17th International Conference on
Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes
9-12 May 2016, Budapest, Hungary

THE AIR QUALITY IN TWO-DIMENSIONAL URBAN CANYONS WITH GABLE ROOF BUILDINGS: A NUMERICAL AND LABORATORY INVESTIGATION

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Abstract: in this work we compare two typical methods (numerical simulation and laboratory experiment) of modelling air flows at the urban scale to assess air quality in street canyons. We have investigated, both via numerical simulations and laboratory experiments, the effect of gable roofs, on the air quality in urban canyons with different aspect ratios. In particular, we have focused on the flow regimes, turbulence characteristics and air exchanges between the urban canyon and the outer flow. Results highlight how the choice of the roof shape can be meaningful for building design, planning strategies and regulatory purposes.

Key words: *Urban boundary layer, natural ventilation, two-dimensional street canyons, gable roof, CFD, RANS simulation, laboratory simulation*

INTRODUCTION

Though some authors have demonstrated the decisive impact of roof slope on wind flow (e.g. Huang et al., 2009; Yassin, 2011), this topic has not been investigated systematically, even if the gable roof building is a widespread typology in many regions all round the world. We have consequently investigated the effect of gable roofs on the air flow and quality in urban canyons with different aspect ratios W/H (W is the canyon width and H is the canyon height). In particular, we have focused on the flow regimes, turbulence characteristics and air exchanges between the urban canyon and the outer flow. The experiments were performed both via numerical and laboratory simulations.

MATERIALS AND METHODS

Both in laboratory and numerical simulations, we have investigated the flows in urban canyons, formed by identical buildings with symmetrical dual-pitched roofs and a constant flow perpendicular to the canyon axis. The roof pitches varied from 0° (flat roof) to 45° and the canyon aspect ratios W/H from 1 to 4: a wide range of real building configurations has been therefore covered, including most of the values indicated by Grimmond and Oke (1999) for real cities.

Laboratory simulations

Laboratory experiments have been performed in a closed-loop water-channel. The channel is 50 cm high, 40 cm wide and 800 cm long. The canyon array consists in 20 identical buildings: 2 cm high and wide parallelepipeds were chosen, in order to have an obstruction factor close to 3% (Blocken, 2015). The test section is located at around 650 cm downstream of the channel inlet, where the neutral boundary layer can be considered fully-developed. Small pebbles, with an equivalent diameter of 0.5 cm were displaced over the channel bottom for 300 cm upstream the canyon array, in order to increase the roughness of the bottom and to reproduce a logarithmic velocity profile. As flow velocities have been measured by means of a non-intrusive image analysis technique, namely Feature Tracking Velocimetry (FTV), the fluid was seeded with non-buoyant particles, the test section was lighted by a green laser sheet and images were recorded by a high-speed camera at the resolution of 2240 x 1760 px and 200 Hz. FTV has proved to be less sensitive to the appearance and disappearance of particles, and to high velocity gradients than classical Particle Image Velocimetry (PIV). More details on FTV can be found in Besalduch et al. (2013). The Reynolds number Re, based on the canyon height, is about 5,000, largely higher than the minimum value of 3,400 suggested by Hoydysh (1974) for the flow to be independent on Re.

Numerical simulations

Numerical simulations have been performed by means of the open source CFD library OpenFOAM 2.3 (Weller et al. 1998). A Reynolds Averaged Navier-Stokes model (RANS) with two equation k-ε closure (Launder and Spalding, 1974) was set up; simpleFoam (Patankar and Spalding, 1972), a steady state solver for incompressible turbulent flows, and a second order schemes for discretization were employed. A fully-developed steady turbulent flow was generated. A uniform, indefinite succession of buildings was simulated by imposing periodic boundary conditions in the streamwise direction. The simulation domain is three canyons long in the streamwise direction, and 15 H high, in order to fulfil the condition reported for flow simulation around buildings in the best practice guidelines of Franke et al. (2011). Re, based on the canyon height, is about 43,000. largely higher than the minimum value of 15,000 suggested by Snyder (1981) for the flow to be independent on Re. Cyclic boundary conditions were imposed at the inlet and outlet for all the variables, except for pressure, whose gradient is adjusted to obtain the required mean velocity. The upper boundary of the computational domain was considered a symmetry plane. At ground and building surfaces no-slip conditions were imposed for velocity, while Neumann zero gradient conditions were imposed for pressure and turbulent quantities (kinetic energy, energy dissipation rate and turbulent viscosity). OpenFOAM has been already extensively and successfully used to perform wind RANS simulation in urban environment (e.g. Hertwig et al. 2012); moreover, Takano and Moonen (2013) proved that a similar OpenFOAM configuration was able to properly reproduce a two-dimensional periodic array of flat roof buildings.

RESULTS

In all the figures from 1 to 5 the flow moves from right to left. Fig.1 shows a comparison between the non-dimensional mean velocity field u/U (i.e. the mean velocity magnitude u non-dimensionalised by the mean free stream velocity U) measured with numerical (left side) and laboratory (right side) simulations, with some streamlines as well, in the case of flat roof and W/H = 1. The stable single vortex, typical of the skimming flow regime, is well reproduced, as well as the velocity magnitude and the streamlines. The same considerations apply to Fig.2 (u/U fields from numerical and laboratory simulations for pitched roof and W/H = 1) and Fig.3 (u/U fields from numerical and laboratory simulations for pitched roof and W/H = 2), even if in those cases the effect of the pitched roofs in reducing the velocity outside the canyon is slightly overestimated by the numerical simulations. In case of flat roof (Fig.1), the outer stream is almost unperturbed, with a steep increase of the velocity with Z; the free stream velocity U is already attained at Z/H = 3. From the comparison of Fig.1 with Fig.2 we can see that the pitched roof determines a perturbation that propagates significantly above the roof, with wavy streamlines also above the ridge of the roof and a zone of reduced velocity that extends upwards that is larger than in the flat roof case.

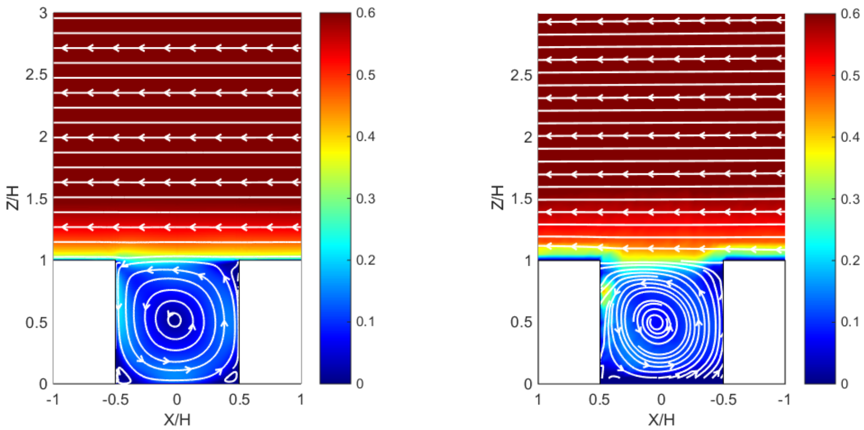

Figure 1. Non-dimensional mean velocity u/U fields (color map) with streamlines (white lines) from numerical (left side) and laboratory (right side) simulations, for flat roof and W/H = 1.

The left and central panel of Fig 4 (W/H = 1) and 5 (W/H = 2) show the non-dimensional Turbulent Kinetic Energy TKE/U^2 in the case of pitched roof; the right panel of Fig.4 shows the same quantity in the case of flat roof and W/H = 1. TKE is lower within the urban canyon than above it. The numerical simulation is able to correctly reproduce the features of the TKE fields, even if it tends to overestimate their values. From Fig.4 we can state that the pitched roofs determine much higher values of TKE in the outer flow stream than the flat ones. Moreover, the TKE generated on the upstream roof building tends, in the pitched roof case, to propagate down to the eave height of the downstream building, promoting turbulent mixing inside the canyon as well. This phenomenon is stronger in the W/H = 2 case (Fig.5).

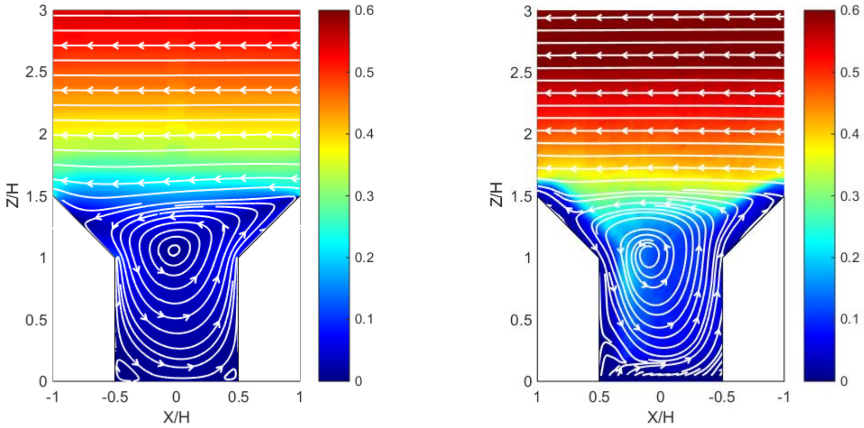

Figure 2. Non-dimensional mean velocity u/U fields (color map) with streamlines (white lines) from numerical (left side) and laboratory (right side) simulations, for pitched roof and W/H = 1.

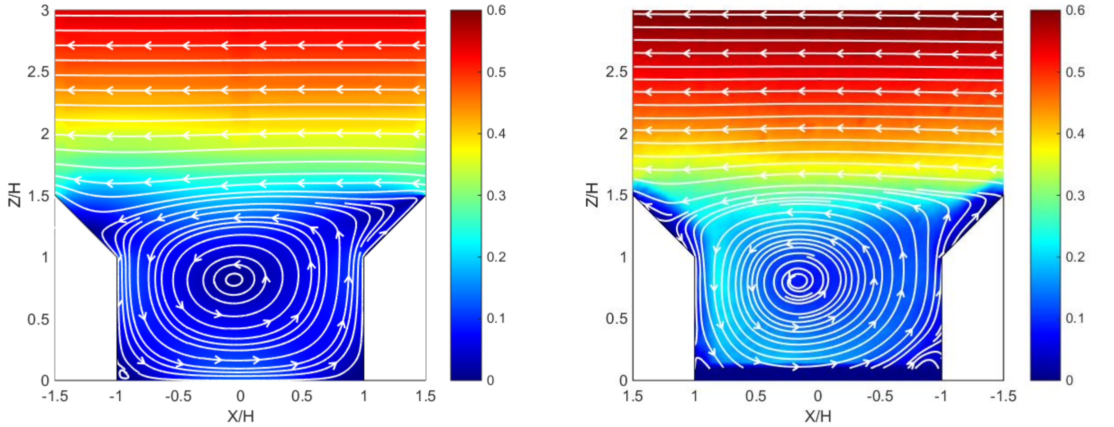

Figure 3. Non-dimensional mean velocity u/U fields (color map) with streamlines (white lines) from numerical (left side) and laboratory (right side) simulations, for pitched roof and W/H = 2.

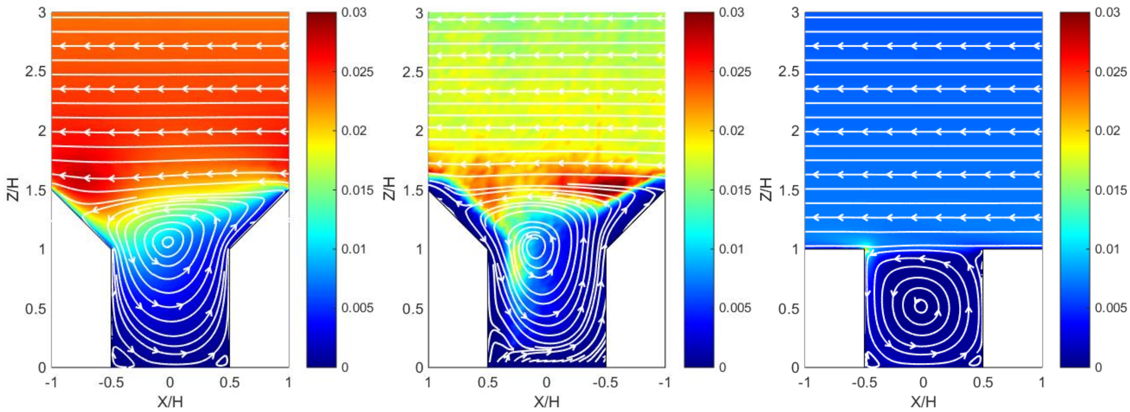

Figure 4. Non-dimensional mean Turbulent Kinetic Energy (TKE/U^2) fields (color map) with streamlines (white lines) for W/H = 1: numerical (left side) and laboratory (center) simulations, for pitched roof, numerical simulations for flat roof (right side).

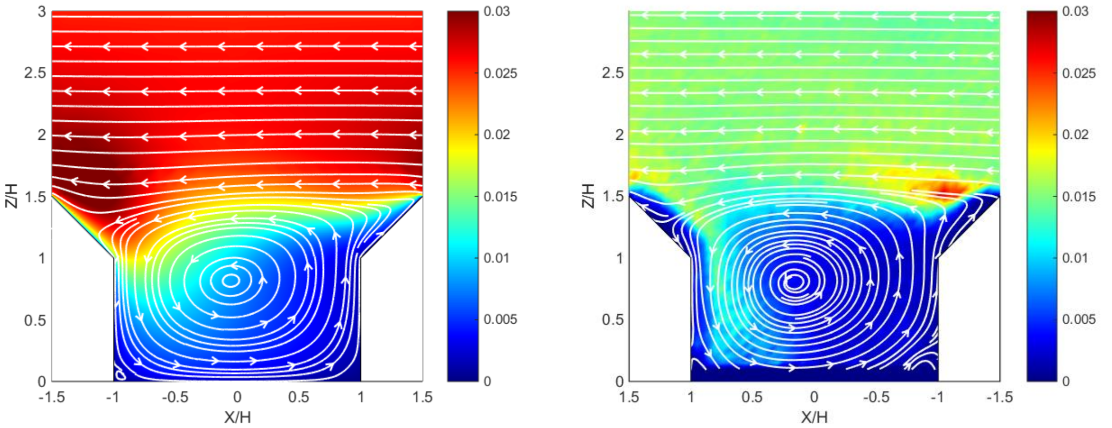

Figure 5. Non-dimensional mean Turbulent Kinetic Energy (TKE/U^2) fields(color map) with streamlines (white lines) from numerical (left side) and laboratory (right side) simulations, for pitched roof and W/H = 2.

From the analysis of the u/U and TKE/U^2 fields we can state that numerical code here employed is able to properly simulate the flow in urban canyons and that the pitched roof strongly modifies the flow.
The air quality and the comfort in an urban canyon depend essentially on the air exchanges between the canyon and the overlying boundary layer. We have so investigated the air-exchange rate, ACH (Ho et al., 2015), which is an integral parameter measuring the rate of air removal from a street canyon, depending on the mean and turbulent flow (<ACH> and ACH ', respectively):

$$ACH = \langle ACH \rangle + ACH' = \int_b \langle w_+ \rangle dx + \frac{1}{2}\int_b \sqrt{\langle w'^2 \rangle dx} \qquad (1)$$

where $\langle w_+ \rangle$ is the mean upward velocity, at the roof ridge height, b is the line connecting two consecutive ridges and $\langle w'^2 \rangle$ is estimated, under the assumption of isotropic turbulence, as:

$$\overline{w'^2} = -2\nu_t \left(\frac{\partial \bar{w}}{\partial z} \right) + \frac{2}{3}k \qquad (2)$$

Figure 6 shows the ACH (non-dimensionalised by U·b) and its components versus W/H, for flat and pitched roof. Both ACH values and trends from numerical simulations are very similar to the ones measured in the laboratory. The ACH values for pitched roof are higher than the flat roof ones, showing that pitched roofs tend to enhance the natural ventilation inside the canyon

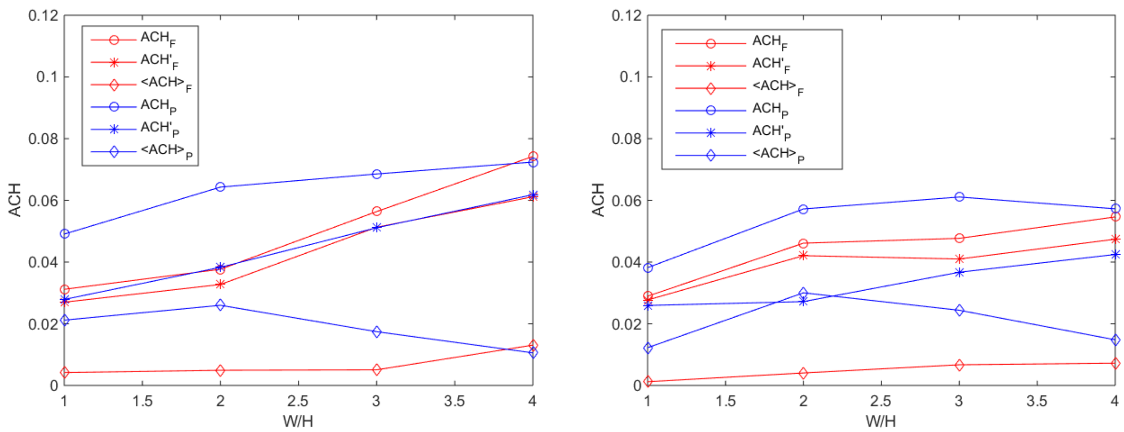

Figure 6. ACH versus W/H from numerical (left side) and laboratory (right side) simulations; flat roof values are plotted with red lines, pitched roof values with blue lines; total ACH is plotted with circles, mean ACH component with asterisks and turbulent ACH component with rhombi.

CONCLUSIONS

We have investigated, both via numerical and laboratory simulations, the effect of gable roofs, on the air quality in urban canyons with different aspect ratios. The numerical code applied here has shown to be able to properly reproduce laboratory investigations An integral parameter, the air exchange rate ACH, has been used to summarize the results: both numerical and laboratory investigations have highlighted the meaningful role of the roof pitch in enhancing turbulence, which increases the air exchange rate between the street canyon and the outer flow, thus promoting pollutant and heat dispersion. As a consequence, we can state that using a gable roof is a way to increase the air quality. The present results could have an immediate practical impact on the building design and on planning strategies, as the roof shape can be a useful tool to enhance natural ventilation and pollutant or heat dispersion, i.e. the air quality in urban areas.

REFERENCES

Bealduch L.A., Badas M.G., Ferrari S. and Querzoli G., 2013: Experimental Studies for the characterization of the mixing processes in negative buoyant jets. *Eur Phys J WoC*, **45**, 01012.

Blocken B., 2015: Computational fluid dynamics for urban physics: importance, scales, possibilities, limitations and ten tips tricks toward accurate and reliable simulations. *Build Envir*, **91**, 1-27.

Franke J., Hellsten A., Schlunzen K.H. and Carissimo B, 2011: The COST 732 Best Practice Guideline for CFD simulation of flows in the urban environment: a summary. *Int J Environ Pollut*, **44**, 419.

Grimmond C.S.B.and Oke T.R., 1999: Aerodynamic properties of urban areas derived from analysis of surface form. *J Appl Meteor*, **38**, 1262-92.

Hertwig D., Efthimiou G.C., Bartzis J.G. and Leitl B.,2012: CFD-RANS model validation of turbulent flow in a semi-idealized urban canopy. *J Wind Eng Ind Aerodyn*, **111**, 61–72.

Hoydysh W.G., Griffths R.A. and Owaga Y.A., 1974: Scale Model Study of the Dispersion of Pollution in Street Canyons, Proceedings of the 67th Annual Meeting of the Air Pollution Control Assn., Denver, Colorado (USA), June 9-13.

Ho Y.K., Liu C.H. and Wong M.S., 2015: Preliminary study of the parameterisation of street-level ventilation in idealised two-dimensional simulations. *Build Environ,* **89**:345–55.

Huang Y., Hu X. and Zeng N., 2009: Impact of wedge-shaped roofs on airflow and pollutant dispersion inside urban street canyons. *Build Environ.*, **44**, 2335–47.

Launder B.E. and Spalding D.B., 1974: The numerical computation of turbulent flows. Comput Methods Appl Mech Eng 1974;3:269–89. doi:10.1016/0045-7825(74)90029-2.

Patankar S. and Spalding D., 1972: A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows. *Int J Heat Mass Transf*, **15**, 1787–806.

Snyder W.H., 1981: Guideline for fluid modeling of atmospheric diffusion. vol. 81. Environmental Sciences Research Laboratory, Office of Research and Development, US EPA.

Takano Y. and Moonen P., 2013: On the influence of roof shape on flow and dispersion in an urban street canyon. *J Wind Eng Ind Aerodyn*, **123**, Part A:107–20.

Weller H.G., Tabor G., Jasak H. and Fureby C., 1998: A tensorial approach to computational continuum mechanics using object-oriented techniques. *Comput Phys*, **12**, 620–31.

Yassin MF., 2011: Impact of height and shape of building roof on air quality in urban street canyons. *Atmos Environ*, **45**, 5220–9.