Thermal - Visual Comfort Analysis

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***Abstract*—Balance is an important characteristic of nature. It is important to establish a sustainable balance of key parameters if one is to move towards growth and development. The same characteristics are attributed to both thermal and visual comfort. If a person is thermally or visually uncomfortable, he or she will be unable to work effectively thus reducing human efficacy. A combination of photometric and radiometric quantities will help us determine a suitable and effective comfort zone.**

Keywords—Thermal, Visual, Efficacy, Photometric, Radiometric, Comfort Zone.

I. INTRODUCTION

In a country like India which experiences a wide variation of temperature, there is bound to be some kind of discomfort as a result of temperature differences and or geographical changes taking place. Not too long ago the Earth and especially the northern hemisphere experienced a climatic phenomenon called the 'polar vortex' which resulted in a decrease in global temperatures during that period. On a localized level our area of interest is the area of Manipal. Manipal is a university township located at 13.3470° N, 74.880° E, which experiences mostly hot and humid climate. This feature can be attributed to the close proximity of the Arabian Sea which is not more than five kilometers from the main city. In order to develop a sustainable comfort model we will be interested in temperature, relative humidity, illuminance and glare. These radiometric and photometric quantities respectively will form the foundation of our study. We will also look at predicted mean vote (PMV) and percentage people dissatisfied (PPD) as the two qualitative comfort indices for thermal comfort and visual comfort probability(VCP) and unified glare index (UGR) for visual comfort. Our study was conducted in a closed model room with dimensions 3.75m×3.75m×2.5m (length, breadth, height).

II. COMFORT MODELS

A. Thermal comfort

The thermal model we have considered involves the following radiometric quantities viz.; temperature, mean radiant temperature, humidity, air velocity, clothing insulation and human activity level. These parameters form the foundation of predicted mean vote and percentage people dissatisfied

The range of acceptable values for PMV is from -3 to +3. A negative value is indicative of feeling cold whereas a positive value is indicative of feeling hot. However, feeling hot and cold are relative terms and scientifically they refer to loss or gain of radiant heat[1]. Mathematically P.M.V. is given as:

$$P.M.V. = (0.303e^{-0.036M} + 0.028) * L \quad (1)$$

In the above equation M stands for metabolic rate and L stands for thermal load – defined as the difference between internal heat production and the heat loss to the actual environment – for a person at comfort skin temperature and evaporative heat loss by sweating at the actual level. According to ASHRAE standards the comfort zone with respect to this model lies between -0.5 and +0.5 and 0 is the value indicating thermal neutrality[2].

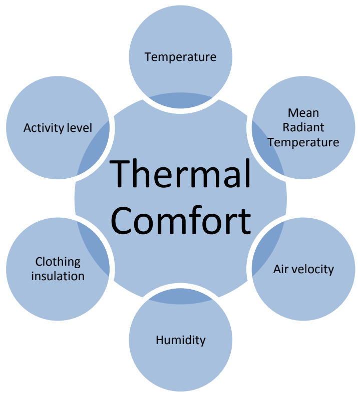


Fig. 1. Thermal comfort model

Predicted mean vote is derived from the physics of heat transfer combined with an empirical fit to sensation. PMV establishes a thermal strain based on steady state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain. PPD however, is the predicted percentage of people dissatisfied at each PMV[3]. Based on the PMV index we have two types of comfort control methods: steady and dynamic comfort control. The former is apt to maintain thermal comfort at a constant level, while the later at iteratively varying comfort levels [4].

Some of the factors which cause thermal discomfort are radiant temperature asymmetry, vertical air temperature differences, floor surface temperature, drought, metabolic rate, etc.

In order to measure exterior and interior radiometric quantities we will be using analog precision grade temperature sensors along with relative humidity sensors in a grid arrangement interfaced with LabVIEW™ .To maintain a static environment we will sought the use of an air conditioning unit which will help us tune the interior temperature of the room according to the desired values.

B. Visual comfort

The visual comfort model in consideration involves only three photometric quantities viz.; irradiance, illuminance, luminance and the metrics used for visual comfort are UGR and VCP.

According to the International Commission on Illumination, i.e. the CIE, defines glare as the visual conditions in which there is excessive contrast or an inappropriate distribution of light sources that disturbs the observer or limits the ability to distinguish details and objects [5]. Broadly speaking there are two types of glare; the first one is disability glare and the other is discomfort glare. They are categorized so according to the effect they have on the viewer.

The CIE has also defined the UGR as a quantitative measure of the amount of glare in a specific environment. It is basically the logarithm of the glare of all the visible lamps, divided by the background luminance L_b [5]. It is mathematically expressed as

$$U.G.R. = 8 * \log\left(\frac{0.25}{Lb} * \Sigma n\left(L^2 n * \frac{Wn}{P^2 n}\right)\right) \quad (2)$$

In the above equation L_b is the background luminance, L_n is the luminance of each light source numbered n, W_n is the solid angle as seen by the observer and P_n is the Guth position index, which depends on the distance from the line of sight of the viewer.

IESNA specifies that in any room the glare must be less than equal to 28. Any room designed should keep in mind lamp lumen depreciation, glare both across and lengthways and minimum natural illuminance. This will also ensure energy savings. Quality of light is also important in the determination of visual comfort and it involves color rendering, contrast, ambience, color temperature, uniformity and glare.

Visual comfort is linked to people's expectations whereas visual performance is solely dependent on the visual system, both natural and artificial. Therefore any lighting installation which doesn't meet expectations may be considered uncomfortable even though visual performance is more than adequate. This only suggests that lighting conditions influence task performance as they directly and continuously involve the stimuli. Therefore in many ways lighting has a contrasting psychological and physiological effect. Visual comfort probability is another important metric for analyzing a visual system. It is given by

$$Lv = 9.2 * \sum_{i=1}^{n} \frac{Ei}{\o i(\o i+1.5)} \quad (3)$$

Where L_v is the veiling illuminance is cd/m^2, E_i is the illuminance from the ith glare source at the eye in lux and $\o_i$ is the angle between the target and the ith glare source in degrees.

In order to control the illuminance and glare in the room we will be making use of motor controlled blinds (vertical) which at different angles will give us a certain percentage of daylight. To measure illuminance we will be using a combination of optical sensors and phototransistors calibrated against a standard lux meter and interfaced with LabVIEW™.

III. THERMAL ANALYSIS

The thermal analysis deals with all the thermal parameters both interior and exterior to the room. This analysis involves the study of heat signatures, temperature differences and other strategically important radiometric quantities.

Thermal analysis is quintessentially important for a thermal engineer as this forms the backbone of his or her work. A good thermal analysis follows a relatively flexible procedure, however it should finally aid in providing comfort to the occupants of the area and also in seamless and effective cooling, heating, ventilation and or dehumidification of a HVAC unit.

A. Solar Irradiance

Solar irradiance has a direct relationship with external climatic conditions. The parameters which are directly or indirectly connected with spectral irradiance are temperature, humidity and sky illuminance. The program which we wrote involved complex computations and took into account angle of declination, angle of elevation, extra-terrestrial irradiance, latitude of the place and other reflection and diffusion constants. The generalized program has the capability to predict irradiance values for future days as well.

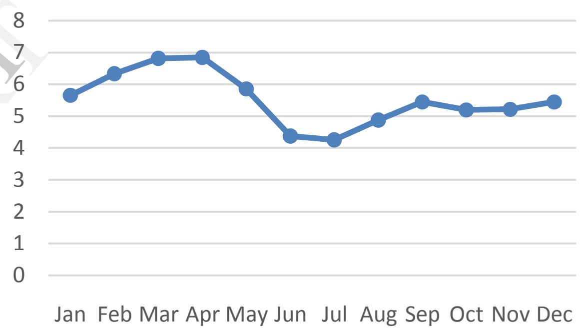


Fig. 2. Solar irradiance (KWhr-m^{-2}) vs. months of the year

B. Thermal gain

The thermal mass of the buildings structure absorbs the daytime thermal gains and then, during the night time, the heat stored in the thermal mass of the building is released back to the room. There needs to be contact between the air within the room and the buildings thermal mass in order for thermal transfer to occur.

In the ASHRAE-55 standards thermal gain is a vital parameter as it gives a quantitative overview of the ability of the room to capture heat and release it. The minimum thermal gain of the room was found to be 97.8 W-hr. and the maximum was found to be approximately 700 W-hr. Thermal gain is basically a cumulative sum of all possible sources of heat radiation. These also include electrical installation wattage as well the as the heat gains coming through the window and the material used to design the window and the exterior coating of the rooms exposed portions.

The figure below will give us an overview of hourly gains in all visible thermal zones, dated 5th of May 2014. Hourly gains are basically plotted for each unique source of thermal gain.

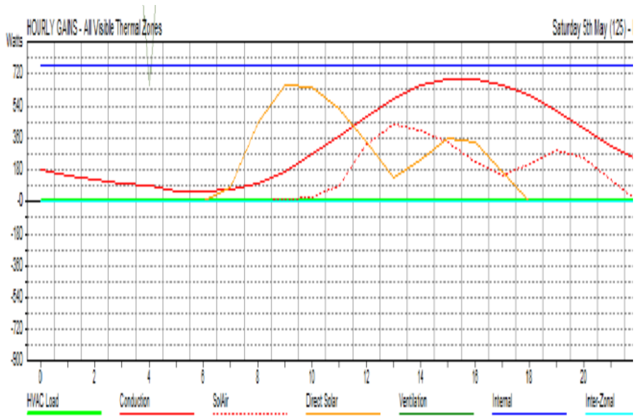


Fig. 3. Hourly gains vs. hour of the day

C. External temperature

Natural temperature and temperature differences are due to asymmetric heating and cooling of the Earth's atmosphere. Using an adaptive predictive model we were able to find monthly averages of future months apart from the actual readings taken for the first six months of the year. From the figure below it is clear that the average temperature is about 35°C during summers and about 24°C during winters. The blue line indicates highest temperature whereas the dark red line indicates lowest temperatures.

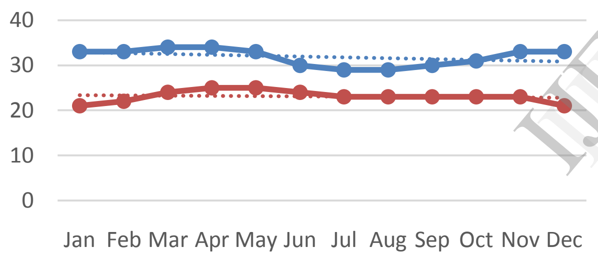


Fig. 4. Temperature (°C) vs months of the year

D. Internal temperature

The average temperature in the room with blinds closed and air conditioning switched off was about 36°C. This value is 9°C in excess to the upper limit of the comfort zone. Therefore by far the room is naturally uncomfortable. Reasons for the same are, direct exposure to sun light, poor ventilation, poor design of the room and large windows. The following graph shows temperature variations for the month of March in the interior of the room.

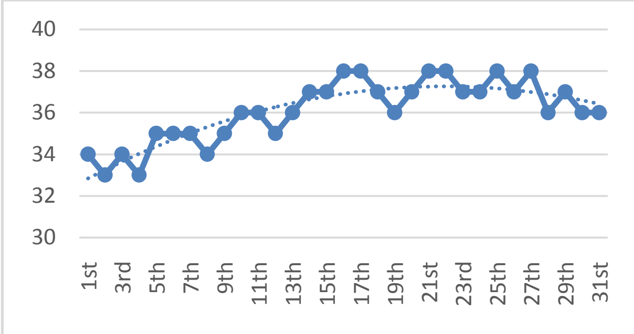


Fig. 5. Internal temperature (°C) vs. day of the month

From the figure above the trend line which is given by the dotted blue line indicates a second order polynomial function.

E. Relative humidity

Relative humidity is the amount of water vapor actually present in the air compared to the greatest amount of water vapor the air can hold at that temperature. Optimum relative humidity is usually between 30% and 60%. The figure below gives us the average relative humidity throughout the year.

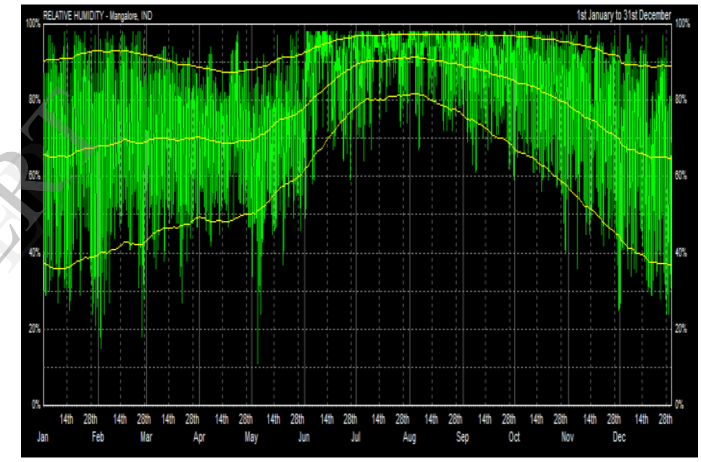


Fig. 5. Relative humidity (%) vs. months of the year

Many dehumidifiers include a built in humidistat, a device that allows you to set the desired levels of humidity for the room. Once the room reaches the desired level, the dehumidifier will cycle on and off automatically to maintain that level. Earlier it has been mentioned that motor controlled blinds were installed in the room to vary the illuminance in the rooms. Variation in blind angle at various temperatures directly affected the humidity values over a period of time.

From the 3D figure below it is seen that a temperature of 24°C with blind angles between 30° - 60° is best as relative humidity is within the comfort zone and illuminance at these angles was seen to least affect the visual comfort index.

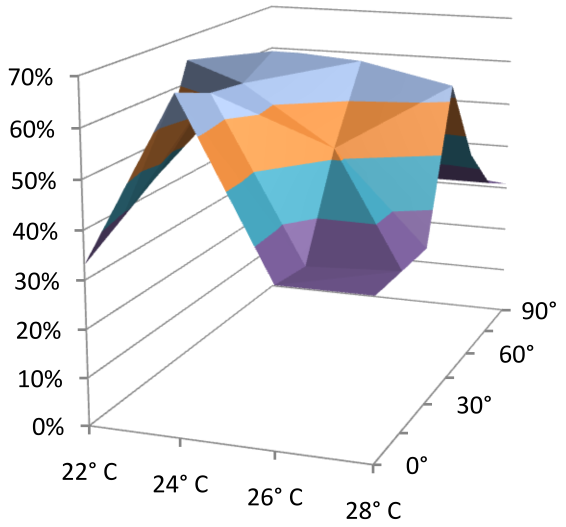


Fig. 6. Relative humidity vs. ambient indoor temperature vs. blind angle.

The above 3D figure bears resemblance to normal distribution, same which is the case for the spectral responsitivity curve. In spite of this similarity there is no clarity whether or not they do bear any mathematical relationship.

F. Predicted mean vote and percentage people dissatisfied

For the calculation of PMV and PPD, some of the assumption made are, activity = 1met – 1.2met for sedentary work, air speed = 0.15m/s-0.20m/s – indicative of no ventilation in the room. Clothing insulation was assumed = 1.1clo which indicates average clothing and average occupancy of the room was always = 2. Other required values such as temperature and relative humidity were obtained from sensor data. PMV and PPD at certain tuned temperatures and blind angles were calculated and it was seen that for temperatures less than 23°C was found to be negative and temperatures greater than 25°C was found to be positive. Although at some blind angles we might be in the comfort zone, however at 24°C and at a blind angle of 45° the PMV was found to be zero and corresponding PPD was as low as 5%. Not only that but between blind angles of 30° through 60° the average PMV was found to be 0.067, which is well within the comfort zone and close to thermal neutrality. The PPD at this PMV was found to be only 5%.

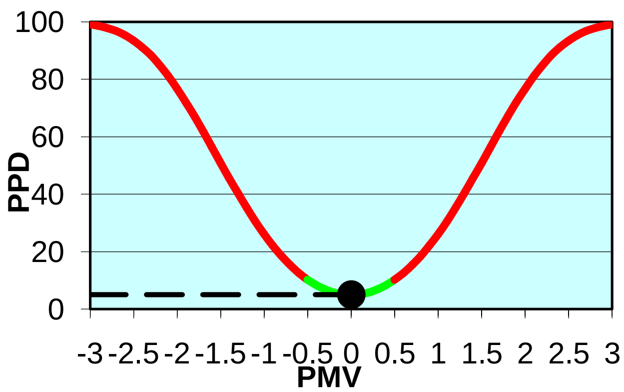


Fig. 7. PPD vs PMV at 24°C, blinds position = 45° and relative humidity = 54%

G. Psychometric analysis

Psychometric analysis gives a thermodynamic overview of the room and gives information about quantities like, dew point, enthalpy, vapor pressure etc. For different weather conditions the chart was prepared. The chart gave us an overlook of how much heating or cooling is required to bring the temperature of the room back to the comfort zone i.e. between 23°C - 27°C.

The thermodynamic values obtained from the psychometric chart for 24°C at 45° blind angle are as follows.

- Wet bulb temperature = 17.7°C
- Humidity ratio = 10.1g/Kg of dry air
- Specific volume = 0.86m^3/Kg
- Enthalpy = 49.79KJ/Kg
- Vapor pressure = 12.113 mm Hg
- Dew point temperature = 14.2°C

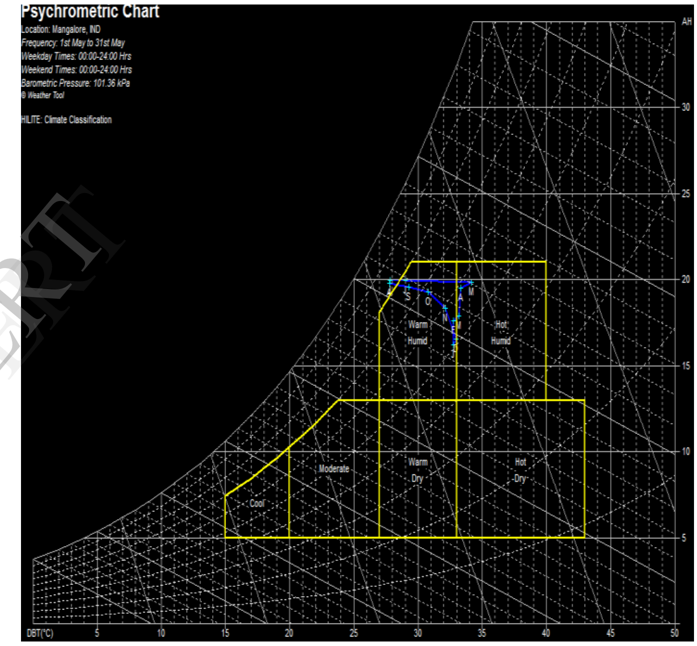


Fig. 8. Humidity ratio (g/Kg of dry air) vs. dry bulb temperature (°C) vs. enthalpy (KJ/Kg of dry air) vs. saturation (%).

IV. Visual Analysis

In this analysis we will be shifting our focus from radiometric quantities to photometric quantities. Visual comfort is a rather challenging task to achieve but the most efficient and invariably the most inexpensive way to achieve this is through daylighting. Daylighting is a traditional method used for illumination since ancient times and till today is one of the popular substitutes for partial replacement of artificial light sources during the day[6].

A. Daylight factor

Daylight factor helps us determine how much angular displacement a window or blinds require in order to maintain minimum illuminance. Mathematically it is expressed as

$$Daylight\ factor = \frac{Internal\ \ illuminance}{External\ \ illuminance} * 100 \qquad (3)$$

On an average daylight factor in Manipal is about 1.3% to 1.5%. The maximum daylight factor can go up to as much as 3.8% on a bright sunny day with no cloud cover.

According to daylight factor, buildings or rooms can be classified into three types, viz. base building, variant 1 and variant 2 respectively. The figure below will further subscribe that our model room comes under category – base.

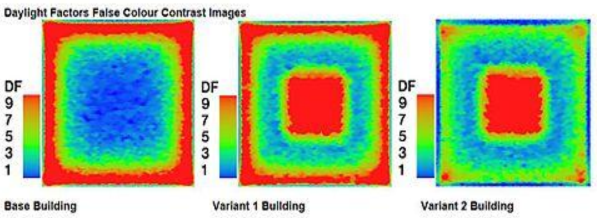


Fig. 9. Daylight factors and false color contrast images

B. Exterior illuminance

Sky illuminance or exterior illuminance in Manipal was reviewed to be approximately 82,000 lux on an average. Exterior illuminance was calculated by calibrating a standard 6V, 1W solar cell against a lux meter and acquired data using a data acquisition card.

C. Interior illuminance

Calculation of interior illuminance is almost in all cases done with respect to the work plane. The work plane considered here is 0.820m above the floor. Acquisition of interior illuminance values were done using a combination of optical sensors and phototransistors calibrated against a standard lux meter. For blinds angle of 45° the maximum illuminance at the center of the room was found to be 625.3 lux on an average.

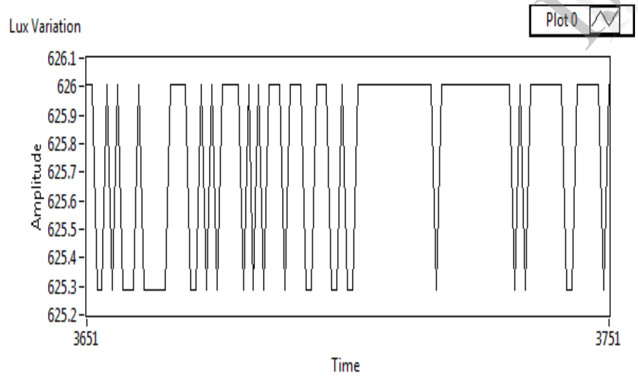


Fig. 10. Lux variation at the center vs time

It is to be noted that only few samples of data have been represented in the figure above for a specific times frame in seconds.

The interior illuminance at the center of the room seems to be having a direct relationship with the interior temperature. From fig. 5. , the interior temperature increases every day for the month of March, correspondingly the interior illuminance increased marginally. Hence there exists some unknown dynamic variable which relates these two quantities. In spite one of them being a radiometric and the other a photometric quantity.

This however confirms that light has a dual nature. If the illuminance increased as temperature increased that means some part of light in the form of photons caused heating to occur as they bounced off the surfaces of objects, illuminating them as well as transferring a part of their energy in the form of heat. This phenomenon is more discernible during summer than during winter.

D. DIALux™ analysis

DIALux™ is a powerful tool used primarily for design and analysis of lighting systems and lighting installations. This software provides holistic information about photometric quantitites and provides reports for paramters in the the visual domain.

Fig. 11. Gives us an overview of the illuminance at each point on the work plane. The entire work plane is considered to be a grid of 64×64 points. The uniformity ratio is also well within the scope of visual sense. Uniformity ratio should essentially be less than 0.4 according to IESNA standards. In this case uniformity ratio is only 0.146 .For simplification of simulation we have considered a dummy 60W led luminaire with an arbitrary lumen output. Since natural daylight is not completely predictable it would be naïve to try doing manual calculations based on sky illuminance values.

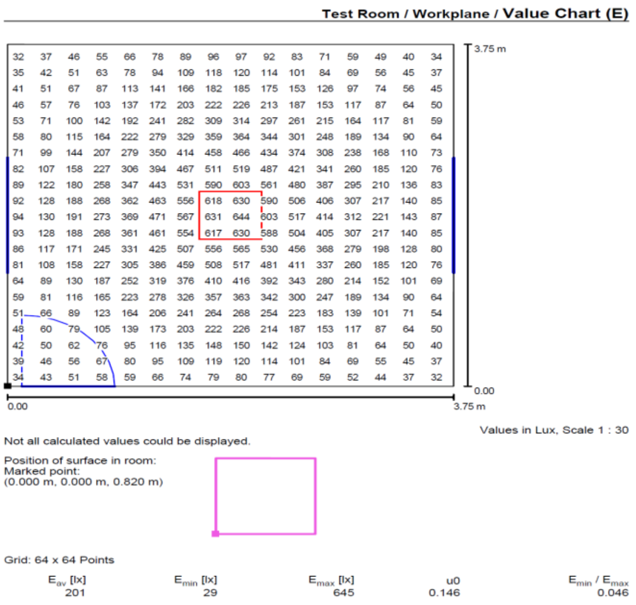
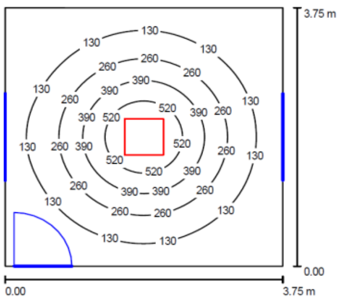


Fig. 11. Work plane illuminance chart

Test Room / Summary



Height of Room: 2.350 m, Mounting Height: 2.350 m — Values in Lux, Scale 1:49

Surface	ρ [%]	E_{av} [lx]	E_{min} [lx]	E_{max} [lx]	u0
Workplane	/	201	29	645	0.146
Floor	20	167	55	296	0.328
Ceiling	80	27	6.18	34	0.233
Walls (4)	50	52	18	104	/

Workplane:

Height:	0.820 m	**UGR**	Lengthways-	Across	to luminaire axis
Grid:	64 x 64 Points	Left Wall	16	16	
Boundary Zone:	0.000 m	Lower Wall	16	16	
		(CIE, SHR = 0.25.)			

Illuminance Quotient (according to LG7): Walls / Working Plane: 0.192, Ceiling / Working Plane: 0.132.

Luminaire Parts List

No.	Pieces	Designation (Correction Factor)	Φ (Luminaire) [lm]	Φ (Lamps) [lm]	P [W]
1	1	Philips CR434B W60L60 AC-MLO (1.000)	3598	3600	49.0
			Total: 3598	Total: 3600	49.0

Specific connected load: 3.48 W/m² = 1.73 W/m²/100 lx (Ground area: 14.06 m²)

Fig. 12. Summary report

The figure above depicts categorically the average, minimum and maximum values of illuminance at each plane along with their corresponding uniformity ratios. It is to be duly noted that the illuminance value at the center of the room is about 628.33 lux which is very close to our practical value of 625.3 lux. Not only that but the glare according to UGR is 16 both lengthwise and across the axis of the dummy luminaire (placed at the center). This means that the visual system has about less than average glare. This amount of glare is sufficient to allow people to perform intricate tasks such as sewing etc. which require high amount of precision and coordinated eye – hand movement. The visual comfort probability at this point is 78%.

The average illuminance in the room has been seen to be 201 lux on an average and this amount of light is just enough to see across both ends of the room without much strain. However this condition is for closed blinds, when the blinds are allowed to open and move freely they should be adjusted in such a way that minimum illuminance is maintained and sufficient amount of light is allowed to illuminate the room. This policy of a virtual lumen depreciation is obviously free of cost as well as very effective.

On moving the blinds, it was seen that from 30° to 60° the average illuminance in the room jumped to 541 lux on an average. In spite of rotating the blinds the change in illuminance is not enough to cause visual discomfort. In accordance to IESNA standard, this amount of lux is sufficient to perform a range of activities. Material which is used as the curtain for the blinds should be made of non-reflective material, so as to prevent unwanted localized heating of the room.

CONCLUSION

From our results we conclude that thermal comfort can be achieved at an operating temperature of 24°C with blinds positioned between 30° through 60°. Thermostats of air conditioners should be set to this temperature and the ambient temperature should be allowed to cycle around this value. Not only that but we have concluded that illuminance is best maintained using blinds. Sources of glare can be reduced by using polarized material on the surface of various objects.

In most arrangements which include artificial sources as the primary source of light, the design of the visual system should be so that glare is maintained at a certain level and preferably below 18. Also the minimum illuminance for conducting a particular task must be maintained as prescribed by IESNA. Lastly in view to reduce carbon footprint, it is preferable to use tinted paper on windows to trap infrared radiation from the sun. This in turn will reduce the total thermal gain coming from windows by almost 74% and in turn reduce the thermal load which is being born by the air conditioning unit. This will result in energy savings.

Not a lot of emphasis has been paid to both thermal and visual comfort as a combined metric. They have moreover been seen as completely separate models. However it important to strike a balance between the two models to make sure that people are not affected in any way i.e. there is neither visual impairment nor thermal discomfort. In this regard the two models are seen more complementary than complementing but this will change as we establish a relationship between the parameters of the two models, i.e. between photometric and radiometric quantities.

In today's context a thermal-visual comfort analysis is first done by suitably satisfying the thermal models needs and there after tuning the sources of light to suit our visual needs. Fig. 13. , shows the procedure of computational experiments and evaluation, where comfort time refers to the time frame during which the environmental condition maintains within the personal thermal comfort zone or PTCZ[4]. The dynamic thermal comfort zone (DTCZ) depends on how a person can adapt to a change in environmental parameters.

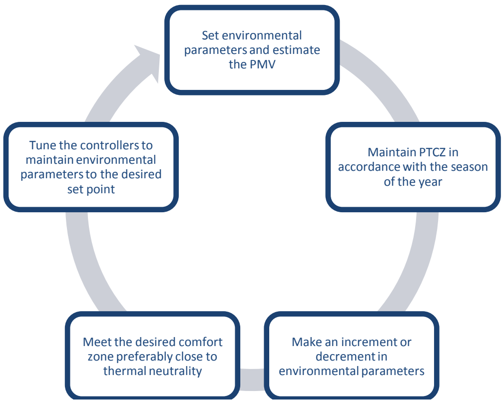


Fig. 13. Computational method flowchart for thermal comfort through parameter tuning

ACKNOWLEDGMENT

We would like to thank Dr. Vinod V. Thomas, Director, Manipal Institute of Technology, for giving us the necessary permission required to go ahead with this study. We would also like to thank Dr. Savitha G. Kini, head of department, electrical & electronics and Dr. Chandrashekara S. Adiga, Deputy Registrar, Manipal University, for their support and continuous involvement in our activities.Lastly we would like to express our heartfelt gratitude towards our families for their undying support during the tenure of this study, for without them we would not be where we stand today.

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