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Research Article

Optimization of energy transmittance through building envelope for hot dry climate

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ABSTRACT

Fenestrations of the buildings are playing an important role in the building's energy efficiency for the tropical climate. The energy that comes from the glass window into the building can be restricted by providing shading on the windows. So, to provide the shading on the window, the most common way is fixed shade like overhang and fin. Shading devices are very helpful to control the SHGC and light transmittance through the fenestrations of the building. Most of the studies analyze the impact of WWR, shadings, and SHGC on a building's energy demand but did not consider the combined effect of these parameters. By considering all the parameters of the building envelope in the analysis like WWR, orientation, shading devices, projection factor, and type of glass, the energy demand in the building can be significantly reduced. The goal of this paper is to analyze the variation of residential envelope transmittance value with the window-wall ratio, projection factor, and fixed shading devices and also to optimize the energy from building envelope elements in residential buildings using a statistical method, namely the Taguchi method. The transmittance of energy through the building envelope is calculated in 8 cardinal directions by providing shading with the fin and overhang. Based on the result, the optimum energy saving achieved by selecting the optimum combination of the process parameters for minimizing the energy from the building envelope is A1B1C3D2 i.e. window to wall ratio 7%, triple glazing type of glass used, shading with the overhang fin, and orientation in the west direction. The result shows the most significant factor among the selected parameter is the window to wall ratio. Also, by focusing on the building envelope parameters, an architectural designer may reduce the building energy demand significantly and offer more alternatives to achieve energy-efficient buildings.

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INTRODUCTION

The increase in the growth rate of the world population and industrial developments have led to a surge in the global demand for energy in recent years. In this regard, the building sector is the largest energy consumer across other sectors and also has a large contribution of carbon dioxide emission in the world. According to the National Fenestration Rating Council [1], the solar heat gain coefficient (SHGC) tells us about the unwanted heat coming inside the building from different products such as glass and windows. The value of the sensible heat gain coefficient lies between 0 and 1. There are many tools to reduce the energy consumption in the buildings and one of the simple ways to reduce energy consumption is by using the building's wall materials. The impact of the wall building materials, specifically aerated concrete walls on heat loss is more than insulation material and have the lowest heat loss from the building [2]. In buildings, windows play a significant role in energy consumption. Windows have a variable contribution in cooling energy consumption and heating energy consumption [3]. In the energy performance of the building, the sensible heat gain coefficient is a key parameter besides some other parameters like the overall heat transfer coefficient of the window, property of glass, and window-wall ratio which influence the value of the SHGC. The orientation and positioning of a building will have a significant effect on the building's energy consumption. Solar heat gain in the building will minimize by selecting the optimum orientation of the building. For the high-rise buildings, there is a 6% difference in energy consumption by selecting the worst and best positioning of the building [4]. A low value of SHGC indicates that the glass has a high potential to restrict the solar heat gain and therefore the glass is quite useful in restricting solar heat gain in the hot climate.

A high value of SHGC indicates more solar heat transfer to the building which increases the energy consumption required to cool the building. So, to optimize the energy performance of the building, an optimal value of SHGC is to be considered. A low value of SHGC can be achieved with the help of suitable shading devices and the glazing property of glass. To reduce the direct solar radiations, different types of shading design has been used like overhang and fin. Depth of the overhang is an important factor that affects the energy performance of a building [5]. Bellia et al. [6] analyzed office buildings for the Italian climate and described the effects of solar shading devices. They found that energy saving with the help of shading devices is 20%, 15%, and 8% for Palermo, Rome, and Milan respectively. With the help of shading devices, radiant heat gain within the building envelope will minimize and reduce the air conditioning cooling load [7] and also the cooling cost [8]. The design of shading also plays a critical role in daylighting design [9], and the utilization of daylight in the building space [10]. By analyzing the effect of dynamic shading on building energy and thermal comfort, Yao [11] found that by using external shading, 30.87% of building energy consumption can be reduced for the city Ningbo in China. Suji Choi et al. [12] explains the benefit of movable external shades and the movement of movable external shades control by an algorithm. Nicholas DeForest et al. [13] highlighted the electrochromic glazing effect for the different climates of the US. They analyze the energy-saving potential as approximately 64.6 kWh/m^2 to 323 kWh/m^2. In the hot dry climate, the inappropriate use of the shading devices on the glazing of the building's windows can cause an increase in the cooling load and glare. Reffat et al. [14] investigated the integrated daylighting systems in the building windows to achieve energy-efficient buildings. In the hot dry climate, with the use of daylighting system energy can be saved up to 40% in total energy consumption.

WWR affects the building energy demand in a different climate; the orientation of the window also plays a significant role in building energy demand. The effect of WWR for different orientations has been analyzed [15] and Szerman [16] explains that by using dimming control and classical windows, 77% of light energy and 14% of total energy can be saved. Energy-saving strategies for the building depend on the climate. In a cold climate, a low U- value is needed for the windows [17] to provide a higher solar transmittance value. In a hot climate, SHGC needs to be determined for the unshaded large-glazed buildings and orientation exposure towards the high direct solar irradiation [18].

The building's energy demand can also be reduced by using passive cooling techniques and provides optimal values of building envelope design parameters. Bhowmick et al. [19] have studied the impact of windows, green roof, green wall, and green shaded on thermal comfort. Boyano et al. [20] suggested that the obstacle in improving the building energy efficiency is not having sufficient knowledge regarding the factors that determine energy consumption. Most of the studies show that various factors must be considered when analyzing building energy performance, like properties of the insulation [21], heat gain [22-23], climatic parameters [24], and characteristics of building as window orientation [25-27], etc. The energy performance of the building may also be influenced by the factors such as building inertia [28], the geometry of the building [29], or Window to wall ratio [30-31].

In the recent studies regarding the energy analysis from building envelope, Moeller et al. [32] investigated the influence of building physics and occupant activity on the building energy demand. They calculated the energy consumption of the building by considering window opening, radiators and internal heat transfer from neighbouring apartments. Maureen et al. [33] also explored the window energy efficiency in Argentina and discovered that windows have a high impact on the building energy demand. However, this study did not include the type of shading impact on the building's energy demand. Although, there is a need to analyze the combined effect of building envelope parameters like WWR, orientation, shading devices, projection factor, and type of glass.

The present study emphases on a hot dry climate like India, where energy consumption in residential buildings is expected to be large because of having a large population. From the literature review, many researchers focus on these topics but very few studies have addressed residential envelope transmittance value for the buildings. Most of the studies were carried out in different climates and did not include simultaneous optimization of residential envelope transmittance value with the different parameters. Most of the researchers included few factors for the analysis of energy transfer from building envelope. In this paper, we have analyzed the residential envelope transmittance value with more parameters which are orientation, projection factor, shading devices, type of glass, and window to wall ratio. This study will provide a direct correlation between the design of the building envelope and heat gains. It also provides the optimum values of these factors to minimize the energy transfer from the building envelope into the buildings. The aim is to identify the most influential parameters for the residential building's energy and the contribution of each parameter in the building's energy. This study aims to analyze the effect of building envelop parameters on the energy coming inside the building. Using the mathematical model, we identified the effect of the parameters (window-wall ratio, orientation, projection factor, and shading devices), and optimized the energy transfer from the building envelope to the building by selecting optimal values of the parameters.

METHODOLOGY

Taguchi Method

It is not easy to use traditional design experimentation because when the number of process parameters increases, a large number of experimental works have to be carried out. To overcome this problem, Genuchi Taguchi developed a statistical method called the "Taguchi method" to improve the quality of the product. This method uses special orthogonal arrays to study the entire parameter space with a little number of experiments used in engineering analysis involving a series of experiments to acquire data and the behaviour of a given process. The Taguchi method is one of the conventional approaches for the design of a high-quality product and a powerful tool that enhances work efficiency. This method is considered advantageous in terms of saving time, reducing the cost, and discovering significant factors during conducting experiments. The Taguchi method can be used to reduce the variability of a product's response. The mean is close to the desired target and hence it is considered useful to determine a feasible combination of design parameters.

Analysis of the Signal-to-Noise (S/N) Ratio

In Taguchi method, we first identify the controlled and uncontrolled factors (noise factors). Then the noise factors can be manipulated to force variability to occur. Higher the signal-to-noise value finds the optimal control factor which reduces the effect of the noise factors. Variation of responses from the nominal value is measured by the signal-to-noise ratio. These variations measures under different noise conditions.

a) Larger is better
b) Nominal is better
c) Smaller is better

To find optimal output response variation, we used the "smaller is better" noise condition. As our objective is to minimize the residential envelope transmittance value. S/N ratio is calculated using equation 2.1. The unit of measurement of the S/N ratio is the decibel (dB).

$$S/N = -10\log_{10}\left[\frac{1}{m}\sum_{i=1}^{m} d_i^2\right] \quad (1)$$

where m is the number of experiment and d_i represent overall proximity index for i^{th} experiment.

MATHEMATICAL MODEL

Residential Envelope Heat Transmittance

The transmittance of energy from a residential envelope of the building (except the roof), characterizes its thermal performance. By providing the optimum value of residential envelope parameters the heat gain will minimize from the building envelope. It also improves electricity consumption and thermal comfort. The transmittance of heat from the residential envelope is defined by the total heat gain per unit area of the building excluding the roof portion. The transmittance value from the residential envelope is calculated using equation (2) [34].

$$\begin{aligned} RETV = A*(1-WWR)*U_{opaque} + B*WWR*U_{non-opaque} \\ + C*WWR*SHGC_{equivalent} \end{aligned} \quad (2)$$

Equivalent SHGC

In a building envelope, the transmittance of energy from fenestration is calculated by the amount of solar heat that comes through the building envelope. Therefore, solar heat

Table 1. Coefficients for Envelope Transmittance Value

Climate zone	A	B	C
Hot-Dry	6.11	1.9	70.94
Warm-humid	5.19	1.34	66.7
Temperate	5.27	0.95	78.92

gain coefficient is used from ASHRAE 90.1-2016. Shading equivalent factor is calculated for the fenestration in a different cardinal direction, i.e. North, East, South, West, North-East, South-East, South-West and North-West. Shading equivalent factor for the different type of shading devices like overhang and fin is calculated using equation (3) [34] as mentioned below.

$$SEF = C_3 \times PF^3 + C_2 \times PF^2 + C_1 \times PF + C_0 \qquad (3)$$

Equation (3) comprises the value of the projection factor. For equation (3), the value of the projection factor varies from 0.25 to 1. By applying shading devices like overhang and fin, the value of equivalent solar heat gain coefficient needs to be calculated. Using equation (4), the equivalent solar heat gain coefficient is calculated for the different orientations of the building envelope [34].

$$SHGC = SHGC_{unshaded} / SEF \qquad (4)$$

Table 2. Details of construction Materials

Wall	200mm AAC blocks with 15mm plaster on both side
Glass in windows	Single clear glass, VLT 85%, U-value 5.8 (W/m^2.K)
PVC panel	4mm thick PVC panel used in windows and doors

Table 3. SHGC values for projections factor in ASHRAE 90.1-2016

Projection factor	SHGC factor
0 to 0.1	1.00
>0.10 to 0.20	0.91
>0.20 to 0.30	0.82
>0.30 to 0.40	0.74
>0.40 to 0.50	0.67
>0.50 to 0.60	0.61
>0.60 to 0.70	0.56
>0.70 to 0.80	0.51
>0.80 to 0.90	0.47
>0.90 to 1.0	0.44

RESULTS AND DISCUSSION

Analysis of RETV

Glass windows play an important role in the buildings' energy efficiency for the tropical climate. The energy that comes from the glass window into the building can be restricted by providing shading on the window. By providing shading, energy consumption is reduced significantly. So, to provide the shading on the window, the most common way is a fixed shade like overhang and fin. There is also another approach to reduce energy gain by providing dynamic shades in the building. Shading is very helpful to control the SHGC and light transmittance through the fenestrations of the building. The analysis of RETV with the parameters is considered only for single glazing glass and the climate for those areas located at latitudes ≥15°.

Variation of RETV (W/m^2) with window to wall ratio and projection factor is shown in Figure 1. The RETV is calculated in 8 cardinal directions for the constant projection factor of 0.3, 0.4, 0.6, and 0.8 by providing shading with the fin as shown in Figure 1. We can observe that the RETV

Table 4. Coefficients of Shading Equivalent Factors (Latitudes ≥ 15°)

	Overhang + fin				Overhang				Fin			
	C_3	C_2	C_1	C_0	C_3	C_2	C_1	C_0	C_3	C_2	C_1	C_0
North	-0.03	-0.23	1.09	0.99	-0.02	-0.1	0.43	0.99	0.14	-0.39	0.62	0.99
East	4.49	-6.35	4.70	0.52	-0.05	0.42	0.66	1.02	0.12	-0.35	0.57	0.99
South	-4.09	8.14	-0.73	1.32	-1.01	1.91	0.24	1.12	0.53	-1.35	1.48	0.88
West	-1.21	3.92	-0.56	1.28	1.52	-2.51	2.3	0.76	0.02	-0.15	0.46	1.01
North-East	-0.95	1.5	0.84	1.18	2.19	-3.78	2.62	0.72	-1.64	3.07	-1.05	1.3
South-East	2.67	-4.99	5.68	0.32	-0.93	1.37	0.76	0.99	0.68	-1.47	1.35	0.88
South-West	-0.5	1.36	2.45	0.73	-3.23	5.61	-1.56	1.32	1.86	-3.81	2.71	0.69
North-West	-6.85	11.7	-3.92	1.89	-0.22	0.19	0.74	1.01	-2.02	2.63	-0.18	1.14

value is maximum for 90% of WWR. The graph also shows different values of RETV for the different window-to-wall ratios and orientation of the window. With the use of fin shading, it is preferred to select a North-West orientation to avoid maximum energy transfer to the building.

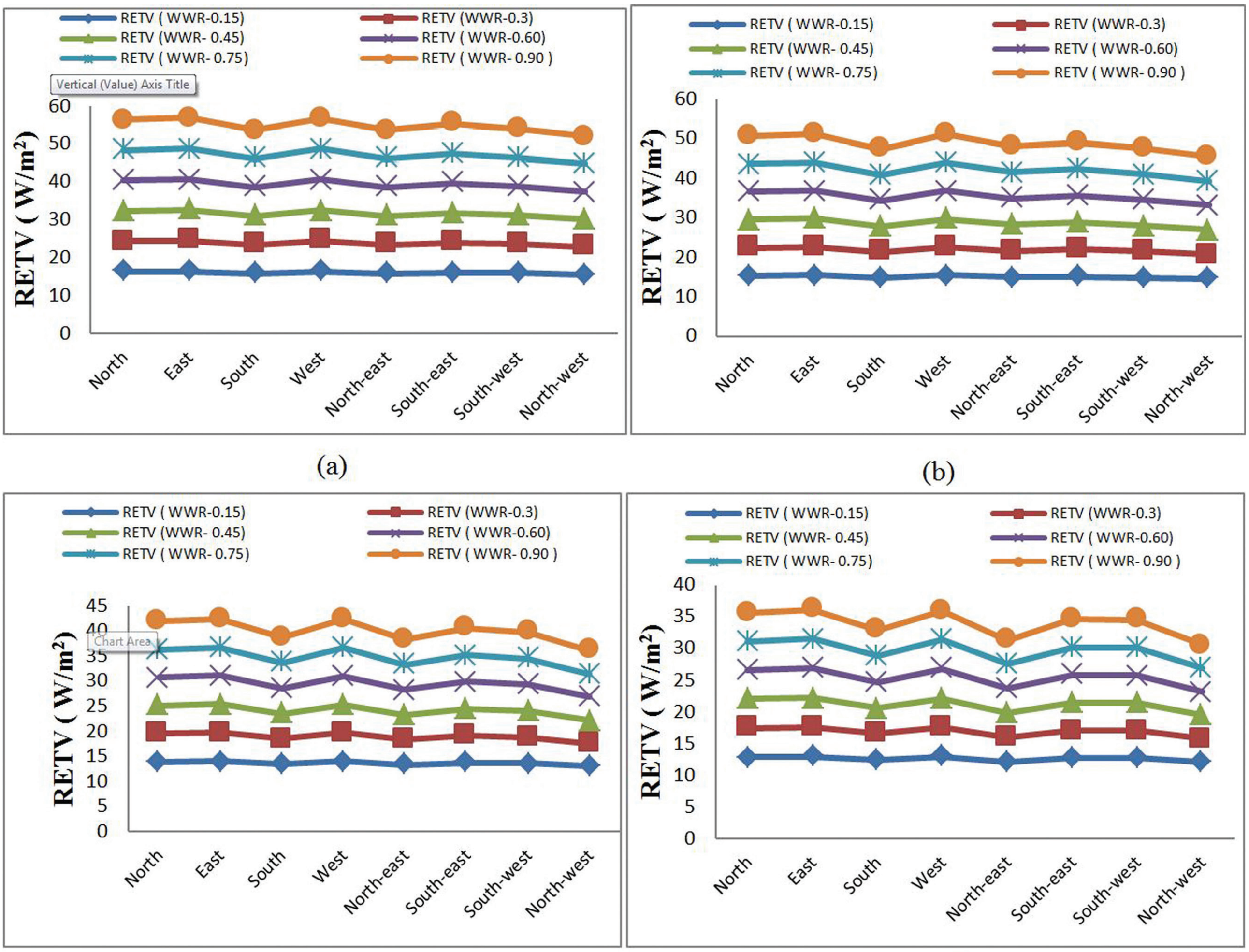
In Figure 2, the maximum RETV for the constant WWR is observed in the north direction with the overhang shading. For a given orientation the value of RETV decreases as the projection factor increases. For a north direction, the values of RETV decreases from 16.56 W/m^2 to 13.003 W/m^2 for 15% WWR as the projection factor increases from 0.3 to 0.8. It is preferred to avoid orientation in the north direction as the value of RETV is maximum. From Figure 2, the south orientation is more feasible as compared to other orientations to minimize energy transfer in the building envelope.

As shown in Figure 3, in the case of overhang plus fin shading, the RETV shows a minimum value in the south direction for a constant projection factor. From the graph, it is preferred to give the south or south-east or south-west orientation of the ventilation and windows for the minimum energy transfer to the building. In the case of overhang with fin, the maximum energy transfer in the building envelope is from the north orientation.

It has been observed from the graph that the RETV values depend on the projection factor and window-wall ratio. As the projection factor increases the value of RETV decreases. The RETV value directly depends on the WWR, as the WWR increases the energy transmittance in the building envelope also increases.

Optimum Parameters of RETV

Optimization was carried out to identify the optimal combination of the building envelope design parameters i.e., window-wall ratio (A), type of glass (B), shading (C), and orientation (D), and their levels that simultaneously



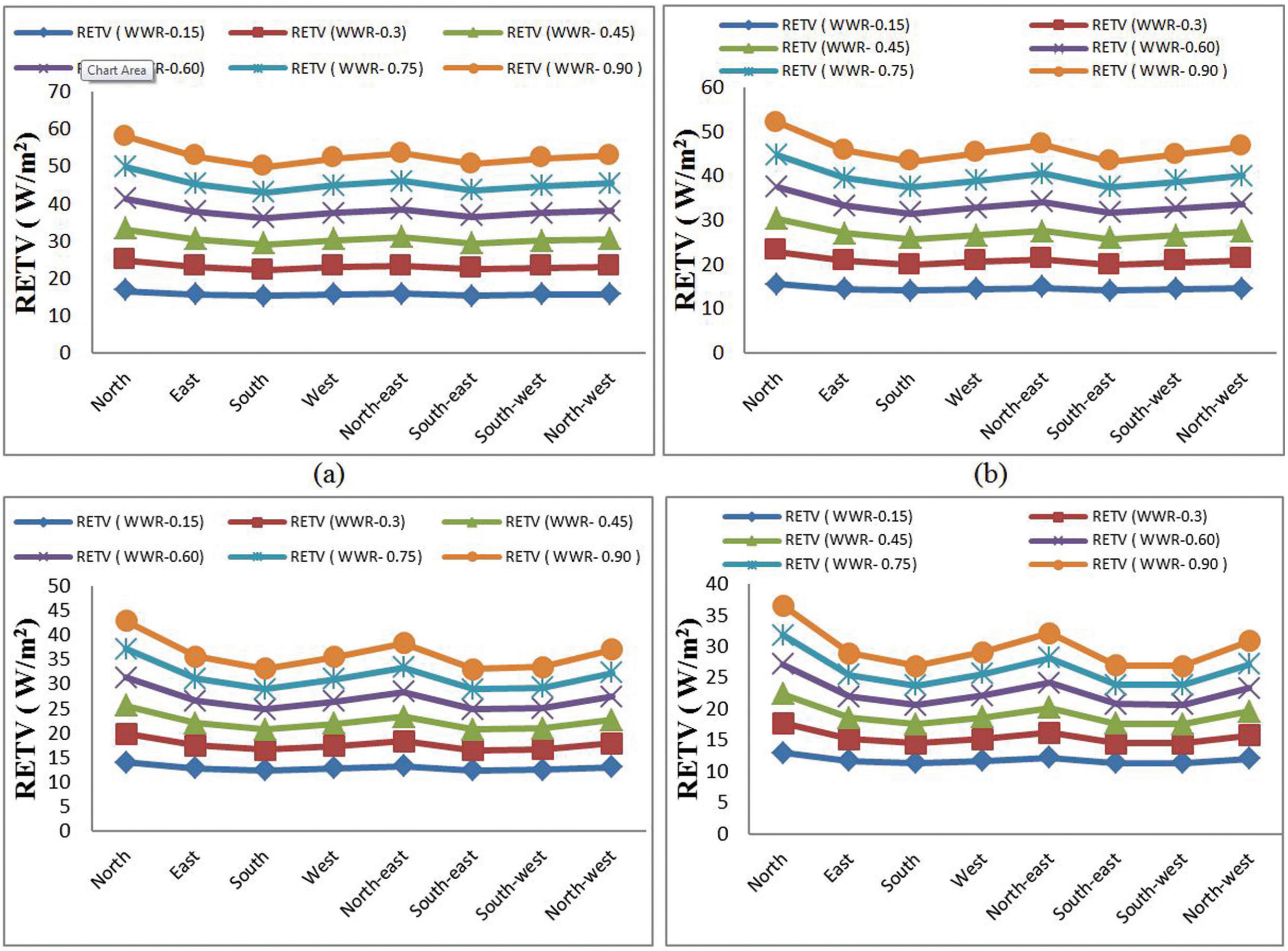
(a)

(b)

(c)

(d)

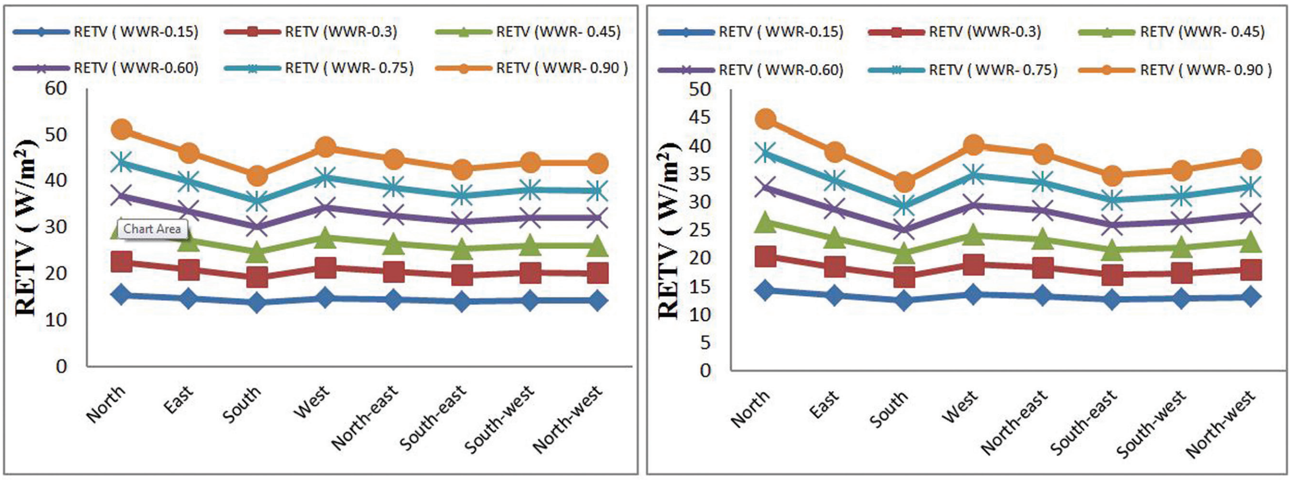
Figure 1. RETV per m^2 in 8 cardinal directions using different projection factors for the shading with the fin, for projection factor (a) 0.3, (b) 0.4, (c) 0.6, and (d) 0.8.



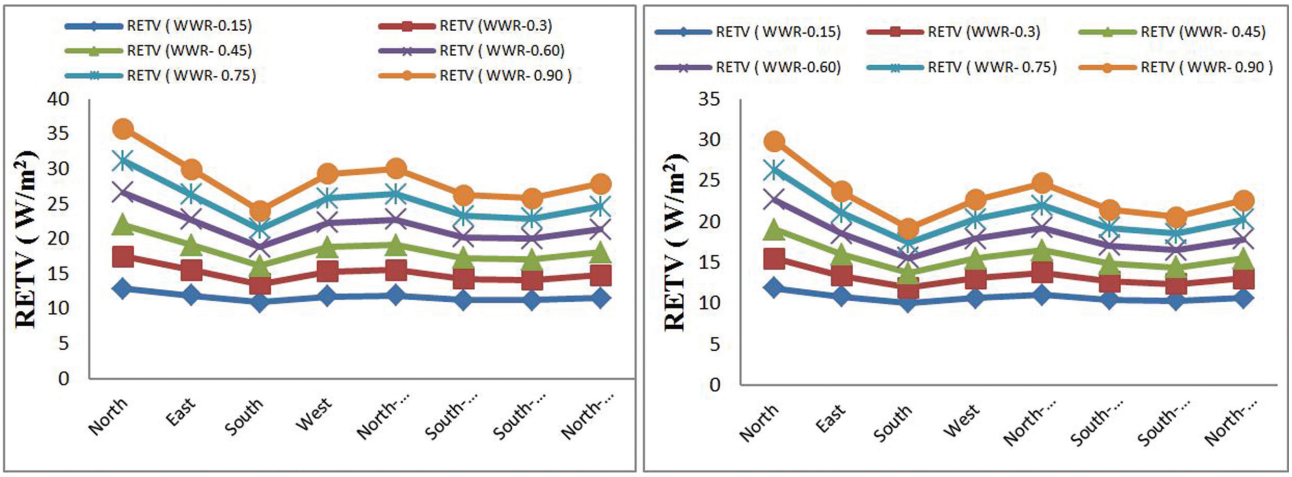
(a) (b)

(c) (d)

Figure 2. RETV per m^2 in 8 cardinal directions using different projection factors for the shading with overhang, for projection factor (a) 0.3, (b) 0.4, (c) 0.6, and (d) 0.8.



(a) (b)



(c) (d)

Figure 3. RETV per m^2 in 8 cardinal directions using different projection factors for the shading with overhang plus fin, for projection factor (a) 0.3, (b) 0.4, (c) 0.6, and (d) 0.8.

Table 5. Design parameters and their levels

Design parameters	Symbol	Unit	Level 1	Level 2	Level 3
Window-wall ratio	A	-	0.07	0.15	0.30
Type of glass	B	W/m^2.K	0.6	2.8	5.8
Shading	C	-	Fin	Overhang	Overhang + fin
Orientation	D	-	East	West	North

Table 6. Taguchi's L9 orthogonal array

WWR	Type of Glass	Shading	Orientation	RETV (output response)	SNRA1	MEAN1
0.07	0.6	f	E	11.29223	-21.0556	11.29223
0.07	2.8	O	W	11.21768	-20.9981	11.21768
0.07	5.8	Of	N	11.54333	-21.2466	11.54333
0.15	0.6	O	N	14.88949	-23.4576	14.88949
0.15	2.8	Of	E	13.61217	-22.6785	13.61217
0.15	5.8	f	W	16.19539	-24.1878	16.19539
0.3	0.6	Of	W	18.02999	-25.1199	18.02999
0.3	2.8	f	N	22.26928	-26.9541	22.26928
0.3	5.8	O	E	22.67778	-27.112	22.67778

optimizes output response. Three levels of each design parameter were considered and the nine experiments as per Taguchi's L_9 standard orthogonal array (OA) were performed for each experiment. The design parameters and their levels are shown in Table 5 and the experimental plan of L_9 (OA) along with the experimental results are shown in Table 6.

The effect of design parameters on residential envelope transmittance value is analyzed using signal to noise ratio and ANOVA technique. As our objective is to minimize residential envelope transmittance value, we consider the "smaller the better" signal-to-noise ratio. The values of signal to noise ratio for residential envelope transmittance value are shown in Table 7. The mean signal to noise ratio of the design parameters is shown in Table 8.

The rank of each design parameter is shown in Table 7. The rank indicates the sensitiveness of each parameter to residential envelope transmittance. It shows that residential envelope transmittance value is more sensitive to the window-wall ratio followed by the shading, type of glass, and orientation. Design parameter's optimum combination is obtained by considering the minimum value of the S/N ratio. Thus, Table 7 shows that the optimum combination of the design parameters for minimizing the residential envelope transmittance is $A_1B_1C_3D_2$. i.e., window to wall ratio at level 1, type of glass at level 1, shading at level 3, and orientation at level 2.

The statistical significance of process parameters on the RETV is obtained by the ANOVA technique and the result of ANOVA are shown in Table 9. Table 9 shows the contribution of each parameter. From the table, it is seen that the most contributing factor in RETV is a window to wall ratio. It means that the most affecting parameter for the RETV is a window to wall ratio followed by, shading, types of glass, and orientation used in the residential building.

$$\begin{aligned}\mathrm{RETV} = 5.86 &+ \left(4.821 * \mathrm{WWR}\right) + \left(1.034 * \mathrm{Type\ of\ glass}\right) \\ &+ \left(1.095 * \mathrm{shading}\right) + \left(0.187 * \mathrm{Orient.}\right)\end{aligned} \tag{5}$$

The regression equation for the design parameters and RETV is given in equation (5). The value of R^2 is calculated for the fitness of data with the regression equation. The value of R^2 for the equation is 96.20% which shows the relationship between data and regression equation.

Table 7. Response for Signal to Noise Ratios (Smaller is better)

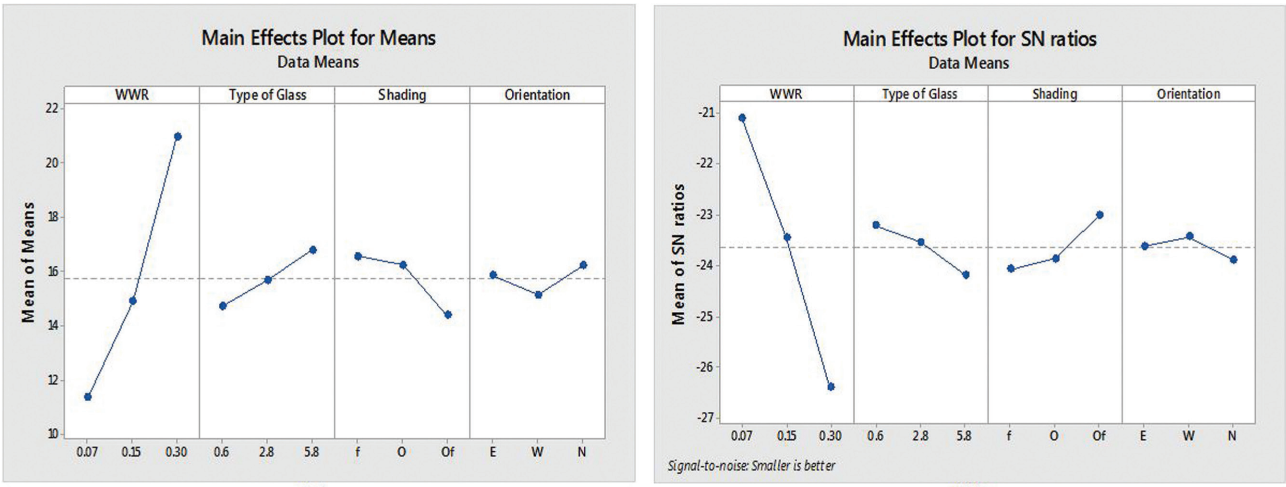
Level	WWR	Type of glass	Shading	Orientation
1	-21.10	-23.21	-24.07	-23.62
2	-23.44	-23.54	-23.86	-23.44
3	-26.40	-24.18	-23.02	-23.89
Delta	5.30	0.97	1.05	0.45
Rank	1	3	2	4

Table 8. Response for means

Level	WWR	Type of glass	Shading	Orientation
1	11.35	14.74	16.59	15.86
2	14.90	15.70	16.26	15.15
3	20.99	16.81	14.40	16.23
Delta	9.64	2.07	2.19	1.09
Rank	1	3	2	4

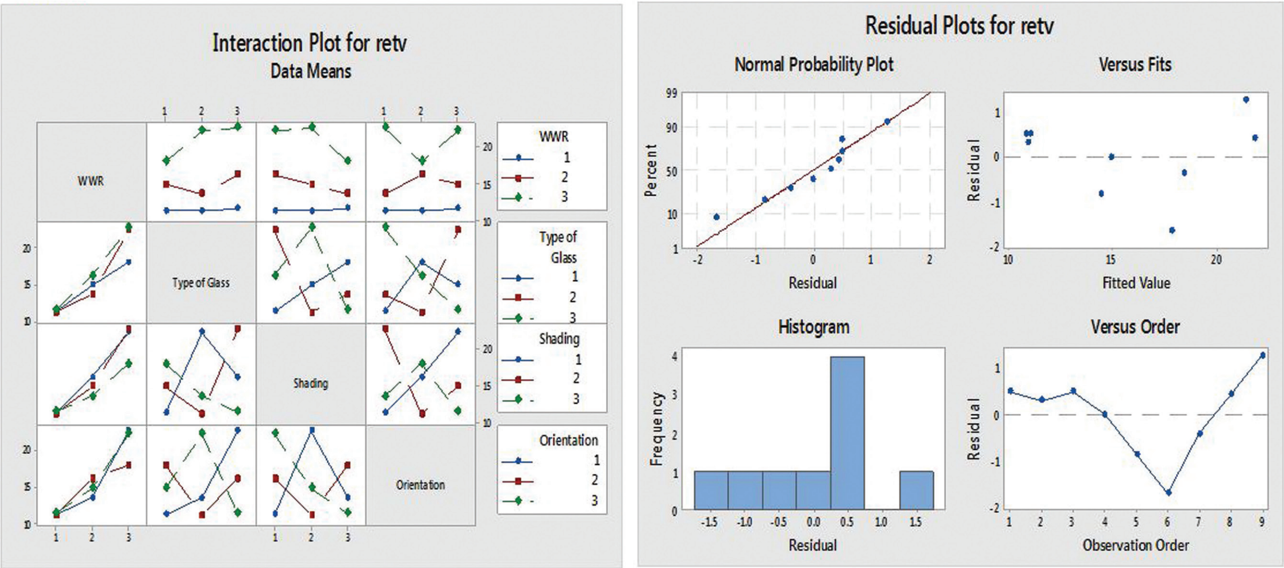
Table 9. Analysis of Variance

Source	DF	Seq SS	F-value	P-value	Contribution
WWR	1	139.431	92.06	0.001	89.55%
Type of glass	1	6.417	4.24	0.109	4.03%
Shading	1	7.197	4.75	0.095	5.26%
Orientation	1	0.209	0.14	0.729	1.15%



(a) (b)

Figure 4. Main effects plot for (a) means, and (b) S/N ratios.



(a) (b)

Figure 5. Interaction and residual plot for RETV.

CONCLUSION

India is a hot dry climate country and having a large population. The energy demand is higher for residential buildings because of having a large population, so the residential buildings can be converted into energy-efficient buildings by focussing the residential envelope transmittance value. The residential envelope transmittance value can be reduced significantly by selecting an optimum value of the parameters i.e. WWR, type of shading, orientations, and type of glass used in the building. Many factors are known to affect the energy efficiency of residential buildings. The energy performance of a building depends on the factors such as location, climatic condition, window-wall ratio, the type of glass used in the window, and the shadings used. In this study, we investigated the influence of WWR, orientations, type of glass, and projection factor on the building energy performance and optimized the energy transfer from these factors by selecting the appropriate combination of the factors. The result shows that WWR is the most influencing parameter for the residential envelope transmittance value. Based on the result, the optimum energy saving will be achieved when the window to wall ratio is 7%, the glass used in the building envelope is triple glazing and the shading (overhang with fin) is in the west direction.

By understanding the contribution of each factor to the energy demand, we can significantly reduce the energy consumption in the buildings. This study will help the architecture, consumers, and planners of the building to increase building energy efficiency through the design of the building envelope. It will also aid to identify the parameters on which designers have to focus more. The limitation of this study is that the roof part is not included and in future studies, it could be included along with some more parameters like internal loads and HVAC system parameters used in the buildings.

NOMENCLATURE

f	Fin
O	Overhang
Of	Overhang + fin
PF	Projection Factor
RETV	Residential envelope transmittance value (W/m^2)
SEF	Shading Equivalent Factors
SHGC	Equivalent solar heat gain coefficient
$U_{non-opaque}$	Overall heat transfer coefficient of a non-opaque component in the building envelope (W/m^2.K)
U_{opaque}	Overall heat transfer coefficient of an opaque component in the building envelope (W/m^2.K)
WWR	Window to wall ratio

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