TURBULENT SCHMIDT NUMBER ESTIMATE OVER URBAN CANOPIES

Annalisa Di Bernardino[1], Paolo Monti[1], Giovanni Leuzzi[1] Fabio Sammartino[1] and Giorgio Querzoli[2]

[1] DICEA, University of Rome "La Sapienza", Via Eudossiana 18, Rome, Italy.

[2] Dipartimento di Ingegneria del Territorio, Università di Cagliari, Cagliari, Italy.

SAPIENZA UNIVERSITÀ DI ROMA

DICEA - DIPARTIMENTO DI INGEGNERIA CIVILE, EDILE ED AMBIENTALE

1 INTRODUCTION

Urban environments are usually studied (numerically and experimentally) by considering simplified building geometries by using arrays of obstacles with archetypal arrangements (Oke, 1988; Badas et al., 2018).

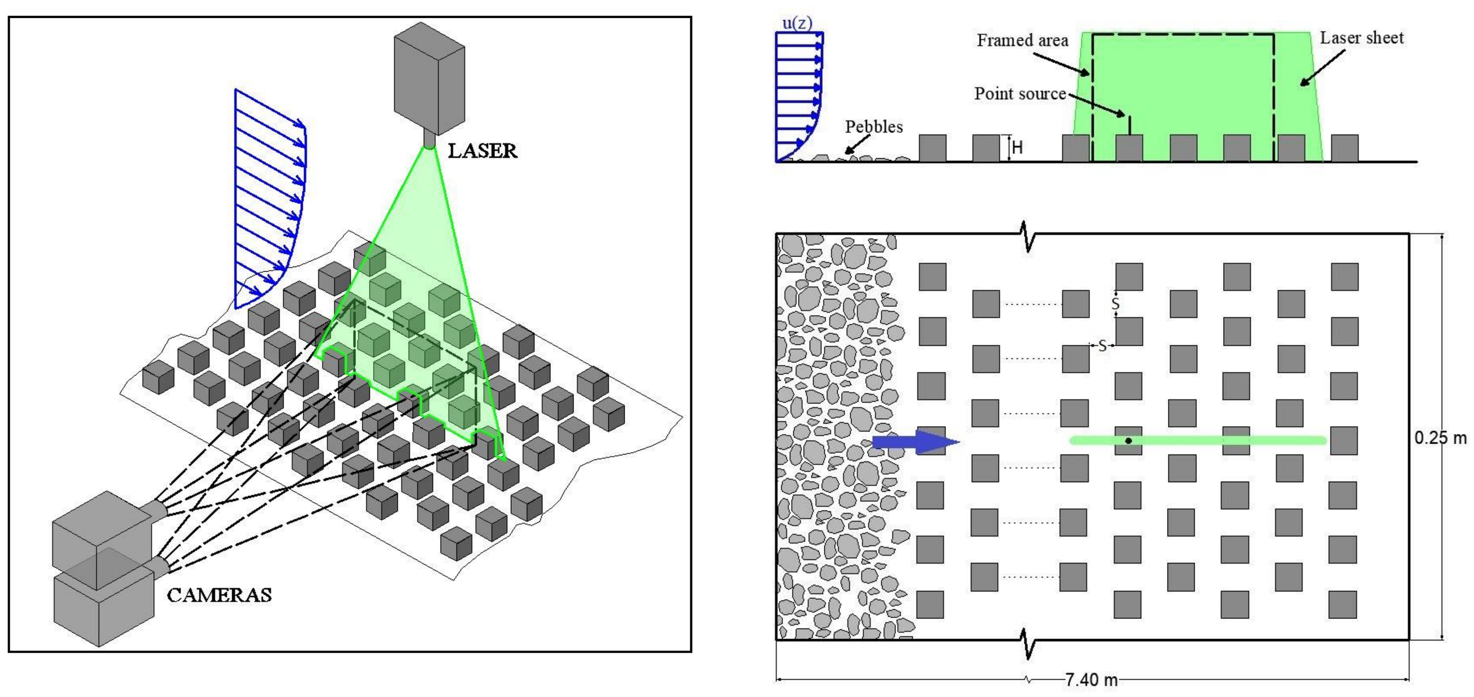
Since pollutant dispersion in cities is mostly investigated numerically through Reynolds-Averaged Navier-Stokes models, a question arises regarding the values to assign to the turbulent mass and momentum fluxes in the governing equations. These unknowns are currently modelled by using first-order closures, which involve the definition of exchange coefficients such as the eddy diffusivities of momentum (K_M) and mass (D_t).

In current practice, K_M is assumed proportional to the turbulent kinetic energy and to its rate of dissipation, while $D_t = K_M(Sc_t)^{-1}$, where Sc_t is the turbulent Schmidt number. The choice of Sc_t is not straightforward and influences considerably the numerical results. It must be set prior the simulation and it is generally assumed to fall in the range 0.2-1.3 (Blocken et al., 2008). Experimental estimates of Sc_t require the simultaneous knowledge of turbulent fluxes of momentum and scalars, generally obtained in the laboratory (Monti et al., 2007; Carpentieri et al., 2012; Nosek et al., 2016; Tomas et al., 2017; Di Bernardino et al., 2018).

2 METHOD

- Laboratory estimation of the turbulent Schmidt number above an idealized three-dimensional urban canopy
- Reproduction of a urban canopy by means of staggered array of cubic obstacles of equal heights with plan area index, λ_P=0.25, placed on the channel bottom
- A point source emitted a passive tracer at a constant rate above the cube array
- Simultaneous measurements of pollutant concentration and velocity permitted the estimation of the vertical fluxes of mass and momentum
- K_M and D_t were estimated in order to investigate the dependence of Sc_t on the height above the canopy

3 EXPERIMENTAL SETUP



FLOW CHARACTERISTICS

- height: 0.35 m
- width: 0.25 m
- length: 7.40 m
- water depth: 0.16 m

The test section is located 5.0 m downwind of the inlet, where the boundary layer under neutral conditions is fully-developed. This condition is realized thanks to small pebbles that cover the channel bottom upstream the buildings.

- obstacles **H=0.015 m**
- free stream velocity (U): 0.34 m s^{-1}
- Reynolds number: ≅ **400** (considering the friction velocity)

SOURCE CHARACTERISTICS

Pollutant emission simulated by a mixture of water and Rhodamine-WT, continuously released by the source located at the center of the upwind building belonging to the interrogation area.

GEOMETRICAL CONFIGURATION

λ_P = 0.25 (wake interference regime)

ACQUISITION SYSTEM

- **LD PUMPED ALL-SOLID-STATE GREEN LASER**
  - wavelength: 532 nm
  - power: 5 W
- **RHODAMINE WT – WATER** ($C_{29}H_{29}N_2O_5Cl$)
  - excitation wavelength: 532 nm (green)
  - emission wavelength: 687 nm (red)
  - source concentration: 2.5 x 10^{-3} kg m^{-3}
  - mass flow rate: 11.9x10^{-11} kg s^{-11}
  - source height: 1.67H
- **High Speed-CMOS-Camera**
  - resolution: 1280 x 1024 pixels
  - frame rate: 250 Hz
- **Notch Filter 26.6 nm – 532 nm**

INVESTIGATED AREA

10.2 cm long (x-axis – streamwise direction) and **8.2 cm** height (z-axis – vertical direction).

The origin (x=0, z=0) is defined at the center of the cube located in the central section of the channel, considering x positive downwind and z upward.

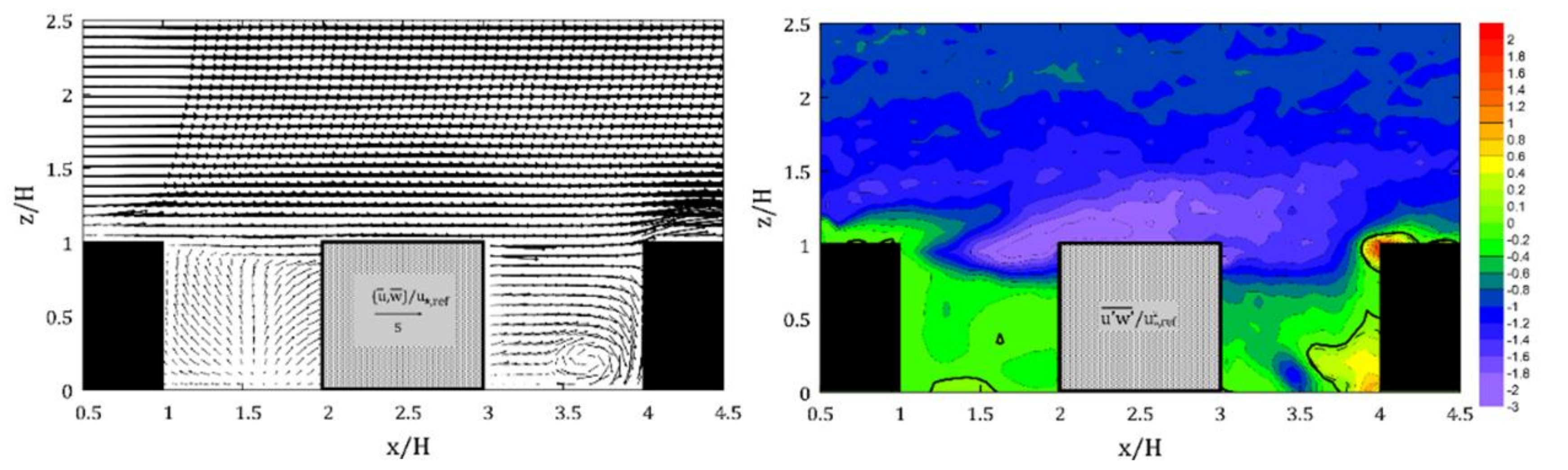
IMAGE ANALYSIS TECHNIQUE

Velocity fields → **Feature Tracking** (FT) algorithm that allows the reconstruction of the velocity field identifying local region of interest (i.e. features) in several consecutive images, based on light intensity gradients, i.e. using lagrangian approach.

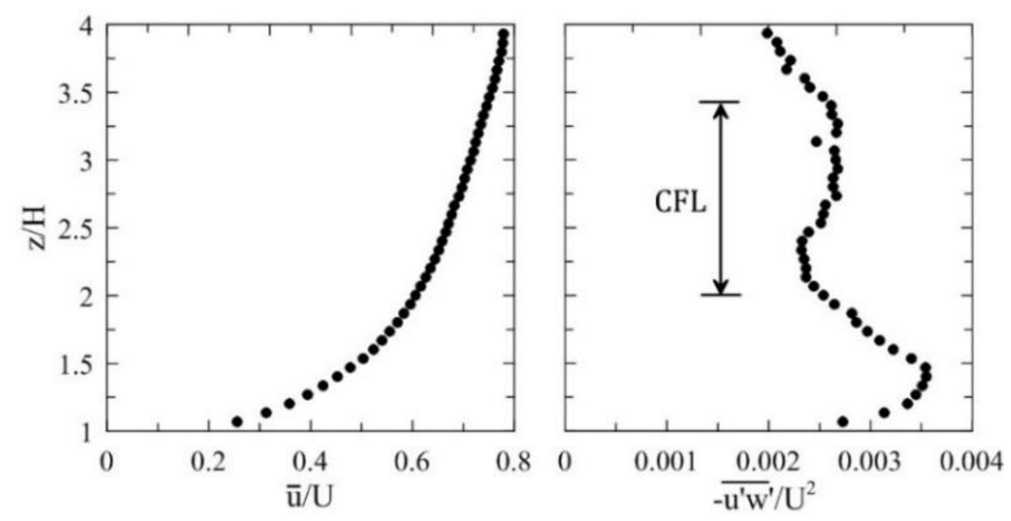
Concentration fields → **Laser-Induced Fluorescence** (LIF). Concentration fields are investigated installing a Notch Filter on the camera, so as to identify only the fluorescent tracer.

Spatial resolution: **0.5 mm**

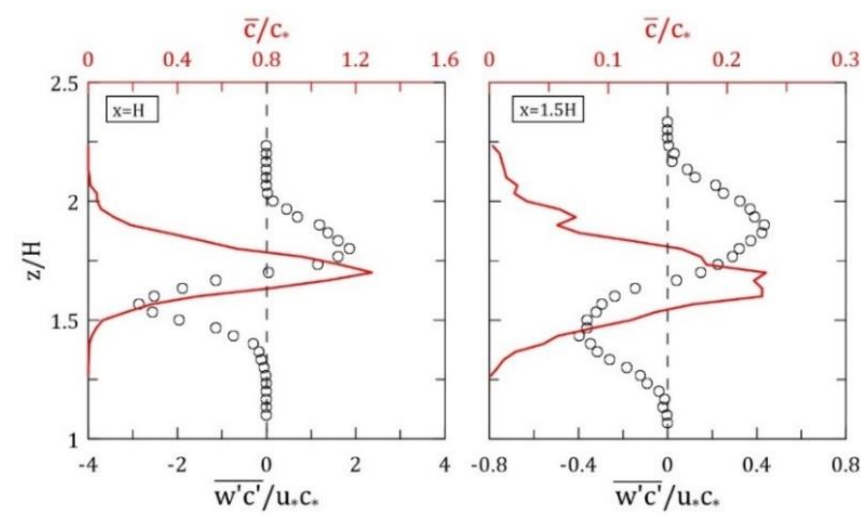
4 RESULTS



Normalized mean velocity (left panel) and vertical momentum flux (right) in the vertical plane passing through the middle of the cubes. The region of optical occlusion due to out-of-plane cubes is shown in grey.



Vertical profiles of the normalized streamwise mean velocity (left panel) and vertical momentum flux (right) in the vertical plane passing through the middle of the cubes.

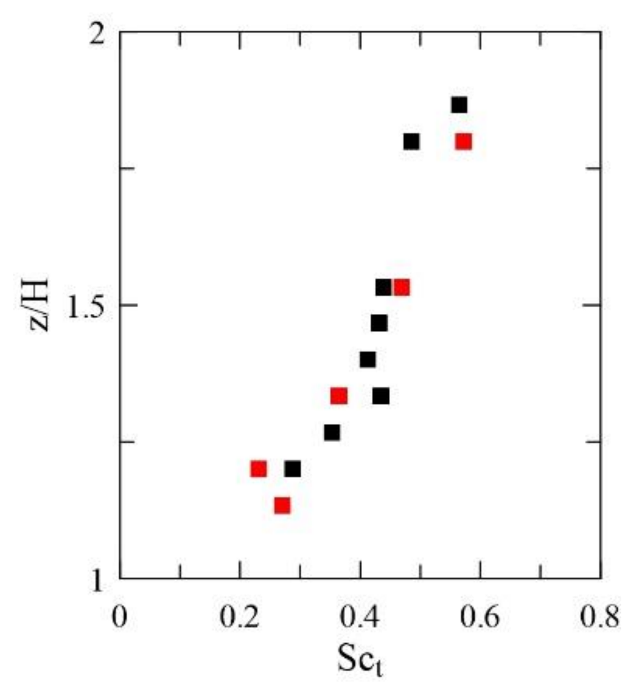


Vertical profiles of the normalized concentration ($\overline{c}/c_*$, red line) and vertical turbulent mass flux ($\overline{w'c'}/u_*c_*$, circles) taken at two downwind distances from the tracer source.

$$K_M = \frac{-\overline{u'w'}}{\frac{\partial \overline{u}}{\partial z}} \qquad D_t = \frac{-\overline{w'c'}}{\partial \overline{c}/\partial z}$$

$$Sc_t = \frac{K_M}{D_t}$$

In current practice Sc_t is assumed as a constant set prior to numerical simulation.
It is sometimes determined after a series of tests conducted at different Sc_t against experimental data (Blocken et al., 2008).



Vertical profiles of the turbulent Schmidt number at x=1.5H (black square) and x=2.5H (red square).

5 CONCLUSIONS

Both the estimated Sc_t show a clear increase with height up to $z \approx 1.75H$, i.e. within the roughness sublayer, and share nearly the same profile. This supports the hypothesis that the two profiles have been taken in a region where Sc_t no longer depends on the downstream distance.

The values obtained fall in the range 0.2-0.6, i.e. in line with other results reported in the literature in the case of flat terrain (Koeltzsch, 2000).

Further investigation is needed to assess reliable Sc_t, taking also into consideration other array geometries.

REFERENCES

- Badas, M.G., M. Garau, A. Seoni, S. Ferrari and G. Querzoli, 2018: Impact of rooftop stack configuration on 2D street canyon air quality. J. Phys.: Conf. Ser. 1110, 012003.
- Blocken, B., T. Stathopoulos, P. Saathoff and X. Wang, 2008: Numerical evaluation of pollutant dispersion in the built environment: Comparison between models and experiments. J. Wind Eng. Ind. Aerod., 96, 1817-1831.
- Carpentieri, M., P. Hayden and A. G. Robins, 2012: Wind tunnel measurements of pollutant turbulent fluxes in urban intersections. Atmos. Environ., 46, 669–674.
- Di Bernardino, A., P. Monti, G. Leuzzi and G. Querzoli, 2018: Pollutant fluxes in two-dimensional street canyons. Urban Clim., 24, 80-93.
- Koeltzsch, K., 2000: The height dependence of the turbulent Schmidt number within the boundary layer. Atmos. Environ., 34, 1147-1151.
- Monti, P., G. Querzoli, A. Cenedese and S. Piccinini, 2007: Mixing properties of a stably stratified parallel shear layer. Phys. Fluids, 19, Article number 085104 (1-9). DOI: 10.1063/1.2756580.
- Nosek, S., L. Kukačka, R. Kellnerová, K. Jurčàkovà and Z. Jaňour, 2016: Ventilation processes in a three-dimensional street canyon. Boundary-Layer Meteorol., 159, 259-284.
- Oke, T., 1988. Street design and urban canopy layer climate. Energy Build., 11, 103-113.
- Tomas, J. M., H. E. Eisma, M. J. B. M.·Pourquie, G. E. Elsinga, H. J. J. Jonker and J. Westerweel, 2017: Pollutant Dispersion in Boundary Layers Exposed to Rural-to-Urban Transitions: Varying the Spanwise Length Scale of the Roughness. Boundary-Layer Meteorol., 163, 225–251.