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CORRELATION OF AIR CHANGE EFFICIENCY WITH ARCHIMEDES NUMBER IN A VENTILATED TEST ROOM

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ABSTRACT

The "step-down" tracer gas technique was used to evaluate experimentally in a mechanically ventilated test room the effect of varying thermal boundary conditions, inlet flow rates, and inlet - exhaust grids position on the Air Change Efficiency (ACE) values. The paper shows that the measured global ACE values are strongly correlated to the Archimedes number (Ar). Reynolds number becomes influent only for Ar tending to zero and in this area a marked discontinuity has been observed, suggesting that switching from cooling to heating may produce a relevant variation on the performance of the ventilation system.

KEY WORDS

Thermal boundary conditions, Ventilation Strategy, Age of the air, Air Change Efficiency.

INTRODUCTION

A relevant research work has been done on the effect of a thermal heterogeneity in a ventilated room by Nielsen (1991), Heiselberg (1994), Etheridge and Sandberg (1996), and Fisk et al. (1997). A previous paper by the authors (Di Tommaso et al, 1999) has shown how variable thermal boundary conditions may create secondary convective flows affecting the performance of a ventilation system, expressed through its Air Change Efficiency (ACE).
New results are now presented in which 468 different experimental conditions are obtained varying air supply velocity, air supply temperature, walls temperatures, geometry of the room walls and of air inlets/outlets, etc.

EXPERIMENTAL PROCEDURE

The experiments were performed using a 2.4 m (width) × 4.0 m (length)× 2.4 m (height) m full size Controlled Ventilation Chamber (CVC), described in details along with the adopted measurement protocol by Di Tommaso et al. (1999).

The HVAC performance was evaluated measuring local mean age of the air, relative ventilation efficiency and Air Change Efficiency (ACE). Particular attention has been devoted to the ACE, defined by Sandberg and Sjoberg (1983) as

$$ACE = \frac{\tau_n}{\tau_{exc}} \cdot 100 \qquad (1)$$

where τ_n is room volume / flow rate, and τ_{exc} the average time of air replacement of the room:

$$\tau_{exc} = 2 \cdot \frac{\int_0^\infty t \cdot C_e(t) \cdot dt}{\int_0^\infty C_e(t) \cdot dt} \qquad (2)$$

being $C_e(t)$ the concentration measured inside the exhaust duct.
In order to measure the ACE of the ventilation system, the step-down method (Sandberg, 1981), using methane as a tracer gas, has been adopted. Three ventilation strategies, shown in Figure 1, have been investigated.

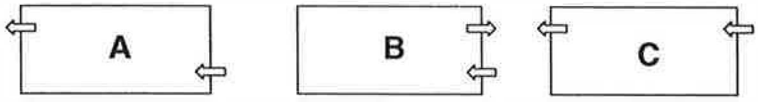

Figure 1: The investigated ventilation strategies

Measurements have been performed at 1, 2 and 3 ach's. Air concentration was sampled by means of a rotary sampling valve at 25 points uniformly distributed on a moveable sampling grid transversal to the room length, a 26th sampling point was located in the exhaust duct. Measurements were repeated positioning the sampling grid at four distances (0.5, 1.5, 2.5, and 3.5 m, corresponding to x/L = 0.125, 0.375, 0.625 and 0.875) from the wall on which the inlet grid is located. Permutation of ventilation strategies, air flow rates and sampling grid position, gives a series of 36 measurements that have been repeated for all the 13 thermal boundary conditions shown in Table 1, giving a total of 468 tests.

TABLE 1
BOUNDARY THERMAL CONDITIONS TESTED IN THE CVC.

#	case	inlet air temperature (°C)	wall temperature (°C)	all other walls temperature (°C)	indoor air temperature (°C)
1	isothermal	20.0	20.0	20.0	20.0
2	warm air	25.0	20.0	20.0	20.7
3	warm wall	20.0	20.7	20.0	20.2
4			21.2		20.2
5			21.8		20.3
6			22.4		20.3
7			23.1		20.5
8	cold air	15.0	20.0	20.0	19.4
9	cold wall	20.0	17.0	20.0	19.4
10			17.6		19.5
11			18.2		19.6
12			18.8		19.7
13			19.3		19.8

MEASUREMENTS RESULTS AND DISCUSSION

All the experimental results were synthetically expressed in terms of ACE are reported for the three investigated ventilation strategies as a function of Archimedes number, defined as:

$$Ar = \frac{\beta \cdot g \cdot \Delta T \cdot L}{u^2} \qquad (3)$$

in which

ΔT = temperature difference between inlet air and the coldest (or hottest) wall of the enclosure
g = gravity acceleration
β = volume thermal expansion coefficient, calculated at the mean temperature between the inlet air and the air close to the wall
L = characteristic length
u = air speed, equal to the average velocity at the inlet grid

The characteristic length L is defined as the height of the inlet grid in the cases of cold and hot inlet air, and as the height of the hot or cold wall (2.4 m) in the other cases. This leads to two different definitions of Ar, as well, underlined by the different colour of the symbols in Figures 2-4.

Due to the convention adopted for ΔT, cooling conditions are represented by a $Ar < 0$, and heating conditions are identified by a $Ar > 0$. The measured data are also characterised by the values of Reynolds number, in which air speed is calculated at the exit of the inlet grid and the characteristic length is the square root of the inlet grid surface.

A global evaluation of the behaviour of the adopted ventilation strategies under the tested boundary conditions is qualitatively summarised in Table 2, and shown in Figures 2, 3 and 4.

TABLE 2
SUMMARY OF FINDINGS

Strategy	Mode	For increasing absolute value of Ar, ACE...
 A	heating	increases
	cooling	diminishes
 B	heating	increases
	cooling	diminishes
 C	heating	increases
	cooling	increases

The results summarised in Table 2 do not offer a simple physical interpretation. For example, when air, colder than the room walls, is introduced in the CVC from below, one would expect that the lower the Archimedes number, the higher the ACE values (tending to a displacement situation), while what happens is actually the opposite. The interpretation may be given by analysing the *local relative ventilation efficiency* (LRVE) values, which for the sake of brevity are shown here in a three-dimensional interpolation form only for this case (e g, strategy A, "warm wall" case, 3 ach's, ACE = 68 %) in Figure 5.

Near the floor the ventilation flow weakly interacts with the convective flow induced by the warmer wall, which reaches there its minimum velocity values, and LRVE values almost reach 2.0, while values of about 0.8 ÷ 1.0 are measured in the upper region, where convection produces a quasi-perfect mixing situation. Increasing the inlet flow rate the quasi-perfect mixing situation persists near the ceiling, while near the floor the LRVE increases. In global terms, this means that ACE will increase when the absolute value of Ar decreases.

The same thing happens for the case of "cold inlet air".

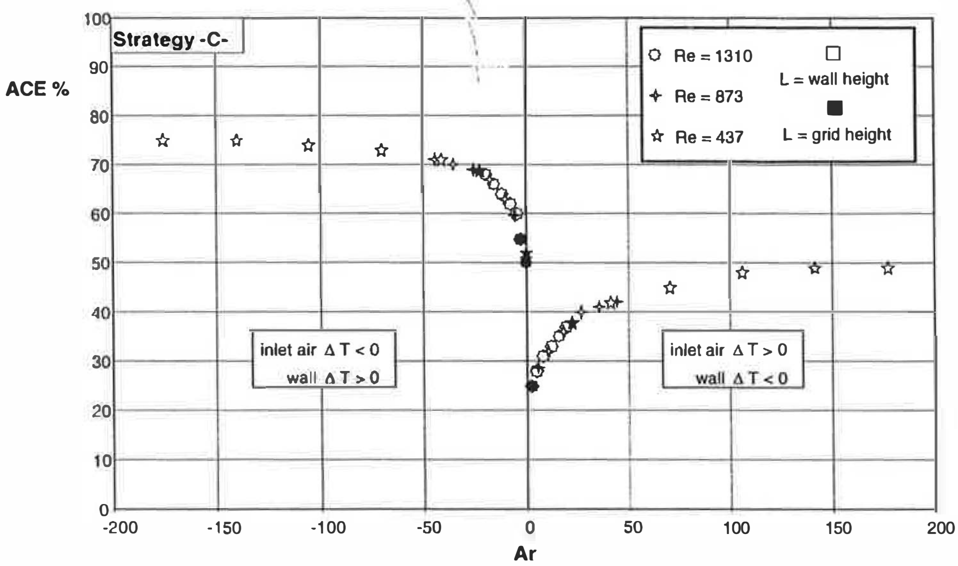

Figure 4: Air Change Efficiency vs. Archimedes number at three different Reynolds number for ventilation strategy -C-. Ar positive heating conditions; Ar negative cooling conditions

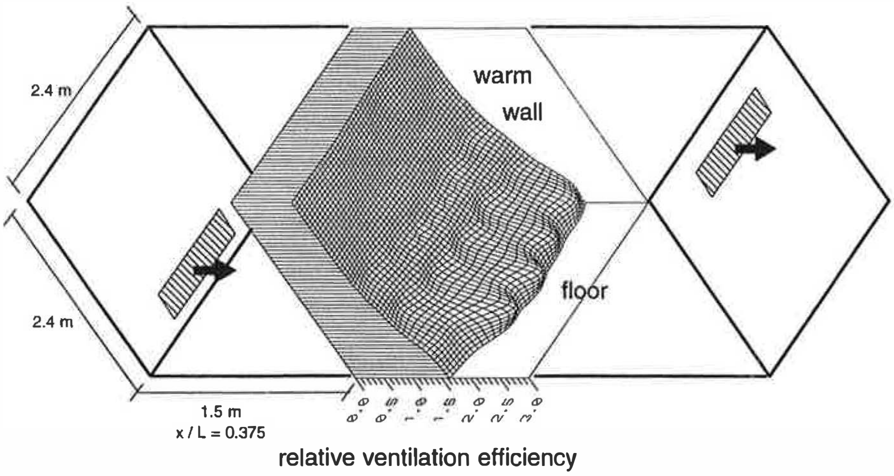

Figure 5: Relative Ventilation Efficiency measured for the "warm wall" case (ACE = 68%), ventilation strategy -A-, 3 ach's and sampling grid position at 1.5 m from the inlet (x/L = 0.375).

Therefore, with moderately negative Ar or in isothermal conditions and for ventilation strategies -A- and -B-, the CVC realises a sort of stratification with the highest ACE values, but if a very little positive temperature difference is introduced (in our case the smallest one is of the order of 0.6 ±0.1 °C) that is enough to destroy the stratification.

In general terms, when Ar > 0 the mixing effect will increase as the supplied momentum increases (intended as the inlet momentum plus the momentum generated by the secondary flow induced by

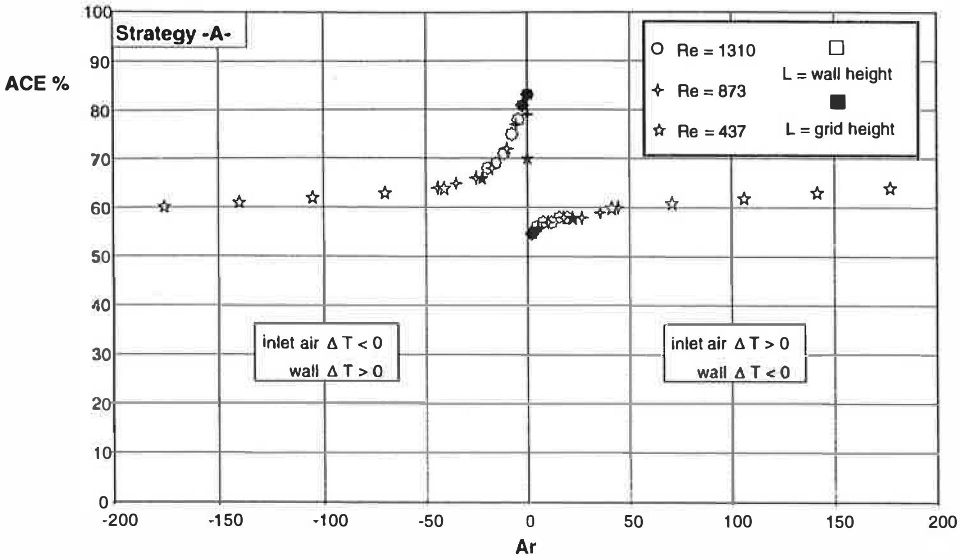

Figure 2: Air Change Efficiency vs. Archimedes number at three different Reynolds number for ventilation strategy -A-. Ar positive heating conditions; Ar negative cooling conditions

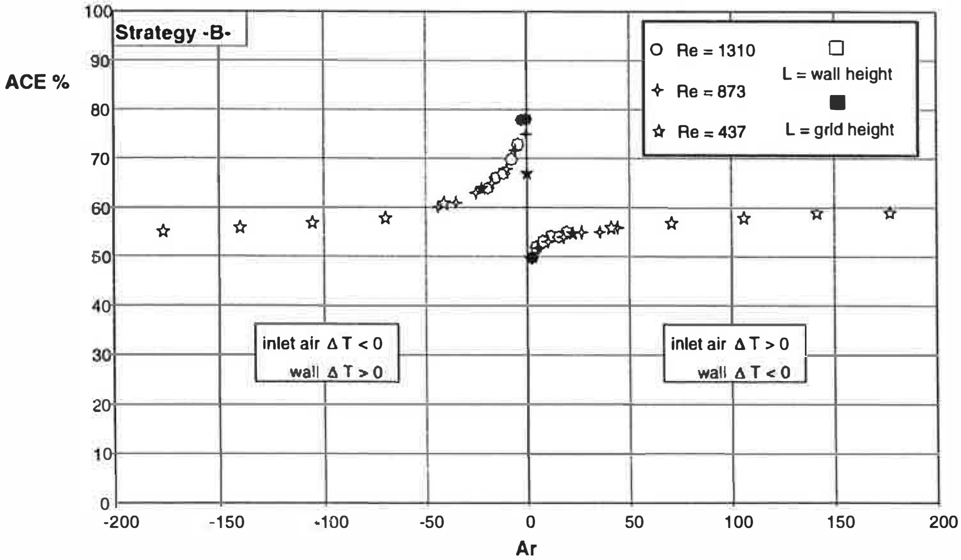

Figure 3: Air Change Efficiency vs. Archimedes number at three different Reynolds number for ventilation strategy -B-. Ar positive heating conditions; Ar negative cooling conditions

the thermal buoyancy force), i.e. as Ar decreases. Therefore, the ACE values fall to 50 % for Ar close to zero, and slowly increase for increasing positive Ar.
For strategy -C-, in the cooling case the buoyancy effect tends to push down the inlet air and for small Ar values the result is a relatively uniform mixing of the air inside the room (ACE = 55 %). Increasing the ΔT (thus increasing the absolute value of Ar), will produce an increase of LRVE near the floor, and a global increase of ACE. In heating conditions the ACE values are positively correlated to Ar, as the distribution pattern of air goes from a short circuit to perfect mixing situation.
The quantitative results described by figures 2 - 4 and explained as an example by fig. 5, are "CVC-sensitive", and therefore cannot be generalised. However, the main finding is that there is a definite correlation between the ACE and Archimedes values, and that, for Ar tending to zero, ACE values tend to two neatly different values ACE(-0) and ACE(+0), with *ACE(-0) always greater than ACE(+0)*. The transition from ACE(-0) to ACE(+0) is given by decreasing Reynolds number for strategies A and B (air inlet down) and by increasing it for strategy C (air inlet up).

CONCLUSIONS

The control of the thermal boundary conditions in a Controlled Ventilation Chamber (CVC) allowed to perform 468 tests simulating isothermal, heating and cooling conditions, with different ventilation strategies. The Air Change Efficiency (ACE) has been measured.
The conclusions which may be drawn from the experimental results are that for all strategies it has been found that Archimedes number (Ar) is the independent variable dominating the phenomenon when temperature differences are present. Furthermore, for all strategies, the limit to which ACE tends for Ar tending to zero is different depending whether it approaches zero from left or right, and the difference is noticeably dependent on Reynolds number.
In order to increase the knowledge of the internal fluid dynamics generated by the ventilation system and the thermal disturbance on the boundary walls, future experimental investigations will be performed adopting more sophisticated experimental techniques like Laser Döppler Velocimetry, which is currently being tested in the CVC.

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