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INTEGRATING SOLAR RADIATION, BUILDING MASS, THERMAL INSULATION, AND AIR VENTILATION FOR ENERGY CONSERVATION IN BUILDINGS

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ABSTRACT

This research investigates the effect of integrating solar radiation, internal building mass, thermal insulation and natural ventilation on building thermal performance. A field study and a computer simulation were conducted on the Beliveau house located in Blacksburg- Virginia. The house designer implemented several new ideas for integrating solar radiation, thermal mass, thermal insulation, and air ventilation to conserve energy. The goal of this study is to investigate the relationships between these design variables. The field study was used to monitor the actual performance of the house. The house was first simulated using the BEANS software. The simulation results were validated with the field readings. Second; a matrix of alternative solutions with different building masses, solar radiation gains, and thermal insulation factors were simulated by BEANS software to test their energy performance. Statistical relations have been derived between the energy consumption (as the dependent variable) and the solar radiation, thermal insulation, and building mass (as independent variables). The results showed that the direct controlled solar radiation which is admitted to the space factored 31% of the energy load in the house, while the thermal insulation and the internal building mass factored 48%, and 21% of the energy load of the house respectively. The derived factors are hoped to give the designers useful guidelines to weight these design alternatives.

KEY WORDS

Energy conservation, System integration, Building mass, Solar radiation, Thermal insulation.

INTRODUCTION

Energy conservation and the environmental performance of buildings are among the major concerns in evaluating building performance. Building designers can significantly contribute to the energy saving when the built environment if proper design decisions are made regarding the selection and integration of building physical components.

Much research has been conducted to investigate the potential for energy saving in buildings. much research addressed the effect of the different building components on thermal performance such as thermal mass (Anderson, 1995), solar radiation (Thomas, 1998)(Akbari, 1998), thermal insulation (Kosny, 1998), and surface reflectance (Heldebrandt, 1998). As a result, many passive solar buildings have been built with the goal of saving energy. The major concern in these designs was to reduce energy consumption. Beliveau house is a unique example of a passive solar house, where energy conservation was not the only goal in the design. The main concern of the design of this house was to select the building systems that might achieve designer goals as theyrelates to the holistic design aspects. The holistic aspects include selection of finish materials, structure, natural lighting, air quality, space quality, as well as the energy conservation in the house. The designer based his strategy on controlled direct solar gain, floor thermal mass, optimum thermal insulation of the house envelop, natural ventilation, and the utilization of an heat exchanger.

This research invistegated the thermal performance of this house, and determining the contribution to the energy saving of the main passive thermal control building strategies, which was implemented in this house.

DESCRIPTION OF THE BELIVEAU HOUSE

The house was designed and constructed by Prof. Yvan Beliveau and his family members, who are the owners of the house. It is located in Blacksburg, Virginia, which is warm and relatively humid climate in summer, and cold in winter. The total living floor area of the house is 6430 square feet, see figure1. The main construction material of the house is wood. The walls are composed of 0 .5" wood cladding from outside, R13 glass fibers insulation faced with building paper, and 0.5" gypsum board on the inside. The floor of the main level is constructed of a composite concrete and wood structure. It consists of ¾" plywood and 2.5" fiberglass reinforced concrete slab connected to 2x10" wood joists. The main objective of this slab is to provide a thermal mass inside the house, and at the same time to provide a suitable surface for installing dark ceramic floor tiles. This floor is placed against the south facade, which has the most house glazing area, The designer's intention was to provide passive solar heating. The windows are double-glazing with 1-1/8" air cavity and adjustable bronze blind inside this cavity. This window design allows for controlling the solar radiation admitted through it. The roof is composed of two layers with a ventilating cavity in between. The top layer is composed of black asphalt shingles placed over 1" plywood. The inside layer consists of R22 fiberglass thermal insulation and 6/8" wood board on ½" sheet rock. The out door ventilation air is admitted to the house through a heat exchanger which recovers up to 70% of the heat, and distributes it through a ducting system to the occupied spaces. The windows allow for cross ventilation when it is desired.

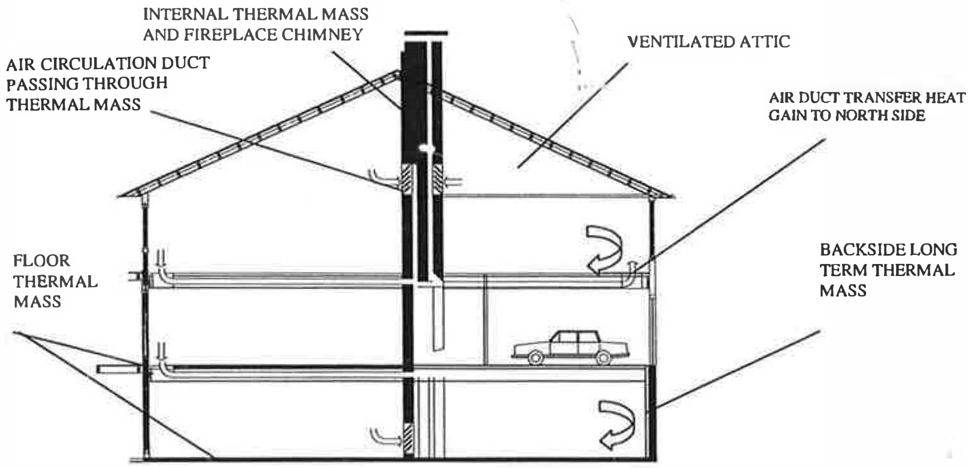

Figure 1 : Section through the house

FIELD TEST

Four thermal couples were installed in the main house spaces, two sensors measure the inside air temperature, one measures the floor surface temperature, and one measures the outside air temperature. A solar radiation sensor was placed in the southern side of the house, and a wind velocity censor was used to measure the outside air velocity. The data acquisition system recorded the highest reading and the average reading of the eight sensors at five-minute time intervals. The house was monitored through hot periods and cold periods of the year. The objectives are to record the house performance, and to validate the house computer simulation results.

COMPUTER SIMULATION

BEANS - Building Service- software designed by ARUP group, United Kingdom (ARUP 1998) were used to simulate the house. The computer simulation results were synchronized with the actual field readings. To predict the contribution of each of the tested design variables to the heating and cooling load in the house, a matrix of alternative solutions with different building masses, solar radiation gains, and thermal insulation factors were simulated by BEANS software. Correlation analysis, and regression analysis were carried out to examine these results.

RESULTS

The field readings showed that the house was within the comfort zone through 87% of the tested period without active heating or cooling. The house got most advantage of thermal mass when there was a heat front after cool days, or a cool front after hot days, see figure 3. It also showed significant impact in reducing cooling load when utilizing nighttime ventilation, see figure 4.

The heating strategy of the house was based on utilizing the direct solar radiation admitted to the space, and absorbed by the thermal mass, this heat is re-radiated to the space when the space cooled down, see figure 2. The heat exchanger played a major role in providing ventilation of 0.75 air change per hour while it recovered 70% of the energy loss through ventilation in both the heating and the cooling periods. The simulation results showed that the average daily solar radiation admitted to the house throughout the year was 16813 kw (11080 KW in the heating periods and 5731 kw in the cooling periods). The average daily heat gain and loss through the building envelop other than solar radiation was 24887 kw (23652 kw heat loss in the heating period, and 1234kw heat gain in the cooling period). At the same time, the average daily heating and cooling load was 15434 kW. The results also showed a difference between the average daily heat gain/loss through building envelope and average daily heating and cooling load of 4103 kw (21% of the heating and cooling load), which results from storing heat in the thermal mass.

In percents: this shows that solar radiation factored 31% of the energy load of the house while the building envelope factored 48% of the energy load .

The same house has been simulated again as if it had been built and run in a conventional way. The floor of the main level has been replaced with conventional wood floor without the thermal mass, the existing windows were replaced with ordinary double glazing window, the natural ventilation has been deleted and the house was run as a closed envelop. The predicted performance of the house under these changes showed that the average daily heating load is approximately 44000kw, and the average daily cooling load 13160kw.

A correlation analysis has been conducted between the solar radiation, thermal mass, thermal insulation and the heating/cooling load of the house. The correlation coefficient between solar radiation, heating gain/loss through the building envelop, and thermal mass against the heating/cooling load of the building was 99.5, 99.2, 97 respectively. A regression analysis has been made between the above variables. This analysis showed the following relation;

$$\text{Heating Load} = -.422 - .4667\ \text{SOL} - .732\ \text{LOAD} - .257\ \text{MASS} \quad (1)$$

$$\text{Cooling Load} = -.422 - .4667\ \text{SOL} - .732\ \text{LOAD} + .257\ \text{MASS} \quad (2)$$

where;

Heating Load = the heating load which is needed to maintain the house within the comfort zone, and within a controlled air temperature of 19-27C. It is represented in a positive sign.

Cooling Load = the cooling load which is needed to maintain the house within the comfort zone, and within a controlled air temperature of 19-27C. It is represented in a negative sign.

SOL= The total direct and indirect solar radiation (kW/h) admitted through the building envelop. This solar radiation was controlled with movable blinds, which is lowered if the direct solar radiation exceeds 50 W/sqm.

LOAD= heat gain or loss through the building envelope (kW/h). The heating loss represented in negative sign and the heating gain represented in a positive sign.

MASS= the overall internal mass of the building which is placed in the floor slab and the internal walls (kg/(sqm of floor area*1000)-.3).

The analysis also showed that in the absence of the solar radiation, there is a negligible relation between the building mass and the heating /cooling load. On another hand, in the absence of the direct solar radiation, the thermal mass showed different impact on energy saving in the cooling periods where compared to the heating periods. The thermal mass has a positive impact on energy savings in both all cooling periods and in the heating periods were there is big daily variation in the climate condition, the correlation coefficient between indirect solar gain and the thermal mass in theses periods was .98. At the same time the analysis showed negative impact of the thermal mass on the energy saving in the long heating periods, the correlation coefficient between indirect solar gain and the thermal mass in theses periods was .99. It should be pointed out that the direct solar radiation gain is the radiation admitted to the space in its short wave (mainly through the windows). While the indirect solar radiation gain is the impact of the solar radiation that hits the outside building surfaces and generates energy impact inside the building.

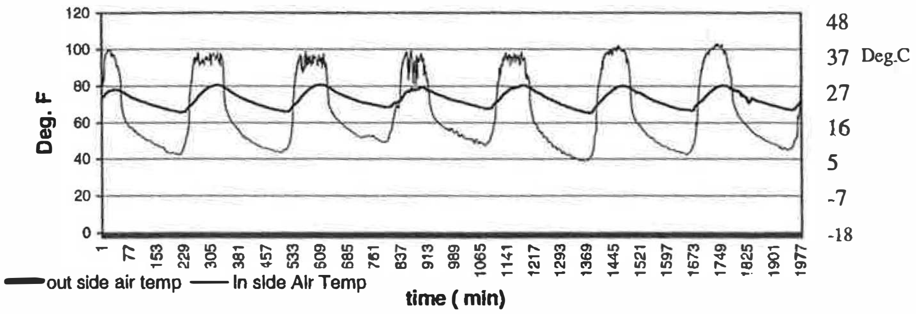

Figure 2: Passive house performance in cold nights and warm days

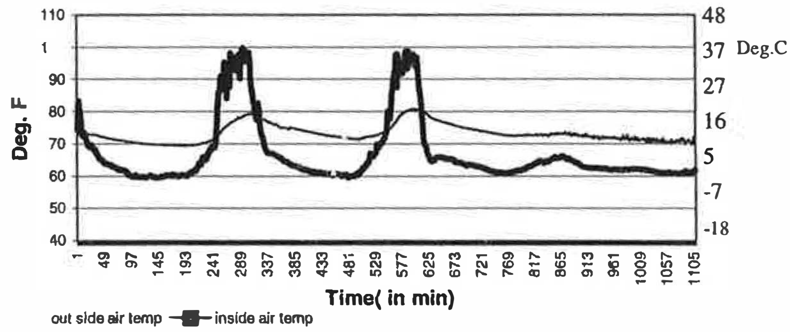

Figure3: The house performance in cold days after hot days

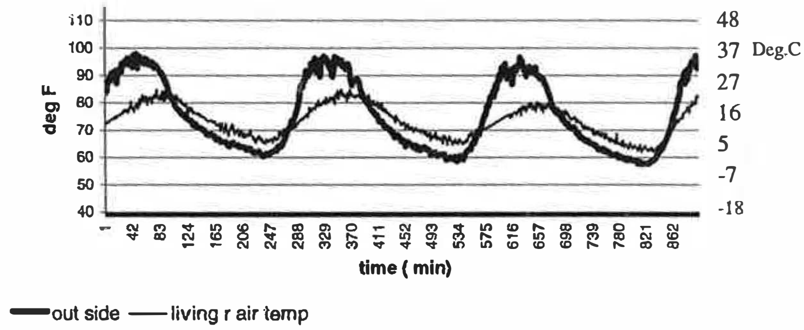

Figure 4: Passive house performance at hot periods with natural ventilation at night

DISCUSSION

The tested building showed considerable energy saving in both the heating and the cooling periods, which was reached about 73% of the similar conventional building design.

The analysis also showed that the integration of controlled direct solar radiation, thermal insulation and thermal mass can produce efficient energy building design, and at the same time they serve the other design considerations. The statistical relations, which is generated in this research are hoped to allow the designer to make the necessary tradeoffs between these design variables, and on the light of a clear understanding of the impact of these variables on the energy performance of the building.

CONCLUSION

This research clearly showed that energy efficient buildings can be achieved by integrating the different design aspects, which has impacts on the energy consumption, It also showed that the designers can reduce the energy consumption in buildings by considering these aspects as a holistic design strategy. This research indicated that the relationships generated by the computer simulation models give a clear view of the impact of each building component on the overall energy consumption in the building.

The scope of this research was limited to the global impact of the solar radiation, thermal insulation, thermal mass, and ventilation on energy consumption in buildings. More researches are needed to investigate the other design variables that may contribute to the energy saving in buildings, which can be associated with a cost benefit analysis.

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