Investigation of Thermal Comfort in Transitional Spaces of an Institutional Building of Jaipur through Computer Simulation

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Abstract: ***The study of thermal comfort in transitional spaces has become important for last 10 years. The current comfort standards like ASHRAE 55 do not reflect the climatic diversity of India. In this regard, an attempt has been made in this paper to investigate thermal comfort in transitional spaces of an institutional building in hot and dry climate of Indian subcontinent. Both computer simulation and empirical method are used to derive the comfort temperature for selected transitional areas of the building block. Thermal Comfort factors are analyzed through regression analysis for the study area. It is observed that, the comfort temperature derived from the simulation and empirical method are very similar and close to each other. A thermally acceptable comfort range of 30.06-30.39°C is established from result. Results from this study shows that people are comfortable at a higher range of temperature than that suggested by ASHRAE 55. An extended comfort range has been suggested for naturally ventilated buildings in hot and dry climate of India.***

Keywords: thermal comfort: transitional spaces; simulation method; empirical method

1. Introduction

Two distinct features are emerging in architecture for the last 30 years: 1) Rising importance of Thermal Comfort in buildings and 2) Emergence of Transitional space as one of the key areas of the building. According to ASHRAE-55 2013, thermal comfort refers to "conditions of mind that express satisfaction with the thermal environment" [1]. This definition implies that thermal comfort varies from person to person and cannot be defined in an absolute way. Temperature preferences vary greatly among individuals and there is no single temperature that can satisfy everyone [1]. Prior to development of mechanical air conditioning systems, natural heating and cooling methods were used in buildings i.e. shading, thermal mass and natural ventilation to achieve thermal comfort [2]. People slowly moved away from these methods when mechanical cooling became available in the early 1900s. In 1902, the first mechanical cooling system was built. The emergence of air conditioning has made it possible to have a comfortable indoor environment in any climate. This led to designs which ignored variable climatic conditions and as a result less energy efficient buildings are produced [2]. These buildings consume more energy which resulted in energy crisis. Research were made to counter the issue of over consumption of energy. Among these researches, research on thermal comfort became very important. ASHRAE Standard 55 addressed the issues of thermal comfort. ASHRAE Standard 55 is applicable for "environmentally controlled spaces"[3]. However, the PMV model used by ASHRAE Standard 55 is not applicable for naturally ventilated buildings[3].

Transitional spaces are an ancillary space that acts as buffer spaces between the indoor and outdoor environment such as entrance canopies, stairwell, corridors, courtyards and atriums. These spaces accounts for 30-40% of the total volume of the buildings [4]. However, maintaining a thermally acceptable environment in the transitional spaces poses challenges to the architects and designers. At the end of 19th century, architectural space was defined as stable space enclosed by walls, until Frank Lloyd Wright proposed a theory of "flowing space" in the Charter of Machu Picchu of the International Association for Architecture. It contributed to the definition of the generally accepted cognitive of "Continuity of space" in the later centuries [5]. The structur a list architect, Aldo Van Eyck, is the first person to propose the theory of "intermediary space". He described "intermediary space" as the space that "neither belongs to interior, or to exterior space", because it functions "both with in-and-outside space" unlike western architecture [5]. Transitional spaces play a vital role in traditional Indian Architecture. It varies in scale, use and type. The transitional spaces of various forms are being witnessed in Indian Architecture which includes courtyards, corridors, entrance foyers, lobbies, atriums etc. Climatic conditions of the region also play a major role in designing the particular transition space. Since, Indian buildings are mostly naturally ventilated, PMV model for thermal comfort cannot be used here. An alternative is required to study how thermal comfort can be achieved in transitional spaces of Indian buildings.

2. Need for Study

Recently thermal comfort in transitional space is emerging as a key research area. Regarding this in 2008 Adrian Pitts said that, Predicted Mean Vote limit can be extended beyond +-0.5 for a cool climate. In 2009, Qi Jie Kwong defined the Neutral Temperature 26.8°C and Acceptable comfort range from 25.8 to 28°C of an enclosed lift lobby for hot and humid climate. In 2013, Adrian Pitts defined a Predicted Mean Vote range of Atrium as $-1.0<PMV<+1.0$ for hot and humid and Circulation zone as $-1.5<PMV<+1.5$ for cool

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climate. In 2014, Dr. Sam C.M Hui defined the Neutral Temperature 26.27°C for summer and 23.44°C for winter for hot and humid climate. In 2016, Guoying Hou defined Neutral Temperature 22.5°C for summer and 20.8°C for winter and acceptable comfortable range from 14.5-27.8°C for summer and from 14.0-27.0°C for winter for cool climate. In India, researches have been done on psychrometric chart by Sanjay Mathur in Jaipur, 2016. They found that the subjects are comfortable at a higher comfortable range than the range suggested by ASHRAE 55 [3].

Research on thermal comfort was done mainly in two areas a) Indoor spaces b) Outdoor spaces. However, very less research is available in the field of thermal comfort in transitional spaces in hot and dry climate of Indian subcontinent. This raises the necessity of doing research in that particular area, especially in India, where most of the buildings are naturally ventilated. People have attempted to quantify thermal comfort earlier. In order to do that psychrometric chart was developed in 1970s. This chart considers a comfort range of 20°C to 26°C as an acceptable limit for the “environmentally controlled spaces”. It was constructed for designing the indoor environment of conditioned buildings (commercial and residential). Since then, it has gradually begun for evaluating the indoor climate in naturally ventilated buildings as well [3]. Application of this chart is equally important in transitional spaces. As said earlier, very little research is available in the area. One might think that, there is no need of thermal comfort in transitional spaces. Thus the null hypothesis is, thermal comfort in transitional spaces follows the psychrometric chart in hot and dry climate of Indian subcontinent.

3. Profile of Study Area

Jaipur has been chosen as an example of hot and dry city of Indian subcontinent. It is situated at 26.9124°N and 75.7873°E, referring to geographic co-ordinates. Jaipur has a monsoon influenced hot semi-arid climate (Köppen climate classification) with long, extremely hot summers and short, mild to warm winters. The temperature during the summer months varies between 32°C to 45°C and 22°C to 8°C during the winter months with a mean relative humidity of 30% to 50%.

Figure 1: Ground floor plan of Aayojan School of Architecture

Source: author

The current study is limited to the transitional spaces of institutional buildings at Jaipur. To test the case, Aayojan school of Architecture is chosen. The institute is located in the outskirts of Jaipur in RIICO Institutional block, Sitapura, Goner road. Academic block has been chosen (*Fig 1*) for the study because a) the amount of time spent in this block is comparatively more than the other b) it consists of more transitional spaces than the other blocks. The transitional spaces selected are corridor, courtyard, entrance canopy and stairwell (*Table 1*).

4. Data &software used for Modelling

Air temperature (T_{ai}), Air speed (AS_i), Relative Humidity (RH_i), Metabolic Rate (M_i) Clothing Insulation (I_{cli})and Mean Radiant Temperature (T_{ri}), are used to calculate Thermal Comfort (TC_i). The study was performed in the month of October 2019. Due to limited time, the study could not be extended for other months. The parameters of the indoor environment i.e. air temperature, air speed and relative humidity were monitored using Testo 480VACinstrument (Range: -20-70°C for Air Temperature, 0-100% for Relative Humidity and 0-5m/s for Air Speed).The parameters were measured at the entrance canopy, corridor, courtyard and stairwell of Aayojan School of Architecture at 1.1m above the floor level based on ASHRAE Standard 55. Air temperature is measured in °C, Air Speed is measured in m/sec and Relative Humidity is measured in percentage (*Table 2*).

Table 1: Key characteristics of the building

Name of the space	Corridor	Courtyard	Entrance canopy	Stairwell
Location in the block	not applicable (internal)	north-west	north-west	east
Length	33.3 M	10.6 M	10.0 M	8.8 M
Width	4 M	10.6 M	6.4 M	3.2 M
Height	3 M	Not applicable (o.t.s)	3 M	3 M
Material- outer wall	exposed brickwork	not applicable	exposed brickwork	exposed brickwork
Material- inner wall	cement plastered	cement plastered	cement plastered	cement plastered
Material- flooring	marble	stone	marble	marble
Material- roofing	reinforced concrete	not applicable (o.t.s)	reinforced concrete	reinforced concrete
Color wall	white	not applicable (o.t.s)	white	white
Color floor	white	grey	white	white
Average no. of occupants	14	6	12	10

Source: Primary data survey

Metabolic Rate and Clothing Insulation values are obtained from the sample survey. A standardized questionnaire was developed for survey that was divided into 4 parts. Part A consists 16 questions of general information (not used for calculation), part B consists of 3 questions forthermal comfort evaluation (7-point sensation scale is used for calculation), part C consists of 3 questions for thermal history (7-point sensation scale is used for calculation), part

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D consists of 4 questions for thermal sensation and preference (7-point sensation scale is used for calculation). A total of 50 responses are collected from the survey. Each occupant participated in the survey after they had settled in the environment of the entrance canopy, corridor, courtyard and stairwell of Aayojan School of Architecture for more than 15 minutes before survey. Thermal Comfort, Thermal Sensation and Thermal Preference votes are obtained from the survey.

Table 2: Field Measurements

Variable	Readings			
Air Temperature (°C)	Corridor	Courtyard	Entrance canopy	Stairwell
Morning (8:00 A.M)	24.41	24.73	24.83	24.11
Afternoon (12:00 P.M)	30.72	30.48	31.5	30.09
Evening (5:00 P.M)	30.01	29.4	30.02	29.02
Derived Mean	28.1	27.9	28.7	27.7
Mean internal temperature	28.1			
Relative Humidity (%)	42	42	43	41
Derived Daily Mean	42			
Air Speed (m/s)	0.5	0.5	0.5	1
Derived Daily Mean	0.6			
Metabolic Rate (Met) Mean	1.3	1.3	1.4	1.3
Clothing Insulation (Clo) Mean	0.49	0.47	0.51	0.45

Source: Primary data survey

Mean Radiant Temperature for the above-mentioned spaces is calculated using Energy simulation software- ECOTECT 2011. Basic data regarding weather data of Jaipur and building plans of respective areas are given as input. ECOTECT 2011 performed the thermal simulation based on input. Further, simulation is done is at three time intervals of a day i.e. 8. 00AM, 12. 00PM and 5. 00PM.

5. Method

The above-mentioned data are used for the block to develop the following factors: air temperature, air velocity, relative humidity, metabolic rate, clothing insulation and mean radiant temperature.

a) Air temperature (T_{ai})

The temperature of the air surrounding the occupant. It is expressed in degree Celsius[1][6].

$$T_{ai} \quad (1)$$

b) Air speed (AS_i)

An average of the instantaneous air velocity over an interval of time[2][6].

$$AS_i \quad (2)$$

c) Relative Humidity (RH_i)

The ratio of the partial pressure (or density) of the water vapor in the air to the saturation pressure (or density) of water vapor at the same temperature and the same total pressure[3][6].

$$RH_i \quad (3)$$

d) Metabolic rate (M_i)

It is the rate of transformation of chemical energy into heat and mechanical work by metabolic activities of an individual, per unit of skin surface area (expressed in units of met) equal to 58 W/sq.m which is the energy produced per unit skin surface area of an average person seated at rest[4][6].

$$M_i \quad (4)$$

e) Clothing insulation (I_{cli})

It is the resistance to sensible heat transfer provided by a clothing ensemble, expressed in units of clo where1 clo is equal to 0.155 sq.m °C/W[5][6].

$$I_{cli} \quad (5)$$

f) Mean radiant temperature (T_{ri})

ASHRAE defines mean radiant temperature (MRT) as "the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual surroundings"[6][6].

$$T_{ri} \quad (6)$$

g) Energy simulation using ECOTECT 2011 to find Mean Radiant Temperature

Mean Radiant Temperature for the above-mentioned spaces is calculated using Energy simulation software- ECOTECT 2011. Basic data regarding weather data of Jaipur and building plans of respective areas are given as input. ECOTECT 2011 performed the thermal simulation based on input. Further, simulation is done is at three time intervals of a day i.e. 8. 00AM, 12. 00PM and 5. 00PM. The simulation is performed on every floor of the spaces. The result is shown in Table 3.

h) Finding Operative temperature (T_O) as Comfort temperature (T_C) from Mean Radiant Temperature

The derived mean value obtained from the simulation is put into the following equation:

$$T_o = T_a + T_r / 2^7 \quad (7)$$

The result derived from the equation is the comfort temperature found in simulation method. To corroborate the result, further sample survey is conducted. The result from the sample survey is used to find the comfort temperature through empirical method.

i) Relationship between Thermal Comfort and Air temperature (T_{ai}), Air speed (AS_i), Relative Humidity (RH_i), Metabolic Rate (M_i) Clothing Insulation (I_{cli}) and Mean Radiant Temperature (T_{ri})

To study the empirical method, several factors were considered. According to ASHRAE-Standard 55, Thermal comfort is dependent on Air temperature (T_{ai}), Air speed (AS_i), Relative Humidity (RH_i), Metabolic Rate (M_i), Clothing Insulation (I_{cli}) and Mean Radiant Temperature

[1]See *ASHRAE Standard-55, 2010, pp 3*
[2]See *ASHRAE Standard-55 2010, pp 3*
[3]See *ASHRAE Standard-55 2010, pp 3*
[4]See *ASHRAE Standard-55 2010, pp3*
[5]See *ASHRAE Standard-55 2010, pp 3*
[6]See *ASHRAE Standard-55 2010, pp 3*
[7]See *ASHRAE Standard-55, 2010, pp 13*

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(T_{ri}). Therefore, a relationship is established. It is expressed through the following:

$$TC_i = f\,(T_{ai}, AS_i, RH_i, M_i, I_{cli}, T_{ri}) \quad (8)$$

j) Regression Analysis

The exact nature of relationship between Thermal Comfort and Air Temperature, Air speed, Relative Humidity, Metabolic Rate, Clothing Insulation and Mean Radiant Temperature is further analyzed through regression analysis for the selected area. The derived *intercept* value is used for derivation of comfort temperature.

k) Derivation of Empirical Comfort Temperature using method of Fanger (1970)

[In 1970, P.O Fanger developed the PMV model derived from laboratory studies and climatic chamber research for thermal comfort evaluation. In that he argued that thermal comfort is influenced by air temperature, air velocity, relative humidity, metabolic rate clothing insulation and mean radiant temperature. He derived the formula for calculating the comfort temperature.]

The comfort temperature for the study area is derived through the following:

$$T_c = T_a + (4 - C_m) / a$$

[See Thermal Comfort in Enclosed Lift Lobby of a Tropical Educational Institution, 2010, pp 16][7](9)

Where T_c is the comfort temperature, T_a is the mean internal temperature, $C_m$is the mean comfort vote and *a* is the *intercept* of the regression coefficient. The derived intercept value (*a*) is used to predict the empirical thermal comfort temperature.

l) Corroboration of results from simulated method and empirical method

Both the methods are compared to find the similarity between them. The results are discussed below.

6. Result and Discussion

The results are divided into two parts A) Result from simulation B) Result from empirical data.

Table 3: Mean Radiant Temperature

Time interval	Corridor				Courtyard	Entrance Canopy				Stairwell			
	Ground floor	First floor	Second floor	Third floor	Ground floor	Ground floor	First floor	Second floor	Third floor	Ground floor	First floor	Second floor	Third floor
8.00 AM	22-25	22-25	22-25	22-25	22-25	25-28	25-28	25-28	25-28	25-28	25-28	25-28	25-28
12.00 PM	31-34	31-34	31-34	31-34	28-31	31-34	31-34	31-34	31-34	28-31	28-31	31-34	31-34
5.00 PM	19-22	19-22	19-22	19-22	19-22	22-25	22-25	22-25	22-25	22-25	22-25	22-25	22-25
Mean	25.5	25.5	25.5	25.5	24.5	27.5	27.5	27.5	27.5	26.5	26.5	26.5	26.5

Source: Simulation from ECOTECT 2011

m) Result from simulation

The mean internal temperature (T_a) obtained from the field measurement is 28.1°C. The Mean Radiant Temperature obtained from the simulation method is 32.02°C. Hence the obtained value is put into the equation 7 and an operative temperature also known as comfort temperature is derived. The derived operative temperature is 30.06°C. This is also known as comfort temperature [See *ASHRAE Standard-55, 2010, pp 13*].

n) Result from Empirical data

The mean internal temperature (T_a) obtained from the field measurement is 28.1°C. The value of mean thermal sensation vote known as comfort vote (C_m) was established by calculating the total average sensation scale, and identified as 3. The value of the *intercept* (*a*) from the linear multiple regression analysis is 0.435. Hence all the obtained values are put into the equation 9. The derived comfort temperature (T_c) is 30.39°C.

It is found that the comfort temperature derived from the simulation method and empirical methods are very similar and close to each other. According to the simulation method, the people are comfortable at 30.06°C. The empirical method also proved this. Therefore, people are comfortable truly at 30.06-30.39°C. This is an exception to psychrometric chart. Thus the null hypothesis is rejected. Thermal comfort in transitional spaces does not follows the psychrometric chart in hot and dry climate of Indian subcontinent. The comfort zone defined in the psychrometric chart is between 20-26°C. However, our current study proves that the upper limit of psychrometric chart can be increased up to 30-31°C, which is 4°C more than the accepted range.

7. Conclusion

Indian buildings are mostly naturally ventilated. In these buildings, transitional spaces play a major role in lighting, ventilation and socialization. Hence, thermal environment of the transitional spaces is equally important as indoor and outdoor environment. It plays a major role in buildings of Indian climate. Temperature change is one of the main factors of discomfort in all these spaces. Temperature preferences vary from individual to individual and hence one cannot satisfy everyone. Also human thermal perception towards a space is very important. Regarding this, ASHRAE Standard states that an environment is thermally acceptable if 80% of the people are satisfied with the environment. The comfort zone defined on psychrometric chart accounts for only air-conditioned buildings. It says that, the upper limit of comfort temperature is 26°C. However, comfort temperature derived from study area is between 30.06-30.39°C.Study also shows that, subjects are comfortable at the above mentioned temperature, which is almost 4°C higher than acceptable limit prescribed by ASHRAE. Thus, the study proposes that the upper limit of the chart can be modified for hot and dry climate in Indian context.

A more comprehensive study can be conducted over a prolonged period of time for data collection in multiple sectors of the city, effect of metabolic rate and clothing

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insulation, behavioral adaptations of the occupants which is left out due to limited space. It is also important to study the effect of air velocity in all these spaces.

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Author Profile

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