A laboratory investigation of flow and turbulence over a two-dimensional urban canopy

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Purposes

- To determine mean and turbulent fields in correspondence of a two-dimensional array of parallelepiped obstacles in the case of neutral boundary layers
- To examine differences between different geometrical configurations, as a function of the Aspect Ratio of the array, in order to investigate the main characteristics of the turbulence both in skimming flow and wake interference regime
- To analyze the mean velocity, the variance, the Reynolds stress, the skewness factor, the production term of the turbulent kinetic energy and its rate of dissipation for each geometrical configuration
- To study the concentration fields associated with stationary sources of passive tracers located within and above the canyon array
- To measure the mean, the variance and the skewness factor of the concentration
- To determine parametrical laws relating concentration fields and canyon geometry

Introduction

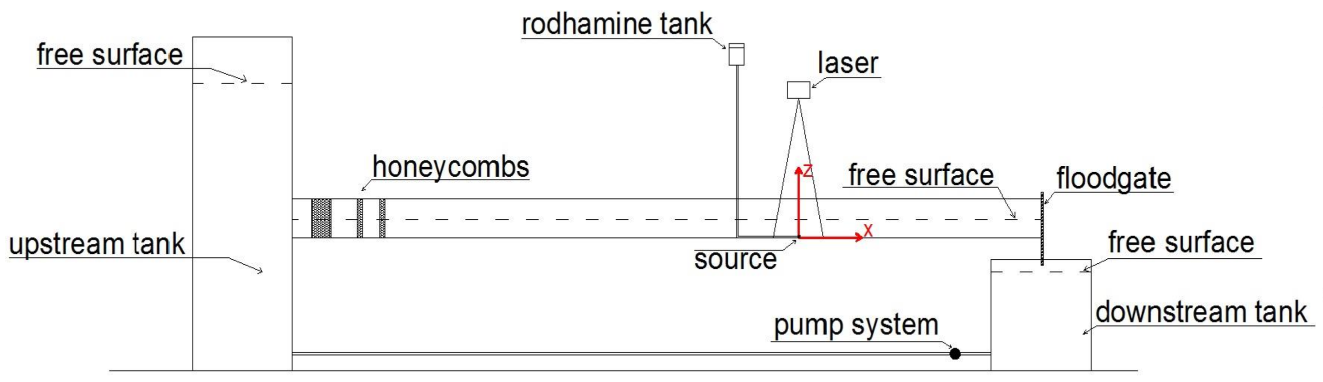
Interaction between urban areas and atmosphere has obtained increasing attention in research in last decades, because of the rapid growth of population in large cities, that determined degradation of environmental quality and human comfort and increase of air pollution. One of the most important parameters used to describe the geometrical configuration, developed by Hussain M. and Lee B. M. (1980), is the Aspect Ratio AR=W/H, i.e. the ratio of the spacing between buildings, W, to the height of the buildings.

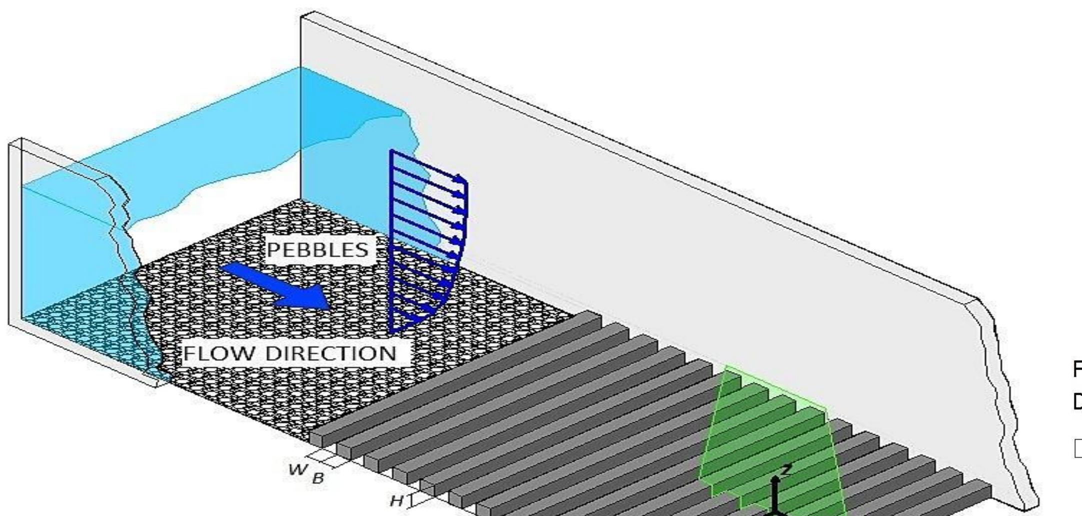
Both three-dimensional and two-dimensional building array are investigated through numerical simulations and experiments to study turbulence flow and concentration fields.

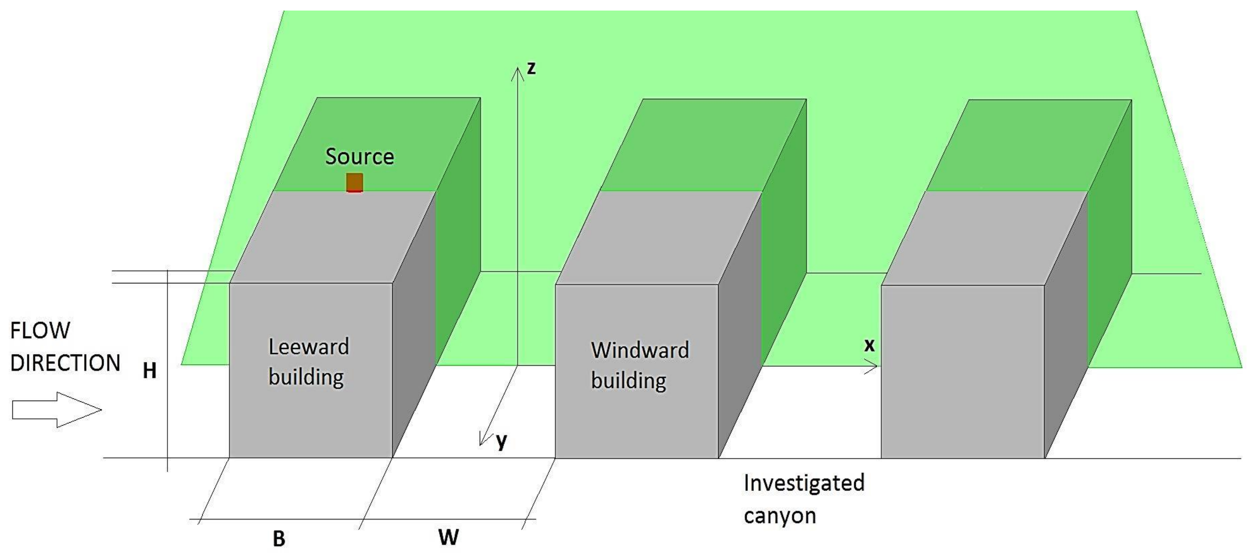
For example Salizzoni P. et al. (2011) studied the turbulent transfer between a two-dimensional cavity and the overlying boundary layer, presenting the vertical profile of different parameters.

While, Brevis W. et al. (2014) and Li X.-X. et al. (2014) used numerical simulation (LES) to simulate transport processes within and above a two-dimensional street canyon.

Experimental set up







Measurement technique

- **High Speed-CMOS-Camera**
  - resolution: 1280 × 1024 pixels
  - maximum frame rate: 120000 frames per second
- **LD PUMPED ALL-SOLID-STATE GREEN LASER**
  - wavelength: 532 nm
  - power: 5 W
- **RODHAMINE WT – WATER** ($C_{29}H_{29}N_2O_5Cl$)
  - excitation wavelength: 540 nm
  - emission wavelength: 625 nm

Feature Tracking is a technique that allows reconstruction of velocity field identifying local regions of interest (features) in several consecutive images, based on light intensity gradients, i.e. using a lagrangian approach.

In all the experiments presented the frame rate is set to 250 frames per second and the time duration of each experiment is 40 s.

WATER CHANNEL AND FLOW CHARACTERISTICS

- height: 35 cm
- width: 25 cm
- length: 740 cm
- water depth: 15 cm

The test section is located nearly 500 cm downwind of the inlet, where the boundary layer can be considered fully-developed.

This condition is realized thanks to small pebbles that covers the channel bottom, in order to increase the roughness of the surface itself.

- free stream velocity (U): **33 cm s⁻¹**
- Reynolds number: ≅ **52000** (considering the free stream velocity)

TEST AREA DIMENSIONS

The test area is **9.9 cm** long (x-axis - streamwise direction) and **7.2 cm** height (z-axis - vertical direction).

We define the origin (x=0, z=0) at the centre of the investigated canyon, considering x positive downwind and z upward.

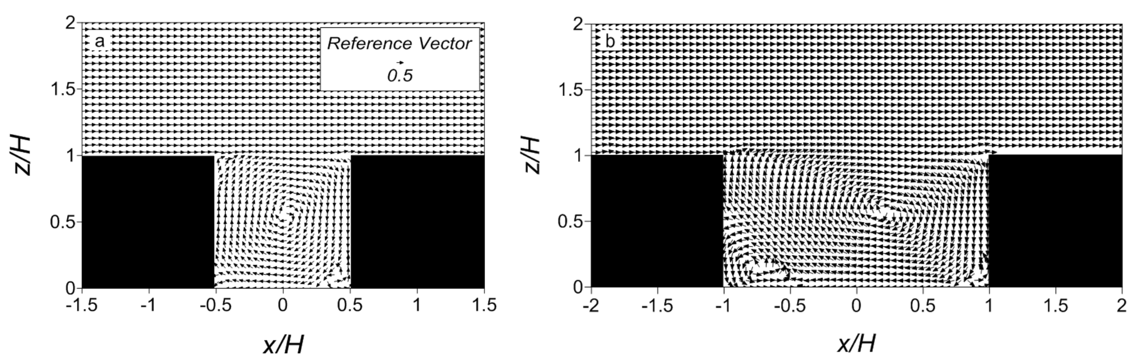
GEOMETRICAL CONFIGURATION

Two different spacial configurations are investigated, fixing a series of parallelepipeds of square section B=H=2 cm and L=25 cm long (along the y-axis) to the channel bottom.

- **AR=1**, corresponding to W=2 cm → *SKIMMING FLOW*
- **AR=2**, corresponding to W=4 cm → *WAKE INTERFERENCE REGIME*

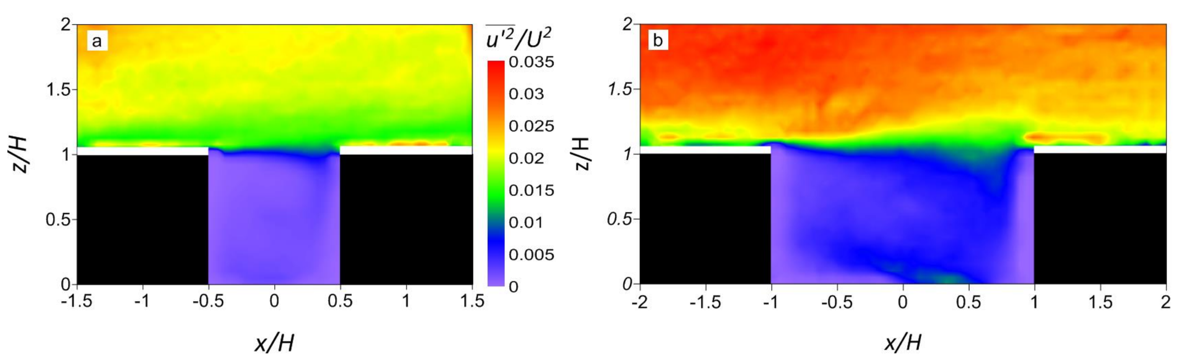
Results

MEAN VELOCITY FIELD



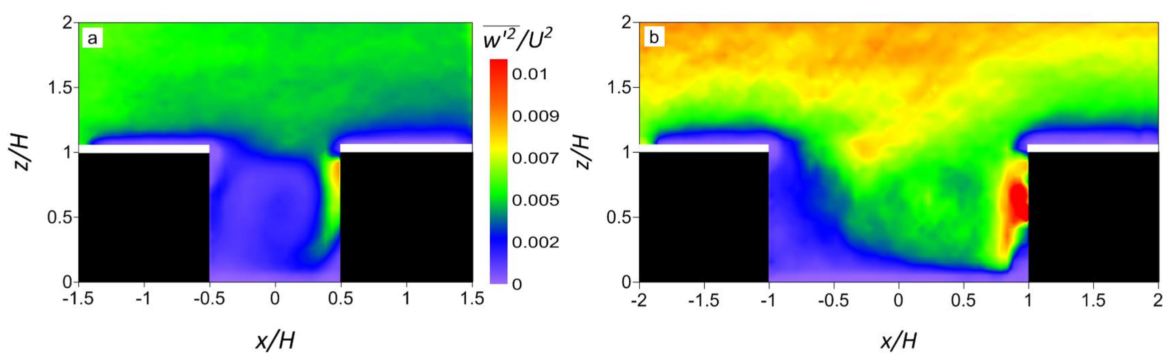
Velocity components are expressed as $\overline{u}/U$ and $\overline{w}/U$. For AR=1 (a) the vortex is slightly shifted downstream and towards the top of the canyon and, at the bottom-right corner of the canyon, a little counter-rotating vortex is present. For AR=2 (b), instead, the main vortex is significantly shifted downstream and a well-defined counter-rotating vortex form near the leeward building.

HORIZONTAL VELOCITY VARIANCE



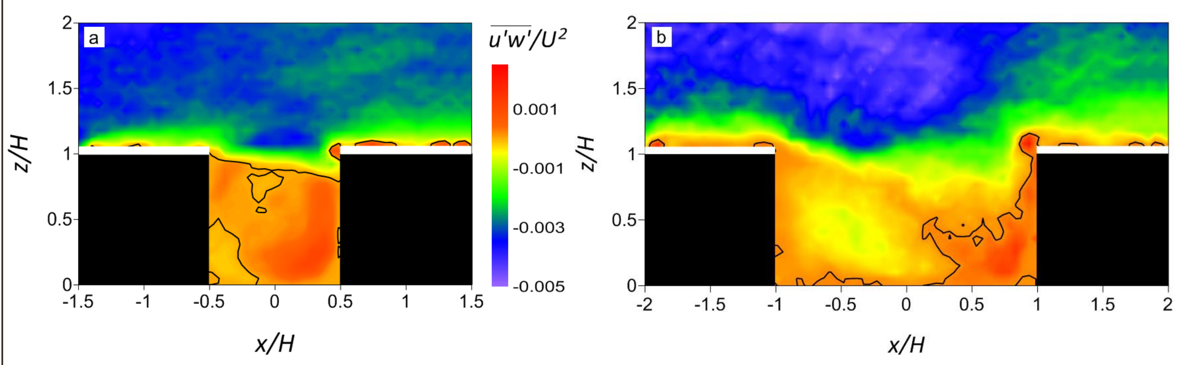
According to other works reported in the literature, the variance of the non-dimensional horizontal velocity components, $\overline{u'^2}/U^2$ (here primes are fluctuations around the mean) assumes lower values inside the canyon (nearly one order of magnitude) irrespective of AR.

VERTICAL VELOCITY VARIANCE



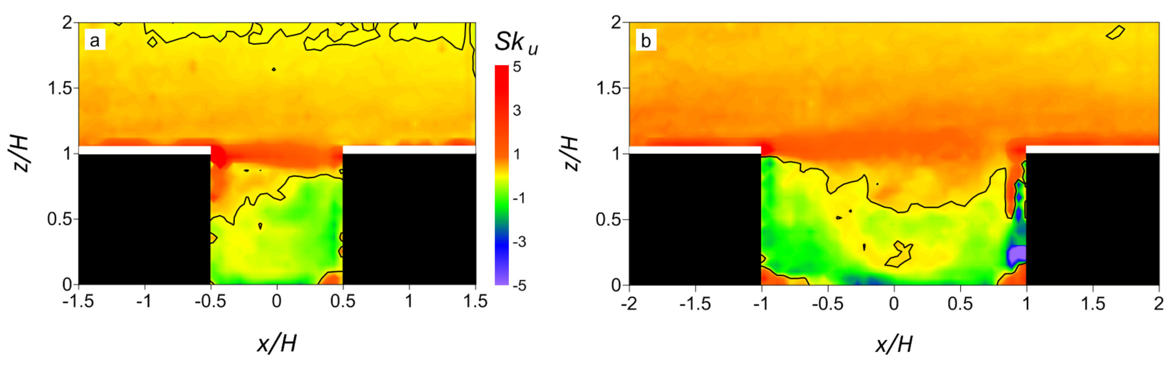
The non-dimensional vertical velocity variance, $\overline{w'^2}/U^2$, shows large values within a tongue-like feature, coming from the outer flow, near the windward wall when AR=1 (a). That feature is much more large for AR=2 (b), where in the right-half of the canyon $\overline{w'^2}/U^2$ is of the same order of that present in the outer flow.

REYNOLDS STRESS



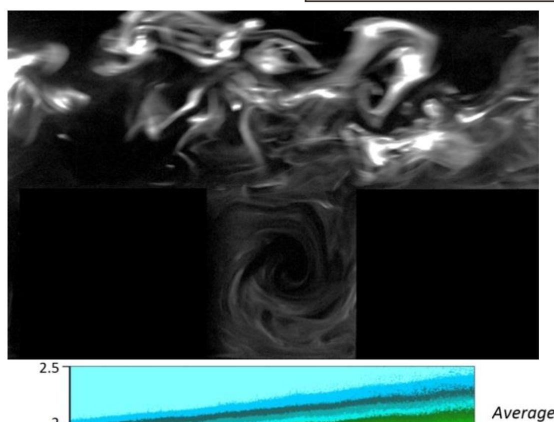
The non-dimensional, vertical momentum flux $\overline{u'w'}/U^2$, is negative above the canyon for both the configurations, while, inside, it strongly depends on AR. In fact, for AR=1 (a) it is positive almost everywhere while, for AR=2 (b), it is positive only near the bottom right corner of the canyon.

HORIZONTAL SKEWNESS FACTOR

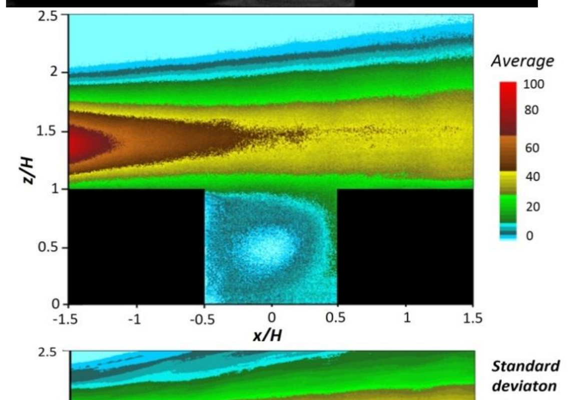


$Sk_u = \overline{u'^3}/(\overline{u'^2})^{3/2}$ for AR=1 (a) and 2 (b) is negative almost everywhere inside the canyon for both ARs, except near the canyon top, where, for AR=1, a region of large, positive Sk_u is present. For AR=2, large (positive) values are located also near the buildings top. The skewness factor of the vertical velocity component has been calculated too, but is not presented here.

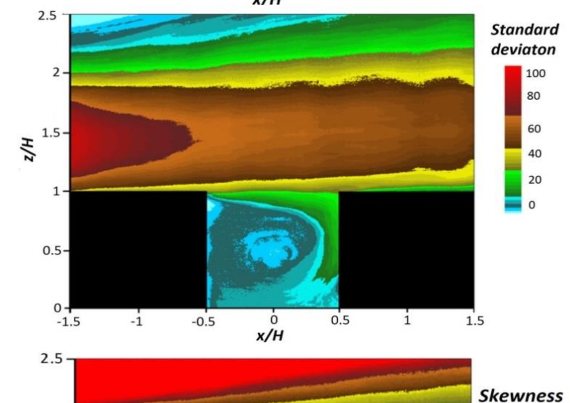
CONCENTRATION FIELD



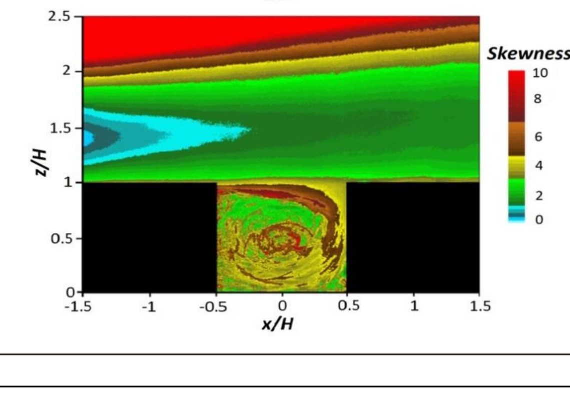
Example of the instantaneous concentration field associated with an emission of a passive tracer from a point source located above the canyon top.



The average concentration field (in arbitrary units) for AR=1 shows maxima values near the source and the vortex inside the canyon is apparent.

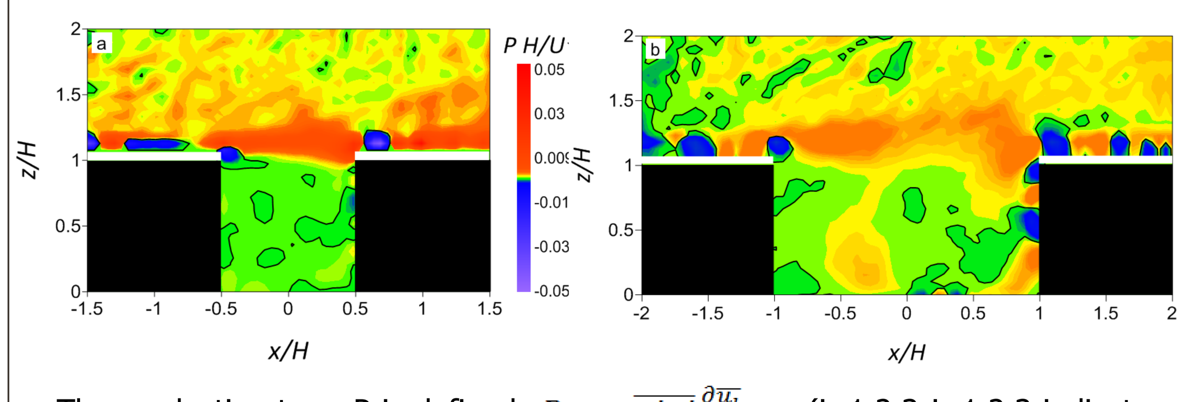


The standard deviation field follows the average trend. Inside the canyon, higher values are located near the downstream building, where the tracer gets into the canyon.



The skewness assumes higher values near the edges of the plume and lower where the concentration is higher.

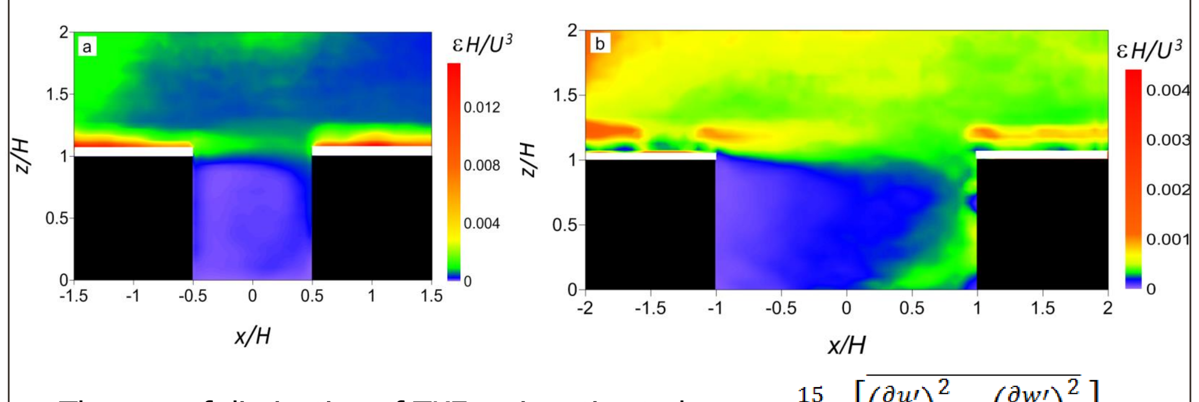
SHEAR PRODUCTION TERM



The production term P is defined $P = -\overline{u_i' u_j'}\frac{\partial \overline{u_i}}{\partial x_j}$ (i=1,2,3 j=1,2,3 indicate the axis of the coordinate system).

It is positive above the canyon top particularly for AR=1 (a), where the region of maxima corresponds with the mixing, characterized by strong vertical shear. For AR=2 (b) the region of maxima is still present, even though it is less evident.

DISSIPATION RATE



The rate of dissipation of TKE, ε, is estimated as $\varepsilon = \frac{15}{4}\nu\left[\left(\frac{\partial u'}{\partial z}\right)^2 + \left(\frac{\partial w'}{\partial z}\right)^2\right]$.

Lower values occur for both ARs within the canyon, particularly near the leeward building. Above the canyon, ε reaches higher values, with peaks above the rooftops.

Conclusions

- Analysis of the mean flow and of the turbulence inside and above a 2D urban canopy layer through a water channel experiment
- Focus on the representation of 2D maps of vertical and horizontal mean velocity, vertical and horizontal velocity variance, Reynolds stress, skewness of horizontal and vertical velocity, different terms of the shear production of the TKE budget and the dissipation rate ε
- The study concerns two different kind of flow, skimming flow and wake interference regime, according to aspect ratio
- Evaluation of concentration fields considering a stationary, point source, giving special attention to mean concentration, concentration variance and skewness factor

References

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