A PARAMETRIC STUDY OF THE IMPACTS OF PITCHED ROOFS ON FLOW AND POLLUTION DISPERSION IN STREET CANYONS

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ABSTRACT

This study uses Computational Fluid Dynamics (CFD) to simulate flow and pollutant dispersion in a regular urban structure that consists of six equally spaced street canyons with a centred test street. This structure is known to be adverse for local ventilation and pollutant removal. The impacts of pitch rise and roof arrangement on the flow and dispersion in the test street are studied parametrically. The pitch rise is set in the range of 1–3m, which gives rise-to-run ratios of 2:12–6:12. Four different roof arrangements of flat and pitched roofs on the adjacent buildings of the test street are tested, to give a total of 12 case studies. The case with flat roofs on all the buildings is modelled to provide a reference for comparison.

It is found that for all the studied cases, the flow in the test street canyon maintains a single vortex flow pattern. However, all the studied cases have lower velocity and TKE in the test canyon, which leads to reduced ventilation. After analysing the results of each case, we conclude that a high pitch rise and the presence of a pitched roof on the leeward building are the main contributors to this adverse effect. Owing to the lower velocity and TKE, the average pollutant concentration in the canyon is increased in each studied case. In the worst case scenario, the average pollutant concentration is increased by 19%.

INTRODUCTION

Street canyons, where long narrow streets are bordered by a continuous row of buildings on both sides, are a typical urban geometry in many European cities, and are known to suffer from problems of high pollution and heat accumulation. There have been many studies of flow and dispersion in street canyons that were based on the assumption of flat-roof buildings throughout the length of the street (Gromke and Blocken, 2015, Gu et al., 2011, Guillas et al., 2014, Uehara et al., 2000, Wen et al., 2013). This assumption might not be representative, because roofs are usually designed to have slopes for the purpose of draining rain water.

Variations in roof structure impact on the aerodynamic properties of the flow inside street canyons, and therefore on the dispersion of pollutants. Kastner-Klein et al. (2004) observed double vortices inside a square street canyon when an 8:12 pitched roof presented on the leeward building. Takano and Moonen (2013) found that a downward roof slope greater than 18° was essential to induce double-vortex flow inside a street canyon. Rafailidis and Schatzmann (1996) discovered that the impact of a pitched roof on flow properties was highly dependent on its position as well as on the aspect ratio (AR) of the street canyon. They found that an upstream 12:12 pitched roof confined within the urban canopy and a downstream 12:12 pitched roof protruding from the urban canopy helped to reduce pollutant concentration inside street canyons with AR=1.0 and AR=2.0 respectively. Huang et al. (2009) further pointed out that a slanted roof on an upwind building had much stronger aerodynamic impacts than the same geometry on a downwind building. However, the most roof configurations mentioned in the above literature are too sharp to be found in the real world, so that it is useful to examine additional conventional roof structures in more detail.

This work uses two-dimensional Computational Fluid Dynamics (CFD) to simulate flow for several cases of a full-scale homogeneous street canyon, with different realistic roof configurations. The effects of two parameters, pitch rise and roof arrangement, are analysed in this study.

SIMULATION

The commercial CFD software—ANSYS FLUENT is used for simulation. The standard k-ε model is used to model turbulence. In order to reduce computational cost, the CFD modelling is carried out under two-dimensional geometry. Thus, all of the model geometries correspond to long homogeneous street canyons.

Geometry

A sketch of typical model geometry is illustrated in Figure 1. An urban structure is characterized by six equally spaced building rows that create five consecutive street canyons. The aspect ratio of each street canyon is fixed at AR=1.0. The buildings are 12m wide and 12m tall up to the eave. The roof structures are varied, which is discussed after this sub-section. The 3rd street canyon is chosen as the test canyon. Two line sources with the same emission

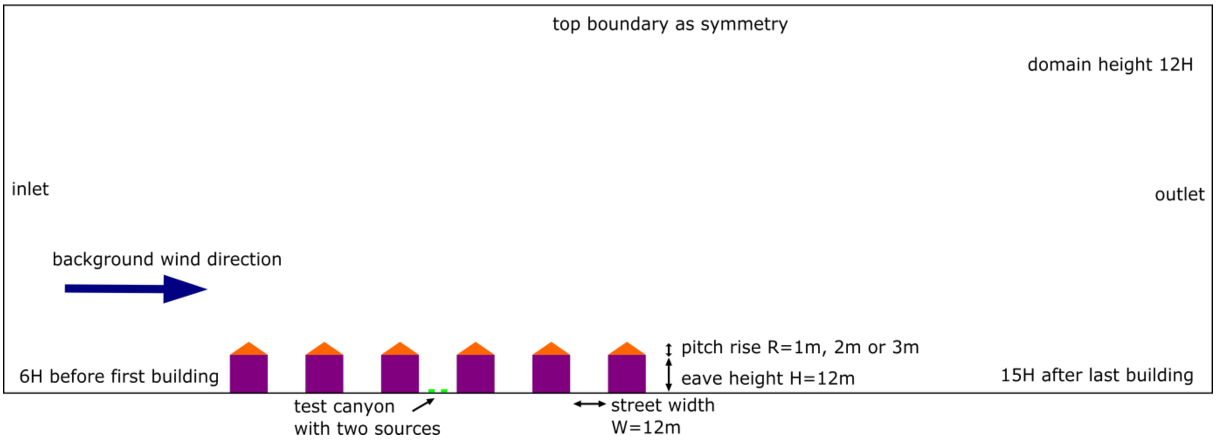

Figure 1: A sketch of modelling domain and street canyon geometry.

rate are placed on the ground to model traffic emission from two traffic lanes. The sources are 0.3m wide and 1m from the centre of the canyon.

Parameters

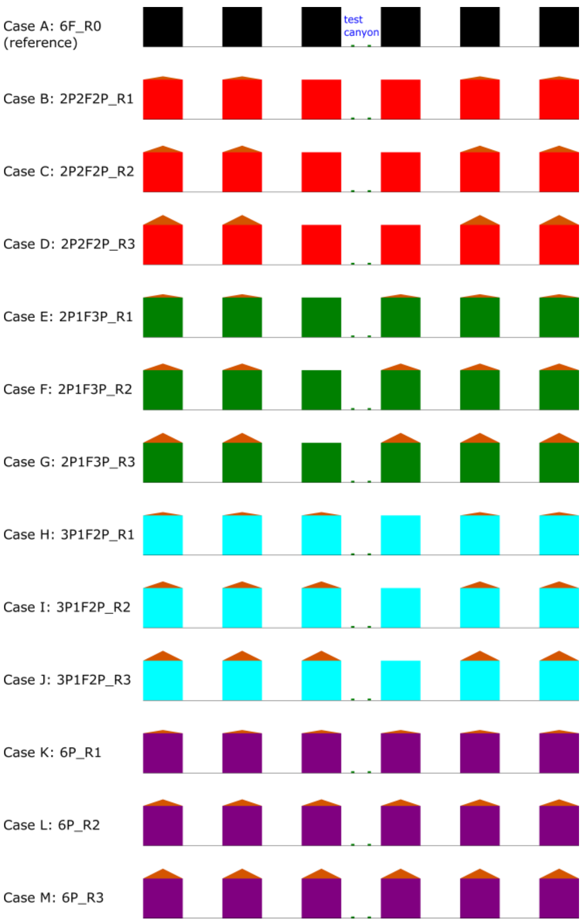

Figure 2: Modelling geometries of thirteen cases with different pitch rises and roof arrangements.

Pitch rise and roof arrangement are treated as two parameters in this study. The pitch rise R is set as 1m, 2m or 3m, which provide conventional roof slopes. Four different roof arrangements are studied and compared with a reference—the flat-roof case. The variations of these two parameters, in the aggregate, give 12 cases and 1 reference, which are shown in Figure 2.

The name of each case is also listed in Figures 2. The naming protocol is made up of two parts that are separated by an underscore. The characters before the underscore indicate roof arrangement and the characters after the underscore indicate the height of pitch rise. For example, for case I: 3P1F2P_R2, 3P1F2P represents a roof arrangement consisted of 3 pitched-roof buildings, 1 flat-roof building and 2 pitched-roof buildings along the approaching wind direction; R2 means that pitched roofs are 2m high.

CFD modelling settings

The boundary conditions used in the current modelling are summarized in Table 1. The velocity, turbulent kinetic energy (TKE) and dissipation at the inlet are specified following the AIJ guidelines (Tominaga et al., 2008). They are given as Equation(1), (2) and (3). In these equations, the reference height z_{ref} is 72m; the reference velocity U_{ref} is 7.7m/s; the power index α is 0.18; the model constant C_μ is 0.09. These values give an atmospheric boundary layer which is the prototype of the modelled boundary layer used in Kastner-Klein et al. (2004). The emission sources are also specified as inlet boundaries, but they have small constant velocity and zero turbulence.

$$U = U_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (1)$$

$$k = \left[0.1U\left(\frac{z}{z_{ref}}\right)^{-\alpha-0.05}\right]^2 \quad (2)$$

$$\varepsilon = {C_\mu}^{1/2} k \frac{U_{ref}}{z_{ref}} \alpha \left(\frac{z}{z_{ref}}\right)^{\alpha-1} \quad (3)$$

The distance of each boundary to the buildings is shown in Figure 1, which comply with the recommended distances in the COST best practice guideline (Franke et al., 2007) and the AIJ guidelines (Tominaga et al., 2008).

Table 1: Boundary condition

Name	Boundary type
Inlet boundary	Velocity inlet with velocity, TKE and dissipation profiles
Outlet boundary	Outflow
Top boundary	Symmetry
Ground	Solid wall
Building surfaces	Solid wall
Emission sources	Velocity inlet with very small velocity and zero turbulence

The total cell number for each case is around 190,000. More than 80 cells are put along the building height, which is sufficiently fine for mesh-independent results. The detailed mesh information is summarized in Table 2.

Table 2: Mesh information

Total cell number	191,268
Cell number along building height H	84
Cell number along street width W	87
Min & Max cell length along H	0.07m & 0.15m
Min & Max cell length along W	0.05m & 0.15m

Validation

A full discussion of the choice of modelling parameters, mesh sensitivity and validation is beyond the scope of this paper. In our previous work (Wen et al., 2013), the flow in a similar street canyon was validated against the experimental work of Kastner-Klein et al. (2004). In addition, we tested different turbulence models and wall functions, and found that the standard k-ε model with the scalable wall function was a reliable option. A mesh resolution with around 40 nodes along the building height was necessary for obtaining mesh-independent results. As mentioned before, the meshes used in the current study are much finer than this criterion.

DISCUSSION AND RESULTS ANALYSIS

The results of the models runs for the reference case and the 12 studied cases are discussed in this section. The results are presented as contours and profile plots of velocities, turbulent kinetic energy and pollution concentration. The discussion consists of a brief review of flow patterns and pollutant distribution found in the test street canyon and quantitative analyses of flow properties above and in the test canyon.

Vortex flow and uneven pollutant distribution in reference case

In the reference case that has flat roofs on all the buildings, a clockwise vortex is predicted inside the 3rd canyon as well as the 4th canyon (see Figure 3). Moreover, the velocity in the canyon is an order of magnitude lower than that above the canyon. This flow pattern is consistent with many experimental observations. A good illustration is the measured flow pattern of Karra (2012), which is given in Figure 4. This experiment, conducted in a water channel with a Reynolds number around 9,500, modelled the flow in and above a scaled-down street canyon (building height 6cm, aspect ratio=1.25). There were 3 and 2 additional buildings, which had identical sizes to the buildings adjacent to the test street, placed before and after the test canyon, in order to smooth the turbulence and to achieve a fully-developed boundary layer profile. The velocity information inside the test street was measured by Particle Image Velocimetry (PIV).

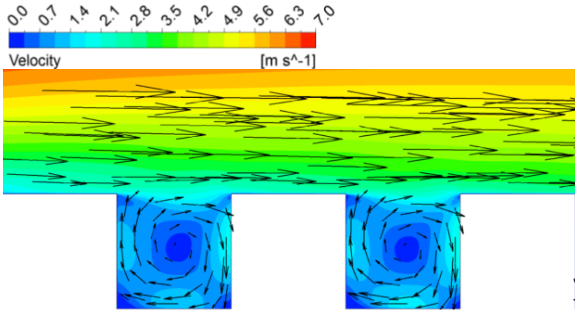

Figure 3: Combined velocity magnitude contour and velocity vector around the 3rd and 4th street canyon, case A: 6F_R0 (reference case).

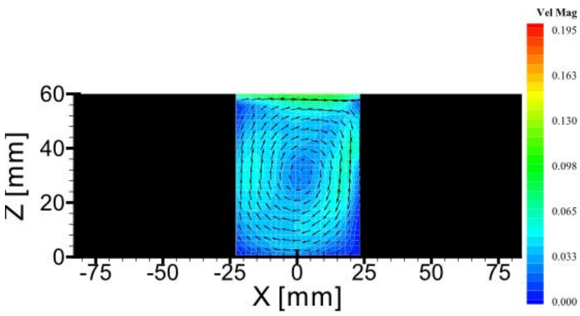

Figure 4: Combined velocity magnitude contour and velocity vector in the test street canyon. Adapted from Karra (2012).

Due to the clockwise vortex, traffic emission at the bottom of the 3rd canyon is ventilated upwards from leeward side. As a consequence, the concentration at the leeward part of the 3rd canyon is universally higher than that at the windward part (see Figure 5). As the velocity in the canyon is much lower than that above the canyon, the effectiveness of pollutant removal is poor, and large amounts of pollutants accumulate near the emission sources and the leeward bottom corner. On the other hand, the pollutants above the canyon are efficiently flushed by the free-stream flow, so that the concentration out of the 3rd canyon is very low.

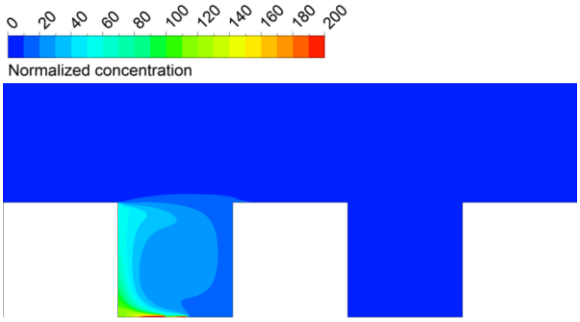

Figure 5: Normalized concentration contour around the 3rd and 4th street canyon, case A: 6F_R0 (reference case).

Results of 12 studied cases

For each of the 12 studied cases, the flow in the test street canyon also maintains a single vortex pattern, and the pollutant distribution is similar to the reference case. Thus, it is difficult to determine the impact of pitched roofs by comparing the velocity and concentration contours.

To overcome this limitation, we adopt profile plots to present the model results. Horizontal velocity U, vertical velocity V and turbulent kinetic energy k are plotted on three vertical lines. The positions of these lines are given in Figure 6.

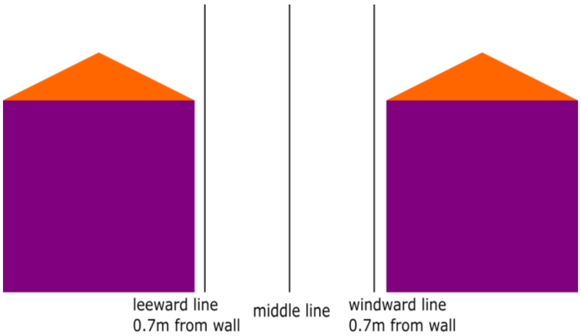

Figure 6: The positions of three vertical lines for plotting data.

In Figure 7, the horizontal velocity U on the middle is plotted to 0.5H above the roof level. By plotting to this height, we can notice the different horizontal velocities in and above the canyons. In Figure 8 and 9, the vertical velocity W on two side lines (0.7m or 0.06H away from the walls) is plotted to a height of 1.2H. In Figure 10 and 11, the TKE k on the side lines is plotted to a height of 0.9H. All of these flow properties are presented in dimensionless forms that are normalized by a free-stream velocity—U_0=7m/s (note: U_0 is different from the reference velocity U_{ref}). In these figures (i.e. Figure 7 to Figure 11), the cases with the same pitch rise are assigned to the same line style, and the cases with the same roof arrangement are assigned to the same colour. The reference profile is marked by black solid dots.

After examining the profiles in these figures, we find several important effects related to pitch rise and roof arrangement.

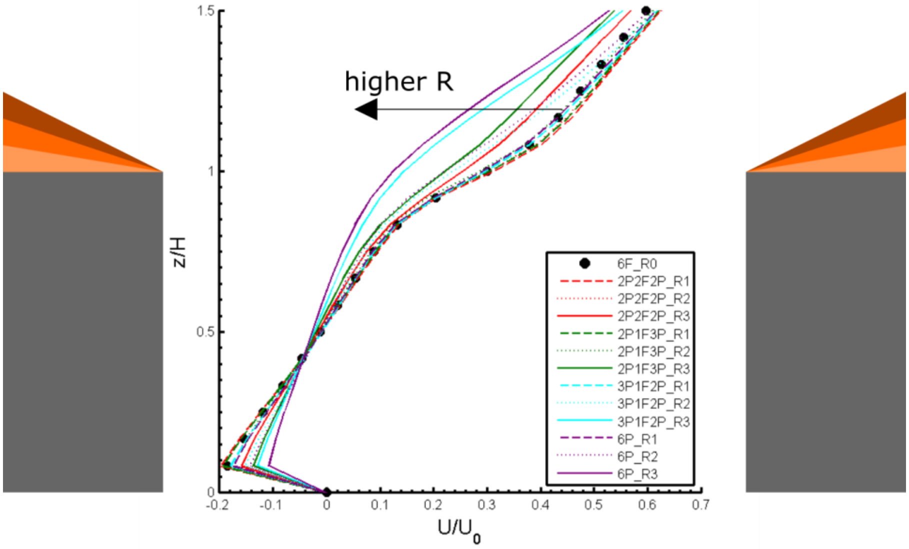

Figure 7: Horizontal velocity U on the middle line in the 3rd street canyon.

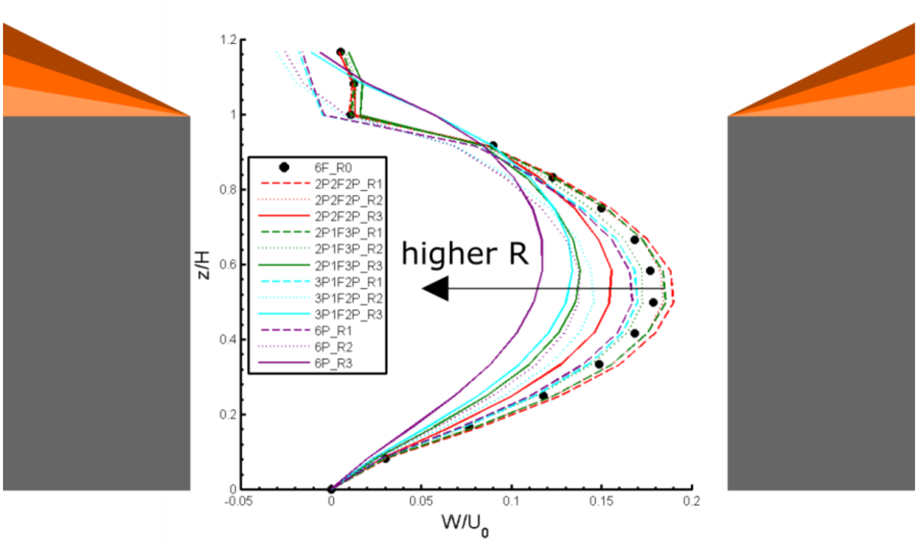

Figure 8: Vertical velocity W on the leeward line in the 3rd street canyon.

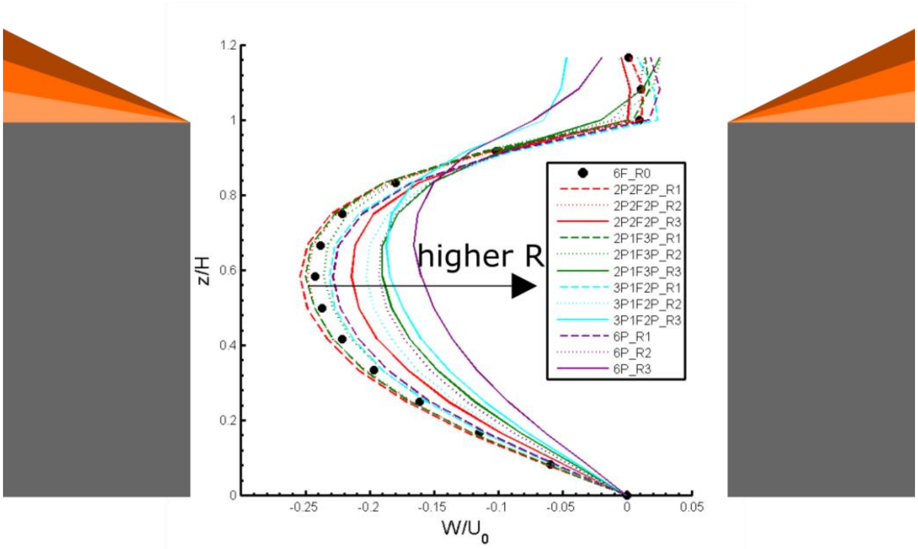

Figure 9: Vertical velocity W on the windward line in the 3rd street canyon.

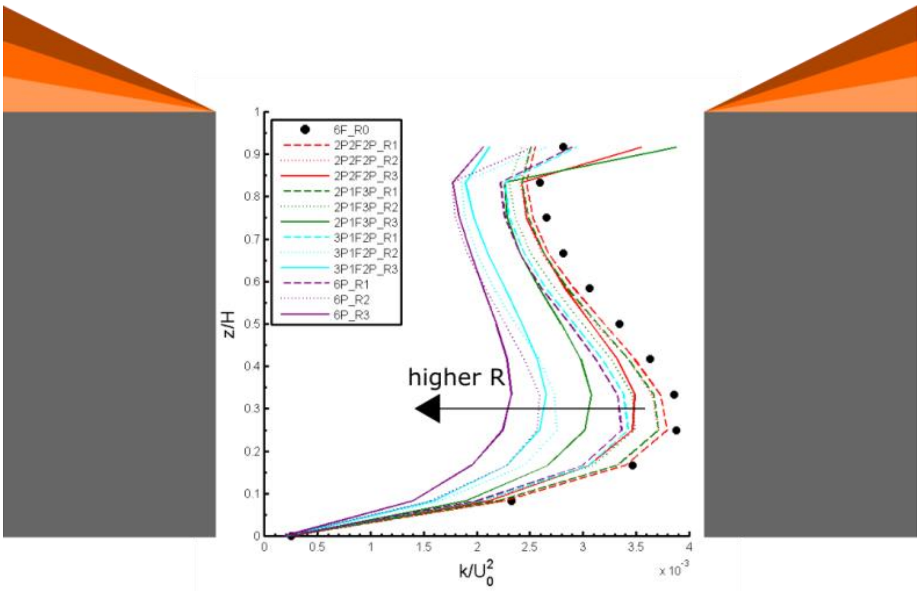

Figure 10: Turbulent kinetic energy k on the leeward line in the 3rd street canyon.

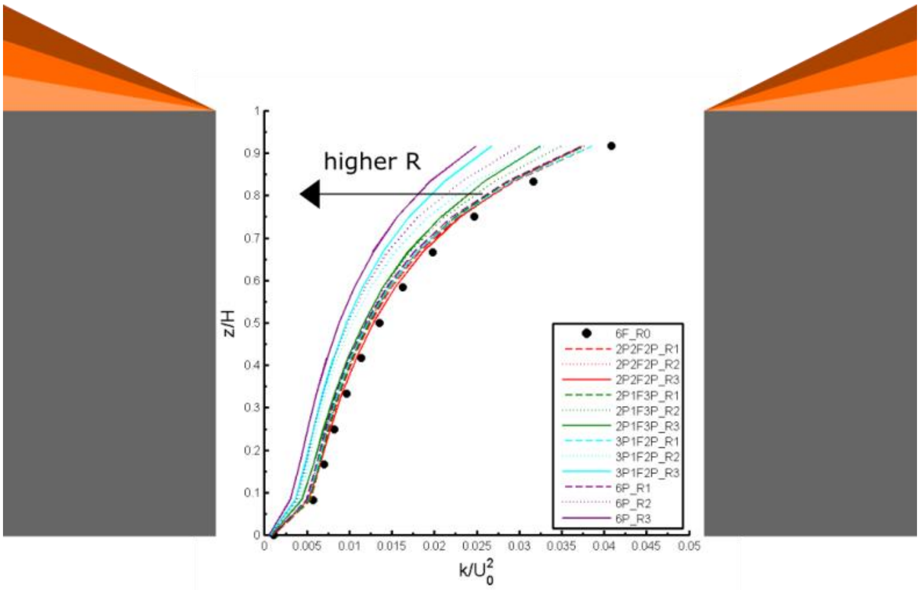

Figure 11: Turbulent kinetic energy k on the windward line in the 3rd street canyon.

The effect of pitch rise

The horizontal velocity above the roof level is reduced by the pitched roofs, and this effect is even more significant with high pitch rise R. As can be easily noticed from Figure 7, 3P1F2P_R3 (solid cyan) and 6P_R3 (solid violet) have the lowest horizontal velocity above the roof level. 2P2F2P_R3 (solid red), 2P1F3P_R3 (solid green), 3P1F2P_R2 (dot cyan) and 6P_R2 (dot violet) have the median velocity. 2P2F2P_R2 (dot red), 2P1F3P_R2 (dot green) and the four cases with 1m pitched roofs (dashed lines) have the highest horizontal velocity above the roof level. In addition, for the same roof arrangement, it is always that 3m, 2m and 1m pitch rises lead to the high, median and low horizontal velocities above the roof level.

The flow strength in the canyon is greatly weakened by high pitch rise. This trend can be observed through both U and W. In Figure 7, the horizontal velocity in the canyon is positively related with that above the canyon. Thereupon, 3P1F2P_R3 (solid cyan) and 6P_R3 (solid violet) have the weakest horizontal velocity magnitudes (absolute values of U) in the canyon. At a height of 0.1H, they are only around 55% and 65% of the reference velocity respectively. In Figure 8 and 9, the effect of pitch rise is even clearer. The 3m pitch rise (solid lines) induces much smaller vertical velocity magnitudes on two side lines, compared with the reference case and the corresponding cases with the same roof arrangement but lower pitch rise. At half building height, 6P_R3 has lowest vertical velocities on both lines which are both only around 60% of the reference velocity.

Pitch roof has a similar impact on TKE. As can be observed in Figure 10 and 11, the cases with pitched roofs have lower TKE than the reference at most positions. For a fixed roof arrangement (the same colour lines), the 3m pitch rise always results in the lowest TKE, and the 1m pitch rise always results in the highest TKE. In addition, the relative reduction of TKE on the leeward side line is larger than the relative reduction on the windward side line.

The effect of roof arrangement

The difference in flow properties is dominated by not only pitch rise but also by roof arrangement. In addition, the impact of roof arrangement is relatively strong for the cases with high pitch rise.

As can be observed in Figure 7, 8, 9 and 10, the magnitude of W and k for the cases with different roof arrangement but the same pitch rise, can always be sorted as a sequence which is schematically shown in Figure 12.

One possible explanation for this finding is that either the leeward pitched roof or the windward pitched roof can result in the lower levels of flow properties than the reference case. The leeward pitched roof, which is at an upstream position, influences the approaching flow and therefore has a main impact on the flow and turbulence in the test canyon. Hence, 3P1F2P and 6P cases have much smaller flow properties than the other cases. On the other hand, the windward pitched roof, which is at a downstream position, only has limited impact on the canyon's windward part. Hence, 2P2F2P and 2P1F3P cases have slightly smaller flow properties than the reference. When pitched roofs appear on both adjacent buildings (i.e. 6P cases), the worst scenario for ventilation happens.

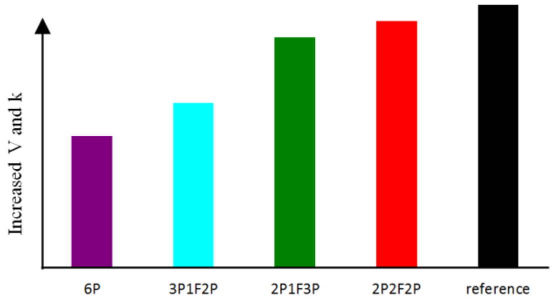

Figure 12: Schematic diagram of the relationship between flow properties and roof arrangement

The special cases

3P1F2P_R3 and 6P_R3, which have a 3m pitched roof on the leeward building, are two special cases among all the studied cases. They not only have the lowest velocity and TKE throughout the canyon but also show different velocity profiles from the others. In Figure 7, the horizontal velocities for these two cases increase uniformly above the roof level. In contrast, the other cases have a logarithmic velocity profile above roof level. In Figure 8 and 9, these two cases have very smooth vertical velocity profiles below 1.2H, but all the other cases show a sudden change of vertical velocity at the roof level. This finding suggests that the vortex structure in 3P1F2P_R3 and 6P_R3 is elongated along the vertical direction. Hence, it can be considered that the 3m pitched roof on the leeward building is critical to make the effective AR larger than 1.0, so that a slightly larger vortex is formed as typically observed in street canyons.

The effect of pitch rise and roof arrangement on average concentration

The change of average concentration from the reference is used as a criterion to evaluate the effectiveness of pollutant removal for each case. These changes are summarized in Table 3 in a form of percentage.

Table 3: The changes of average concentration from the reference case

	R=1m	R=2m	R=3m
2P2F2P	+7%	+8%	0%
2P1F3P	+7%	+8%	+3%
3P1F2P	+9%	+18%	+11%
6P	+9%	+19%	+16%

According to the results, all of the 12 studied cases are less effective to remove pollutants compared with the reference case. The highest increases of average concentration are 3P1F2P_R2 and 6P_R2, which are 18% and 19% respectively.

For the cases with the same pitch rise, the 3P1F2P and 6P cases always have higher average concentration than the 2P2F2P and 2P1F3P cases. It is owing to the pitched roof on the leeward building, which induces lower velocity and TKE in the canyon than the cases with a flat roof on the leeward building. For the cases with the same roof arrangement, the 2m pitched roofs always make the worst scenario, which is not consistent with the impact of pitch rise on ventilation that 3m pitched roofs always cause the lowest velocity and TKE in the canyon. It suggests that for the cases with 3m pitched roofs, the change of average concentration cannot be simply explained by the decrease of velocity and TKE. A possible reason is that the vortex flow pattern is elongated in the vertical direction, so that pollutants are spread in a larger area.

CONCLUSION

We confirm that roof type and roof arrangement have a significant effect on mean flow field, velocity, turbulence and consequently on ventilation and pollution dispersion within the street canyon. Four main conclusions follow:

1. In all simulated cases, pitched roofs always lead to weaker advection and turbulence in the canyon. As a result, the average pollutant concentrations for all 12 studied cases are higher than the concentration for the reference case.
2. For any of the studied roof arrangement, the higher the pitch rise, the lower the velocity and turbulence in the canyons. This means that ventilation is worst affected by the highest pitch rise.
3. For the same pitch rise, street ventilation is found to relate most heavily to the presence of pitched roofs near the test street canyon and their positions.
   (a) A pitched roof on the windward building always has a weak adverse effect.
   (b) A pitched roof on the leeward building always has a strong adverse effect on ventilation and pollutant removal.
   (c) The worst case for ventilation is when there are pitched roof on both buildings.
4. In terms of average pollution concentration within the street canyon, the worst scenarios are case I and case L that have an intermediate (R=2m) pitched roof on the leeward building. The average concentrations for these two cases are 18% and 19% higher than that for the reference case. This finding is consistent with Conclusion 3, but it is surprising that the highest pitch rise cases, despite having the worst ventilation, do not have the highest average concentration in the canyon.

REFERENCES

FRANKE, J., HELLSTEN, A., SCHL NZEN, H. & CARISSIMO, B. 2007. *Best practice guideline for the CFD simulation of flows in the urban environment,* COST Office.

GROMKE, C. & BLOCKEN, B. 2015. Influence of avenue-trees on air quality at the urban neighborhood scale. Part I: Quality assurance studies and turbulent Schmidt number analysis for RANS CFD simulations. *Environmental Pollution,* 196**,** 214-223.

GU, Z.-L., ZHANG, Y.-W., CHENG, Y. & LEE, S.-C. 2011. Effect of uneven building layout on air flow and pollutant dispersion in non-uniform street canyons. *Building and Environment,* 46**,** 2657-2665.

GUILLAS, S., GLOVER, N. & MALKI-EPSHTEIN, L. 2014. Bayesian calibration of the constants of the – turbulence model for a CFD model of street canyon flow. *Computer Methods in Applied Mechanics and Engineering,* 279**,** 536-553.

HUANG, Y., HU, X. & ZENG, N. 2009. Impact of wedge-shaped roofs on airflow and pollutant dispersion inside urban street canyons. *Building and Environment,* 44**,** 2335-2347.

KARRA, S. 2012. *An investigation of traffic related pollutants dispersion in heterogeneous street canyon.* Doctor of Philosophy, University College London.

KASTNER-KLEIN, P., BERKOWICZ, R. & BRITTER, R. 2004. The influence of street architecture on flow and dispersion in street canyons. *Meteorology and Atmospheric Physics,* 87**,** 121-131.

RAFAILIDIS, S. & SCHATZMANN, M. 1996. Study on different roof geometries in a simplified urban environment.

TAKANO, Y. & MOONEN, P. 2013. On the influence of roof shape on flow and dispersion in an urban street canyon. *Journal of Wind Engineering and Industrial Aerodynamics,* 123, Part A**,** 107-120.

TOMINAGA, Y., MOCHIDA, A., YOSHIE, R., KATAOKA, H., NOZU, T., YOSHIKAWA, M. & SHIRASAWA, T. 2008. AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings. *Journal of Wind Engineering and Industrial Aerodynamics,* 96**,** 1749-1761.

UEHARA, K., MURAKAMI, S., OIKAWA, S. & WAKAMATSU, S. 2000. Wind tunnel experiments on how thermal stratification affects flow in and above urban street canyons. *Atmospheric Environment,* 34**,** 1553-1562.

WEN, H., KARRA, S. & MALKI-EPSHTEIN, L. 2013. Modelling of street canyon geometries in CFD – A comparison with experimental results. *13th Conference of International Building Performance Simulation Association.* Chambery, France.