VI–6. Thermal Behaviour of Building Walls in Transient Conditions

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ABSTRACT

The thermal behaviour of external walls of buildings is analyzed in unsteady state temperature conditions. The calculation method used has been the direct resolution of the Fourier's thermal diffusion equation.

The performance of exterior walls is studied in physical connection with the inside environment in order to determine how the internal temperature is affected by all components of the environment itself (i.e. the air, the internal walls, bodies etc.).

Different types of peripheral walls have been analyzed with special regard to the arrangement of the wall components (such as insulating layers, loadbearing structures, air space etc.).

INTRODUCTION

The problem of reduction in energy consumption and the consequent need to reduce thermal dispersion in buildings has drawn the attention of technicians and specialists on the thermal insulating characteristics of perimetral walls with the main regard to the thermal resistance.

However other characteristics, which affect in a lesser extent the overall heat loss, may directly influence the comfort of the people living in the building. The latter characteristics are the thermal diffusivity of the outside wall and the thermal capacity of the internal ambient.

It should be emphasized that the thermal behaviour of a perimetral wall, subjected to periodic temperature variations, cannot be considered independent from the thermal capacity of the internal ambient.

A more general concept of "insulation" of the internal environment from the outside temperature variations should involve all the characteristics of both the walls and the ambient which contribute in making the inside temperature independent from the outside thermal conditions.

As far as regards the influence of the internal ambient characteristics it should be noticed that high thermal capacity values of the internal structures (such as floors, partitions and contents) determine a stronger amplitude reduction of the temperature wave and may affect energy consumption. Furthermore a higher phase lag occurs between the outside and inside maximum temperature values.

THEORETICAL BACKGROUND AND SCOPE

The unsteady state thermal behaviour of outside walls has been the subject of a number of studies, some of which date back to some time ago[1,2].

The need to reduce energy consumption has recently resulted in a higher number of works on the matter[3–11].

Different methods with different degrees of accuracy have been developed in order to evaluate the temperature inside the building and the operating conditions of the heating plant, considering as well how the internal components of the building contribute to the transient conditions[4,5].

The analytical method proposed in this paper and already suggested in Reference 5, adopts the direct solution of the Fourier equation applied to the peripheral wall, where the boundary conditions take into account the influence of the internal environment.

The results obtained in a closed form, show straightforwardly how the temperature variations in the building depend on the contribution of partitions, floors and internal air thermal capacity.

These observations lead to study the thermal behaviour of the outside walls in closed connection with the internal environment to which they are related.

The aim of this paper is to analyze the thermal behaviour of different wall types related to internal environments having different characteristics. The construction types considered consist of brick combined with different insulating materials and air gaps.

An analysis has been made of the most suitable sequence of the layers forming the wall to obtain a better thermal insulation of the internal ambient according to the concept explained above.

MATHEMATICAL MODEL.

The general problem has been analyzed theoretically considering an opaque wall formed by 'n' homogeneous layers related to an internal environment characterized by a heat capacity uniformly distributed and delimited by floors and partitions with definite dimensions and properties. Ventilation plant and thermal sources may operate in the internal zone (see Fig. 1). It is assumed that the outside temperature varies with a stabilized sinusoidal wave $\theta_e = \theta_{eo}\cos\omega\tau$. The inside temperature varies according to a stabilized sinusoidal wave $\theta_i = \theta_{io}\cos(\omega\tau - \gamma)$ with an amplitude θ_{io} and phase γ depending on the characteristics of the outside wall examined and on the different boundary internal conditions mentioned above. The values of θ_{io} and γ can be obtained by the direct solution of one dimensional Fourier's thermal diffusion equation applied to the wall with the following boundary conditions:

$$x=0 \quad h_i(\theta_i - \theta^1) = -\lambda^1\left(\frac{\partial\theta^1}{\partial x}\right) = \varphi \tag{1}$$

$$x=x_i \quad \lambda^i\frac{\partial\theta^i}{\partial x} = \lambda^{i+1}\frac{\partial\theta^{i+1}}{\partial x};\ \theta^i = \theta^{i+1} \tag{2}$$

$$x=x_n \quad h_e(\theta^n - \theta_e) = -\lambda^n\left(\frac{\partial\theta^n}{\partial x}\right) \tag{3}$$

where φ is the periodic heat flux transmitted to the inside environment. Under the conditions set out above the thermal flux is given by the expression:

$$\varphi = -M\frac{\partial\theta_i}{\partial\tau} - h_t\sum\frac{S_t}{S_p}(\theta_i - \theta^i_{\ell t/2}) - E(\theta_i - \theta_e) - \varphi_s \quad (4)$$

Under the considered conditions the exact solution of the Fourier's equation assumes the following form[5]:

$$\theta^i = A^i x_i + B^i + (C^i_1 f^i_c + C^i_2 f^i_s + C^i_3 f^i_{cs} + C^i_4 f^i_{sc}) \cos\omega\tau$$
$$+ (-C^i_1 f^i_s + C^i_2 f^i_c + C^i_3 f^i_{sc} - C^i_4 f^i_{cs}) \,\mathrm{sen}\,\omega\tau \quad (5)$$

where:

$$f^i_c = \mathrm{Cosh}\, y^i \cos y^i \quad f^i_s = \mathrm{Senh}\, y^i \,\mathrm{sen}\, y^i$$
$$f^i_{cs} = \mathrm{Cosh}\, y^i \,\mathrm{sen}\, y^i \quad f^i_{sc} = \mathrm{Senh}\, y^i \cos y^i$$
$$y^i = x_i\sqrt{\omega/2a^i}$$

For the cases studied here the terms relating to ventilation and heat sources have not been considered. Therefore the balance equation (4) becomes:

$$\varphi = -M\frac{\partial\theta_i}{\partial\tau} - h_t\sum\frac{S_t}{S_p}(\theta_i - \theta^i_{\ell t/2}) \quad (6)$$

The connection between the outside wall and the internal ambient is apparent from the equation (1) and (6). It is observed that it is possible to take into account the air space inside the peripheral wall considering an equation similar to (6) for the air gap. In addition when the outside walls include transparent surfaces the analysis can be developed according to Reference [6].

Finally this method can be applied to a wave of arbitrary shape using harmonic components derived by Fourier's analysis.

INFLUENCE OF THE INTERNAL ENVIRONMENT ON THE BEHAVIOUR OF THE OUTSIDE WALL.

In order to examine how the thermal capacity of the internal ambient, the dimensions and the physical properties of floors and partitions affect the dynamic response of the outside walls, as examples of application, a series of calculations have been developed using the balance equation in a simplified form (6). The calculations have been carried out taking into account floor and ceiling only because internal partitions, usually lightweighted, have negligible influence.

Two types of floors have been considered with weight corresponding to the main building systems adopted in Italy. The first designated as "heavy" consists of 0.15 m of concrete, and the second designated as "light" consists of 0.15 m of cellular concrete. The physical properties of these materials are reported in Table 2.

The outside wall examined consists of 0.12 m of common bricks, 0.06 m of mineral wool, an air space and a final layer of 0.008 m of asbestos-cement. The surface resistance is 0.043 m²°C/W external, and 0.086 m²°C/W internal.

The diagram of Fig. 2 shows some results obtained from the calculations carried out, where the amplitude reduction ρ and phase lag γ are reported as a function of the St/Sp ratio between the floor and ceiling surface, and that of outside wall. The diagram shows the considerable effect of these internal structures on ρ and γ.

Namely a strong decrease of the amplitude reduction can be noticed with the increasing of the S_t/S_p ratio. This effect which depends on the floor and ceiling thermal properties and on their thickness, is much stronger when heavy structure is used. Finally it can be seen that the phase lag γ is very little affected by the aforementioned characteristics of the floor and ceiling.

Table 1 shows the ρ and γ values for a series of outside walls related to an internal environment with uniform air thermal capacity M = 4 kJ/m²°C and delimited by floor and ceiling of the light type. These results agree with the trends shown in Fig. 2.

ANALYSIS OF THE MOST SUITABLE SEQUENCE OF LAYERS FOR AN OUTSIDE WALL.

The dependence of ρ and γ has been examined as a function of the presence and position of the air space in the perimetral wall. Moreover the influence of the insulating material position in the wall has been analyzed.

The results demonstrated that the presence of an air space leads to slight variations of the ρ and γ values which tend to become smaller the stronger is the effect of floors and ceiling and of the thermal capacity of the internal zone. However, the smaller ρ values are obtained when the air gap is placed towards the outer side of the perimetral wall. A considerable effect is given by the position of the insulating layer in the perimetral wall.

Fig. 3 compares the values of ρ and γ obtained with the same overall heat transfer coefficient inverting the sequence of layers in the outside wall. When the insulating layer is placed on the outer side of the peripheral wall the smallest ρ values are obtained. Small influence on the values of the phase lag γ is noticed when changing the layer sequence. The results reported in Table 1 show what has already been noticed, regarding the most suitable position of the insulating material.

CONCLUSIONS

The analysis developed with the direct method of exact solution of the Fourier's equation has clearly shown the influence exerted by the characteristics of the internal environment on the transient phenomenon. It has been noticed that the amplitude reduction ρ decreases by increasing the ratio between the floor and ceiling surface and the outside surface S_t/S_p, and by increasing the air thermal capacity M.

The effect is stronger the higher is the thermal capacity of floor and ceiling and the air capacity considered.

The phase lag, instead, is affected by the characteristics of inside wall in a lesser extent.

The influence of the position of the insulating layers and air space in the outside wall has also been considered. The results obtained show a slight decrease of ρ due to the presence of air spaces. This decrease is more appreciable, however, when the air gap is placed on the outer side of the peripheral wall. A considerable effect on amplitude reduction ρ is obtained placing the insulating layer on the outer side of the wall with the same overall heat transfer coefficient. The layer sequence appears to affect to a lesser extent the phase lag γ.

NOMENCLATURE

- a thermal diffusivity, m^2/s
- c specific heat J/kg°C
- c′ volumetric heat, J/m^3°C
- E ventilation term ($nc'V/S_t$), W/m^2°C
- h boundary heat transfer coefficient, W/m^2°C
- ℓ thickness, m
- M thermal capacity of the room ambient air, kJ/m^2°C
- n number of changes of outdoor air for ventilation, 1/s
- S surface area, m^2
- U thermal transmittance, W/m^2°C
- V room volume, m^3
- x linear abscissa, m
- γ phase lag, h
- δ density, kg/m^3
- θ temperature, °C
- λ thermal conductivity, W/m°C
- ρ amplitude reduction
- τ time, s
- φ heat flux, W/m^2
- ω pulsation of sinusoidal swing, rad/s

SUBSCRIPTS

- e refers to external environment
- i refers to internal environment
- p refers to peripheral wall
- s refers to thermal source
- t refers to floor or ceiling

SUPERSCRIPTS

1, 2, 3, . . . , i, . . . , n refers to number layer or separation surface among successive layer.

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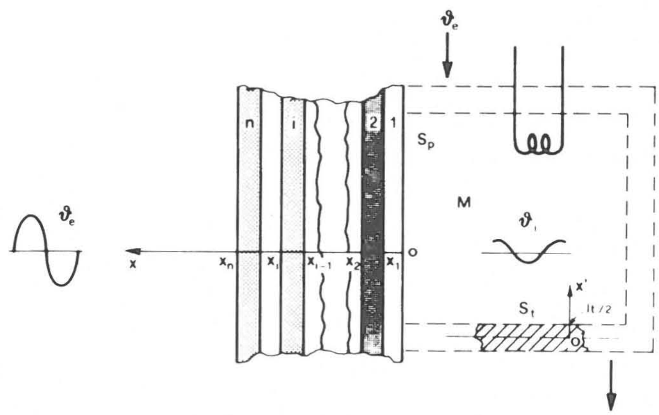

Figure 1. Schematic diagram of the system considered in the theoretical model.

TABLE 1

OUTSIDE WALLS	U [W/m^2°C]		S_t/S_p				
			0	0.5	1	2	4
1 Asbestos-cement 0,006 m Air-space 0,02 m Common brick 0,12 m	2,10	ρ	0,24	0.20	0.17	0.13	0.09
		γ [h]	6.6	6.8	6.9	7.1	7.4
2 Asbestos-cement 0,006 m Air-space 0,02 m Common brick 0,25 m	1,57	ρ	0.2	0.06	0.05	0.04	0.0
		γ [h]	10.6	10.8	11.0	11.3	11.5
3 Asbestos-cement 0,006 m Air-space > 0,02 m Lightweight brick 0,20 m	1,46	ρ	0.2	0.15	0.13	0.09	0.06
		γ [h]	7.9	8.1	8.3	8.4	8.6
4 Common brick 0,12 m Air-space > 0,02 m Plasterboard 0,013 m	1,92	ρ	0.51	0.36	0.27	0.18	0.11
		γ [h]	5.8	6.3	6.6	6.9	7.2
5 Common brick 0,25 m Air-space > 0,02 m Plasterboard 0,006 m	1,55	ρ	0.16	0.11	0.09	0.06	0.04
		γ [h]	10.1	10.7	11	11.3	11.6
6 Asbestos-cement 0,006 m Glass-wool 0,04 m Air-space > 0,02 m Common brick 0,12 m	0,68	ρ	0.05	0.04	0.04	0.03	0.02
		γ [h]	7.47	7.67	7.82	8.0	8.23
7 Asbestos-cement 0,006 m Glass-wool 0,06 m Air-space > 0,02 m Common brick 0,12	0,51	ρ	0.04	0.03	0.03	0.02	0.01
		γ [h]	7.6	7.8	7.9	8.1	8.3
8 Asbestos-cement 0,006 m Glass-wool 0,08 m Air-space > 0,02 m Common brick 0,12 m	0,40	ρ	0.03	0.03	0.02	0.02	0.01
		γ [h]	7.7	7.9	8	8.3	8.5
9 Common brick 0,12 m Glass-wool 0,04 m Air-space > 0,02 m Asbestos-cement 0,006 m	0,68	ρ	0.33	0.17	0.11	0.07	0.04
		γ [h]	8.2	8.2	8.2	8.2	8.2
10 Common brick 0,12 m Glass-wool 0,06 m Air-space > 0,02 m Asbestos-cement 0,006 m	0,51	ρ	0.26	0.13	0.08	0.05	0.03
		γ [h]	8.9	8.6	8.5	8.4	8.4
11 Common brick 0,12 m Glass-wool 0,08 m Air-space > 0,02 m Asbestos-cement 0,006 m	0,40	ρ	0.21	0.10	0.07	0.04	0.02
		γ [h]	9.4	8.9	8.7	8.6	8.5

TABLE 2—Physical Properties of Materials

Materials	λ (W/m°C)	δ (kg/m³)	c (J/kg°C)	a (m²/s)
Common brick	0,81	1800	920	$4{,}9\cdot10^{-7}$
Lightweight brick	0,56	950	920	$6{,}4\cdot10^{-7}$
Plasterboard	0,21	875	840	$2{,}8\cdot10^{-7}$
Asbestos-cement	0,35	2000	840	$2{,}1\cdot10^{-7}$
Glass-wool	0,040	30	840	$1{,}6\cdot10^{-6}$
Concrete	1,70	2200	880	$8{,}8\cdot10^{-7}$
Cellular concrete	0,15	700	920	$2{,}3\cdot10^{-7}$

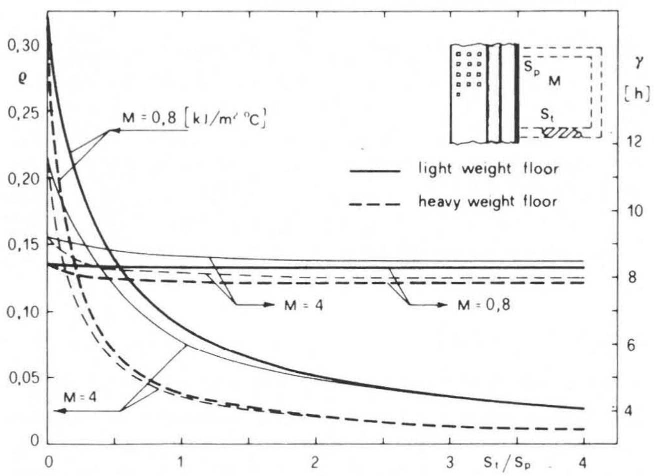

Figure 2. Amplitude reduction ρ and phase lag γ versus St/Sp ratio: influence of different floors and of the air thermal capacity M.

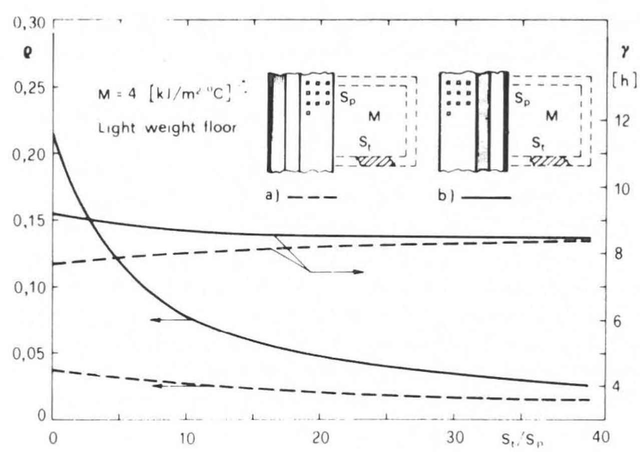

Figure 3. Amplitude reduction ρ and phase lag γ versus St/Sp ratio: influence of insulating layer position.