# Experimental Investigation on the Retention of Air Pollutants Indoors


**André Augusto Isnard**
Pontifícia Universidade Católica do Rio de Janeiro - Departamento de Engenharia Mecânica
Av. Marquês de São Vicente 225 , CEP22453-900, Rio de Janeiro, RJ, Brazil.
isnard@mec.puc-rio.br

**Marcos Sebastião de Paula Gomes**
Pontifícia Universidade Católica do Rio de Janeiro - Departamento de Engenharia Mecânica
Av. Marquês de São Vicente 225 , CEP22453-900, Rio de Janeiro, RJ, Brazil.
mspgomes@mec.puc-rio.br

**José Maurício do Carmo Pinto**
Pontifícia Universidade Católica do Rio de Janeiro - Departamento de Engenharia Mecânica
Av. Marquês de São Vicente 225 , CEP22453-900, Rio de Janeiro, RJ, Brazil.
Jmauric68@yahoo.com.br

**Renata Fortini**
Pontifícia Universidade Católica do Rio de Janeiro - Departamento de Engenharia Mecânica
Av. Marquês de São Vicente 225 , CEP22453-900, Rio de Janeiro, RJ, Brazil.
renatafortini@gmail.com



*Abstract. The present work investigated, experimentally, the turbulent dispersion process inside building environments. Experiments have been carried out for characterizing the flow and dispersion of a pollutant in a scaled model (1:10): a cubic chamber of 0.4m x 0.4m x 0.4m, with two ventilation windows, designed to study the impact of ventilation strategies on the indoor particle concentration. The physical situation corresponded to the release of inertialess particles from a point source positioned at one of the corners of the chamber. After the sudden interruption of the aerosol generation process, the particles persist inside the scaled room, with the number concentration decaying exponentially with time. The main parameter in the investigation was the characteristic time constant for the variation in the pollutant concentration. The measurements of the variation in the fine fog particles concentrations have been performed by means of a fast photo-detection technique developed for this purpose and based on the attenuation of light. The velocity field has been evaluated with the particle image velocimetry (PIV) approach. The dimensionless residence time H ($H=\tau U_{in}/l$, where $\tau$ is the characteristic time constant for the concentration decay process, $U_{in}$ is the inlet air velocity, and l is the inlet window height) for the particles in the chamber was measured for different ventilation velocity conditions. H was found to be 840 ± 63.*



***Keyword:*** *Air quality, Indoor pollution.*


## 1. Introduction

Indoor air pollution has become a major subject over the past few decades. In the urban environment, outdoor air which is heavily polluted by industrial activities and vehicle emissions, penetrates inside building, and influences the indoor air quality. In addition, indoor particle sources, such as tobacco smoke and cooking vapours can have a greater effect on personal exposure (Abt et al., 2000). Processes involved in ventilation are the most important in determining the quality of indoor air. It is important to get adequate mixing of inlet air with room air, in order to obtain a uniform fresh air distribution. Models have been developed to design the mechanical ventilation in order to improve indoor air quality (Chow, 1995 and Chow, 1996).

The investigation of contaminant dispersion in a furnished, ventilated room is a challenger and complicated task. Factors such as asymmetry of the furniture, configurations of multiple pieces of furniture and the orientation of furniture with respect to the ventilation inlet make the airflow patterns in rooms much more complex and can result in non-uniform contaminant concentrations (Buchanan et al., 1995; Chung and Dunn-Rankin, 1998; Posner et al., 2003; Richmond-Bryant et al., 2006). Particle deposition on surfaces and adapted ventilation strategy can substantially reduce indoor particle concentrations, resulting in improving the indoor air quality. To predict particle pollution in buildings, size-resolved deposition rate can be used. Reviews of experimental studies on the particle deposition process were reported by Hinds (1982), Wallace (1996) and recently by Lai (2002). Generally, these studies give large variability in deposition rate for each particle size. Size of the room, roughness of the surfaces, airflow rates, inlet/outlet locations, furnished or unfurnished room, are parameters that influence the indoor particle deposition rate.

The particle removal from indoor air depends on the airflow rate but, it depends on the airflow pattern within the room as well. Bouilly et al. (2005) found that the influence of the inlet/outlet locations is stronger for fine particles (lower than 5 μm in diameter) than for coarse particles and that an increase of the ventilation rate does not necessary lead to higher deposition. So the choice of a ventilation strategy, i.e. the airflow rate as well as the inlet/outlet locations, has to be carefully taken into account in order to limit the particle pollution in rooms.

A topic of relevant concern in the air pollution area consists on the evaluation of the residence time of a scalar in a system geometry configuration. A real situation is exampled by finding the time that a pollutant persists inside an industrial building after an accidental release. Once the source of pollutant is cut-off it takes some time to the cleaning of the environment, which is associated to the renewing air ventilation. The identification and quantification of the important parameters governing such transport (e.g. some characteristic residence time for the pollutant indoor) is an essential requirement in the development of models by which we might, for example, predict the transport of pollutants indoor. This paper represents a contribution towards such understanding.

In the present work, experiments have been carried out for characterizing the flow and dispersion of a pollutant in a scaled model (1:10): a cubic chamber of 0.4m x 0.4m x 0.4m, with two ventilation windows, designed to study the impact of ventilation strategies on the indoor particle concentration. The physical situation corresponded to the release of inertialess particles from a point source positioned at one of the corners of the chamber. After the sudden interruption of the aerosol generation process, the particles persist inside the scaled room, with the number concentration decaying exponentially with time. The main parameter in the investigation was the characteristic time constant for the variation in the pollutant concentration. The measurements of the variation in the fine fog particles concentrations have been performed by means of a fast photo-detection technique developed for this purpose and based on the attenuation of light. The velocity field has been evaluated with the particle image velocimetry (PIV) approach. The dimensionless residence time $H$ ($H=\tau U_{in}/l$, where $\tau$ is the characteristic time constant for the concentration decay process, $U_{in}$ is the inlet air velocity, and $l$ is the inlet window height) for the particles in the chamber was measured for different ventilation velocity conditions. The dimensionless residence time $H$ was first suggested by Humphries and Vincent (1976) for characterizing the residence time of small particles in the near wake regions of bluff bodies of simple shapes in external flows.

The physical modeling in laboratory conditions is very valuable because the small scale experiments permit the control of the parameters governing the problem, allowing for a better comprehension of a particular phenomenon. In the present study, the set of conditions for the experiments were selected to be the simplest as possible but it is believed that the main characteristics of the real process were maintained. It is hoped that the data collected will help in improving the understanding of the phenomena and in the development of numerical models for predicting the dispersion indoor. However it is important to observe these experiments do not reproduce some important characteristics of the pollutant dispersion in the real situations which involve more complex geometries also including furniture inside the rooms.

This study was intended to serve as a preliminary investigation for developing risk assessment strategies for dealing with the dispersion of pollutants at indoor environments. The basic ideas were: (i) to investigate the physics involved in the dispersion process, (ii) to characterize experimentally the residence time for fine inertialess particles in a simplified room scaled model, and (iii) to generate experimental data which could be used in the development of numerical codes for simulating the dispersion process in similar circumstances.

## 2. Experimental Set-up

Four basic systems were required for the experimental investigation: a reduced scale cubic experimental chamber, a photo-detection system, the Particle Image Velocimetry (PIV) system, and an aerosol generation apparatus.

Particle concentration decay measurements were performed in a cubic chamber with 0.4 m sides, made of transparent acrylic. The layout of the chamber is shown in figure 1. The room model is equipped with a mechanical ventilation system. The airflow was adjusted via an electronic fan speed controller. The ventilation air enters the room through the inlet section (0.04 m x 0.04 m) and exhausts through the outlet section (0.04 m x 0.04 m).

The measurements of the tracer concentration variations were performed by means of a fast photo-detection technique, developed for this purpose (Sano, A.M, and Gomes, M.S.P., 2003; Sano, A.M., 2003) and based in the attenuation of light. This system included a probe (figure 2) containing a pair of emitter-detector optic devices, corresponding to a light emitting diode (LEDs) and a photo-transistor as the sensors. The probe with the optic sensors was located at the geometric centre of the cubic chamber. This system was controlled by a data acquisition program implemented in the software LabView and by a data acquisition board model AT-MIO-16E10 from National Instruments, placed in a PC type computer.

Before assembling the final set-up, it was first necessary to determine which optic-electronic devices could be employed as the emitter-detector sensors. The performance of different devices was evaluated according to the technical specifications provided by the manufacturers. The LED L-1060SRC (1.8 mm), Super Bright, from Multicomp was selected as the light emitter since it presented higher luminous intensity (visible light), low cost and shorter dimensions. The photo-transistor BPW85C was chosen for the system photo detector after an evaluation of several parameters such as spectral response, time response, size and lower cost.

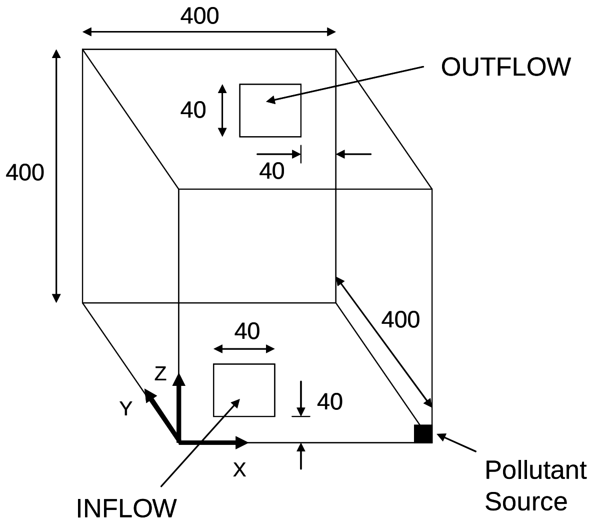


Figure 1 – Schematic diagram of the experimental cubic chamber (dimensions are in millimeters)

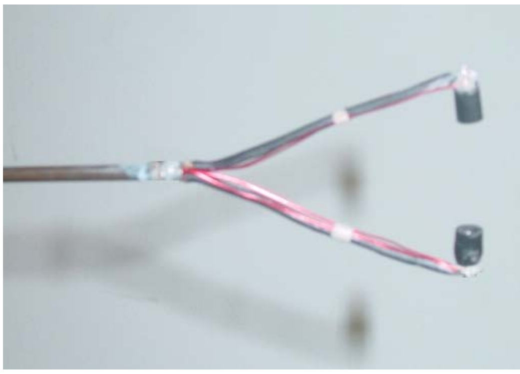

Figure 2 – Probe containing the pair of emitter-detector optic devices, corresponding to a light emitting diode (LEDs) and a photo-transistor as the sensors.

The optic system worked based on the opacity associated to the fog presence. The voltage signals at the detectors were correlated with the variation of the incident light (generated by the emitter). This variation of incident light was related to the opacity caused by fog presence. An electronic circuit was developed for providing the conditioning of the signals generated by the optic devices and maintaining the fast time response of the system at the same time.

A Particle Image Velocimetry (PIV) system from TSI was employed for the inflow velocity measurements and calibration of the mechanical ventilation system during the experiments. It measures the instantaneous flow velocity by determining the distance gone through by particles in a time interval between two laser pulses. The laser beam is converted into a plane light sheath and the particles locations in the plane are registered by a digital camera. In a fraction of seconds later, another light pulse generates another plane and a second photograph is taken registering the new particles positions. The PIV algorithms obtain the particles displacements from the two images and calculate their velocities.

Tests were performed with different inlet flow velocities in the cubic model. The inlet velocities during the tests were $U_{in}$= 1.3m/s, 2.8m/s, 5.0m/s e 10.3 m/s, corresponding, respectively, to the following Reynolds numbers (based on the square window height): *Re*= 3.4E+03; 7.1E+03; 1.3E+04 and 2.7E+04. A commercial fog machine was employed for generating the fine aerosol used in the experiments. The size distribution of these particles was measured with a TSI 3320 Aerodynamic Particle Sizer, and the larger aerodynamic diameters were on the order of 1 micron. Such particles exhibited very small Stokes numbers (St = particle relaxation time / time scale associated with the flow) and therefore were considered virtually inertialess under the flow conditions of interest. The same technique has been used in previous works for measuring particles concentration decay in external flows, as for example, in: Humphries and Vincent (1976, 1978), Crowe et al. (1985), MacLennan and Vincent (1982), Fackrell (1984), and Gomes et al. (1997 and 1999). These fog particles were responsible for representing the dispersed phase (the pollutant) and also they were employed in the determination of the velocity fields when using the PIV technique.

A schematic diagram of the experimental set-up is presented in figure 3. The continuous emitting fog source was positioned at one of the corners of the cubic chamber. The fog was injected in the cubic chamber by a 3mm in diameter tube. An on-off valve was used for interrupting the flow of fog towards the source. Although the valve was manually actuated, the fast action resulted in an almost instantaneous shut-off. The shut-off process was sufficiently fast not to interfere with the concentration decay measurements. It was possible to conclude that the time constant associated with the shut-off process was much smaller than the smallest time constant associated with the dispersion experiments (about 3.3s, as it will be seen in the results section).

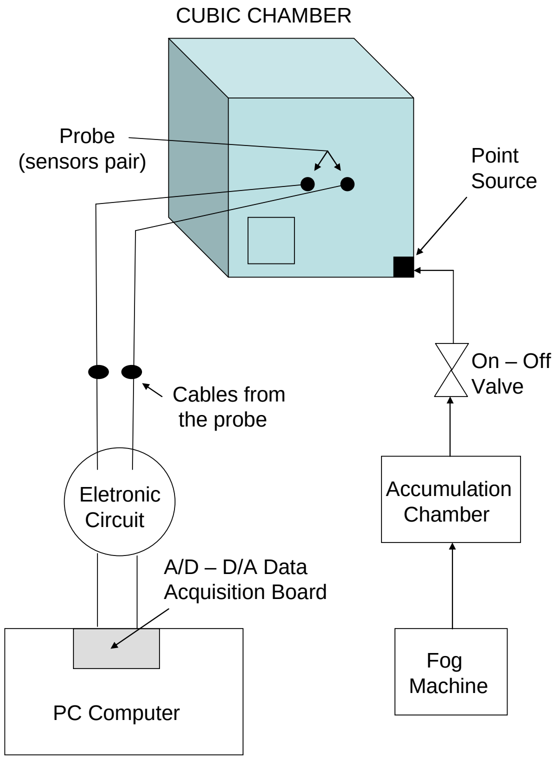


Figure 3 - Schematic diagram of the experimental set-up.

Measurements for the change in the concentration of particles (fog) were performed by the emitter-detector system. In this system, the tension level measured at the photo-detector output is proportional to the incident luminosity at the detector. Therefore, the signal at the photo-detector is inversely proportional to the presence of fog in the optical path between the LED (emitter) and the photo-detector, since the attenuation of light depends on the local particulate concentration. The system was not calibrated for performing absolute concentration measurements, but the objective of the experiment was to characterize the dynamics of the dispersion phenomenon: the rate for the concentration decay. For a given experimental condition of the inlet velocity ($U_{in}$), the mean residence time was determined from the exponential decay of the fog concentration in the model location after the switching-off of the fog source. The general methodology was performed in the following sequence:

1. The fog source was turned on for a period of time, until the tension level measured at the photo-detector reaches an arbitrary level (200mV), and then turned off, interrupting the particle generation process.
2. At the same time that the fog generation was interrupted, the data acquisition program started recording the attenuated light signal coming from the emission-detector optical sensors. The lowest signal (highest particulate concentration) was used in the normalization of the trace. The normalization enabled successive different traces to be amalgamated, in order to provide for an average trace which was more stable.
3. At the end of the concentration decay, the signal returned to its maximum value, corresponding to inexistence of fog in the emitter-detector optical path.
4. The normalization of each trace was performed by: (i) Subtraction of the voltage signal ($V(t)$) from the average maximum value ($\overline{V}\max$); (ii) Division of this trace by the average initial signal (average initial constant signal from 2, above).
5. The trace was then stored in memory, and the above procedure repeated many times. The many successive normalized traces were then combined to provide a "running" average, thus making it possible to reduce unwanted noise without the need for filtering which could distort the time response of the original signal. Typically, we recorded 20 consecutive such events for a given set of experimental conditions. The final result was a relatively smooth trace from which most of the random variations had been averaged out.
6. Finally, for the same single set of experimental conditions, a section of the resultant averaged trace was analyzed. An exponential function was fitted to the experimental data by least squares regression, and the value of the time constant ($\tau$) of the decay was therefore obtained.

A typical normalized trace ($C^*$) (measured voltage signal associated with the particulates concentration level) versus the elapsed time after the source generation was interrupted, for the geometric centre of the chamber, is shown in figure 4. The plotting of a large number of such events indicated exponential behavior of the concentration decay, some time after the instant at which the fog is cut off at the injection source. The “fitting region” in the figure represents the interval of data used in the calculations of the time constant for the particulates retention process.

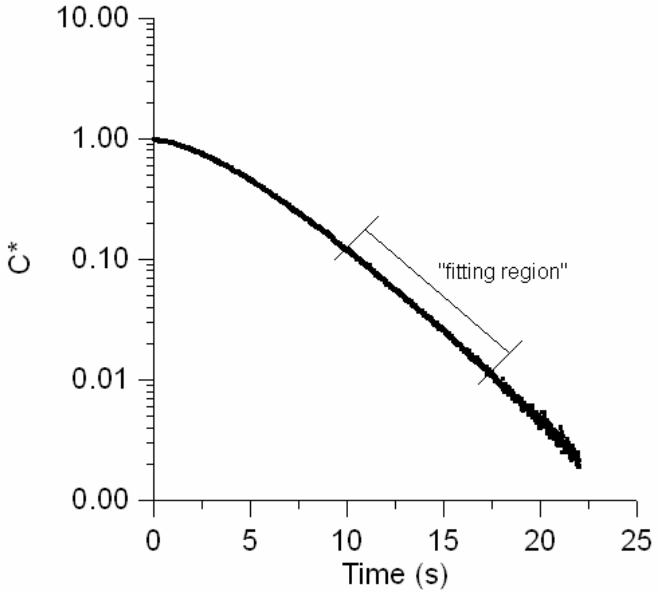


Figure 4 - A typical normalized trace *C*(t)* corresponding to the measured signal (voltage output from the photo detector sensor associated with the particulates concentration level) versus the elapsed time as function of time $t$ .

## 3. Results

### *3.1. Concentration Decay Results*

Figure 5 presents the experimental values for the time constant ($\tau$) of the concentration decay process plotted versus the Reynolds number (*Re*), based on the inlet window height (*l*) and the inlet velocity ($U_{in}$) for the geometric centre of the cubic chamber. The error bars indicate the uncertainty in the determination of $\tau$ as represented by two standard deviations (i.e., corresponding to a 95.4% confidence interval). The figure shows that the values of $\tau$ decrease with increasing Reynolds number. A power law curve fitting is also shown, which represents the experimental data with very good agreement.

Values of the dimensionless time *H* were calculated ($H=\tau U_{in}/l$, where $\tau$ is the characteristic time constant for the concentration decay process, $U_{in}$ is the inlet air velocity, and *l* is the inlet window height) based on the measured time constants presented in figure 6 versus the Reynolds number, for the cubic chamber model. From the results it is possible to assume a single value for *H* which covers the whole range of *Re* investigated (about $3\times10^3$ to $3\times10^4$), corresponding to $H = 840 \pm 63$.

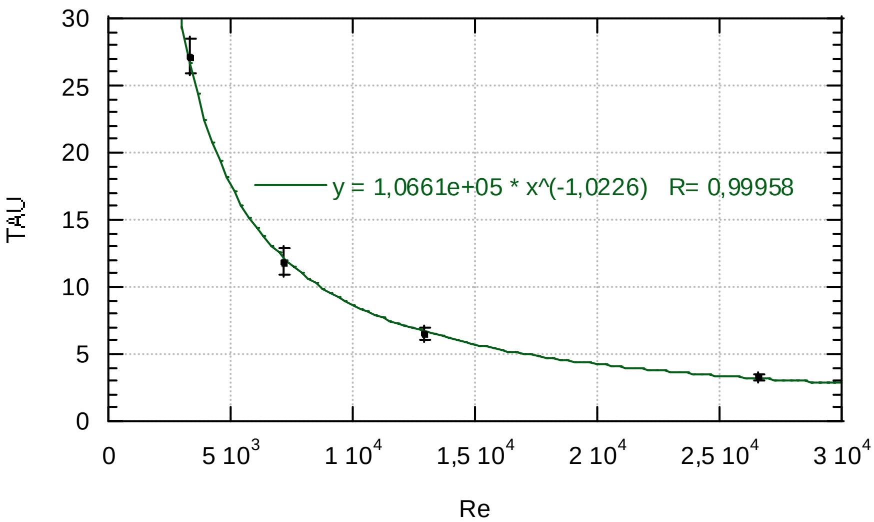


Figure 5 – Experimental results for $\tau$ (time constant for the concentration decay) versus *Re*. The continuous line represents a power law curve fitting calculated from the experimental data.

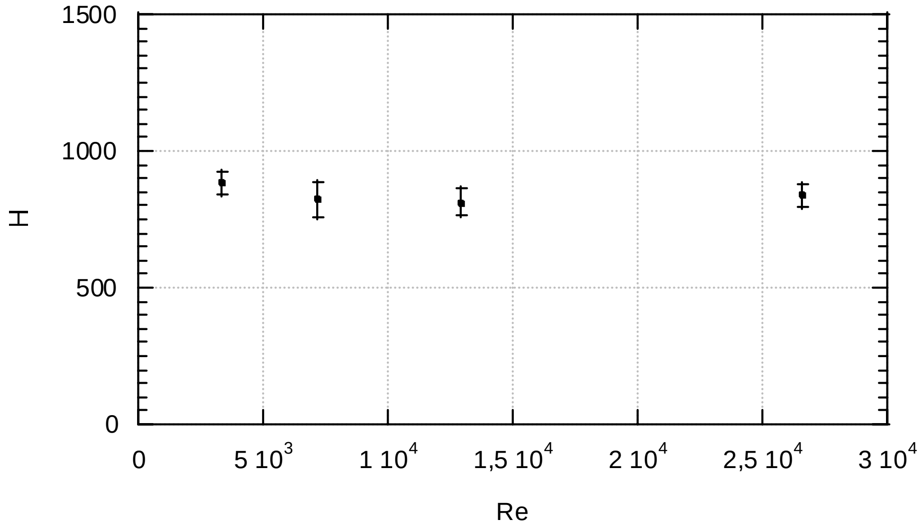


Figure 6– Experimental results for $H$ (dimensionless time for the concentration decay) versus *Re*.

**4. Conclusions**

Laboratory experiments were performed for investigating the dispersion and residence time of pollutants inside building environments. The indoor environment was simulated by a scaled model, a cubic chamber of 0.4m x 0.4m x 0.4m, with two ventilation windows, designed to study the impact of ventilation strategies on the indoor pollutant concentration. A "tracer-decay" technique was employed in the cubic chamber experiments to determine the characteristic residence time of fine "inertialess" particles released at on of the corners of the chamber. Changes in the concentration of particles were monitored by means of an optical system operating on the principles of light extinction. Measures of the time constant for the exponential decay of the particle concentration inside the chamber were carried out for different inlet velocities, corresponding to Reynolds numbers (*Re*) from about $3\times10^3$ to $3\times10^4$. The results showed that the values of $\tau$ decrease with increasing Reynolds number.

The dispersion was also characterized by a dimensionless residence time *H*. The plot of the dimensionless residence time (*H*) as a function of *Re* indicated that *H* was independent of Re (variations in *H* within the experimental uncertainty), and that for the chamber geometry investigated $H = 840 \pm 63$. Based on this result, one may possibly suggest that a characteristic *H* number might exist for flows inside other typical indoor configurations.

The extrapolation of laboratory scaled model results to full-scaled situations requires caution. In real scale situations several effects may be present which, for simplification purposes, were not taken into account during the small-scale experiments. Therefore it is expected that the *H* values may vary quite significantly from one situation to the other. The ideal investigation should take into account experiments in both reduced scale models and in real scale, and these should be complemented by numerical simulations.

**5. Acknowledgements**

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**7. Responsibility Notes**

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