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Energy and Buildings 29 (1999) 129–133

ENERGY
AND
BUILDINGS

Incorporation of thermal inertia in the aim of installing a natural nighttime ventilation system in buildings

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Received 28 May 1998; accepted 13 July 1998

Abstract

The objective of this study is to propose a simplified characterization of thermal inertia, as part of the installation of a system of summer refreshment by means of nighttime cooling ventilation. On the basis of a previous study, conducted by relying upon a modal analysis, the interactions between the thermal inertia of a building and the variation of the air exchange rate have been explained. It can then be shown that the notion of useful thermal mass has herein been altered in order to take the thermal inertia of the building into account; it would then be suitable to substitute this notion for an approximated calculation of the building's main time constant. Moreover, the necessity of adding a parameter that characterizes the rapid dynamics of a particular zone's air temperature can be justified. Lastly, a characterization of the thermal inertia based upon the three-criteria calculation is proposed. An approximated value of the time constant both during the period of nighttime cooling and beyond this period, as well as an approximated value of the height of the line associated with the rapid dynamics, can be computed. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Time constant; Nighttime cooling ventilation; Pilot study; Rapid dynamics; Summer refreshment; Thermal inertia; Approximated criteria

1. Introduction

Incorporating thermal inertia during the design of a building remains a delicate issue. In fact, thermal inertia is not a directly accessible phenomenon; its consequences can only be observed when isolated. Its effects can vary significantly depending upon both the nature of the outdoor thermal cycles to which the system is being submitted and the position of the selected response observation [1,2].

However, at the beginning of a project, the designer must apply a set of simplified criteria so as to guide the overall building design. The useful thermal mass or an approximated value of the main time constant is generally employed in order to anticipate the effects of thermal inertia. However, these global criteria do not take the nature of the thermal cycles into account and often appear as being insufficient [3].

In previous research work [4,5], we have proposed a simplified characterization of the thermal inertia of a one-zone building, which could be used in the pilot project and which does take the nature of the thermal cycles into account. The aim of this paper then is to apply this previous body of work to the natural nighttime cooling ventilation of buildings. Such a technique can be used as an alternative to air conditioning in order to alleviate problems associated with summer overheating, whose intensity and frequency increase as the insulation of new buildings reaches higher levels.

In Section 2, we will recall the basic principles of the technique of refreshment by means of nighttime ventilation. Afterwards, in Section 3, we will analyze the influence of the air exchange rate on the zone's temperature dynamics, in an effort to derive key information on installing this kind of technique inside a building. Lastly, in the paper's final section, a simplified characterization of thermal inertia, applicable to a pilot study, will be proposed.

2. Providing summer refreshment by means of nighttime cooling ventilation

Alleviating the effects of acute summertime heat can be obtained from different processes: cold floors or ceilings [6], indirect or direct evaporation [7,8], or natural nighttime

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PII: S0378-7788(98)00057-7

ventilation [9,10]. This last process consists of increasing the air exchange rate during the unoccupied nighttime period in order to dissipate the heat accumulated inside the building mass during the day. Blondeau et al. [9] have shown that some sites are more favorable to the installation of a nighttime cooling ventilation system. A higher value of the differential between average daytime and nighttime temperatures does serve to demonstrate the efficiency gained from this technique. These same authors have also proven that nighttime ventilation yields its best results when the building is equipped with rather advanced solar protection devices. An experiment conducted by Sperandio et al. [10] has revealed that distributing fresh air inside a building enhances the system's overall efficiency; this technique therefore proves more efficient for smaller building volumes.

In order to avoid any discomfort at the beginning of the occupied period, such a technique requires the use of scenarios adapted to current regulations. Moreover, the presence of air conditioning as a complement to this system is, in general, not desirable in that air conditioning acts to modify the building's previous thermal behavior, thereby eliminating any of the potential beneficial impacts generated from the nighttime ventilation. It is quite obvious that the potential gains from nighttime cooling ventilation are closely tied to the building's thermal inertia, yet we often ignore that the increased air exchange rate actually modifies the initial thermal system's characteristics and thus its thermal inertia. In the following section, we will analyze the significant influence exerted by the air exchange rate on the building's dynamic behavior.

3. The thermal inertia and the air exchange rate

3.1. Characterization of a building's thermal inertia

The thermal behavior of a system in its dynamic state is fully defined by the set of eigenvalues and their corresponding eigenfunctions, which represent the intrinsic characteristics. In addition, these values and functions have made it possible to obtain the initial definition of the thermal inertia [11]. Eigenvalues serve to establish the time scale of all dynamic phenomena to which the thermal system is being submitted. The shape and amplitude of the eigenfunctions then allow analyzing the action of each mode on the system's various components.

Natural modes, which are infinite in number, can be summarily categorized into rapid modes and slow modes. Some of these are indeed dominant while others are weak. In fact, some modes on their own suffice in correctly reconstituting the dynamic state. The slow dynamics is usually dominated by several modes of large time constants; the first of these generally exerts the greatest influence. This initial mode serves to translate the magnitude of the coupling, by the air, of those walls delimiting the zone. A study of natural modes also shows that a dominant rapid mode associated with the time constant, τ_r, always exists around which we will be able to combine the rapid dynamics (see Fig. 2). This mode proves to be even more rapid as the air/walls coupling becomes stronger.

In a previous study [4], we have modeled, by means of analysis, the dynamic behavior of a one-zone building. The resolution of the associated system of differential equations enables distinguishing two categories of eigenvalues.

(1) The 'local' eigenvalues, solutions to subsystems of differential equations associated with the various walls of the building which will be denoted $\lambda^{(n)}$; these natural modes of walls can be observed in the presence of excitations of different sorts as a result of external stresses. In other cases, these exert no influence whatsoever on the behavior in the system's variable state.

(2) The 'global' eigenvalues, which translate the coupling of the various walls through air exchange, are solutions to the complete system of coupled differential equations. It's in fact these eigenvalues which will serve to influence the system's dynamics. Denoted $\mu^{(n)}$, these

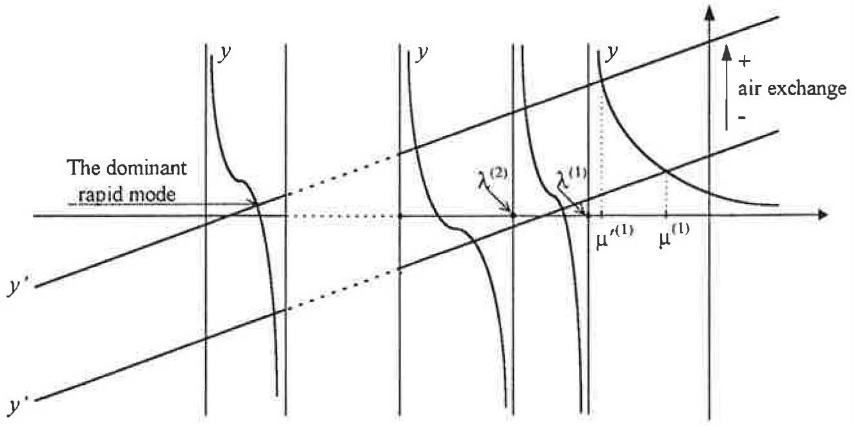

Fig. 1. Influence of the air exchange rate on the natural modes.

global eigenvalues are solutions to an equation of the following form:

$$\pounds_1 \cdot \mu^{(n)} + \pounds_2 = \sum_{k=1}^{\hat{N}} \frac{H_k}{\det[\mathrm{Dp}_k]} \qquad (1)$$

where: $\pounds_1 = \mathrm{Ca} \cdot V$ is the calorific capacity of the internal air volume, $\pounds_2 = \mathrm{Ca} \cdot \mathrm{Qr} + \sum_{k=1}^{N} Hi_k \cdot A_k$ depends upon both the air exchange rate and a term that translates the coupling between the air volume and the walls, H_k characterizes the coupling between the wall (k) and the other components of the building, and $\det[\mathrm{Dp}_k] = 0$ is the equation for determining the eigenvalues of the 'local' system that characterizes the wall (k).

We will show in the following section that formalizing the notion of a useful thermal mass in order to characterize only the low dynamics has, in this context, been maladapted for incorporating the thermal inertia of a building in the case of installing a nighttime cooling ventilation system.

3.2. Impact of the air exchange rate on the eigenvalues

In order to highlight the action of air exchange on the thermal inertia, we will use the graphic representation displayed in Fig. 1, extracted from Neirac [2], which enables determining the global natural modes $\mu^{(n)}$, by means of intersecting the two curves y and y' which have been defined as follows (see Section 3.1):

$$y' = \pounds_1 \mu^{(n)} + \pounds_2 \qquad (2)$$

$$y = \sum_{k=1}^{N} \frac{H_k}{\det[\mathrm{Dp}_k]}. \qquad (3)$$

In this figure, vertical rights represent the local eigenvalues of the various walls. It can be observed that as the air exchange rate increases, the line y' is displaced upwards and all natural times decrease. Their limits tend towards the local natural time of one of the system's walls; in particular, the initial global time constant tends to the largest of the walls' time constants.

As an example, Table 1 presents the first twelve time constants of a cell for air exchange rates of 1, 5 and 10 volumes per hour. The cell has a volume of 300 m^3 and is insulated on the inside by 2 cm of insulator. The external wall's surface area is 120 m^2, and the cell is composed of both a low flooring on fill material and 60 m^2 of internal, 8-cm thick concrete walls.

For higher air exchange rates, the low dynamics will in fact be distinguished by a 'disorderly' time evolution in the walls. The air then does not ensure its role of coupling between walls which will therefore become thermally dissociated. The notion of useful thermal mass, which implicitly assumes a good air/walls coupling, appears in this case to be poorly adapted for translating the modifications in the thermal inertia as a function of the air exchange rate. Van der Mass and Roulet [12] and Van der Mass et al. [13] have already noticed this phenomenon from experimental tests conducted on one of the Leso buildings in Lausanne, Switzerland.

Table 1
Evolution of the time constants (hours) as a function of the air exchange rates

Mode number	Air exchange rate (volume per hour)		
	1	5	10
1	53.61	32.85	25.01
2	6.38	6.36	6.35
3	0.801	0.783	0.769
4	0.562	0.562	0.562
5	0.206	0.204	0.202
6	0.168	0.167	0.167
7	0.092	0.091	0.091
8	0.077	0.077	0.077
9	0.054	0.052	0.051
10	$\tau_r = 0.046$	0.044	0.044
11	0.044	$\tau_r = 0.040$	$\tau_r = 0.035$
12	0.032	0.032	0.031
approached τ_1	49.87	24.68	15.13

An approximated calculation of the time constant of the dominant slow mode, which integrates the variations in the air exchange rate as proposed in Section 4, allows incorporating this phenomenon to the greatest extent possible. On the last line of Table 1, we have undertaken this approximated calculation as a function of the air exchange rate:

In Fig. 1, the presence of a rapid dynamics τ_r specific to the building itself which cannot be related to a mode wall is also to be noted. This mode τ_r is related, in essence, to the air exchange rate and will become even more rapid as the ventilation flow increases. Expression (4) yields an approximated value of this constant. During the period of nighttime over-ventilation, this mode does indeed play an important role, as we will see in the following section:

$$\tau_r = \frac{\mathrm{Ca} \cdot V}{\mathrm{Ca} \cdot \mathrm{Qr} + \mathrm{Kg} \cdot \mathrm{Ag} + \sum_{k=1}^{N} Hi_k A_k} \qquad (4)$$

with: Ca the calorific capacity of air [Wh/m^3°C], Qr the air exchange rate [m^3/h], Kg the heat transmission coefficient of glazing [W/m^2°C], Ag the surface of the glazing [m^2], Hi_k the superficial exchange coefficient of the wall (k) [W/m^2°C], A_k the surface of the wall (k) [m^2], V the internal air volume of the cell [m^3].

The thermal resistance of the interior insulation is then integrated into the coefficient Hi_k.

3.3. Influence of the air exchange rate on a zone's temperature response

During the installation of a nighttime cooling ventilation system, it is critical to understand the air temperature response of a zone under the action of the outdoor temperature effects. In this respect, Fig. 2 presents the spectra of a zone's air temperature response for different air exchange rates. It can be noted that the magnitude of the first mode becomes less distinct as the air exchange rate increases, due to the effect of the poorer coupling between walls. In contrast, the dominant rapid mode τ_r exhibits a more significant influence on the zone's air temperature response. For a rate of one volume per hour, the rapid response accounts for 4% of the rise to the steady state; on the other hand, this increases to 35% for a rate of 10 volumes per hour.

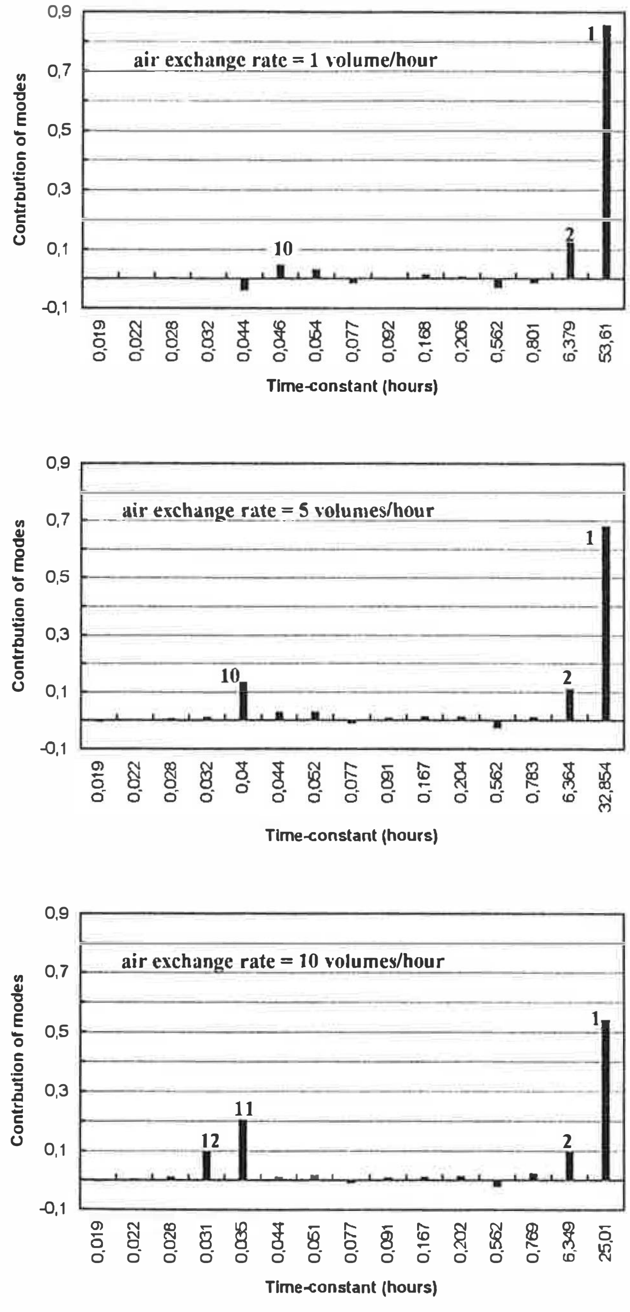

Fig. 2. Response spectra of the indoor air temperature of a cell, with interior insulation, as a function of the air exchange rate.

During the period of nighttime ventilation, the rapid dynamics represent a sizable portion of a zone's air temperature response, thereby proving the necessity of including to the characterization of the thermal inertia a parameter that takes into account the rapid response of a zone's temperature during the period of nighttime ventilation.

4. Simplified criteria for taking the thermal inertia into account

According to the conclusions drawn in the previous section, we now propose characterizing the thermal inertia by means of the three following parameters:

τ: approximated value of the time constant that characterizes the low dynamics during the occupied period of no ventilation;

τ_s: approximated value of the time constant that characterizes the low dynamics during the unoccupied period of nighttime ventilation; and

r: the proportion borne by the rapid dynamics of the zone's air temperature response during the unoccupied period of nighttime ventilation.

4.1. Calculation of the approximated time constants

This calculation can be carried out by applying a property of temperature fields, as demonstrated by Sicart [11]. When a temperature field exhibits the form of a natural mode, the ratio of the energy contained in the system to the outgoing flow is equal to the time constant associated with this mode. This property allows performing an approximated calculation of the time constant of the dominant mode which displays a form that's close to the one of the steady state associated with the convective power stresses from heating. The methodology behind this calculation has been detailed in Refs. [1,4]. It can be pointed out in Table 1 that the approximated calculation differs from the value of the initial time constant to a greater extent as the air exchange rate increases, which is in fact logical because several slow modes do dominate the dynamics.

4.2. Calculation of the parameter r

An approximate value of the indicator r can be taken as the height of the line (i.e. the contribution of the natural mode), associated with the rapid dynamics, of the spectrum of a zone's air temperature response to an outdoor temperature-related stress [14]. This criterion r can indeed be calculated by noting that the portion accounted for by the rapid dynamics in a zone's air temperature response can be approximated by the ratio of the heat flow introduced into the air to the flow being exchanged with the walls at the outdoor air temperature:

$$r = \frac{\mathrm{Ca} \cdot \mathrm{Qr}}{\mathrm{Ca} \cdot \mathrm{Qr} + \mathrm{Kg} \cdot \mathrm{Ag} + \sum_{k=1} Hi_k \cdot A_k} \qquad (5)$$

For the example cited in Section 3.2, $\tau = 49.9$ h, $\tau_s = 15.1$ h, and $r = 0.365$.

5. Conclusion

In this paper, we have demonstrated that the notion of a useful thermal mass is insufficient as a means of incorporating the thermal inertia, within the scope of a pilot study focusing on the case with a nighttime cooling ventilation system. It would be most appropriate to substitute the calculated approximated value of the dominant time constant for the low dynamics. While remaining rather simple, such an approach does nonetheless present the advantage of integrating the thermal system's dynamic characteristic variations during the variation of the air exchange rate.

Moreover, it is vital to include a parameter that serves to characterize the rapid dynamics during the period of nighttime ventilation, a step which can be performed simply by means of evaluating the height of the line associated with the dominant rapid mode. Lastly, in order to be truly effective, this method should be linked to the site's reported weather conditions as well as to the solar protection rate.

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