Investigation of Different Materials for Solar Passive Building Design and Heat Transfer and Energy Consumption of Passive House in a Severely Cold Area

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ABSTRACT

The energy consumption associated with the cooling of the buildings is huge. In India buildings consume about 33% of country's power production for cooling and day lighting. The building enclosures such as walls, roofs and glasses play very vital role in reducing cooling loads in the buildings. The proper combination of window glass materials and wall materials can cut down the cooling costs extensively. In the present work, five different glass materials such as clear, bronze, grey, green and blue-green glass materials were selected and four different building materials such as burnt brick, cinder concrete, dense concrete and fly ash brick either side plastered with cement plaster were selected. In order to improve the heat transfer in enclosure structure of passive houses in cold area with complex climatic conditions, a three-dimensional model is established to investigate the time-by-case changes of outdoor temperature and solar irradiation based on the principle of integral change and the method of response coefficient and harmonious wave reaction. The variations of hourly cooling and heating loads with outdoor temperature and solar irradiation are analyzed. As simulated by cloud computing technology, the passive building energy consumption meets the requirements of passive building specifications. In the present research, super-thermal insulation external wall, enclosure structure of energy-conserving doors and windows, and high efficiency heat recovery system are employed to achieve a constant temperature without active mechanical heating and cooling, which suggests a strategic routine to remarkably decrease the total energy consumption and annual operation cost of passive building.

Keywords: passive house; heat transfer coefficient; energy consumption; Passive buildings; Energy efficient materials

1- INTRODUCTION

Buildings are responsible for about 40% of total energy use in the world and they also account for more than 40% of the global carbon dioxide emissions. With the recent boom in the construction sector, there has been a sudden increase in energy consumption, especially in countries like India. Buildings are consuming 33% energy in India. In that 8% of energy is consumed by commercial buildings and 25% of energy is consumed by the residential sector [1]. Passive building design is the most important factor in ensuring energy efficiency in buildings. Buildings with passive design can consume around 10% - 15% less energy as compared to conventional buildings without incurring any incremental cost [2]. Thus, it is necessary to focus on the vital aspect of energy efficiency at the design stage of the building itself. Previously, a study has been carried out on numerical computation of window design to reduce radiation in buildings using clear and brown glass window materials [3]. Thermal requirement of maximum window to wall ratio was studied earlier [4]. Optimization studies of the insulation location inside the flat roof were reported in the literature [5]. The evaluation of thermal and optical properties was studied earlier [6]. Impact of window to wall ratio on life cycle environment was presented in the literature [7]. Thermal response of laterite buildings was reported in literature [8]. As the earth's temperature is increased by human energy consumption, great attention has been focused on high-comfort green buildings with renewable energy and near zero energy consumption, which are named "passive houses" and limit the sum of primary energy consumption to less than 120 kWh/(m^2·a). Early in 2005, Feist suggested the characteristics of combined heating and ventilation system in passive houses by investigating the energy consumption level and comfort index [9]. Passive housing and its standard were firstly proposed in Germany. After a long period of technical improvement, the standard required for passive houses gradually became more detailed and rigorous. In 2006, Schnieders tested eleven passive houses in Germany and concluded that passive houses can save 80% of space energy consumption, with the total primary energy consumption (including household electricity) being controlled lower than 50% of the traditional new buildings [10]. Based on the thermal performance of passive houses with arch roof in New Delhi, India, it is concluded by Arvind that the annual energy consumption of heating and cooling can be saved by 1481 kWh/a and 1814 kWh/a , respectively, with only 52 euros per year in carbon emission cost [11]. The energy saving rates of passive houses are much higher than that of traditional buildings; thus, it is of great significance to study and develop passive houses for the sustainable development of China where building energy consumption accounts for 1/3 of total energy consumption. In 2010, China built the first certified passive house of China—Hamburg House was built in Shanghai Expo Park [12]. In 2014, the first high-rise passive building in the area with hot summer and cold winter was built in Zhuzhou, Hunan Province of China [13]; and the first cold region passive house, Chenweili Bay, was built in Yingkou, Liaoning Province of China [14]. In 2015, the China passive Ultra-Low Energy Consumption Building Alliance organized for the China Academy of Architectural Sciences and other units to compile and issue the Passive Ultra-Low Energy Consumption Green Building Technical Guidelines (Residential Buildings) as the technical standard of passive houses in China [15].

2- METHODOLOGY

The building models with dimensions 3.5 m X 3.5 m X 3.5 m were designed in Design builder. The thickness of the wall is 0.2 m plastered either side with 0.015 m cement plaster each side. Fig. 1. (a) shows the dimensions of a building model and Fig. 1. (b) shows the building model with 30% window to wall ratio. The window to wall ratio is the ratio of vertical fenestration area to the gross external wall area. The window to wall ratio for the building models taken is 30% as per the ECBC. The dimensions of the window are 2 m X 1.8375 m for 30% window to wall ratio. The roof material used is reinforced cement concrete of 0.15 m plastered either side by 0.015 m cement plaster each side. For floor, dense concrete was used. The roof and floor materials are same for the all building models studied. Fig. 2. shows the images of the wall materials used in the study. The wall materials used for the study are burnt brick, cinder concrete, dense concrete and fly ash bricks. Reinforced cement concrete is used as the roofing material. Thermo-physical properties of the wall materials are considered as per the Indian standards [16]. Table 1. shows thermo-physical properties of wall materials. The passive house requires adaptation to climate characteristics and site conditions so that the energy consumption of heating, air conditioning, and lighting can be minimized through passive architectural design. In order to improve the efficiency of energy preservation equipment and systems, renewable energy is used in all areas to provide a comfortable indoor environment with minimal energy consumption. The indoor environmental parameters and energy efficiency indexes of passive houses must conform to standards so the energy consumption without using mechanical heating and cooling is reduced to a certain level under the premise of ensuring human body comfort. In recent years, passive building standards in China have been studied and explored in a deep way.

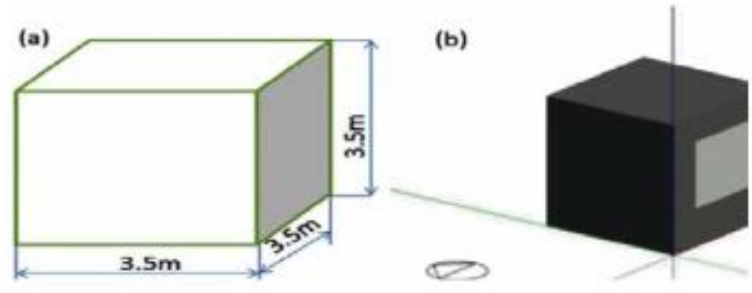

Fig. 1. (a) Dimensions of a building model; (b) Building model with window

Fig. 2. Images of different building wall materials

The main factors of building energy consumption—envelope structure and ventilation efficiency—in the design strategy of passive buildings in a severely cold area are firstly determined to establish the building model and confirm the passive house design parameters. Then, the harmonic response method is used to calculate the thermal loads and heat transfer of wall roof, exterior window, and indoor with the various heat sources being divided into convection and radiation parts. By means of harmonic response method, the cooling load caused by the exothermic decay and delay between the different enclosure structures is specially evaluated in the radiation heat calculations, and the heat transfer caused by air penetration is included in the convection to calculate the total load. Finally, the relevant thermal loads and energy consumption are estimated and analyzed. The investigation strategy and simulation routine in the present study are schematically illustrated in Figure 3.

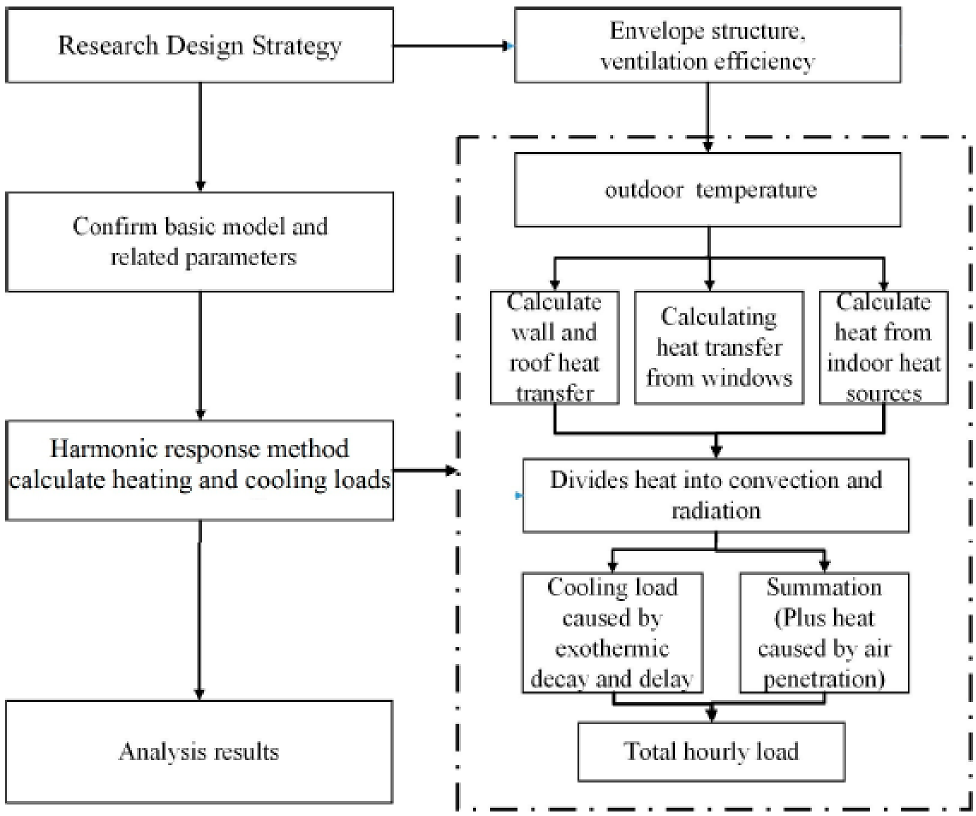

Figure 3. Schematic investigation strategy in simulation processes.

In order to realize a passive building, a certain thickness of high-efficiency thermal insulation materials, special passive doors and windows, mechanical ventilation equipment for heat recovery, and air tightness control are inbuilt, as shown in the schematic passive house structure in Figure 4. The enclosure structure is the main constituent, being directly in contact with the external environment and thereby acting as the dominant medium through which heat transfer and energy move between the inside and outside of passive building. In the enclosure structure, the external wall as the primary constituent contributes to the major area and contacts all the other parts of thermal maintenance system. In the whole building energy consumption, the external wall accounts for >40%, so the external wall design for thermal insulation is of great significance to the enclosure structure of passive house. The external insulation structure, as a structural complex to effectively reduce the energy consumption, is set up to connect with walls through an appropriate way in the enclosure structure. The external insulation medium mainly consists of special materials with obvious capability for heat insulation, heat preservation, and energy saving. According to the practical construction features, the external wall insulation can be classified into three forms: interior thermal insulation, exterior insulation, and sandwich insulation [17], as shown in Table 4 which provides the advantages and disadvantages of three different thermal insulation structures. Due to the lower thermal resistance than that of base wall, the heat transfer coefficient of the composite wall varies with the thickness of the thermal insulation material, thus affecting the heat preservation and thermal insulation of the whole building. For the aerated concrete and reinforced concrete composite wall, the heat transfer coefficient decreases with the increasing thickness of the thermal insulation material, as the calculated results shown in Figure 5. Although the thermal insulation performance can be achieved by increasing the heat preservation material, the heat transfer coefficient of the entire composite wall will remain constant when the wall thickness rises to high values.

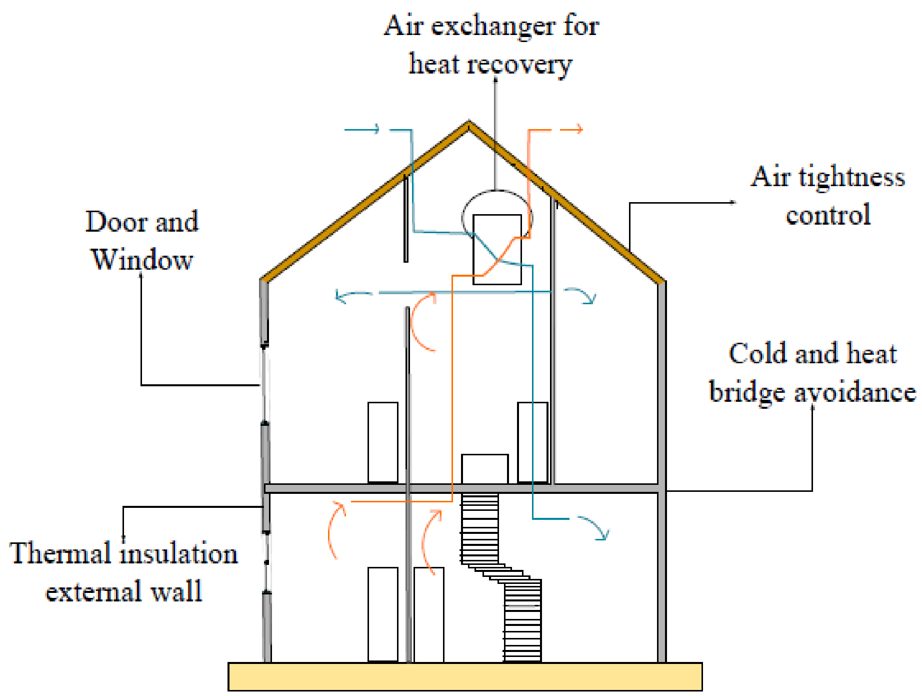

Figure 4. Schematic diagram of the passive house structure.

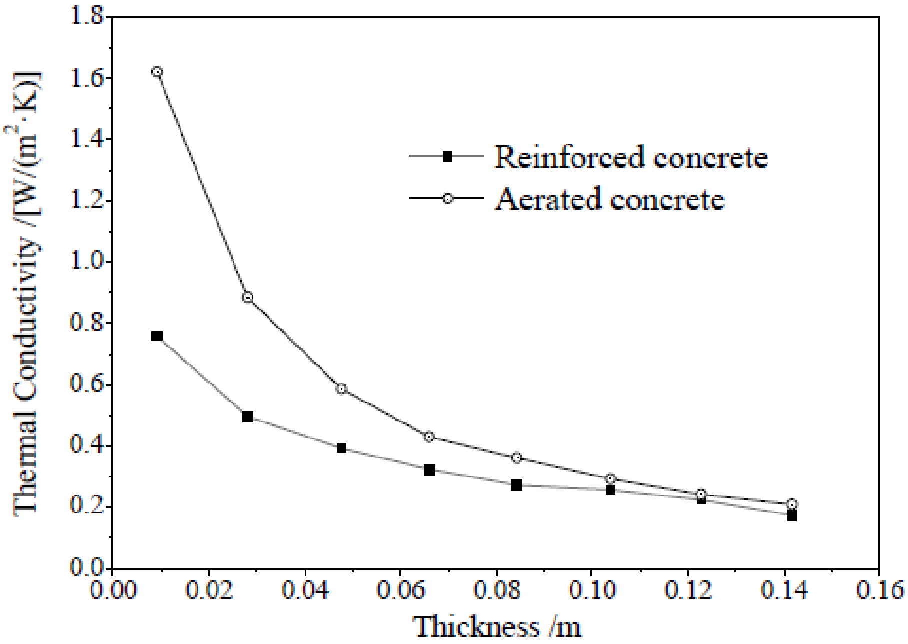

Figure 5. Heat transfer coefficients as a function of material thickness.

2-1 Energy Conservation of Door and Window

n the whole building envelope, the house window is the weakest part with a high percentage of energy consumption approaching to 50%. Hence, improving the thermal transfer performance of window is a pivotal way to reduce the whole building's energy consumption. Senying window identified as P120, which is constituted by window frame and glass system, is the first passive window certified by German PHI in China, with the whole heat transfer coefficient being less than 0.6 W/(m2·K). The window frame of P120 is composed of the inner aluminum-wrapped-wood frame and the outer aluminum frame which are integrated together by polymer buckle connections, as shown by the cross-sectional schematics and photograph of P120 in Figure 6.

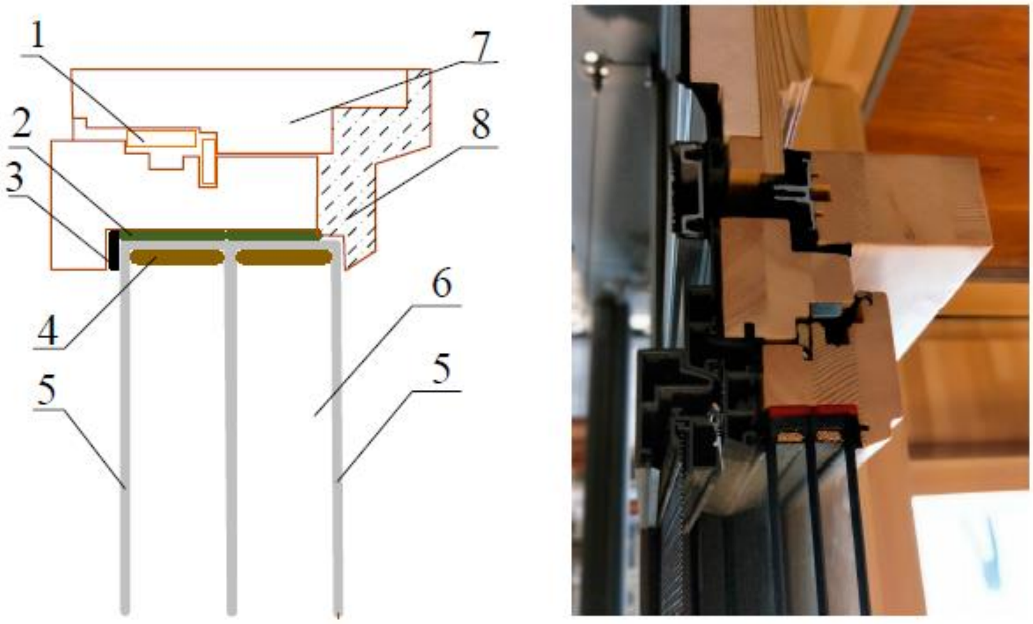

Figure 6. Window profile: (1) polymer connection clasp; (2) warm-edge interval bar; (3) seal layer; (4) dry molecular sieves; (5) tempered glass in 5 mm thickness; (6) argon in a glass cavity of 18 mm thickness; (7) window frame; (8) intensified insulation. The cross-sectional photograph of P120 window enclosure structure is also shown in the right panel.

2-2 Heat Transfer and Energy Consumption Cost

By means of harmonic reaction method as implemented in Ecotect program, the outdoor temperature, air flow rate, and solar irradiation variation through a day are calculated to investigate the hourly thermal loads of passive building, in which the coldest and hottest days of typical weather are selected as representatives, as the results show in Figure 7. It is shown from Figure 7a that the outdoor temperature in the hottest day rises and then declines with a peak value arising at 14:00, while the coldest daily temperature fluctuates in a small magnitude with the highest and lowest values appearing at 5:00 and 13:00, respectively. As shown in Figure 7b, the hottest and coldest days represent almost identical fluctuations of air flow rate with the peak values showing at 13:00 and 14:00, respectively, although the overall air flow rate in the hottest day is distinctly lower than that in the coldest day. For the hourly solar irradiation in the hottest day, as exhibited in Figure 7c, the direct irradiation rises sharply to attain a large value at 4:00 and through a placid peak at noon and then begins to rapidly decrease at 18:00 in almost symmetrical way.

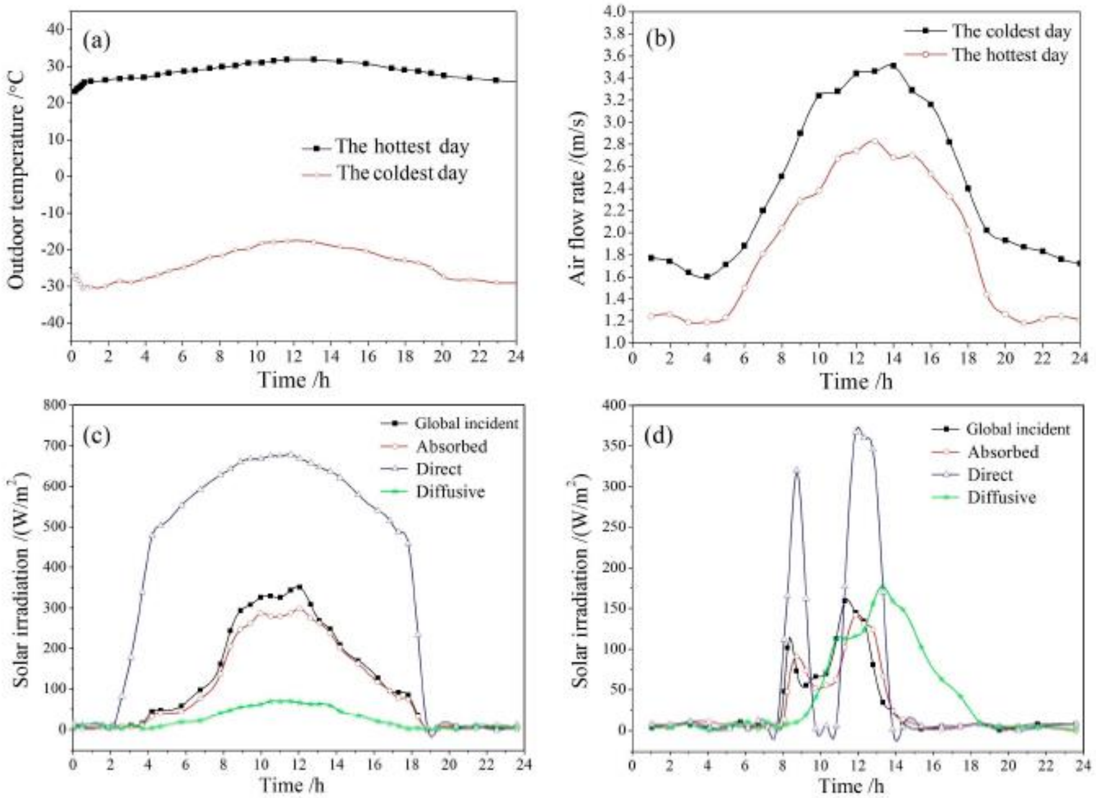

Figure 7. (a) Outdoor temperature and (b) air flow rate as a function of time; solar irradiation intensity vs. time on the (c) hottest day and (d) coldest day.

3. RESULTS AND DISCUSSIONS

3.1. Heat gain in buildings in hot & dry region:

The summer solstice is the day with the most sunlight hours during the whole year due to noon sun's highest altitude. The hours of sun light varies from one latitude of the place to another latitude of the place. June 21st is the most sun light hours day during the whole year for latitudes 25oN and 29oN. For latitudes up to 21oN, the most sun light hours during the whole year can be obtained when the noon sun is at the zenith. The most sun light hours during the whole year for Ahmedabad, Bangalore, Bombay and New Delhi are different due to their different latitudes. Fig. 8. (a) shows the solar chart of Ahmadabad on peak summer of May 15th. Fig. 8. (b) Shows the heat gain in different building models of various walls and window material combinations in four orientations of the window location (East, West, North and South) in the Ahmedabad climatic region. The solar chart or sun path diagram is a graphical representation of the sun paths in the sky for various days in the year. The radial lines show the solar azimuth and concentric circles show the solar altitudes. The center of the chart indicates the zenith and outer most circles indicate the horizon. The series of curved lines passing from east to west represents the sun's path for selected days of each month. These curved lines are crossed by another series of curved lines which show the hour lines. The intersection point of sun's path line and the hour line is the position of the sun in that hour of that particular day. Fig. 8. (a) Shows the position of the sun at 3 PM on peak summer day of May 15th in Ahmedabad climatic region (23.07o N, 72.63oE) when the window is placed in the South orientation. From Fig. 8. (b), it is clear that the solar heat gain in building through south wall is the least for all the wall and window glass material combinations among four locations of window glasses studied. Table 1. shows solar heat gain in burnt brick buildings with different glass materials in four orientations of window glass in Ahmedabad region. From Table 1, it is noted that heat gain in buildings is less in south orientation as compared to the other orientations. it is also observed that burnt brick buildings with grey glass window in south direction is observed to be the best due to less heat gain of 23.42 kWh and burnt brick buildings with a clear glass window in south direction is observed to be the worst due to the high heat gain of 24.9 kWh. Table 2. shows solar heat gain in cinder concrete brick buildings with different glass materials in four orientations of window glass in Ahmedabad region. From Table 2, it is observed that heat gain in buildings is less in south orientation as compared to the other orientations. It is also observed that cinder concrete buildings with grey glass window in south direction is observed to be the best due to less heat gain of 22.85 kWh and cinder concrete buildings with a clear glass window in south direction is observed to be the worst due to the high heat gain of 24.33 kWh. Table 3. shows solar heat gain in dense concrete buildings with different glass materials in four orientation of window glass for Ahmedabad region.

Table1. Solar heat gain in burnt brick buildings with different glass materials in four orientations of window for Ahmadabad region

Direction	Clear glass (kWh)	Bronze glass (kWh)	Grey glass (kWh)	Green glass (kWh)	Blue green (kWh)
East	27.33	23.98	23.72	23.81	24.00
West	27.13	23.84	23.61	23.69	23.89
North	25.05	23.51	23.41	23.45	23.55
South	24.9	23.52	23.42	23.45	23.54

Table 2. Solar heat gain in cinder concrete buildings with different glass materials in four orientations of window glass for Ahmadabad region

Direction	Clear glass (kWh)	Bronze glass (kWh)	Grey glass (kWh)	Green glass (kWh)	Blue green (kWh)
East	26.86	23.45	23.22	23.29	23.5
West	26.66	23.33	23.12	23.19	23.4
North	24.49	22.93	22.84	22.87	22.96
South	24.33	22.93	22.83	22.85	22.95

Table 3. Solar heat gain in dense concrete buildings with different glass materials in four orientations of window glass for Ahmadabad region

Direction (kWh)	Clear glass (kWh)	Bronze glass (kWh)	Grey glass (kWh)	Green glass (kWh)	Blue green (kWh)
East	26.05	22.5	22.26	22.34	22.55
West	25.77	22.31	22.07	22.14	22.36
North	23.32	21.65	21.55	21.58	21.68
South	23.1	21.62	21.51	21.56	21.64

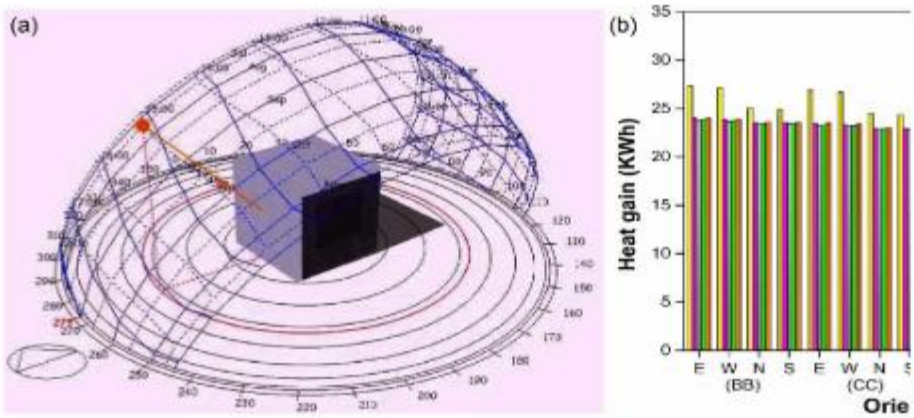

Figure 8. (a) Solar chart of Ahmadabad on peak summer day; (b) Heat gain through building models in Ahmadabad climatic conditions

3-2 Periodic Cost

Based on the simulation results of energy demand, the annual energy and life cycle costs and the ventilation latent heat are calculated with the cloud computing technology of Green Building Studio (GBS), as the results show in Tables 4 and 5 and Figure 9. The annual energy and life cycle costs of the passive house are 17,796¥, and 282,388¥ respectively with an annual carbon dioxide emission of 8.3 SUV, in which the annual peak energy demand of 79.9 kWh/m2 is much less than the passive house standard of 120 kWh/m^2, as listed in Table 8. The electricity source is directly delivered from electricity power transmission center by high voltage cable; hence, there is no other exhaust emission in the energy production chain except for carbon dioxide emission. For the life cycle energy, the electric power consumption of 3638.13 kWh is higher than gasoline of 2587.96 kJ in a year. Because active mechanical cooling is not used in passive room, the energy consumption of cooling room mainly originates from natural ventilation. The natural ventilation of the modeled passive building is needed to operate for 696 h, which is only 42% of the required time for mechanical cooling, and thus can save an annual electric energy of 10,780 kWh. The energy cost analyses shown in Figure 9 imply that the space heating cost dominates the total heat energy demand (except area lighting) with an average percentage of >80% from October to April of the second year. The total energy cost reaches the highest value of 1.2¥ /m^2 in January and attains the lowest valley of 0.3 ¥ /m^2 in May and September due to the high efficiency heat transfer of natural ventilation.

Table 4. Energy carbon cost (annual).

Energy cost/¥		17,796
Life cycle cost/¥		282,388
CO_2 emissions (large SUV equivalent)		8.3 SUV
Energy intensity/(MJ/m^2)		586
Peak energy demand/(kWh/m^2)		79.9
Life cycle energy	Electricity/kWh	3638.13
	Gasoline/kJ	2587.9

Table 5. Ventilation latent heat (annual).

Natural ventilation time/h	696
Mechanical cooling time/h	1667
Electric power saving/kWh	10,780

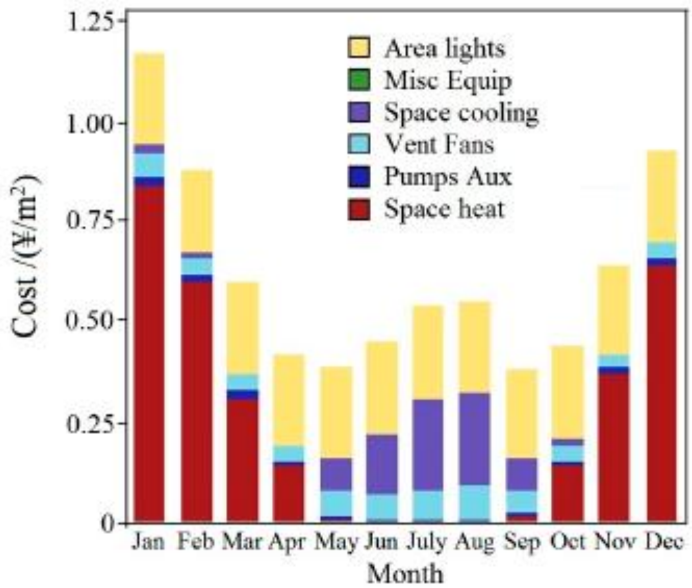

Figure 9. Total energy cost monthly through a year.

4- CONCLUSIONS

The heat transfer coefficient, cooling and heating loads, and energy demand of passive house in severely cold area are studied by heat simulations with the energy cost being analyzed to explore the widely applicable energy-saving methods. The changes of temperature and air flow rate in winter are investigated to realize preferable designs of passive building in severely cold areas, which use super thick thermal insulation structure for external wall and roof, special energy-saving window, and efficient heat recovery system. Open curtain walls are employed for the external thermal insulation system with extruded polystyrene sheets to control the heat transfer coefficient of external wall being less than 0.1 W/(m^2·K). The aluminum-coated wood window frame is combined with the four-glass/three-cavity structure to decrease heat transfer coefficient of entire window to 0.6 W/(m^2·K), in which heat-preservation interval belts are supplied to ensure sufficient air tightness. The high efficiency heat recovery system with thermal recovery rate of more than 75% can achieve a constant room temperature by recovering waste heat. The designed passive building does not need additional ground source heat pump and mechanical heating and cooling equipment in both summer and winter. The mean cooling and heating loads per area of the whole passive building are reduced to 33.58 W/m^2 and 3.79 W/m^2 respectively, with the annual energy demand decreasing to 79.9 kWh/m^2 (decreases by 33% compared with international standard), which meet and even exceed the passive specifications of buildings in Northern China. This work helps in selecting an appropriate wall and the window glass material combination for reducing cooling loads in buildings. From the results, it is observed that the best combination of wall and window glass materials is found to be fly ash brick with grey glass window and the worst combination of wall and window glass materials is found to be dense concrete with a clear glass window in all four orientations of window placing and among all the wall and glass material combinations studied. The fly ash brick buildings with grey glass window placed in south orientation is the best from the lowest heat gain point of view as they gain the least amount of heat of 21.51 kWh, 12.55 kWh, 14.91 kWh and 24.13 kWh in Ahmedabad, Bangalore, Bombay and New Delhi climatic regions, respectively among studied wall and window material combinations. The results of the study help in designing energy efficient passive buildings.

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