Time-dependence of the Room Temperature during intermittent Heating for various Types of Wall

(Dipendenza dal tempo della temperatura di stanza durante riscaldamento intermittente per diversi tipi di parete)

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Abstract - The influence of intermittent heating on room temperature is studied for three types of wall and several values of internal heat capacity; also the effect of the solar radiation is taken into account. Moreover, the problem of energy saving is analyzed in dependence of the heating power and the type of wall.

Sommario - Si studia l'influenza congiunta del riscaldamento intermittente e dell'irraggiamento solare sulla temperatura di stanza, per diversi tipi di parete e valori della capacità termica interna. Viene, inoltre, analizzato il problema del risparmio energetico in funzione delle caratteristiche termiche della parete, e della potenza riscaldante.

1. INTRODUCTION

The problem of thermal performance of walls was widely investigated in the last twenty years. The influence of the room thermal capacity assumed as uniformly distributed was pointed out by Magrini [1] for the case of periodic state, single-layer opaque wall and sinusoidal external temperature variations; also the air changes in the room and the transient state were then considered [2,3]. The extension of the above problems to the case of multi-layer walls is due to Warsi and Choudhury [4], Columba and Lo Giudice [5, 6], Boffa, Ferro and Sacchi [7,8]. Particular attention to the influence of the solar radiation and to the responce-time in the transient state was paid by Faggiani and Fantini [9] and by Sovrano and Zorzini [10,11]. The transfer function method, firstly introduced by Mitalas and Stephenson [12,13], has been recently employed for the typical italian buildings [14] in relation to CNR's Progetto Finalizzato Energetica. Also a number of experimental works were made about these problems [15-17].

Today the increasing cost of fuel and the consequent necessity of a more limited time of heating in buildings suggest to extend these studies, in order to analyze the thermal behaviour of the couple wall-room subjected to solar radiation and intermittent heating. Therefore, purpose of the present work is to investigate the time-dependence of the room temperature in relation to three types of wall and three expositions during intermittent heating. Specifically, the considered walls are shown in Fig. 1: the first (light) is formed by two thin layers of asbestos-cement and one of polystyrene foam; the second (medium) by light-weight bricks, polystyrene foam and plaster; the third (heavy) by two layers of common bricks and one of polystyrene foam. The three walls are characterized by the same value of the thermal transmittance (Table 1):

$$\left(\frac{1}{h_e} + \frac{x_1}{\lambda_1} + \frac{x_2}{\lambda_2} + \frac{x_3}{\lambda_3} + \frac{1}{h_i} \right)^{-1} = 0.47\ \mathrm{W/m^2\ °C}$$

being $h_e = 23\ W/m^2 °C$ and $h_i = 8.1\ W/m^2 °C$.

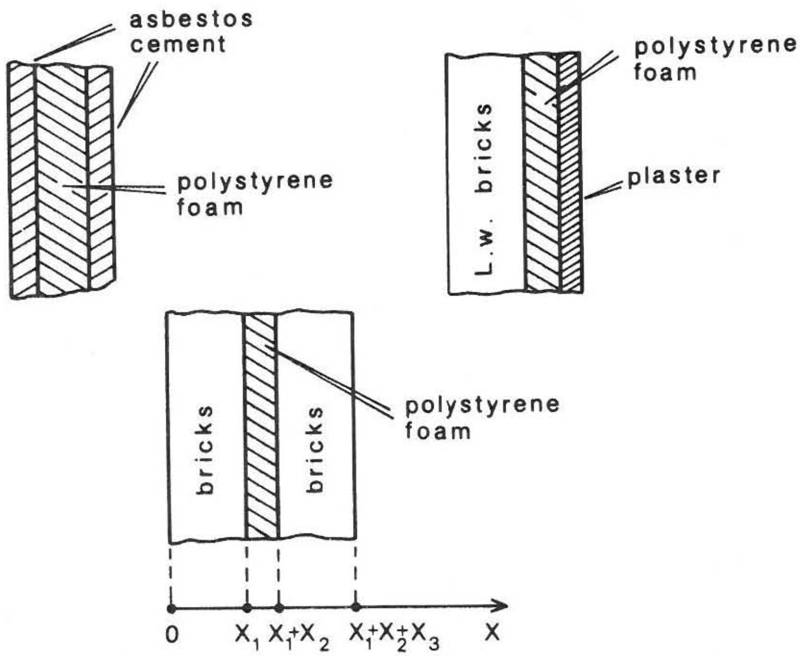

Fig. 1 - Light, medium and heavy walls.

The influence of the solar radiation is taken into account by means of the well-known sol-air temperature, t_e , which is shown in Fig. 2 for the averaged

Material	λ	α	Thicknesses		
			Light wall	Medium wall	Heavy wall
Asbestos-cement	0.63	0.48	0.60		
Common bricks	0.70	0.48			12
Light-weight bricks	0.62	0.48		12	
Plaster	0.70	0.44		2.0	
Polystyrene foam	0.031	1.25	6.0	5.5	5.0

Table 1 - Thermal conductivity, $W/m^2 °C$; thermal diffusivity x 10^6, m^2/s; thicknesses of the layers x 100, m.

conditions of Pisa and for East, South and West expositions. Concerning the ratio between adsorbed and incident radiation, it has been fixed as 0.85.

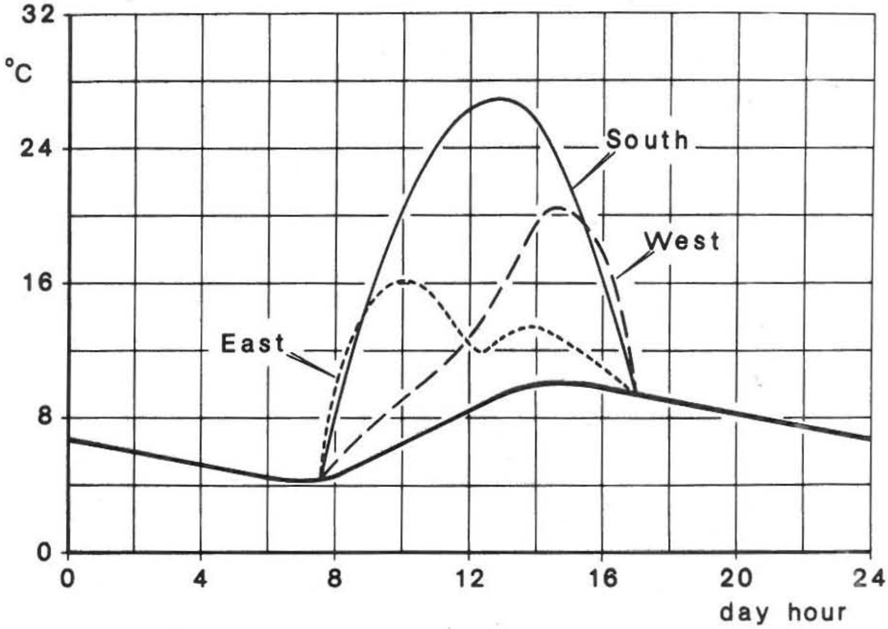

Fig. 2 - Sol-air temperature versus time for East, South and West expositions; January.

2. EQUATIONS

Under the hypothesis of constant properties and perfect thermal contact between the layers, the governing equations are:

$$(1)\qquad \frac{\partial t_1}{\partial \tau} = \alpha_1 \frac{\partial^2 t_1}{\partial x^2}$$

$$(2)\qquad \left(\frac{\partial t_1}{\partial x}\right)_{x=0} = \frac{h_e}{\lambda_1}\left[t_1(x=0,\tau) - t_e(\tau)\right]$$

$$(3)\qquad t_1(x=x_1,\tau) = t_2(x=x_1,\tau)$$

$$(4)\qquad \left(\frac{\partial t_1}{\partial x}\right)_{x=x_1} = \frac{\lambda_2}{\lambda_1}\left(\frac{\partial t_2}{\partial x}\right)_{x=x_1}$$

$$(5)\qquad \frac{\partial t_2}{\partial \tau} = \alpha_2 \frac{\partial^2 t_2}{\partial x^2}$$

(6) $$t_2(x = x_1 + x_2, \tau) = t_3(x = x_1 + x_2, \tau)$$

(7) $$\left(\frac{\partial t_2}{\partial x}\right)_{x=x_1+x_2} = \frac{\lambda_3}{\lambda_2} \left(\frac{\partial t_3}{\partial x}\right)_{x=x_1+x_2}$$

(8) $$\frac{\partial t_3}{\partial \tau} = \alpha_3 \frac{\partial^2 t_3}{\partial x^2}$$

(9) $$\left(\frac{\partial t_3}{\partial x}\right)_{x=x_1+x_2+x_3} = \frac{h_i}{\lambda_3}\left[t_i(\tau) - t_3(x = x_1 + x_2 + x_3, \tau)\right]$$

(10) $$t_1(x, \tau = 0) = t_2(x, \tau = 0) = t_3(x, \tau = 0) = t_o$$

(11) $$E\frac{d t_i}{d \tau} = -\lambda_3 \left(\frac{\partial t_3}{\partial x}\right)_{x=x_1+x_2+x_3} + \dot{Q}$$

Equations (1), (5) and (8) are Fourier's equations for the three layers; (3) and (6) express the temperature equality at the contact interfaces, (4) and (7) the thermal flux equality; (2) and (9) express the external and internal heat exchanges respectively. About the last two equations, the first one says that the layer temperatures have the same value, t_o, at the initial instant; the second one that the time variations of the room temperature depend both on the heat exchange at the internal side of the wall ($x=x_1+ x_2+ x_3$) and on the heating power. If this is electrically supplied, $\dot{Q}$ can be taken as a function of time which assumes the value $\dot{Q}$ = constant when the heating goes, and the value 0 when it does not. In the case of heating by hot water, $\dot{Q}$ must be expressed as:

$$\dot{Q} = (S_t/S_w)h'_i(t_t - t_i)$$

being S_w and S_t the wall and heat exchanger areas, h'_i the heat transfer coefficient between the hot water and the room, finally t_t the temperature of the first one. However, taking into account that: i) the time-dependence of t_t is like that of $\dot{Q}$; ii) during the periodic state the oscillations of t_i influence the difference $t_t - t_i$ less than $\pm 4\%$ and only in the transient state this influence can attain $\pm 10\%$ at most; iii) the uncertainties of λ, α, E and in particular h_e, h_i and h'_i are often larger than above limits; it can be concluded that for this kind of problem a reasonable accuracy is obtained by simply assuming $\dot{Q} = \dot{Q}_o$ and $\dot{Q} = 0$ also in the case of hot water heating.

The above equations have been solved following a resolution method reported by Ozisik [18], with the aid of a P6066 Olivetti mini-computer(1).

(1) For sake of brevity further details on the resolution method must be omitted.

3. RESULTS AND CONCLUSIONS

Part of the results of numerical calculations are reported in figures 3,4 and 5. In all these graphs the zero-time is fixed when the temperatures of room and wall periodically oscillate as t_e does: in such a way the influence of the arbitrary initial condition (10) vanishes at all.

From Fig. 3 it appears that for a given value of the internal heat capacity, E, the amplitudes of the room temperature oscillations are markedly larger in the case of light wall, both during the transient and the periodic state. This observation is yet valid when heating is performed twice a day instead of once (Fig. 4). Moreover, changes in solar exposition do not modify this trend. Therefore, a first simple conclusion can be drawn: with the same energy consumption the heavy wall assures smaller oscillations of t_i than those corresponding to the light wall.

However, when E increases the just pointed out difference tends to decrease (Fig. 5): this means that the characteristic of more constant temperature assured by the heavy wall is particularly evident for residential buildings and offices, in which E is only due to furniture, internal walls and air, but it could become less evident in the case of warehouses.

Another interesting aspect which distinguishes the heavy wall from the light one is that the choice of the heating beginning is slightly important for the former, while it is very critic for the latter. If the beginning instant changes from 2 a.m. to 8 a.m. (Fig. 3) the amplitude of the room temperature oscillations remains nearly unchanged in the case of heavy wall, but it varies from 2°C to 4°C in that of light wall. In other words, the beginning instant must be carefully chosen in relation to the external temperature, t_e , in the last case; obviously such a choice becomes more important for the South and West expositions because of the marked peak which characterizes the time-dependence of their temperatures (Fig.2).

Let's now consider the problem from a different point of view (Fig. 6). In order to obtain these graphs the heating is made to start so that the room temperature, t_i, reaches the value of 20°C at 9 a.m. Successively the temperature is controlled every 450 s until 8 p.m.: if it results larger than 20°C the heating is stopped (namely $\dot{Q}$ is put equal 0), if t_i results less than 20°C the heating is made to start again ($Q = \dot{Q}_o$). In this way a fixed value of the room temperature is assured in the time interval from 9 a.m. to 8 p.m. Obviously such a calculation must be repeated for several values of $\dot{Q}_o$ in order to evaluate the energy consumption, because the heating time which is necessary to obtain t_i = 20°C at 9 a.m. decreases if $\dot{Q}_o$ is increased [19].

Some time-dependences of t_i obtained by means of these calculations are reported in Fig. 6; some values of the energy consumption in Table 2.

	$\dot{Q}_o$= 7.30W/m^2	$\dot{Q}_o$= 23.5W/m^2
Light wall	106	98
Heavy wall	104	101

Table 2- Energy consumption, J per day; t_i = constant from 9 a.m. to 8 p.m.

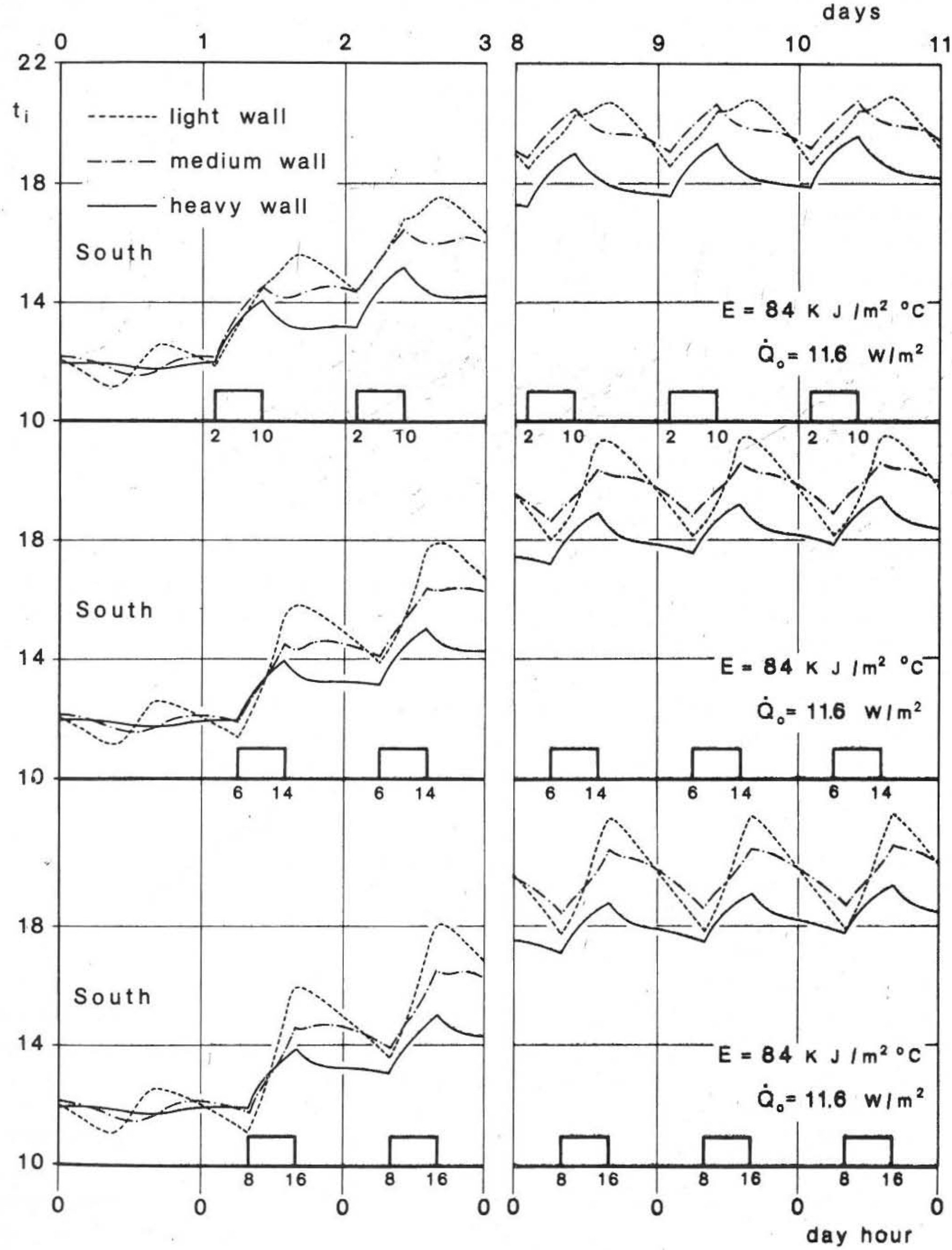

Fig. 3 - Internal temperature, t_i, versus time for heavy, medium and light wall at three beginning istants of heating.

The following conclusions can be drawn: i)the increase of $\dot{Q}_o$ leads to a saving of energy both for heavy and light wall, but it also implies a small level of comfort during the night; ii)this loss of comfort is small in the case of heavy wall, more marked in that of light wall; iii)within ±5% the energy saving reaches its maximum when $\dot{Q}_o$ is 4 times the minimum which is necessary to steadily maintain t_i= 20°C being the external temperature equal to $\bar{t}_e$ (i.e. 9.1,12 and 9.2°C for East, South and West exposition respectively).

According to the above conclusions in the case of light wall a marked increase of $\dot{Q}_o$ seems useful only for buildings destined to office, where no people live during the night.

Finally in Fig. 7 the initial (heating) and the final (cooling) transients and also the intermediary interval in which t_i is maintained constant within ± 0.7°C are reported: for the heavy wall the internal temperature decrease is slower than that corresponding to the light wall, as the increase does during the heating. Moreover, during the initial transient with E = 84 kJ/m²°C the energy consumption decreases of about 25% both for heavy and light wall if $\dot{Q}_o$ changes from 7.7 to 17 W/m² ; on the contrary this saving becomes negligible with E = 42 kJ/m²°C.

Concluding this work, authors remark that the problem of energy saving, which is briefly analized here, must be considered in dependence of the following quantities: internal heat capacity, type of wall, solar exposition, heating power and mainly level of required comfort. Such a study will be made in a future paper.

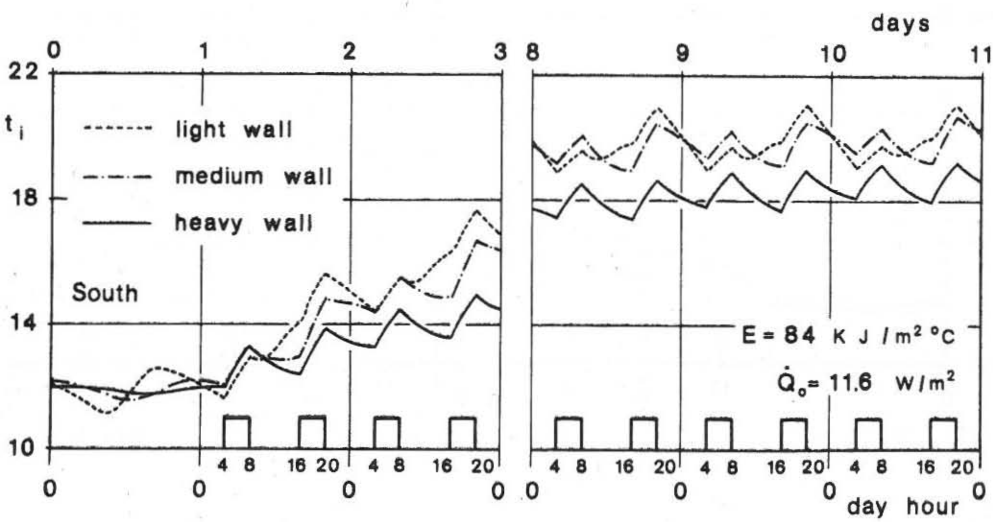

Fig. 4 - Internal temperature, t_i, versus time for heavy, medium and light wall; heating twice a day.

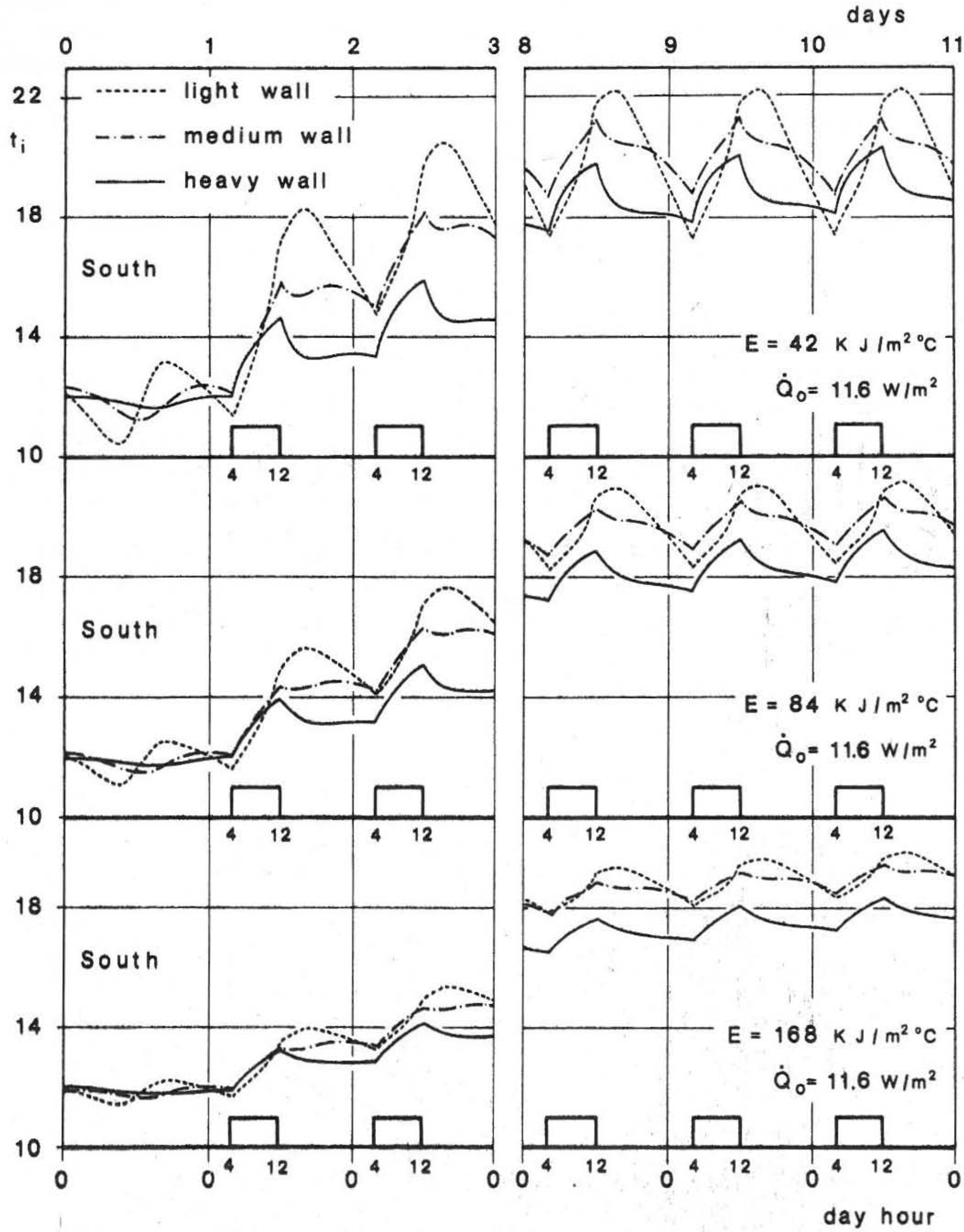

Fig. 5 - Internal temperature, t_i ,versus time for heavy, medium and light wall and for three values of E.

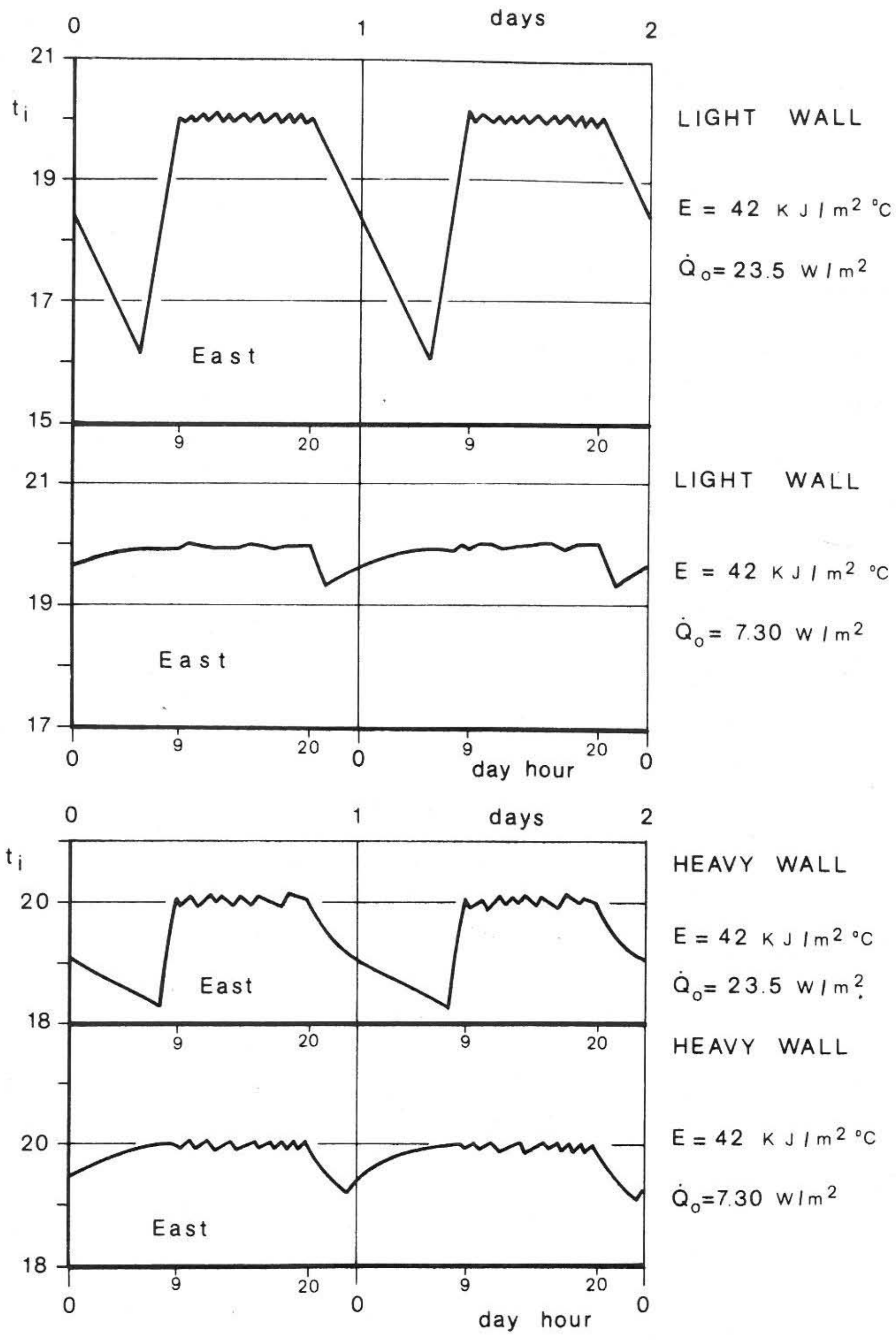

Fig. 6 - Cyclic time —dependence of t_i for heavy and light wall and for two values of $\dot{Q}_o$. Constant internal temperature from 9 a.m. to 8 p.m.

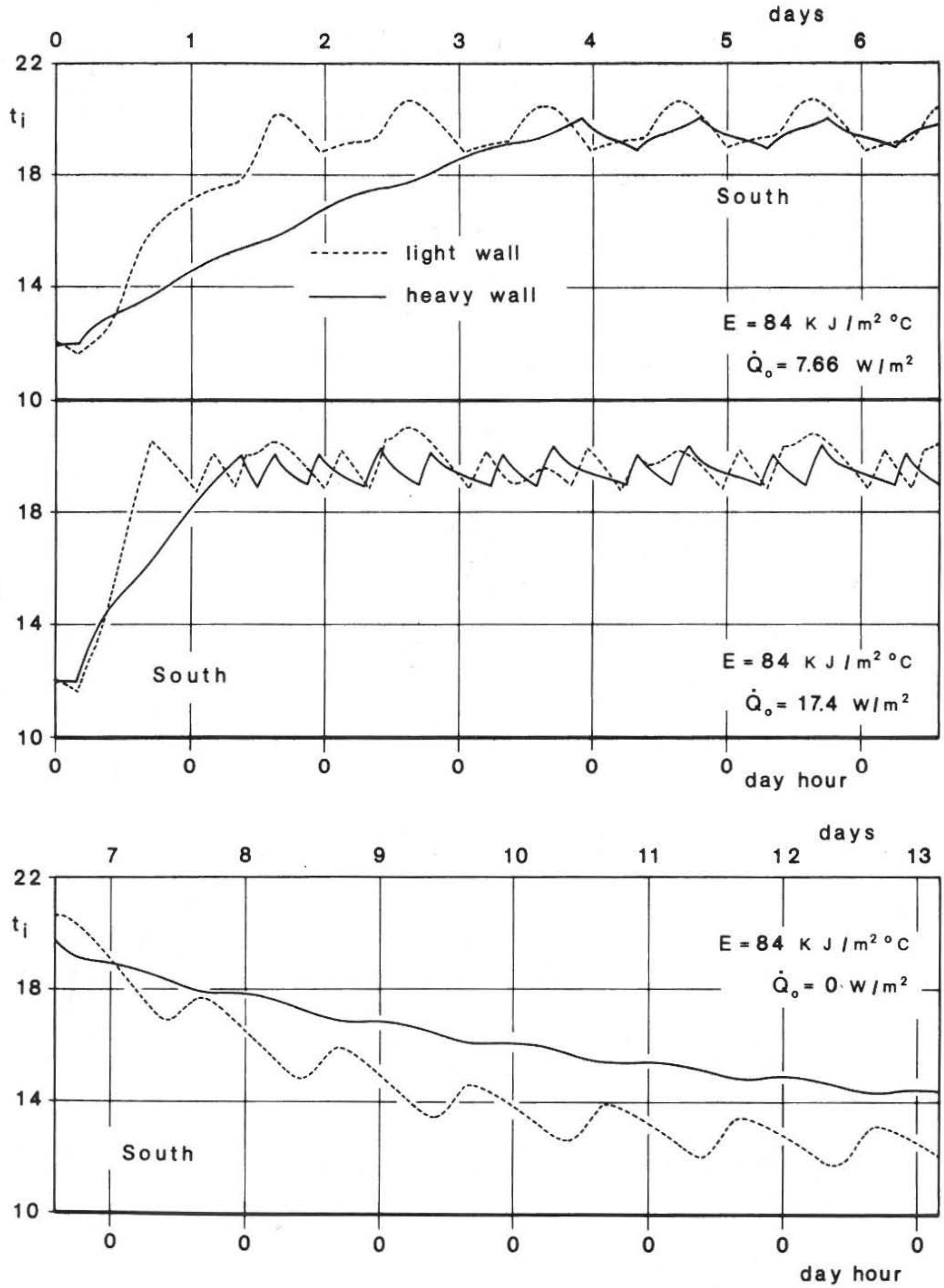

Fig. 7 - Initial heating, constant temperature interval and final cooling for heavy and light wall. During the constant temperature interval the heating starts when $t_i \leq 19°C$ and stops when $t_i \geq 20°C$.

LIST OF SYMBOLS

x	coordinate, m
x_1, x_2, x_3	thicknesses of the wall layers, m
$\lambda_1, \lambda_2, \lambda_3$	thermal conductivities of the wall layers, W/m °C
$\alpha_1, \alpha_2, \alpha_3$	thermal diffusivities of the wall layers, m^2/s
t_e	sol-air external temperature, °C
t_i	room temperature, °C
t_1, t_2, t_3	temperatures of the wall layers, °C
E	room thermal capacity per unit area, $J/m^2 °C$
$\dot{Q}$	heating power per unit area, W/m^2
h_e	external heat transfer coefficient, $W/m^2 °C$
h_i	internal heat transfer coefficient, $W/m^2 °C$
t_o	uniform wall temperature at $\tau=0$, °C

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