Wind Tunnel Simulation of the Atmospheric Flow and Dispersion Process in an Urban Area

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Abstract. The present work investigated, experimentally, the turbulent dispersion process in three-dimensional urban street canyons at laboratory scale. Experiments have been carried out in a wind tunnel for characterizing the dispersion of a pollutant around a scale model (1:400), which represented a group of ten-floor buildings surrounding a square. The main parameter in the investigation was the characteristic time for the variation in the pollutant concentration (time constant). The measurements of the variation in the concentrations have been performed by means of a fast photo-detection technique, developed for this purpose and based in the attenuation of light, and the velocity field has been evaluated with the particle image velocimetry (PIV) approach. The results were presented in terms of a plot of the dimensionless characteristic time H ($H = \tau U / L$, where τ is the characteristic time constant, U is the free-stream velocity, and L is a characteristic dimension for the urban geometry) versus the Reynolds number.

Keyword: *atmospheric pollution, urban area, wind tunnel experiments, concentration of pollutants.*

1. Introduction

In the last decades it has been observed an increase of the atmospheric pollution in urban areas and its effects on human health. At the same time, there has been an intensification of the studies on the atmospheric flow and dispersion near buildings (Hosker, 1984; Hall et al., 1996; Santos, 2000; Mavroidis and Griffiths, 2001, 2003).

At long distances from the source, where the plume cross-section becomes large compared to the dimensions of individual obstacles, conventional dispersion models are used to simulate flow and dispersion patterns (e.g. Carruthers et al., 1994). Closer to the source, where the interaction between the plume and single structures dominates the plume path and its dispersion, field trials and wind tunnel models studies are required. The interaction of plumes with buildings and other structures is the major factor affecting short-range dispersion of atmospheric pollutants in urban areas.

Both numerical and physical models are important instruments for assessing the pollutants dispersion in the atmosphere. A large number of commercial and research numerical models are currently available for a wide range of different applications, depending on the specific characteristics of the study. The evaluation of the numerical code accuracy and the definition of the optimal set-up are very important tasks. Small scale physical models are very useful for developing, improving or testing numerical codes.

In this application, the dispersion in an urban area was modeled, in order to evaluate the characteristic time for the concentration decay in the system. Starting from these considerations, the aim of this study was to build an experimental dataset useful for characterizing the physical processes involved in the dispersion phenomena and for calibrating the numerical codes. Experiments have been carried out in a wind tunnel for characterizing the dispersion of a pollutant around a scale model (1:400), which represented a group of ten-floor buildings surrounding a square. The measurements of the variation in the concentrations have been performed by means of a fast photo-detection technique and the velocity field has been evaluated with the particle image velocimetry (PIV) approach.

The temporal variation of the concentration due to the turbulent dispersion is exponential and, therefore, the characterization of the process may be performed by the measurement of the time constant for the variation in the concentration. A fog machine was used as the pollutant source. The particulate material allowed for the flow visualization and it was also employed in the determination of the velocity field when using the PIV technique.

2. Experimental Set-up

The experiments were undertaken in the wind tunnel projected and built in the Thermo-sciences Laboratory of the Mechanical Engineering Department at PUC-Rio, located in Rio de Janeiro, Brazil. The tunnel is of the open type. The working section of the tunnel has $150cm$ length $\times$ $50cm$ width $\times$ $35cm$ height. The tunnel was project to operate in a velocity range which is continuously variable from about 0.3 to $28m/s$. The velocity profile was verified by visualization and also by the PIV (Particle Image Velocimetry) technique measurements (between 0.5 to $10m/s$). The characterization of the freestream turbulence intensity and the turbulence length scale were not accomplished yet, because only now a hot wire anemometer is available in the laboratory. Considering the flow visualization and the project of the flow straightening screens in the wind tunnel inlet contraction, it is expected the freestream turbulence level to be less than 1% and the turbulence integral scale to be smaller than $1mm$. Entry of the air to the working section takes place through a $8.25:1$ contraction. Air leaves it through a 4.2º / 6.7º diffuser and transformation to a round cross section leading to the fan. After the fan, the air is exhausted directly to the atmosphere. Air movement is achieved using a fan of axial type, powered by an 8 HP, ac induction motor. Fan speed is controlled by a variable-frequency, transistor-inverter speed controller.

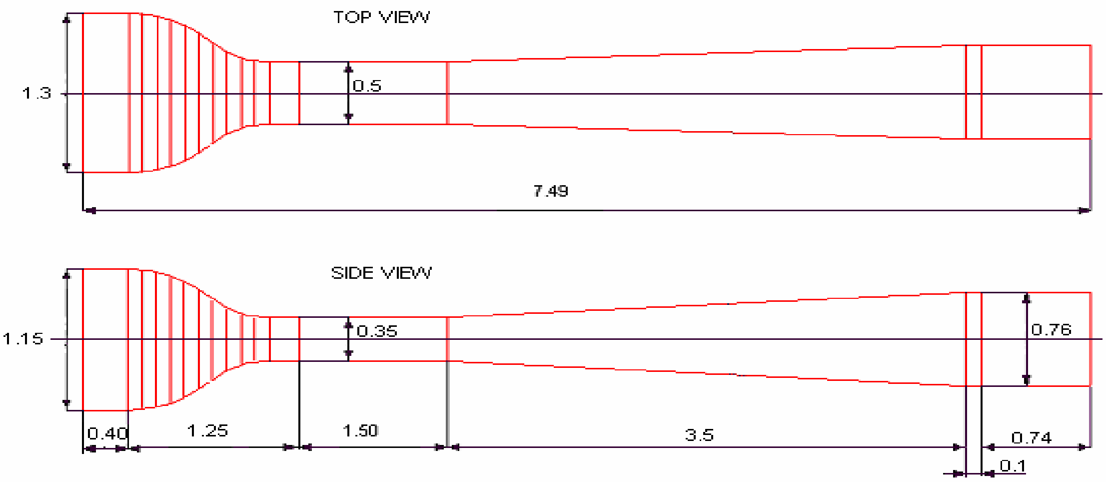


Figure 1 – Wind tunnel – The dimensions are presented in meters.

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 and Sano, A.M., 2003) and based in the attenuation of light. This system was composed by pairs of emitter-detector optic devices, corresponding to light emitting diodes (LEDs) and photo-transistors as the sensors.

A small-scale model was employed for the representation of the urban environment in the wind tunnel experiments. The scaled model (scaling factor: 1:400) simulates a group of eight ten-floor buildings surrounding a square (see figure 2). Eight pairs of emitter-detector optic sensors were positioned between the buildings, across the street canyons as shown in figure 3. This system was controled 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.

On this system assembly it was first necessary determining which optic-eletronic dispositives would 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 between other devices to be the system photo detector after an evaluation of some related parameters such as spectral response (it reaches the 700 nm wave length, corresponding to the light emitted by the LED), time response in microseconds order, size and lower cost.

The optic sensors (emitter-detectors) were positoned at the center of specific (see figure 3) building walls so that the incident luminous signal from a sensors pair didn´t interfere with other pairs and neither was affected by the laboratory illumination. The optic system worked based on the opacity associated to the fog presence. The tension signals at the detectors measured the variation of the incident light (generated by the emitters). This variation of incident light was related to the opacity caused by fog presence. An eletronic circuit was developed for providing the conditioning of the signals generated by the optic devices.

Figure 2 – Small-scale (1:400) model of an urban area.

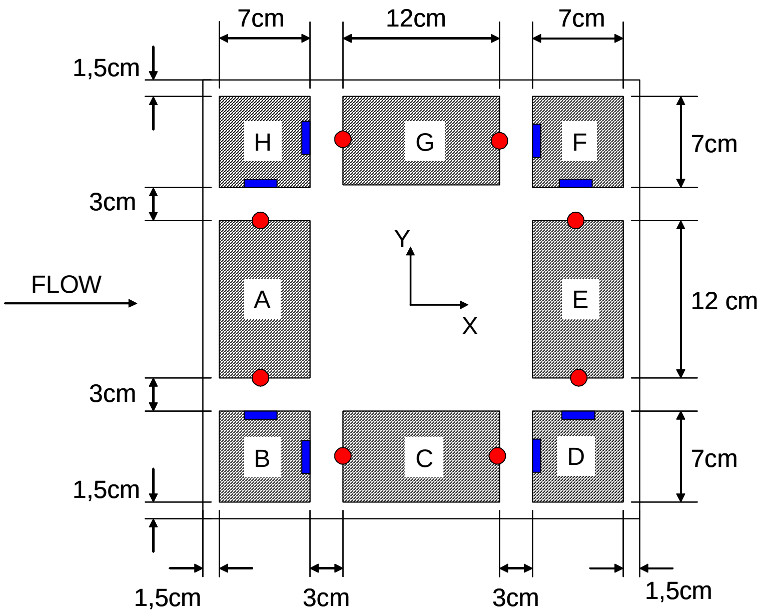


Figure 3 – Maquette geometry: LEDs (red) and photo-detectors (blue) arrangement. The flow direction corresponds to the x axis. Building height is $L = 10cm$. Vertical location d of the sensors is half building height $d = 5cm$.

The Particle Image Velocimetry (PIV) system from TSI was employed for the velocity measurements in the wind tunnel. 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 CCD 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. One of the prototype buildings was made from transparent glass, permiting the flow visualisation in the central region at the maquette. The calibration for the standard dimension was achieved by means of a known lenght at the captured images.

Tests were performed with different inlet flow velocities in the wind tunnel. The free stream velocities during the tests were $U = 1,3 m/s$, $U = 2,5\ m/s$, $U = 4,9 m/s$ and $U = 9,6 m/s$.

A commercial fog machine was employed in the experiments. The fog allowed for the flow visualization and it was employed in the determination of the velocity field when using the particle image velocimetry technique. Due to the small size of the fog particles (particle aerodynamic diameter < 2 to 5 micron), they perfectly follow the flow. Therefore, the fog may be used for tracking the flow particles. In situations where turbulence dominates the dispersion phenomenon, the fog may also be used for simulating the pollutant dispersion.

The continuous emitting fog source was positioned in the wind tunnel test section 44 cm upwind of the urban area prototype. The fog was injected by a 3 mm in diameter and 35 cm long metal tube, a small device with aerodynamic shape positioned 7 cm above the floor of the test section. Four equidistant orifices in the tube provided for the fog injection in the test section. The injection velocity was low enough to ensure that the source momentum effects were not significant. The presence of the source tube causes some perturbation on the flow, increasing the turbulence (and the pollutant dispersion) upwind of the model. However, on the model region where the optic sensors were located, these perturbations are secondary and the dispersion phenomenon is dominated by the large scale separated flow in the surroundings of the buildings.

Measurements for the change in the concentration of the tracer (fog) were performed by the emitter-detector system. The local concentration was related to the attenuation of light due to the presence of fog in the optical path between each emitter and detector pair. 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. Therefore, the main interest was to measure the variations in the concentration. For a given experimental condition of the free stream velocity (U), 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 (Gomes et at., 1997) was performed in the following sequence:

1. The fog source was turned on for a brief period of time, usually on the order of 3 s, and then turned off, thus producing a sharp discontinuity (or "front") in 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 each of the emission-detector optical sensors. During the time that the "front" was transported from the point of generation to the measurement location, the average attenuated signal remained at a constant value. This lowest signal 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 trace from the average maximum value; (ii) Division of this trace by the average initial signal (average 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 electronic filtering which might distort 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 analysed. For this purpose, approximately two decades were chosen between the relative signal values. An exponential function was fitted to the experimental curve by least square regression, and the value of the time constant (τ) of the decay was therefore obtained.

The measured signal corresponds to the attenuation of the light beam, which is directly related to the pollutant (fog) concentration at the optical path between the emmiter and the detector. A typical normalized trace of the measured signal along the elapsed time, for a certain location at the model, may look like:

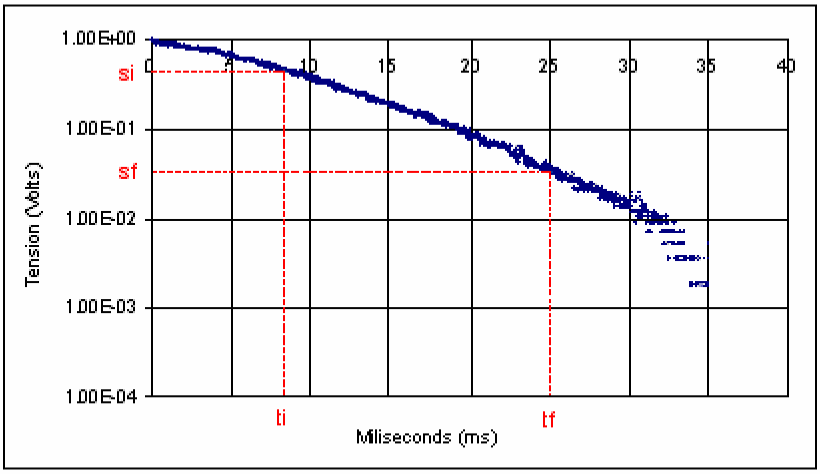


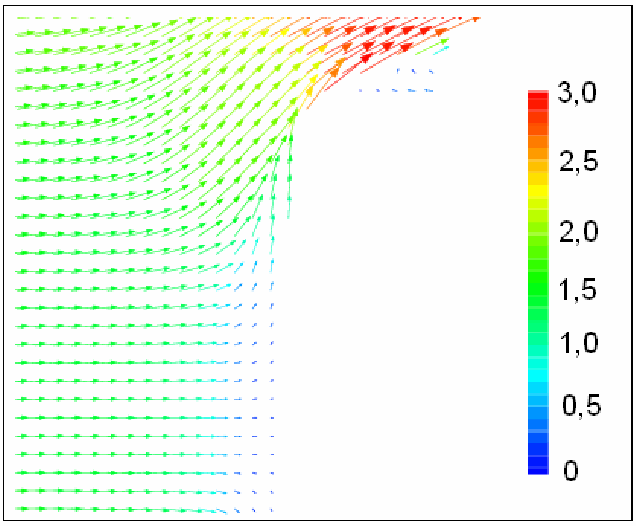
Figure 4 - A typical normalized trace of the measured signal (tension associated with particulates concentration level) along the elapsed time, for a certain location at the model, as function of time t.

3. Results

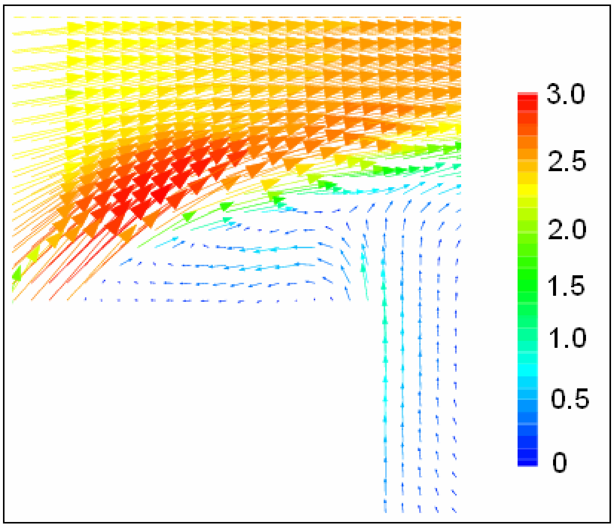
The physical modeling in wind tunnels is very valuable because the small scale experiments permit the control of the parameters governing the problem, allowing for a better comprehension about a particular phenomenon. However, it is important to observe that these experiments do not reproduce some important characteristics of the pollutant dispersion in the real scale. One important limitation corresponds to the impossibility to reproduce, in laboratory, the large scale horizontal oscillations of the wind which occurs in the atmosphere. In this way, the extrapolation of wind tunnel results to full scale situations requires some caution. For bluff bodies, such as the buildings (model) used here, there is a minimum Reynolds number of about 10^4 required to maintain adequate turbulent flow (Mavroids et al., 2003). For the wind tunnel experiments the Reynolds number was in the range of $8{,}4\times10^3$ to $6{,}4\times10^4$ which was sufficient to maintain a turbulent flow pattern.

Another important consideration is related to the flow velocity profile impinging on urban buildings. There are two length scales associated with the flow around a building, those from disturbances to the airflow generated by the building itself and those of the approaching boundary layer wind field. The interaction between these two flows governs the plume dispersion pattern around the building. Generally, the near-field flow pattern is dominated by the obstacle scale and the far field by the wind field, but the degree of overlap of these combined effects in the near field is considerable (Mavroids et al., 2003). In the present experiments, as a first approach, a uniform velocity profile was employed for the wind simulation, which is not realistically representative of an atmospheric boundary layer. Also, the surface layer scaling was not taken into account, considering that, on the model location (where the optic sensors were located), the dispersion phenomenon is dominated by the large scale separated flow, which is promoted by the sharp building geometries. The wind tunnel experiments, presented in this paper, were concerned only with neutrally stable atmospheres.

Fields of velocity vectors on the plane y = 0 (see figure 3), obtained by means of the particle image velocimetry (PIV) technique, are presented in figures 5 and 6. Figure 5 (a) shows that, as the mean flow approaches building A, it decelerates longitudinally and accelerates vertically to pass around it. The velocity vectors in the region above the building A are presented in figure 5 (b) for the same freestream velocity (U=2.5 m/s). The flow separates above the buiding and a small recirculation is observed in this region. Figure 6 represents the velocity field in the recirculation region between buildings A and E, for a free stream velocity corresponding to U = 2.5 m/s. This recirculation is responsible for capturing the pollutant and extending the dispersion process for some time after the original pollutant (fog) source have been interrupted.



(a)



(b)

Figure 5 – Velocity vectors (m/s) on plane y = 0 for U = 2.5 m/s (free stream velocity) obtained by means of the PIV technique. (a) Details for the building A impinging flow area and (b) flow area above building A.

Preliminary experiments were carried out in which concentration decays were obtained for measurement at the eight locations by the pairs of emitter-detector optic sensors positioned between the buildings. The results (not shown) revealed that, for a specific velocity and geometry condition, differences between the measured values of τ were much smaller than the experimental uncertainty. Thus, it was concluded that the rate of concentration decay was independent of where the measure was made, confirming what was found in studies for bluff bodies of different shapes (e.g., Humphries and Vincent, 1976; Vincent, 1977).

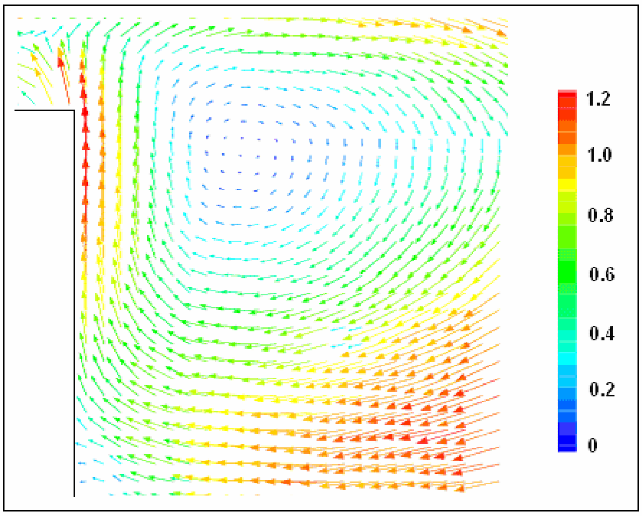


Figure 6 – Velocity vectors (m/s) on plane y = 0 for U = 2.5 m/s (free stream velocity) obtained by means of the PIV technique: details of the recirculation area between buildings A and E.

Figure 7 presents the experimental values measured for the time constant (τ) for the concentration decay plotted against Reynolds number (based on the building height L). The error bars describe the uncertainty in the measure of τ as represented by 2 standard deviations (i.e., covering a 95.4% confidence interval). The figure shows that for higher values of Reynolds number the values for τ decrease. This result coherently indicated that the urban area cleaning process was faster for situations where the wind was more intense.

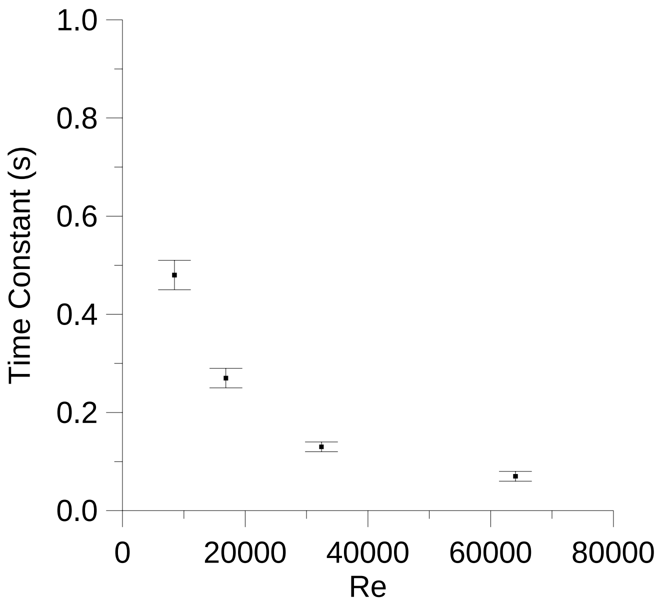


Figure 7 – Experimental results for τ (time constant for concentration decay) versus Reynolds number. The experimental values presented are (Re, τ) : $(8455; 0,48 \pm 0,03s)$, $(16844; 0,27 \pm 0,02s)$, $(32423; 0,13 \pm 0,01s)$, $(64046; 0,07 \pm 0,01s)$.

It's convenient calculate a non-dimensional time H , where H can be defined as (Gomes et al., 1997):

$$H = \frac{\tau\, U}{L}$$

where U and L are, respectively, the characteristic velocity and characteristic length of the system (building height).

Figure 8 presents the results for the non-dimensional time H versus Reynolds number. The results show that the values of H found in the experiments were $H = 6.7 \pm 1.0$ for $\text{Re} > 8000$. The values of H were found independent of the Reynolds number for the values of Re investigated (8000 to 65000). In Gomes et al. (1997), a study conducted for the investigation of the dispersion process in the near wake region of a two-dimensional flat plate placed normal to the free stream, it was found that the values of H ($H = 9.5 \pm 1.5$) became independent of Re for $\mathrm{Re} > 4000$. In this study, the aerosol was released upwind from the plate from a two-dimensional line source. MacLennan and Vincent (1982), who investigated this same geometry, reported on values for H of about 5, for $\mathrm{Re} > 4000$. The reasons for the difference were explained in terms of the two-dimensionality of the aerosol transport processes in the Gomes et al. experiments, as opposed to the tri-dimensional MacLennan and Vincent experiments. In this study, the aerosol was introduced into the upstream flow from a point source. The particle concentration in the near wake of the flat plate was therefore influenced not only by transport of particles across the near wake boundary by a combination of freestream turbulence and vortex shedding, but also by lateral particle dispersion inside the near wake region. This effect provided a mechanism for a more rapid fall in the local aerosol concentration, and hence for a smaller τ and H.

The geometry considered in the present work provided a flow recirculation formation in the central area of the model (see figure 6), which was responsible for capturing the particles released from a line source (simulated by four point sources aligned on a tube across the tunnel width) and for extending the dispersion process. The tri-dimensionality of the small-scale urban area model investigated in the present work allows for the particle dispersion to take place in all directions. On the other hand, the cavity formed by the central area surrounded by the eight buildings is a much more restrictive geometry, with respect to the pollutant dispersion, than the ones investigated by Gomes et al. and MacLennan and Vincent (flat plates). It is interesting to observe that the values of H found in the present investigation were higher than those found in MacLennan and Vincent, and were lower then those found in Gomes et al. This may indicate that the tri-dimensional effects made the dispersion process more effective and were as important as the restrictions imposed in the dispersion by the cavity geometry.

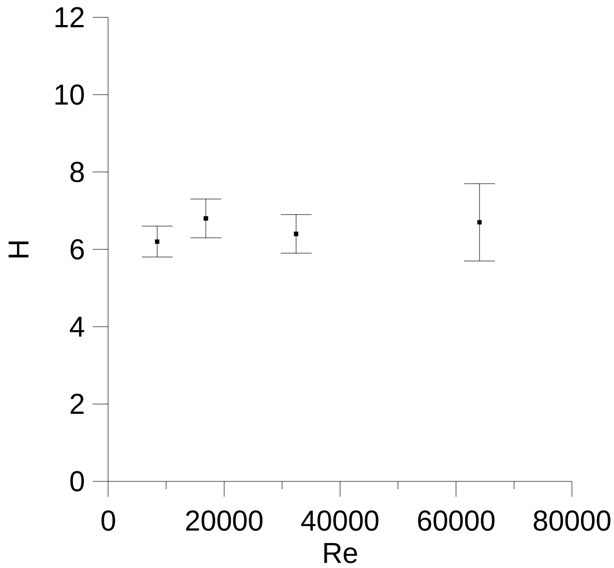


Figure 8– Experimental results for H (non-dimensional time for concentration decay) versus Re. The experimental values presented are (Re, H): $(8455;\ 6,2 \pm 0,4)$, $(16844;\ 6,8 \pm 0,5)$, $(32423;\ 6,4 \pm 0,5)$, $(64046;\ 6,7 \pm 1,0)$.

4. Conclusions

The concentrations decay was investigated in a wind tunnel simulation for the dispersion process in an urban area. Also the wind flow in such conditions was assessed. The urban environment was simulated by a laboratory scale model representing a typical block of a big city, composed by eight buildings surrounding a square. The velocities inside the test section of the wind tunnel were measured by means of Particle Image Velocimetry (PIV) technique. The concentrations decay was evaluated by means of a fast photo-detection technique, based in the attenuation of light. The wind tunnel experiments, presented in this paper, were concerned only with neutrally stable atmospheres.

A fog machine was employed in the experiments allowing for the flow visualization and it was employed in the determination of the velocity field when using the particle image velocimetry technique. The concentration experiments consisted in interrupting the pollutant emission (fog) in a specific instant of time and measuring the particulates concentration decay from this moment on. The same procedure was performed for different inlet velocities conditions.

The extrapolation of wind tunnel results to full scale situations requires some caution. One important limitation corresponds to the impossibility to reproduce, in laboratory, the large scale horizontal oscillations of the wind which occurs in the atmosphere. The surface layer scaling was not taken into account in the present inquiry, considering that, on the model location (where the optic sensors were located), the dispersion phenomenon was dominated by the large scale separated flow, which is promoted by the sharp building geometries.

Flow velocity fields over the small-scale model were presented. An important flow recirculation was identified at the central region of the urban area prototype, a cavity surronded by the eight buildings. This recirculation was responsible for capturing the pollutant and extending the dispersion process for some time after the original source has been interrupted.

It was found that, for a specific velocity and geometry condition, differences between the measured values of time constant were much smaller than the experimental uncertainty. It was then considered that the time constant was independent of where the measure was made, confirming what was found in studies for bluff bodies of different shapes (e.g., Humphries and Vincent, 1976; Vincent, 1977).

Results for the concentration decay constant time versus Reynolds number were presented. Non-dimensional time H ($H = \tau U / L$, where τ is the characteristic time constant, U is the free-stream velocity, and L is a characteristic dimension for the urban geometry) related to the concentration decay was also presented as function of the Reynolds number. The experimental results showed that the time constant for the concentration decay in the system fell as Re increased. The results also showed that the values for dimensionless time H were $H = 6.7 \pm 1.0$ for $\mathrm{Re} > 8000$. The values of H were found independent of Re for the range investigated: $65000 > \mathrm{Re} > 8000$. This result was in accordance with the conclusions from others authors in works found in the literature: Gomes et al. (1997) and MacLennan and Vincent (1982). Both investigated the concentration decay in the near wake region of a two-dimensional flat plate. The values found for the dimensionless time H in the present paper were lower than those found by Gomes et al. and were higher than those found by MacLennan and Vincent. The deviations found in the works results were associated to relevant differences in the investigated geometries.

5. Acknowledgements

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7. Responsibility Notes

The authors are the only responsible for the printed material included in this paper.