 0.0015\ y^4 + 0.0061 y^3 - 0.0113 y^2 + 0.0094\ y + 0.9995 \quad (24)$$

$$T^*_{avg\ h^*=0.3} = 4\times10^{-5}\ y^5 - 0.0004\ y^4 + 0.0014 y^3 - 0.0025\ y^2 + 0.0028\ y + 1.0009 \quad (25)$$

$$T^*_{avg\ h^*=0.4} = 2\times10^{-5}\ y^5 - 0.0002\ y^4 + 0.001 y^3 - 0.0028\ y^2 + 0.0036\ y + 1.0018 \quad (26)$$

$$T^*_{avg\ h^*=0.5} = 2\times10^{-5}\ y^5 - 0.0001\ y^4 + 0.0002 y^3 - 0.0004\ y^2 + 0.0011\ y + 1.0024 \quad (27)$$

$$T^*_{avg\ h^*=0.6} = 5\times10^{-5} y^6 - 0.0007\times10^{-5}\ y^5 + 0.0033\ y^4 - 0.0078 y^3 + 0.0091\ y^2 - 0.0043\ y + 1.0039 \quad (28)$$

$$T^*_{avg\ h^*=0.7} = 2\times10^{-5}\ y^5 - 0.0001\ y^4 + 0.0002 y^3 - 0.0004\ y^2 + 0.0011\ y + 1.0024 \quad (29)$$

$$T^*_{avg\ s^*=0.1} = 0.0001\ y^5 - 0.0016\ y^4 + 0.0071 y^3 - 0.0139\ y^2 + 0.0124\ y + 0.9993 \quad (30)$$

$$T^*_{avg\ s^*=0.2} = 1\times10^{-4}\ y^5 - 0.0011\ y^4 + 0.0048 y^3 - 0.0096\ y^2 + 0.0093\ y + 0.9987 \quad (31)$$

$$T^*_{avg\ s^*=0.3} = 0.0001\ y^5 - 0.0012\ y^4 + 0.0048 y^3 - 0.0089\ y^2 + 0.0077\ y + 1.001 \quad (32)$$

$$T^*_{avg\ s^*=0.4} = 3\times10^{-5}\ y^5 - 0.0003\ y^4 + 0.0017 y^3 - 0.0041\ y^2 + 0.0045\ y + 1.0006 \quad (33)$$

$$T^*_{avg\ s^*=0.5} = 0.0001\ y^5 - 0.0015\ y^4 + 0.0069 y^3 - 0.0143\ y^2 + 0.0128\ y + 0.999 \quad (34)$$

$$T^*_{avg\ s^*=0.6} = 1.39\times10^{-4}\ y^5 - 0.0016\ y^4 + 0.00689 y^3 - 0.01294\ y^2 + 0.01097\ y + 0.99851 \quad (35)$$

$$T^*_{avg\ s^*=0.6} = 1.14\times10^{-5}\ y^5 - 1.07\times10^{-4}\ y^4 + 5.53\times10^{-4} y^3 - 0.0013\ y^2 + 0.00182\ y + 1.00096 \quad (36)$$

4.1 Modified form of Predicted Mean Mote equation

A modified form of PMV equation is developed and this equation is the function of Metabolic rate, M; Work, W; Insulation of clothing, I_{cl}; Indoor temperature (T_{in}). This equation fit well when the metabolic rate M is within the range of 70 to 116 W/m^2. This range corresponds to standing activity

(Awbi 2003). The work value W depends on physical work performed by the occupants and it is always less than the metabolic rate M. Also, if Work increases, the metabolic rate also increases.

The insulation value of clothing in the range of 0.015 to 0.23 m^2K/W. All the available clothing will have the insulation value within the above range. The factors included in the modified Predicted mean vote equation and its level of variation are given in table 2 .

Factors	Level 1	Level 2	Level 3
Metabolic rate, M, (W/m^2)	70	93	116
Work, W (%)	25% of M	50% of M	75% of M
Insulation of clothing, I_{cl}, (m^2K/W)	0.015	0.1225	0.23
Indoor temperature, I_{in} (Kelvin)	219	307	315

Table- 2: Modified PMV equation factors and its values

By using Taguchi's L9 array the above parametric values are arranged and the corresponding Predicted mean vote values are predicted and are given in table3.

Exp No	M	W	I_{cl}	T_{amp}	PMV by Fanger's equation
1	70	25	0.015	299	0.35
2	70	50	0.1225	307	1.62
3	70	75	0.23	315	2.66
4	93	25	0.1225	315	5.15
5	93	50	0.23	299	0.498
6	93	75	0.015	307	0.84
7	116	25	0.23	307	4.3
8	116	50	0.015	315	4.07
9	116	75	0.1225	299	-0.81

Table- 3: L9 orthogonal array with modified PMV factors

From the predicted PMV value in the table 3 , the regression model is developed and given in equation 37 and its R^2 value is 0.9965**.** This equation is the simplified form of Fanger's equation. The coefficients of the equation 37 are given in table 4.

$$PMV=x_1*M+x_2*W+x_3*(MW)+x_4*I_{cl}+x_5*T_{in}+x_6 \qquad (37)$$

Coefficient	value
x_1	0.056014493
x_2	0.017295652
x_3	-0.000695652
x_4	1.547286822
x_5	0.221708333
x_6	-69.01801546

Table -4: Coefficients of modified PMV equation 37.

The closeness of modified equation of PMV with Fanger's PMV equation is predicted and its deviation with Fanger's PMV value is given in table 5 to 7 for various a*, h* and s* cases.

a*	Y (m)	Average temperature at plane XZ, T_{in} (K)		PMV value		Error %
		Regression model	CFD	Fanger's Equation	Modified PMV equation	
0.01	0.5	307.40	307.4	2.33	2.33	-0.25
0.0225	1	307.32	307.3	2.32	2.31	0.36
0.04	1	307.05	307.0	2.27	2.25	0.8
0.0625	2	306.84	306.8	2.25	2.20	1.99
0.09	2	306.75	306.7	2.24	2.18	2.44
0.125	3	306.4	306.4	2.21	2.108	4.63
0.16	3	306.38	306.2	2.19	2.103	3.96
0.2025	4	306.58	306.5	2.23	2.14	3.7
0.25	4.5	307.12	307.1	2.29	2.26	0.99

Table-5: Discrepancy of modified PMV equation with Fanger's equation for a* cases

h*	Y (m)	Average temperature at plane XZ, T_{in} (K)		PMV value		Error %
		Regression model	CFD	Fanger's Equation	Modified PMV equation	
0.1	0.5	306.86	306.9	2.25	2.2	1.7
0.2	1	306.09	306.7	2.1	2.03	2.9
0.3	1.5	306.75	306.7	2.24	2.18	2.44
0.4	2	306.99	307.0	2.27	2.23	1.39
0.5	2.5	307.16	306.9	2.27	2.276	-0.26
0.6	3	307.24	307.07	2.28	2.29	-0.6
0.7	3.5	308.11	307.8	2.41	2.43	-1.06

Table-6: Discrepancy of modified PMV equation with Fanger's equation for h* cases

s*	Y (m)	Average temperature at plane XZ, T_{in} (K)		PMV value		Error %
		Regression model	CFD	Fanger's Equation	Modified PMV equation	
0.1	0.5	306.86	306.8	2.25	2.20	1.79
0.2	1	306.67	306.6	2.23	2.167	2.8
0.3	1.5	306.76	306.8	2.25	2.18	2.78
0.4	2	306.95	306.7	2.24	2.22	0.46
0.5	2.5	306.81	306.7	2.244	2.19	1.85
0.6	3	307.36	307.4	2.33	2.32	0.41
0.7	3.5	307.52	307.4	2.34	2.35	0.677

Table-7: Discrepancy of modified PMV equation with Fanger's equation for s* cases

From the above tables 5 to 7, the maximum discrepancy of modified PMV equation with Fanger's equation is 4.63% and hence it is noticed that the modified PMV equation is having a good fit with Fanger's equation.

5. CONCLUSION

In this paper, the thermal comfort prevailed inside a room with window openings at the adjacent walls are studied under the generalized window opening area and its orientation on the wall surface. Computational fluid dynamics technique is used to simulate the indoor air and the average indoor temperature at the plane parallel to the floor iss predicted at different heights. Also the effect of window opening area (a*), position of window opening from the ground surface (h*) and orientation of window opening in lateral and longitudinal direction (s*) on the indoor air temperature are studied. From the predicted indoor average temperature, regression model are developed and the regression model are having good fit with the CFD simulated results. Finally, a modified PMV equation is developed from the Fanger's thermal comfort equation through Taguchi's L9 orthogonal array and regression analysis. The developed modified equation of PMV is also having a good agreement with Fanger's equation.

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