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Modeling and performance evaluation of energy efficient buildings envelope using exergy analysis method

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Abstract-In the present study, the extended concept of exergy analysis has been applied to a building located in New Delhi with a volume of 60 m^3 and having a single-glazed window on the south facing wall .With this study thermal energy and thermal exergy flow were investigated to calculate the total thermal energy and exergy in and out from the building. This allows performing a complex exergy analysis of the building in both heating and cooling cases. The calculations were carried out by using the developed mathematical model of building and measured solar radiation data on horizontal and vertical wall surface. The thermal energy and thermal exergy flows for a space of a typical residential building of natural ventilation system with different parametric changes (i.e. wall thickness, roof thickness, window material properties, window dimensions, wall material thermal conductivity) have been modelled and compared from the reference case .

Keywords-Thermal energy and thermal exergy, building envelope, thermal conductivity, convective and radiative heat transfer co-efficient.

I. Introduction

In many countries, the energy required for building space conditioning has the highest share of total energy consumed in residential sector. The building sector represents about 33% of electricity consumption in India, with commercial sector and residential sector accounting for 8% and 25% respectively [1] and a major share of this energy is used to maintain thermal comfort inside the building at around 20ºC. All kinds of energy utilization calculations, including cooling/heating loads of rooms in buildings are based on energy conservation laws means based on the first law of thermodynamics. To carry out the detail analysis of the energy flow processes can be applied second law of thermodynamics, in which entropy concept described as well, in addition to first law of thermodynamics. Because of the low temperature range, the required exergy demand for heating and cooling application is low, which is generally met by high grade energy source (i.e. electricity).The widely held perception is that about 30% to 40% of annual global energy consumption is due to buildings and 60% of that is due to HVAC. In India, HVAC and lighting appliances were the main parts of the energy consumption in buildings, which plays an important role in consumption of energy. Therefore in building sector has a lot of scope presents to save energy by using alternating source of energy in place of high grade energy use by improving the quality match between energy supply and demand.

II. Description of the reference building.

For this study, selected a rectangular shape reference building room with dimensions (5m X 4 m X 3) in size with one wall (5m X 3 m) facing south and having a single –glazed window (2.5m X 2 m) with lightly heat absorbing glass.

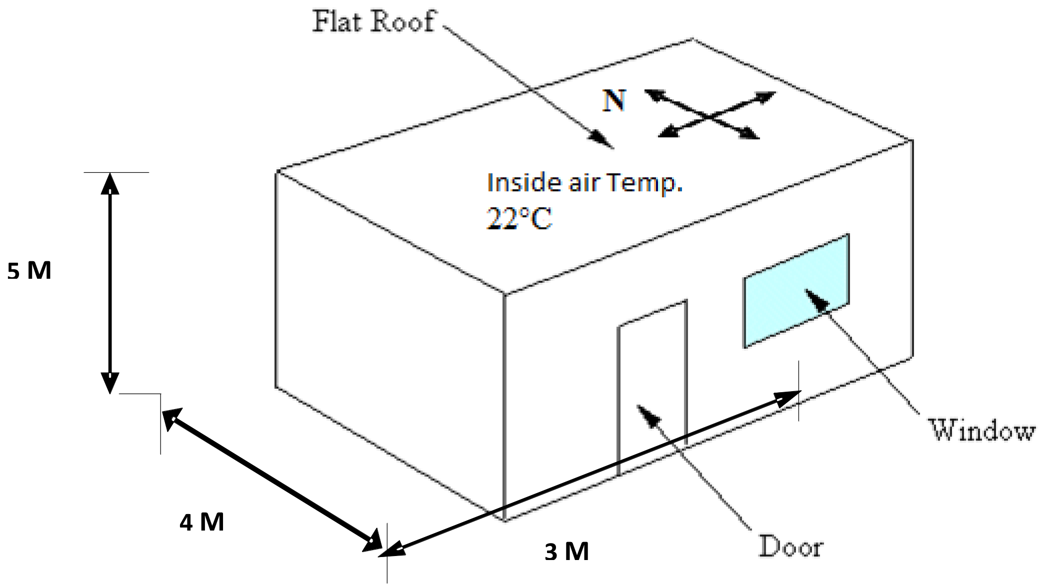

Fig.-1 Schematic diagrams of the Building Model

The physical properties of building envelope components were listed below:

Table-1: Physical properties of the building envelope components

No.	Building envelope component	Orientation	Area *[m2]*	Thickness *[m]*	K-value *[W/ m C]*	F_s - value
1	Wall	north	15	0.3	0.72	-
2	Wall	south	15	0.3	0.72	-
3	Wall	east	20	0.3	0.72	-
4	Wall	west	20	0.3	0.72	-
5	Roof	horizontal	12	0.25	0.4	-
6	Window (lightly heat absorbing glass)	south	5	-	U_g = 5.6[W/ m2° C]	0.51

Table-2: Physical properties of the building envelope components (Continued)

No.	Building envelope component	Solar absorptance		Convective heat transfer co-efficient (h_c) [W/m2C]	Radiative heat transfer co-efficient (h_r) [W/m2C]	Thermal resistance for the internal surface which is in contact with the room air [$W^{-1}m^{2o}C$]
		Inside	Outside			
1	Wall	0.6	0.6	8.7	3.8	0.125
2	Wall	0.6	0.6	8.7	3.8	0.125
3	Wall	0.6	0.6	8.7	3.8	0.125
4	Wall	0.6	0.6	8.7	3.8	0.125
5	Roof	0.6	0.6	8.7	3.8	0.125
6	Window	0.6	0.6	8.7	3.8	0.125

The other relevant information is given below:

C_c= 0.66 k J/kg°C

C_{pa} =1.005 k J/kg°C

$m_a c_{pa}$ = 122.7 k J/°C

$\Delta\omega = 0.03$

$\emptyset = 28.35°$N for Delhi

$\beta = 90°$ for vertical walls

$S^s = 285\ W/m^2$

m_a =197.2 kg

$\Delta R = 220\ kJ/hm^2$

$\epsilon_{w/r} = 0.9$

$\rho_{w/r} = 1858.26\ kg/m^3$

$N_o = 5$

$N_e = 5$ (One person per computer unit)

$Q_{ga,o}$=75 W/person

$Q_{ga,e}$= 230 W/ computer unit

T_{sun}= 6000 K

$T_{skin\ tempreture}$=315K

$T_{equipement\ surface}$ = 334K

The total thermal energy gain from artificial lighting is 200W and the building is natural ventilated with a rate of $2h^{-1}$ air change rate. The infiltration air flow rate is assumed constant at 0.5 per hour all over the day. It is assumed that initially all inside and outside surfaces are on equal temperature to the initial temperature of the inside air. The mean inside air temperature is 22°C.There is no mechanical ventilation and no dehumidification in the buildings.

III. Energy and exergy demands of the reference building.

The energy and exergy values of the reference building at inlet and outlet were estimated by using the measured solar radiation data on both horizontal and vertical surfaces of walls and the fundamental thermodynamics equations (1-22) which has been based on first and second law of thermodynamics. Solar radiation measurements are carried out on 07.04.2012 at New Delhi, India {N 28° 34'} {E 77° 11'} {GMT +5.5 Hours}[Table-3].These values are accounted for an hour in a mild summer day

Table- 3 :.Radiation data of April 7, 2012 on the roof and walls of a building at I.I.T .New Delhi, India

Time + (in hrs)	Ambient air temperature T_{oa} (°C)	Solar radiation on horizontal Surface (W/M^2)			East Wall	West Wall	South wall	North wall	RH (%)
		Diffuse	Beam	Total					
7:30	29	104.12	49.55	153.67	343.45	57.24	92.00	59.29	53
8:00	29	152.54	160.61	313.15	507.00	75.64	118.57	102.22	52
8:30	29.5	176.76	189.95	366.71	525.40	75.64	159.46	110.40	52
9:00	30	205.81	262.17	467.99	541.76	87.91	228.97	110.40	51
9:30	32	220.34	338.45	558.79	535.62	100.17	233.06	120.62	48
10:00	34	234.87	356.52	591.39	486.56	106.31	302.57	116.53	44
10:30	34	232.45	503.29	735.74	449.76	120.62	337.32	132.88	41
11:00	34	278.45	468.93	747.38	335.28	139.02	335.28	134.93	40
11:30	35	295.40	384.46	679.86	243.28	141.06	316.88	126.75	40
12:00	36	273.61	401.60	675.20	192.17	167.64	370.03	132.88	39.5
12:30	36	263.92	540.50	804.42	183.99	175.82	380.25	136.97	35
13:00	37	256.66	520.99	777.65	169.68	220.79	372.07	134.93	30
13:30	37	251.82	482.76	734.58	151.28	275.99	349.59	128.79	29
14:00	37	249.39	433.96	683.35	136.97	365.94	335.28	122.66	27
14:30	37	234.87	405.41	640.28	132.88	439.54	323.01	128.79	25
15:00	37	227.60	288.11	515.72	122.66	488.60	275.99	122.66	28
15:30	37.5	205.81	240.06	445.87	108.35	453.85	233.06	116.53	30

16:00	38	174.33	162.10	336.44	89.95	402.54	175.82	98.13	29
16:30	38	133.17	99.66	232.83	73.60	349.59	130.84	87.91	29
17:00	37	108.96	36.56	145.52	51.11	233.06	94.04	59.29	31.5
17:30	36	62.95	15.04	78.00	30.67	122.66	47.02	38.84	34

Table-4: Thermal energy (Q_{th}) and thermal exergy (Ex_{th}) flows in the reference building for the 13:00 hour of the dated 07/04/2012 at New Delhi.

items	Thermal Energy (Q_{th}) in (W)		Thermal Exergy (Ex_{th}) in (W)	
	Input	Output	Input	Output
South Wall North Wall East Wall West Wall Roof	499.2 474.2 685.9 764.8 549.7	-	25.1 23.7 34.3 38.3 27.5	-
Solar heat gain through window	948.8	-	899.8	-
Heat transfer through Ventilation	4656.7	-	807.2	-
Heat transfer through Infiltration	1164.5	-	201.9	-
Internal heat gain	1725	-	102.9	-
Cooling Load	-	11468.9	-	583.2
Total	11468.9		2159.5	583.2

The total thermal energy input is dominated by the thermal energy input by the transmission through wall and ventilation,which is 3.0 kW and 4.6 kW respectively . The heat addition through infiltration is 1.2 kW. A graphical representation of the comparative values of thermal energy and thermal exergy are shown in fig.4.

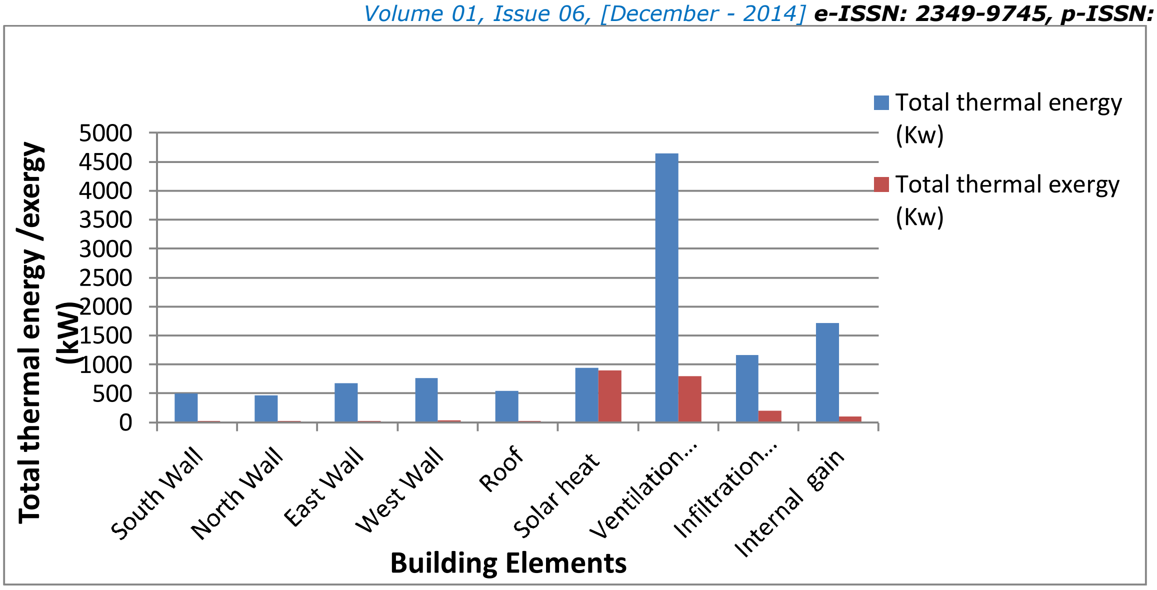

Fig.4 Thermal energy and exergy values in buildings

The total thermal energy input is dominated by the heat transmission through walls of the buildings and ventilation which is almost 30% and 40 % respectively of the total thermal energy input .It is identified from fig.5 that the total thermal exergy output is much smaller than the total thermal exergy input. From energy analysis it could be concluded that the reducing of ventilation heat gain even important as reducing solar gain through window and walls .

However, the exergy analysis shows that there is not much potential present in the heat gain through internal gains from occupancy and appliances, whereas the solar gains have a high exergetic potential. The exergy analysis shows that the solar gain creates the main exergy losses in air –conditioned building room during space cooling .Therefore; it is required to minimize the solar gain in buildings through walls and window.

IV. Parametric Analysis of thermal energy and thermal exery values

In the parametric study of building envelope, numbers of variables are possible and listed below:

1. Wall thickness
2. Wall material
3. Roof thickness
4. Type of window glass
5. Shape
6. Size and place of window
7. Ceiling height
8. Colour

9. Texture etc.

Out of these variables, five major parameter were considered in this study, i.e. wall thickness, roof thickness, wall thermal conductivity, window material, window dimensions.

4.1 Changing the thickness of the walls

This study deals with the comparative analysis of thermal energy and thermal exergy values in the reference building by changing the thickness of the wall, while the rest of parameters were kept constant for calculation of heat transmission through building envelope. The thermal energy and thermal exergy values by infiltration and ventilation are not sensitive to the changes of the wall thickness. The infiltration and ventilation values are depending on the air flow rates that were assumed constant because the indoor air temperature at that hour is constant. The thermal energy and thermal exergy values by internal and solar gains are also constant at that hour. The following cases were analyzed:

- Case A:wall thickness =0.20m
- Case B: wall thickness = 0.25m
- Case C:wall thickness = 0.35m
- Case D :wall thickness =0.40 m

Table-5: Comparative values of thermal energy (Q_{th}) and thermal exergy (Ex_{th}) by transmission through walls and for cooling of all cases in the reference building at 13:00 hrs on 07/04/2012 at New Delhi.

items	Thermal Energy (Q_{th}) in (W)		Thermal Exergy (Ex_{th}) in (W)	
	Input	Output	Input	Output
Case A:wall thickness =0.20m				
South Wall North Wall East Wall West Wall	642.2 610.1 882.7 984.2	-	32.1 30.5 44.2 49.2	-
% increase heat input	22 %	-	28.6 %	-
Cooling Load	-	12163.9	-	608.9
% increase cooling load	-	5.8 %	-	4.2 %
Case B :wall thickness =0.25m				
South Wall North Wall East Wall West Wall	562 533.8 772.2 861.1	-	28.1 26.0 38.6 43.0	-
% increase heat input	11.5 %	-	11.8 %	-
Cooling Load	-	11773.8	-	588.7
% increase cooling load	-	2.8 %	-	0.9 %

Case C:wall thickness =0.35m				
South Wall North Wall East Wall West Wall	499.1 426.5 617 688	-	24.9 21.3 30.8 34.4	-
% decrease heat input	7.9 %	-	8.2 %	-
Cooling Load	-	11275.8	-	563.8
% decrease cooling load	-	1.7 %	-	3.3 %
Case D:wall thickness =0.40m				
South Wall North Wall East Wall West Wall	408.1 387.6 560.6 625.2	-	20.4 19.3 28 31.3	-
% decrease heat input	18.3 %	-	18.5 %	-
Cooling Load	-	13449.6	-	672.5
% decrease cooling load	-	3.9 %	-	15.2 %

4.2 Changing the thickness of the Roof

In this study presented the comparative analysis of thermal energy and thermal exergy values in the reference building by changing the thickness of the roof, while the rest of parameters were kept constant for calculation of heat transmission through building envelope. The thermal energy and thermal exergy values by infiltration and ventilation are not sensitive to the changes of the roof thickness. The infiltration and ventilation values are depending on the air flow rates that were assumed constant because the indoor air temperature at that hour is constant. These make also the thermal energy and thermal exergy values by internal and solar gains were constant at the hours. The following cases were considered:

- Case A:roof thickness =0.20 m
- Case B: roof thickness = 0.30 m
- Case C:roof thickness = 0.35 m
- Case D :roof thickness =0.40 m

Table-6 :Comparative values of thermal energy (Q_{th}) and thermal exergy (Ex_{th}) by transmission through roof and for cooling of all cases in the reference building at 13:00 hrs on 07/04/2012 at New Delhi.

items	Thermal Energy (Q_{th}) in (W)		Thermal Exergy (Ex_{th}) in (W)	
	Input	Output	Input	Output
Case A:Roof thickness =0.20m				
Heat gain through roof	649.9	-	32.5	-

% increase heat input	15.4 %	-	18.2 %	-
Cooling load	-	11569.1	-	578.5
% increase cooling load	-	0.9%	-	0.8
Case B: Roof thickness =0.30 m				
Heat gain through roof	479.8	-	23.9	-
% decrease heat load	12.7%	-	13.1 %	-
Cooling Load	-	11399	-	569.9
% decrease Cooling Load	-	0.7%	-	2.2 %
Case C: Roof thickness =0.35m				
Heat gain through roof	424.26	-	21.2	
% decrease heat load	22.8%	-	22.9%	
Cooling Load	-	11343.5	-	567.2
% decrease Cooling Load	-	1%	-	2.7 %
Case D:roof thickness =0.40m				
Heat gain through roof	380.3	-	19.1	-
% decrease heat load	30%	-	30.5%	-
Cooling Load	-	11299.5	-	564.9
% decrease Cooling Load	-	1.4 %	-	2.1 %

4.3 Changing the thermal conductivity of wall

This study focuses on variation of wall thermal conductivity by adding or removing the insulation .This study presents the comparative analysis of thermal energy and thermal exergy values in the reference building by changing the thermal conductivity of the wall material, while the rest of parameters were kept constant for calculation of heat transmission through building envelope . The thermal energy and thermal exergy values by infiltration and ventilation were not sensitive to the changes of the thermal conductivity of walls. At this hour the thermal exergy values by internal and solar gains were constant. The following cases considered:

- Case A:Wall thermal conductivity, K = 0.40W/ m C
- Case B: Wall thermal conductivity, K = 0.50W/ m C
- Case C: Wall thermal conductivity, K = 0.60 W/ m C
- Case D : Wall thermal conductivity, K = 0.80W/ m C

Table-7: Comparative values of thermal energy (Q_{th}) and thermal exergy (Ex_{th}) by transmission through and for cooling of all cases in the reference building at 13:00 hrs on 07/04/2012 at New Delhi.

items	Thermal Energy (Q_{th}) in (W)		Thermal Exergy (Ex_{th}) in (W)	
	Input	Output	Input	Output
Case A: Wall thermal conductivity, K = 0.40W/ m C				

South Wall North Wall East Wall West Wall	324.9 308.7 446.5 497.9	-	16.3 15.4 22.3 24.9	-
% decrease heat load	34%	-	35.1 %	-
Cooling Load	-	10622	-	531.1
% decrease Cooling Load	-	7.4 %	-	8.9 %
Case B: Wall thermal conductivity, K = 0.50W/ m C				
South Wall North Wall East Wall West Wall	385.5 366.2 529.7 590.7	-	19.8 18.3 26.5 25.5	-
% decrease heat load	22.8 %	-	25.7 %	
Cooling Load	-	10916	-	545.8
% decrease Cooling Load	-	4.8 %	-	6.5 %
Case C: Wall thermal conductivity, K = 0.60W/ m C				
South Wall North Wall East Wall West Wall	440.2 418.2 604.8 674.4	-	22.1 20.9 30.2 33.7	-
% decrease heat load	11.8 %	-	11.9 %	-
Cooling Load	-	11182.4	-	559.1
% decrease Cooling Load	-	2.4 %	-	4.2 %
Case D: Wall thermal conductivity, K = 0.80W/ m C				
South Wall North Wall East Wall West Wall	535.0 508.3 735.2 819.8	-	26.7 25.4 36.8 40.9	-
% increase heat load	7.1 %	-	6.9 %	-
Cooling Load	-	11643.1	-	582.2
% increase Cooling Load	-	1.5 %	-	0.2 %

4.4 Changing the solar heat gain factor (Fs) for window.

This study deals with the comparative analysis of thermal energy and thermal exergy values in the reference building by changing the properties of window material, while the rest of parameters were kept constant for calculation of heat transmission from walls/roof, and windows . The thermal energy and thermal exergy values by infiltration and ventilation are not sensitive to the changes of the window material types. At this hour the thermal exergy values by internal is constant. The thermal energy and thermal exergy values by solar gain through window are depends on properties of window material and it is not constant. The following cases were analyzed:

- Case - A: Type of Sun protection : None

Type of glazing: Single

Solar heat gain factor (F_s): 0.76

- Case - B: Type of Sun protection : None

  Type of glazing: Double

  Solar heat gain factor (F_s): 0.66

- Case - C: Type of Sun protection : Densely heat absorbing glass

  Type of glazing: Single

  Solar heat gain factor (F_s): 0.39

- Case -D: Type of Sun protection : Densely heat absorbing glass

  Type of glazing: Double

  Solar heat gain factor (F_s): 0.25

Table-8 :Comparative values of thermal energy (Q_{th}) and thermal exergy (Ex_{th}) by transmission through window and for cooling of all cases in the reference building at 13:00 hrs on 07/04/2012 at New Delhi.

items	Thermal Energy (Q_{th}) in (W)		Thermal Exergy (Ex_{th}) in (W)	
	Input	Output	Input	Output
Case A: Type of Sun protection : None ,Type of glazing: Single Solar heat gain factor (F_s): 0.76				
Solar Heat gain through window	1413.9	-	1340.9	-
% increase heat load	32.9%	-	32.9%	-
Cooling Load	-	11933.8	-	2600.6
% increase Cooling Load	-	4 %	-	20.5%
Case B: Type of Sun protection : None,Type of glazing: Double ,Solar heat gain factor (F_s)0.66				
Solar Heat gain through window	1190.7	-	1119.3	-
% increase heat load	0.2%	-	19.6%	-
Cooling Load	-	11710.5	-	2379
% increase Cooling Load	-	2.1%	-	10.2%
Case C: Type of Sun protection : Densely heat absorbing glass ,Type of glazing: Single ,Solar heat gain factor (F_s): 0.39				
Solar Heat gain through window	725.5	-	681.9	-
% decrease heat load	23.5 %	-	24.3%	-
Cooling Load	-	11245.5	-	1941.6
% decrease Cooling Load	-	1.9%	-	10.1%
Case D: Type of Sun protection: Densely heat absorbing glass ,Type of glazing: Double ,Solar heat gain factor (F_s): 0.25.				

Solar Heat gain through window	465.1	-	437.2	-
% decrease heat load	50 %	-	51.2%	-
Cooling Load	-	10985.1	-	1696.9
% decrease Cooling Load	-	4.3%	-	21.4%

V. Conclusion

In this research comprehensively discussed the exergetic performance of the building by using a room model. The energy and exergy analysis of the reference building for the 13:00 Th Hrs of dated 07/04/2012 at New Delhi has been carried out. It is found through analysis that the changes of the thickness of the walls and the roof, as well as the thermal conductivity of wall by adding or removing the insulation, do not make any difference to the thermal energy and thermal exergy values caused by infiltration, ventilation airflows and internal gains.

In parametric study it is assumed that the thermal energy and thermal exergy values of the infiltration and ventilation is constant. The results for the thermal energy and exergy flow through buildings were presented in table - 4. The heat gain through transmission and ventilation were calculated to be 3.0 kW and 4.7 kW respectively using equations (6 and 10). Solar and internal gains were found to be 0.9 kW and 1.7 kW respectively. According to the heat load calculations by using equation (1), which is presented in table-4, the heat demand of the building load is calculated to be 11.5 kW. It is found that the largest thermal energy and exergy input to the building occurs through ventilation. While a part of exergy leaves from building envelope, some of it still remains (stored) however, all of the exergy is consumed in the building envelope. The results of the total thermal energy and the total thermal exergy saving were presented in table 10. This approach reveals that the exergy is a useful method for
Comparisons of different options, with reference case. The solar exergy consumption across the subsystem wall is greater than the window. This is because of the higher area and the thermal conductivity value of the wall. The lowest exergy input occurs through north facing wall for the same surface area in building and it value is 0.49 kW. As result of exergy analysis, the exergy input through window is remarkable (0.9 kW).

It is seen that an optimum value of wall thickness occurs after 0.28m, after that if the wall thickness is increased the heat transmission through the wall is decreased significantly. In fig.5 the highest saving in thermal energy and exergy value are obtained for case 4 (at thickness of 0.4 m) while the rest of parameter were kept constant. The horizontal axis shows the change in wall thickness and the vertical axis shows the total energy and total exergy values.The results of parametric study is presented in table 10.

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