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A Simplified Method for Optimizing Daylighting Hours in Summer Climate Condition

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Abstract

The prediction of indoor temperature is indispensable for optimal use of daylighting and maintaining thermal comfort inside any building, which can be made using mathematical models. The models require long term input data of climatic parameters, like solar radiation, ambient temperature, relative humidity, and wind speed. Since, it is difficult to get such data of required parameters in developing countries. Therefore, a model with less number of input parameters is needed to predict the level of indoor temperature. In this study a simplified method was proposed for determination of optimum daylighting hours in summer season at Nawabshah, Pakistan without any structural modification using only input of outdoor temperature. Outdoor temperature was measured for an entire year and indoor temperature for one month. The relationship between these parameters were made using curve fitting tool MATLAB software. The model equation was formulated for prediction of indoor temperature and optimal use of daylighting hours. The model results revealed that the daylighting can be used for 1008 hours in any summer season of the year. The model was validated for a one month input data with ASHRAE standards using CBE thermal comfort simulation tool. The proposed model and simulation results were found to be identical.

Keywords: Windows opening, daylighting utilization, indoor temperature, mathematical model, thermal comfort

Nomenclature

A	Area at working plane height (m²)
M	Metabolic rate, in Watts per square meter of the body surface area
W	Effective mechanical power, in Watts per square meter, equal to zero for most activities
Icl	Thermal resistance of clothing, in square meters degree Celsius per Watt
fcl	Ratio of surface area of the body with clothes to the surface area of the body without clothes
ta	Air temperature, in degree Celsius
tr	Mean radiant temperature, in degree Celsius
Var	Relative air velocity, in meter per second
Pa	Water vapor partial pressure, in Pascal
hc	Convective heat transfer coefficient, in Watts per square meter degree Celsius
Evb	Direct beam illuminance
Erv	Ground-reflected illuminance
Evd	Diffused illuminance

INTRODUCTION

Light is a fundamental need for man and many other life forms [1]. If daylighting can be used in a larger extent to replace artificial lighting, it might be seen as renewable lighting [2]. Recently, there has been an increasing interest among architects and building designers to incorporate daylighting as a means to reduce energy use in buildings [3, 4]. It is because citizens in industrialized countries spend approximately 90% of their day in confined spaces [5]. The artificial lighting consumption can reach up to 20-60% of total electric consumption in an office building [6]. Therefore, it is essential to reduce the electrical energy consumption [7]. Over the last three decades, several measures were considered to reduce the utilization of artificial lighting and to increase daylighting in the buildings [8]. The amount of daylight entering a building is mainly through window openings [9]. However, buildings experienced significant amount of heat gain or loss through window and this will affect the thermal comfort of buildings′ occupants [10, 11]. Too much daylight introduces solar heat gains that can increase cooling loads associated with the window systems [12]. Inappropriate thermal comfort conditions in a building lead to lower work efficiency and higher possibility of the personnel errors [13, 14].

Moreover, it is quite possible to get required natural illumination inside a building without rise of indoor temperature using shading devices having proper size and position of windows [15]. Shading devices are necessary to prevent undesirable heat coming through the windows during the overheated period [16, 17]. Fixed shading systems can effectively control solar heat gain and reduce glare, however, they do not address variable sun angles. Therefore, they greatly reduce thermal comfort [18]. In such circumstances, the estimation of annually optimum daylighting hours at comfort temperature are needed to optimize the use of daylighting in fixed shading windows system. Other problem is the size of windows and their positions. The admission of daylight through windows and the provision of a view out are the primary functions of windows [19]. The size and positions of the window not only determines the total energy demand of a building directly through the availability of sunlight, but also indirectly through the availability of daylight [8].

ILLUMINATION and THERMAL COMFORT MODELS

Usually, illuminance from natural sources is frequently analyzed in terms of daylight factor, which is the ratio of the internal illuminance to the outdoor illuminance [9]. The global illuminance on a verticals Surface, Evg, can be written following equation.

$$Evg = Evb + Evd + Erv \quad (1)$$

Daylighting utilization with the opening of windows can disturb the comfort temperature. The comfort temperature in free-running buildings depend on the outdoor temperature [20]. The relationship between comfort temperature (Tc) and the outdoor temperature (To) for free-running buildings can be found using Eq. (2).

$$T_c = 13.5 + 0.5T_o \quad (2)$$

The percentage difference in between two variables can be determined using Eq. (3) and Eq. (4)

$$Percentage Temperature\ Difference = \left|\frac{T_1 - T_2}{(T_1 - T_2)/2}\right| \times 100\% \quad (3)$$

$$Percentage\ Illumination\ Difference = \left|\frac{E_1 - E_2}{(E_1 - E_2)/2}\right| \times 100\% \quad (4)$$

Where T_1 & T_2 are indoor temperature (^oC) in office-1 and office-2 respectively, E_1 & E_2 are indoor illumination (lux) in office-1 and office-2 respectively.

Daylighting application in buildings are only effective when the occupants of the buildings are comfortable. Thermal comfort is difficult to measure and it depends on the air temperature, humidity, radiant temperature, air velocity, metabolic rates, and clothing levels [13]. A method of describing thermal comfort was developed and is referred as Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) [21]. Thus following equations are used to determine PMV and PPD.

$$PMV = (0303e^{-0.036M} + 0.028) \times \{(M - W) - 3.05 \times 10^{-3} \times [5733 - 6.99(M - W) - P_a] - 0.42 \times [(M - W) - 58.15] - 1.7 \times 10^{-5} M(5867 - P_a) - 0.0014M(34 - t_a) - 3.96 \times 10^{-8} f_{cl} \times [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} h_c (t_{cl} \_ t_a)\} \quad (5)$$

Where

$$h_c = \begin{cases} 2.38(t-t)^{0.25} & for\, 2.38 \times |t_{cl} - t_a|^{0.25} > 12.1\sqrt{Var} \\ 12.1\sqrt{Var} & for\, 2.38 \times |t_{cl} - t_a|^{0.25} > 12.1\sqrt{Var} \end{cases} \quad (6)$$

$$f_{cl} = \begin{cases} 1.00 + 1.290 \times I_{cl} & for\, I_{cl} \le 0.078 m^2\, K/W \\ 1.05 + 0.645 \times I_{cl} & for\, I_{cl} > 0.078 m^2\, K/W \end{cases} \quad (7)$$

$$t_{cl} = 35.7 - 0.028(M - W) - I_{cl}\{3.96 \times 10^{-8} f_{cl} \times [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] + f_{cl} h_c (t_{cl} - t_a)\} \quad (8)$$

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad (9)$$

Many researches worked on different aspects of building structures of newly planned buildings. However, less literature is available in energy saving strategies of existed buildings without any alteration. This study focused on the optimization of daylighting in existing building without modification or alteration of its structure, shape and form, just by means of windows opening and closing in different time periods. The methods used for thermal comfort analysis by different researchers are time consuming due to requirement of various input parameters as shown in Eq. (5)-(9). However this study will focus on simple method for evaluation of thermal comfort to determine daylighting uses potential, which require only one input parameter. The findings of this study could be helpful for possible saving of energy with little awareness of building occupiers by maintaining indoor temperature, illumination level and thermal comfort inside the building.

MATERIALS and METHODS

First, the detailed survey was conducted for calculation of lighting load and energy consumption of the examined building. Then, a comparative study of two selected offices were carried out to analyze the Indoor Illumination and Temperature level. For this, a “two-approach” experimental program was adopted and followed in both two offices. The first approach consisted all windows closed, and second approach was opening of same windows in succession in both the offices. In both the approaches all lighting appliances were turned off. The effects of positions of windows and size of windows on indoor illumination and temperature was investigated. Meanwhile, comfort temperature was analyzed based on outdoor temperature for summer season using Eq. (2). Then, in our proposed method, MATLAB Software was used to predict indoor temperature by developing the equation model for relationship between indoor and outdoor temperature in selected location. The predicted temperature was compared with comfort temperature to determine optimum hours for daylighting utilization in different months of summer season. Finally, different parameters like air temperature (^oC), mean radiant temperature (^oC), air speed (m/s), humidity (%), metabolic rate (met), and clothing level (clo) were used as input parameters in ASHRAE standards using CBE thermal comfort simulation tool [22]. The results obtained from our simplified method was validated with outcomes of this tool.

Experimental setup

The parameters like indoor temperature and illumination level were analyzed for the month of June, 2014 and outdoor temperature was analyzed for complete summer season of the same year. Other parameters like air temperature (^oC), mean radiant temperature (^oC), air speed (m/s), humidity (%), metabolic rate (met), and clothing level (clo) were analyzed for the month of September, 2015 in same selected locations during the office hours from 08:00 AM to 02:00 PM. Equipments used for analyses of above parameters were Digital lux meter, Thermometer, Anemometer and Multifunctional environment meter.

Office and windows

The research has been carried out in two offices namely office-1 and office-2 in first floor of the building. Office-1 has interior three windows oriented towards east having total area of 9.84 ft^2 whereas office-2 has exterior same number and area of windows oriented towards west having fixed overhang shade as shown in Fig. 1. Each office space is 13.75ft long, 7.83ft wide, and 11.58ft high. The location of these offices in building are shown in Fig. 2.

Figure 1. (a) Windows of office-2 (b) Windows of office-1 and (c) fixed over hang shade

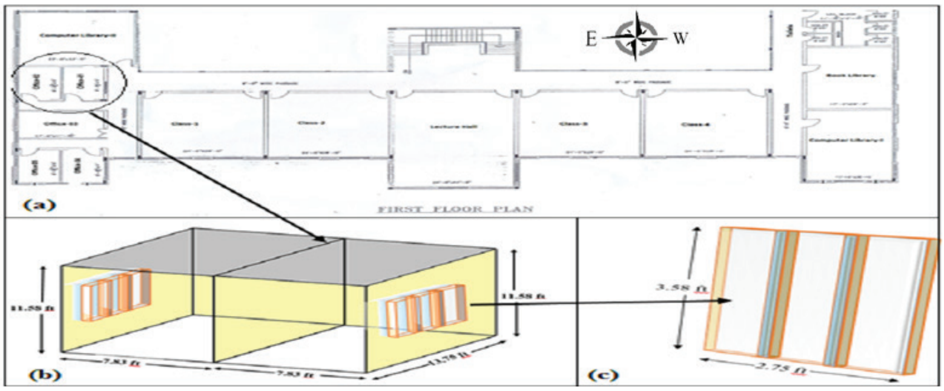

Figure 2. (a) Map of a building first floor plan. (b) 3D view of offices (c) dimensions of window

Local climate

District Nawanshah is situated in the middle of Sind Province bounded between 250-59 to 270-15 north latitude and 670-52 to 680-54 east longitudes [23]. The selected location has two main season's i.e. summer and winter. The summer season of the selected location lasts for seven months, while the winter season varies for five months. Generally, in summer season lasts from April to October and winter from November to March [24]. The monthly average temperature in summer season is between 29-35 ^{0}C during office hours from 08:00 AM to 02:00 PM. The constant increase in summer energy consumption due to building acclimatization is becoming a major concern for industrialized countries [25]. Realizing this condition the study was carried out for summer season only.

RESULT and DISCUSSION

Generally, indoor temperature depends on outdoor temperature. Once the outdoor (ambient air) temperature is known, the indoor temperature can be predicted and maintained as per requirements. The outdoor temperature of the area was in the range of 21 ^{0}C to 48 ^{0}C during office hours for the whole months of summer season. The hourly average monthly outdoor temperature for the summer season months of year 2014 and the trend of hourly outdoor temperature is given in Fig. 3.

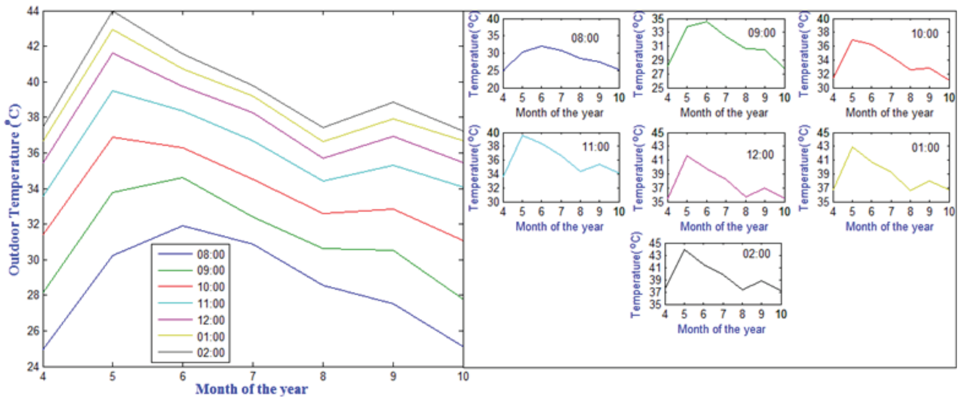

Figure 3. Hourly average monthly outdoor temperature for summer season months of the year 2014

Impact of windows area and positions on Indoor Illumination

The illumination level was recorded by applying both approaches in office-1 of the selected building. In first approach, the hourly average minimum level of illumination recorded was 9.94 lux while the maximum value was 10.64 lux as shown in Fig. 4a. In second approach, the natural illumination produced by opening of first window was utilized. The hourly average minimum and maximum level of illumination was 12.78 and 24.04 lux respectively. By opening second and third windows its level was recorded on the range of 13.69 and 29.09 lux and 14.08 and 32.77 lux respectively.

Similarly, both approaches on office-2 were applied. In first approach, the values of indoor illumination was in the range of 95.2 and 103.6 lux. In second approach with the opening of 1st, 2nd and 3rd windows, the indoor illumination level was between 216.3 and 227.5 lux, 291.2 and 305.3 and 394.0 and 415 respectively as shown in Fig.4b.

Illumination level in office-1 could not comply with illumination standards using both the approaches. Whereas in office-2 the permissible level of illumination was found in 2nd approach by using daylighting when all three windows were opened.

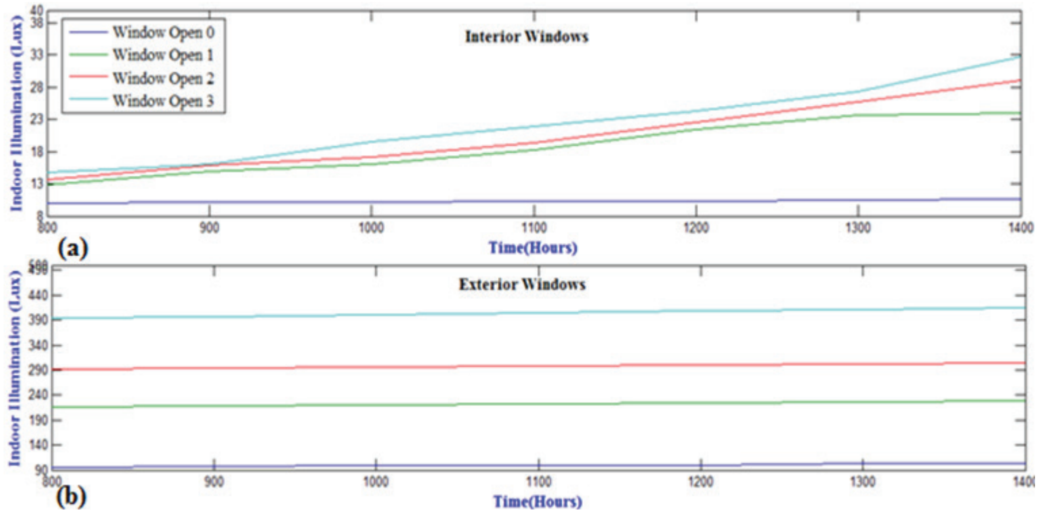

Figure 4. Impact of windows area and positions on Indoor Illumination in two offices

Impact of windows area and positions Indoor temperature

The indoor temperature level was also recorded by applying both approaches in the office-1 of the selected building. In first approach, the hourly average minimum and maximum levels of indoor temperature were 29 and 32.5^{o}C during office hours shown in Fig. 5a. In second approach, hourly average indoor temperature level was on the range of 29.1 and 34.4^{o}C, 30.3 and 36.0^{o}C and 30.1 and 37.3^{o}C during opening of first, second and third windows respectively.

Similarly, both approaches on office-2 were applied. In first approach, the hourly average values of indoor temperature level was in the range of 29 to 33.7^{o}C. In second approach with the opening of 1st window, the indoor temperature was between 31 and 35.1^{o}C. While 2nd and 3rd opening of windows the temperature level was increased and recorded on the range of 29 and 36.4^{o}C and 29 and 38.3^{o}C respectively as shown in Fig. 5b. Temperature level in both the office could not comply with comfort temperature during both the approaches.

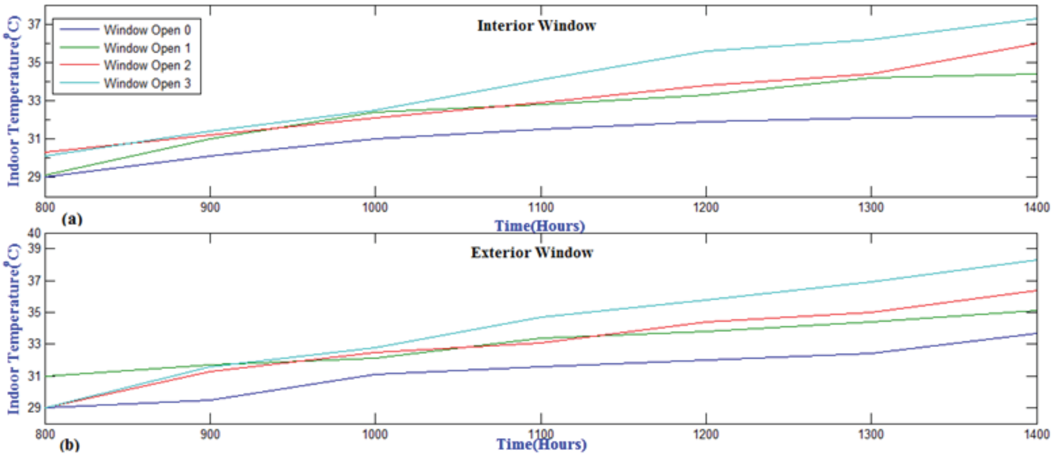

Figure 5. Impact of windows area and positions on Indoor Illumination in two offices

Exterior windows vs Interior windows

Percentage difference of indoor illumination and temperature was analyzed in both the offices having exterior and interior windows using Eq. (3) and (4). Exterior windows provided much required illumination level in office than the office having interior windows. The percentage difference of indoor illuminations in both the offices were recorded on range of 170.5-185.4%. But there was minor indoor temperature difference and was recorded as 2.64-3.72% as shown in Fig. 6. Overhang external shades and movement of air through exterior windows was the main cause of this minor temperature difference. Interior window provided very less level of indoor illuminations and couldn't comply with indoor illumination standards. Therefore further study was carried out for office-2.

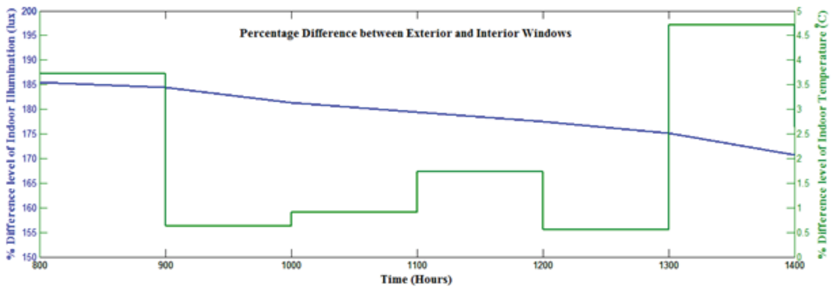

Figure 6. Percentage difference of Indoor Illumination and Temperature in office-1 and office-2

Thermal comfort and outdoor temperature

The comfort temperature in the relation with outdoor temperature for the different months of summer season was analyzed using Eq. 03 and the comfort temperature for the months of summer season is shown in Fig. 7. The results given in Table. 1 shows that daylighting should be used by opening three windows in office-2, when indoor temperature complies with the comfort temperature. It was therefore needed to predict the indoor temperature for different months of summer season to optimize the use of daylighting during office hours.

Table 1. Comfort temperature and monthly average ambient temperature

Month	April	May	June	July	August	September	October
Comfort Temperature (ºC)	29.7	31.8	33.4	32.4	31.2	30.7	29.1
Max Temperature (ºC)	40	43	45	42	39	39	37
Mean Temperature (ºC)	30	34	37	35	33	32	29
Min Temperature (ºC)	21	24	29	28	27.6	25	20

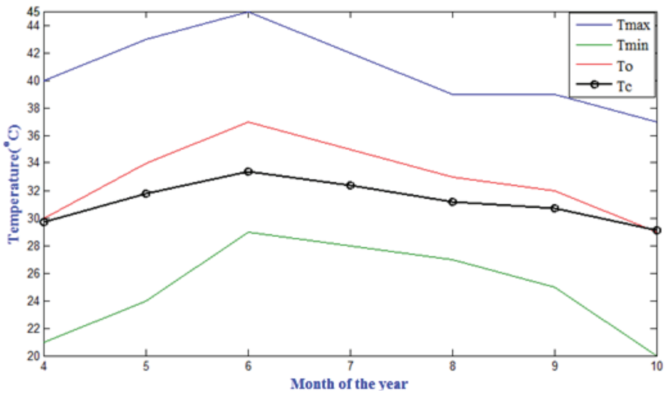

Figure 7. Comfort temperature for the months of summer season in selected location

PROPOSED METHOD for DAY-LIGHTING OPTIMISATION

Our proposed method is based on prediction of indoor temperature and its comparison with comfort temperature. Optimum daylighting can be used at the time period when the indoor temperature is comfort. Indoor temperature was predicted in selected locations of the building by using Curve fitting tool in MATLAB to find the best fit between indoor temperature (T_I) and outdoor temperature (T_O). The data points were fitted by means of 5th degree polynomial curve as shown in Fig. 8. The best fit was chosen to develop the equation model for relationship between indoor and outdoor temperature in selected location and such relationship can be determined by using Eq.(9). Based on the developed equation model, indoor temperature was predicted as shown in Fig. 9.

$$T_I = p1*TO^5 + p2*TO^4 + p3*TO^3 + p4*TO^2 + p5*TO + p6 \quad (9)$$

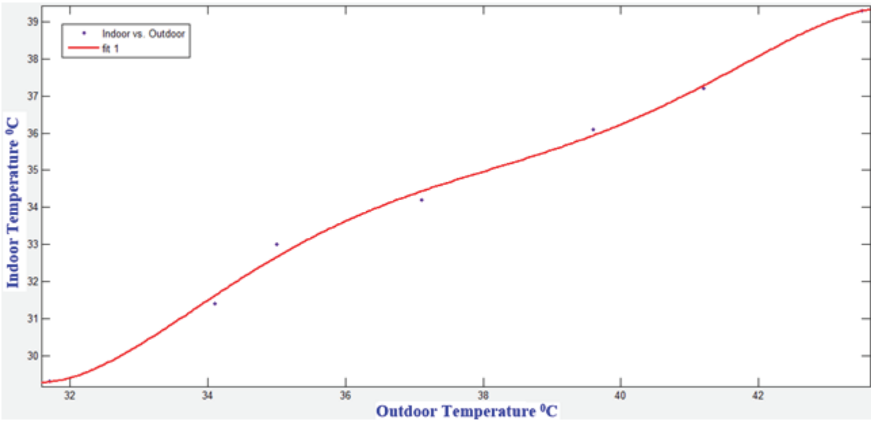

Figure 8. Relationship between indoor and outdoor temperature using MATLAB curve fitting

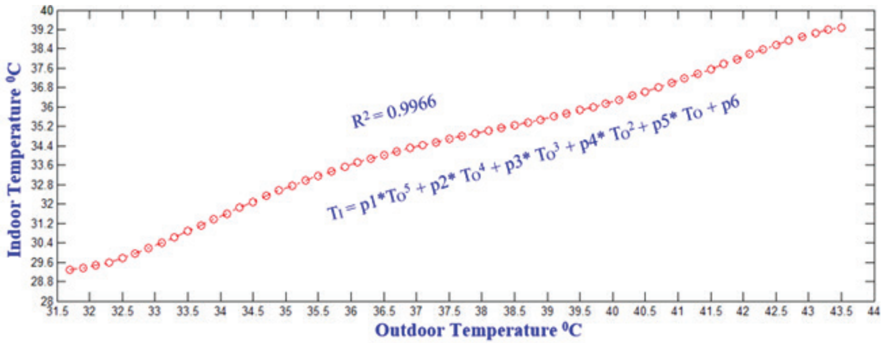

Figure 9. Prediction of indoor temperature with Outdoor temperature

Determination of optimal daylighting hours

Since the office-2 has exterior windows shading device, the level of temperature was not within comfortable limit. If selected locations had dynamic window shades then indoor temperature could have been maintained [26]. Without replacement of window shades, the daylighting was optimized with the help of predicted indoor temperature values. The optimal daylighting hours for all months of summer season were analyzed to utilize natural illumination while maintaining the thermal comfort temperature inside the office of selected building. According to the findings windows should not be opened throughout the office hours and should be opened until the indoor temperature is comfortable. The optimum daylighting hours, outdoor temperature and predicted comfort temperature for summer season is shown in Table. 2. The optimal daylighting hours for different months which totaling the 1008 hours in an entire summer season is shown in Fig. 10.

Table 2. Outdoor Temperature, predicted indoor temperature and daylighting hours

Month	**April**	**May**	**June**	**July**	**August**	**September**	**October**
Maximum Outdoor Temperature (ºC)	32	34	36	34	33	32	32
Predicted Indoor Temperature (ºC)	29	31	33	31	31	30	29
Optimum daylighting hours (A.M)	08:00 – 10:00	08:00 – 10:00	08:00 – 10:00	08:00 – 10:00	08:00 – 10:00	08:00 – 10:00	08:00 – 10:00

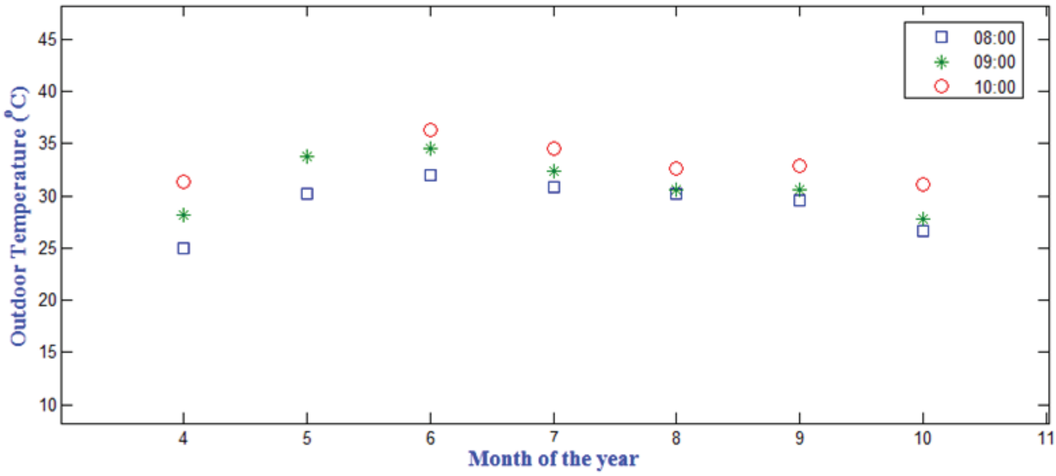

Figure 10. Optimum daylighting hours for the months of summer season

VALIDATION of PROPOSED METHOD

The model Eq. (9) was formulated based on the measured indoor temperature data of June, 2014. The formulated model equation required only one input that was outdoor temperature data. Therefore, the required outdoor temperature from April to October, 2014 was acquired for input of formulated model. To validate predicted result, thermal comfort for month of September 2015 was estimated to verify the formulated model results. ASHRAE Standards were adopted using CBE Thermal comfort simulation. This tool needs six input parameters to find thermal comfort which is characterized using the ASHRAE thermal sensation scale, given in Table. 3. The average thermal sensation response of a large number of subjects, using the ASHRAE thermal sensation scale, is called the predicted mean vote (PMV) [13]. All six parameters were determined and recorded during office hours in the month of September, 2015, are shown in Table. 4.

Table 3. The relationship between PMV and thermal sensation [27]

PMV	Thermal sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

Table 4. Measured parameters for simulation thermal comfort

Parameter	Values
Air Temperature (°C)	28.3 to 38.3
Mean Radiant Temperature (°C)	28.3 to 38.3
Air Speed (m/s)	1.0 to 1.2
Humidity (%)	44 to 54
Metabolic rate (met)	1.0
Clothing Level (clo)	1.5

The result obtained by adopting ASHRAE standard showed that thermal comfort can be maintained for two hours during 08:00 AM to 10:00 AM when all windows are opened for daylighting admission in office as shown in Fig. 11 and Fig. 12. The result of our simple method completely validated with ASHRAE Standards as it was predicted in our method that there will be comfort temperature during 08:00 am to 10:00 AM, when all windows are opened for daylighting utilization.

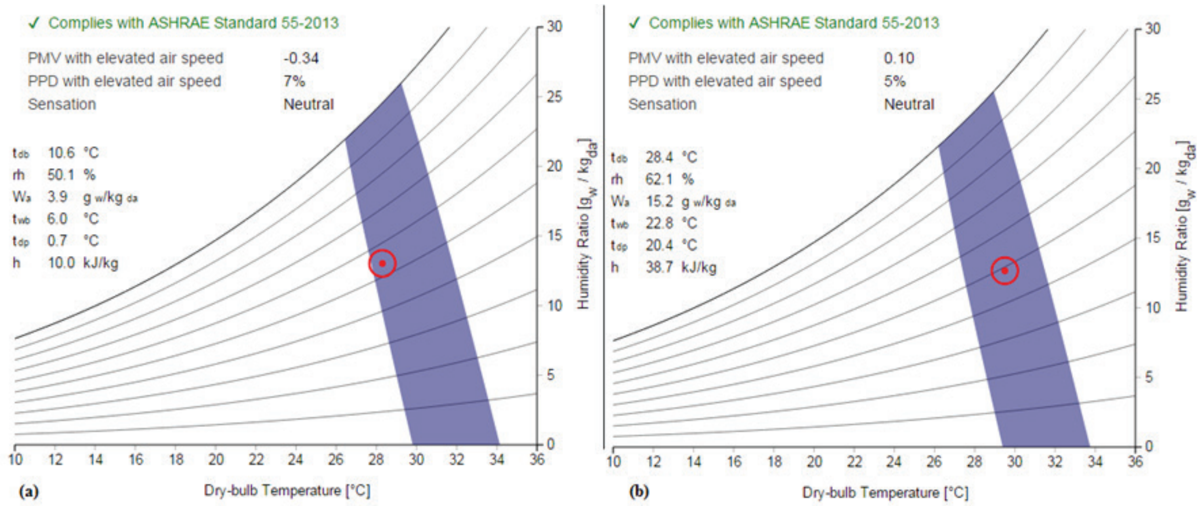

Figure 11. ASHRAE Standard 55-2013 for thermal comfort at (a) 08:00 AM, (b) 09:00 AM

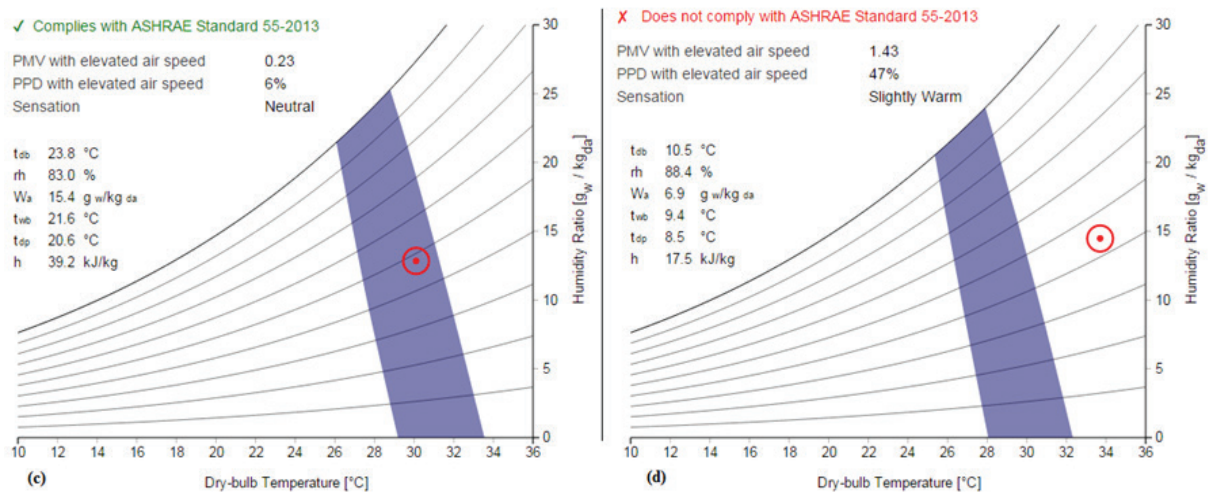

Figure 12. ASHRAE Standard 55-2013 for thermal comfort at (c) 10:00 AM, (d) 11:00 AM

CONCLUSION

The daylighting was utilized by means of opening and closing of windows without any structural modification of the selected building. A "two-approach" experimental program was adopted and followed in both two offices. The first approach consisted all windows closed, and second approach was opening of three windows one by one. The effect of windows area and their position on indoor temperature and illuminations was analyzed in two offices. The maximum percentages difference of indoor illumination and temperature level in both the offices were 185.5 and 4.71 respectively. This huge difference pertaining to illumination level was due to exterior position and east orientation of windows in office-2. Whereas the less difference of indoor temperature in both the offices was due to external fixed shade and air movement in office-2. However the temperature was not in the range of comfort level during office hours in second approach of experimental program. Therefore, a simplified method was adopted to balance the daylighting and thermal comfort for the months of summer season in selected location. The measured data was used to formulate an equation model using recorded data of ambient air temperature to predict the level of indoor for all months of summer season. The optimum daylighting hours were determined by comparing predicted indoor temperature with comfort temperature of different months for summer season. It was found from the study that daylighting can be utilized for 1008 hours in complete summer season of the year. This simplified method was then validated with ASHRAE Standards using CBE Thermal comfort simulation tool. The proposed model and simulation results were found to be identical.

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