IOP Conference Series: Earth and Environmental Science

PAPER • OPEN ACCESS

A comparative study on effects of various insulating layers of roof system on energy usage of building envelope

IOP Conf. Series: Earth and Environmental Science **354** (2019) 012055 doi:10.1088/1755-1315/354/1/012055

A comparative study on effects of various insulating layers of roof system on energy usage of building envelope

A Raut[1], S Khatoon[2] and P Goud[1, 3]

[1]Department of Civil Engineering, Sree Dattha Institute of Engineering and Science, Hyderabad, India
[2]Department of Civil Engineering, Lords Institute of Engineering and Technology, Hyderabad, India

E-mail: ashwin7588@gmail.com

Abstract. The purpose of paper is to analyse the effectiveness of various roof systems based on insulations layers in hot climatic condition of Hyderabad, India. In this paper, Energy analysis using Autodesk's Green Building Studio cloud computing software has been done. The Energy analysis results gives indication about the Energy usage of building as well as overall life cycle costing. The roof system has been studied with their carbon emission and Embodied Energy to understand the sustainability aspect of the insulating layers in combination to provide a green roof system. The materials used for studying the insulating effects of roof system which were analysed in combinations were cork, gypsum board, expanded polystyrene, rock wool, fibre glass, PVC mesh, Polyurethane, etc. Due to the insulating layers the heat transfer is reduced through the roof system, which affects the cooling load of building envelope which reduces the energy consumption. The study is significant to understand the occupant's indoor comfort, environmental and long-term economic benefits of insulation for a building envelope.

1. Introduction

Globally, the building sector is responsible for one third of the total greenhouse gases emission (GHGs) in the atmosphere. Also, building sector is responsible for consumption of approximately 40%, 25% and 40% of global energy, water and other non-renewable resources respectively; causing serious adverse effects to the environment [1]. It is expected that due to rapid urbanization and rapid increase in socio-economic status of people in the developing countries, the building sector will be forecasted to have sharp incline in growth. Eventually, the demand for energy and resources will grow further causing serious environmental concerns [2]. The energy requirements in building sector is divided into embodied energy; operational energy and demolition & disposal energy, altogether it is known as life cycle energy of building [3]. The major contribution of energy is from embodied and operational energy. The embodied energy can be reduced by proper selection of materials and techniques used for construction; whereas, operational energy reduction is much more complicated as it depends on the occupant's comfort and habits.

The rapid socio-economic growth has put onus on the building sector to provide indoor air comfort condition to the occupants. Thus, to provide the indoor air comfort to the occupants, urban dwellers has been depended on the mechanical means of heating/cooling. Hence, the building sector in urban areas are becoming more and more energy consumptive. There has been need to find passive strategy for providing occupants with indoor air comfort to reduce the dependency on the mechanical heating/cooling. Proving an insulation layer is one of the ways to reduce the heat transfer through building envelope. The roof is one of the important segments of building envelope which is most susceptible to the direct solar irradiation which causes heat gain within building envelope.

Various researchers have analyzed passive cooling strategies for providing comfort condition to the occupants such as architectural shading [4], very low SHGC windows [5], insulated and reflective walls & roofs [6,7], optimized natural/mechanical ventilation [8-10]. Jamaludin *et al* [11] in his research conducted on the natural ventilation strategies for low rise multi residential building found that the natural ventilation lowers the temperature values below 30 ℃ whereas the relative humidity values were observed above 70%, thus providing the comfort condition. In another research, Kubota *et al* [8] suggested various passive cooling strategies including roof insulation, shading, night ventilation, court- yard/forced ventilation and micro climate for the studies conducted on the vernacular Malay houses. In Italy, Pisello and Contana [12] research suggested that the use of cool roof system lowers the overheating during peak summer up to 4.7 ℃ for traditional residential buildings.

Roof system restricts exposure of solar irradiation and other external environmental factors to the indoor environment, the roof thickness and combination of insulation layers proves to be crucial factor in reducing effects of direct solar irradiation. The modification in roof architecture is one of the passive cooling techniques used in green building constructions. The effects of combination of roof insulation was studied at Hyderabad region, India having arid climatic conditions. The focus of this research is to analyze the various combination of roof systems and its effect on the embodied and operational energy of building. As there are serval insulating options available currently in the market, but reduction of energy consumption and the lowered embodied energy roof material can truly serve as a green roof system for building sector.

2. Insulating materials

Various materials have been identified which are used as building insulation materials to lower the heat transfer through building envelope components. The materials for the study were Suspended ceilings (rock wool), Fiber Glass, Gypsum board, PVC Mesh – Polyurethane (insulation) layer. All these materials have very low thermal conductivity as reported in table 1. Using all these materials, roof slabs were modelled for the study to understand the effects on insulation layers on building energy system. The modelled slab system with various layers and their respective material data has been presented in table 1. All the modelled four slab system having various insulating layers are compared with conventional roof system.

3. Thermal parameters

The analytical method was used to calculated the U-value (Thermal Transmittance), Thermal Diffusivity and Thermal Effusivity. The insulation performance during the non-steady heat transfer condition requires the understanding of Thermal Diffusivity and Thermal Effusivity of material. Thermal diffusivity relates to the propagation of speed of transfer of heat through a material. The material used for insulation layer should have lower thermal diffusivity. The calculated values of Thermal Diffusivity are shown in table 1. Whereas, Thermal Effusivity (heat penetration coefficient) is the rate at which a material can absorb heat. The lower the diffusivity of the material, absorption of the heat will be lower from one layer to another layer in the building roof system. Thus, for better insulation purpose the thermal diffusivity should be as low as possible. The value of the thermal diffusivity of materials for roof insulation layer is presented in table 1.

The U-value represents the amount of heat transfer through the element of a building. The lower the U-value, better the effectiveness of the thermal insulation in the building envelope. The U-values of various roof insulation combination are presented in figure 1. The slab having expanded polystyrene and Rock wool as an insulating layer shows lowest heat transfer rate, thus proving to be energy efficient component for building envelope. All the insulated roof slab layer has comparatively lower heat transfer rate than that of conventional roof slab (U-value – 4.404 W/m^{2}K). The theoretical values for insulation i.e. U-value hints at the effectiveness of insulating layer but for the effects of insulating layer we need to perform the simulation for building energy analysis.

Table 1. Roof slabs having various insulating layers and its properties.

ROOF	Materials	Thickness (m)	Specific heat capacity (J/kg K)	Thermal conductivity (w/m K)	Density (kg/m^3)	R-value (m^2 k/w)	Thermal Diffusivity (m^2/s)	Thermal Effusivity (e)
ROOF SLAB 1	Concrete layer	0.15	1000	1.05	2400	0.143	4.38E-07	1587.451
	water proof course	0.01	1277	0.33	500	0.030	5.17E-07	459.026
	Cork	0.08	1900	0.04	240	2.000	8.77E-08	135.056
	Gypsum board	0.01	1090	0.17	668	0.074	2.33E-07	351.824
	cement plaster	0.01	780	0.72	2162	0.014	4.27E-07	1101.898
ROOF SLAB 2	Concrete layer	0.15	1000	1.05	2400	0.143	4.38E-07	1587.451
	water proof course	0.01	1277	0.33	500	0.030	5.17E-07	459.026
	Expanded Polystyrene	0.07	1200	0.033	1040	2.121	2.64E-08	202.938
	Suspended ceiling (Rock wool)	0.04	840	0.045	1000	0.889	5.36E-08	194.422
	cement plaster	0.01	780	0.72	2162	0.014	4.27E-07	1101.898
ROOF SLAB 3	Concrete layer	0.15	1000	1.05	2400	0.143	4.38E-07	1587.451
	water proof course	0.01	1277	0.33	500	0.030	5.17E-07	459.026
	Fibre glass	0.08	700	0.04	1500	2.000	3.81E-08	204.939
	Gypsum board	0.01	1090	0.17	668	0.074	2.33E-07	351.824
	cement plaster	0.01	780	0.72	2162	0.014	4.27E-07	1101.898
ROOF SLAB 4	Concrete layer	0.15	1000	1.05	2400	0.143	4.38E-07	1587.451
	water proof course	0.01	1277	0.33	500	0.030	5.17E-07	459.026
	PVC MESH	0.03	1250	0.25	1400	0.120	1.43E-07	661.438
	Polyurethane (insulation)	0.03	0.03	0.02	500	1.500	1.33E-03	0.548
	cement plaster	0.01	780	0.72	2162	0.014	4.27E-07	1101.898
ROOF SLAB 5	Concrete layer	0.15	1000	1.05	2400	0.143	4.38E-07	1587.451
	water proof course	0.01	1277	0.33	500	0.030	5.17E-07	459.026
	cement plaster	0.01	780	0.72	2162	0.014	4.27E-07	1101.898

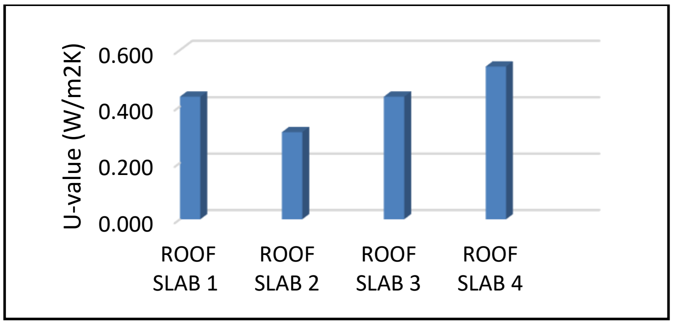


Figure 1. U-value for various roof slab systems.

IOP Conf. Series: Earth and Environmental Science **354** (2019) 012055 doi:10.1088/1755-1315/354/1/012055

4. Building energy analysis

The energy analysis was conducted for various roof system to understand the insulation's effectiveness and its benefits on overall energy savings and costing. The energy analysis was conducted on the modelled house as shown in figure 2, the tool used for simulation purpose was Autodesk's Green Building Studio cloud computing software. The modelling was done in Autodesk REVIT software for G+1 Story building, the location for weather data for the Coordinates of Hyderabad, India region (Latitude – 17.3850 °N; Longitude – 78.4867 °E). The comparative analysis was conducted based on the assumptions that all the parameters for the modelled house were kept constant; except the roof system having values shown in Table 1 were modified depending on the roof system for simulation.

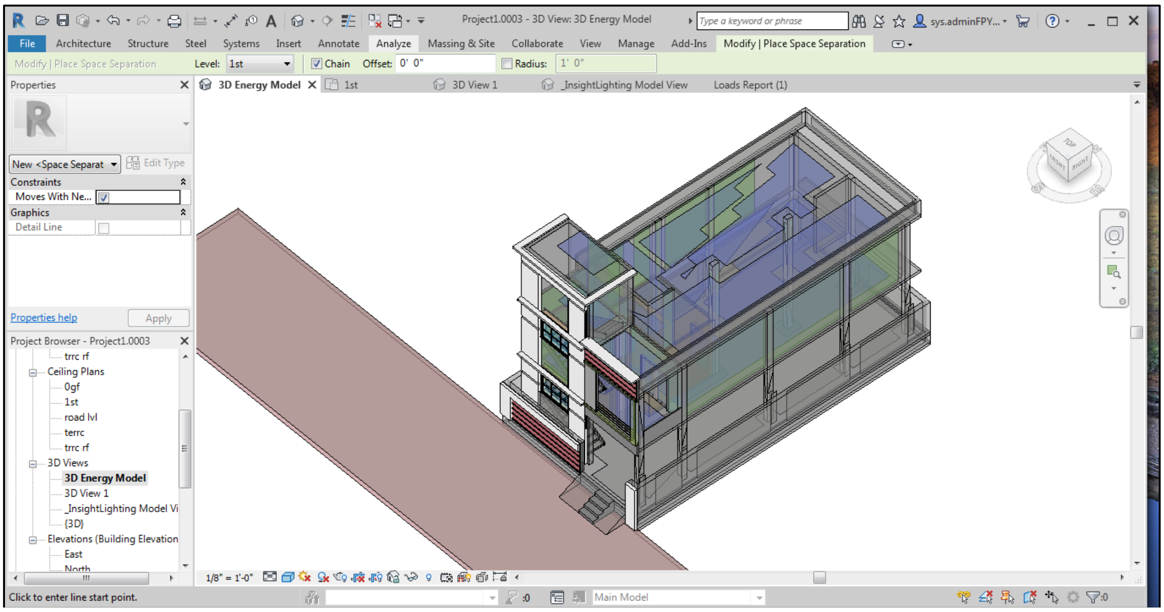


Figure 2. Snapshot of 3D building energy model in Revit Software.

Table 2. Energy analysis parameters for various roof insulation systems.

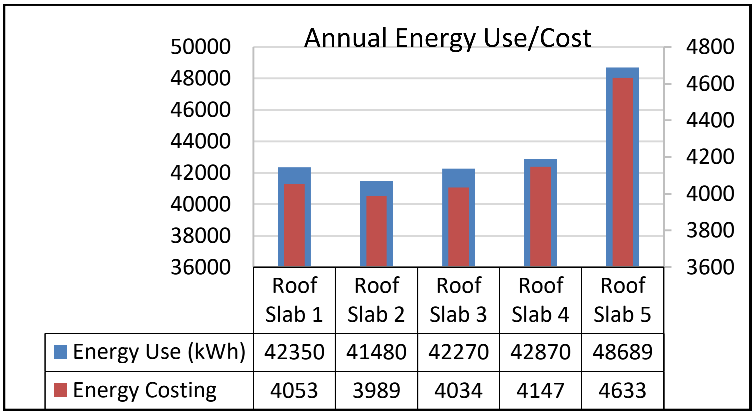
Sr. No.	Type of Roof	Energy Use Intensity (EUI) (KWh/sm/Yr)	Life Cycle Electricity Use (kWh)	Life Cycle Energy Cost ($)
1	Roof System 1	190	12,46,219	57,342
2	Roof System 2	184	11,93,481	56,751
3	Roof System 3	188	12,23,411	56,931
4	Roof System 4	195	13,16,118	58,043
5	Roof System 5	221	14,52,327	64,721

The comparative energy analysis of the roof system based on various insulating layers has been presented in table 2. From the table 2, it is evident that the Roof System 5, which is conventional non-insulated roof system has highest energy usage as compared to insulated roof systems. The Roof system 2 which comprises of expanded polystyrene and rock wool proves to be most efficient amongst other insulating layers. The effectiveness of the polystyrene and rock wool embedded roof system is due to its low thermal conductivity and the lowest U-value amongst other insulating layers. As the Energy Use Intensity (EUI) and Life Cycle Usage of energy is comparatively reduced, eventually lowering the life cycle energy costing of the building energy requirement. The monetary benefits with the usage of insulating roof system on the energy saving comes to be approximately 10-12% (approx.

IOP Conf. Series: Earth and Environmental Science **354** (2019) 012055 doi:10.1088/1755-1315/354/1/012055

6,600$ – 8000$) of the non-insulating roof system.

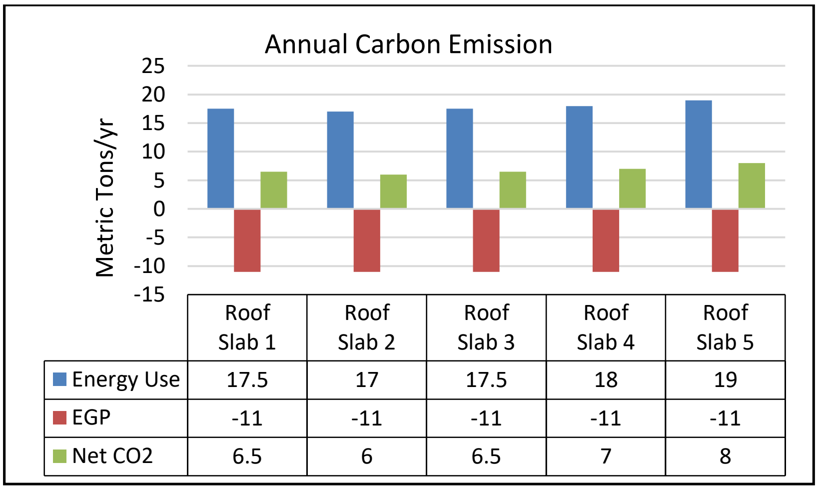
Figure 3 shows the annual energy usage for various roof systems. As it has been mentioned earlier, due to the low U-value of insulating roof system as compared to the non-insulating roof system, the heat transfer rate is lower thus the requirement for maintain the indoor air comfort condition (Cooling Load) is reduced causing the annual energy usage for the HVAC equipment's will be minimal. The energy use and values and its annual costing for the cooling load has been provided in figure 3. The impact of insulation layer proves to be energy efficient as well as economical. Due to the energy savings, the usage of the insulation in the roof system proves to be passive technique in providing thermal comfort to the occupant having sustainable features.



	Roof Slab 1	Roof Slab 2	Roof Slab 3	Roof Slab 4	Roof Slab 5
Energy Use (kWh)	42350	41480	42270	42870	48689
Energy Costing	4053	3989	4034	4147	4633

Figure 3. Annual energy use/cost for various roof slab systems.

Figure 4 represents the annual carbon emission due to the energy usage of the building. The energy usage is directly related to the carbon emission as the production of electricity generally requires burning of non-renewable resources such as coal. The insulating effect of roof system shows a positive impact on lowering of overall carbon emission of building. The carbon emission can be reduced up to 1.5 metric tons/Yr, if buildings are constructed with insulated roof system. As discussed earlier, the insulating layer not only plays a vital role in providing indoor air comfort, but also has indirect environmental benefits in reducing the overall carbon emission during the life cycle of the building.



	Roof Slab 1	Roof Slab 2	Roof Slab 3	Roof Slab 4	Roof Slab 5
Energy Use	17.5	17	17.5	18	19
EGP	-11	-11	-11	-11	-11
Net CO2	6.5	6	6.5	7	8

Figure 4. Annual carbon emission for various roof slab systems.

Lastly, the energy analysis gives us the monthly electricity consumption based on the monthly peak energy demand. Figure 5 shows the average monthly energy consumption based on the weather data. It is evident that due to the arid climatic conditions in Hyderabad region, the demand for cooling load is higher. The cooling load demands peaks at summer i.e. month of April, May and June. The demand for cooling is higher when there is low insulation i.e. in case of the conventional roof systems. The results show that insulation of expanded polystyrene and rock wool reduces the cooling load required for the HVAC system, thus reducing the monthly energy consumption.

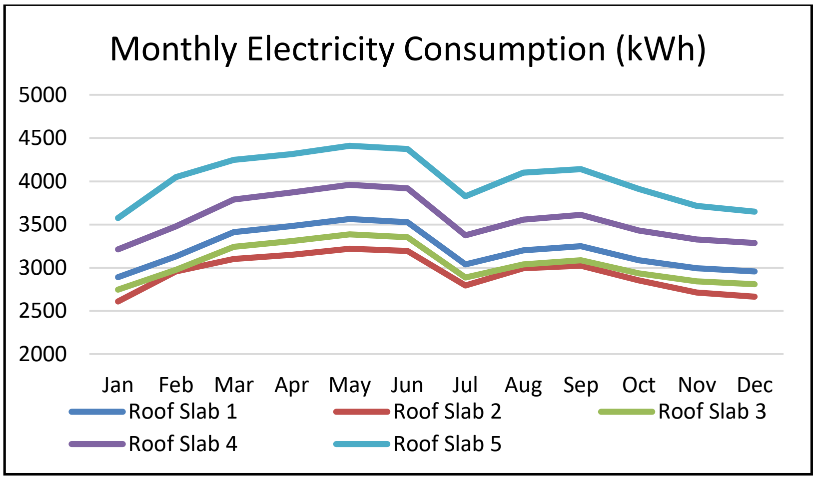


Figure 5. Annual carbon emission for various roof slab systems.

5. Embodied energy analysis

Apart from the performance of insulation layer which eventually will result in the lower energy consumption (operational energy) of building, we need to understand and select the materials as an insulating layer in such a manner that the overall embodied energy should be low. Embodied energy of material is defined as the energy required for the material to be considered during its life cycle i.e. cradle to grave or cradle to site. Various stages of Embodied Energy calculation are presented in figure 6.

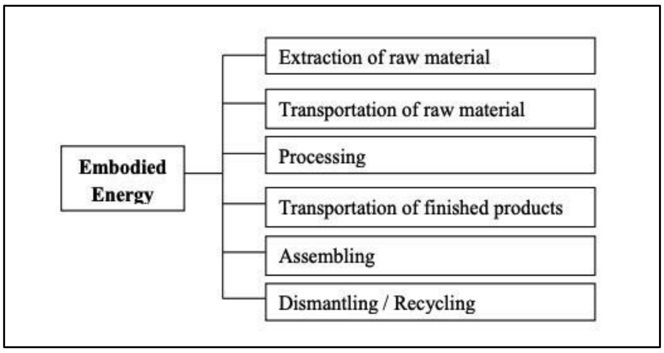


Figure 6. Stages of calculation of embodied energy for material.

The total energy required during the life cycle of building can be estimated as addition of embodied energy and operational energy. The choice of materials plays a vital role in reducing the embodied energy of building. The sustainable or recycled material has low embodied energy which proves to be one of the key criteria for green building system. Thus, the calculation of embodied energy for various roof system for the study is important to understand its sustainability aspect. The figure 7 shows embodied energy calculated for various roof insulation combinations. From figure 7, it is evident that the insulation layers in Roof system 2 &3 are higher than that of Embodied Energy of other roof systems. The Embodied Energy for the Expanded polystyrene, Rock Wool, Fiber glass and Gypsum Board were found to be 88.6 MJ/kg, 16.8 MJ/kg, 20 MJ/kg and 3.15 MJ/Kg respectively. But, the operational energy savings for roof system having above mentioned material is lower as these materials are better insulators. Thus, we have to properly select material in such a manner that it should have low embodied energy as well as high thermal insulation capacity. Hence, if we are able to find such material it will prove to be sustainable, environment friendly, economical (by lowering energy requirements) and thermally efficient.

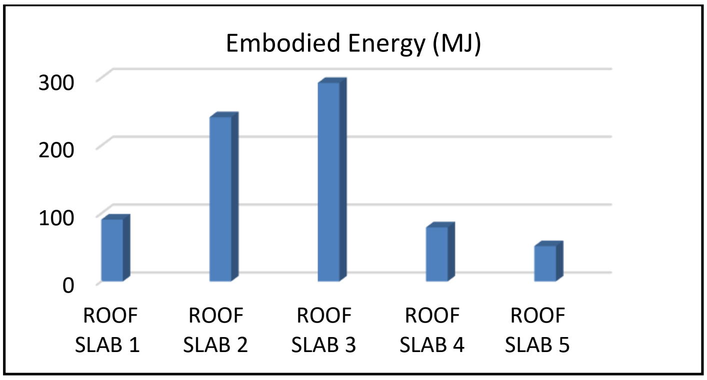


Figure 7. Embodied energy calculations for various roof slab systems.

6. Conclusion

This paper explores the effectiveness of insulation layers for building envelope to reduce the energy consumption and energy costing. The research successfully suggests the value-added function of insulation layers not only to provide thermal indoor air comfort by restricting the dissipation of heat through the exposed roof surface but also proves to be energy efficient for building envelope. The analysis points out that Expanded polystyrene and Rock wool proves to be energy efficient and economical but has high embodied energy. Thus, it is suggested that the focus should be on adopting materials having low overall energy consumption i.e. embodied energy and operational energy, which should be consider while designing and selection of building materials. The possibility of insulating material has been explored to provide overall sustainability during its life cycle. The low U-value roof system proves to be having long term economic benefits over the conventional roof system for building envelope.

References

[1] Ayan United Nations Environment Programme 2015 Why buildings 2015 available at: http://www. unep.org/sbci/AboutSBCI/Background.asp (accessed February 05, 2015)
[2] Mirrahimi S, Mohamed M F, Haw L C, Ibrahim N L N, Yusoff W F M and Aflaki A 2016 The effect of building envelope on the thermal comfort and energy saving for high-rise buildings in hot–humid climate *Renew. Sust. Energ. Rev.* **53** 1508-19
[3] Praseeda K I, Reddy B V and Mani M 2016 Embodied and operational energy of urban residential buildings in India *Energ Buildings* **110** 211-9
[4] Al-Tamimi N A and Fadzil S F S 2011 The potential of shading devices for temperature reduction in high-rise residential buildings in the tropics *Procedia Engineering* **21** 273-82
[5] Krarti M, Erickson P M and Hillman T C 2005 A simplified method to estimate energy savings of artificial lighting use from daylighting *Build Environ.* **40** 747-54
[6] Dias D, Machado J, Leal V and Mendes A 2014 Impact of using cool paints on energy demand and thermal comfort of a residential building *Appl. Therm. Eng.* **65** 273-81
[7] Chiraratananon S and Hien V D 2011 Thermal performance and cost effectiveness of massive

walls under Thai climate *Energ. Buildings* **43** 1655-62
[8] Kubota T and Toe D H C 2015 Application of passive cooling techniques in vernacular houses to modern urban houses: A case study of Malaysia *Procedia-Social and Behavioral Sciences* **179** 29-39
[9] Toe D H C and Kubota T 2015 Comparative assessment of vernacular passive cooling techniques for improving indoor thermal comfort of modern terraced houses in hot–humid climate of Malaysia *Sol. Energy* **114** 229-58
[10] Kubota T, Toe D H C and Ossen D R 2014 Field investigation of indoor thermal environments in traditional Chinese shophouses with courtyards in Malacca *J Asian Archit Build* **13** 247-54
[11] Jamaludin A A, Hussein H, Ariffin A R M and Keumala N 2014 A study on different natural ventilation approaches at a residential college building with the internal courtyard arrangement *Energ. Buildings* **72** 340-52
[12] Pisello A L and Cotana F 2014 The thermal effect of an innovative cool roof on residential buildings in Italy: Results from two years of continuous monitoring *Energ. Buildings* **69** 154-64