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CFD evaluation of mean pollutant concentration variations in step-down street canyons

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Abstract:

Atmospheric pollution became a big issue in densified urban areas where the ventilation in streets is not sufficient. It is particularly the case for street surrounded by high buildings so-called street canyons. The ventilation and, thus, the concentrations in this kind of street are highly relying on geometric properties of the street (width of the street, heights of the buildings, etc.). Reynolds-averaged Navier-Stokes equations are used to investigate the impact of two geometric street ratios on pollutant dispersion: the ratio of the leeward to the windward building height ($H1/H2$) and the ratio of the street width to the windward building height ($W/H2$). The aim is to quantitatively assess the evolution of mean pollutant concentrations in the case of step-down street canyons with $H1/H2$ ranging from 1.0 to 2.0 and street width ratios $W/H2$ ranging from 0.6 to 1.4. Three types of recirculation regimes could be established, depending on the number and the direction of the vortices occurring inside and outside the canyon. Evolution of pollutant concentrations as a function of both ratios is provided as well as the recommended regimes in the perspective of reducing pollutant concentration in step-down street canyons at pedestrian level and near building faces.

Keywords: Air quality, Computational fluid dynamics, Street Canyon, Aspect ratio, Building characteristics

31 1. Introduction

32 Air quality has become a major concern, especially in urban areas where air pollutant sources
33 are numerous and population density is high. Air quality is influenced by traffic-related
34 emissions and the local atmospheric environment which is highly dependent on street geometry.
35 Indeed, narrow streets surrounded by high buildings are more often subject to high pollutant
36 concentrations than wide streets with lower building heights, due to poorer ventilation. An
37 estimation of pollutant concentrations in streets depending on building configurations could
38 help urban planners to understand the impacts of street geometry on air quality and provide
39 keys to making suitable choices to lessening air pollution levels, as one of the key point
40 discussed by Bibri and Krogstie (2017) in order to achieve smart sustainable cities of the future.
41 The effects of street geometry on pollutant dispersion have already been studied extensively
42 with both experimental (Gerdes and Olivari, 1999; Hotchkiss and Harlow, 1973; Pavageau and
43 Schatzmann, 1999; Vardoulakis et al., 2003) and numerical methods (Aristodemou et al., 2018;
44 Bijad et al., 2016; Santiago and Martin, 2005; Tominaga and Stathopoulos, 2017; Vardoulakis
45 et al., 2003) and also at full-scale with in situ measurements (Qin and Kot, 1993; Vardoulakis
46 et al., 2002). Some authors have even studied the effects of roof shape on pollutant dispersion
47 (Takano and Moonen, 2013; Wen and Malki-Epshtain, 2018). However, most of these works
48 were conducted in symmetrical street canyons using buildings with the *same* height. Indeed,
49 streets surrounded by buildings of the same height do exist although streets with different
50 building heights, so-called asymmetrical street canyons, are found more often. Addepalli and
51 Pardyjak (2015) studied cases of step-down street canyons with a taller building on the leeward
52 side and showed that there are significant modifications of flow patterns depending on building
53 height and street width ratios. Xiaomin et al. (2006) performed a similar work with different
54 kinds of streets, including deep and wide symmetrical streets and step-up and step-down
55 asymmetrical streets, and showed that there are three major types of regimes in street canyons
56 depending on height and width ratios, especially in the case of step-down street canyons. In
57 spite of the several studies already done, and although there is a need for urban planners and
58 decision makers, quantitative information on how concentrations evolve with the modification
59 of street geometry is still lacking. Thus, further work is required in this direction.

60 The aim of this work is to provide information on how mean pollutant concentrations
61 quantitatively evolve in a step-down street canyons. More specifically, it is to assess the
62 evolution of concentration in the street according to two specific ratios: the ratio of the leeward
63 building height to the windward building height (H_1/H_2), and the ratio of the street width to the
64 windward building height (W/H_2). This assessment is carried out using computational fluid

65 dynamics (CFD) simulations. Section 2 presents the numerical model used in this work with
66 the governing equations, the boundary conditions and the numerical settings. Section 3 presents
67 the validation of the model versus experimental data in which a mesh sensitivity test and an
68 evaluation of the best turbulent Schmidt number are carried out. Finally, section 4 describes the
69 results of the study for several mean concentrations and a discussion of the results is proposed
70 in section 5.

71

72 **2. Numerical model**

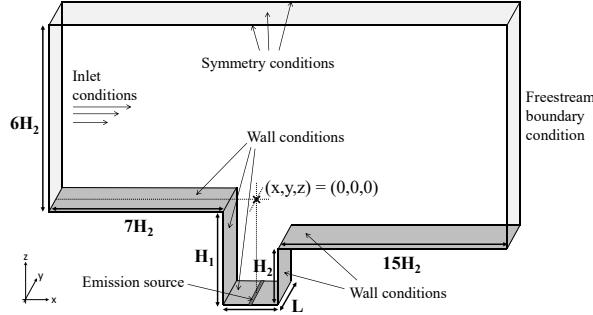
73 *2.1. Computational domain and boundary conditions*

74 Fig. 1 shows the computational domain of the street canyon, the dimensions of interest, the
75 localization of the different boundary conditions and the emission source as well as the domain
76 size.

77 In this study, $H1$ corresponds to the height of the leeward building, $H2$ corresponds to the height
78 of the windward building, W corresponds to the width between the two buildings and L
79 corresponds to the length of the street. Here, we study the case of long canyons ($L/W>7$)
80 (Vardoulakis et al., 2003) with the assumption that the interactions in the y -direction are
81 negligible. To ensure this assumption a 3D simulation was computed for this study, and the
82 results were compared to 2D results. Using a street canyon with $L/W=10$, it was found that the
83 differences between 2D and 3D simulation are fewer than 8% for $|y|\leq 3H$ with $y=0H$ the center
84 plane of the street. For $3H < L/W < 5H$, differences are still acceptable but can reach 20% (more
85 details can be found in the appendix 1). According to this results, all simulations were done in
86 2D in order to reduce calculation costs.

87 We followed the recommendations given by Franke et al. (2007) concerning the boundary
88 conditions and the domain size: the inlet boundary is placed $7\times H2$ away from the canyon; a
89 symmetry condition is applied at the top and the lateral boundaries, with the top placed $6\times H2$
90 away from the roofs of the buildings; the outlet boundary is placed $15\times H2$ away from the street
91 to allow for flow development using a freestream outlet, and no-slip conditions were applied to
92 all the other boundaries (roofs/walls of the buildings and the ground).

93 Lastly, traffic exhaust is modelled by a line source along the middle of the street ($x=0$) where a
94 source term of emission is added in the pollutant transport equation. The source term
95 corresponds to a mass flow rate chosen to $1.10^{-4} \mu\text{g/s}$.



96

97

Fig. 1. Sketch of the computational domain

98

2.2. Governing equations

99 CFD simulations were carried out in OpenFOAM 5.0. Since in real contexts, full steady state is
100 not always reached, all the simulations were performed using the unsteady pimpleFoam solver
101 which is able to capture time instabilities. Reynolds-averaged Navier-Stokes (RANS)
102 methodology was used to solve the continuity and the momentum equations throughout the
103 computational domain by considering air as an incompressible fluid. This assumption can be
104 made because of the low wind velocities (<5m/s) giving Mach numbers under 0.3 (Anderson,
105 2009). The corresponding continuity (1) and momentum (2) equations are given below:

106
$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

107
$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\bar{u}_i \bar{u}_j)}{\partial x_j} = -\frac{1}{\rho} \left(\frac{\partial \bar{P}}{\partial x_i} \right) + \nu \left(\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \right) - \frac{\partial \bar{u}'_i \bar{u}'_j}{\partial x_j} \quad (2)$$

108 where \bar{u}_i and u'_i are the i th mean and the fluctuating velocities, respectively, x_i is the i th
109 Cartesian coordinate, \bar{P} is the mean pressure and ν is the kinematic viscosity.

110 Using RANS to solve turbulent flows requires choosing a turbulence model to solve the
111 Reynolds stress tensor $\bar{u}'_i \bar{u}'_j$ (3). The RNG k- ε turbulence model proposed by Yakhot et al.
112 (1992) was chosen for turbulent closure because the numerical results fitted well with the
113 experimental data (see section 3.1.). The corresponding equations for turbulent kinetic energy
114 (4) and turbulent dissipation rate (5) of the RNG model are given below. Taking $R=0$ and using
115 the correct constants, these equations also correspond to the standard k- ε turbulence model.

116
$$\bar{u}'_i \bar{u}'_j = \frac{2}{3} k \delta_{ij} - \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (3)$$

117
$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\nu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_i}{\partial x_j} - \varepsilon \quad (4)$$

118 $\frac{\partial \varepsilon}{\partial t} + \bar{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left(\frac{\nu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k} \left(C_{\varepsilon 1} \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \frac{\partial \bar{u}_i}{\partial x_j} - C_{\varepsilon 2} \varepsilon \right) - R \quad (5)$

119 $R = \frac{C_\mu \eta^3 (1 - \eta/\eta_0) \varepsilon^2}{1 + \beta \eta^3} \frac{k^2}{k} \quad (6)$

120 $\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (7)$

121 where $\eta = Sk/\varepsilon$ and $S^2 = 2S_{ij}S_{ij}$ the mean strain tensor, \bar{u}_i is the i th mean velocity, x_i is the
 122 i th Cartesian coordinate, ν is the kinematic viscosity, k is the turbulent kinetic energy, ε is the
 123 turbulent dissipation rate, δ_{ij} is the Kronecker delta and ν_t is the turbulent viscosity. All the
 124 other parameters are model constants given in Table 1 for both the standard and the RNG k- ε
 125 turbulence models.

126 Table 1. Turbulence model constant values

Model	C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	σ_k	σ_ε	η_0	β
Standard k- ε	0.09	1.45	1.9	1.0	1.3	-	-
RNG k- ε	0.085	1.42	1.68	0.72	0.72	4.38	0.015

127

128 Pollutants are considered as passive scalars since no chemical effects are solved in this study.
 129 The equation governing advection-diffusion for the passive pollutant dispersion given in
 130 OpenFOAM was modified to take into account turbulent diffusivity. The corresponding
 131 equation is given below:

132 $\frac{\partial C}{\partial t} + \frac{\partial (u_i C)}{\partial x_i} - \frac{\partial}{\partial x_i} \left[\left(D_m + \frac{\nu_t}{Sc_t} \right) \frac{\partial C}{\partial x_i} \right] = E \quad (8)$

133 where C is the pollutant concentration, D_m is the molecular diffusion coefficient, Sc_t is the
 134 turbulent Schmidt number and E is the source term of the pollutants (emissions).

135 The ratio ν_t/Sc_t corresponds to the turbulent diffusion coefficient. The value of Sc_t is constant
 136 throughout the computational domain and fixed at 0.2. This value was chosen for the validation
 137 step (see section 3.2.).

138 *2.3. Numerical settings*

139 Second order schemes were adopted for all the gradient, divergent and Laplacian terms. In
 140 particular, for the Laplacian terms we used the ‘Gauss linear corrected’-scheme which is an
 141 unbounded second order conservative scheme, the second order ‘Gauss linear’-scheme for the

142 gradient terms and the ‘Gauss linearUpwind’-scheme for the divergent terms, the latter scheme
 143 being an unbounded upwind second order scheme.

144 All the simulations were run until the convergence was reached. To ensure the convergence of
 145 the simulations, the values of the streamwise velocity U and the pollutant concentration C were
 146 monitored for several points all over the canyon. Since all the simulations reached steady-state,
 147 they were stopped when the values monitored were constant over time. Moreover, at the end of
 148 the simulations all the residuals were under 10^{-5} .

149 **3. Model validation**

150 The model was validated versus the experimental wind tunnel data proposed by Soulhac et al.
 151 (2001). This experiment setup consists of a regular street canyon with $H1/H2=1$ and $W/H2=1$
 152 with a gas released continuously at the center of the street. A summary of the boundary
 153 conditions used for this validation is given in Table 2. A comparison between experimental and
 154 numerical streamwise velocity was made to evaluate mesh sensitivity; another comparison
 155 between experimental and numerical pollutant concentrations was made to find the turbulent
 156 Schmidt number which gave the best results compared to the experiment.

157 Table 2. Summary of the boundary conditions

	Experimental velocity profile which corresponds to a power law profile with
Inlet	$U = U_{ref} \left(\frac{z}{z_{ref}} \right)^\alpha$, where $U_{ref}=5.54\text{m/s}$ is the velocity at z_{ref} , $z_{ref}=0.63\text{m}$ is the reference height, $\alpha=0.127$ is the power law exponent and z the height from the ground. $k = 1.5(UI)^2$, with $I \approx 0.16$. $Re^{-1/8}$ the turbulent intensity, with $R_e = U \cdot H/v$ the Reynolds number where $U=4.43\text{m/s}$ is the mean inlet velocity, $H=0.6\text{m}$ is the injection height and $v=1.56 \cdot 10^{-5}$ is the kinematic viscosity.
Outlet	$\epsilon = C_\mu^{0.75} \frac{k^{1.5}}{l}$ with $C_\mu=0.085$ the CFD constant, and l the turbulence length taken as equal to the injection height (0.6m).
Top	The inlet profiles start from the upwind roof height ($z=0$) and end at the domain top height ($z=6H_2$).
Lateral surfaces	Symmetry plane
Ground and building surfaces	No slip condition ($U=0\text{m/s}$)
Emission	Line source with emission rate $q_m=1.10^{-4}\text{ }\mu\text{g/s}$ localized at the middle of the street

158

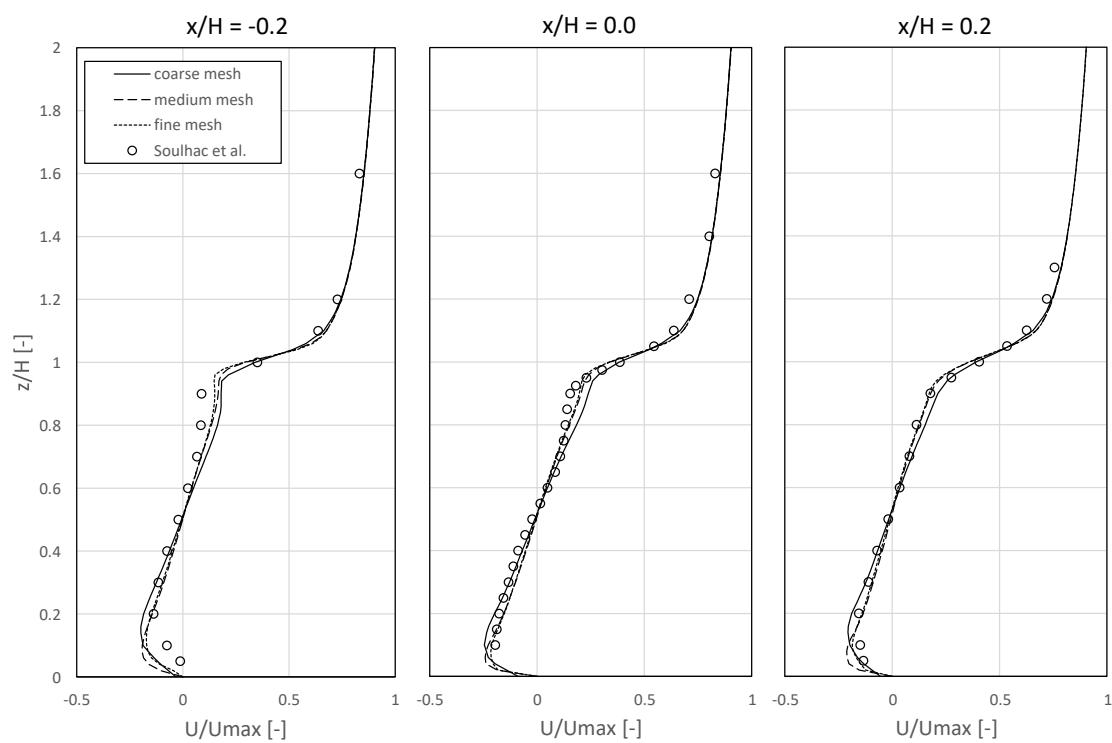
159

160 *3.1. Mesh sensitivity*

161 Mesh sensitivity tests were carried out and compared to the experimental streamwise velocity
 162 results to find the best compromise between the precision of the numerical results and
 163 calculation costs.

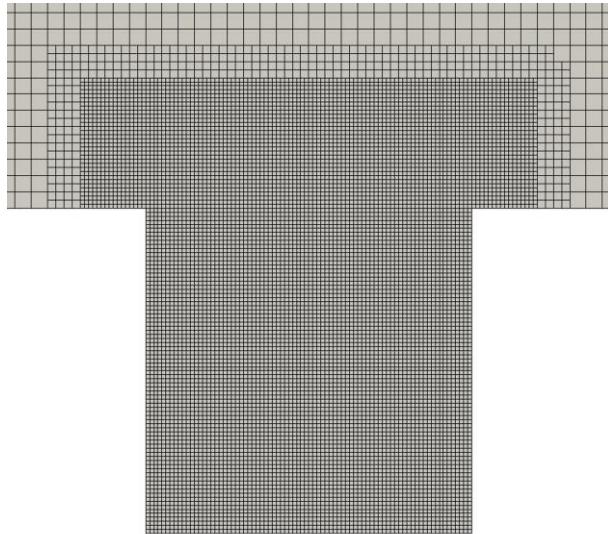
164 Fig. 2 shows this comparison for three localized velocity profiles: on the leeward side of the
 165 street ($x/H=-0.2$), in the middle of the street ($x/H=0.0$) and on the windward side of the street
 166 ($x/H=0.2$). Three mesh-dependent results are proposed and the grid expansion ratio between
 167 the coarse and the medium grid and between the medium and the fine grid is 2. Velocities and
 168 heights are proposed in dimensionless form, corresponding to U/U_{max} with $U_{max}=5\text{m/s}$ and z/H
 169 with $H=0.1\text{m}$, respectively.

170 The results show good agreement between the experimental and numerical data whatever the
 171 mesh refinement considered. There is a noticeable difference in the numerical results between
 172 the coarse and the medium mesh in the street canyon ($z/H < 1$). The difference between the
 173 medium and the fine meshes is almost imperceptible apart from the low heights for which the
 174 fine mesh results are closer to the experimental results. Thus, in the light of these results, the
 175 fine mesh grid was adopted, and an illustration of the selected meshing is provided in Fig. 3.



176

177 Fig. 2. Vertical distribution of numerical streamwise velocities for different mesh refinements compared to Soulhac et al.
 178 (2001) experimental data



179

 180 Fig. 3. Illustration of the selected meshes
 181

182 An additional mesh sensitivity study was performed on the variable of interest C , the pollutant
 183 concentration, using the Grid Convergence Index (GCI) methodology proposed by Roache
 184 (1994). This methodology is used to assess the mesh-related errors of a given mesh grid in view
 185 of the fine and coarse grid results and depending on the grid expansion ratio and the order of
 186 the numerical scheme used. The GCI for fine mesh grid error evaluation is given below:

$$187 \quad GCI_{fine\ grid} = 3 \frac{|f_2 - f_1|}{f_1} (r^p - 1)^{-1} \quad (9)$$

188 where f_1 and f_2 are the results using the fine and coarse grid, respectively (here $f_1 = C_{fine}$ and
 189 $f_2 = C_{coarse}$), r is the grid expansion ratio between the fine and the coarse grid and p is the
 190 order of the numerical scheme.

191 The grid convergence index for the fine grid was calculated for 370 points uniformly distributed
 192 in the street canyon with $p = 2$ (second order schemes) and $r = 4$ (the fine mesh is four times
 193 smaller than the coarse mesh). The corresponding mean $GCI_{fine\ grid}$ is 2% and the maximum
 194 4%, thus corresponding to a sufficient grid resolution. The typical dimension of the chosen cells
 195 is $0.0125 \times H2$.

196 *3.2. Turbulent Schmidt number*

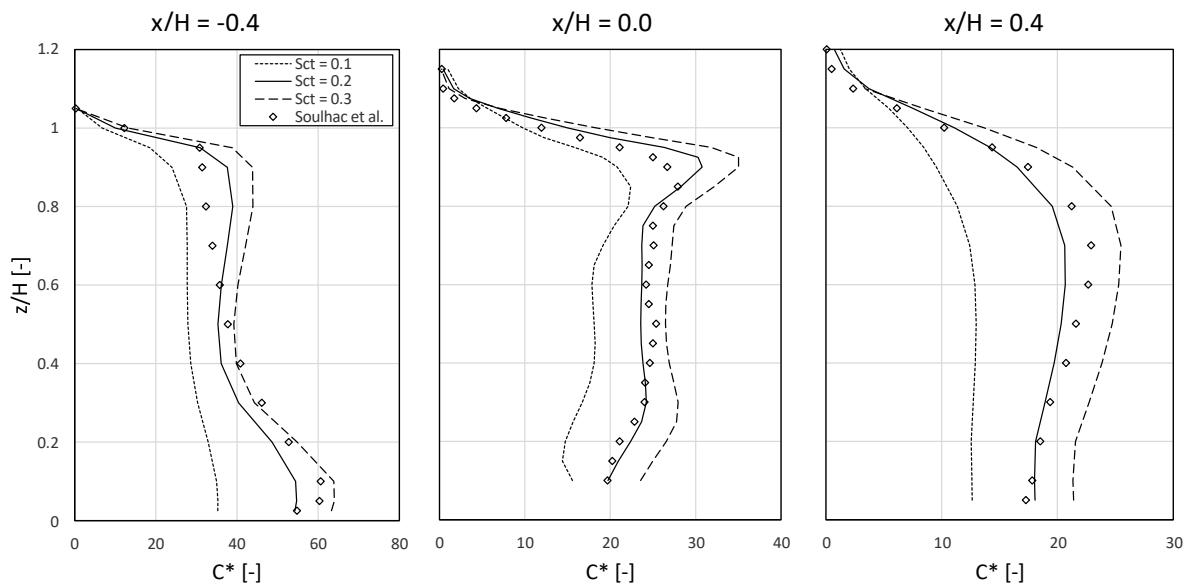
197 According to Tominaga and Stathopoulos (2007), the optimal values of the turbulent Schmidt
 198 number Sc_t are widely spread between 0.2 and 1.3 and have a considerable influence on
 199 pollutant mass transfer. Thus, Sc_t must be chosen with care. To make this choice, several

200 simulations were performed for $0.1 < Sc_t < 0.7$ with steps of 0.1 and the results were compared
201 with the experimental data.

202 Fig. 4 shows the results for three localized concentration profiles: close to the leeward building
203 ($x/H = -0.4$), in the middle of the street ($x/H = 0.0$) and close to the windward building ($x/H = 0.4$).
204 The three closest numerical results compared to the experiment are shown and differ only by
205 the turbulent Schmidt number used: 0.1, 0.2 and 0.3. Concentrations and heights are proposed
206 in dimensionless form. The same dimensionless form as before was used for the heights (z/H)
207 and the dimensionless concentration was obtained using (10).

208
$$C^* = C \cdot U_H \cdot H_2 \cdot L / q_m \quad (10)$$

209 where C^* is the dimensionless concentration, C is the concentration, U_H is the velocity just over
210 the windward building ($0.05H_2$ over the roof) and far from the canyon in the experimental setup
211 of Soulhac et al. (2001) with $U_H = 2.75$ m/s, H_2 is the windward building height, L is the
212 pollutant injection length and q_m is the pollutant emission rate.



213
214 Fig. 4. Vertical distribution of numerical dimensionless concentrations for different Sc_t compared to Soulhac et al. (2001)
215 experimental data
216

217 The results show good agreement between the numerical and experimental data for $Sc_t = 0.2$.
218 Regarding this turbulent Schmidt number, for the leeward side there is generally an
219 overestimation of the concentrations in the upper part of the street and an underestimation in
220 the lower part of street while there is a general underestimation for the windward side. The
221 numerical results are less accurate with $Sc_t = 0.1$ and $Sc_t = 0.3$, so the value of 0.2 was kept for

222 the rest of the study. Using this turbulent Schmidt number, the mean normalized absolute error
223 over the experimental profiles was 10%. The corresponding 95th percentile was less than 30%
224 and the maximal differences between the experimental and numerical results occurred near the
225 ground.

226 The models used in the present paper (RANS and RNG k- ε) give a global underestimation of
227 the turbulent momentum diffusion leading to low turbulent Sc_t . The turbulent Schmidt number
228 taken as 0.2 is in coherence with other authors results who took a low Sc_t as 0.3 for the same
229 models (Tominaga and Stathopoulos, 2007). It should be noted that the value of 0.2 could not
230 be the best for all the geometric ratios considered in this work. However, it was decided to
231 always use the same Sc_t in the whole study, which is a common practice done by the scientific
232 community (Takano and Moonen, 2013 ; Wen and Malki-Epshtain, 2018 ; Cui et al., 2016), in
233 order to only compare the influence of the geometric properties of the buildings on the mean
234 concentrations and to avoid multi parameter comparisons.

235 **4. Effects of street dimensions on mean concentrations**

236 Exactly the same conditions as defined previously were used for the present study, except for
237 the geometric properties of the street and in particular $H1$ and W . To study the mean
238 concentrations in the street canyon, several couples of height ratios $H1/H2$ and width ratios
239 $W/H2$ were considered. The present work is limited to a step-down street canyon configuration
240 where $H1/H2 > 1.0$. The following height ratios were used: 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0. For
241 each of these height ratios, 5 width ratios were considered: 0.6, 0.8, 1.0, 1.2 and 1.4, giving a
242 total number of 30 simulations and an overall idea of how could evolve mean concentrations in
243 step-down street canyons. This number does not include certain particular cases that were also
244 simulated when the results were strongly different between two cases (e.g. when for a given
245 width ratio, two successive height ratios results in two different regimes). A case table of all the
246 ratios considered in this work is proposed in Table 3.

247

248

249

250

251 Table 3. Case table of all geometric ratios considered (● : couples of ratios initially considered
 252 aftermath) ○ : specific cases considered

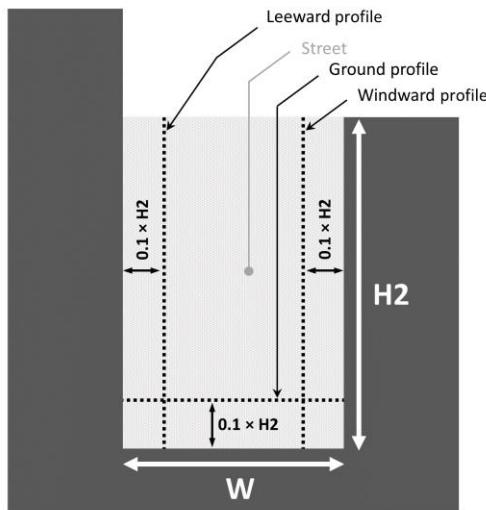
$H1/H2$	0.6	0.8	1.0	1.2	1.4
$W/H2$					
2.0	●	●	●	●	●
1.9					
1.8	●	●	●	●	●
1.7					
1.6	●	●	●	●	●
1.5		○			
1.4	●	●	●	●	●
1.3			○	○	○
1.2	●	●	●	●	●
1.1	○	○			
1.0	●	●	●	●	●

253

254 Fig. 5 shows the localization of the mean concentrations studied in this paper. Here, we study:

- 255 - The concentration averaged all over the street (in the $W \times H2$ area),
 256 - The mean concentration on a vertical profile placed $0.1H_2$ from the windward building
 257 facade (concentration averaged for the $H2$ height) and another vertical profile placed $0.1H_2$
 258 from the leeward building facade (concentration averaged for the $H2$ height). These mean
 259 concentrations are relevant for people living in the buildings near the street.
 260 - The mean concentration for a horizontal profile placed $0.1H_2$ from the ground
 261 (concentration averaged for the W length). This mean concentration is relevant for
 262 pedestrians in the street.

263



264

265

266

267 All the concentrations will be given in dimensionless form. The dimensioned concentrations
268 could also be retrieved using (10) with $U_H=2.75\text{m/s}$, $H_2=0.1\text{m}$, $L=0.0025\text{m}$ and $q_m=1.10^{-4}\mu\text{g/s}$.

269 4.1. Vorticity and recirculation regimes in the street canyon

270 Flow velocities and recirculation patterns have a significant impact on pollutant dispersion and
271 thus on pollutant concentrations inside and outside the street canyon. The modifications of flow
272 velocities and recirculation patterns are caused solely by the geometric properties of the street
273 (H_1/H_2 and W/H_2) as all the simulations were run using the same velocity inlet profile.

274 Out of the total number of simulations performed, three types of recirculation regimes were
275 found. Fig. 6 shows an example of each regime with the velocity vectors and the corresponding
276 y -vorticity ω_y given by equation (11). These three regimes stand out due to their number of
277 recirculation zones inside and outside the canyon.

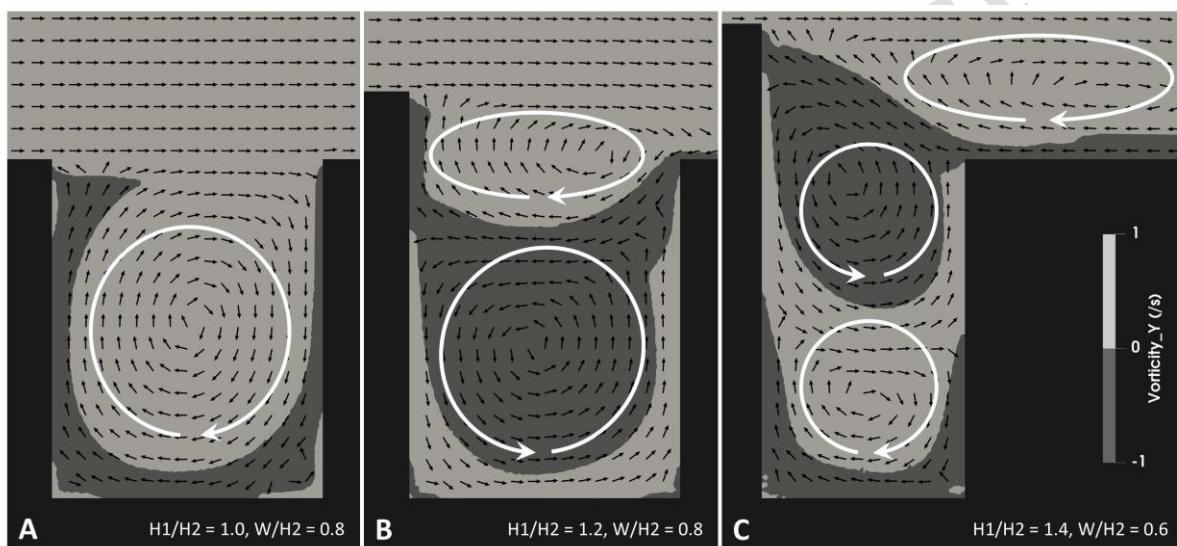
$$278 \quad \omega_y = \frac{\partial U_x}{\partial z} - \frac{\partial U_z}{\partial x} \quad (11)$$

279 Regime A corresponds to a big single vortex localized in the canyon. For this regime, vorticity
280 is globally positive in the canyon, which means that the vortex rotates clockwise. Regime B
281 corresponds to two vortices, one large vortex in the canyon and a second localized mostly over
282 the canyon and the windward building. The large vortex in the canyon is very similar to that of
283 regime A, but here the vorticity is mostly negative, and the vortex rotates counterclockwise.
284 The second vortex localized outside the canyon rotates clockwise. Regime C corresponds to
285 three vortices, two contra-rotative vortices localized in the canyon and the third vortex mostly
286 localized over the windward building. This regime appears to be a combination of regimes A

287 and B, with the clockwise-vortex of regime A in the low part of the street and the
288 counterclockwise-vortex of regime B situated just over it. The same clockwise-outside-vortex
289 of regime B is also observed.

290 Xiaomin et al. (2006) gave the critical value of $H1/H2$ for several $W/H2$ corresponding to the
291 limit between regime A and regime B/C without distinction between B and C. Their results are
292 compared with those of the present study for $W/H2$ from 0.6 to 1.4 and are shown in Fig. 7 with
293 the gray area corresponding to the switching area between regime A and regime B/C. The
294 boundary conditions were the same between both studies.

295



296

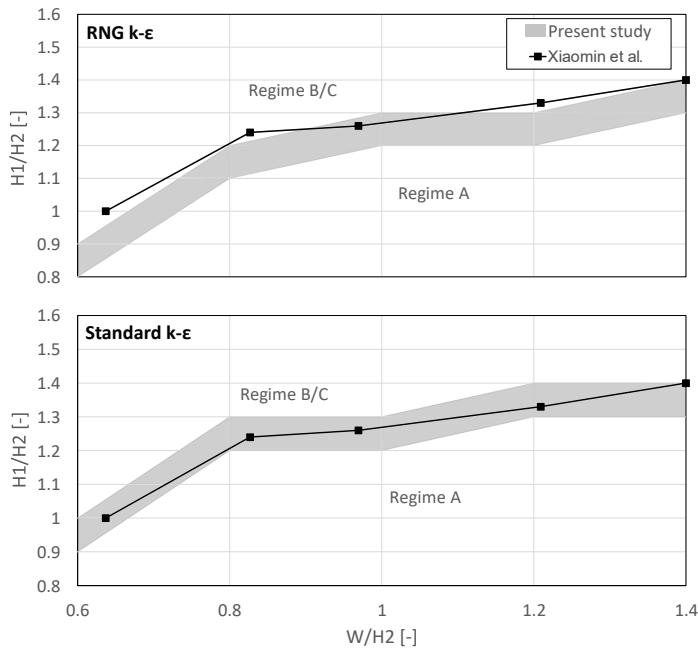
297 Fig. 6. Recirculation patterns, velocity vectors and y-vorticity for different geometric ratios $H1/H2$ and $W/H2$

298

299 The results obtained after the simulations showed a trend similar to that of the results of
300 Xiaomin et al. (2006). The critical value of $H1/H2$ increases when the distance between the
301 buildings increases and the zone of change between regime A and regime B/C is quite similar
302 for both studies. However, critical values seem to be reached sooner according to our results
303 (i.e. for smaller $H1/H2$) with a maximal difference of 0.1 compared to the results of Xiaomin et
304 al. (2006).

305 Some simulations were rerun using the turbulent conditions of Xiaomin's et al. (2006), that is,
306 using the standard $k-\epsilon$ turbulent closure. The results, also presented in Fig. 7, show this time
307 perfect concordance between both studies. Thus, turbulent closure schemes have an influence

308 on the critical values of $H1/H2$. This difference between critical values when using standard k-
 309 ϵ or RNG k- ϵ are, however, quite small with a maximum difference of 0.1 for the ratio $H1/H2$.



310
 311 Fig. 7. Comparison of regime changing zones between the present study and the results of Xiaomin et al. (2006) using RNG
 312 and standard k- ϵ turbulent closure.

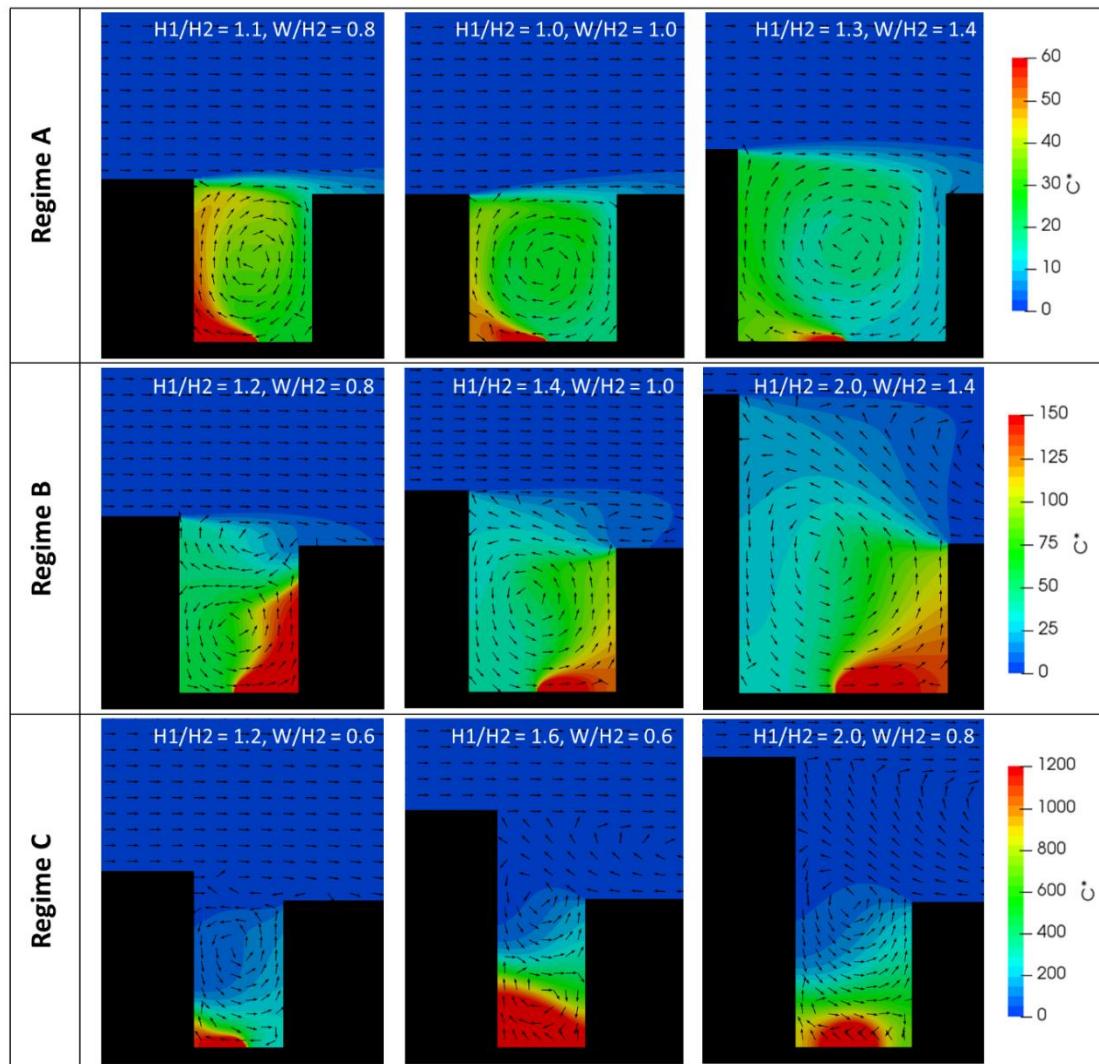
313

314 *4.2. Impact of the regimes on pollutant dispersion*

315 Three examples of pollutant dispersion in the street canyon for each regime are shown in Fig. 8.
 316 The overall concentrations in the street canyons being very different between the three regimes,
 317 the color scale is different for each of them. The velocity vectors are provided in order to better
 318 understand the differences in the concentration fields for the three regimes.

319 The evolution of the concentration field, the overall magnitude of concentration, and the most
 320 impacted building are directly linked with the type of regime being established. In regime A,
 321 the pollutants released at ground level are mostly dispersed towards the leeward building due
 322 to the single clockwise vortex established in the street. In regime B, the apparition of a second
 323 vortex due to the increase of the leeward building height and the decrease of the distance
 324 between building leads to a change in the dispersion of pollutants. The vortex in the street being
 325 in this case counter clockwise, the most impacted building became the windward building.
 326 Moreover, concentrations are overall higher in this case and it seems to be the consequence of
 327 the clockwise vortex localized just above which is driving a part of the pollutants which left the
 328 street to the street again. For the last regime, regime C, both buildings are highly impacted. The

difference with the regime B is not only the apparition of a third vortex, but the fact that two vortices are localized in the street between the buildings. Due to this two vortices, the pollutants released at ground level are dispersed to the leeward building but, because of the second vortex in the canyon, they are more homogenized in the low part of the street and seem to be more stagnant. It should also be noted that global velocities in the street tend to decrease with the increase of the leeward building height and the decrease of the distance between building which also conduct to higher pollutant concentrations.



336

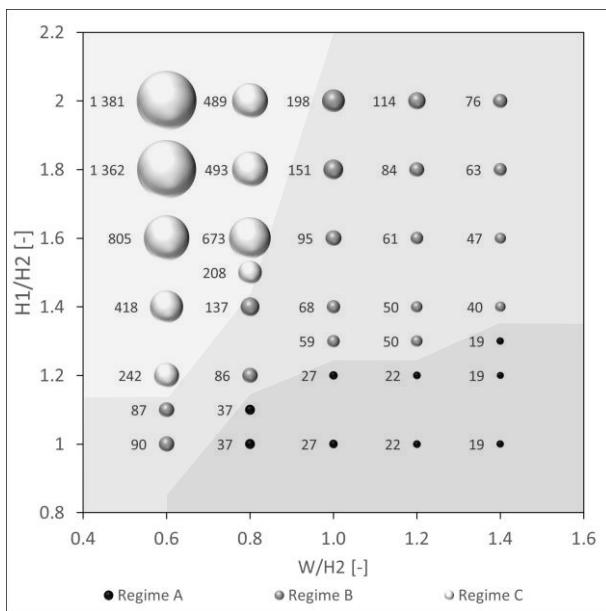
337 Fig. 8. Three examples of dimensionless concentrations in a street canyon for each type of regime.

338 4.3. Mean concentration in the street canyon

339 Initially, the results were studied by considering the mean concentrations of the whole street.
340 Fig. 9 shows the dimensionless street averaged concentrations (i.e. the mean concentration of

341 the $W \times H2$ surface) proposed for several $H1/H2$ and $W/H2$ ratios and the different types of
 342 regime are also specified.

343



344

345 Fig. 9. Dimensionless street averaged concentrations according to the ratio $H1/H2$ and $W/H2$

346

347 The results show that the evolution of mean concentrations is highly dependent on the type of
 348 regime in place. The mean concentrations are indeed highest when regime C is in place and
 349 lowest when regime A is in place.

350 In regime A, for a given distance between buildings (i.e. a given $W/H2$), the mean
 351 concentrations are the same whatever the height of the leeward building. Thus, only the distance
 352 between buildings has an impact on the mean concentrations in the street. For a fixed leeward
 353 building height, the mean concentrations in the street increase when the distance between
 354 buildings decrease. This increase is not constant and becomes higher when ratio $W/H2$
 355 decreases. For example, the mean concentration increases by 23% between $W/H2=1.2$ and
 356 $W/H2=1.0$ and then by 37% between $W/H2=1.0$ and $W/H2=0.8$. Lastly, for the $H1/H2$ and
 357 $W/H2$ ratios studied in this work, the factor between the lowest and the highest mean
 358 concentration for regime A is equal to 2.

359 In regime B, the evolution of the mean street concentrations is dependent on both ratios $H1/H2$
 360 and $W/H2$: for a given leeward building height, the mean street concentrations increase when
 361 the distance between the buildings decreases; for a given distance between buildings, the mean
 362 concentration increases when the leeward building height increases. In addition, the increases

363 between mean concentrations are not constant and become higher when $H1/H2$ increases and
364 $W/H2$ decreases. The factor between the highest and lowest mean concentrations in the case of
365 regime B is around 5.

366 In regime C, the evolution of the street mean concentrations is also dependent on both ratios
367 $H1/H2$ and $W/H2$ but is no longer monotonous. Indeed, for a given distance between the
368 buildings, the mean street concentrations first increase and then become constant. If the leeward
369 building height is high enough, this mean concentration can then decrease. In this third case, a
370 maximal mean concentration is reached. Mean street concentrations are highest for this regime
371 with, in the worst-case concentrations, 50 times that of the regular case $H1/H2=W/H2=1.0$.

372 Lastly, considering the whole series of simulations run in this study, for a given $H1/H2$ ratio,
373 the mean concentrations increase as the distance between buildings decreases, whatever the
374 three regimes observed. The evolution of the mean concentrations for a given $W/H2$ is
375 nevertheless dependent on the regime.

376

377 *4.4. Mean concentration on the building sides*

378 The results were then studied considering only the windward and the leeward building sides.
379 Fig. 10 shows the dimensionless windward side averaged concentrations (i.e. the mean
380 concentrations averaged over the windward profile) proposed for several $H1/H2$, and $W/H2$
381 ratios and the different types of regime are also specified. Fig. 11 gives the same information,
382 but considering the dimensionless, averaged leeward side concentrations (i.e. the mean
383 concentrations averaged over the leeward profile).

384 As can be seen in Fig. 10. and Fig. 11., the evolution of the mean concentrations on the two
385 building sides are similar. However, the mean concentrations could be higher or lower on the
386 windward side, depending on the recirculation regimes.

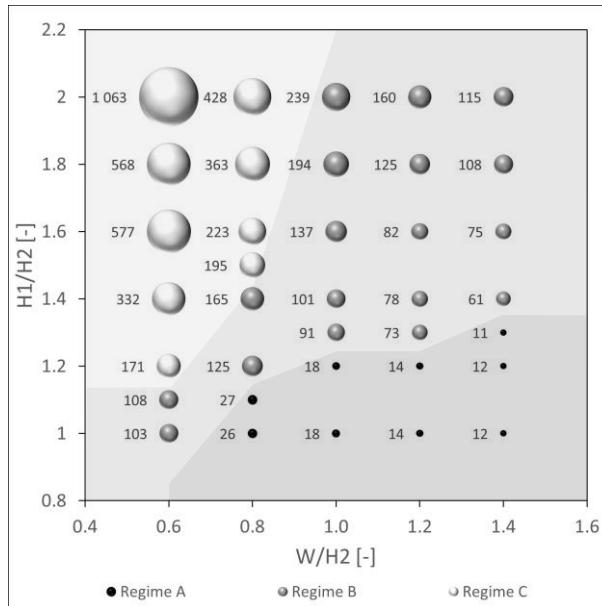
387 In Regime A, for a given distance between buildings (i.e. a given $W/H2$ ratio), the mean leeward
388 and windward concentrations are constant whatever the $H1/H2$ ratio. However, the mean
389 concentration values are different, with concentrations globally twice as high on the leeward
390 side. This observation is linked to the characteristics of regime A described in section 4.1.
391 Indeed, for all the cases in which regime A occurs, a large clockwise rotating vortex appears
392 which spreads the pollutants released at ground level to the leeward side.

393 In regime B, the mean concentrations are no longer constant for a given distance between
394 buildings but depend on both ratios $H1/H2$ and $W/H2$. This time the mean concentrations are
395 higher on the windward side according to the counterclockwise vortex occurring in regime B,
396 which spreads the pollutants released at ground level to the windward side. The mean
397 concentrations on the windward side are globally three times higher than those of the leeward
398 side.

399 In regime C, the mean concentrations still depend on both ratios $H1/H2$ and $W/H2$ and the
400 concentrations are much higher than in regime B. The mean concentrations are globally higher
401 on the leeward side but this is not always true. Indeed, for $H1/H2=2.0$ and $W/H2=0.8$, the mean
402 windward concentration is higher. It is much more difficult to interpret this difference than
403 those of the two previous regimes because two vortices are localized in the canyon in this case.
404 However, in this case the vortex is clockwise and localized near the emission source. The
405 pollutants released near the ground are thus initially spread to the leeward side and it is only
406 afterwards that the second vortex spreads them to the windward side. This explains why the
407 mean concentrations are mostly higher on the leeward side than on the windward side.

408 Finally, if we focus on how the mean concentrations evolve when the regimes change (e.g.
409 when switching from regime A to regime B), there is a notable difference between the windward
410 and leeward sides. Indeed, for a switch from regime A to regime B, whereas the mean
411 concentrations increase by a factor 6 on the windward side, the concentrations on the leeward
412 side are almost equal. Moreover, on the leeward side, the mean concentration observed in the
413 case of regime B did not increase much when $H1/H2$ increased or $W/H2$ decreased compared
414 to the windward side.

415

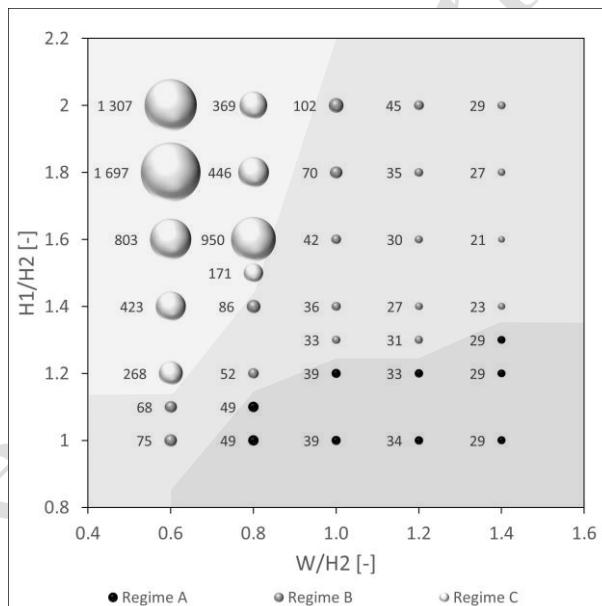


416

 Fig. 10. Dimensionless windward profile averaged concentrations according to the ratios $H1/H2$ and $W/H2$.

417

418



419

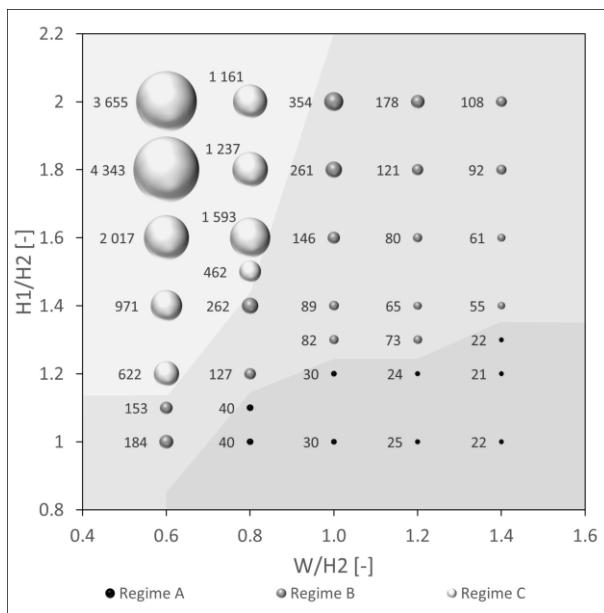
 Fig. 11. Dimensionless leeward profile averaged concentrations according to the ratios $H1/H2$ and $W/H2$.

420

4.5. Mean concentration at ground level

Finally, the results were studied at ground level and Fig. 12 shows the dimensionless ground averaged concentrations (i.e. the mean concentrations averaged over the ground profile) proposed for several $H1/H2$ and $W/H2$ ratios; the different types of regime are also specified.

426 At ground level, the evolution of mean concentrations is similar for the leeward profile and the
 427 whole street: regime A leads to constant mean concentrations for a given distance between
 428 buildings; regime B leads to mean concentrations depending on both the distance between
 429 buildings and difference in height between the two buildings; regime C leads to the same
 430 observation as regime B, the difference being that for a given distance between buildings, a
 431 maximal mean concentration is reached, after which this concentration decreases with the
 432 increase in the difference in height between the two buildings.



433

434 Fig. 12. Dimensionless ground profile averaged concentrations according to ratio $H1/H2$ and $W/H2$.

435

436 5. Discussion

437 Choices were made regarding the turbulence model used as well as the isothermal assumption
 438 taken to fulfil this work. These choices could affect the presented results and are worth
 439 discussing about.

440 Based on comparison with experimental data, the RNG turbulence model was selected. This
 441 model is an isotropic linear $k-\epsilon$ based model that is known to have some limitations for highly
 442 transient cases, especially in a wake of a body, including flows behind the leeward walls of
 443 street canyons. To avoid such problems, non-linear turbulence models or anisotropic models
 444 such as the Reynolds Stress Model (RSM) should be used. However, these models are time
 445 consuming and are more difficult to converge. In addition, they seem to give not as much
 446 improvements as expected in the case of isolated buildings or street canyons. Indeed,

447 Papageorgakis and Assanis (1999) showed that the linear RNG k- ϵ turbulence model gives
448 significant improvements compared to the standard turbulence model for recirculatory flow
449 such for backward facing step cases. Moreover, according to the same authors, the non-linear
450 RNG turbulence model is not very attractive, yielding not to great improvements. Finally,
451 Koutsouarakis et al. (2012) showed for six street canyons with different aspect ratios that the
452 RNG turbulence model gives the best performances for each case compared to the standard
453 turbulence model as well as compared to RSM.

454 The whole study was conducted considering neutral (isothermal) conditions since ambient and
455 wall temperatures were considered equal. Thus, only the forced convection due to the wind was
456 considered. More complex cases could appear when the building walls are heated by solar
457 radiations conducting to unstable conditions where natural convection appears. For this cases,
458 results in terms of recirculation regimes or pollutant concentrations can be different. Wang et
459 al. (2011) studied the cases of leeward, ground, and windward heated walls in a regular street
460 canyon and compared the results with the neutral case (without wall heating). They found that,
461 except for the case of the windward heated wall, the recirculation pattern in the street is always
462 the same. Concentrations are different depending on the case, but they are always lower than
463 for the neutral case. These results are confirmed by Allegrini et al. (2013) who did the same
464 work with several wind speed and also simulated a case where all walls are heated. This case
465 also leads to the same recirculation pattern as for the neutral case. According to these results, it
466 could be said that the results given in this study are not only good for one considering neutral
467 cases but are also a good first approximation of thermally unstable cases. Pollutant
468 concentrations being greater for the neutral case than for the unstable case leading thus to a
469 safer approach.

470 6. Conclusion

471 The effects of step-down street canyon geometric properties on recirculation patterns and mean
472 pollutant concentrations in a street were studied with a CFD model. This study considered 6
473 height ratios $H1/H2$ (from 1.0 to 2.0 with a 0.2 step) and 5 width ratios $W/H2$ (from 0.6 to 1.4
474 with a 0.2 step). The main conclusions are as follows:

475 (a) Three types of regimes can occur as a function of both the height and width ratios of the
476 street. Flow velocities and direction in the street, and thus pollutant concentrations,
477 depend heavily on the type of regime being established. The three types of regime were
478 characterized by the number of vortices established and their direction: regime A
479 corresponded to a single clockwise vortex in the canyon; regime B corresponded to a

480 counter-clockwise vortex in the canyon and a clockwise vortex over the windward
481 building; regime C corresponded to two contra-rotating vortices in the canyon and a
482 clockwise vortex over the windward building.

483 (b) The critical values of $H1/H2$ corresponding to a change in the type of regime for a given
484 width ratio were determined. The critical values obtained were differed as a function of
485 the turbulence closure scheme used. These differences were never greater than 0.1 when
486 using standard or RNG k-epsilon turbulence schemes.

487 (c) Whatever the mean concentration considered (in the whole canyon, at pedestrian level
488 or near the building faces), the mean concentrations were lowest in the case of regime
489 A and highest in the case of regime C. Regime B therefore corresponded to an
490 intermediary state.

491 (d) The mean concentrations increased globally as differences in building height increased
492 ($H1/H2$ ratio), and with the decrease of street width ($W/H2$), except for the case of
493 regime A where the evolutions of mean concentrations depended only on street width.

494 (e) The quantitative evolution of the mean pollutant concentration in the whole street at
495 pedestrian level and near the building faces was proposed.

496 As a summary, in order to have a good ventilation in step-down street canyons and in the
497 perspective of reducing mean pollutant concentration of the whole street at pedestrian level and
498 near building faces, we recommend choosing carefully the height ratio $H1/H2$ as well as the
499 width ratio $W/H2$ in order to be in the case of a regime A.

500 These conclusions and results were obtained for a given type of street canyon and they should
501 be extended to consider other types such as step-up street canyons and wider and deeper
502 canyons. Moreover, these results were obtained considering flat roofs. However, this type of
503 roof is not the only kind of roof used for buildings and further works should be carried out to
504 obtain information on other types of roof.

505

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509

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