Journal of Thermal Engineering *http://eds.yildiz.edu.tr/journal-of-thermal engineering/Articles*
Yildiz Technical University Press, Istanbul, Turkey *Manuscript Received February 05, 2015; Accepted March 08, 2015*
Vol. 1, Special Issue No. 4, pp. 433-439, October, 2015.

This paper was recommended for publication in revised form by Regional Editor Ahmed Kadhim Hussein

BUILDING ENVELOPE PERFORMANCE WITH DIFFERENT INSULATING MATERIALS – AN EXERGY APPROACH

Y. Anand
School of Energy Management
Shri Mata Vaishno Devi University
Katra (J&K) – India

***S. Anand**
School of Energy Management
Shri Mata Vaishno Devi University
Katra (J&K) – India

A. Gupta
School of Energy Management
Shri mata Vaishno Devi University
Katra (J&K) - India

S. K. Tyagi
Sardar Swaran Singh
National Institute of Renewable Energy
Kapurthala (Punjab)-India

Keywords: Exergy Demand Rate, Exergy, Thermal Comfort, Building Envelope

** Corresponding author: Sanjeev Anand, Phone: +91-9419104580,*
E-mail address:anandsanjeev12@gmail.com

ABSTRACT
Buildings are now considered as investments, everyone is interestd in. But they end up consuming lot of energy, hence its performance is necessary to be checked. Building performance can best analysed by keeping a close watch on the bulding operations and the exergy analysis is a better and comprehensive way to understand it in totality. Buildings have now a days become the largest producer of green house gases, thus making them a potential option for analysis. This is why national and international organizations have joined hands to raise governances to carryout symbolic proposals in building's sustainability, energy efficiency and environmental protection. The energy consumption due to thermal loads can be minimized by effective and judicious use of building resources which includes building design and its operations. The present communication deals with the detailed analysis of a building envelope for four different cases i.e. no insulation on walls and roof and oven dry wood, polyurethane foam and fiberglass as insulation for the roof and walls respectively. The behavior of the building envelope for all the cases, with the variation of the ambient temperature revealed that the exergy analysis is a quintessential analyzing the buildings for optimizing their energy consumption. Results revealed that polyurethane (PU) foam can be considered to be the best option for optimum performance from the building envelope.

INTRODUCTION
Industry, transportation, and buildings sector consumes world's main primary energy. Out of these, the buildings need to be checked carefully for their effective operations as they utilize a generous proportion of the primary energy. This accounts for adequate use of energy and to produce a generation of equipments that consume lesser energy. There are many ways to calculate the energy requirement of each of these sectors. These approaches vary from the changes in the energy resources, variations of prices and methods of production. One approach of conservation of energy can be the responsible allotment of resources i.e, curtailing the heating ventilation and air-conditioning (HVAC) load by availing climate responsive materials which contribute in designing efficient buildings, or by

erecting small and just fit building envelopes. Therefore, performing the necessary analysis prior to the construction, can help the designer to achieve better solutions in building design and operation. A wide range of building simulation methods are available, ranging from the numerical methods to digital programs which are capable to generate hourly results. As stated above, the energy consumption by the built structures is enormous but the residential structures are one of the major consumers. The HVAC systems consume 16% – 50% of energy, the largest share among all other applications in the buildings [1]. Nowadays, almost all the calculations pertaining to the energy usage in a building utilises the Principle of Energy Conservation and the First Law of Thermodynamics. This creates a scope for performing the exergy analysis to study the energy flow of the buildings or the built structures [2, 3]. The definition of exergy states it as the usable form of energy or that energy. It is also that form of energy which can be entirely converted into other forms. Also, it is defined as the degree of the withdrawal of the state of the system from that situation. So, as the definition suggests, the mechanical and electrical workload should consist of pure exergy, as most of them can be converted to other usable forms [4]. Exergy Analysis can exactly identify the regions and origins of the incompetencies in a process or a system [5]. Exergy analysis is thus an effective way to achieve energy efficiency and rational use of resource, by the application of the principles of the conservation of mass and energy and also the second law of thermodynamics. Today, the buildings must be intended to use the viable sources for air conditioning. The heating or cooling system working for low – exergy are stated as those systems where the under valued energy is used as source [6]. Lee and Sherif, 2001 [7] showed that the supply temperatures for a air system working on forced convection, must be close to the required temperature inside the room. It should also be noted that the exergy expenditure throughout the process is in proportion to the entropy created in the process. The total exergy (kW) going into a system, due to the interaction of heat and mass, at the environmental temperature T_{envir}, is [8],

$$X_{inside} = \sum m_i x_i - \sum Q \left(1 - \frac{T_{envir}}{T}\right) i + \sum W, \quad (1)$$

the destruction of the exergy (kW) being [8]:

$$\sum X_{dest} = \sum T_o S_{gen} = T_{envir} \left[\left(m(s_f - i) - \frac{Q}{T}\right)\right] \quad (2)$$

Where s being the system's entropy (kJ/kg K)
The exergy balance (kW) is given as [8],

$$\sum X_{inside} = \sum X_{dest} + \sum X_{outside} \quad (3)$$

The exergy efficiency is given as follows [8]

$$\eta = \frac{\sum X_{outside}}{\sum X_{inside}} = 1 - \frac{\sum X_{dest}}{\sum X_{inside}} \quad (4)$$

Some researchrs have investigated a heating system of low exergy for the total exergy input rate [9, 20]. Also, the relationship and differences between the energy, exergy and entropy of a building when subjected to heating conditions were discussed by Shukuya [10]. Shukuya and Hammache [11] had compared the exergy consumption during heating originating from the power plant and passing through the boiler to the building envelope, for steady state condition. Shukuya [12] discussed that how the concept of exergy can be used to built space heating and cooling systems. The use of computational fluid dynamics (CFD) model for analyzing the reduction in the summer cooling load by using ventilation on roof was investigated and a direct comparison between the open and the closed roof structures was presented [13]. An overview of multiphysics applications using COMSOL for building physical construction simulation was carried by Schijndel [14]. The overview includes heat, air and moisture transfer, separately and jointly. Also the study of the building unified with semitransparent photovoltaic thermal system (BISPVT) [15], the analysis of the building heating and cooling system [16] and the use of exergy analysis to find the efficiency of waste water treatment plant [17] was done by researchers. Also, both industrial and academic world are now a days focussing on the developing materials used for insulation made up of sustainable composites, reinforced with natural fibres. The review suggesting the use of the basalt fibre and its composites as reinforcement of different matrices as polymer (both thermoplastic and thermoset), metal and concrete was presented [18].

Eymard et. al. [19] investigated the mechanical behaviour, at a local scale, of a solution of a thick thermal insulation pneumatically placed from the outside for refurbishment was done to show the strength of the critical area: the interface with its concrete substrate.

It is thus evident that exergy analysis is a good means to establish the energy flow in the built structures, but is very less studied. The study should be done under the umbrella of the insulation materials used, as it also influences the thermal transport. So, a few easily available and established insulating materials have been taken for the analysis.

The focal purpose of the present work is to conduct an exergy based analysis for the building, for the achieving the thermal comfort of 23°C, inside the building envelope for the entire duration of the day i.e from 08:00 a.m. to 06:00 p.m. The analysis is further extended to the various wall insulation conditions for a building and a comparison of their performance with respect to the exergy and energy has been done.

SYSTEM DESCRIPTION

In the present work a building with a volume of 46.22m^3 is considered. The area of the four walls and the roof are taken as 8.832m^2, 12.082m^2, 14.097m^2, 12.082 m^2 and 12.735m^2 respectively. The net floor area is similar to the roof area. The simulation is done for the thermal comfort of 23°C. The weather is for a location at Shri Mata Vaishno Devi University located in the state of Jammu & Kashmir, India with the latitude as 32.5400° N and longitude as 74.9540° E. The outdoor temperature and solar intensity is measured for a typical day in July` 2014 for every hour, starting from 8:00 a.m. till 06:00 p.m., shown in Table 1. The data for outside temperature and solar radiation is measured using digital temperature indicator and pyranometer respectively. The digital temperature indicator uses a thermocouple as sensing element for precise observations with

Table 1: Temperature and Incident radiation as on a typical day of July 2014.

Time		Temperature (^{o}C)	Solar Radiation (W/m^2)
A.M.	**8:00**	31	200
	9:00	32.6	575
	10:00	34	730
	11:00	34.4	876
P.M.	**12:00**	34.8	810
	1:00	34.3	600
	2:00	35.5	780
	3:00	36.4	650
	4:00	36.6	430
	5:00	33	140
	6:00	30	110

Table 2: Property for the construction material [21]

	Type	Material	Calculated U Values ($Wm^{-2}K$)
Case 1	Without Insulation	Plaster + Brick + Plaster	Wall = 3.24
			Roof = 3.684
Case 2	Oven Dry Wood	Plaster + Brick + Plaster + Wooden Insulation	Wall = 2.6765
			Roof = 3.684
Case 3	Polyurethane Foam	Plaster + Brick + Plaster + Polyurethane Insulation	Wall = 2.1041
			Roof = 3.684
Case 4	Fibre Glass	Plaster + Brick + Plaster + Fibre Glass Insulation	Wall = 2.3063
			Roof = 3.684

regard to temperature. The pyranometer used for measurement of solar radiation is a KIPP ZONEN SP Lite pyranometer with a sensitivity of 74 $\mu V/Wm^{-2}$. The materials choices for the construction are relevant to the location. The standard construction material consisting of brick for the walls, reinforced concrete for the roof and stones for the floor are used. The brick walls are covered with sand/cement plaster on both the sides, contributing to the thickness of 0.2286 m. This is followed by a variation of the insulation material of 0.05 m thickness inside the building. The Oven Dry Wood, Polyurethane Foam and Fibre Glass are used as the insulation are having the thermal conductivity of 0.0769, 0.03 and 0.04 respectively. Based on the standard construction material and their physical properties, the typical over all heat transfer coefficient values have been calculated and are shown in Table 2.

A MATLAB version R2012b was used to generate the code and the required graphical plots. The system has been analyzed for four cases (a) without any insulation on walls and roof, (b) Oven Dry Wood as insulation, (c) Polyurethane Foam as insulation and (d) Fiberglass as insulation; used along with the standard building materials.

ANALYSIS

The sum of the losses from all the surfaces denoted by i is the transmission heat loss rate and determined as [20]:

$$\dot{Q_T} = \sum(U_i.A_i.Fx_i).(T_i - T_o) \quad (5)$$

where $\dot{Q}_T$ in kW is the heat loss rate due to transmission and U_i in $Wm^{-2}K^{-1}$ is the thermal transmittance on the respective surface. T_i and T_o are the inlet and outlet temperatures. A_i is the area.

Fx_i is the correction factor for specific temperature, taken as unity i.e. 1 for all the surfaces.

The ventilation heat loss rate $\dot{Q}_V$ in kW is calculated by [20]:

$$\dot{Q}_V = (C_p.\rho.V.n_d).(T_i - T_o) \quad (6)$$

where C_p of air is 1.005 $kJkg^{-1}K$ at 20℃ and ρ of air 1.205 kgm^{-3} at 20℃ and n_d is the air exchange rate and its value is 1. V is the volume of the structure.

The heat gain rate due to solar is determined from [20]

$$\dot{Q}_S = \sum(I_{s,j}.(1 - F_{wf}).A_{w,j}.g_j.F_{she}.F_{nor}) \quad (7)$$

where $\dot{Q}_S$ in kW is the solar heat gain rate, $I_{s,j}$ is the solar radiation in Wm^{-2}, F_{wf} is the window frame fraction and is taken as 0.3, $A_{w,j}$ is the window area and is taken as 0.1, g_j is the glazing's total energy transmittance and is 0.23, $F_{she}$is the shading effects of the surrounding buildings and the the correction for the non-orthogonal radiation on the window pans is F_{nor}.

$$F_{she} = F_{nor} = 0.9\text{, for all cases [20]} \quad (8)$$

Gain due to the Internal heat due to occupants is

$$\dot{Q}_O = \dot{Q}_O".no_O \quad (9)$$

and internal heat gain due to equipment is neglected

Lighting power due to artificial lighting [20]

$$P_L = \dot{Q}_L = p_l.A_N \quad (11)$$

where $\dot{Q}_O$", no_O, A_N, $\dot{Q}_L$ and p_l are the internal heat gain rate due to occupants = 0.1, number of occupants = 1, Net area, lighting gains rate and specific power = 0.1, respectively.

Energy Balance as per the 1st law of thermodynamics is [20]:

Heat Demand Rate = (Sum of Heat Gain Rate + Sum of Heat Loss Rate)

$$\dot{Q}_h = \dot{Q}_T + \dot{Q}_V + \dot{Q}_S + \dot{Q}_O + \dot{Q}_L \quad (12)$$

The specific number for the heat demand rate is [20],

$$\dot{Q}"_h = \frac{\dot{Q}_h}{A_N} \quad (13)$$

Considering [20], $\dot{Q}_{Ge} = \dot{Q}_h$ (14)

where, $\dot{Q}_{Ge}$ is the heat transfer rate in generation

The exergy load rate for lighting can be considered as [20],

$$\dot{Ex}_{plant} = P_L . F_{q,el} \quad (15)$$

where, $F_{q,el}$ is the factor of quaity for the electrical energy and is taken as 0.9.

Building's overall energy and exergy load rates are [20],

$$\dot{E}_{p,total} = \dot{Q}_{Ge} . F_P + P_L . F_{p,el} \quad (16)$$

where, F_P is the primary energy factor and is equal to 3, $F_{p,el}$ primary energy factor for electricity and is 4.2

$$\dot{Ex}_{total} = \dot{Q}_{Ge} . F_P . F_{q,s} + P_L . F_{p,el} \text{ [20]} \quad (17)$$

$F_{q,s}$ =1, Quality factor for source and, the exergy demand rate number [20]

$$\dot{Ex}"_{total} = \frac{\dot{Ex}_{total}}{A_N} \quad (18)$$

RESULTS AND DISCUSSIONS

The present study, was carried considering a building envelope of volume 46.22 m^3. The analysis for evaluating the heat demand rate, the exergy, the exergy demand rate and the heat demand rate number for a building envelope with (a) without insulation (b) with oven dry wood as a insulation material, (c) Polyurethane Foam as insulation, and (d) Fibre Glass as insulation; was done. Further, the analysis based on the actual data detailed in the Table 1 and Table 2 for the indoor air temperature of 23ºC and a variation of the ambient temperature on a typical day of July 2014.

Fig. 1 shows the transmission heat loss for a built volume with the configuration of the building component roof and walls for the four cases. From the figure, it is clear that the ambient temperature influences the transmission heat loss with the lowest at a temperature of 30ºC for the Polyurethane Foam insulation and the overall heat transfer coefficient being influenced by the lowest thermal conductivity of the Polyurethane Foam. Further, the factor influencing the transmission heat loss for insulating materials like the cell structure etc is ignored in these calculations. It is also important to mention that the Polyurethane Foam should be kept free from moisture for improved results, owing to the ill effects of the moisture. Also the percentage increase in all the cases is same with the increase in the temperature. However, the energy requirement drastically reduces by adopting suitable insulating material as compared to the building having no insulation materials. The program helps us in analyzing any number of insulating materials before their selection is made for such applications.

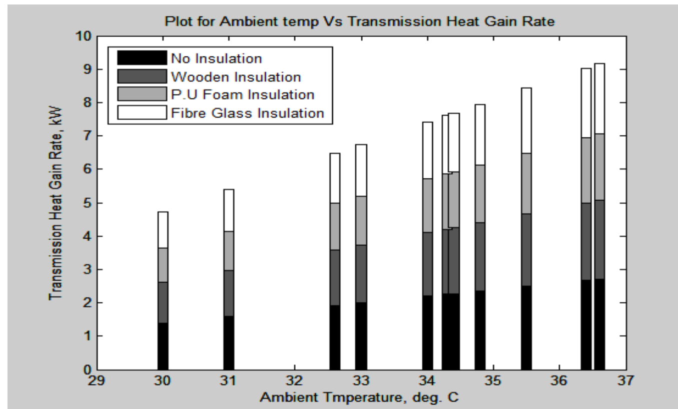

Fig. 1: Variation of Transmission Heat Loss Rate with the Ambient Temperature

Fig. 2 shows the heat gain through ventilation for a chosen value of air changes required per hour and from the figure, it is clear that the other parameters of the equation being constant the heat gain will directly depend upon the variation in the ambient temperature. This clearly shows how the ventilation rate is influenced by the change in ambient temperature. The details also reveal that this gain is highest at 4 p.m. where the ambient temperature is also highest for the day.

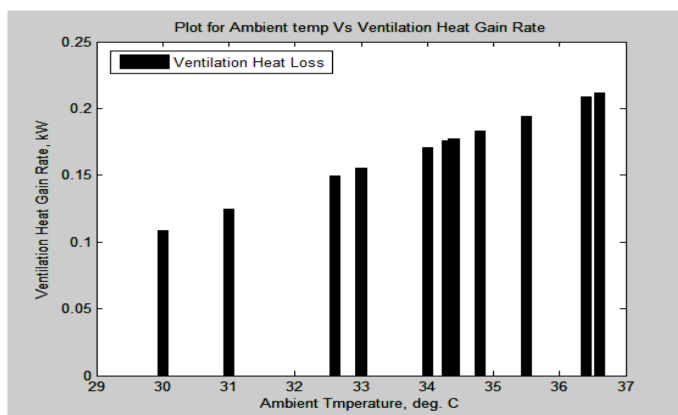

Fig. 2: Variation of Ventilation Heat Loss Rate with the Ambient Temperature

Fig. 3 quantifies the solar heat gain through the transparent surface and will always depend upon the properties of the glazing material. The figure again shows the variation in the solar heat gain with the ambient temperature. However, this variation depends directly on the solar radiation at that particular instant.

The solar radiation varies from 200 Wm^{-2} at 08:00 hrs. to 110 Wm^{-2} at 18:00 hrs with the maximum value of the solar heat gain rate at an ambient temperature of 34.4° C with a typical solar radiation value of 876 W/m^2 as calculated from the equation 7.

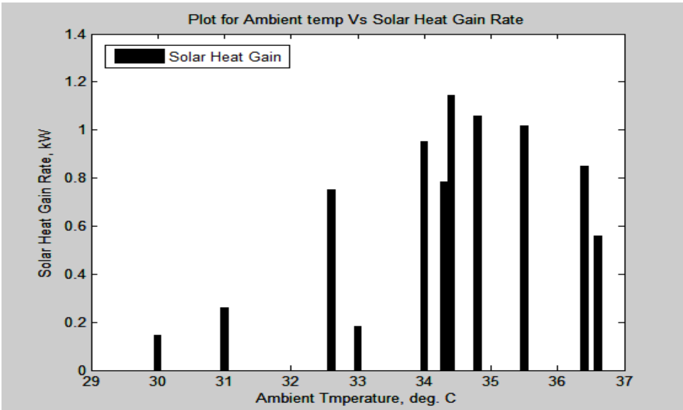

Fig. 3: Variation of Solar Heat Gain Rate with the Ambient Temperature

Fig 4 depicts the variation in the heat demand rate with the ambient temperature. The figure clearly shows that the lowest heat demand rate is 2.6478 kW at a temperature of 30°C. Further, from the figure, it is observed that the heat demand rate suddenly falls at a temperature of 33°C, 34.3 °C and 36.6°C. This is attributed to the lower contribution of the solar heat gain through the transparent surfaces as the solar radiation levels are quite low at these temperatures. The figure also shows the contribution of each component of heat demand rate with observed changes in the solar heat gain rate.

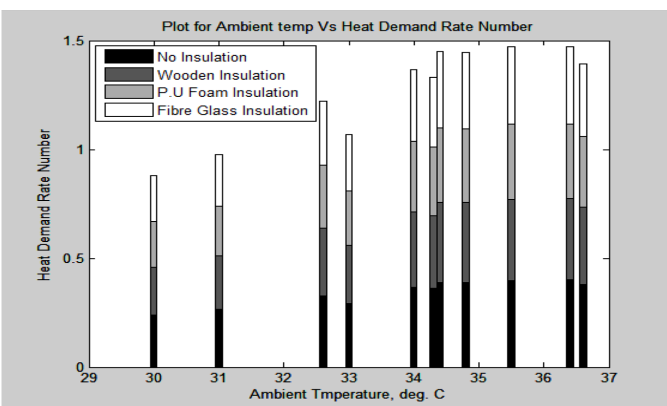

Fig. 4: Variation of Heat Demand Rate with the Ambient Temperature

The Fig. 5 depicts that the variation of the heat demand rate number for a particular ambient temperature throughout the day. The number is usually referred to establish a comparison of different buildings within each other. In the present study, four different applications for a particular building envelope have been adopted and based on the figure the building envelope employing Polyurethane Foam as insulating material on the wall and roof is consuming less energy than the others for achieving the thermal comfort.

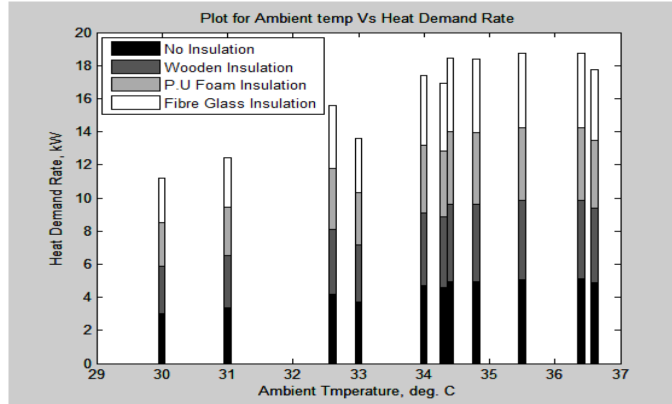

Fig. 5: Variation of Heat Demand Rate Number with the Ambient Temperature

Fig. 6 describes the variation in the exergy load rate with the ambient temperature and it's clear that the same varies with the varying temperature. However, at the temperature of 33°C, 34.3°C and 36.6°C it is more influenced by the amount of the solar radiations as detailed in Table 1. The high values of the exergy load rate in the present scenario reveal the highest value of Primary energy factor F_P equal to 3 and, $F_{p,el}$, the primary energy factor for electricity equal to 4.2. Another significance of the increased value is that no renewable energy technology is being used in the present study. The exergy load rate values can be reduced by employing renewable energy devices.

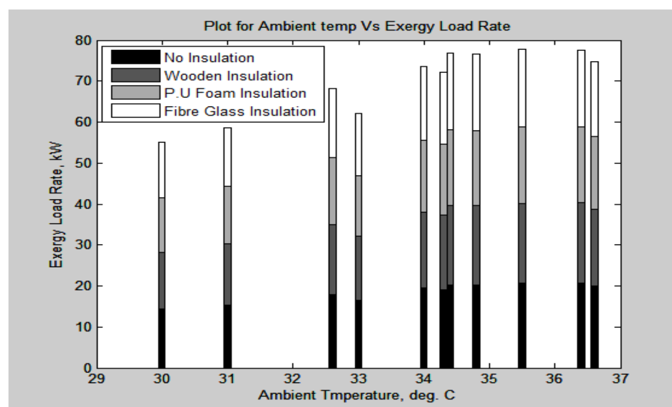

Fig. 6: Exergy Load Rate with the Ambient Temperature

Fig. 7 shows the exergy load rate number which is required for comparing the buildings. This number signifies that the exergy analysis in the buildings is very essential for providing the occupants a serene, fresh and fitter environment. It is observed that the least number with variation in ambient temperature is for the Polyurethane Foam material as an insulation material and thus can be concluded that the same achieves a thermal comfort much faster as compared to other materials. This quantification can be extended further for comparing buildings and thus minimizing energy consumption.

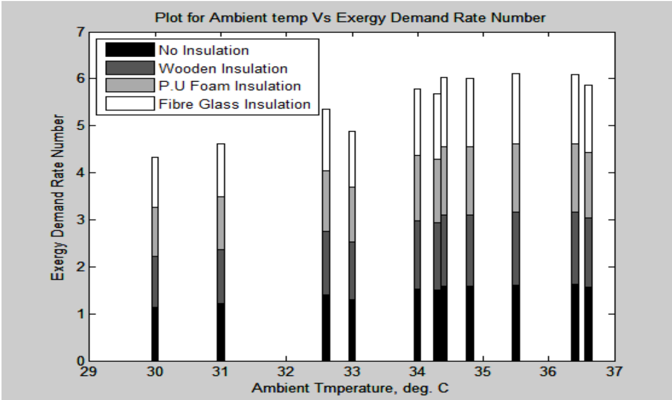

Fig. 7: Variation of Exergy Demand Rate Number with the Ambient Temperature

CONCLUSION

The presented study signifies the futuristic need for the building simulation programs for evaluating building envelope performances. This is aimed at developing sustainable healthy buildings. The study demonstrates the building envelope behavior for four different cases adopted for quantifying the parameters explained earlier for achieving thermal comfort. The detailed mathematical equations and the MATLAB programming helped in simulating and the results thus obtained shows that for a fixed thickness of different insulation, polyurethane foam can be considered to be the best option for achieving thermal comfort. The behavior thus obtained is influenced by the ambient temperature thus making exergy analysis an important tool to be adopted for building systems. The results revealed that the ambient temperature influences the transmission heat loss with the lowest at a temperature of 30^{o}C for the Polyurethane foam insulation. However, the energy requirement drastically reduces by adopting suitable insulating material as compared to the building having no insulation materials. The lowest heat demand rate is 2.6478 kW at a temperature of 30^{o}C. The heat demand rate suddenly falls at a temperature of 33^{o}C, 34.3 ^{o}C and 36.6^{o}C due to lower contribution of the solar heat gain through the transparent surfaces as the solar radiation levels. The variation of the exergy load rate with the ambient temperature is more influenced by the amount of the solar radiations depending upon a particular time in a day.

Exergy load rate number signifies that the exergy in the building is favourable enough to provide its occupants with a serene, fresh and fitter environment by comparing the buildings. It is found that the least number with variation in ambient temperature is for the Polyurethane foam as an insulation material and thus can be concluded that the same achieves a thermal comfort much faster as compared to other materials. The detailed program derived from this paper can be used by building professionals for getting the energy consumption pattern for the buildings with which the correct heating and cooling load can be estimated.

REFERENCES

1. Mandil, C., 2004. Oil Crisis and Climate Challenges: 30 years of energy use in IEA Countries. In: International Energy Agency, Paris. Available via DIALOG. http://s3.amazonaws.com/zanran_storage/www.iea.org/ContentPages/9507952.pdf
2. Schmidt, D. and Juusela, M.A., 2004. Low exergy systems for heating and cooling of buildings. In: Proceedings of the 21st Conference on Passive and Low Energy Architecture, Eindhoven, The Netherlands, pp. 1-6.
3. Schmidt, D., 2004. Design of low exergy buildings - method and a pre-design tool. *International Journal of Low Energy and Sustainable Buildings,* 3, pp. 1-47.
4. Koroneos, C., Nanaki, E. and Xydis, G., 2010. Solar air conditioning systems and their applicability - An exergy approach. *Resources, Conservation and Recycling*, 55(1), pp. 74-82.
5. Rosen, M.A., 2001. Energy and exergy based comparison of coal fired and nuclear steam power plants. *Exergy international Journal*, 1(3), pp. 180-192.
6. VTT Research notes, 2004. Heating and cooling with focus on increased efficiency and improved comfort. In: Ala-Juusela M, (ed), Guidebook to IEA ECBCS Annex 37, low exergy systems for heating and cooling of buildings guidebook summery report, VTT research notes 2256, VTT Finland. Available via DIALOG. http://www2.vtt.fi/inf/pdf/tiedotteet/2004/T2256.pdf.
7. Lee, S. and Sherif, S., 2001. Thermodynamic analysis of a lithium bromide/water absorption system for the cooling and heating applications. *International Journal of Energy Resources*, 25, pp. 1019 – 1031.
8. Koroneo, C., Nanaki, E. and Xydis, G., 2010. Solar air conditioning systems and their applicability – An exergy approach. *Resource conservation and Recycling*, 55 pp. 74 – 82.
9. Balta, M.T., Kalinci, Y. and Hepbasli, A., 2008. Evaluating a low exergy heating system fom the power plant through the heat pump to the building envelope. *Exergy and Buildings*, 40(10), pp. 1799 – 1804.
10. Shukuya, M., 1994. Energy, entropy, exergy and space heating systems. In: Proceedings of the 3rd International Conference on Healthy Buildings, 1, pp. 369 – 374.
11. Shukuya, M. and Hammache, A., 2002. Introduction to the concept of exergy – for a better understanding of low temperature heating and high temperature cooling systems. In: VTT Research Notes 2158, Espoo, Finland, Available via DIALOG. http://virtual.vtt.fi/virtual/proj6/annex37/presentation_of_annex_37/introduction_to_exergy.pdf.
12. Shukuya, M., 2009. Exergy concept and its applications to the built environment, *Building and Exvironment*, 44(7), pp. 1545 – 1550.
13. Villi, G., Pasut, W., Carli, M.D., 2009. CFD modelling and thermal performance analysis of a wooden ventilated roof structure. *Building Simulation*, 2, pp 215–228.
14. Van, Schijndel, A.W.M., 2011. Multiphysics modeling of building physical constructions. *Building Simulation*, 4, pp 49–60.

15. Vats, K. and Tiwari, G.N., 2012. Energy and exergy analysis of a building integrated semitransparent photovoltaic thermal (BISPVT) system. *Applied Energy*, 96, pp. 409–416.
16. Zhou, Y. and Gong, G., 2013. Exergy analysis of the building heating and cooling system from the power plant to the building envelop with hourly variable reference state. *Energy and Buildings*, 56, pp. 94–99.
17. Horrigan, M., Corcoran, B., Delauré, Y., Phelan, T., Mcnamara, G. and Fitzsimons, L., 2014. The use of exergy analysis to benchmark the resource efficiency of municipal waste water treatment plants in Ireland. In: 1st South East European Conference on Sustainable Development of Energy, Water and Environment Systems – S SDEWES Ohrid, Macedonia. Available via. DIALOG. http://www.ohrid2014.sdewes.org/ and http://doras.dcu.ie/20100/1/The_use_of_exergy_analysis_to_benchmark_the_resource_efficiency_of_municipal_waste_water_treatment_plants_in_Ireland.pdf.
18. Fiore, V., Scalici, T., Di, Bella, G. and Valenza, A., 2015. A review on basalt fibre and its composites. *Composites Part B*, 74, pp. 74-94.
19. Eymard, M., Plassiard, J.P., Perrotin, P. and Fay, S.L., 2015. Interfacial strength study between a concrete substrate and an innovative sprayed coating. *Construction and Building Materials*, 79, pp. 345–356.
20. Balta, M.T., Dincer, I. and Hepbasli, A., 2010. Performance and sustainability assessment of energy options for building HVAC applications. *Energy and Buildings*, 42(8), pp. 1320-1328.
21. Forests Product Laboratory, 2010. Wood Handbook - Wood as an engineering material, *U.S. Department of Agriculture, Forest Services, Research and Development*, http://www.fpl.fs.fed.us/utilities/information.php?info_id=2.