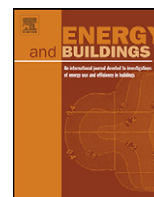




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Mean age of air in a naturally ventilated office: Experimental data and simulations

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ABSTRACT

Indoor air quality has an important role as health determinant; it relates to the health and comfort of building occupants.

The present paper investigates the wind-forced natural ventilation rates of an office as observed with tracer decay, according to ISO 16000-8:2007 Standard, both with an experimental and numerical procedure; experimental data were used to validate the numerical method. Moreover the only infiltration rate case was analyzed.

Natural ventilation was created by opening the window and the door of the office. A simulation model of the room was carried out by using the computational fluid dynamics (CFD) code Fluent. The experimental set up of the procedure was developed by a portable gas chromatograph. In both the numerical and experimental approach the mean age of air linking to ventilation efficiency was calculated. The defined experimental procedure can be applied to different situations, in order to evaluate the efficiency of both natural and forced ventilation existing systems. When the ventilation is due to the opening of the window and the door, the simulation results are in a good agreement with the experimental ones, therefore the model could be applied to different situations, in order to reduce costs and time in the evaluation of indoor air quality.

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1. Introduction

An important parameter in assessing thermal comfort and indoor air quality is the local mean age of air, other than air temperature, relative humidity, air velocity and species concentrations [1,2]. These fundamental parameters are very important for the evaluation of the indoor comfort conditions, especially for working offices, where people spend a lot of time.

Mechanical ventilation and air-conditioning of buildings are responsible of a lot of non-renewable fossil-based energy consumptions in the world, therefore natural ventilation can be used as a cheap cooling source for the building [3–5]. The effective distribution of fresh air within an occupied space is of considerable importance in ensuring thermal comfort and good indoor air quality. Natural ventilation is less controllable than mechanical one. The maximum room depth over which fresh air distribution would be effective and the position of windows and doors are very important in designing a naturally ventilated room [6]. The local mean age of air [7–9] is the average time for air to travel from an inlet to any point of the room;

so it is a very significant indicator of the freshness of room air.

The first step of this study was a Literature survey: many air flow simulation models [10–13] were found, while only a few applications of the tracer gas techniques for measuring the local mean age of air of an existing room exist.

This paper aims to the numerical and experimental investigation of the local mean age of air in a room office. The tracer gas decay method was set-up, according to ISO 16000-8 standard [14], in order to evaluate the air exchange efficiency in an office of the Engineering University of Perugia, placed in the base of Terni.

For the air quality measurements, CO₂ was used as a tracer gas. A simulation model was set up in order to calculate the mean age of air; the CFD code Fluent was used and data to validate the model were deduced from an appropriate experimental campaign. The measurements were carried out in four different conditions: both door and window closed, door opened and window closed, door closed and window opened and both door and window closed. In order to set-up the experimental methodology, preliminary measurements were carried out. A portable gas chromatograph was used as experimental facility; during the measurement campaign, also indoor and outdoor conditions of air temperature and humidity were monitored by a weather station. Two different experimental campaigns were carried out, in January and October 2009, for both which the mean age of air was calculated.

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2. Local mean age of air: the ISO 16000-8 methodology

ISO 16000-8 [14] describes the use of a single tracer gas for determining the local mean age of air in a building which is naturally or mechanically ventilated. The mean age of air in a building zone is defined as the average time that air has spent in a zone of the building accumulating contaminants and it is an important factor in assessing the quality of ventilation. Tracer gas techniques for measuring ventilation rely on the possibility of differentiating air already within the test room from new air coming into the space.

The Standard lists different possible tracer gases that could be used: the carrier gas must be chemically inert, non-toxic and without risk for health in the concentration ranged used, stable, odorless, non-flammable, non-explosive, unable to be absorbed by walls and furniture. Commonly used gases include nitrogen, helium, argon and carbon dioxide.

The user should be able either to mark the air already in the space and follow how the marked air is replaced by new ventilation air or mark the incoming air and measure how this marked ventilation air is distributed through the space.

ISO 16000-8 describes different procedures for tracer gas dilution, including three different methods: concentration decay method, active homogeneous emission and passive homogeneous emission method.

In this study the decay method was used. The principle of *decay method* is to mark the air in the ventilated room with tracer gas and to determine the rate at which the marked air is replaced by unmarked air: this is the most practical method to monitor ventilation conditions on a short-term.

Two different systems could be chosen for injecting tracer gas:

- *graduated syringe*, or other container of known volume with controlled content release;
- *compressed tracer gas supply*, with a critical orifice and an electronic mass flow controller or other tracer gas flow rate measurement device.

In order to create a uniform initial gas concentration, the following systems could be used:

- *fans*: allow a good mixing within and between zones;
- *injection lines*: dispense tracer gas by means of manifolds or switches;
- *swinging doors*: after tracer injection in all zones, the doors between different zones may be swung back to increase the inter-zonal mixing.

The gas concentration history in a point of the room is recorded as a function of time and the local mean age of air is obtained from the quotient of the integral of the concentration of the tracer gas and its initial concentration at time t_0 . So the mean age of air τ_p is given by Eq. (1):

$$\tau_p = \frac{\int_{t_0}^{\infty} C_t dt}{C_{t=t_0}} \quad (1)$$

where τ_p is the local mean age of air; t is the time; $C_{t=t_0}$ is the initial tracer gas concentration at time $t = t_0$ (in $\text{cm}^3 \text{m}^{-3}$ of tracer gas).

If the test room has a total volume of V_R , the tracer gas volume V_I to be injected into the room is given by Eq. (2):

$$V_I = C_{t=t_0} \cdot V_R \quad (2)$$

The integral in Eq. (1) is evaluated from the measured tracer gas concentration history. The logarithm of the tracer gas concentration vs. time should be plotted and if this plot is linear from the

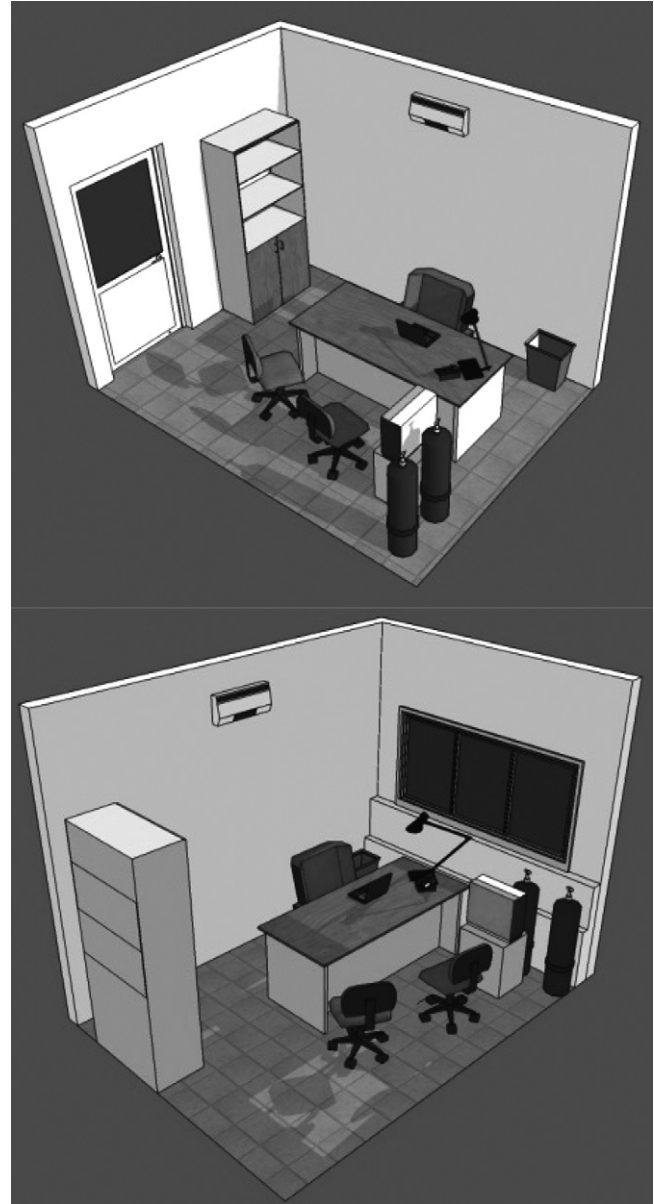


Fig. 1. 3D office view: (a) NE view and (b) NO view.

time $t = t_0$, the local mean age of air can be calculated simply from the inverse of the absolute value of the slope. If it is not linear, a numerical integration technique, as the trapezoid method, could be used for the exponential decay [14].

All the calculated values of the local mean age of air shall be accompanied by estimating its uncertainty that could be evaluated in compliance with Annexes C and D of ISO, 16000-8 [14]. It depends on many factors: the uncertainty of measuring a concentration of CO_2 , the uncertainty of integral and the uncertainty owing to an additional error involved when using the trapezoid integration.

3. Experimental facility and measurements methodology

The test room is represented in Fig. 1; it is an office with a gross volume of about 30 m^3 . The flow and temperature field was not affected by external factors with respect to the set conditions for natural ventilation, in fact the fan coil in the room was turned off during the measurements. A gas chromatograph micro-GC VAR-

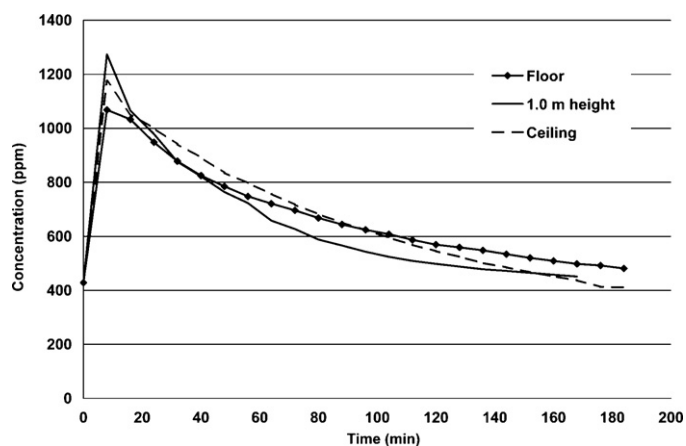


Fig. 2. Measured decay curves of concentration vs. time in three different points of the room.

IAN Inc CP-4900 model with a thermal conductivity detector (TCD) was used for the tracer gas concentration measurements. It is a micro-machined analyzer; both the injection and the sampling can be made automatically. The auto-sampler provides to introduce a sample automatically indoor [15]. Data acquisition and post-processing phase can be managed by STAR WORKSTATION 6.41 Software.

During the measurement sessions, a weather station Oregon Scientific WMR968 monitors both outdoor and indoor air conditions. Finally the inlet air speed was measured on the window, referred to the normal of the surface.

The use of tracer gases can have adverse effects on the health of the room occupants, depending on their type and concentration. The choice of carrier gas is often dependent upon the type of gas detector which is used: carbon dioxide was chosen in this case.

The presence of people in the test room during the measurements should be a carbon dioxide source; therefore the concentration of CO₂ was recorded before the tracer gas was introduced in the office. Operators stayed outside of the office during the measurements and, in order to protect their health from CO₂, the limits of European Agency for Safety and Health at Work (2010) were considered: a allowed maximum gas concentration equal to 0.15% in volume was fixed.

The tracer gas was introduced automatically by a flux meter (1000 l/h) in a central point of the office, because of the small dimensions of the test room.

In order to guarantee uniformity conditions in the test room, preliminary measurements were necessary. The purpose of tracer gas feedings for the decay technique is in fact to achieve an uniform concentration of tracer gas through the ventilated system.

Two fans were used for creating a uniform initial concentration of CO₂ and were placed on the south-east and south-west corners of the room. The operators switched on the fans in the office after the achievement of the maximum concentration of carbon dioxide; the fans remained switched on for 5 min, the time necessary for a good mixing in a so small volume. At the beginning, in order to control the uniformity of the tracer gas, the air in three different positions was sampled: near the floor, next to the ceiling and in the centre of the room straight (1.0 m height from the floor), after the fans were turned off. The measured decay curves of concentration vs. time in the different positions of the sampling (Fig. 2) showed that the CO₂ concentration changes are less than the limits fixed by the law (5%). So in the experimental campaign just one point was considered for the measurements: the point at 1.0 m height was chosen.

The measurements were carried out automatically with different sampling times; in January sampling was set every 8 min, in October every 2 min. In the January campaign, in fact, the sampling rate was too long, especially for the conditions with open door and open window, when a quick reduction of the CO₂ concentration was measured.

The steps of measurement methodology were:

- measurement of the beginning concentration of CO₂ in the office;
- tracer gas injection into the zones and evaluation of gas concentration straight after the introduction of CO₂;
- switching on of fans for 5 min and new sampling of CO₂ concentration;
- carbon dioxide automatic samplings for a total time greater than the expected average age of air.

In the experimental campaign four different cases of natural ventilation were considered:

- Case 1: both door and window closed;
- Case 2: closed door and opened window;
- Case 3: opened door and closed window;
- Case 4: both door and window opened.

4. Experimental results

The first measurement campaign was carried out in January 2009, the second one in October 2009. Thanks to the first measurement campaign, the test procedure was defined. Then a second measurement session was repeated to validate the simulation model. The sampling time and mean outdoor and indoor conditions during the tests are shown in Table 1.

4.1. January campaign

In the Case 1 the only contribution of the air permeability of the frames was evaluated. Then the tracer gas was injected into the office at a constant rate of 1000 l/h for 120 s and the concentration of the tracer gas was recorded. The concentration of CO₂ returned at the original value after 3 h.

In the Case 2 CO₂ was introduced for 140 s at a constant rate of 1000 l/h and during the input the door was closed; after the fans shutoff, the door was soon opened; in this case CO₂ concentration decreased quickly and about 30 min later it was equal to the initial concentration.

In the Case 3 the window (external dimensions 0.6 m × 0.8 m height) was opened when a good air mixing was assured into the office. The test lasted for 120 min: CO₂ was also introduced for 140 s by the flowmeter; 30 min later the tracer gas concentration was less than the original concentration.

The Case 4 is the maximum naturally ventilation condition for the office. Also in this trial CO₂ was introduced for 140 s at a constant rate of 1000 l/h; CO₂ reduced very quickly and after the fifth sampling (32 min) it was lower than the initial concentration.

The curves of CO₂ concentration vs. time in the four different cases are shown in Fig. 3; the decay curve begins with the third sampling (uniform CO₂ distribution).

4.2. October campaign

In the January campaign carbon dioxide was sampled with a 8-min rate. However results showed that a such sampling time is not adequate to define a decay curve, especially in Cases 3 and 4. Therefore the methodology was improved for the second campaign, until to achieve 2 min sampling rate. The injection methodology

Table 1
Measurements conditions.

	January campaign			October campaign			
	T [°C]		Sampling rate [min]	T [°C]		v [m/s] Window	Sampling rate [min]
	Outdoor	Indoor		Outdoor	Indoor		
Case 1	9.0	15.6	8	–	–	–	–
Case 2	9.0	19.2	8	21.8	23.0	–	2
Case 3	11.8	18.7	8	22.0	22.7	0.6	2
Case 4	9.0	19.4	8	21.6	22.5	0.6	2

was the same as in the January campaign. The second campaign was focused on the validation of the simulation model but, since the Case 1 is not available with Fluent, the test was carried out in Cases 2–4. The curves of CO₂ concentration vs. time are represented in Fig. 4; also in this campaign the decay curve begins with the third sampling.

5. Numerical method

5.1. Geometry and mesh generation

The office dimensions are 2.8 m × 3.9 m × 2.8 m height; the gross volume is 30.6 m³ while the net volume, obtained by subtracting the bulk of the furniture, is 29.4 m³. In the office it is possible to identify a table with a PC workstation, some chairs, a cabinet.

Test office presents two openings: there are a large window and a door on the opposite side of the window.

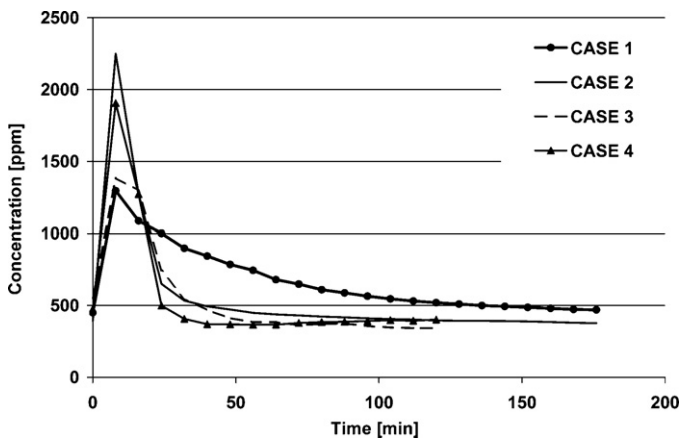
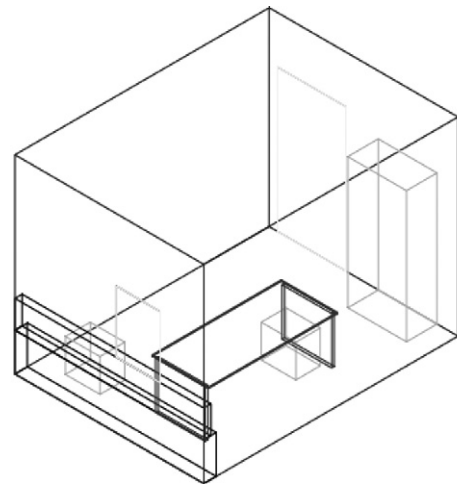


Fig. 3. Comparison between CO₂ concentration vs. time in the four cases (January measurement campaign).

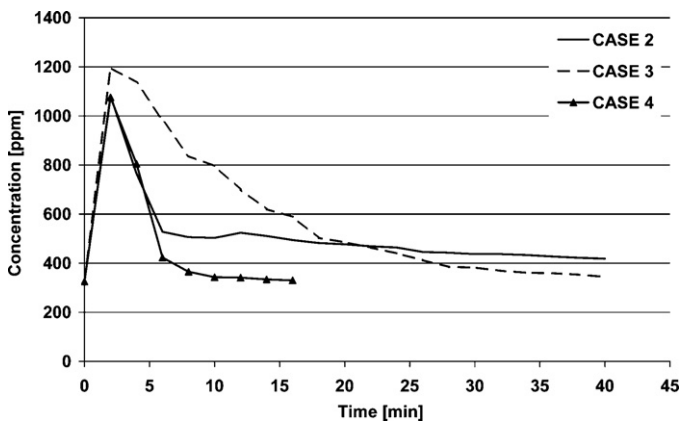


Fig. 4. Comparison between CO₂ concentration vs. time in the four cases (October measurement campaign).

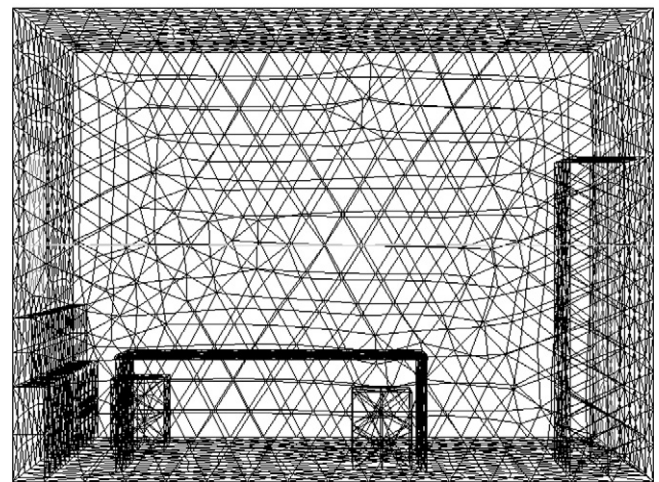


Fig. 5. 3D Fluent model view and mesh.

The 3D geometric model (Fig. 5), obtained by simplifying the real geometry, was created with a CAD system, then imported in the pre-processor Gambit.

Grid generation depends on geometrical complexity, physics and PC calculator. Within the current pre-processor both structured and unstructured meshes can be created. In the former all interior nodes of the mesh have an equal number of adjacent elements. For the current 3D case, this implies hexahedral elements. Unstructured meshes, by contrast, allow any number of elements to meet at a single node. The tetrahedron is the most common element.

For the current application, a balance between hexahedral and tetrahedral elements was chosen; the grid size was 0.25 m.

5.2. Method and model set-up

The CFD approach involves the numerical solution of a set of partial differential equations describing the fundamental laws of

fluid motion. The commercial Fluent software uses the numerical technique of finite volumes; it shares the domain into elementary volumes and substitutes the initial differential equations with algebraic equation of balance, one for each elementary volume [16,17].

The aim of this study is to simulate the motion of air in a room, caused by opening a window or a door; this causes the air entry from outside or from contiguous rooms and the air outlet from the same room. The motion of air could be shown by introducing a known amount of a substance (tracer) and the determination of tracer concentration over time (decay method).

Only results of Case 4, opened window and opened door, are showed, while for Case 2 (closed door and opened window) the flow field did not converge and in Case 3 (opened door and closed window). We are actually searching for convergence.

In the Case 4 simulation, $k-\epsilon$ model was chosen, because of its proven accuracy, robustness and computational economy for most applications. The decay of the tracer gas was simulated by applying the Discrete Phase Model (DPM) present in Fluent. It allows to simulate a discrete second phase in a Lagrangian frame of reference, which consists of spherical particles dispersed in the continuous phase. It is able to compute their trajectories, as well as heat and mass transfer to/from them. The coupling between the phases and its impact on both the discrete phase trajectories and the continuous phase flow can be included.

The discrete phase formulation contains the assumption that the second phase is sufficiently dilute that particle–particle interactions and the effects of the particle volume fraction on the gas phase are negligible. These issues imply that the discrete phase must be present at a fairly low volume fraction, usually less than 10–12%. Three particle types can be selected, inert, droplet and combusting; all particle types have predefined sequences of physical laws that can be activated; in this case the tracer CO_2 is inert.

The uniformity of the tracer, consistent with the possibilities provided by the solver, was carried out modelling the injection in a finite, but high number of points and dividing the volume of injected gas by the amount of paths to consider. At this aim injection group that allows to introduce the characteristic of the tracer for the first and last point of the group was selected, with a linear interpolation of the values of the properties specified at all points. The coordinates of the injection points were interpolated, whereas the tracer concentration was kept constant and equal to 11% by volume, such as in the experimental conditions (see Section 3). The influence of the number of injections on the quality of the solution was evaluated progressively increasing the number of groups, from a preliminary value of 500 points to the end value of 640.000. The turbulent flow field in steady state was initially solved, then the discrete phase was introduced in un-steady state. In order to consider the un-steady state of this second phase of simulation, it was necessary to change the solver (*un-steady*); the following parameters were defined:

- *Time step size* (time interval for the discretization of the domain): 1 s;
- *Number of time step* (period of observation of the phenomenon): 900 s;
- *Max iteration for time step* (maximum number of iterations to obtain the convergence): 1000.

According to experimental procedure (Section 3), since the tracer was sampled every 2 min at 1.0 m height in the centre of the room, it was chosen to graphic the decay curve on a neighbourhood of this point and to see the results simulations on a horizontal plane through it.

Table 2
Input data: air properties.

Density (kg/m^3)	1.225
Viscosity (kg/m s)	1.7894×10^{-5}
Specific heat (J/kg K)	1006.43
Thermal Conductivity (W/m K)	0.0242

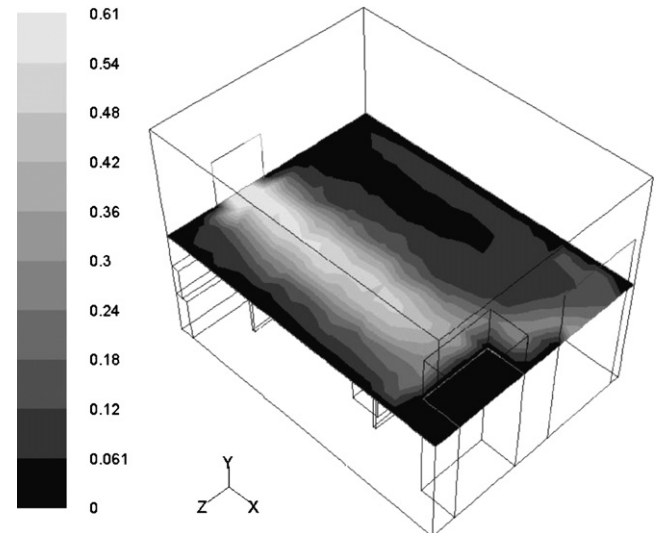


Fig. 6. Velocity field in a plan at 1.0 m height from the floor (m/s).

5.3. Input data

Air properties are reported in Table 2; it was considered in thermal equilibrium with walls, ceiling, floor and furniture; the only heat exchanges occur with door and window.

The chosen boundary conditions are shown in Table 3 for the examined situation.

In all simulations, walls, ceiling and floor were considered adiabatic walls (boundary condition) and the DPM condition of *reflect* (when a particle of the tracer impacts on the wall, it bounces and there is a change in its momentum) was assumed.

The DPM condition *escape* (a particle of tracer impacts the window and goes out) was considered when window and door were opened.

5.4. Numerical results

The first step was the velocity field in steady state before the tracer gas introduction; then the steady state model discrete phase was activated and the tracer gas concentration vs. time was calculated, in order to determine the decay curve.

The velocity field in a plan at a height of 1.0 m from the floor (the same as the experimental measurements) is sketched in Fig. 6.

In Fig. 7, the tracer gas concentration in the same plan after 1'30'' and after 2'30'' is reported for Case 4.

Data related to same point on the experimental survey in the centre of the room were used to calculate the mean age of air (see Section 3). The decay curve is reported in Fig. 8.

6. Mean age of air calculation

The calculation of the local mean age of air was carried out according to the methodology explained in ISO 16000-8 [14]. Therefore the CO_2 concentration decay was represented in a semi-log graph and the original concentration of CO_2 was subtracted.

Table 3
Input data: boundary conditions (Case 4).

Surface	$k-\varepsilon$ model	Heat transfer model	DPM model
WINDOW inlet velocity	$v = 0.6$ m/s Hydraulic diameter HD = 0.78 m Turbulence index $I = 4.4\%$	$T = 21.6$ °C	ESCAPE
DOOR outlet pressure	Hydraulic diameter DH = 1.42 m Turbulence index $I = 5.5\%$	$T = 22.5$ °C	ESCAPE

Table 4
Mean age of air in the different cases: experimental and numerical data (C, closed; O, opened; D, door; W, window; n.a., not available).

Case		January		October		Simulation
		Mean age of air (min)	Uncertainty (%)	Mean age of air (min)	Uncertainty (%)	Mean age of air (min)
Case 1	CD-CW	46.15	7.70	n.a.	n.a.	n.a.
Case 2	OD-CW	11.15	7.90	13.60	5.00	n.a.
Case 3	CD-OW	≤ 5.90	n.a. (>5%)	9.85	13.15	n.a.
Case 4	OD-OW	≤ 2.28	n.a. (>5%)	2.79	5.23	2.50

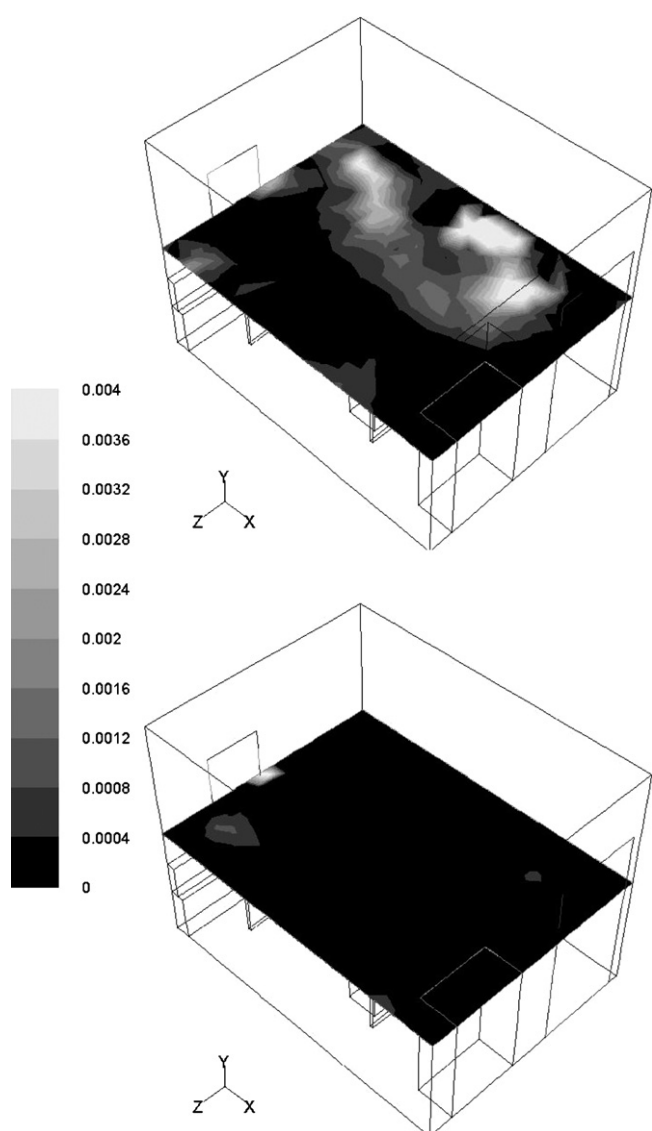


Fig. 7. Tracer gas concentration after 2'00'' (a) and after 4'00'' (b) with both door and window opened (Case 4) (kg/m^3).

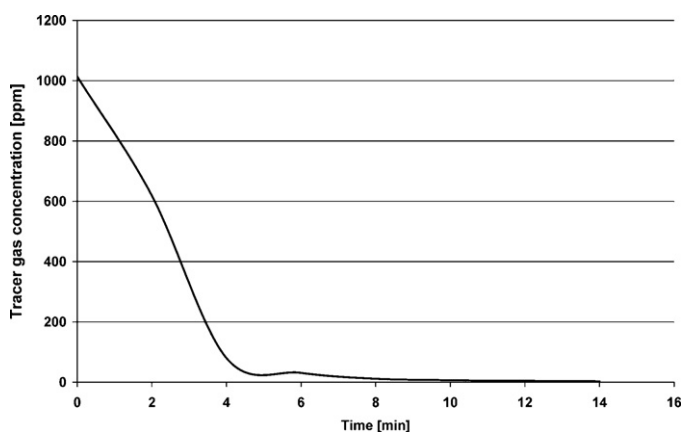


Fig. 8. Tracer gas concentration vs. time, both door and window opened (Case 4).

In some cases, when the decay was purely exponential, the mean age of air was calculated directly by the inverse of absolute value of the regression line slope; in other cases it was calculated using two contributions: the first one was calculated by means of the trapezoid method, the second one coincided with the area delimited by the linear line, such as in ISO 16000-8 [14].

Results for both the experimental campaigns and numerical simulation are reported in Table 4.

In both the experimental campaigns, the mean age of air diminishes as obvious, from Case 1 to Case 4, with the opening area increasing. Nevertheless, the values of the January campaign are lower than the corresponding ones of the October campaign; this is due to the higher indoor-outdoor temperature difference, which allows in January a more easy circulation of air across the openings. Data of Case 3 and 4 in January represent a maximum, because the concentrations were measured with a 8-min sampling rate.

Considering Case 4, a good agreement was found between experimental and simulated data (2.50 and 2.79 min, respectively), with a difference of about 10%.

The model could be therefore employed to simulate different conditions of indoor and outdoor air temperature and air velocity, in order to evaluate their influence on the mean age of air.

Finally the uncertainty was calculated according to ISO 16000-8 [14]. For the calculation, an uncertainty due to the insufficient uniformity of the gas in the office equal to 5% was assumed; this value is the highest measured. In the different cases the global uncertainty was in the range 5–13%.

7. Conclusions

Indoor air quality within workplaces is very important because of occupants sensitivity to poor air quality. Indoor air pollution might increase the chance of both long and short term problems for people, reducing the productivity and comfort and giving, in some cases, also health problems. Therefore, the investigation of indoor air quality in office buildings will help in the characterization of the discomfort levels of pollutants and in implementing corrective measures to improve the air quality where required [18–20]. In the literature, the local mean age of air is used as an important index to evaluate indoor air quality in ventilated rooms [21]. Moreover, the recent ISO 16000-8 standard describes a methodology to calculate the local mean age of air by means of an experimental procedure using a single tracer gas.

In the present paper results from an experimental and numerical study about air quality in a naturally ventilated office room are exposed. In this research the tracer gas concentration decay method was employed in order to evaluate the age of air in an office of the Faculty of Engineering at the University of Perugia, situated in the base of Terni.

Four different conditions of natural ventilation were considered: door and window closed (Case 1); door opened and window closed (Case 2); door closed and window opened (Case 3); door and window opened (Case 4). For the air quality measurements, CO₂ was used as tracer gas.

Measurements were carried out in two different campaigns, in January and October 2009. Thanks to the experimental campaigns, a methodology according to the ISO 16000-8 standard was set up.

The decay method was employed to evaluate the variation of tracer gas concentrations in time. The local mean age of air was calculated through tracer gas measurements and numerical simulations; then the uncertainty of local mean age of air was estimated.

The highest value of the local mean age of air is about 46 min in the Case 1, when both the window and the door were closed. Similar values of the mean age of air (about 11–13 min) were obtained for Cases 2 and 3, while very low values (less than 3 min) were obtained for Case 4. The differences between January and October values are due to the air temperature difference between indoor and outdoor, that is higher in January and gives a lower value of the mean age of the air, due to the higher air velocity across the openings.

A good agreement was found between experimental and numerical data for Case 4, with a difference of about 10%. The measurement uncertainty was finally comprised in the 5–13% range.

The experimental methodology could be applied for both natural and forced ventilation systems study and for the evaluation of the efficiency of the forced ventilation schemes [10], but the numer-

ical model could be very useful for the prediction of the mean age of air, allowing costs and time reduction in the indoor air quality evaluation.

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