Journal of Applied Sciences

ISSN 1812-5654

ANSInet
an open access publisher
http://ansinet.com

Journal of Applied Sciences 6 (15): 3128-3133, 2006
ISSN 1812-5654

Thermal Behaviour of Building Wall Elements

[1]M.M. Vijayalakshmi, [2]E. Natarajan and [3]V. Shanmugasundaram
[1]Department of Civil Engineering, Sathyabama Institute of Science and Technology,
Chennai-119, India
[2]Institute for Energy Studies, Anna University, Chennai-600 025, India
[3]Department of Civil Engineering, Anna University, Chennai-600 025, India

Abstract: Effective utilization of energy is required to conserve energy and reduce unwanted pollution. The energy used by the buildings is mainly determined by the thermophysical properties of building envelope. The time lag and decrement factor of a building envelope are the important characteristics that controls the energy required for maintaining the required conditions of interior living space. In this context, the objectives of this study are to investigate the thermal behaviour of opaque wall materials under the influence of solar energy and to analyse the influence of thermophysical properties of different wall types on the interior environment. The results of a finite difference mathematical model were compared with the experimental findings and suitable thermal performance properties were suggested for different applications.

Key words: Time lag, decrement factor, thermo-physical properties, wall

INTRODUCTION

Energy is an important necessity for the growth of a society. Energy required per capita continuously increases and it results in serious implications on pollution, climate change and resource depletion. Making houses energy efficient leads to a reduction in the amount of energy used. Efficient use of energy will pave way for sustainable development, as it results in better utilization of energy and less pollution.

Buildings are generally large consumers of energy in all countries (Tzikopoulos *et al.*, 2005; Gupta, 2000). The Worldwatch Institute report indicates that the construction of buildings consumes 40% of the stone, sand and gravel, 25% of the virgin wood, 40% of the energy and 16% of the water used globally every year in the world (Arena and de Rosa, 2003).

Worldwide energy consumption has risen by 30% in the last 25 years (Lopes *et al.*, 2005). In the last 25 years, the energy consumption of residential sector of Japan is reported to have become doubled while the population has increased only by 10%. Households in South Africa consume 29% of municipal electricity and it is expected to increase to 37% by the year 2015 (Mathews *et al.*, 1999). In 1999, energy consumption in buildings represented 27.6% of total energy consumption in China (Lang, 2004).

Energy use, by the way of the energy content of the construction materials in a residential building, depends on the type of construction, which is determined by the type of climate and other requirements. It varies from 3 to 5 GJ m^{-2} of floor area as in residential constructions of India to 8 to 10 GJ m^{-2} as in earthquake resistant official buildings of Japan (Debnath *et al.*, 1995; Tatsua, 1993).

A considerable share of energy is required for space conditioning, especially if the building is located in regions of harsh (cold or hot) climatic conditions. In Europe, the building sector accounts for 28 to 45% of the total energy consumption and residential buildings consume 67% of the total energy consumed in building sector. In USA, the energy consumption for heating, ventilation, air conditioning and lighting accounts for nearly 40% of the total fossil fuel consumed. In Argentina, the domestic sector occupies the third place among the biggest consumers, with a share of 22% (Arena and de Rosa, 2003). The domestic sector of India consumes about 11% of the energy produced (Debnath *et al.*, 1995). In Hong Kong, where the climate is subtropical with summer from March to early November, the air-conditioning accounts for 50 to 60% of the total electricity use (Lam, 1995).

Energy savings in a building can be achieved by appropriate energy efficient design of a building. Traditional solutions of providing thermal comfort by extensive plantation oriented landscaping and heavy mass buildings are no longer valid because of land costs and shortage of building materials, in

Corresponding Author: M.M. Vijayalakshmi, Department of Civil Engineering, Sathyabama Institute of Science and Technology, Chennai-119, India Tel/Fax: +91-44-2235 3608

developing countries. However, traditional respect for environment coupled with newer scientific developments in building materials, structural design and decentralised utilization of energy efficient appliances can be used to identify new and more sustainable solutions.

Extensive use of fossil fuels for energy generation led to their depletion and serious environmental pollution. Energy saving through improved energy efficiency is to be promoted in every sector in general and in building sector in particular, due to its consumption of considerable amount of energy. The energy-efficient buildings consume relatively less energy for maintaining comfortable indoor thermal environment.

Thermal behaviour of the building quantifies the ability of the building to maintain comfortable inside living condition, although outside conditions (temperature, humidity and air velocity) varies from season to season. A building gains heat from solar radiation and gains heat from or loses heat to the environment by convection, depending upon the outside conditions. The heat transfer between the outer and inner surface of the wall depends upon the thermal conductance of the layers of the wall, roof, window and door materials. The thermal balance between the inner surface and room inside environment is determined by the thermal radiation and convective heat transfer of the inner surface.

In this study, the thermal behaviour of opaque wall forms under the influence of solar energy is analysed both experimentally and theoretically in order to find the time lag and decrement factor of various wall materials. The main aim is to determine thermal behaviour of different forms of wall used in passive solar buildings.

Sol-air temperature: The combined effect of incident solar radiation and outdoor air temperature on the building envelope is indicated by an imaginary (or equivalent) temperature called sol-air temperature (Ulgen, 2002). It is an equivalent temperature such that the total heat transferred is the same as due to the combined effect of the incident solar radiation and the temperature difference between the outside air and the outer wall surface. Sol-air temperature is used as outdoor design temperature.

$$T_{sa} = T_{oa} + \frac{\alpha}{f_o} I_t - C_f$$

where, T_{sa} is the sol-air temperature (°C), T_{oa} is the outside air temperature (°C), α is the absorptivity of the surface, f_o is the outside heat transfer film coefficient, I_t is the total solar radiation on the surface and C_f is the correction factor, whose value is taken as 4°C for horizontal surfaces facing up and 4 cosβ for any inclined surface (β is the surface tilt angle measured between the surface normal and the vertical).

Thermal performance: The inner surface temperature of the wall changes with time. It depends on solar radiation on wall, outer air temperature, the indoor conditions and thermo-physical properties of wall and roof material. The solar radiation and outer air temperature causes a continuous change in the temperature distribution through the wall. The time lag and the variation of surface temperature in a typical case is shown in the Fig. 1.

Thermal time lag is the time delay between the occurrence of maximum temperature at the inside and outside of wall surface during periodic flow of heat. It is expressed in hours. The decrement factor (or Attenuation factor) is the ratio between the amplitude of the inner surface temperature and that of outer surface temperature.

Problem geometry: In this study, the heat transfer in the opaque wall under analysis is assumed to be only in one direction and time-dependent. The problem geometry is shown in Fig. 2.

One dimensional, transient heat conduction equation for this problem is as follows:

$$k\frac{\partial^2 T}{\partial x^2} = \rho c \frac{\partial T}{\partial t} \tag{1}$$

where k is the thermal conductivity, ρ is the density and c is the specific heat of the opaque material. The above equation is solved under two boundary conditions and one initial condition. On both sides of wall, convection boundary conditions are present. At the outer surface, the boundary condition is:

$$k\left(-\frac{\partial T}{\partial x}\right)_{x=0} = f_o\left[T_{sa} - T_{oa}\right] \tag{2}$$

The Eq. 2 includes the solar heat absorbed by the wall surface (represented by the sol-air temperature) and the convective heat loss to the ambient air from the exterior surface. The boundary condition at the interior surface can be written as:

$$k\left(-\frac{\partial T}{\partial x}\right)_{x=L} = f_i\left[T_{is} - T_{ia}\right] \tag{3}$$

Here, f_i is the heat transfer coefficient at the inner wall surface, f_o is the heat transfer coefficient at the outer wall surface, T_{is} is the wall inner surface temperature, T_{sa} is the wall outer surface (sol-air) temperature.

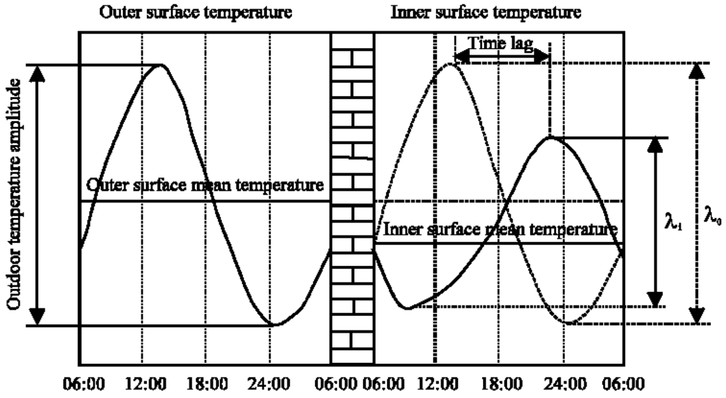

Fig. 1: Outer and inner surface temperature amplitudes

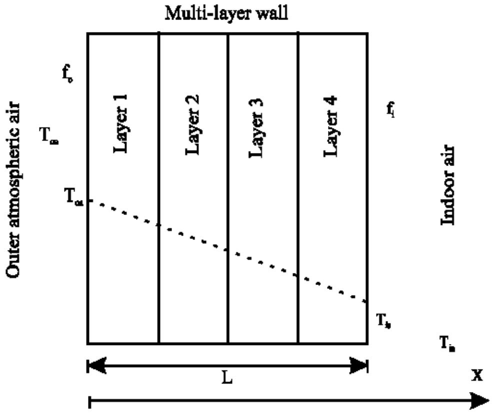

Fig. 2: The schematic of the problem geometry

The Eq. 1 can be solved by analytical procedures (Ulgen, 2002; Threlkeld, 1998) and or by numerical methods (Asan and Sancaktar, 1998). In this study, it is solved by formulating finite-difference equation of partial differential Eq. 1 for multi layer wall under convective boundary conditions, as per Crank-Nicolson method (Anderson, 1995; Patankar, 1980). To test the correctness of the code developed, computed inner surface temperature profile is compared with experimentally measured values of wall structures.

Experimental set up: The schematic diagram of simulation unit for measuring thermal behaviour of wall and roof forms, used in this study, is shown in the Fig. 3. It consists of three compartments. In compartment C1, the outer environment conditions are simulated with the help of a heating coil, a cooling coil and a fan. In compartment C2, the indoor environment conditions are simulated by another programmable controller. The middle compartment C3 holds the sample of building element of 500×500 mm size. The results of the experiments and the data collected from the case studies were used for validating the model.

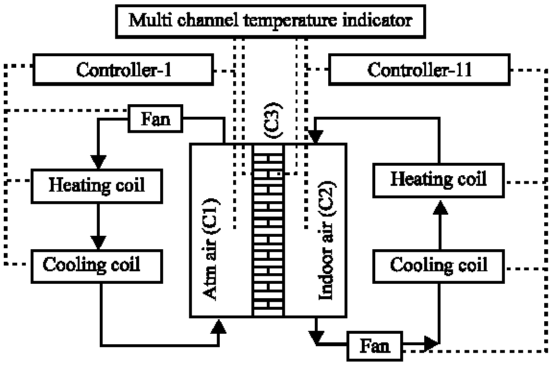

Fig. 3: Schematic of the experimental set-up

Table 1: Average thermo-physical properties of wall materials

Material	Density (kg m^{-3}) ρ	Thermal conductivity (Wm^{-1}K^{-1}) K	Specific heat Capacity (J kg^{-1}K^{-1}) c
Burnt brick	1820	0.811	880
Cement mortar	1648	0.719	920
Cement plaster	1762	0.721	840
Air	1.226	0.026	1005
Expanded polystyrene foam	24	0.035	1340

The sol-air temperature on different walls of the building is computed from the climate and solar radiation data book (Mani, 1981). The sol-air temperature is simulated in the compartment C1 and the monthly average temperature is maintained in the compartment C2.

The average thermophysical properties of the elements of the wall forms are summarised in Table 1. The thermal performance parameters of different wall forms analysed in this study and the relative positions of their individual layers are shown in the Table 2. Out of nine forms, the wall form 1, 2, 5 and 6 were analysed by both theoretical and experimental methods, while the other wall forms were analysed only by the theoretical method.

RESULTS AND DISCUSSION

The overall heat transfer coefficient (U), the Thermal Time Delay (TTD) and Decrement Factor (DF) for various wall forms are summarised in the Table 2. The overall heat transfer coefficient (U) indicates the heat flow rate per unit area per unit temperature difference under steady state conditions, including convective resistance on both sides. The experimentally found values of TTD is found to differ by maximum of 12% and DF by about 18%. This difference can mainly be attributed to the non-uniformity in the material properties of experimentally tested samples and partly to heat losses on the edges of the samples, in spite of insulation. For instance, 220 mm brick wall is theoretically analysed by using the thermophysical properties of brick, when the actual wall is made of brick and cement mortar. When effective thermophysical propertiec (i.e., the properties of equivalent homogeneous wall form) are used the error in TTD and DF is found to decrease to 7 and 10%, respectively.

It is preferable to have low U-values in hot climates, because it can substantially bring down the heat gain and hence the cooling loads. The volumetric heat capacity (which is a product of density and specific heat) of a building component represents its ability to store heat energy before reaching steady state condition. The heat storage capacity is taken as the square root of the product of volumetric heat capacity and thermal conductivity. The thermal diffusivity is the ratio of thermal conductivity and volumetric heat capacity. The thermal capacity and thermal diffusivity of the building material determines the time lag, decrement factor and magnitude of heat loss or heat gain. The multi-layer cavity walls and insulated walls have better ability to reduce inner surface temperature fluctuations due to lower U-value, lower decrement factor and higher time delay.

If the TTD is higher, the temperature fluctuation on the inner surface is delayed in comparison with the outer surface and hence the heat can be made to enter into the indoor space at a time when it is desired by suitably selecting the wall material. The DF indicates the reduction in amplitude of the indoor temperature fluctuation. The lower DF is desirable because the indoor temperature can be maintained fairly at the constant temperature irrespective of fluctuating outdoor temperature.

The 220 mm brick wall is found have a TTD of 6 h and the DF of 0.26. The TTD and DF are found to improve with increase in number of layers, cavity wall instead of solid brick wall and addition of insulation. The best results are exhibited by the multi-layered and insulated rat-trap bond Cavity Wall (CW3), followed by other wall forms as shownin the Table 2.

The value of TTD and DF are greatly influenced by the volumetric heat capacity and thermal diffusivity of the material. The increase in heat storage capacity has a positive effect on the results (i.e., it increases the TTD and decreases the DF), because of its ability to store more heat so as to delay the heat transfer. However, increase in thermal diffusivity increases the heat spreading rate and thereby reducing the TTD and DF. These effects are exhibited in the thermophysical characteristics shown in the Table 1. It implies that by combining wall layers of different thermophysical properties, desirable TTD and DF can be achieved. In the buildings located in hot climates, wall materials having low thermal diffusivity and large thermal capacity could lead to low DF and short TTD.

The addition of 50 mm EPS insulation to the wall from BW2 decreases the U-value to 0.529 Wm^{-1} K. By comparing the U-values of wall samples BW3 and BW4, it is clear that the location of the insulation layer does not influence the U-value of the wall. The U-value of Cavity

Table 2: Thermal performance parameters of various wall forms

Description of the wall (from outer to inner side)	Sample code	U ($W\,m^{-2}\,K^{-1}$)	TTD (h)	DF
220 mm Brick wall	BW1	2.334	6.00	0.264
12.5 mm Cement plaster + 220 mm Brick + 12.5 mm Cement plaster	BW2	2.165	6.50	0.213
12.5 mm Cement plaster + 50 mm EPS insulation + 220 mm Brick + 12.5 mm Cement plaster	BW3	0.529	10.75	0.175
12.5 mm Cement plaster + 220 mm Brick + 50 mm EPS insulation + 12.5 mm Cement plaster	BW4	0.529	8.75	0.195
220 mm Rat Trap Bond (RTB) Cavity Brick wall	CW1	1.883	7.50	0.198
12.5 mm Cement plaster + 220 mm (RTB) Cavity Brick wall + 12.5 mm Cement plaster	CW2	1.760	8.25	0.167
12.5 mm Cement plaster + 50 mm Insulation + 220 mm (RTB) Cavity Brick wall + 12.5 mm Cement plaster	CW3	0.399	13.25	0.104
12.5 mm Cement plaster + 220 mm (RTB) Cavity Brick wall +50 mm Insulation +12.5 mm Cement plaster	CW4	0.399	9.75	0.148
12.5 mm Cement plaster + 220 mm (RTB) Cavity Brick wall filled with EPS in the cavity + 12.5 mm Cement plaster	CW5	0.829	11.50	0.126

Wall (CW1) is considerably lower than the solid Brick Wall (BW1), because it contains cavity filled with trapped air, which acts as a good heat insulator. The addition of cement plaster on both sides of the cavity wall decreases the U-value by 6.53%. As seen from the Table 2, the further addition of 50 mm insulation on outer or inner surface can reduce the U-value considerably. Instead of adding insulation on both sides of the cavity wall, it may also be filled up in the Cavity Wall (CW5), but it is less effective compared to the case of adding insulation on the outer surface.

Addition of layers to the wall or increasing the thickness of any layer or decreasing the thermal conductivity of the layer results in decreased U-values. Since heat gain in the building during the summer and heat loss from the building during the winter is proportional to U-value, lower U-value ensures lower indoor temperature fluctuations.

The thermal time delay is mainly influenced by the thermophysical properties of the material and their relative location. It is marginally influenced by the other climatic conditions. The results in the Table 2 indicate that the increase in the thermal capacity due to additional layers increases the thermal time delay. The thermal time delay is increased to 10.75 h when thermal insulation of 50 mm is added on the outer wall. But the thermal time delay is found to be only 8.75 h, if the same insulation is added on the inner surface of the brick wall. The cavity wall is found to have higher thermal time delay compared to the full brick wall. Addition of insulation to the cavity wall also results in higher thermal time delay depending on their relative location.

It is seen from the Table 2, if the insulation is closer to the outer wall the thermal time delay is found to be higher. It could be explained from the heat storage mechanism of the building material. The insulation on the outside reduces the heat flow rate into the building material. Reduced heat flow into the mass results in longer time to fill up the thermal storage capacity of the mass. If the insulation is provided inside, the process of filling the thermal energy up to its storage capacity does not get affected significantly and hence shorter TTD.

The location of insulation material within the building component can affect its performance under transient heat flow. The best performance can be achieved by placing the insulating material close to the point of entry of heat flow. However, it is common to use insulation to the inside or between wall cavities, because it is easy to locate and protect it from the outer temperature fluctuations and moisture.

CONCLUSIONS

The walls of any building thermally interacts with the surrounding throughout a day due to change in environmental temperature and solar radiation. The walls may be built as single layered or multi-layered forms so as to have suitable thermal storage capacity and diffusivity to obtain appropriate thermal time delay and decrement factor. The knowledge of thermal behaviour of building wall forms will enable the designer to select appropriate wall forms for different building surfaces to suit the functional requirements of a building interior space. A wall form with high heat storage capacity may be preferred for those spaces used for long periods of time, while a wall form with low heat storage itself would be sufficient for spaces which are to be used for short period during specific interval of time in a day.

The thermal performance of the building wall materials can be predicted by the finite difference mathematical model. The thermophysical properties of the wall strongly influence the magnitude and timing of the maximum heat transfer rate into the building indoor space. The large heat storage capacity increases the TTD and decreases the DF, while the higher thermal diffusivity leads to converse effects. The location of individual layers (particularly insulating layers) in a multi-layered wall forms significantly influences the TTD and DF, by affecting the time required for filling up the heat storage capacity.

Multi-layered wall forms obtained by combining different elements so as to get effective heat storage capacity and diffusivity, can be the best option for the buildings (like residential houses) which are used for the whole day. Buildings that are used for short period of time in a specific part of the day (say forenoon or afternoon) may be designed with single layered wall forms. In stead of the conventional practice of using same materials for all wall surfaces of the building, the various surfaces of the buildings may be provided with different material layers and thickness so as to have required thermal time delay and decrement factor depending on their orientation and incident solar radiation to ensure better indoor conditions. The results of this study would be useful for improved passive solar design of the buildings for effective functional use of buildings.

REFERENCES

Anderson, J.D., 1995. Computational Fluid Dynamics. The Basics with Applications. Mcgraw-Hill International Editions, New York.

Arena, A.P. and C. de Rosa, 2003. Life cycle assessment of energy and environmental implications of the implementation of conservation technologies in school buildings in Mendoza-Argentina. Building Environ., 38: 359-368.

Asan, H. and Y.S. Sancaktar, 1998. Effects of wall's thermo-physical properties on time lag and decrement factor. Energy and Buildings, 28: 159-166.

Debnath, A., S.V. Singh and V.P. Singh, 1995. Comparative assessment of energy requirements for different types of residential buildings in India. Energy and Buildings, 23: 141-146.

Gupta, C.L., 2000. Energy Efficient Buildings. Renewable energy technologies: Applications to industries and agriculture. Proceedings of the millennium international conference on renewable energy technologies (MILCONRES), Feb 9-11, IIT, Chennai, pp: 281-291.

Lam, J.C., 1995. Building Envelope Loads and Commercial Sector Electricity Use in Hong Kong. Energy, 20: 189-194.

Lang, S., 2004. Progress in energy-efficiency standards for residential buildings in China. Energy and Buildings, 36: 1191-1196.

Lopes, L., S. Hokoi, H. Miura, K. Shuhei, 2005. Energy efficiency and energy saving in Japanese residential buildings-research methodology and surveyed results. Energy and Buildings.

Mani, A., 1981. Handbook of Solar Radiation Data for India. Allied Publishers, New Delhi.

Mathews, E.H., M. Kleingled and P.B. Taylor, 1999. Estimating the electricity savings effect of ceiling insulation. Building Environ., 34: 505-514.

Patankar, S.V., 1980. Numerical Heat Transfer and Fluid Flow. Hemisphere Publishing Corporation, Mcgraw-Hill, Book Company, New York.

Tatsua, O., 1993. The estimation of energy consumption and amount of pollutants due to the construction of buildings. Energy and Buildings, 19: 303-311.

Threlkeld, J.L., 1998. Thermal Environmental Engineering. Printice-Hall, Englewood Cliffs, N.J.

Tzikopoulos, A.F., M.C. Karatza and J.A. Paravantis, 2005. Modelling energy efficiency of bioclimatic buildings. Energy and Buildings, 37: 529-544.

Ulgen, K., 2002. Experimental and Theoretical investigation of effects of wall's thermophysical properties on time lag and decrement factor. Energy and Buildings, 34: 273-278.