PERIODIC HEAT FLOW THOUGH VENTILATED WALLS: THE INFLUENCE OF AIR-SPACE POSITION UPON ROOM TEMPERATURE

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Abstract. The thermal behaviour of a room equipped with different types of ventilated walls and subject to external temperature oscillations is analyzed. The results obtained confirm that the types of ventilated walls, found in a previous study to be preferable from the energy point of view under steady-state conditions, exhibit acceptable behaviour also when such temperature oscillations are present.

1. Introduction.

Ventilated walls have been recently attracting a good deal of research attention because their potential applications to climate control affect both the energy saving and comfort of buildings. In another paper presented at this Congress (1), the Authors reported the results of a study on the energy behavior of a room equipped with four different types of ventilated walls of equal thermal resistance with three different ventilation schemes.

More precisely, the walls denominated as types 1 and 3 had a layer of insulating material between the air space and the outer face, while in walls 2 and 4 the same layer was positioned between the air space and the external wall face. Moreover, in walls 1 and 2 the thicker brick layer (therefore of higher thermal capacity) is included in the outer face, while in types 3 and 4 it is in the inner one. Regarding the ventilation schemes of the interspace-to-room system, in case A, all the airflow into the interspace, of thermal capacity c (i.e. the product of the air mass flow by its specific heat), is collected from the outside and is used to turnover the air in the room; in case B the turnover air, is introduced directly in the room, has thermal flow defined as g, and is later used to ventilate the wall at the moment of ejection; in the limit case Y, wall ventilation is effected using a large airflow that is independent of room-air turnover (c>>g); finally, also the reference case R of a non-ventilated wall (though with the same thermal resistance) is considered.

The energy analysis developed in (1) has suggested a good compromise to be the choice of wall 2, with ventilation A during winter and B during summer. This report deals with ventilated-walls under conditions of periodic heat flow by analyzing the same structures with varying external temperature, solar radiation and air-conditioning system power. Indeed, under non-steady-state conditions, the arrangement of air spaces in ventilated walls is determined, not only by the ratio z between the air-space-to-outside thermal resistance and overall wall thermal resistance, but also by the distribution of thermal capacities within the wall (2,3). Furthermore, ultimate solution of the problem will depend on the thermal characteristics of structures within the room. Regarding the analysis, the operations followed to derive the main relations used are outlined in the appendix (2).

2. Statement and solution of the problem

In the case in which thermal stress is a periodic function of time, with angular frequency ω and period $\chi=\omega/2\pi$, it is also necessary to consider the room's internal structure (vertical and horizontal partitions), as it has a considerable influence. Complex thermal variations T_i of the room can arise from temperature oscillations of the external air in the shade T_0, oscillations of the radiation component (T_e-T_0) of the sol-air external temperature, or from oscillations of the power Q_s of the air-conditioning system (i.e. "equivalent temperature" Q_sR_t). We can thus write (2):

(1) $$T_i = L_1T_0 + L_2\left(T_e - T_0\right) + L_3Q_SR_t$$

which can yield the frequency spectrum of the room's thermal response. Eq.(1) is a linear function completely characterized by the three parameters L_1, L_2, L_3 which are dimensionless, complex quantities with modulus of one or less. Then, the actual trend of the inside temperature versus time can be obtained by calculating the Fourier antitransform of Eq.(1).

$$T_i(\tau) = \frac{1}{2\pi}\sum_{j=-m}^{m} T_i(\omega_j)\cdot e^{i\omega_j\tau}$$

with m indicating the maximum number of harmonic functions present in the expansions of T_0, T_e and Q_s. For some harmonic components, the coefficients L_i (i=1,2,3) depend on the chosen ventilation scheme, as well as the elements of the transfer matrices of the two faces of the ventilated wall and those of the elements transfer matrices relative to the structural components (vertical and horizontal partitions) which make up the room interior. Regarding the ventilation schemes R, A, B and Y; an expression for these coefficients is presented in the appendix.

On the basis of Eq. (1), it seems that situations where coefficients L_1 and L_2 are small in modulus are preferable; in this way room temperature is less influenced by sudden climatic changes (variations in T_o and/or T_e-T_0). On the other hand, large values of L_3 seem preferable, in order to be able to "correct" room temperature variations with limited use of the climate-control system. Eq.(1) is a generalization Eq.(1) from (1), to which it reduces under stationary conditions ($\omega\rightarrow0$); under such conditions, only temperature differences must be present in Eq.(1), and so it must hold that L_1=1. In the particular case in which a constant temperature is imposed within the room (T_i=0), Eq.(1) takes the form:

$$Q_sR_t = -\frac{L_1}{L_3}T_0 - \frac{L_2}{L_3}(T_e - T_0),$$

which quite similar to Eq.(1) of (1), and depends only on ratios (L_1/L_3) and (L_2/L_3). Even more particularly, for a passive room (Q_s=0), (3), without no air turnover (g=0), and a non-ventilated wall, we can write: L_1=L_2 (see Appendix); then, from Eq.(1), we can deduce: T_i= L_2T_e.

3. Numerical results.

As a sample application, we have considered a reference room of 3x4x4m, with a single external wall of 3x4m^2, and volume of 48m^3. The ventilated external wall is the same that is considered in (1), the inner structures are made up of a partition of light 0.08 cm brick with plaster on both faces and by tile-lintel floors 0.20m thick; the air in room has been represented by a pure thermal capacity M (per surface unit of external wall) assumed to be M=8.4 kJ/m^{2}K. The geometric and thermo-physical characteristics of the materials have been reported in Table I of (1). Regarding the thermal conductivity and diffusivity of the tile-lintel floor, we have assumed values of 0.80W/mK and 3.6 10^{-6} m^2/s, respectively.

In contrast to the steady-state case, under oscillatory conditions, the reference case depends on wall type; so we actually should utilize four different reference cases, one for each wall type.

However, since wall types 1 and 2 and types 3 and 4 differ only in that the position of the insulating layer and interspace have been switched, and since these two layers are essentially resistive, with a very good approximation we can state: 1R≅2R and 3R≅4R. More substantial differences exist between the first two types of walls (1, 2), as well as between types (3, 4), which differ in the placement of the 0.25m brick layer and the 0.08m light brick.
Figure 1 shows the curve of $|L_1|$ versus the period χ (in hours) for all examined cases, for an air-turnover rate of n=0.5. The values of $|L_1|$ for the reference case (R) and case B, for examined values of χ, depend very little on wall type and are very close to each other. Thus, the graph presents cases R and B by a single curve (bold). From figure 1, it can be seen that the values relative to case 2A (considered optimal for energy saving) result clearly lower than those of the reference case: thus insuring better control of room temperature in response to outside in-shade temperature variations during winter. From this point of view, during summer ventilation pattern B offers no great advantage with respect to the reference case; it is evident that case 2Y yields values smaller $|L_1|$ than case R only during short periods (χ<7.4 h).
Figure 2 plots $|L_2|$ as a function of χ, with n=0.5, for the various cases examined: it should be recalled that in case Y the L_2 value is always zero and the internal environment is completely dissociated from the effects of insolation. Now, consider the differences between the values of $|L_2|$ for ventilation scheme A and those for the corresponding reference cases: these are always positive and generally increase with rising χ. Instead, the $|L_2|$ for ventilation pattern B are all inferior to those of the corresponding reference cases. Here again, the difference between case B and corresponding reference case increases, albeit slightly, as a direct function of χ.
With regard to variations in the intensity of solar radiation, we can confirm that during summer (ventilation pattern B), only a small improvement is achieved with respect to the reference case, while a clear worsening, still relative to the reference, is evident during the winter (ventilation pattern A) but however, this produces limited effects, because of the poor insolation characterizing this season. As the air turnover rate increases, the trends of the curves representative of the various cases, do not change qualitatively. At constant χ, the values of $|L_1|$ and $|L_2|$ for any given wall and ventilation type increase as a function of n. As the air turnover rate increases, so does the influence on the interior thermal behavior of both the in-shade temperature and insolation. $|L_3|$ is relatively independent of wall type and adopted ventilation system, but depend considerably on the air turnover. Figure 3, presents $|L_3|$ as a function of χ, with n=0.5 and n=2, practically equivalent in all the cases considered here (case 1Y presents higher values, but is of limited importance here). As the air turnover rate increases, the value of $|L_3|$ decreases. The higher n is, the less sensitive is the room's thermal state to the action of the conditioning system; the difference between the L_3 values for n=0.5 and n=2 increases, though only slightly, as a function of χ.
Figures 4 and 5 plot the phase trend (in degrees) respectively for factor L_1 and L_2 as a function of period χ (in hours) relative to wall type 2, with n=0.5. Regarding figure 4, it is evident that the phase trend of L_1, in relation to configurations A and Y remains inferior to those of the reference case R, while the phase for configuration B practically coincides with that of case R.
The L_2 phase trend (Fig.5) is quite different (configuration Y has been excluded, because L_2=0): here the discontinuity in the curves is only apparent because of the effects of periodicity. The L_2 phase of configuration A results greater than that of the reference case, and the difference between the two phases, although particularly notable due to the high-order harmonics, remains

sensitive to the fundamental harmonic case (χ=24 hours). For example, for the case of χ=24 hours and in the reference case, there is a time delay of about 8 hours, while for configuration A this delay is about 10 hours. Such behavior must be considered positive, because it tends to shift the temperature peaks caused by variations in insolation towards the nighttime, when comfort requirements are minor.

Finally, it is note-worthy that, for coefficient L_2, as well, the phase relative to configuration B is very close to the reference case. The curves plotted in the previous figures do not change qualitatively with increases in the air turnover what can be seen is that phases L_1 and L_2 increase appreciably with increasing n, for any given χ and configuration. The greater is the air turnover, the greater also is the time needed for variations in the in-shade air temperature and insolation to make themselves felt within the room. The L_3 phase does not depend very much on ventilation pattern and practically coincides with phase L_1 relative to the reference case. Phase L_4 increases with increasing "n", reducing the promptness the conditoning system's effects.

4. Conclusion.

The linear structure of the problem is such that, for any given configuration, room thermal variations turn out to be linear combinations, suitably weighted by complex coefficients, of the external air temperature in the shade (coefficient L_1), the insolation (coefficient L_2) and the power of the conditioning system (coefficient L_3), see relation Eq (1). For control of the interior temperature, situations are desirable in which coefficients L_1 and L_2 are "small" in modulus, but with a "considerable" phase in order to limit and delay the influence of climatic changes on the interior (temperature of external air in the shade and insolation effects). On the other hand, coefficient L_3 should be "high" in modulus, but "small" in phase, in order to render the action of the conditioning system more effective and prompt. The analysis performed reveals the frequency spectrum of the moduli and phases of the above-mentioned coefficients regarding the four types of walls considered and the more suitable ventilation schemes for summer and winter. In particular, regarding wall type 2, considered optimal with respect to energy saving (1), we have observed the following: that coefficient L_4 is practically the same as that of the reference case when considering the summer and ventilation pattern B; that for ventilation pattern Y, the values of $|L_1|$ are lower than the reference case when considering solely oscillation of short period, while the its phase turns out not much inferior to the reference case; that in winter with (ventilation pattern A), wall type 2 is preferable to the reference case with respect to both $|L_1|$ and phase L_2; that coefficient L_3 is quite independent of wall type and ventilation scheme for all the cases examined.

Thus, we can conclude that wall type 2, aside from being optimal with respect to energy consumption, also demonstrates behavior, which though not satisfying all requirements for modulus and coefficient L_i phase, is overall quite acceptable for the various examined ventilation patterns under periodic heat flow.

Appendix.

We would like provide a brief outline of the calculation of coefficients L_i (i = 1,2,3), defined implicitly in Eq.(1). Through this appendix all quantities are relative to one unit of external wall surface. Let the 2x2 matrices with elements E_1, F_1, G_1, H_1 and E_2, F_2, G_2, H_2 be the transfer matrix belonging respectively to the external and internal wall faces. Each of these matrices will be calculated as the ordinate product of the transfer matrix of the single-layers making up the face in question. The first and last of these layers will be considered a purely resistive type representing the thermal boundary resistance (2,4). In the following we use the definitions:

$$N=E_2F_1+F_2H_1, \qquad \sigma=N(cF_1F_2)^{-1}, \qquad \eta=(1-e^{-\sigma})/\sigma.$$

The internal part of the room is formed by P structural elements (vertical and horizontal partitions). In many cases, the a given inner wall of area Sn is symmetrical and separates spaces having the same temperature. In these cases, the surface passing through the middle of the wall can be considered to be adiabatic; thus only the half-wall facing the room results important for the thermal problem of room itself. So, if we define as g_n and h_n the third and the fourth elements of the transfer matrix relative to the n^{th} inner half-wall, and we represent the air and objects in room as a purely thermal capacity M, the influence of the room's internal structure is explained by elements of type (2,4):

$$\Lambda_0 = j\omega M + \sum \frac{g_n}{h_n} v_n$$

where the summation must be extended to all internal p structures and v_n represents the ratio between the surfaces of the n^{th} structure and the external wall. Regarding the ventilation patterns examined in the work (R, Λ, B,Y), let us consider the following relations (2):

R: $$\Lambda = g + \frac{1}{F_2}\left(H_2 - \frac{F_1}{N}\right) + \Lambda_0 , \qquad L_1 = \frac{1}{\Lambda}\left(g + \frac{1}{N}\right) \; ; \; L_2 = \frac{1}{\Lambda N} \; ; \; L_3 = \frac{1}{\Lambda R_t}$$

A: $$\Lambda = g + \frac{1}{F_2}\left[H_2 + \frac{F_1}{N}(\eta - 1) - \eta\right] + \Lambda_0$$

$$L_1 = \frac{1}{\Lambda}\left[g + \frac{\eta(F_1 + F_2 - N)}{F_1 F_2} + \frac{1-\eta}{N}\right] \qquad L_2 = \frac{1}{\Lambda}\left[\frac{\eta}{F_1} + \frac{1-\eta}{N}\right] \qquad L_3 = \frac{1}{\Lambda R_t}$$

B: $$\Lambda = g + \frac{1}{F_2}\left[H_2 + \frac{F_1}{N}(\eta - 1) - \eta\right] + \Lambda_0 , \quad L_1 = \frac{1}{\Lambda}\left(g + \frac{1-\eta}{N}\right), \quad L_2 = \frac{1-\eta}{\Lambda N}, \quad L_3 = \frac{}{\Lambda R_t}$$

Y: $$\Lambda = g + \frac{H_2}{F_2} + \Lambda_0 , \quad L_1 = \frac{1}{\Lambda}\left(g + \frac{1}{F_2}\right) \; ; \; L_2 = 0 \; ; \; L_3 = \frac{1}{\Lambda R_t}$$

The stationary case can be obtained from the previous relations as the limit case for $\omega \to 0$, that is, the limit for low frequencies. It can be clearly seen that

$$N \to R_t, \qquad \Lambda_0 \to 0, \qquad \sigma \to [cR_t z(1-z)]^{-1}$$

and therefore

$$E_1 = H_1 = 1, \qquad F_1 = zR_t, \qquad G_1 = 0, \qquad E_2 = H_2 = 1, \qquad F_2 = (1-z)Rt, \qquad G_2 = 0$$

and, finally, through the expression for L_i shown above, we can easily obtain the limit-case expression of $\lambda_i = L_i(\omega \to 0)$, which obviously corresponds to those used in (1).

References

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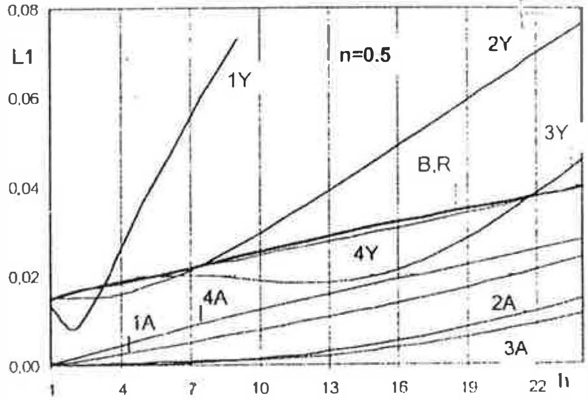

Fig 1

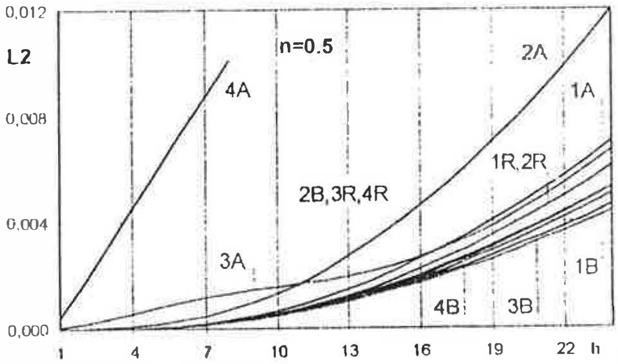

Fig 2

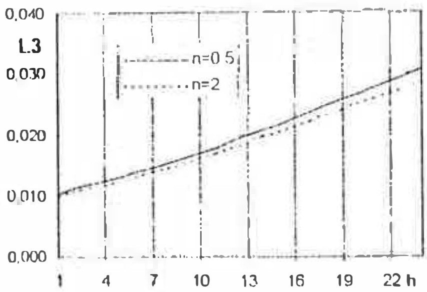

Fig.3

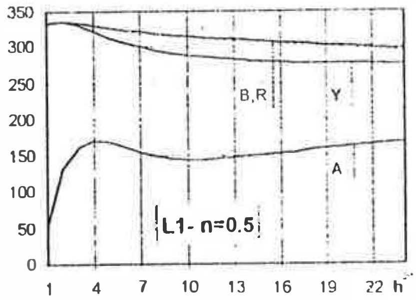

Fig 4

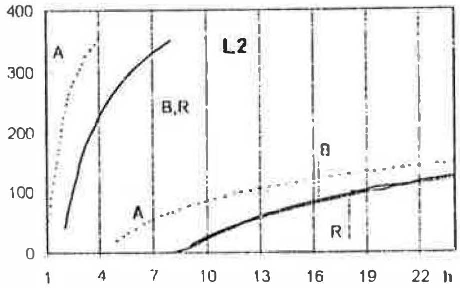

Fig.5