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1 Effects of wind speed and atmospheric stability on the air pollution 2 reduction rate induced by noise barriers

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14

15 ABSTRACT

16 People around the world increasingly live in urban areas where traffic-related emissions can
17 reach high levels, especially near heavy-traffic roads. It is therefore necessary to find short-term
18 measures to limit the exposure of this population and noise barriers have shown great potential
19 for achieving this. Nevertheless, further work is needed to better understand how they can act
20 on pollution reduction. To do this, a Reynolds-Averaged Navier-Stokes model that takes into
21 account thermal effects is used to study the effects of wind speed and atmospheric stability on
22 the concentration reduction rates (*CRR*) induced by noise barriers. This study shows that the
23 *CRR* behind the barriers may depend on both wind and thermal conditions. Although only the
24 wind direction, and not the wind speed, has an impact on *CRR* in a neutral atmosphere, this
25 parameter can be changed by both wind speed and thermal variations in non-neutral
26 atmospheres. Stable cases lead to a higher *CRR* compared to unstable cases, while the neutral
27 case gives intermediate results. Finally, it is shown that the variation of *CRR* is negligible for
28 Richardson numbers ranging from -0.50 to 0.17.

29 **Keywords:** Computational fluid dynamics, Noise barrier, Air pollution, Wind speed, Thermal
30 stratification

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33 **Highlights**

- 34 • Wind speed does not change concentration reduction rates (*CRR*) for neutral cases.
- 35 • For neutral cases, perpendicular winds lead to the lowest *CRR*.
- 36 • The global *CRR* decreases as a function of height and distance from the barriers.
- 37 • *CRRs* are higher for stable cases ($Ri > 0$) and lower for unstable cases ($Ri < 0$).
- 38 • *CRRs* remain unchanged for a given Richardson number ranging from -0.50 to 0.17.

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66 1. Introduction

67 Nowadays, more than one in two people live in urban areas with 82% in the United States and
68 74% in Europe, and this percentage will continue growing to reach 68% worldwide in 2050
69 (United Nations, 2019). Traffic-related emissions can reach high levels in such areas,
70 particularly near heavy-traffic roads. Concentrations of air pollutants such as nitrogen dioxide
71 (NO₂) and particulate matter (PM) can reach high values in the vicinity of this kind of road and
72 lead to several diseases (Anderson et al., 2012; Kagawa, 1985; Kim et al., 2015). In addition, it
73 has been shown that people living near these roads are more likely to be at risk (Chen et al.,
74 2017; Finkelstein et al., 2004; Petters et al., 2004). In Europe, emissions and therefore
75 concentrations of air pollutants are expected to decrease in the future as air quality regulations
76 increase and actions are taken (European Commission, 2013). Nevertheless, it will take time to
77 achieve a significant decrease and, in the meantime, many people will still live in areas where
78 air quality is poor. It is now necessary to find ways to limit exposure to air pollution for people
79 living near busy roads and to better understand solutions that have already been found, like
80 noise barriers.

81 Noise barriers are civil engineering elements located along roadways and designed to protect
82 inhabitants from noise pollution. These elements, often placed between heavy-traffic roads and
83 residences, also have a beneficial impact on air quality. Indeed, several authors have
84 investigated the efficiency of noise barriers in reducing atmospheric pollutant concentrations
85 behind the barriers using in-field (Baldauf et al., 2008, 2016; Finn et al., 2010; Hagler et al.,
86 2012; Lee et al., 2018; Ning et al., 2010), wind tunnel (Heist et al., 2009) measurements and
87 numerical models (Bowker et al., 2007; Hagler et al., 2011; Schulte et al., 2014). Some authors
88 have studied the effects of barrier heights and distances on pollution reduction (Amini et al.,
89 2018; Gong and Wang, 2018). Other authors have studied the effects of barrier shapes and
90 locations on improving the reduction of atmospheric pollutants (Brechler and Fuka, 2014;
91 Enayati Ahangar et al., 2017; Wang and Wang, 2019). However, although some of these works
92 have been performed by considering different atmospheric stabilities, knowledge is lacking on
93 how the combination of wind conditions and thermal effects can affect pollutant reductions
94 behind barriers. Further work is thus required in this direction.

95 The aim of this work is to study the combined effects of wind and thermal effects on the
96 reduction of pollutant concentrations behind the noise barrier. The scope of the study is limited
97 to the study of the effects of the noise barriers and doesn't include the possible effects of

98 buildings before and after the barriers. More specifically, computational fluid dynamics (CFD)
99 simulations are used to assess the evolution of the concentration reduction rate behind noise
100 barriers for several wind speeds and atmospheric stabilities, ranging from very unstable to stable
101 conditions, including all the intermediate conditions (unstable, slightly unstable, neutral and
102 slightly stable). The two key parameters of this study are defined and described in Section 2.
103 The numerical model, including the governing equations, boundary conditions and model
104 validation used in this work, is presented in Section 3. The results of the study are presented in
105 Section 4, after which these results are discussed in Section 5.

106 2. Description of the study

107 This paper examines the impact of wind speed and atmospheric stability on the reduction of
108 downwind air pollution induced by the presence of noise barriers. It is therefore necessary to
109 define two recurring parameters: the Richardson number and the concentration reduction rate.

110 The thermal effects can be quantified using the Richardson number noted Ri . The
111 corresponding equation taken from (Woodward, 1998) is given in (1).

$$112 \quad Ri = \frac{gH (T_H - T_w)}{U_H^2 T_{air}} \quad (1)$$

113 where g is the gravitational acceleration [$\text{m}\cdot\text{s}^{-2}$], H is the noise barrier height [m], U_H is the
114 reference velocity (which is the velocity at $z = H$ in this study) [$\text{m}\cdot\text{s}^{-1}$], T_{air} is the ambient
115 temperature [K], T_H is mean air temperature at $z = H$ [K], and T_w is the surface temperature of
116 the heated ground [K]. The difference $T_H - T_w$ will be noted ΔT in the following.

117 The Richardson number is also an indicator of atmospheric stability: $Ri = 0$ corresponds to
118 isothermal (neutral) cases, $Ri < 0$ corresponds to unstable cases, and $Ri > 0$ to stable cases. A
119 better discretization of atmospheric stability, related to Pasquill's stability classes, also exists
120 (Woodward, 1998) and is summarized in Table 1.

121 Table 1. Atmospheric stability correlated with the Richardson number (Woodward, 1998).

Atmospheric stability	Richardson number
Very unstable	$Ri < -0.86$
Unstable	$-0.86 \leq Ri < -0.37$
Slightly unstable	$-0.37 \leq Ri < -0.10$
Neutral	$-0.10 \leq Ri < 0.053$
Slightly stable	$0.053 \leq Ri < 0.134$
Stable	$0.134 \leq Ri$

122 The reduction of the pollution behind the noise barriers compared to an area without these
123 barriers is quantified using an indicator called concentration reduction rate (CRR) given in (2).

$$124 \quad CRR (\%) = \left(1 - \frac{C_{nb}}{C_{ref}}\right) \times 100 \quad (2)$$

125 where C_{nb} is the concentration with a noise barrier [$\text{kg}\cdot\text{m}^{-3}$] and C_{ref} is the reference
126 concentration corresponding to the same case but without noise barriers [$\text{kg}\cdot\text{m}^{-3}$].

127 The CRR provides information on both the positive and negative impact of noise barriers
128 ($CRR > 0$ means that noise barriers reduce downwind pollution; $CRR < 0$ means that noise
129 barriers increase downwind pollution) and their effectiveness ($CRR = 40\%$ means that the
130 concentration behind noise barriers is reduced by 40% compared to the same case without
131 them).

132 3. Numerical model

133 3.1. Governing equations

134 Simulations were performed using the *buoyantPimpleFoam* solver from OpenFOAM 6.0. This
135 transient solver is able to resolve Navier-Stokes equations for buoyant and turbulent flows of
136 compressible fluids including the effects of forced convection (induced by the wind) and natural
137 convection (induced by heat transfers).

138 A Reynolds-averaged Navier-Stokes (RANS) methodology was used to resolve the equations.
139 When using this methodology, a new term called Reynolds stress tensor appear and it is
140 necessary to choose a turbulence model to resolve it. The RNG k- ϵ turbulence model proposed
141 by Yakhot et al. (1992) has been selected because it gives significant improvements compared
142 to the standard turbulence model for recirculatory flows (Papageorgakis and Assanis, 1999),
143 whereas anisotropic models such as the Reynolds Stress Model (RSM) may not improve the
144 results (Koutsourakis et al., 2012) for a higher calculation cost and more calculation
145 instabilities.

146 The corresponding continuity (3), momentum (4) and energy (5) equations are given below:

$$147 \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \quad (3)$$

$$148 \quad \rho \left(\frac{\partial u}{\partial t} + u \cdot \nabla u \right) = -\nabla p + \nabla \cdot \left(2\mu_{eff} D(u) \right) - \nabla \cdot \left(\frac{2}{3} \mu_{eff} (\nabla \cdot u) \right) + \rho g \quad (4)$$

149
$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho u e) + \frac{\partial \rho K}{\partial t} + \nabla \cdot (\rho u K) + \nabla \cdot (u p) = \nabla \cdot (\alpha_{eff} \nabla e) + \rho g \cdot u \quad (5)$$

150
$$D(u) = \frac{1}{2} [\nabla u + (\nabla u)^T] \quad (6)$$

151
$$K \equiv |u|^2/2 \quad (7)$$

152 where u is the velocity [$\text{m}\cdot\text{s}^{-1}$], p the pressure [$\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-2}$], ρ the density [$\text{kg}\cdot\text{m}^{-3}$], e the thermal
153 energy [$\text{m}^2\cdot\text{s}^{-2}$], $D(u)$ the rate of strain tensor given in (6), K the kinetic energy given in (7)
154 [$\text{m}^2\cdot\text{s}^{-2}$], g the gravitational acceleration [$\text{m}\cdot\text{s}^{-2}$], μ_{eff} the effective viscosity defined as the sum
155 of molecular and turbulent viscosity [$\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$] and α_{eff} the effective thermal diffusivity
156 defined as the sum of laminar and turbulent thermal diffusivities [$\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$].

157 No chemical reactions are considered in this study. Thus, the equation governing passive scalar
158 transport (8) has been added to the solver. This advection-diffusion equation is given below:

159
$$\frac{\partial C}{\partial t} + \nabla \cdot (uC) - \nabla \cdot \left[\left(D_m + \frac{\nu_t}{Sc_t} \right) \nabla C \right] = E \quad (8)$$

160 where C is the pollutant concentration [$\text{kg}\cdot\text{m}^{-3}$], D_m is the molecular diffusion coefficient [$\text{m}^2\cdot\text{s}^{-1}$],
161 ν_t the turbulent diffusivity [$\text{m}^2\cdot\text{s}^{-1}$], Sc_t the turbulent Schmidt number [-] and E the
162 volumetric source term of the pollutants (emissions) [$\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$].

163 Each simulation was performed using second order schemes for all the gradient, divergent and
164 Laplacian terms. The streamwise velocity U and the pollutant concentration C were monitored
165 for several locations behind the downwind noise barrier and the results were checked to ensure
166 that each simulation has converged. At the end of the simulations, all the residuals were under
167 10^{-5} .

168 3.2. Computational domain and boundary conditions

169 This study focuses on the concentration reduction rates induced by the presence of noise
170 barriers. Thus, to quantify this reduction, two distinct cases have to be considered in terms of
171 computational domain: a case with noise barriers and a case without them. Fig. 1 shows a sketch
172 of the computational domain and the boundary conditions used for the case with noise barriers.
173 The second case is strictly the same but without the noise barriers.

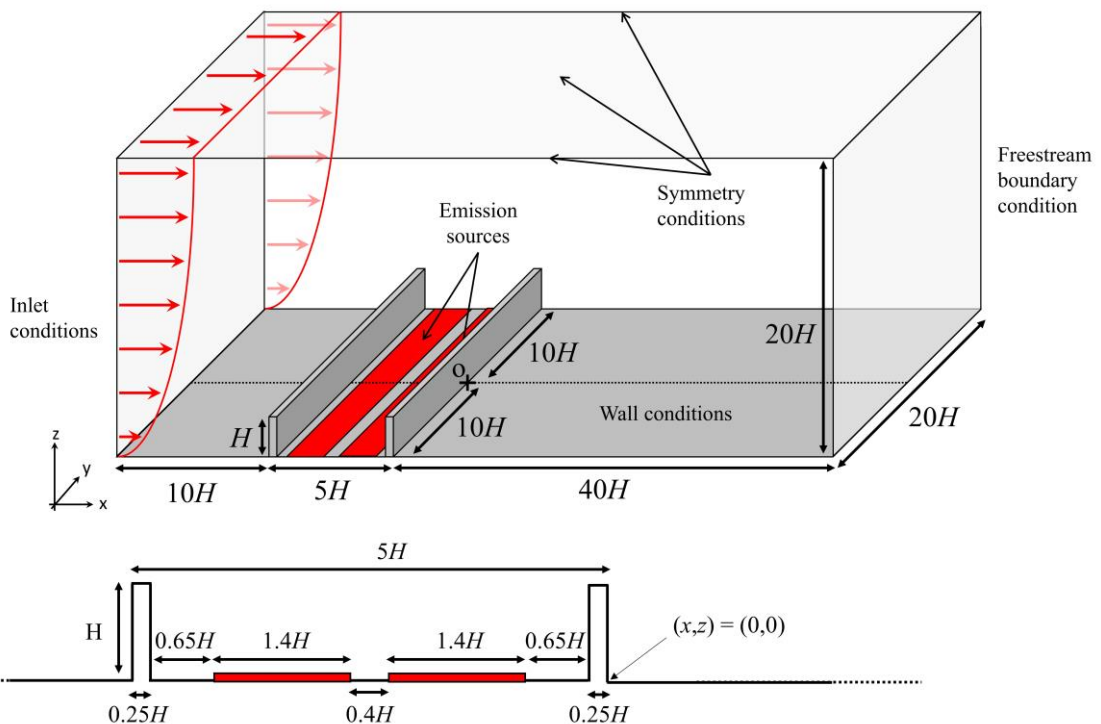


Fig.1. Sketch of the computational domain with $H = 5$ m.

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177 The recommendations given by Franke et al. (2007) were followed concerning the boundary
 178 conditions and domain size. The inlet boundary is localized $10H$ before the upwind noise barrier
 179 where velocity, turbulence and temperature profiles are specified using a perpendicular wind
 180 direction, unless otherwise stated. The outlet boundary is placed $40H$ behind the downwind
 181 noise barrier with a freestream condition to allow the flow to fully develop. Symmetry
 182 conditions are applied for the upper and lateral limits, with the top of the calculation domain
 183 placed $20H$ from the ground and the lateral limits located $20H$ from each other. No-slip
 184 conditions are applied to any other boundaries including the ground and the two noise barriers,
 185 where the temperature can be specified to simulate stable and unstable cases. Finally, traffic
 186 exhausts are modeled by two volumetric sources along the y -direction, with a width of $1.4H$
 187 each, and over one mesh height (0.25 m) where an emission source term is added in the pollutant
 188 transport equation. A mass flow rate of 100 g/s is used for all the simulations performed. Further
 189 information can be found in Table 2.

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Table 2. Summary of the boundary conditions.

	Velocity and turbulence profiles are calculated according to Richards and Hoxey (1993) and Richards and Norris (2011): $U = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (9) \quad k = \frac{u_*^2}{\sqrt{C_\mu}} \quad (10) \quad \varepsilon = \frac{u_*^3}{\kappa z} \quad (11)$
Inlet	with U the wind velocity, k the turbulent kinetic energy (TKE), ε the dissipation of TKE, u_* the friction velocity, κ the von Kármán constant taken to 0.41, z the altitude, z_0 the roughness height taken as 0.5 m, and C_μ a CFD constant taken as 0.085. Fixed temperature: $T_{air} = 293$ K.
Outlet	Freestream outlet.
Top	Symmetry plane.
Lateral surfaces	Symmetry plane.
Ground and noise barriers surfaces	No-slip condition ($U = 0$ m/s). Fixed temperature (T_w) depending on the case studied.
Emission	Surface source with emission rate $q_m = 100$ g/s.

196 The most part of the simulations have been carried out considering a perpendicular incident
 197 wind angle (90°) with respect to the noise barrier, but some simulations were also performed
 198 with a 60° incident angle. The boundary conditions were the same in both configurations and
 199 Fig. 2. presents how the incidence angle is defined.

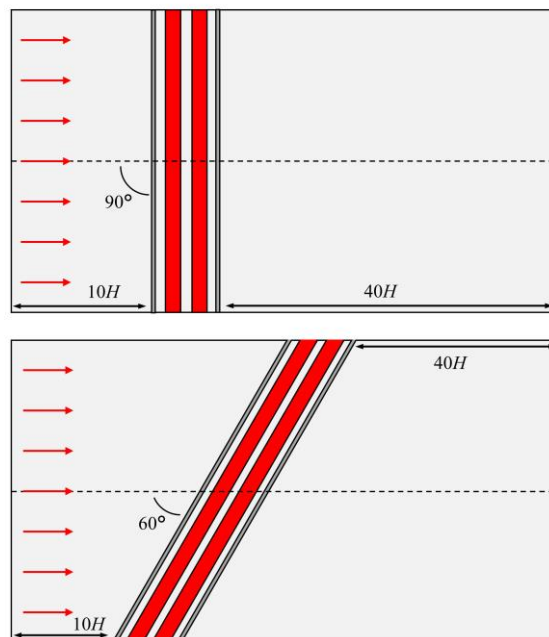
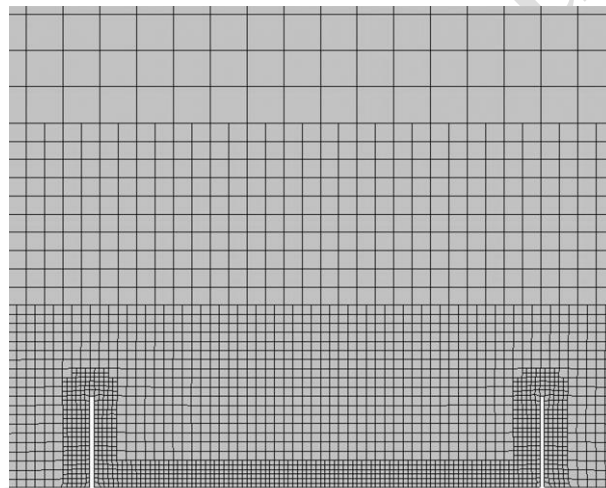


Fig.2. Definition of the wind incidence angle.

202 Mesh sensitivity tests were carried out to ensure that the results are fully independent of mesh
203 size. Successive simulations were performed with different mesh sizes and the Grid
204 Convergence Index (*GCI*) methodology (Roache, 1994) was used to assess the mesh-related
205 errors on both the flow field and the concentration field. Mean *GCI*s of 2% and 1% were
206 obtained for flow and concentration fields, respectively, when comparing the results from mesh
207 sizes of 0.5 m and 0.25 m. Thus, a mesh size of 0.5 m was considered sufficient to avoid
208 excessive calculation costs and was used for the study. This mesh size corresponds to the
209 meshes localized between an altitude of $z = 0$ and $z = 2H$. However, greater refinement was
210 applied near the noise barrier walls and the road because of the strong gradients that can occur
211 in these areas. This mesh size resulted in a total of 2.6 million meshes and an illustration of the
212 meshes selected is provided in Figure 3. The meshing was done using the unstructured grid
213 generator *snappyHexMesh* available with OpenFOAM.

214



215

216 Fig.3. Grid selected for computation.

217

218 Several simulations were performed to study the combined effects of wind speed and thermal
219 effects on the concentration reduction rate behind the barriers. All the simulations performed
220 with their specific conditions (U_H and ΔT) and their corresponding Richardson numbers are
221 given in Table 3. Each of these conditions was simulated twice to obtain results with and
222 without noise barriers to calculate the concentration reduction rates. A total of 64 simulations
223 were carried out including:

- 224 - 24 simulations for the neutral case (6 simulations for each of the three turbulent Schmidt
225 numbers considered to assess their impact on the concentration reduction rates and 6
226 supplementary simulations for a non-perpendicular case);

- 227 - 20 simulations for the stable cases;
 228 - 20 simulations for the unstable cases.

229 All the results were extracted at the center of the computational domain along $y/H = 0$ with
 230 $x/H = 0$ corresponding to the end of the downwind noise barrier wall.

231 Table 3. Summary of the simulations performed with wind velocity and thermal conditions ($\Delta T = T_H - T_w$) and their
 232 corresponding Richardson numbers.

U_H [m/s]	1.18	1.96	3.15	5.51	7.87
Ri [-]					
0	$\Delta T = 0$ K		$\Delta T = 0$ K	$\Delta T = 0$ K	
0.06				$\Delta T = 10$ K	
0.17			$\Delta T = 10$ K	$\Delta T = 30$ K	$\Delta T = 62$ K
0.33	$\Delta T = 7.5$ K		$\Delta T = 19.5$ K		
0.50	$\Delta T = 11.5$ K		$\Delta T = 29.5$ K		
1.20	$\Delta T = 10$ K	$\Delta T = 27.5$ K			
-0.06				$\Delta T = -10$ K	
-0.17			$\Delta T = -10$ K	$\Delta T = -30$ K	$\Delta T = -62$ K
-0.50	$\Delta T = -11.5$ K		$\Delta T = -29.5$ K		
-0.75	$\Delta T = -17.5$ K		$\Delta T = -44.5$ K		
-1.20	$\Delta T = -10$ K		$\Delta T = -71$ K		

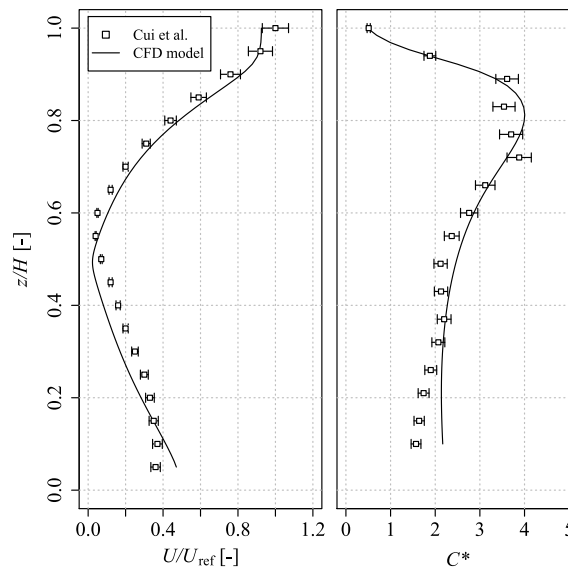
233

234 Finally, the turbulent Schmidt number (Sc_t) is a dimensionless number found in air pollution
 235 CFD to consider the effect of turbulent diffusivity. However, this number is widely spread
 236 between 0.2 and 1.3, depending on the situation studied, and can significantly change the results
 237 in terms of concentration (Tominaga and Stathopoulos, 2007). To assess the effect of this
 238 parameter on noise barrier studies, three Sc_t were considered: 0.3, 0.7 and 1.1.

239 3.3. Model validation

240 The numerical model was compared against the experimental data proposed by Cui et al. (2016)
 241 because they provided results on both velocity and the concentration field for a complex 3D
 242 situation. Indeed, the experiment setup consists of two buildings with the downwind building
 243 being higher than the upwind building. A gas is released at the top of the upwind building and
 244 the ground between the two buildings is heated to simulate several atmospheric stabilities and
 245 heat exchanges. The downwind building is opened and closed by two windows to simulate
 246 indoor/outdoor pollutant exchanges.

247 Fig. 4 shows the comparison between the experimental data and the numerical model used in
 248 this study for an unstable case where $Ri = -1.22$ ($U_{free\ stream} = 0.7$ m/s and $\Delta T = -135$ °C) and for
 249 a vertical profile localized between the two buildings. These results are presented in a
 250 dimensionless form that can be found in the paper of Cui et al. (2016). The results show good
 251 agreement between the numerical model and the experimental data on both velocity and
 252 concentration profiles, with a mean difference of 6% between the experimental and numerical
 253 concentration profiles. The numerical model is therefore capable of accurately reproducing
 254 velocity and concentration profiles in a 3D case with a high thermal gradient. According to
 255 these results, the numerical model was considered validated for the purpose of this study.



256

257 Fig.4. Vertical distribution of dimensionless velocity and concentration for $Ri = -1.22$ given by Cui *et al.* for the wind tunnel
 258 measurements (Cui et al., 2016), and comparison with the CFD model used for this study with $Sc_t = 0.25$.

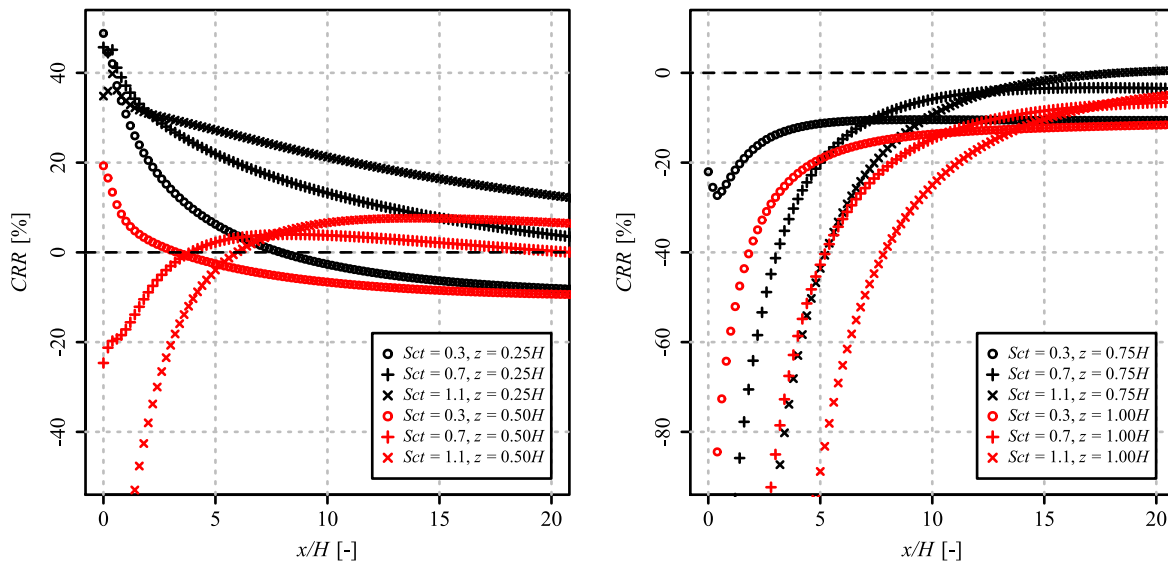
259 4. Results

260 4.1. Study without thermal effects

261 4.1.1. Turbulent Schmidt number sensitivity

262 The evolution of the *CRR* behind the barriers for the three Sc_t considered and for four altitudes
 263 ($z = 0.25H$, $0.50H$, $0.75H$ and $1.00H$) are presented in Fig. 5 as a function of the dimensionless
 264 distance from the downwind noise barrier x/H , with $z = 0.25H$ the pedestrian level
 265 corresponding particularly to the size of a child (1.25 m). The results show considerable
 266 variability for the concentration reduction rate as a function of the turbulent Schmidt number
 267 and no general trend can be observed. Indeed, while for $Sc_t = 1.1$ and $z = 0.25H$ the *CRR* is

268 globally higher than for other turbulent Schmidt numbers, for the three other altitudes the *CRR*
 269 is not globally higher. Additionally, while the *CRR* is globally lower with $Sc_t = 0.3$ and
 270 $z = 0.25H$, this observation is no longer true for the other altitudes. Moreover, the turbulent
 271 Schmidt number has also an impact on the distance after the barriers were there is a positive
 272 impact of the noise barriers ($CRR > 0$), this distance being higher for higher Sc_t .



273
 274 Fig.5. Evolution of the concentration reduction rate behind the downwind wall as a function of Sc_t and for several altitudes
 275 with the same wind profile ($U_H = 1.18$ m/s).

276 According to these results, it is important to state that the turbulent Schmidt number is also a
 277 very sensitive parameter when studying the impacts of noise barriers and its choice should be
 278 considered carefully, especially when performing quantitative studies. For the rest of this paper,
 279 and since no information or studies to determine the best turbulent Schmidt number for noise
 280 barrier studies are available an intermediate turbulent Schmidt number of 0.7 is used, as in
 281 Tominaga and Stathopoulos (2017), and the results are presented qualitatively rather than
 282 quantitatively.

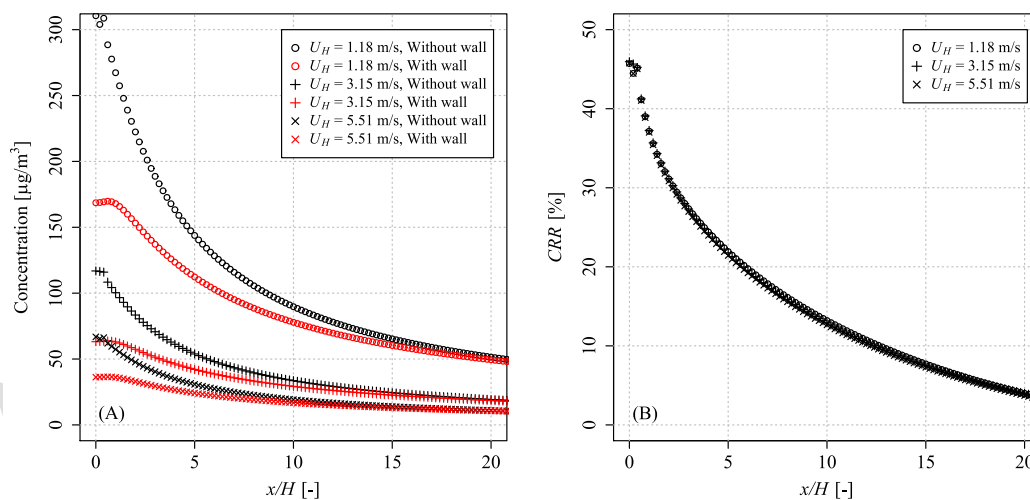
283 4.1.2. Impact of wind speed and wind direction on the *CRR* in neutral atmosphere

284 The impact of wind speed and wind direction on the concentration reduction rate was first
 285 studied in neutral atmosphere, thus, considering only forced convection (i.e. convection due to
 286 the wind).

287 Fig. 6 shows the evolution of the pollutant concentrations behind the barriers for the cases with
 288 and without barriers (A) and the corresponding concentration reduction rates (B) as a function
 289 of the wind speed at $z = 0.25H$. According to Fig. 6 (A), regardless of the wind speed and for

290 $z = 0.25H$, pollutant concentrations were generally higher without the noise barrier than with it.
 291 Additionally, concentrations changed inversely with wind speed, leading to lower
 292 concentrations for higher wind speeds. The concentrations were thus different as a function of
 293 this parameter. However, as depicted in Fig. 6 (B), the *CRR* is the same whatever the wind
 294 speed considered and this is also true for the other altitudes considered ($z = 0.5H, 0.75H$ and
 295 $1.00H$). This result is linked to the fact that, for a given wind direction and without thermal
 296 stratification, the concentration was inversely proportional to the wind velocity (Schatzmann
 297 and Leitl, 2011). Thus, since the concentration evolved in the same way with wind speed both
 298 with and without noise barriers, the *CRR* remained unchanged for a given wind direction under
 299 neutral conditions.

300 The effects of the wind direction under neutral conditions were also investigated and the results
 301 are presented in Fig. 7 for a perpendicular wind (90°) and a wind oriented at 60° . Fig 7 (A)
 302 shows that for the 60° case, the concentrations are lower with the noise barriers and higher
 303 without the noise barriers compared to the perpendicular case. This inevitably leads to a lower
 304 *CRR* for the perpendicular case, as shown in Fig. 7 (B) for $z = 0.25H$ and $z = 0.75H$. The same
 305 result was obtained for $z = 0.50H$ and $z = 1.00H$. Therefore, the *CRR* are higher for oblique
 306 wind directions.



307
 308 Fig.6. Evolution of the concentrations with and without noise barriers (A) and the concentration reduction rates (B) as a
 309 function of wind speed for a perpendicular wind direction at $z = 0.25H$.

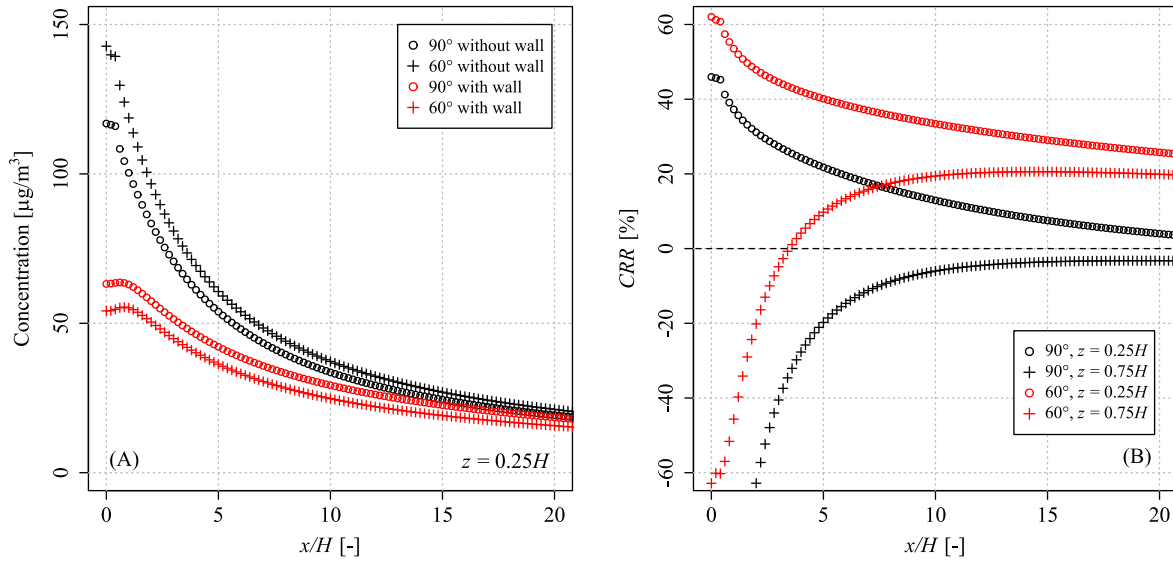


Fig.7. Evolution of the concentrations with and without noise barriers (A) and the concentration reduction rates (B) as a function of the wind direction and for a given wind speed ($U_H = 3.15$ m/s).

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314 According to the previous results, when studying the CRR behind noise barriers for neutral
315 cases, it is necessary to study only one wind speed for each wind direction. Moreover, if the
316 minimal CRR is assessed, the study can be reduced to only one direction. Indeed, the
317 perpendicular direction leads to the lowest CRR while the non-perpendicular directions lead to
318 higher CRR.

319

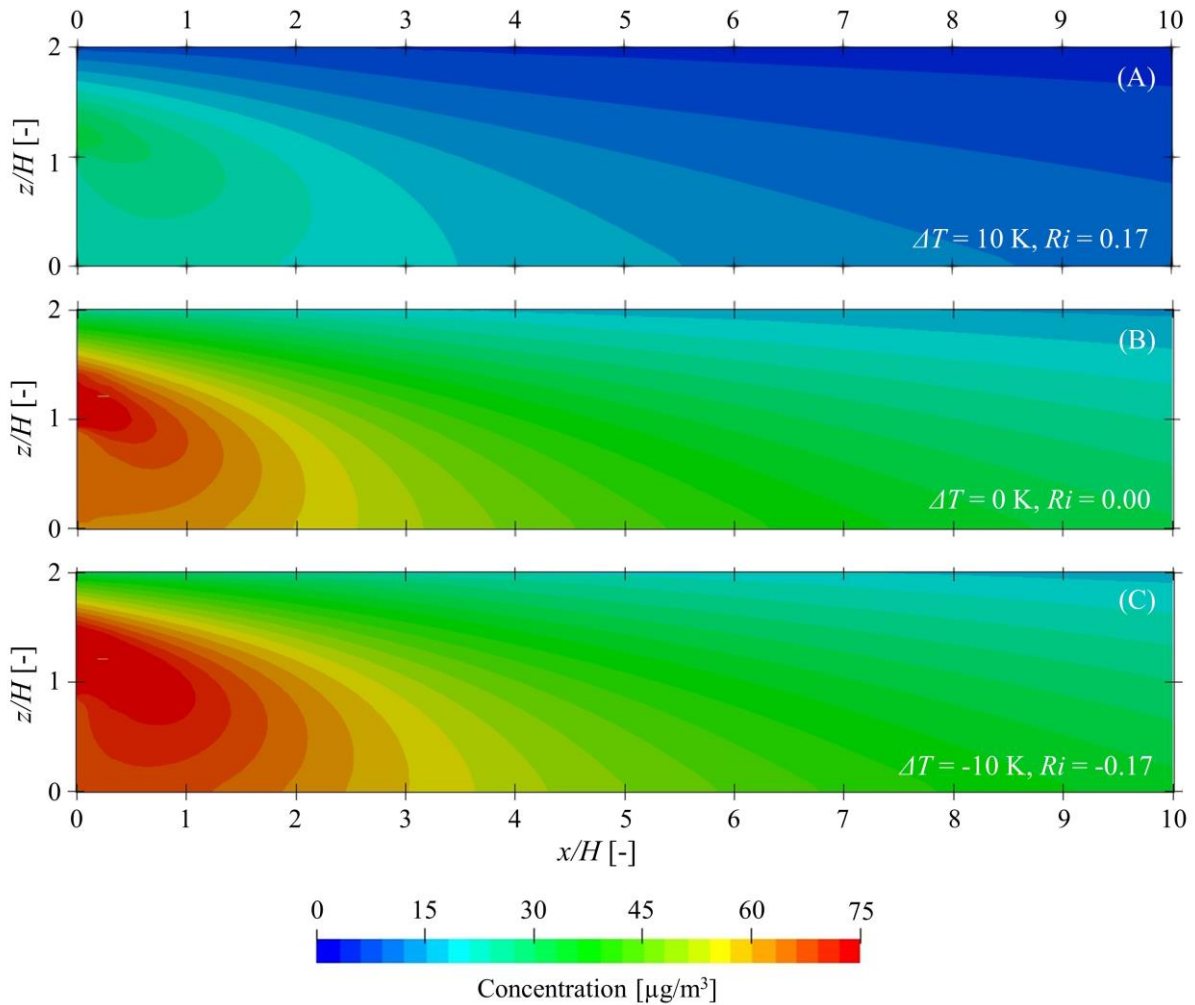
320 4.2. Study with thermal effects

321 4.2.1. Evolution of the CRR as a function of the atmospheric stability

322 The concentration reduction rate was then studied considering mixed convection: forced
323 convection induced by wind speed and natural convection induced by thermal stratifications.
324 The CRR was therefore studied as a function of the Richardson number which includes wind
325 speed (U_H) and thermal variations (ΔT).

326 The first results are presented in Fig. 8 for three different Richardson numbers: (A) $Ri = 0.17$
327 corresponding to a stable atmosphere; (B) $Ri = 0$ corresponding to a neutral atmosphere; and
328 (C) $Ri = -0.17$ corresponding to a slightly unstable atmosphere, for the same wind conditions
329 (perpendicular wind with $U_H = 3.15$ m/s). Thus, ΔT is the only variable here. For the three cases
330 considered, the concentration is highest directly behind the barriers ($x = 0$ m), just above them
331 ($h = 5$ m) and generally decreases as the distance from the barrier increases or the height

332 decreases. However, the concentrations are different depending on the case. Indeed, the
 333 concentrations are lowest for the stable case (A) and highest for the slightly unstable case (C).
 334 The neutral case (B) leads to intermediate results but closer to the unstable one. For a given
 335 wind speed and direction, thermal effects therefore have a high impact on the concentration
 336 behind the barriers and seem to have a greater impact for $\Delta T > 0$ than for $\Delta T < 0$.

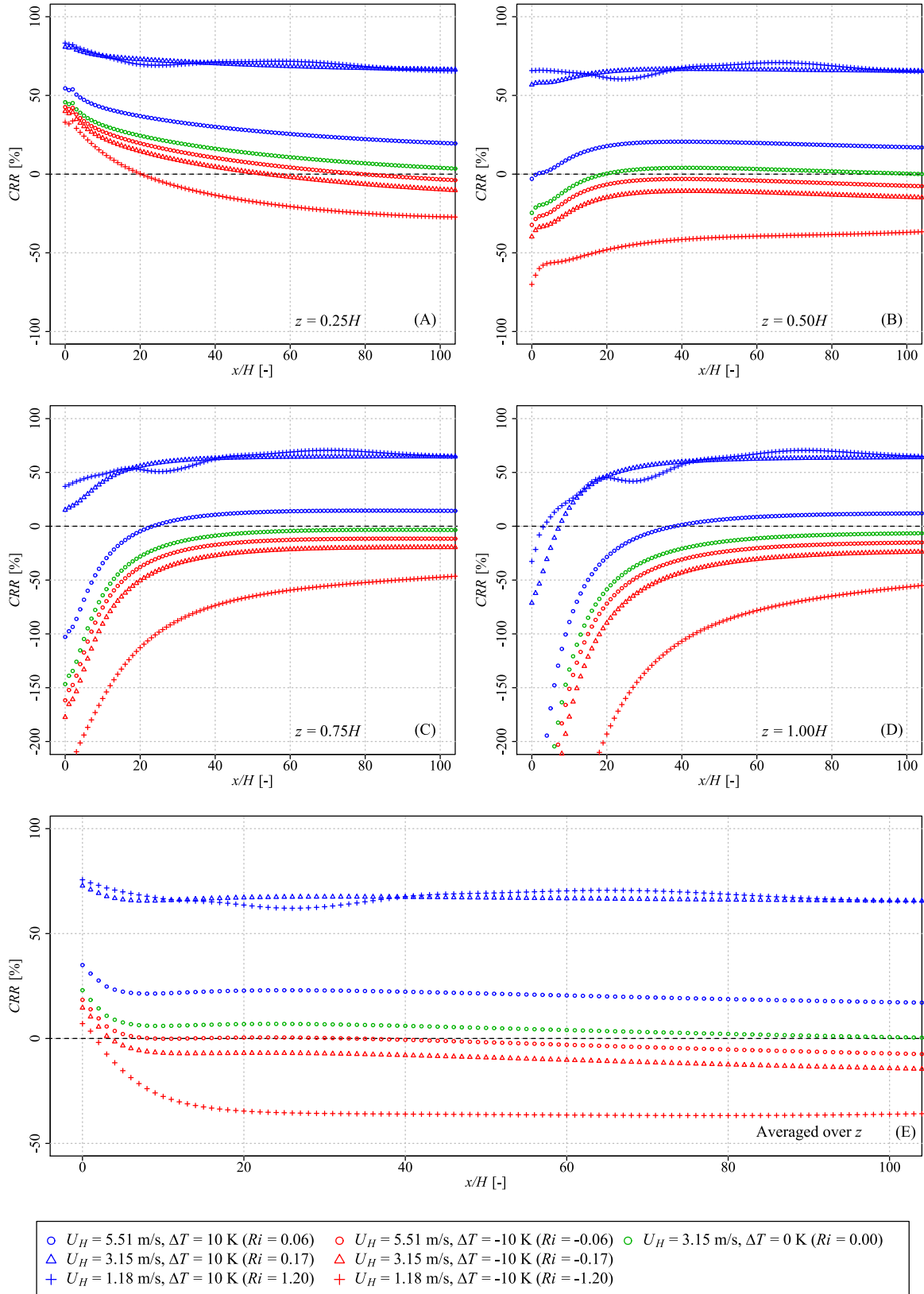


337
 338 Fig.8. Evolution of the concentration behind the downwind barrier as a function of the temperature variation in the same
 339 wind conditions (perpendicular wind, $U_H = 3.15$ m/s).

340 The evolution of the *CRR* as a function of the distance from the downwind barrier was studied
 341 for several atmospheric stabilities by changing both the wind speed (U_H) and the thermal
 342 variation (ΔT). The results for $Ri = -1.20, -0.17, -0.06, 0.00, 0.06, 0.17$ and 1.20 are given in
 343 Fig. 9 for $z = 0.25H$ (A), $0.50H$ (B), $0.75H$ (C) and $1.00H$ (D). Further results are presented in
 344 Fig. 9 (E) and correspond to the *CRR* averaged over z for z ranging from 0 to 5 m giving global
 345 information along the height of the noise barriers.

346 As can be seen in Fig. 9, the evolution of the *CRR* follow the same trends. Indeed, for all the
347 altitudes considered and also for the *CRR* averaged over $z = H$, the results for the neutral case
348 are bounded by the results for the stable cases and the unstable cases: the unstable cases lead to
349 lower *CRRs* compared to the neutral case, with the lowest *CRR* being obtained for the highest
350 instability level ($Ri = -1.20$). On the contrary, the stable cases lead to higher *CRRs* with the
351 highest *CRR* being obtained for the highest stability level ($Ri = 1.20$). However, the evolution
352 of the *CRR* according to the level of stability or instability is not equivalent between the two
353 cases. Indeed, whereas the results are different for the three unstable cases presented in Fig. 9,
354 the *CRR* for the two highest stable cases ($Ri = 0.17$ and $Ri = 1.20$) are very similar. Furthermore,
355 the *CRR* changes more quickly as a function of the Richardson number for the stable cases than
356 for the unstable cases, which is consistent with the previous results discussed in relation with
357 Fig. 8. Thus, atmospheric stability has an impact on the *CRR*, leading to higher *CRRs* for stable
358 cases ($Ri > 0$), quickly reaching maximum values, while lower *CRRs* are obtained for unstable
359 cases ($Ri < 0$) and no maximum values were reached for the Richardson numbers considered in
360 this study.

361 Fig. 9 also shows that the *CRR* not only depends on the distance from the barriers but also on
362 their height. For a given atmospheric stability, the *CRR* decreases with height and can reach
363 negative values corresponding to an increase in pollutant concentration due to the barriers.
364 These observations are related to the heights at which the plumes spread in both configurations,
365 with and without the barriers. Indeed, without the noise barriers the plume spreads along the
366 ground, leading to lower concentrations at $z = H$, while with the noise barriers the plume spreads
367 from the top of the barriers and the concentrations are generally lower at ground level compared
368 to the case without barriers.



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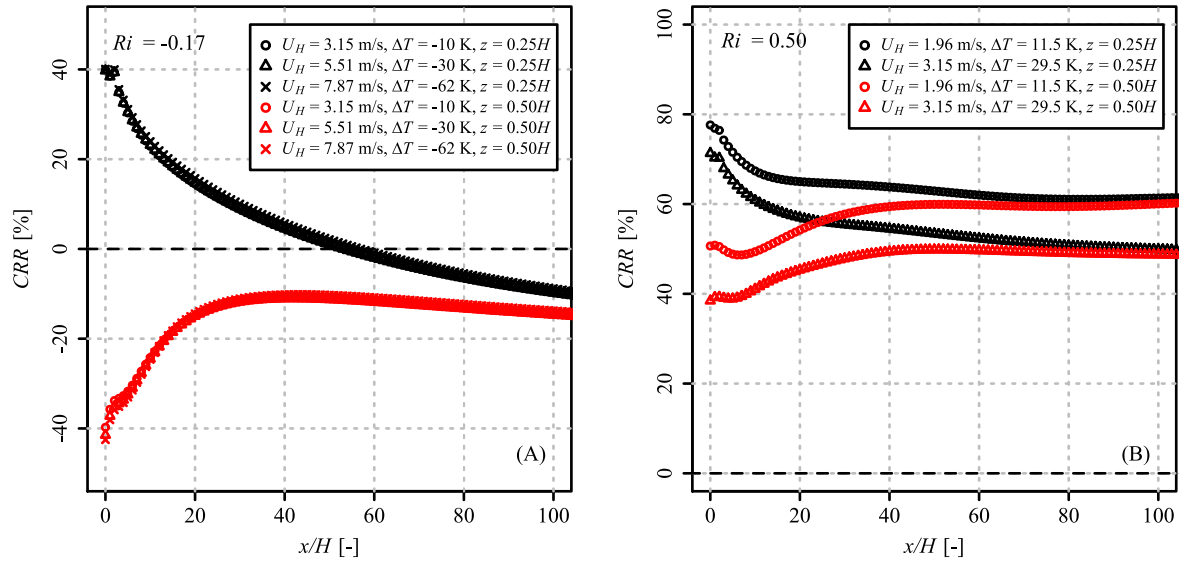
Fig.9. Evolution of the concentration reduction rates for 4 given altitudes (A—D) and averaged over the noise barrier height (E) as a function of the distance from the downwind barrier and for several Richardson numbers.

372 4.2.2. Conservation of the *CRR* with the Richardson number

373 It has been shown previously that the concentration reduction rate for a given wind direction is
374 constant when considering only forced convection (neutral atmosphere) due to an inversely
375 proportional link between the pollutant concentrations and the wind speed. However, this link
376 is no longer valid when considering both forced and natural convection. The question was then
377 to assess if the *CRR* is still constant for stable and unstable cases. To answer this question,
378 several simulations were performed for numerous Richardson numbers but with distinct couples
379 of wind speed and thermal variations. The Richardson numbers considered were $Ri = -1.20$,
380 -0.75 , -0.50 , -0.17 , -0.06 , 0.00 , 0.06 , 0.17 , 0.33 , 0.50 and 1.50 .

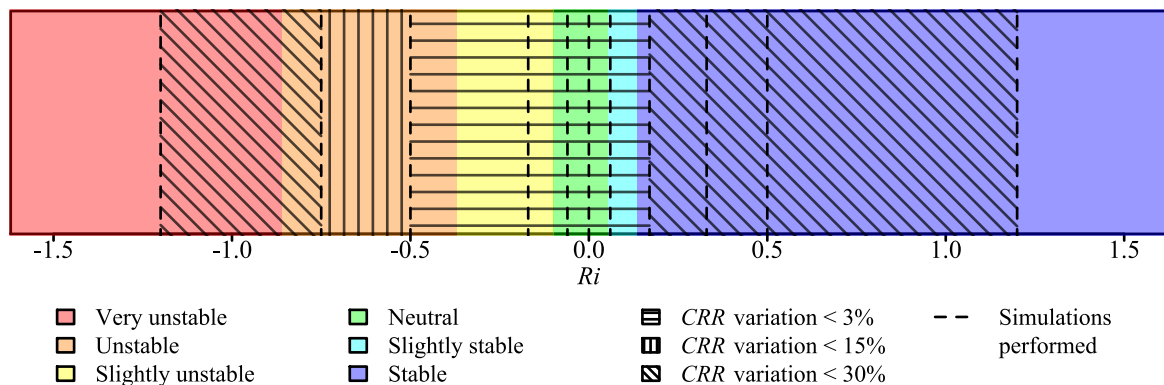
381 Fig. 10 (A) shows the evolution of the *CRR* for three couples of U_H and ΔT giving $Ri = -0.17$
382 (slightly unstable atmosphere) while Fig. 10 (B) shows the evolution of the *CRR* for two couples
383 giving $Ri = 0.50$ (stable atmosphere). According to Fig. 10 (A), the *CRR* can be constant for a
384 given Ri . Indeed, with $Ri = -0.17$, while the pollutant concentrations are not the same for the
385 three couples of U_H and ΔT considered, the *CRR* is quasi-constant ($\pm 3\%$). However, this
386 observation is not true for all the Richardson numbers according to Fig. 10 (B), which shows
387 that for $Ri = 0.50$ the *CRRs* are significantly different for the two couples of U_H and ΔT
388 considered. Thus, the *CRR* can be constant for a given Ri but this is not generalizable.

389 The Richardson numbers for which the *CRR* can be considered constant were assessed and the
390 results are presented in Fig. 11. The results show that, for a Ri ranging from -0.50 to 0.17 , the
391 variation over the *CRR* is less than 3% and the *CRR* can be considered as constant for a given
392 Ri . For Richardson numbers outside this range, the variation over the *CRR* for a given Ri can
393 reach 15% for a Ri ranging from -0.75 to -0.5 and 30% for a Ri ranging from -0.75 to -1.20 and
394 from 0.17 to 1.20 . According to these results, for a given Ri ranging from -0.50 to 0.17 , a unique
395 couple of U_H and ΔT must be considered when assessing the concentration reduction rates
396 behind noise barriers in non-neutral cases.



397

398 Fig.10. Evolution of the concentration reduction rate for $Ri = -0.17$ (A) and $Ri = 0.50$ (B) as a function of wind speed (U_H)
 399 and thermal variation (ΔT) at $z = 0.25H$ and $z = 0.50H$.
 400



401

402

403 Fig.11. Conservation of the concentration reduction rate with the Richardson number.

404 5. Discussion

405 This study provides better understanding of how noise barriers can reduce air pollution and how
 406 this reduction can vary with wind conditions and atmospheric stability. Additional work can be
 407 done to further improve this understanding and is discussed below, as is the relevance of these
 408 results.

409 This study considered only one noise barrier configuration, with two walls of the same height
 410 placed on either side of a heavy-traffic road. Further studies could be performed to verify if the
 411 results obtained for this configuration are generalizable, for example for noise barriers with
 only one upwind or downwind wall and also with a combination of solid and vegetative barriers,

412 but also in presence of buildings before and after the barriers. Additionally, the height of
413 $z = 0.25H$ (1.25 m) was considered to study the evolution of the *CRR* at the pedestrian level,
414 which corresponds to the size of a child. The results were not provided for the size of adult
415 people ($z = 0.35H = 1.75$ m). However, results at this height can be approximated using both
416 results at $z = 0.25H$ and $z = 0.50H$, for example by the means of a linear interpolation such as
417 given in equation (12).

$$418 \quad CRR_{0.35H} = 0.6 \times CRR_{0.25H} + 0.4 \times CRR_{0.50H} \quad (12)$$

419 where $CRR_{0.35H}$ is the *CRR* at $z = 0.35H$, $CRR_{0.25H}$ is the *CRR* at $z = 0.25H$ and $CRR_{0.50H}$ is
420 the *CRR* at $z = 0.50H$.

421 As shown in this paper, the turbulent Schmidt number has a different impact on the *CRR*
422 depending on the location. There is no specific trend in the vicinity of the noise barrier. Indeed,
423 there is an increase in the *CRR* when Sc_t increases at the height of the noise barrier while at
424 ground level little variations are found. However, farther from the noise barrier, trends can be
425 identified: the *CRR* systematically increases with increasing Sc_t , whatever the height
426 considered.

427 It was shown that for a given Ri ranging from -0.50 to 0.17, variations over the *CRR* are
428 negligible. Moreover, the evolution of the *CRR* as a function of distance from the downwind
429 barrier seemed to follow the same trends, as the curves appear the same. Thus, it may be
430 possible to find relationships between the *CRR* and the Richardson number in the range -0.50
431 to 0.17. If such relationships can be found, it will allow estimating all the *CRRs* in this Ri range
432 by performing only one simulation, or with only one in-field measurement.

433 Finally, according to the results of this study, further studies can be simplified. Indeed, for
434 future studies in neutral atmosphere (without thermal variations), they could be reduced to only
435 wind direction and noise barrier configuration studies when assessing the evolution of the *CRR*.
436 For studies including mixed convection (with thermal variations), for a Ri ranging from -0.50
437 to 0.17, only one couple of wind speed and thermal variation is needed to assess the evolution
438 of the *CRR*.

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441

442 **6. Conclusion**

443 The effects of wind speed and atmospheric stability on the concentration reduction rate (*CRR*)
444 of air pollutants induced by noise barriers were studied with a validated CFD model. This study
445 considered both numerous wind conditions (wind speed and direction) and thermal variations,
446 leading to different atmospheric stabilities ranging from very unstable cases to stable cases.
447 Several CFD simulations were carried out and the main conclusions are as follows:

- 448 (a) When no thermal variations are considered, i.e. for a neutral atmosphere, the evolution
449 of the *CRR* depends only on the wind direction: wind speed changes the pollutant
450 concentrations behind the barriers but this parameter does not change the *CRR*.
- 451 (b) A non-perpendicular wind direction leads to higher pollutant concentrations without
452 noise barriers and lower concentrations with the barriers compared to perpendicular
453 cases. The *CRRs* are therefore minimal for a perpendicular wind.
- 454 (c) The *CRR* decreases with height due to the different locations of the plume for the two
455 cases with and without noise barriers. The global *CRR* decreases with distance from the
456 downwind barrier.
- 457 (d) The *CRR* obtained with forced convection (neutral atmosphere) is bounded by the *CRR*
458 obtained with mixed convection (stable and unstable atmospheres): higher *CRRs* are
459 obtained in stable conditions ($Ri > 0$) while lower *CRRs* are obtained in unstable
460 conditions ($Ri < 0$).
- 461 (e) For a given Richardson number ranging from -0.50 to 0.17, the *CRR* is constant with a
462 variation of less than 3%. For numbers outside this range the variation increases to 15%
463 for a Ri ranging from -0.75 to -0.5 and 30% for a Ri ranging from -1.20 to -0.75 and
464 from 0.17 to 1.20.

465 Finally, these results give insights to researchers and civil engineers to better understand
466 variations of air pollutant concentrations behind noise barriers, for example for carrying out
467 further assessment studies on the impact of noise barriers on the reduction of air pollution, and
468 for in-field monitoring campaigns.

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