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RANKING OF INDIAN CITIES BASED ON HEAT INDEX IN MIXED MODE BUILDING

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Abstract:

Thermal comfort depends on one's satisfaction with the ambient temperature. The climate and people of a place determine its comfort. Mixed-mode ventilation methods are becoming more popular as an eco-friendly HVAC alternative. Using a combination of mechanical cooling and natural ventilation, mixed-mode building operations create pleasant interiors while reducing the load on the HVAC system. According to many studies, India is classified into several climate zones. Ranking Indian towns only on climatic comfort is challenging. Differences in climatic conditions and the ways in which people have adapted to those prevailing conditions, people have adapted to a unique base temperature or the neutral temperature however, the base temperature in different cities lying in different climatic condition cannot be the same. One of the most common methods for determining how hot it feels outside is to use a tool called the heat index. Steadman's model of human thermoregulation, air temperature and relative humidity are used in this method. Climate comfort is the focus of this study. By analysing Heat Index values, the Analytical approach ranked India's most comfortable cities. It has been proved that the city of Mumbai, which is in the climate zone of warm and humid with temperatures ranging from 18°C to 35°C, requires less cooling and heating in summer and winter respectively, making it the finest city in terms of Mixed mode ventilated buildings. Leh, which has a cold environment with temperatures ranging from -31°C to 13°C, requires heating throughout the year and is therefore not thermally comfortable.
Keywords: Heat index; Thermal comfort; Mixed Mode ventilation; City ranking

1. Introduction:

In the past two hundred years, the world's population has grown by a factor of only six, but the number of people living in cities has climbed by a factor of 128 (Lilly Rose, 2010). As per the United Nations reports, more than 55% of the world's population lives in urban areas, and by 2050, it will rise to 70% (Mesce & Ringheim, 2011). The rise in the number of buildings that is a direct consequence of urbanisation contributes to an increase in temperature not just locally but also globally (Kikegawa et al., 2006). Urban Heat Island effect which is one of the major issues for urban areas increase the heat stress in hot climate, however supress the effectiveness of cold in cold climate (Hass et al., 2016).

The early thermal indices were primarily created for businesses and the military whose workers had to operate in harsh weather circumstances that might have a detrimental impact on their productivity and efficiency and possibly put their lives in danger (Epstein & Moran, 2006). Human comfort and discomfort led to development of thermal indices suitable for hot condition, Discomfort Index (DI)(Thom, 1959) based on dry bulb, wet bulb temperature, Heat Index (HI) based on ambient temperature and relative humidity(Steadman, 1979), Temperature Humidity Index (THI)(Emmanuel, 2005) also based on ambient temperature and relative humidity, Tropical Summer Index (TSI) based on dry bulb temperature, wet bulb temperature and wind velocity (Sharma & Ali, 1986) Relative Strain Index(RSI) based on air temperature and vapour pressure. Different universal thermal indices evolved, suitable for both climate conditions – Predicted Mean Vote (PMV(Humphreys & Hancock, 2007), (PET) Physiological equivalent temperature (Ohlert et al., 1995) Standard effective temperature (SET) (Gonzalez et al., 1974), Temperature Humidity Index (TSI) (Emmanuel, 2005) also based on ambient temperature and relative humidity, Modified Physiological equivalent temperature (mPET (Y. Chen & Matzarakis, 2018)

Several activity and jobs are affected by thermal discomfort. Workers have to deal with extreme heat stress, which can hurt their work and productivity and even put their lives at risk (Potchter et al., 2018). Thermal comfort improves work efficiency and encourages people to participate in different activities, which will benefit residents from various perspectives, including physical, environmental, economic, and social aspects, thereby promoting the quality of life in cities (L. Chen & Ng, 2012). The thermal comfort of any location depends on primarily four factors: ambient temperature, relative humidity, wind velocity, and solar radiation; however, the thermal comfort also gets affected through Clo value, human metabolism and human body adaptation and many more.

As per the study of (Bansal & Minke, 1988), Indian climate can be categorised in six climatic zones which are hot & dry, warm & humid, moderate, cold & cloudy, cold & sunny and composite. The criteria for the classification of the zones are according to (Table 1).

Table 1 Climate Zone Classification Criteria (Bansal & Minke, 1988)

Climate Zone	Mean Monthly Temp (°C)	Relative Humidity (%)	Precipitation(mm)	Number of clear days
Hot &Dry	>30	<55	<5	>20
Warm & Humid	>30	>55	>5	<20
Moderate	25-30	<75	<5	>20
Cold & Cloudy	<25	>55	>5	<20
Cold & Sunny	<25	<55	<5	>20
Composite	Any of the season does not fall for more than six month			

As per the National Building Code of India 2005, based on mean monthly temperature and mean monthly relative humidity, the climate of India has been classified into five major climatic zones (Hot-dry, warm- humid, temperate, cold, & composite as per (Table 2) (Figure 1). The climatic zones which were used earlier namely 'cold & cloudy' and 'cold & sunny' has been clubbed together as 'cold climate' and nomenclature of 'moderate season' changed to temperate in NBC 2005. The Five climate zone has been marked in the map of India shown in (Figure 1). For climatic classification, six months of prevailing weather conditions must be of a specific category. In case if none of the defined season last for more than six month, then it may be called a composite climate zone (NBC, 2016).

Table 2 Climatic zone classification Criteria (NBC, 2016)

SI No.	Climatic Zone	Mean Monthly Max. Temperature(°C)	Mean Monthly Relative Humidity (%)
1.	Hot-dry	Above 30	Below 55
2.	Warm-humid	Above 30	Above 55
		Above 25	Above 75
3.	Temperate	25 – 30	Below 75
4.	Cold	Below 25	All Values
5.	Composite	Any of the season does not fall for more than six month	

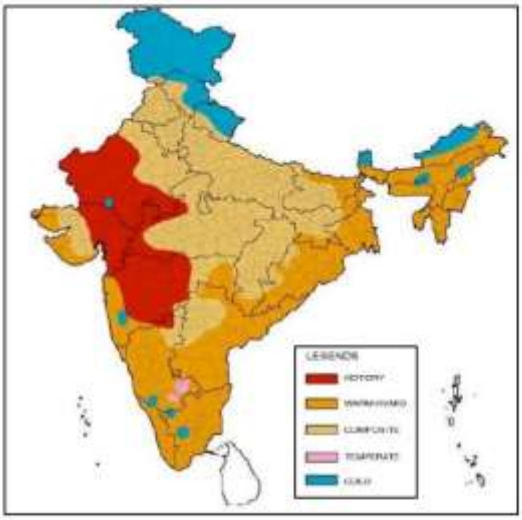

Figure 1 NBC Climatic Zone Classification (Bureau of Indian Standard, 2016)

Further as per study for 60 cities in 2019, based on (ANSI/ASHRAE, 2021), India has been classified in eight climate zone. The classification is based on the analysis of cooling degree days and heating degree days. The indoor temperature always differ from the outdoor temperature due to thermal lag, (Koenigsberger et al., 2013), as the temperature decreases or increases from the base temperature inside the building, mechanical heating and cooling is required accordingly. In case of decrease in temperature, it is heating degree days. In case of increase in temperature, from base temperature it is cooling degree days. Heating Degree days (HDD) or cooling degree days (CDD) is basically the difference of base temperature and mean temperature inside a building (Bhatnagar et al., 2018).

$$HDD = (T_{base} - \frac{T_{max} + T_{min}}{2})^{+}$$

$$CDD = (\frac{T_{max} + T_{min}}{2} - T_{base})^{+}$$

Table 3 Climate Zone Classification Criteria (Bhatnagar et al., 2019)

Climate Zones	CDD Min.	CDD Max.	HDD Min.	HDD Max.	RH Min. (%)	RH Max. (%)
1.	3231	4154	0	8	68	81
2.	3046	4153	0	240	43	57
3.	2181	3638	0	248	54	76
4.	1861	2325	43	182	81	83
5.	1861	2369	182	484	67	73
6.	1328	-	427	-	78	-
7.	128	-	1518	-	84	-
8.	688	-	2018	-	70	-

Mixed-mode (MM) ventilation techniques are gaining popularity as an alternative to conventional heating, ventilation, and air conditioning (HVAC) solutions since they are more energy efficient. Mixed-mode building operation, also known as hybrid building operation, is able to produce comfortable indoor settings while at the same time minimising dependency on energy-intensive HVAC systems. This is accomplished by mixing both natural ventilation and mechanical cooling solutions (Kim et al., 2019).

Natural ventilated building users can live and experience less thermal discomfort than the mixed mode and air conditioned building users (*Energy Conservation Building Code 2017*, n.d.), however, Over the time human body adapt to environmental condition and become accustomed.

In context of India tropical region, mixed mode building users are larger. Using active heating and cooling system only when the indoor comfort condition not achieved alone with the Natural ventilation(Kim & de Dear, 2021). Natural ventilation and active cooling may be operated simultaneously, separately, and based on season for different part of the building(Brager, 2006) (Luo et al., 2015).

This paper is based on thermal comfort in mixed mode building, discussing seasonal variation in temperature and relative humidity, thus based on both factors heat Index Indices has been taken into account for the analysis of thermal comfort in different metropolitan cities.

1. Methods:

To rank the city based on thermal comfort condition, two major factor ambient temperature and relative humidity has been taken into account. The monthly data of temperature and humidity obtained from the online website Indian climate.com. Cities for the analysis has been selected based on climatic zone (NBC, 2016), Tourism potential and importance of cities. Base temperature for each city is different and dependent upon climatic zone as the adaptation condition of inhabitants varies from one area to another area. As per the analysis of Heating Degree days and Cooling Degree days, the base temperature 18°C for heating and 17.4°C for cooling, the proposed heating and cooling temperature is 18°C (Bhatnagar et al., 2018).

The comfortable ambient temperature (when an adult is at rest, clothing is appropriate for the season, they are not exposed to sun radiation, and relative humidity is greater than 50 %). 17°C for the cool and temperate zone, 23°C for the temperate zone, 25°C for the subtropics zone, and 27°C for the tropics zone.

A single base temperature for each city can't give the appropriate information about the thermal comfort due to change in inhabitant's adaptation; Increase in temperature appears to be manageable for the people who live in tropical regions to some extent. Those who live in tropical climates accept perspiring for comfort (Zahid, Maida, Rasul, 2009). To compare the cities thermal comfort, it's necessary to take base temperature of each city as per their climatic condition and adaptation.

Table 4 Proposed Base Temperature for different cities (Zahid, Maida, Rasul, 2009)

City Name	Climatic Zone (NBC, 2016)	Climatic Zone *(Zahid, Maida, Rasul, 2009)*	Base Temp.
Ahmedabad	Hot-Dry	Sub-tropic	25°C
Jaiselmer	Hot-Dry	Sub tropic	25°C
Chennai	Warm & Humid	Tropic	27°C
Mumbai	Warm & Humid	Tropic	27°C
Kolkata	Warm & Humid	Tropic	27°C
Shillong	Warm & Humid	Temperate	23°C
Bengaluru	Temperate	Temperate	23°C
Hyderabad	Composite	Tropic	25°C
Nagpur	Composite	Tropic	27°C
Bhopal	Composite	Sub tropic	25°C
Delhi	Composite	Sub tropic	25°C
Patna	Composite	Sub -Tropic	25°C

Lucknow	Composite	Sub -Tropic	25°C
Leh	Cold	Sub -Tropic	17°C
Srinagar	Cold	Sub -Tropic	17°C

As per (Table 4) base temperature is varying between 17°C - 27°C. Leh shows minimum base temperature 17°C due high adaptation level in cold and dry climatic condition and Chennai, Mumbai and Kolkata shows maximum due to large adaptation level in hot and humid condition.

The indices selected for the analyses of Outdoor Thermal comfort

Heat Index (HI)

Heat index can be defined as perceived temperature felt by the human body. It can be calculated through various parameters like temperature, relative humidity, vapour pressure, Dimensions of human, clothing cover, wind velocity etc., and HI value can be calculated through collection of equation, However not any fixed equation for HI exists. (Steadman, 1979). Heat Index equation based on ambient temperature and relative humidity (Rothfusz & Headquarters, 1990).

HI $= -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783\times10^{-3}T^{2} - 5.481717\times10^{-2}R^{2} + 1.22874\times10^{-3}T^{2}R + 8.5282\times10^{-4}TR^{2} - 1.99\times10^{-6}T^{2}R^{2}$

Where T is ambient air temperature in °F and R is relative humidity.

Table 5. Heat Index (Steadman, 1979)

Relative Humidity %	Air temperature °C										
	21	24	27	29	32	35	38	41	43	46	49
0	18	21	23	26	28	31	33	35	37	39	42
10	18	21	24	27	29	32	35	38	41	44	47
20	19	22	25	28	31	34	37	41	44	49	54
30	19	23	26	29	32	36	40	45	51	57	64
40	20	23	26	30	34	38	43	51	58	[illegible]	
50	21	24	27	31	36	42	49	57	[illegible]		
60	21	24	28	32	38	46	56	65			
70	21	25	29	34	41	51	62				
80	22	26	30	36	45	58					
90	22	26	31	39	50						
100	22	27	33	42							

Serious risk to health - heatstroke imminent
Prolonged exposure and activity could lead to heatstroke
Prolonged exposure and activity may lead to fatigue

The extended heat index can be mapped onto the physiological responses of an idealized human, such as heat fatigue, heat stroke, and even death due to heat and this mapping can provides an indication of regional health outcomes for varying degrees of global warming (Lu & Romps, 2022).

Table 6 Effect of Heat Index on Health (Zahid, Maida, Rasul, 2009)

Heat Index (°C)	Effect on Health
27 – 32	long exposure and/or physical activity – Possible to get tired
32 - 41	long exposure and/or physical activity - Heat cramps and heat exhaustion
41 - 54	long exposure and/or physical activity - Heat cramps and heat exhaustion are likely and heat stroke is possible
> 54 or higher	Heatstroke highly likely with continued exposure

Among all cities, the analysis of the capital city of India (Delhi) is shown in this paper. For the other cities only the data has been shown. The minimum, maximum, and average (ambient dry bulb) temperatures and the city's relative humidity were used to figure out the city's heat index. The Heat index has been calculated using an online heat index calculator (NOAA, 2021) For outdoor shade area.

According to (Table 7) below, the minimum temperature in Delhi is 5.5°C in December and the maximum temperature is 42.7°C in May, with the relative humidity varying from 100% in January to 15.6% in April. This demonstrates that the climate in Delhi is really severe. It gets quite cold in the winter (December - March) and very hot in the summer (April - July) (December - January). During the summer, the temperature can range from 29°C to 43°C, while during the winter; it can go from 22°C to 5°C.

Table 7 Delhi temperature, Relative Humidity and Heat Index Data

Delhi												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Min (°C)	6	8	16	21.2	24.9	26.5	26.1	25.9	22.6	16.4	11.9	5.5
Max (°C)	22.8	27.7	34.8	39.6	42.7	41.2	38.9	33.6	33.2	32.4	28.3	23.1
Avg. (°C)	13.2	18.1	24.4	29.4	32.7	33.4	30.2	29.4	27.7	24.6	19.8	13.7
RH min. (%)	44.9	37.5	24.2	15.6	14.9	30	40.2	60.3	55.4	39.7	36.3	49.4
RH max. (%)	99	94.4	87.5	84.9	74.1	95.1	96.2	95.5	98.2	90.4	93.6	97.2
RH Avg. (%)	75.9	66.6	52.5	44.4	41.7	56.6	79.6	81.8	82	70	70.3	76.5
HI (min.)(°C)	5	7	16	22	25	30	29	28	23	16	12	5
HI max. (°C)	22	27	33	38	41	46	46	41	38	33	28	23
HI avg. (°C)	13	18	24	29	34	39	38	36	32	25	20	13
Base Temp. (°C)	25	25	25	25	25	25	25	25	25	25	25	25
B.T- HI (min.)	20	18	9	3	0	-5	-4	-3	2	9	13	20
B.T - HI (max.)	3	-2	-8	-13	-16	-21	-21	-16	-13	-8	-3	2
B.T - HI (avg.)	12	7	1	-4	-9	-14	-13	-11	-7	0	5	12

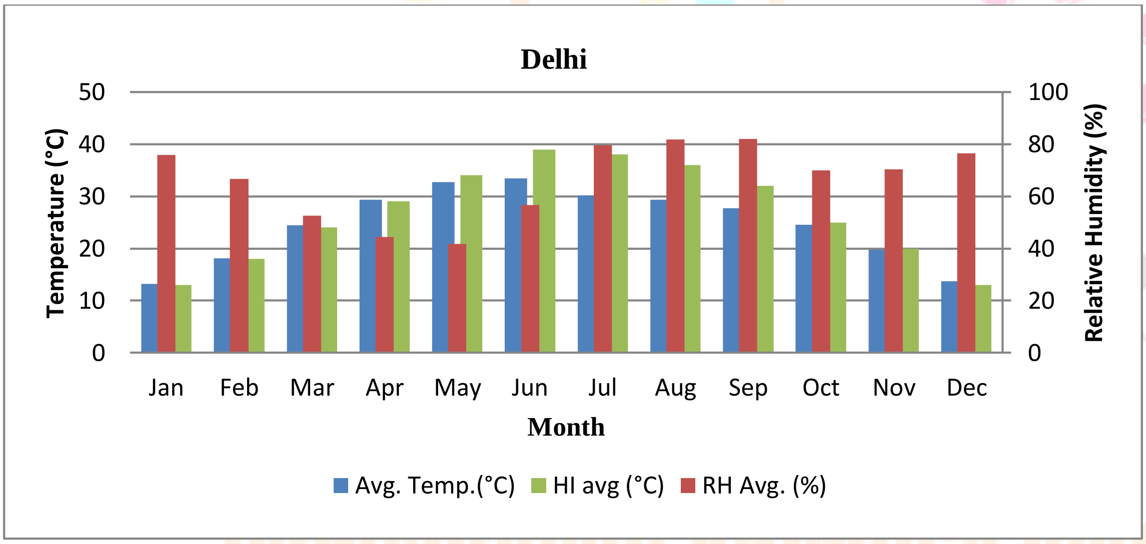

Figure 2 Average Temperature, Heat Index and Relative Humidity Data of Delhi

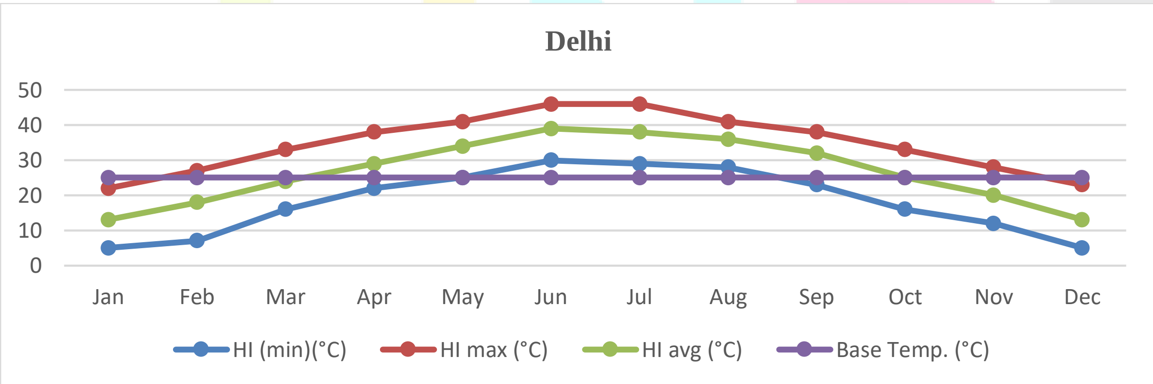

Figure 3 Monthly variation in the heat index as compared to Base temperature

After determining the minimum, maximum, and average heat index, we subtracted the heat index from the base temperature to obtain a sense of how much °C we need to deal with. Positive value of temperature gap shows the low heat index due to low temperature and high humidity and high heat index shows high temperature and low humidity. When the temperature is high, it's important to take measures to keep cool, and when it's low, it's important to keep warm. Temperature gap can be calculated by (Equation 1).

$$°C\ \boldsymbol{Gap}\ (\boldsymbol{min.}) = \boldsymbol{Base\ Temp} - \boldsymbol{Heat\ Index}(\boldsymbol{min.}) \qquad \textbf{(Equation-1)}$$

Similarly temperature gap for maximum and average heat index can be calculated using Equation-1. The positive value of temperature gap shows the cooling temperature, and negative value shows heating required for the month. To reduce the negative value, the sum of square of each month of temperature gap has been taken.

Calculation based on equation 1.
Sum of squares of °C gap (Jan-Dec), when Heat index is min. = 1518
Sum of squares of °C gap (Jan-Dec), when Heat index is max. = 1886
Sum of squares of °C gap Jan-Dec), when Heat index is avg. = 995

After that, total temperature required for thermal comfort need to be calculated using (Equation 2), which is square root of sum of squares of temperature gap (min., max. and average).

$$\boldsymbol{Z}(°\text{C})\boldsymbol{required} = \sqrt{\sum_{jan}^{dec}\{(°\text{C}\ \boldsymbol{gap}(\boldsymbol{min}.)^2 + (°\text{C}\ \boldsymbol{gap}(\boldsymbol{max}.)^2, (°\text{C}\ \boldsymbol{gap}(\boldsymbol{avg}.)^2\}} \quad \textbf{(Equation-2)}$$

Sum of Heat Index which gives the total temperature required for thermal comfort for Delhi is 66.32, using (Equation 2). With the same process, the total Heat Index for other 14 cities has been calculated, the data given below (

Table 8).

$$\boldsymbol{R = 200 - Z} \qquad \textbf{(Equation-3)}$$

Sum of heat index (Z) shows the temperature required for occupant thermal comfort, so by subtracting Z by 200 (value taken greater than the larger value of sum of heat index) , the thermal comfort in term of heat index can be related (Equation 3).

3. Result:

The sum of the Heat Index for each city represents the mechanical energy required in terms of heating and cooling to achieve indoor thermal comfort. The cities with a larger sum of Heat Index require more mechanical energy, while the cities with a smaller sum of Heat Index require a smaller amount of mechanical energy for thermal comfort as shown in (

Table **8**).

Table 8 Total Temperature for Thermal Comfort

City Name	Sum of Heat Index
Mumbai	32.16
Bengaluru	32.88
Chennai	46.97
Shilong	47.7
Nagpur	49.74
Bhopal	53.59
Ahmadabad	58.46
Hyderabad	63.69
Kolkata	64.96
Patna	65.63
Delhi	66.32
Jaiselmer	67.29
Lucknow	68.59
Srinagar	96.95
Leh	158.6

To show the level of thermal comfort in these cities, the sum of Heat Index is subtracted by 200,

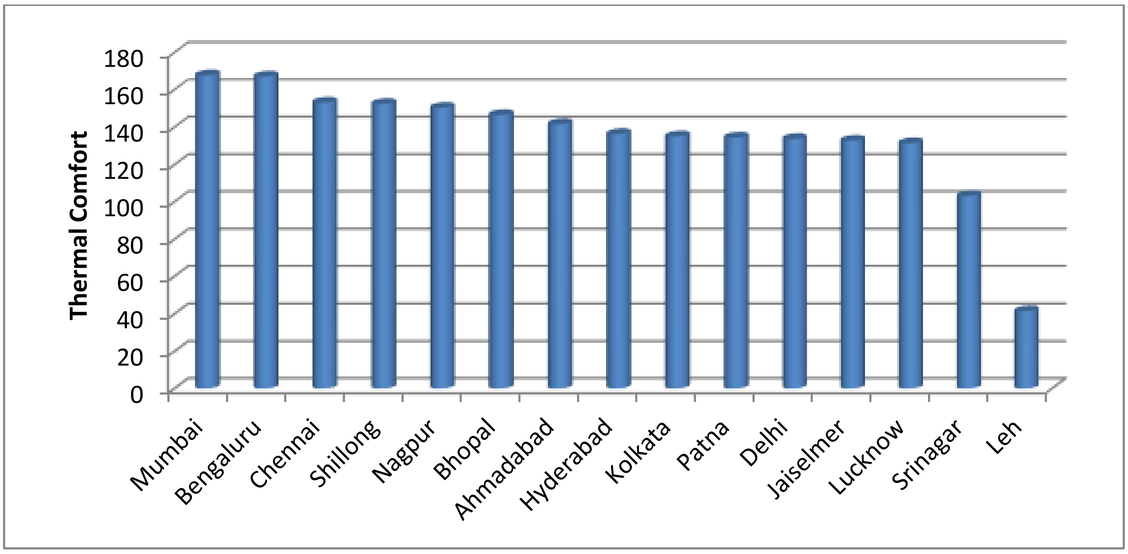

Figure 4 level of Thermal comfort among 15 cities

Based on change in base temperature and climatic condition, Mumbai is most thermally comfortable as it requires less mechanical energy for cooling, and Leh is most thermally uncomfortable as it requires maximum mechanical energy for heating in mix mode building among the given 15 cities.

5. Conclusion

The climate and inhabitant's adaptation, both plays a vital role in determining what constitutes a comfortable temperature in any given region. Cities like Patna, Delhi, and Kolkata demonstrate comfort at a base temperature of 25 degrees Celsius, whereas cities like Shimla, Srinagar, and Gangtok feel overheated at the same temperature. For chilly cities, 17 degrees Celsius is quite comfortable. Although Bengaluru is well known for comfortable climatic condition and urban environments, research suggests that, based on climatic condition and thermal adaptation, Mumbai is at par with Bengaluru and requires moderate mechanical energy for cooling and heating as compare to other cities.

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