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On the Lagrangian and Eulerian Time Scale of the Turbulence within a Two-Dimensional Array of Obstacles

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Abstract

Fields of Lagrangian (T^L) and Eulerian (T^E) time scales of the turbulence within a regular array of two-dimensional obstacles of unit aspect ratio have been determined by means of a water-channel experiment reproducing a neutral boundary layer. It has been found a strong spatial inhomogeneity of both the scales and their ratio, $\beta = T^L/T^E$. The results provide useful information for numerical modelling of pollutant dispersion in urban areas.

Keywords Feature tracking • Canyon • RANS • Turbulence closure • Turbulent dispersion

1 Introduction

Pollutant dispersion can be simulated numerically via the Lagrangian approach, where the concentration field is calculated by simulating the trajectories of fictitious particles released from the source (Thomson 1987). That requires knowledge of the Lagrangian integral time scale of the turbulence, $T^L = \int_0^\infty \rho^L(\tau) d\tau$ (ρ^L is the Lagrangian autocorrelation function of the velocity (Monin and Yaglom 1971) and $d\tau$ is the time lag). Since the direct measurement of T^L requires particle trajectories long enough to get meaningful ρ^L, its estimation is not an easy task, especially in the case of canopy flows (Shnapp et al. 2020).

Knowledge of T^L is also of interest also for simulating pollutant dispersion via the Eulerian approach, in which the concentration can be calculated through Reynolds-averaged Navier–Stokes (RANS) models. As a matter of fact, in this approach, one of the open problems is the choice of the turbulent diffusivity of mass, D_t. Kikumoto (2020)

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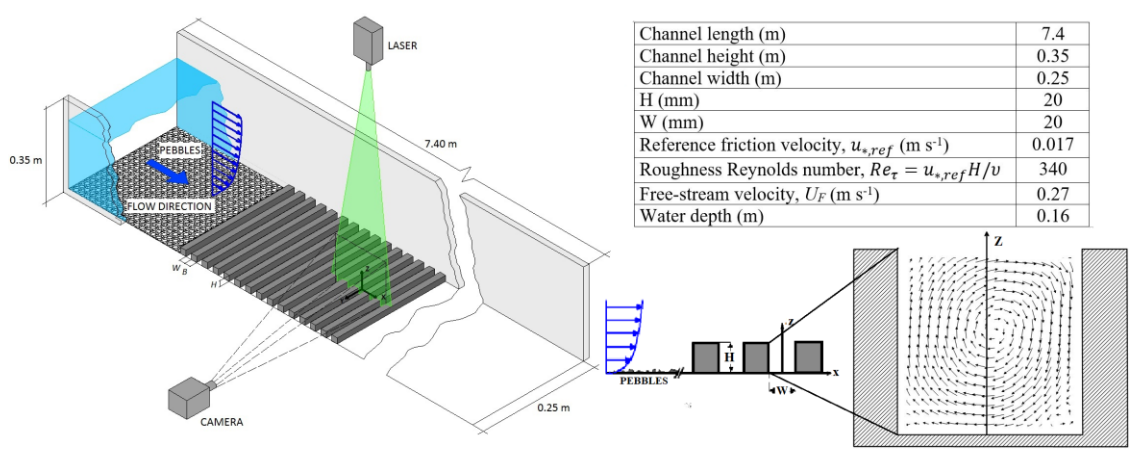
introduced the concept of "concentration diffusivity limiter with travel time", by which it is possible to model D_t with the flight time scaled by T^L.

Since Eulerian statistics can be easily determined from fixed-point measurements, a convenient alternative to the direct estimation of T^L is to measure T^E and then evaluate the Lagrangian scale by means of the coefficient β: $T^L = \beta T^E$ (Corrsin 1963), where $T^E = \int_0^\infty \rho^E d\tau$ is the Eulerian time scale of the turbulence and ρ^E is the Eulerian velocity autocorrelation function. β is a parameter greater than unity, whose value is generally obtained empirically from experimental and numerical experiments (Fattal 2021), obtaining expressions that are valid for flat terrain (Anfossi et al. 2006), sparse urban canopies (Nironi et al. 2015), or above arrays of obstacles (Di Bernardino et al. 2017). However, to our knowledge, β has not still determined within urban canyons.

The aim of this study is the evaluation of β within a two-dimensional canyon with unit aspect ratio (AR=1) that, to our knowledge, has never been investigated.

2 Experimental Setup and Time Scales Measurements

The experimental set-up and conditions are the same as in Di Bernardino et al. (2015), to which the reader is referred for all the details. Figure 1 shows the water channel and some of the main parameters of the experiment. Fluid particle velocities were measured by a feature tracking technique (Cenedese et al. 2005) over a rectangular region 60 mm long (x-axis) and 40 mm high (z-axis), lying on the vertical x–z plane passing through the centre of the channel and aligned with the mean flow.



Channel length (m)	7.4
Channel height (m)	0.35
Channel width (m)	0.25
H (mm)	20
W (mm)	20
Reference friction velocity, $u_{*,ref}$ (m s^{-1})	0.017
Roughness Reynolds number, $Re_\tau = u_{*,ref} H/\upsilon$	340
Free-stream velocity, U_F (m s^{-1})	0.27
Water depth (m)	0.16

Fig. 1 Layout of the experimental set-up and list of the main experimental variables. The vector map reports the average velocity field

A 2-mm thick laser light sheet (5-W) illuminated the measurement plane. The framed area was located 30 buildings downstream of the first building so as to minimize any influence from the change in roughness between the roughness elements (pebbles) and the building array. 10,000 images were acquired during the experiment by means of a high-speed video camera at 250 Hz. The dataset consists of about 3000 sparse velocity samples per frame.

Both the Eulerian and Lagrangian autocorrelations were calculated in the cavity based on the magnitude of the velocity vector, $u = |\boldsymbol{u}|$: $\rho^E(\tau) = \left(\overline{u'(t)u'(t+\tau)}\right)/\sigma^2$, where prime indicates the fluctuation around the mean, the overbar is the time average, σ^2 is the variance of u, and t the time. The trajectories of synthetic fluid particles were reconstructed by integrating the instantaneous (Eulerian) 2D velocity fields following the procedure described in Stocchino et al. (2011). The procedure assumes that crossflow motions are non-dominant as observed in the symmetry plane of two-dimensional canopies by Di Bernardino et al. (2017). Then, $\rho^L(\boldsymbol{x},\tau)$, was computed using the expression of the Lagrangian autocorrelation function reported in Di Bernardino et al. (2017) where the details of the procedure can be found. Under the assumption of (Eulerian) statistical stationarity, the statistical ensemble of trajectories used for the computation of the Lagrangian autocorrelation was obtained releasing a set of 50 particles with a random initial position in the neighbourhood of $\boldsymbol{x}$ (Gaussian distribution with a 0.05H standard deviation, with H indicating the building height) at 5 frame intervals, thus resulting in a dataset of 100,000 trajectories per each initial position. Correlations and integral time scales were computed within the canyon on a set of initial positions consisting of a 7x7 equispaced grid.

3 Results and Discussion

Figure 2a-c show the maps of T^L, T^E, and β, respectively. The reader can refer to Di Bernardino et al. (2015) and (2017) for other turbulence statistics, as well as for the vertical profiles of T^L and T^E above the canopy. Both scales have been normalized by H/U_F, where U_F is the free-stream velocity. The salient feature of T^L (Fig. 2a) is the presence of a maximum localized at the center of the cavity vortex (see Fig. 1), where particles tend to circulate longer. Lower T^L are confined within the shear layer at the cavity top, which plays a key role in the exchange of air and scalars between the canopy and the overlying region (Louka et al. 2000).

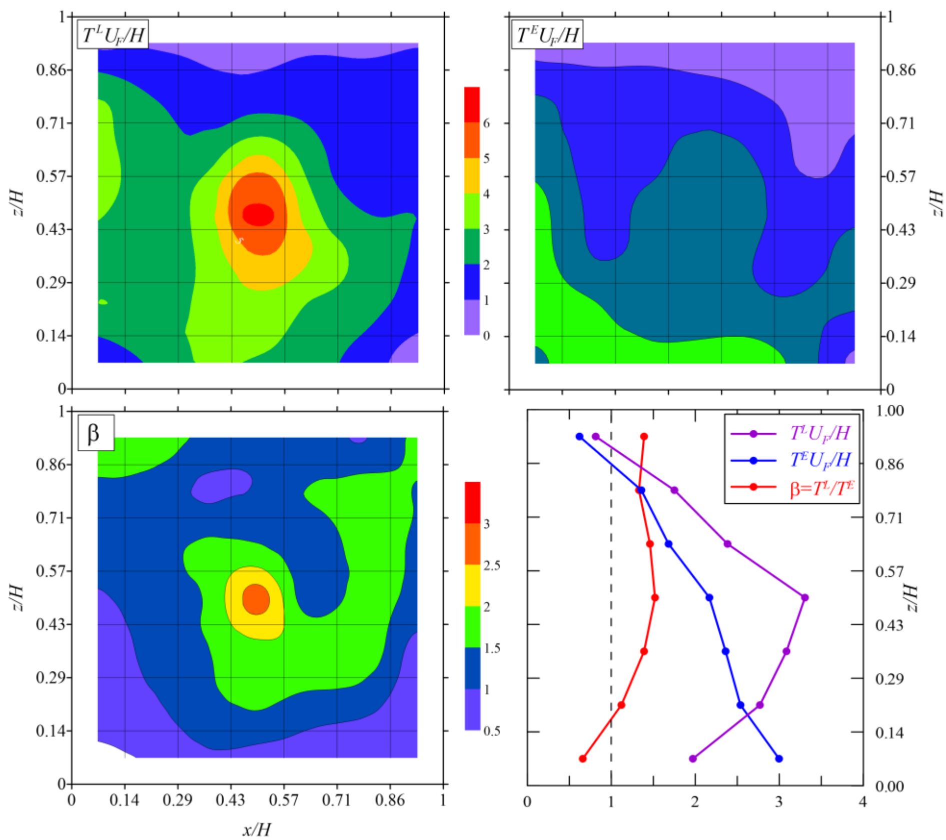


Fig. 2 Maps of T^L(panel a) and T^E (panel b), normalized by T_S and $\beta = T^L/T^E$ (panel c). Panel (d) shows the vertical profiles of T^L, T^E and β averaged horizontally within the cavity

It is worth mentioning that the T^L maximum is $\sim 0.5\ T_S$ (here, $T_S = H/u_{*,ref} = 1.17$ s is the characteristic time scale of the cavity), while the mean T^L in the cavity is $\sim 0.15 T_S$. From this it can be deduced that the assumption of T^L constancy must be taken with the due caution (see also Fig. 2d, where the vertical profile of T^L averaged along the horizontal is shown). In contrast, T^E decreases with the height and it is lower than T^L except that near the bottom. Apart from the lower region, the ratio $\beta = T^L/T^E$ is generally higher than one and shows a maximum (~3) in the middle of the cavity, i.e., where T^L is a maximum.

The average β in the cavity is about 1.3, not far from $\beta = 1.5$ chosen by Lin et al. (2021) in their RANS model to optimize the simulated concentration field within a square cavity (AR=1). Conversely, the uneven distribution of T^L differs from that published by Shnapp et al. (2020), where T^L was practically independent of height. A possible reason could be the different geometrical configuration considered by those authors, i.e., a highly inhomogeneous, three-dimensional canopy.

References

Anfossi D, Rizza U, Mangia C, Degrazia GA, Pereira Marques Filho E (2006) Estimation of the ratio between the Lagrangian and Eulerian time scales in an atmospheric boundary layer generated by large eddy simulation. Atmos Environ 40:326–337

Cenedese A, Del Prete Z, Miozzi M, Querzoli G (2005) A laboratory investigation of the flow in the left ventricle of a human heart with prosthetic, tilting-disk valves. Exp Fluids 39:322–335

Corrsin S (1963) Estimates of the relations between Eulerian and Lagrangian scales in large Reynolds number turbulence. J Atmos Sci 20:115–119

Di Bernardino A, Monti P, Leuzzi G, Querzoli G (2015) Water-channel study of flow and turbulence past a two-dimensional array of obstacles. Bound-Layer Meteorol 155:73–85

Di Bernardino A, Monti P, Leuzzi G, Querzoli G (2017) Water-channel estimation of Eulerian and Lagrangian time scales of the turbulence in idealized two-dimensional urban canopies. Bound-Layer Meteorol 165:251–276

Fattal E, David-Saroussi H, Klausner Z, Buchman O (2021) An Urban Lagrangian Stochastic Dispersion Model for Simulating Traffic Particulate-Matter Concentration Fields. Atmosphere 12:580

Kikumoto H (2020) Turbulent diffusivity limiter with travel time for CFD-Eulerian analysis of point-source pollutant dispersion. Wind Eng. Res. 26:148–156.

Lin C, Ooka R, Kikumoto H, Jia H (2021) Eulerian RANS simulations of near-field pollutant dispersion around buildings using concentration diffusivity limiter with travel time. Build Environ 202:108047

Monin AS, Yaglom AM (1971) Statistical Fluid Mechanics. Vol. 1 MIT Press

Louka P, Belcher SE, Harrison RG (2000) Coupling between air flow in streets and the well-developed boundary layer aloft. Atmos. Environ. 34: 2613-2621.

Nironi C, et al. (2015) Dispersion of a Passive Scalar Fluctuating Plume in a Turbulent Boundary Layer. Part I: Velocity and Concentration Measurements. Boundary-Layer Meteorol 156:415–446

Shnapp R, Bohbot-Raviv Y, Liberzon A, Fattal E (2020) Turbulence-obstacle interactions in the Lagrangian framework: applications for stochastic modeling in canopy flows. Phys. Rev. Fluids 5: 094601

Stocchino A, Besio G, Angiolani S, Brocchini M (2011) Lagrangian mixing in straight compound channels. J Fluid Mech 675:168–198

Thomson DJ (1987) Criteria for the selection of stochastic models of particle trajectories in turbulent flows. J Fluid Mech 180:529–556