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Envelope and indoor thermal capacitance of buildings

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Abstract

The real or *effective* thermal capacitance of buildings quantifies the energy stored within and differs considerably from the *apparent* thermal capacitance, which results by adding distributed specific heats of building elements into a lumped value. In the present study, a method is developed for analyzing the total *effective* capacitance into components concerning the building envelope or parts of it (e.g. ceiling, floor, etc.), the interior partitions, the furnishings, etc. The developed procedure is based on a finite-difference solution of a set of differential equations describing the transient heat conduction in all elements of a building. Applications are made to 21 types of buildings with 15 and 10 wall and roof compositions, respectively, and floor area from 50 m^2 to 2500 m^2. For example, it is found that for typical fully-insulated, one-storey, detached houses, the envelope, interior partitions and furnishings *effective* heat capacitances are 78.1%, 14.5% and 7.4%, respectively, of the total *effective* thermal capacitance. Also, a correlation is developed, which links the *effective* to the easily-calculated *apparent* thermal capacitance of buildings. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Thermal capacitance; Building envelope; Building interior partitions; Components of thermal capacitance; Effective and apparent thermal capacitance

Nomenclature

A	area [m^2]
A_n, B_n	coefficients in Eq. (27)
a_n, b_n	coefficients in Eq. (28)
C	thermal capacitance [J/K]
c	specific heat [J/kg K]
F	floor area [m^2]

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f	initial temperature [K]
G1–G18	wall code numbers
g	radiation heat-transfer factor [W/m^2 K]
h	convection heat-transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
L	heat-loss coefficient [W/K]
L_f	thickness of equivalent furniture slab [m]
Q	indoor load [W]
q	heat flow [W/m^2]
r_n, s_n	coefficients in Eq. (29)
T	temperature [K]
t	time [s]
v	volume [m^3]
x	Cartesian coordinate

Greek symbols

ρ	density [kg/m^3]

Subscripts

a	apparent or referring to air
b	referring to the beginning
ce	ceiling
e	exterior or element of building envelope
eff	effective
env	envelope
fl	floor
fur	furniture
i or ind	indoor
J	number of wall layers
j	wall layer
o	outdoor
p or par	partition
s	surface
tot	total
wa	wall

1. Introduction

For the analysis of the dynamic thermal behaviour of buildings and the estimation of their thermal parameters, various methods are available in the literature, e.g. by using transfer functions [1] or thermal network models [2], developing direct measurement procedures [3], solving numerically the differential equation set which describes the dynamic thermal behaviour of buildings [4, 5] or employing dynamic system models derived from actual building performance data [6, 7]. Also, computer programs are available, as for example the transient system simulation program TRNSYS [8].

In previous publications [9, 10] the *apparent* and *effective thermal capacitances* of buildings were introduced. The former results by adding the distributed specific heats of all building elements into a lumped capacitance, i.e.

$$C_a = \Sigma v_j \rho_j c_j \tag{1}$$

where v_j, ρ_j, c_j are the volume, density and specific heat, respectively, of the concrete frame, exterior and interior wall layers, floor and roof layers, fenestration, furniture, etc. Although the above *apparent thermal capacitance* C_a can be easily calculated from Eq. (1), it is not useful in applications concerning the dynamic thermal behaviour of buildings, apart from making rough estimations and comparisons of the available structural mass for thermal storage. The *real* or *effective thermal capacitance* of buildings, C_{eff}, which quantifies the ability of a building to store thermal energy and is useful in dynamic thermal performance calculations, differs considerably [10] from the *apparent thermal capacitance*, C_a , as the ability of structural elements and furnishings to store heat is different when these are distributed in the building or considered together forming a unified volume. The calculation of the *effective thermal capacitance* of buildings, which is not as straightforward and easy as that of the *apparent thermal capacitance* Eq. (1), may be performed by a method presented in a previous publication [10].

In the present work, the total effective thermal capacitance of buildings $(C_{eff})_{tot}$ is analyzed in components corresponding to the envelope, $(C_{eff})_{env}$, and indoor $(C_{eff})_{ind}$ mass of the building. In the following, the above quantities are referred to as C_{tot}, C_{env} and C_{ind}, for simplicity. Components C_{env} and C_{ind} quantify the ability of the building envelope and indoor mass (i.e. partitions and furnishings), respectively, to store thermal energy. They are calculated using a procedure based on a finite-difference solution of a rigorous set of coupled differential equations describing the dynamic thermal behaviour of buildings. The reasons for analysing the total thermal capacitance, C_{tot}, into envelope and indoor components are summarized below.

1. Thermal parameter C_{env} has a more permanent value than C_{tot}, because the latter depends on the indoor mass, which changes according to the occasional use of a building.
2. C_{env} may be useful in comparisons and classifications of buildings. For example, buildings with the same envelope (and therefore the same value of C_{env}) may be encountered with (i.e. hotels, office-buildings, hospitals) or without (i.e. theatres, banks, supermarkets) indoor partitions.
3. When C_{tot} is used in the calculation of the indoor temperature $T_i(t)$ in terms of time t, using the simple model developed in a previous publication [10], the results show a slow variation of $T_i(t)$ with time because T_i is considered as the mean temperature of indoor air, partitions and furniture. However, in practice, the instant air temperature seems to contribute to the sensation of thermal comfort more than the wall surface temperatures, unless these differ considerably from the comfort temperatures and people are close to a wall. Therefore, it is useful to know the value of C_{env}, which allows, according to the developed simple model [10], the calculation of the indoor air temperature $T_i(t)$ without

taking into account the thermal mass of indoor partitions and furnishings. Therefore, C_{env} may be used instead of C_{tot} in applications concerning the approximate calculation of the level of thermal comfort.

Moreover, in the present study, it is suggested to further analyze the *indoor thermal capacitance* C_{ind} taking into account components concerning the interior partitions, C_{par}, the furnishings C_{fur}, and the ceiling C_{ce} and floor C_{fl}, if these are not included in the building envelope. This analysis reveals the contribution of each indoor element to the total thermal mass of a building. Also, a correlation is developed for the calculation of C_{tot} in terms of the easily-calculated apparent thermal capacitance C_{a}.

2. Numerical simulation of transient heat transfer in the envelope, interior partitions and furnishings of buildings

Transient, one-dimensional heat conduction in any multi-layer element (wall, roof, etc.), of the envelope of a building may be expressed as

$$\rho_{\mathrm{e}j}c_{\mathrm{e}j}\partial T_{\mathrm{e}j}(t,x)/\partial t = k_{\mathrm{e}j}\partial^2 T_{\mathrm{e}j}(t,x)/\partial x^2, \quad x_j \le x \le x_{j+1}, \quad t > 0, \quad j = 1,2,\ldots,J \tag{2}$$

where subscript e refers to the elements of the building envelope; J is the number of layers each element is composed of; $T_{\mathrm{e}j}(t,x)$ is the instantaneous temperature of any layer j at time t and depth x, measured from the outdoor surface; $\rho_{\mathrm{e}j}$, $c_{\mathrm{e}j}$ and $k_{\mathrm{e}j}$ denote the density, heat capacity and thermal conductivity of the jth layer, respectively; and x_j, x_{j+1} are the coordinates of the jth layer surfaces.

The boundary and initial conditions for differential Eq. (2) are expressed by equations

$$q_{\mathrm{o},n}(t) = -k_{\mathrm{e}1}\partial T_{\mathrm{e}1}(t,x)/\partial x = h_{\mathrm{o}}[T_{\mathrm{o}}(t) - T_{\mathrm{e}1}(t,x)], \quad x = x_1, \quad t > 0, \tag{3}$$

$$\begin{aligned} q_{i,n}(t) &= -k_{\mathrm{e}J}\partial T_{\mathrm{e}J}(t,x)/\partial x = h_i[T_{\mathrm{e}J}(t,x) - T_i(t)] + \Sigma_{\mathrm{s}} g_{\mathrm{e,s}}[T_{\mathrm{e}J}(t,x) - T_{\mathrm{s}}(t)], \\ x &= x_{J+1}, t > 0 \end{aligned} \tag{4}$$

$$T_{\mathrm{e}j}(t,x) = f_{\mathrm{e}j}(x), \quad x_j \le x \le x_{j+1}, \quad j = 1,2,\ldots,J, \quad t = 0 \tag{5}$$

where $T_i(t)$, $q_{i,n}(t)$ and h_i are the indoor air temperature, the heat flow and the convective heat-transfer coefficient at interior surface of envelope element e, (wall, roof, etc.), respectively, while $T_{\mathrm{o}}(t)$, $q_{\mathrm{o},n}(t)$ and h_{o} denote the corresponding quantities for the outdoor surface; $g_{\mathrm{e,s}}$ is the radiation heat-transfer factor between interior surface of envelope element e and any other indoor surface s of temperature $T_{\mathrm{s}}(t)$; and $f_{\mathrm{e}j}(x)$ stands for the initial temperature field at the

jth layer. The outdoor air temperature $T_o(t)$ includes the effect of solar radiation (sol–air temperature [1]).

Transient one-dimensional heat conduction and the corresponding boundary and initial conditions in any interior partition, floor or ceiling may be expressed by equations similar to Eqs. (2)–(5), i.e.

$$\rho_{pj}c_{pj}\partial T_{pj}(t,x)/\partial t = k_{pj}\partial^2 T_{pj}(t,x)/\partial x^2, \quad x_j \leq x \leq x_{j+1}, \quad t > 0, \quad j = 1,2,\ldots,J, \tag{6}$$

$$q_{p1}(t) = -k_{p1}\partial T_{p1}(t,x)/\partial x = h_p[T_{p1}(t,x) - T_i(t)] + \Sigma_s g_{p,s}[T_{p1}(t,x) - T_s(t)], x = x_1, \quad t > 0, \tag{7}$$

$$q_{pJ}(t) = -k_{pJ}\partial T_{pJ}(t,x)/\partial x = h_p[T_{pJ}(t,x) - T_i(t)] + \Sigma_s g_{p,s}[T_{pJ}(t,x) - T_s(t)], \ x = x_{J+1}, \quad t > 0, \tag{8}$$

$$T_{pj}(t,x) = f_{pj}(x), \quad x_j \leq x \leq x_{j+1}, \quad j = 1,2,\ldots,J, \quad t = 0 \tag{9}$$

where subscript p refers to interior partitions, floors or ceilings; J is the number of layers each partition is composed of; $T_{pj}(t,x)$ is the instantaneous temperature at any layer j at time t and depth x, measured from the left surface of the partition; ρ_{pj}, c_{pj} and k_{pj} denote the density, heat capacity and thermal conductivity of the jth layer, respectively; x_j and x_{j+1} are the coordinates of the jth layer surfaces; q_{p1} and q_{pJ} are the heat flows at the left ($j = 1$) and right ($j = J$) surfaces of any partition, respectively; h_p the convective heat-transfer coefficient which is supposed to be equal at both surfaces; $g_{p,s}$ denotes the radiation heat-transfer factor between partition surface p and any other indoor surface s of temperature $T_s(t)$; and $f_{pj}(x)$ stands for the initial temperature field at the jth layer of the partition.

The thermal mass effect of furnishings may be simulated in various ways. In the present study, furniture and equipment are represented by an equivalent wooden slab of thickness L_f and surface A_f with properties ρ_f, c_f, k_f. The transient one-dimensional heat conduction and the corresponding boundary and initial conditions in the above *equivalent furniture slab* are expressed by equations similar to Eqs. (6)–(9), i.e.

$$\rho_f c_f \partial T_f(t,x)/\partial t = k_f \partial^2 T_f(t,x)/\partial x^2, \quad t > 0, \tag{10}$$

$$q_{f1}(t) = -k_f \partial T_f(t,0)/\partial x = h_f[T_f(t,0) - T_i(t)] + \Sigma_s g_{f,s}[T_f(t,0) - T_s(t)], \quad t > 0, \tag{11}$$

$$q_{f2}(t) = -k_f \partial T_f(t,L_f)/\partial x = h_f[T_f(t,L_f) - T_i(t)] + \Sigma_s g_{f,s}[T_f(t,L_f) - T_s(t)], \quad t > 0, \tag{12}$$

$$T_f(t,x) = f_f(x), \quad t = 0 \tag{13}$$

where $T_f(t,x)$ is the instantaneous temperature at time t and depth x, measured from the left surface of the *equivalent furniture slab*; q_{f1}, q_{f2} and h_f are the heat flows at the left and right surfaces of the slab and the convective heat-transfer coefficient, which is supposed to be equal at both surfaces; $g_{f,s}$ stands for the radiation heat-transfer factor between surface f of the *equivalent furniture slab* and any other indoor surface s of temperature $T_s(t)$; and $f_f(x)$ stands for the initial temperature field of the slab.

The indoor thermal energy balance and the initial value $T_{i,b}$ for the indoor air temperature $T_i(t)$ are expressed by equations

$$\rho_a v_a c_a \partial T_i(t)/\partial t = \Sigma_n q_{i,n}(t)A_n + [q_{p1}(t) + q_{pJ}(t)]A_p + [q_{f1}(t) + q_{f2}(t)]A_f + Q_i(t), \ \ t > 0, \qquad (14)$$

$$T_i(t) = T_{i,b}, \quad t = 0 \qquad (15)$$

where ρ_a, v_a and c_a are the density, volume and heat capacity of the indoor air; the summation refers to the n elements (walls, roof, fenestration, etc.) of the building envelope with corresponding heat-transfer surfaces A_n (n = 1,2,...); A_p and A_f are the heat-transfer surfaces of the interior partitions and *equivalent furniture slab*, respectively; and Q_i is the total indoor load (heating or cooling, equipment, lighting, people, ventilation and infiltration, solar radiation transmitted through fenestration, etc.).

Solution of the set of differential Eqs. (2)–(15) is obtained by the finite-difference technique using a procedure described in a previous publication [4], with suitable modifications to account for the new particulars of the simulation. Briefly, the solution of the transient heat conduction problems for the building envelope [Eqs. (2)–(5)], the interior partitions [Eqs. (6)–(9)] and the furnishings [Eqs. (10)–(13)] is obtained by employing an implicit finite-difference procedure [11], using at each time step the known indoor air-temperature T_i of the previous time step. The envelope, partitions and furniture heat flows $q_{i,n}$, q_{p1}, q_{pJ} ,q_{f1} and q_{f2} resulting from Eqs. (4), (7), (8), (11) and (12), respectively, are used in the finite-difference form of Eq. (14) to calculate the indoor air-temperature T_i of the next time step, etc.

An example of the calculated indoor temperature T_i in terms of time is shown in Fig. 1 for a fully-insulated, single-storey, detached house of 100 m^2 floor area, with the following characteristics: wall and roof code numbers G1 and 1, respectively (Table 1); 15% fenestration area with overall heat-transfer coefficient 4 W/m^2 K; 1.5 length-to-width ratio of the house; length of the interior partitions (single brick with finishing layers on both sides) equal to half the length of the exterior walls; equivalent furniture slab with area equal to that of the interior partitions and thickness equal to 5 cm; convective heat-transfer coefficients $h_o = 16$ W/m^2 K and $h_i = h_p = h_f = 8$ W/m^2 K; $g_{e,s} = g_{p,s} = g_{f,s} = 0$, for simplicity; initial temperatures of the building envelope, partitions, furniture slab and indoor air $f_{ej}(x) = f_{pj}(x) = f_f(x) = T_{i,b} = 20°C$; indoor load $Q_i = 0$. Solar radiation was not taken into account (for simplicity) and the outdoor temperature variation was expressed by equation

$$T_o(t) = 10 + 7\cos[2\pi(t - 15)/24] \qquad (16)$$

where t is in hours and T_o is in °C.

The example of Fig. 1 shows the temperature variation $T_i(t)$ of the indoor air for the following four cases: (a) house with interior partitions and furnishings; (b) with partitions but without furnishings; (c) without partitions but with furnishings; and (d) without partitions and

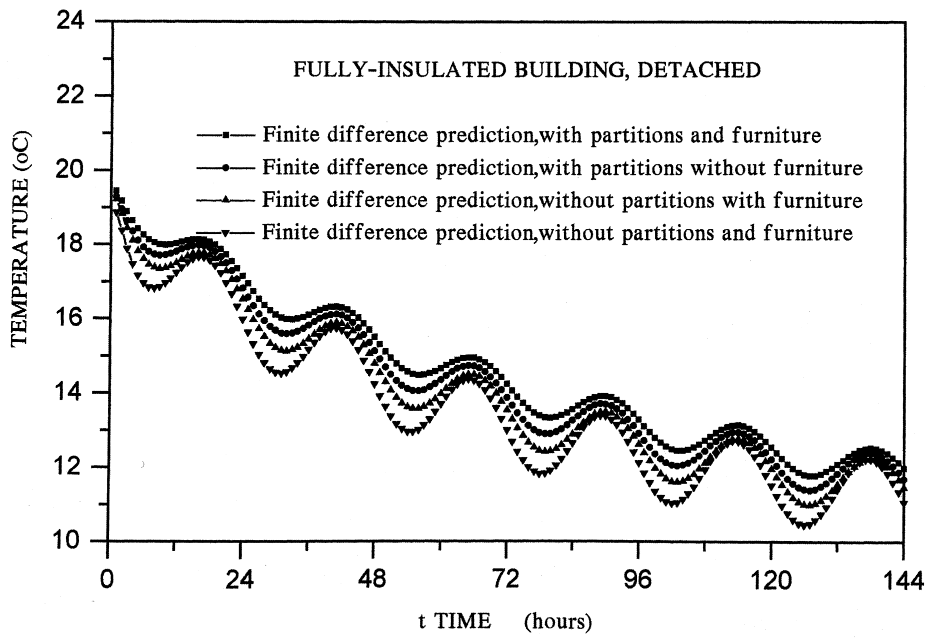

Fig. 1. Predicted indoor temperature variations T_i in terms of time for the house and the conditions described in the text.

furnishings (only building envelope). The quick drop of the indoor air-temperature is clearly shown as the indoor thermal mass is reduced. Also, clearly shown are the predicted indoor temperature oscillations, provoked by the oscillations of the outdoor temperature.

3. Calculation of envelope, partitions and furnishings thermal capacitance

The total thermal capacitance C_{tot} (in J/K) of a building of uniform or mean temperature $T_i(t)$ for a mean outdoor temperature $T_o < T_i$ may be defined as the heat stored within the building, per degree of temperature difference $T_i(t)$-T_o [10]. According to this definition, the energy stored in a building at times t and $t + \mathrm{d}t$ will be $C_{\text{tot}}(T_i$-$T_o)$ and $C_{\text{tot}}[(T_i-\mathrm{d}T_i)$-$T_o]$, respectively. Therefore, the heat transferred from the building to the outdoor environment is

$$C_{\text{tot}}(T_i - T_o) - C_{\text{tot}}[(T_i - \mathrm{d}T_i) - T_o] = -L(T_i - T_o)\mathrm{d}t + Q_i\mathrm{d}t \tag{17}$$

or

$$C_{\text{tot}}\mathrm{d}T_i(t)/\mathrm{d}t = Q_i - L[T_i(t) - T_o] \tag{18}$$

where L (in W/K) is the building heat-loss coefficient and Q_i the rate at which heat is offered to the building from various sources. Integration of Eq. (18) with initial condition $T_i(0) = T_{i,\text{b}}$ yields

Table 1
Code numbers of typical walls and roofs, and their layers [5]

Wall code no.	Code no. of layers	Roof code no.	Code no. of layers
G1	FL, B9,I 4, B9, FL	1	CG,WP, I6, C7, CR, FL
G2	FL, B9, B9, FL	2	CR, FL
G3	FL, B9, A6, B9, FL	3	CC, CP, CR, FL
G4	FL, B6, I5, B6, FL	4	RS, CL, CR, FL
G5	FL, B6, A6, B6, FL	5	CG, CP, CR, FL
G6	FL, B9, I4, B6, FL	6	WP, CP, CR, FL
G7	FL, B9, A6, B6, FL	7	RS, CL, WP, CP, CR, FL
G8	DB, A2, I5, B9, FL	8	RT, W, I8, CR, FL
G9	DB, A2, B9, FL	9	RT, A8, CR, FL
G13	FL, C19, I5, FL	10	CG, I6, CR, FL
G14	FL, C19, FL		
G15	FL, C25, I5, P		
G16	FL, C19, I5, B6, FL		
G17	FL, C19, B6, FL		
G18	FL, M, FL		

$$T_i(t) = T_o + (T_{i,b} - T_o - Q_i/L)\exp(-Lt/C_{tot}) + Q_i/L \tag{19}$$

and the total thermal capacitance C_{tot} is calculated by forcing the above equation to follow the finite-difference solution of the rigorous set of Eqs. (2)–(15). This is obtained by performing a least-squares fit of Eq. (19) to the indoor temperature variation resulting from the finite-difference solution. For example, Fig. 2 shows the predicted indoor temperature variation under the same conditions as in Fig. 1, but with constant outdoor temperature $T_o = 0°C$. The least-squares fit of Eq. (19) to the upper curve gives $C_{tot} = 60.7$ MJ/K.

The total thermal capacitance of a building without interior partitions and furnishings is reduced to the *envelope thermal capacitance* C_{env}. In this case Eq. (19) becomes

$$T_i(t) = T_o + (T_{i,b} - T_o - Q_i/L)\exp(-Lt/C_{env}) + Q_i/L \tag{20}$$

and a least-squares fit of the above equation to the $T_i(t)$ variation of Fig. 2 (lower curve) gives $C_{env} = 47.4$ MJ/K.

Similarly, the intermediate curve in Fig. 2 represents a least-squares fit of Eq. (19), written as

$$T_i(t) = T_o + (T_{i,b} - T_o - Q_i/L)\exp(-Lt/C_{env+par}) + Q_i/L \tag{21}$$

to the finite-difference solution in the case of the same building with interior partitions but without furnishings. The resulting envelope and partitions thermal capacitance is $C_{env+par} = 56.2$ MJ/K. In the case of the same building, without interior partitions but with furnishings, Eq. (19) is written as

$$T_i(t) = T_o + (T_{i,b} - T_o - Q_i/L)\exp(-Lt/C_{env+fur}) + Q_i/L \tag{22}$$

and a similar fitting gives the value of the envelope and furniture thermal capacitance $C_{env+fur} = 51.9$ MJ/K.

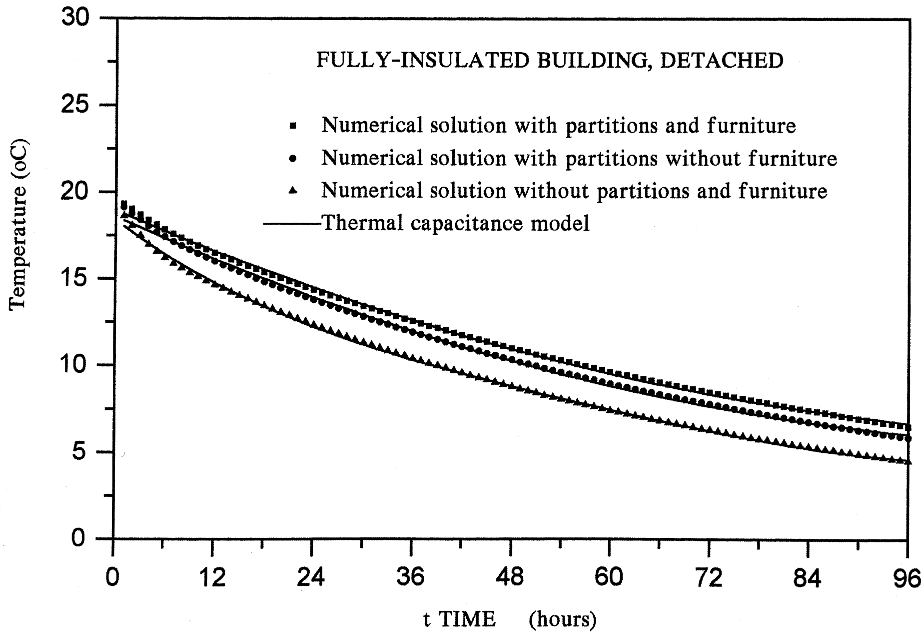

Fig. 2. Least-squares fits of Eqs. (19)–(21) to the predicted indoor temperature variations in terms of time for the house and the conditions mentioned in the text.

According to the above calculations the total thermal capacitance may be split into envelope and indoor components, i.e.

$$C_{\text{tot}} = C_{\text{env}} + C_{\text{ind}} = 47.4 + 13.3 = 60.7 \text{ MJ/K} \tag{23}$$

where the indoor thermal capacitance may be further split into the thermal capacitance of the partitions C_{par} and to the thermal capacitance of the furnishings C_{fur}, i.e.

$$C_{\text{ind}} = C_{\text{par}} + C_{\text{fur}} = 8.8 + 4.5 = 13.3 \text{ MJ/K}. \tag{24}$$

In the case of multi-storey buildings, where interior ceilings and floors are not included in the building envelope, the above equation may be written as

$$C_{\text{ind}} = C_{\text{par}} + C_{i,\text{ce}} + C_{i,\text{fl}} + C_{\text{fur}} \tag{25}$$

where $C_{i,\text{ce}}$ and $C_{i,\text{fl}}$ denote the thermal capacitance of indoor ceilings and floors, respectively.

Also, the developed procedure allows calculation of the contribution of any envelope element to the total thermal mass of a building. Thus, the envelope thermal capacitance C_{env} may be split into the thermal capacitances of the exterior walls, the floor and the ceiling (roof) of the building, $C_{\text{e,wa}}$, $C_{\text{e,fl}}$ and $C_{\text{e,ce}}$, respectively, i.e.

$$C_{\text{env}} = C_{\text{e,wa}} + C_{\text{e,fl}} + C_{\text{e,ce}}. \tag{26}$$

4. Heat capacities of various types of buildings

The various types of buildings and kinds of wall and roof compositions in Greece follow the classification presented in Ref. [5]. Briefly, the building types include detached, semi-detached and attached, one- and two-storey houses and apartment blocks, top- and non-top-floor apartments with two, three or four exterior walls, large indoor areas, corner or centrally-located offices or hospital rooms, etc. The usual wall and roof compositions are summarized in Table 1 and the code numbers of wall and roof layers are explained in Table 2. An example is given in Fig. 3, which shows the calculated effective thermal capacitances C_{env}, $C_{\mathrm{env+par}}$ and C_{tot} in terms of the floor area F for one-storey detached houses with wall and roof code numbers G1,1 and G1,2 (Table 1). The remaining characteristics of the houses are the same as in Fig. 1. It is seen that the thermal capacitance of the less insulated house (G1,2) is lower than the corresponding one for the fully-insulated house (G1,1), because insulation favours the conservation of thermal energy stored within the structure.

In the example of Fig. 4, the effective thermal capacitances C_{env}, $C_{\mathrm{env+par}}$ and C_{tot} for the same (G1,1)-house of Fig. 3 are compared with the corresponding apparent thermal capacitances $(C_a)_{\mathrm{env}}$, $(C_a)_{\mathrm{env+par}}$ and $(C_a)_{\mathrm{tot}}$, which were calculated according to Eq. (1). It is seen that in all cases the apparent thermal capacitances are higher than the corresponding effective ones, because the ability of structural elements and furnishings to store heat is higher when these are considered together forming a unified volume, than when they are distributed in the building thus exposing a large heat-loss surface.

Table 2
Description and thickness of typical wall and roof layers [5]

Code no. of layers	Description	Thickness (m)
A2, A6, A8	Air space	0.02, 0.06, 0.08
B6, B9	Brick	0.06, 0.09
C7, C19, C25	Concrete	0.07, 0.19, 0.25
CC	Cellular concrete	0.10
CG	Gravel concrete	0.07
CL	Lime–concrete mixture	0.02
CP	Pumic concrete	0.10
CR	Reinforced concrete	0.14
DB	Decorative brick	0.09
FL	Finishing layer	0.015-0.020
I4, I5, I6, I8	Insulation	0.04, 0.05, 0.06, 0.08
M	Masonry	0.60
P	Plasterboard	0.0125
RS	Roof slates	0.04
RT	Roofing clay tiles	0.04
W	Wood frame	0.04
WP	Waterproof layer	0.01

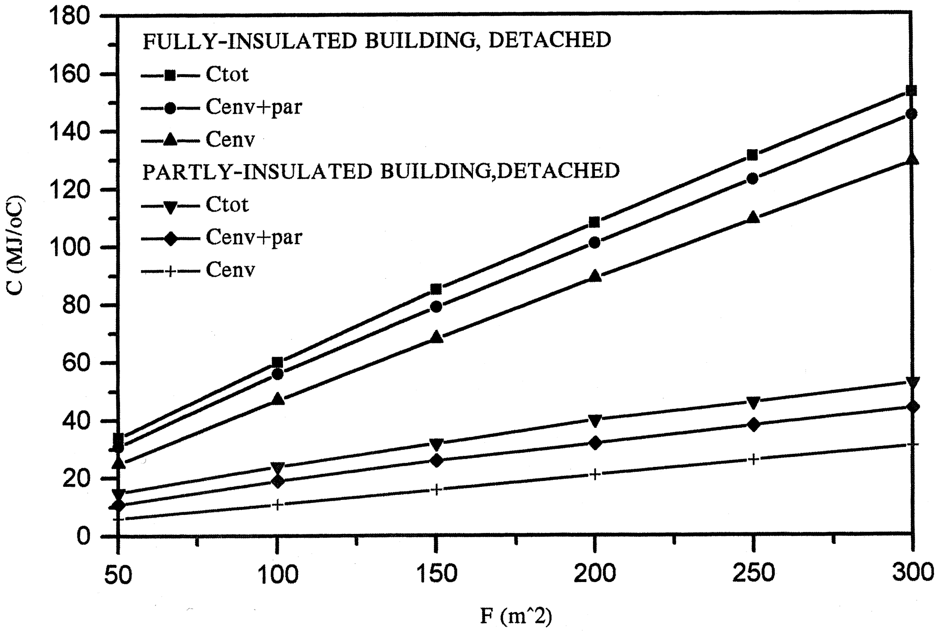

Fig. 3. Effective thermal capacitances C_{env}, $C_{env+par}$ and C_{tot} in terms of the floor area F for the fully-insulated (G1,1) and partly-insulated (G1,2) houses described in the text.

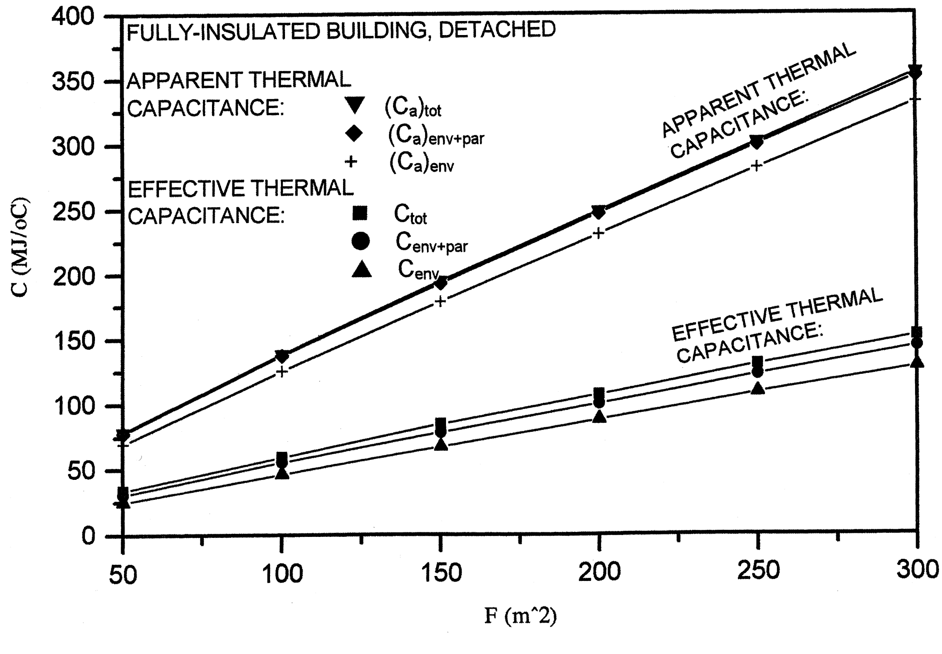

Fig. 4. Effective thermal capacitances C_{env}, $C_{env+par}$ and C_{tot} in terms of the floor area F for the fully-insulated (G1,1) house described in the text, compared with the corresponding apparent thermal capacitances.

5. A correlation between apparent and effective thermal capacitances

Figures 3 and 4 show that the thermal capacitances of buildings of the same type and envelope composition are practically linear functions of the building size, expressed by the total floor area F. This has been verified by making similar calculations for a wide variety of building types and envelope compositions, i.e.

$$(C_{\mathrm{a}})_n = a_n F + b_n, \tag{27}$$

$$(C_{\mathrm{eff}})_n = A_n F + B_n \tag{28}$$

where n refers to the total, envelope, indoor, partitions, furnishings, etc. thermal capacitance. Elimination of F from the above equations gives

$$(C_{\mathrm{eff}})_n = (A_n/a_n)(C_{\mathrm{a}})_n + (B_n - b_n A_n/a_n) = s_n(C_{\mathrm{a}})_n + r_n \tag{29}$$

where coefficients s_n and r_n have been calculated for various types of buildings and envelope compositions. For example, for single-storey detached houses with wall and roof code numbers G1 and 1, respectively, and remaining characteristics the same as those of Fig. 1, the calculated coefficients for n = tot, env + par, env are s_n = 0.4326, 0.4152, 0.3971 and r_n = 0.1574, –1.3438, –2.9406 MJ/K, respectively. The linear relationship of C_{eff} and C_{a}, according to Eq. (29), is

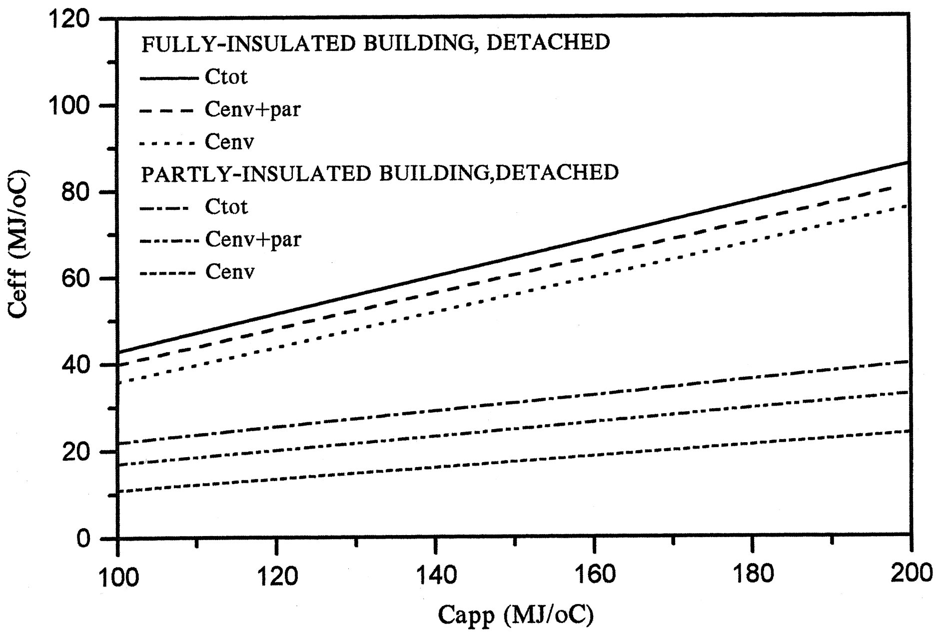

Fig. 5. Effective thermal capacitances C_{tot}, $C_{\mathrm{env+par}}$ and C_{env} in terms of the corresponding apparent thermal capacitances, according to correlation expressed by Eq. (29), for fully-insulated and partly-insulated houses described in the text.

illustrated in Fig. 5 for houses of the same type as above with envelope compositions (G1,1) and (G1,2), i.e. fully-insulated and partly-insulated ones, respectively (Table 1).

The correlation expressed by Eq. (29) is useful in practice because it provides the effective thermal capacitance C_{eff} in terms of the apparent capacitance C_{a}, which can be easily calculated from Eq. (1).

6. Conclusion

In previous studies [9, 10] it was proven that the *effective thermal capacitance model* provides a simple and quick way for studying the transient thermal behaviour of buildings with satisfactory accuracy for a wide range of applications. In the present study, the procedure for calculating the effective thermal capacitance of buildings is extended so that the effective components of the total thermal capacitance, $(C_{\text{eff}})_{\text{tot}}$, may be calculated. These components refer to the envelope, interior partitions and furnishings of a building $(C_{\text{eff}})_{\text{env}}$, $(C_{\text{eff}})_{\text{par}}$ and $(C_{\text{eff}})_{\text{fur}}$, respectively. For example, for the typical 100 m^2 fully-insulated, single-storey, detached house (wall and roof code nubmers G1,1, Table 1) the values of C_{tot}, C_{env}, C_{par} and C_{fur} (subscript eff is omitted for simplicity) are 60.7, 47.4, 8.8 and 4.5 MJ/K, respectively, and the corresponding percentages are 100%, 78.1%, 14.5% and 7.4%. For the partly-insulated house (G1,2, Table 1) with the same characteristics, the corresponding values are 24.3, 11.6, 7.8, 4.9 MJ/K and 100%, 47.7%, 32.1%, 20.2%.

The method developed takes into account heating of cooling systems through term Q_i. Also, the method allows further analysis of components, i.e. calculation of the thermal capacitance of the ceiling, the floor or other parts of the building envelope or interior structures. Therefore, in principle, it might be used to calculate the contribution of people to the thermal mass of the building if their special features [1] were introduced in the model (i.e. human geometry and movement, metabolic rate, convection and radiation heat transfer coefficients, etc.).

Of practical importance is the correlation developed for the calculation of the effective, $(C_{\text{eff}})_n$, in terms of the easily-calculated apparent thermal capacitance $(C_{\text{a}})_n$, where subscript n denotes the various components, i.e. envelope (n = env), interior partitions (n = par), furnishings (n = fur), etc.

The present analysis was applied to 21 types of buildings with 15 and 10 wall and roof compositions, respectively (Tables 1 and 2), i.e. $21 \times 15 \times 10 = 3150$ building cases were examined with floor areas ranging from 50 to 2500 m^2.

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