INDIRECT EVALUATION OF INDOOR ENVIRONMENTAL PARAMETERS BY MEANS OF AUDIT TECHNIQUES

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ABSTRACT Some techniques aimed at the evaluation of microclimatic parameters through the measurement of other indoor physical quantities are critically reviewed. Particularly, the appraisal of the air velocity from the predicted mean vote and the determination of air change from the decay of the CO_2 indoor concentration are analysed. Important warnings for the use of these methods are underlined and the limits of applicability are pointed out.

1 Introduction

Auditing techniques concerning confined environments are becoming well known and widely employed tools as climatic performances of indoors adhere in a closer way to the improved lifestyle of people, in residential as well in working buildings. Presently, many commercial devices and instruments are available in order of allowing technicians to check and to verify the compatibility of indoor climatic conditions of buildings for design purposes or standard requirements. The evaluation of predicted mean vote of a moderate thermal environment and the monitoring of the CO_2 indoor concentration are among the most popular examples in this field.

However, an accurate audit analysis should involve several indoor parameters, that would call for the use of further measurement instruments and techniques that, among other things, imply expensive procedures both in time and money. Consequently, any method able to indirectly evaluate other indoor parameters, with a reasonable accuracy, should be considered with a great attention. The knowledge of the predicted mean vote, in particular, could lead to an estimation of the necessary mean air velocity in a room, while the level of indoor CO_2 concentration may be used for evaluating air change flow rates.

In this work, after a short review of the theoretical basis for the indirect evaluation of mean air velocity and ventilation flow rates, some warnings are underlined that exhort a careful application of these indirect methods.

2 Mean air velocity from predicted mean vote

The knowledge of air velocity values in a confined environment represents a key element in order of characterising indoor thermal comfort conditions. Thermal convective exchanges between air and human body are in fact strongly dependent on the direction and the intensity of the local air velocity vector. Moreover, fluctuations of instantaneous values of the air velocity around its mean value determine a turbulence intensity that could be responsible for local discomfort of people due to air draughts (Fanger *et al.* 1989).

Unfortunately, the estimation of the local value of air velocity is a complex operation, mainly due to the extreme variability of this parameter with the spatial co-ordinates: this would imply simultaneous measurements in several points of a room (Cannistraro *et al.*1991). Even the prediction by means of computer programs of the air velocity at a local level of a room is far from definitive, and it requires great computational effort.

With the aim of providing a contribution towards overcoming of this problem, Olesen *et al.* (1987) suggested a method for the indirect evaluation of the air velocity, starting from the measurement of two microclimatic parameters, that is the operative temperature and the equivalent temperature.

2.1 The method

The indirect evaluation of the air velocity, within the above cited methodology, relies on the analytical definition of the predicted mean vote that, as it is well known, is a function of four microclimatic parameters, plus two subjective parameters. That is:

$$PMV = Y(t_a, t_{mrt}, v_a, \phi, I_{cl}, M) \qquad (1)$$

being t_a the air temperature, t_{mrt} the mean radiant temperature, v_a the air velocity, ϕ the relative humidity, I_{cl} the thermal resistance of the clothing ensemble and M the human metabolic rate.

In confined spaces usually two other temperature indices are utilised and instrumentally detected, that is the equivalent temperature, t_{eq} (the uniform temperature of an imaginary enclosure where air velocity is equal to zero and in which a person will exchange the same dry heat loss by radiation and convection as in the actual environment), and the operative temperature t_{op} (the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment). Both these temperatures can be generally expressed as a function of some of the parameters used for calculating the PMV (Madsen 1979, Olesen et al. 1987):

$$t_{eq} = Y_1(t_a, t_{mrt}, v_a, I_{cl}) \qquad (2)$$

$$t_{op} = Y_2(t_a, t_{mrt}, v_a, I_{cl}) \qquad (3)$$

When the thermal resistance of clothing, the relative humidity (or the water vapour pressure) and the metabolic rate are established, it is possible to consider both previous quantities as depending by t_a, t_{mrt} and v_a; this means, in turn, that predicted mean vote can be expressed as follows:

$$PMV = \theta_1(t_{op}, t_{eq}, v_a) = \theta_2(t_{op} - t_{eq}, v_a) \qquad (4)$$

For assigned values of PMV, finally, air velocity can be then calculated as a function of the difference between operative and equivalent temperatures. That is:

$$v_a = \Upsilon(t_{op} - t_{eq}) \qquad (5)$$

Fig.1 shows the behaviour of the calculated air velocity versus the difference t_{op} - t_{eq}. Besides the above-illustrated analytical representation, these curves could be utilised for a fast evaluation of the air velocity necessary to maintain the set PMV value, avoiding the cited problem that involves a direct measurement of indoor air velocity.

Moreover, as the predicted mean vote, the operative temperature and the equivalent temperature can be all easily measured in several points of a room by means of a thermal comfort meter, it would be theoretically possible to obtain a map of the air velocity in the assigned confined environment, when the simultaneity of the obtained values is not of primary importance.

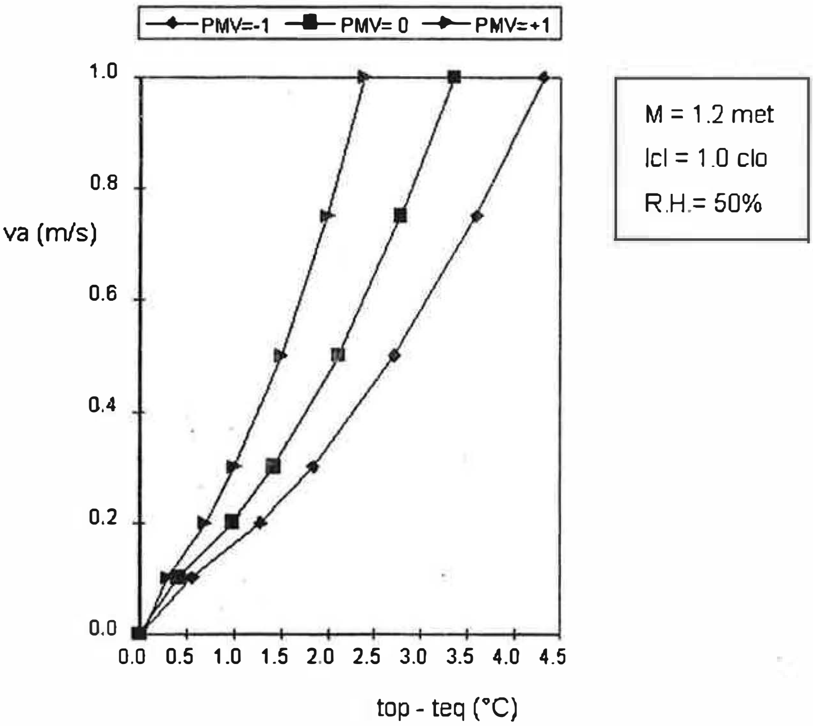

Fig.1 Calculated air velocity as a function of difference between operative and equivalent temperatures

In this sense, the only practical problem is represented by the different response times of the comfort meter when measuring operative (2 min.) and equivalent temperatures (15 min.), that call for some attention to measurement periods.
Unfortunately, the servile application of this methodology could lead to severe errors in the evaluation of the air velocity, as it will be pointed out in the next section.

2.2 Warnings and considerations

The first warning to be underlined when adopting this method is about the entity of the error concerning the value of the calculated air velocity that is introduced by the measurement of the operative and equivalent temperature by means of a thermal comfort meter. This instrument in fact is able to detect the values of these temperatures with a precision of ± 0.5 °C in the usual range of building applications. This means that the arithmetic difference t_{op}-t_{eq} could involve a mean error of ± 0.7 °C, that constitutes a very large range on the *x*-axis of Fig.1 and in practice avoids getting a reliable value of the air velocity. The problem may be avoided by using more precise instruments for gathering operative and equivalent temperatures but, doing this, one should adopt other instruments along with the comfort meter (necessary to obtain the predicted mean vote); moreover, a different instrument, say a globe, would not be able to simulate the dry heat loss from a person like a thermal comfort transducer does by virtue of its particular (elliptic) shape.

Another point of attention is represented by the fact that the correspondence between predicted mean vote and difference of operative and equivalent temperatures is not unambiguously determined (Alfano *et al.* 1994). As matter of fact, different couples of air

temperature and mean radiant temperature can provide same values of t_{eq} (equation 2) and t_{op} (equation 3). This means that various values of the difference t_{op}-t_{eq} can result in the same value of v_a. Only in thermally uniform environments, where $t_a = t_{mrt} = t_{op}$, is it possible to establish an actual relationship between t_a and the difference t_{op}-t_{eq}.
Consequently, the method for the indirect evaluation of the air velocity by means of thermal comfort meter should be avoided. It could be only employed, with a careful attention, simply for singling out the useful zone of a building where the range (not the value) of air velocity is acceptable for comfort purposes.

3 Air change rates from CO_2 concentrations

Indoor levels of carbon dioxide and ventilation rates in buildings are directly linked, as it has been several times pointed out by experimental analyses generally based on the tracer gas techniques.

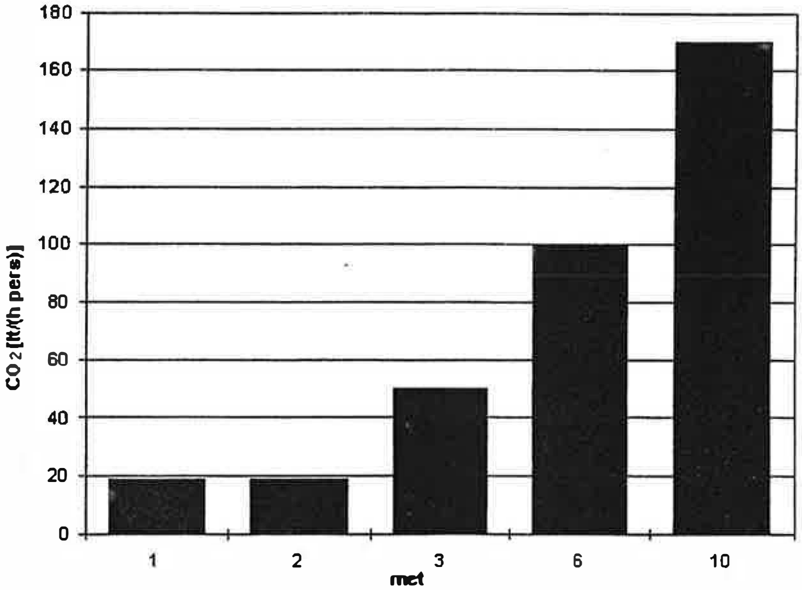

Fig.2 Carbon dioxide generation for people at various activity levels

3.1 The method

It is well known that the indoor CO_2 generation is essentially attributable to respiration and depends by metabolic rates of people at the given activity level, as Fig.2 approximately shows.

This link, however, could lead people to consider always viable the calculation of the ventilation rates by means of measurements of indoor CO_2 concentrations. The Appendix D of the ASHRAE 62 Standard (1989) provides a rationale for minimum physiological requirements for respiration air, based on CO_2 concentrations. This method is similar to that suggested by the last proposed release of the ASHRAE standard for health purposes and for adapted people.

Following the ASHRAE method, the indoor concentration of carbon dioxide C_{in} is expressed in terms of air ventilation rate Q_v, outdoor concentration C_{out} and CO_2 indoor generation G, by means of the following equation:

$$C_{in} = C_{out} + \frac{G}{Q_v} \tag{6}$$

Unfortunately this relationship, when a-critically applied, could lead to major errors in the determination of the ventilation rates. As a matter of fact, the actual relationship between indoor concentration and air changes is a time-dependent equation (Meckler 1993):

$$C_{in}(t) = C_{out}(t) + (C_0 - C_{out}) \cdot e^{-(Q_v \cdot t/V)} + \frac{G}{Q_v} \cdot [1 - e^{-(Q_v \cdot t/V)}] \tag{7}$$

where C_o represents the initial carbon dioxide concentration and V the total volume of the conditioned space.

Equations (6) and (7) only coincide when some important assumptions are satisfied. First of all, the external CO_2 concentration must be assumed as constant, while the indoor concentration should be considered as uniformly diffused. Moreover, a correct application of equation (6) requires that emission and ventilation rates be constant and that the elapsed time be long enough in order to achieve an equilibrium regime between emission of CO_2 and its removal process.

3.2 Warnings and considerations

When previously described situations are not accomplished, equation (6) cannot be employed for computing ventilation rates of a building.

Fig.3 provides a graphic representation of the measured air changes per hour (ach) as a function of the elapsed time for a school building located in Reggio Calabria, in the southern part of Italy. Only for long periods will equation (6) provide comparable values of CO_2 concentrations with actual *ach*s for the given building.

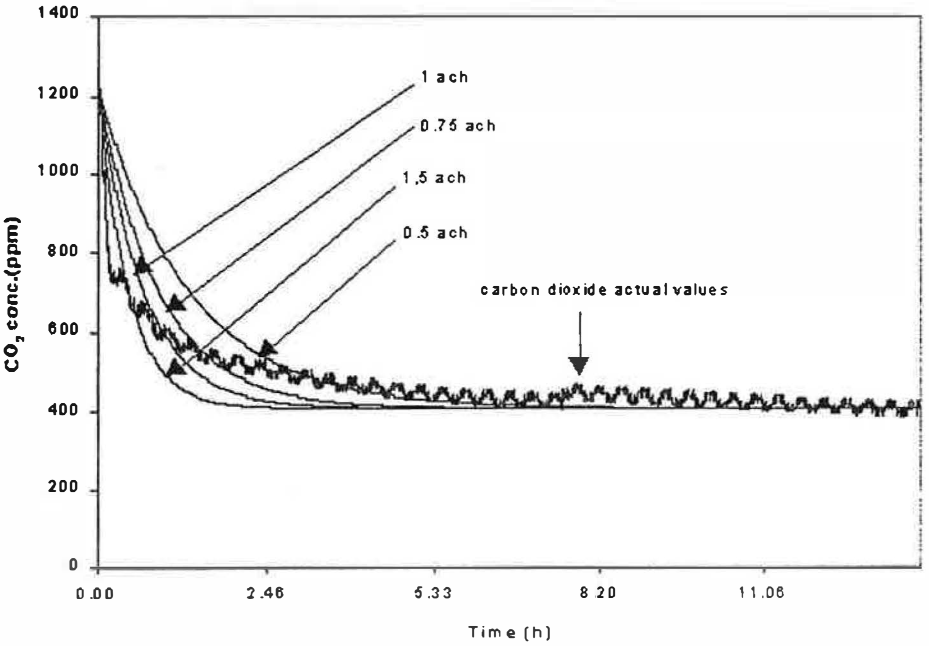

Fig.3 Actual *ach* as a function of the elapsed time

As it is possible to observe, differences between calculated CO_2 concentrations for various values of *ach* and the measured ones are not negligible.
In our experimental case, for example, the presence of an operable grid on the bottom of the door, connecting the room with the corridor, probably determined a strong initial CO_2 outflow: different molecular weights between air and CO_2 produces in fact a stratification in the room, with an accumulation of CO_2 on the bottom of the room. This justifies the rapid decay of the first part of the experimental curve of Fig.3. During the second part of the experiment, when the indoor stratification conditions determine less remarkable differences in the CO_2 concentration with heigth, the air outflow showed a different and slower law.

It is clear, even in this simple application, that the verification of the hypotheses that equal results of equation (6) and (7) is far to be achieved. This suggests that the equilibrium relationship (the ASHRAE equation) should be adopted with a careful attention for evaluating the actual air changes of a room.

4 Conclusions

Although both presented methods for indirectly obtaining air velocity and air changes rates when measuring other microclimatic parameters, are characterised by an easy approach, they should only be applied in the case when the several restrictive assumptions are simultaneously satisfied.

This eliminates in the practice the applicability of these methods for audit purposes.
But the need for the acquisition of several microclimatic parameters (as strongly required by new standard and regulations concerning indoor environments) calls for further investigations in this field: the final goal could be represented by the release of some technical procedures and standards that enable technicians to evaluate several microclimatic parameters while measuring only a few of them.

5 References

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