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1 Large-eddy simulations on pollutant reduction effects of 2 road-center hedge and solid barriers in an idealized street canyon

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15 16 Highlight

- 17 ● The road-center barriers reshaped the vortices in an idealized street canyon.
- 18 ● The barriers reduced concentrations in the perpendicular and oblique wind directions.
- 19 ● The barriers enhanced the vertical pollutant removal at the top of the street canyon.
- 20 ● Larger barriers' width and the hedge's leaf area density decreased near-wall concentration.
- 21 ● The relative effectiveness of hedge and solid barriers varied with wind directions.

22 23 Abstract

24 This study conducted large-eddy simulations (LES) on the pollutant reduction effects of hedge
25 and solid barriers in a three-dimensional idealized street canyon with an aspect ratio of 0.5. The
26 wind direction was perpendicular and oblique (45 degrees) to the street. The results were validated
27 with data from wind tunnel experiments. LES accurately predicted the concentration distribution
28 in the barrier-free case and reproduced well the barrier-induced concentration reduction. In the
29 barrier-free case, a large recirculation vortex was observed. However, the central barriers forced
30 the recirculated airflow in the middle of the canyon and newly formed vortices near the leeward
31 walls. The two counter-direction vortices in the hedge and solid barrier cases transported
32 pollutants toward the center of the canyon and enhanced the vertical pollutant removal at the top
33 of the street canyon. The hedge barrier (solid barrier) reduced spatially-averaged concentration
34 by about 59% (45%) near the leeward wall, 64% (20%) near the windward wall, and 45% (17%)
35 in the whole street canyon compared to the barrier-free case. The effects of leaf area density
36 (LAD) and barrier width were further investigated under the perpendicular wind direction.

37 Increasing the LAD or the width of the hedge barrier decreased concentration near the leeward
38 walls but increased canyon-averaged concentration. Increasing the width of the solid barrier
39 decreased the concentration near the leeward walls and the canyon-averaged concentration. In an
40 oblique wind direction, the hedge and solid barriers reduced by about 30% and 60% the spatially-
41 averaged concentration near the building walls compared to the barrier-free case.

42

43 Keywords

44 Pollutant dispersion, Street canyon, LES, Barrier, Vegetation

45

46 1 Introduction

47 Outdoor air pollution is an important environmental problem in the urban environment [1] and
48 poses a major long-term health risk of respiratory diseases [2]. Vehicular emissions are the
49 predominant source of air pollution in streets [3]. Three main approaches are considered to
50 mitigate air pollution, including (i) controlling the activity (e.g., the number of cars), (ii)
51 controlling the emission intensity (e.g., reducing emission factors), and (iii) controlling source-
52 receptor pathways [4]. Among them, controlling source-receptor (traffic emissions-roadside
53 residences) pathways has been considered as a low-cost passive method for existing streets
54 compared to the other two methods which take a long time to achieve [5,6].

55

56 Road barriers have been identified as effective passive methods to control source-receptor
57 pathways and reduce personal exposure in open roads and street canyons [7]. Road barriers can
58 be divided into porous barrier and solid barrier [8]. Hedges are common porous barriers and are
59 low-level vegetation with continuous leaves covering from the ground to the top. Hedges can act
60 either partially or completely as a baffle between traffic emissions and roadside receptors [9]. On
61 the other hand, solid barriers, including low boundary walls [10] and noise barriers [11,12], act
62 as baffle plates and redirect the flow and thereby affect the dispersion at street level. The essential
63 difference between hedge barriers and solid barriers is that the wind can pass through the hedge
64 barriers at a reduced wind speed depending on the porosity, whereas the wind is forced over the
65 solid barrier. Reducing the porosity (or increasing the density) of hedge barriers may make their
66 effect close to that of solid barriers.

67

68 The pollutant reduction effect of hedge and solid barriers in street canyons is largely dependent
69 on their proper implementation. Several common considerations have been recommended for
70 both hedge and solid barriers. For instance, Gallagher et al. [13] and Gromke et al. [14] reported
71 that one central barrier resulted in greater improvements in pollutant concentration reduction than
72 two sidewise barriers. In addition, increasing the barrier height was found resulting in more

73 effective pollutant reduction near the building walls [14,15]. Moreover, the barrier effects are also
74 dependent on the wind direction. McNabola et al. [10] reported that the solid barriers reduced the
75 pollutant exposure of pedestrians walking on sidewalks by up to 40% and 75% under
76 perpendicular and parallel wind conditions, respectively.

77
78 To reduce construction and maintenance costs, the barrier width is expected to be as thin as
79 possible. Tong et al. [16] showed that increasing hedge barrier width resulted in a greater
80 reduction in concentration behind the barrier in an open road situation. However, the influence of
81 barrier width for both hedge and solid barriers in a street canyon is unclear. In addition, the density
82 or leaf area density (LAD) is an important parameter for vegetation [17,18]. The LAD of hedges
83 is generally higher than that of tree crowns [19]. Gromke et al. [14] reported that increasing hedge
84 density resulted in a concentration decrease near the building walls. However, as a LAD increase
85 also leads to a wind velocity decrease [20], the ventilation rate of the street canyon could decrease.
86 Therefore, further investigations are needed to find out how hedge LAD affects the flow and
87 concentration fields in a street canyon.

88
89 Among the methods of studying the effect of hedge and solid barriers in street canyons, on-site
90 monitoring (field measurement), wind tunnel experiment (reduced scale experiment) and
91 numerical modeling (analytical model and computational fluid dynamics) are frequently adopted.
92 On-site monitoring can provide knowledge of the barrier effect in real-world situations [21–24].
93 Wind tunnel experiments use real fluids to accurately reproduce flows and allow systematic
94 investigations [14]. However, these methods are high-cost and can only provide limited
95 information on complicated flow and concentration fields. With the development of numerical
96 simulations, computational fluid dynamics (CFD) simulation has been widely used to simulate
97 dispersion in street canyons. A commonly adopted method involves conducting CFD simulations
98 after validating an experimental value. In the CFD technique, Reynolds-averaged Navier-Stokes
99 (RANS) models [15] and large-eddy simulation (LES) [5,10,13] are frequently used to represent
100 for barrier effects. In urban environments with complicated flow fields, LES has shown more
101 accurate prediction accuracy on airflow and pollutant dispersion than the RANS model [25,26].
102 However, few studies have been reported to perform CFD simulations using LES on hedge and
103 solid barriers effects in a street canyon and validate the accuracy using experimental values.

104
105 In this study, we conducted LES to estimate the pollutant reduction effect of hedge and solid
106 barriers in a street canyon. The accuracy of LES on the concentration field was validated by wind
107 tunnel experiments [14,27]. Moreover, we investigated the influences of LAD and barrier width.
108 The above studies were based on a wind direction which was perpendicular (90 degrees) to the

109 street. Additionally, the barrier effects were evaluated under an oblique wind direction which was
110 45 degrees to the street.

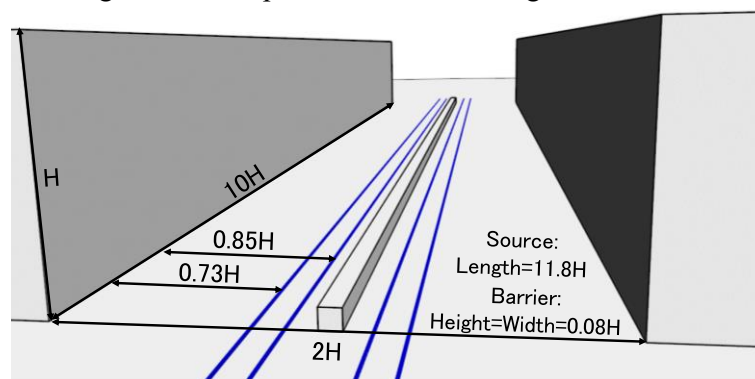
111

112 The remainder of this paper is organized as follows. In Section 2, the simulation settings are
113 described, including street configuration, numerical methods of flow and dispersion modeling,
114 and modeling of hedge barrier and analysis cases. In Section 3, the simulation results are validated
115 against a wind tunnel database. The flow and concentration fields of the barrier-free, hedge barrier
116 and solid barrier cases are presented to investigate the effect of the presence of barriers. The
117 influence of LAD, barrier widths, and wind directions are then analyzed. Finally, conclusions and
118 perspectives are presented in Section 4.

119

120 2 CFD simulation settings

121 2.1 Street canyon configuration, computational domain and grids



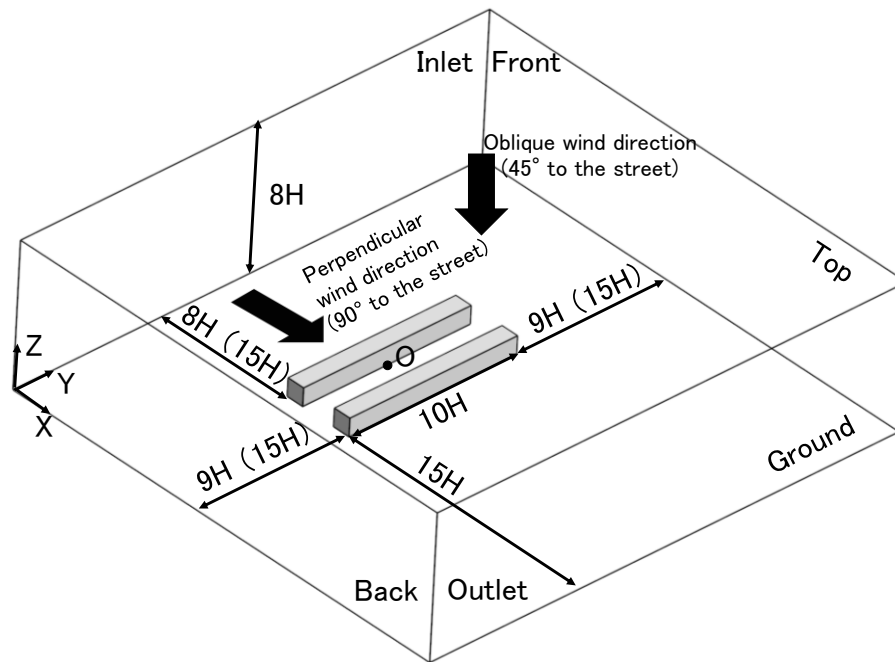
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123

Fig. 1. Schematic of the wind tunnel geometry [14].

124

125 The simulated results were validated against the wind tunnel dataset [14,27], where the detailed
126 description of the wind tunnel experiment can be found. Gromke and Ruck (2012) [27] provided
127 concentration distributions of the barrier-free case near the leeward and windward walls of the
128 street canyon. In addition, Gromke et al. (2016) [14] provided concentration measurement data
129 of street canyons with hedge and solid barriers. The street canyon configuration (Fig. 1) was set
130 according to the full-scale model represented by the wind tunnel model. The length scale between
131 the wind tunnel and the full-scale models was 1:150. The building height H of the isolated street
132 canyon was 18 m. The width and length of the street canyon were $2H$ and $10H$, respectively. The
133 aspect ratio of the street canyon was 0.5. The barrier models and line sources were placed along
134 the street. The line sources exceeded the street canyon by about $1H$ on each side to represent the
135 traffic emission in the intersections. The barriers were located at the center of the canyon, and the
136 height and width of the barriers were considered as $0.08H$ (1.5 m) based on the wind tunnel
137 experiment [14].



138

139 Fig. 2. Simulation domain. The values in parentheses denote domain size in the oblique wind
 140 direction cases.

141

142 Fig. 2 shows the simulation domain. x , y and z represent the streamwise, spanwise and vertical
 143 directions, respectively. The height of the domain was set to $8H$. The distances from the buildings
 144 to the boundaries were based on the Architectural Institute of Japan (AIJ) guidelines [28]. The
 145 distance between the outlet boundary and the downwind building was $15H$. For perpendicular
 146 wind cases, the distance between the inlet boundary and the front face of upwind building was
 147 $8H$, and between the lateral boundaries and the buildings were $9H$. For oblique wind cases, a
 148 larger simulation domain was set. The distance between the inlet boundary and the front face of
 149 upwind building was $15H$, and between the lateral boundaries and the buildings were $15H$. As
 150 shown in Fig. 3, the simulation domain was discretized into hexahedral cells. Based on the
 151 preliminary grid sensitivity check outlined in Appendix A, the total grid number was set to
 152 approximately 1.5 million. The smallest and largest grid sizes in the street canyon were $0.014H$
 153 and $0.056H$, respectively.

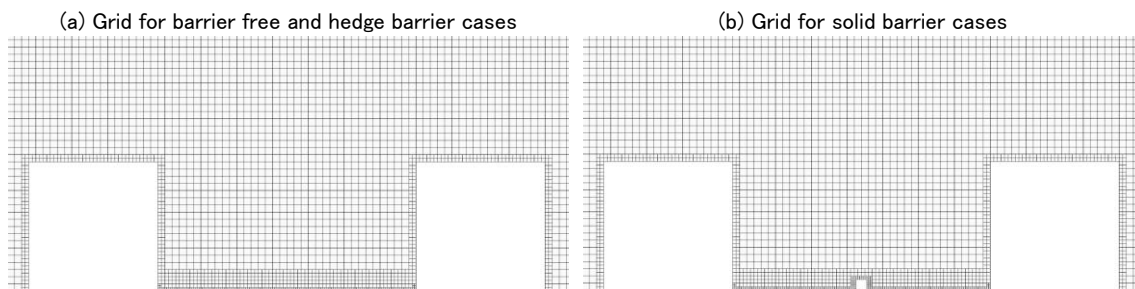


Fig. 3. Grid resolutions in the street canyon.

2.2 Numerical methods and boundary conditions

The transport equations for momentum and concentration for LES can be referred in previous studies [29,30]. The open-source CFD software OpenFOAM v2012 [31] was used. For the turbulence model, the wall-adapting local eddy-viscosity (WALE) model [32] was chosen because it can correctly reproduce the turbulence scaling near the wall without using a damping function. The WALE model was used successfully in the flow and concentration fields in complex urban geometries [33,34]. The momentum and concentration equations were discretized using the total variation diminishing (TVD) scheme [35,36], which combines the first-order upwind difference scheme and the second-order central difference scheme. The PIMPLE algorithm, a merged PISO (Pressure Implicit with Splitting of Operator)–SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm in the OpenFOAM toolkit, was used for pressure–velocity coupling. The sub-grid scale Schmidt number was set to 0.5 [37]. The time step was set to $\Delta t = 0.1$ s ($0.026H/U_H$). The computation was performed for 3600 s before being time-averaged for 3600 s ($930H/U_H$). The time-averaged streamwise velocity U at building height H was $U_H = 4.65$ m/s. The sampling time was considered sufficient to obtain the time-averaged and fluctuation values.

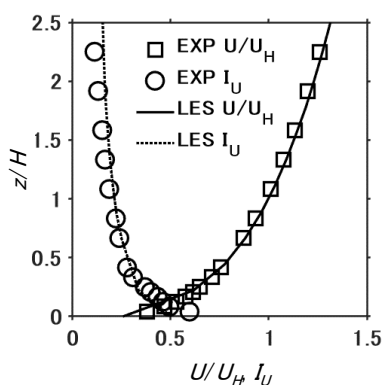


Fig. 4. Time-averaged streamwise velocity U and turbulence intensity I_U in streamwise direction of inflow. U_H and $I_{U,H}$ were the time-averaged streamwise velocity U and turbulent intensity I_U at building height H .

177

178 The inlet boundary conditions (Fig. 4) were set according to the wind tunnel experiments to
179 reproduce the atmospheric boundary layer. The turbulent intensity I_U at building height H
180 was $I_{U,H} = 0.19$. The vertical profiles of U and I_U can be described by power law formulations
181 as follows:

182

$$U(z) = U_H (z/H)^{\alpha_U} \quad (1)$$

$$I_U(z) = I_{U,H} (z/H)^{\alpha_I} \quad (2)$$

183 where power law exponents for U and I_U were $\alpha_U = 0.3$ and $\alpha_I = 0.36$, respectively. In LES, the
184 digital-filter method [38] was used to generate synthetic turbulence at the inlet boundary. The
185 Reynolds stresses and turbulent length scale were approximated from the experiment [39]. For
186 the outlet boundary conditions, the pressure and the gradients of all other variables were set to
187 zero. Slip boundary conditions were used for the top boundary. No-slip boundary conditions based
188 on Spalding's law [40] were prescribed at ground and building surfaces. The lateral boundaries
189 (front and back) were considered as symmetric in the perpendicular wind cases, and as inlet and
190 outlet in the oblique wind cases. The pollutant was emitted using source term in the concentration
191 transport equation with a source intensity of one. The concentration at the inlet was set to 0. The
192 concentration results were presented in nondimensionalized values. The nondimensionalized
193 instantaneous concentration c was calculated from $c = c_{raw}/c_{ref}$, where c_{raw} was the computed
194 concentration and $c_{ref} = (Q/L)/(U_H H)$ was the reference concentration. Q/L was the emission
195 rate per unit length of the source. The nondimensionalized time-averaged concentration and
196 nondimensionalized concentration fluctuation were indicated as C and c' .

197

198 2.3 Modelling of hedge barrier

199 To reproduce the aerodynamic effect of the hedge barrier, a source term was assigned to the
200 momentum transport equation [41]. Assuming the form drag was much larger than the viscous
201 drag, the momentum source term of tree canopy was modelled as follows:

202

$$S_{u_i} = -C_D L A D u_{mag} u_i \quad (3)$$

203 where u_{mag} was the velocity magnitude, u_i was the velocity component in the i -th direction, and
204 C_D was the dimensionless drag coefficient. In the wind tunnel experiment [14], the hedge barrier
205 was modelled by using porous media with different porosities. The porosity was described by
206 pressure loss coefficient λ , given by

207

$$\lambda = 2 C_D L A D \quad (4)$$

208 and λ was measured by

$$\lambda = \frac{\Delta p_{st}}{0.5\rho u^2 d} \quad (5)$$

210 where Δp_{st} was the difference in static pressure between the windward and leeward of the porous
 211 media, $0.5\rho u^2 d$ was the dynamic pressure, d was the porous foam sample thickness in the
 212 streamwise direction. Measurements of λ resulted in 250 m^{-1} for the wind tunnel scale,
 213 representing $\lambda = 1.67 \text{ m}^{-1}$ in the full scale. By considering $C_D = 0.2$ [42], $LAD = 4.2 \text{ m}^2/\text{m}^3$
 214 can be interpreted from λ . Although the hedge influence on the flow turbulence was not
 215 considered in the previous LES studies on the pollutant dispersion in street canyons, the LES
 216 showed accurate accuracy with wind tunnel experiments [41,43]. The reason could be that most
 217 of turbulent kinetic energy was solved at the resolved scale. In this study, over 95% of turbulent
 218 kinetic energy was solved at the resolved scale as shown in Fig. A4 in Appendix A. Therefore,
 219 neglecting the sink or source terms for turbulence was considered acceptable in this study. In
 220 accordance with the experiment, the deposition effect of the hedge barrier was not considered.
 221 Meanwhile, it should be noted that the deposition velocity is largely different depending on the
 222 pollutant species, especially for the particles [44]. Therefore, this study targeted on the gaseous
 223 species with small deposition velocities such as carbon monoxide and nitrogen oxides [45].

224

225 2.4 Analysis cases

226 Table 1 shows the description of barrier configurations for all analysis cases. Cases were
 227 formulated by considering the influence of LAD, barrier width and wind direction. For the basic
 228 cases which corresponded to the experiment configurations, the simulated time-averaged
 229 concentration was validated using experimental data in Section 3.1 and the pollutant reduction
 230 effect from hedge and solid barriers were investigated in Section 3.2. Next, the influence of hedge
 231 porosity was analysed by considering successively the LAD as 1 and $2 \text{ m}^2/\text{m}^3$ [19] in Section 3.3.
 232 Then, hedge and solid barriers with smaller width (1 m and 0.5 m) were considered in Section
 233 3.4. Subsequently, wind direction was considered as 45° in Section 3.5. Other configurations were
 234 the same as in the basic cases.

235

236 Table 1. Description of barrier configurations for all analysis cases.

| Barrier | LAD (m^2/m^3) | Width (m) | Wind direction ($^\circ$) | Note |
|------------------------------------|---------------------------------|-----------|-----------------------------|-------------|
| Basic cases^a | | | | |
| Free | N/A | N/A | | Section 3.1 |
| Hedge ^b | 4.2 | 1.5 | 90 | Section 3.2 |
| Solid | N/A | 1.5 | | Section 3.3 |
| Discussion on LAD | | | | |
| Hedge | 1.0, 2.0, 4.2 | 1.5 | 90 | Section 3.4 |
| Discussion on barrier width | | | | |

| | | | | |
|------------------------------|-----|---------------|----|-------------|
| Hedge | 4.2 | 0.5, 1.0, 1.5 | 90 | Section 3.5 |
| Solid | N/A | 0.5, 1.0, 1.5 | | |
| Discussion on wind direction | | | | |
| Free | N/A | N/A | 45 | Section 3.6 |
| Hedge | 4.2 | 1.5 | | |
| Solid | N/A | 1.5 | | |

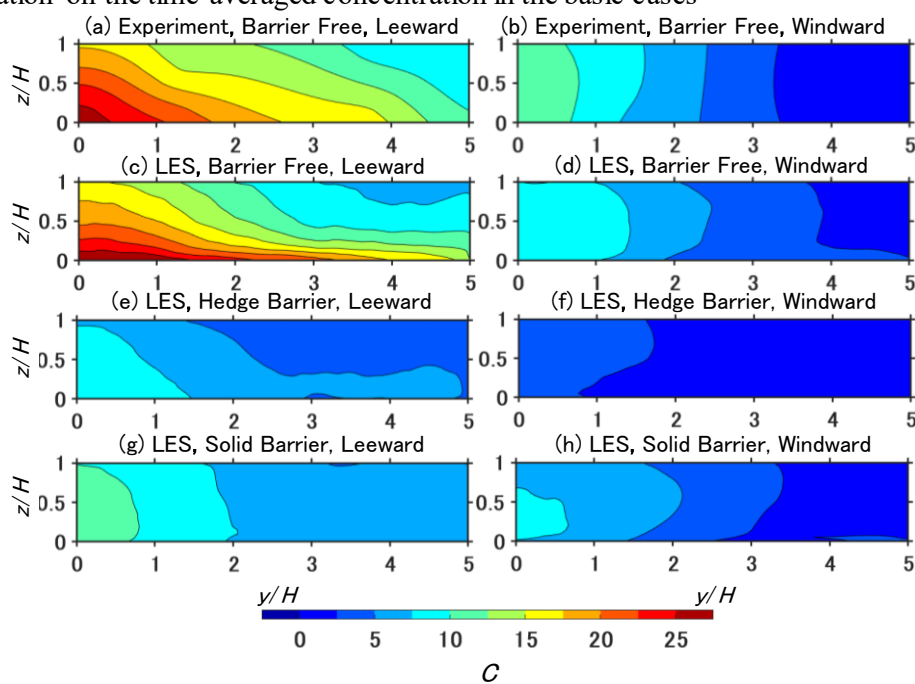
237 ^a The results of basic cases were validated with wind tunnel experiments.

238 ^b The dimensionless drag coefficient $C_D = 0.2$.

239

240 3 Results and discussions

241 3.1 Validation on the time-averaged concentration in the basic cases



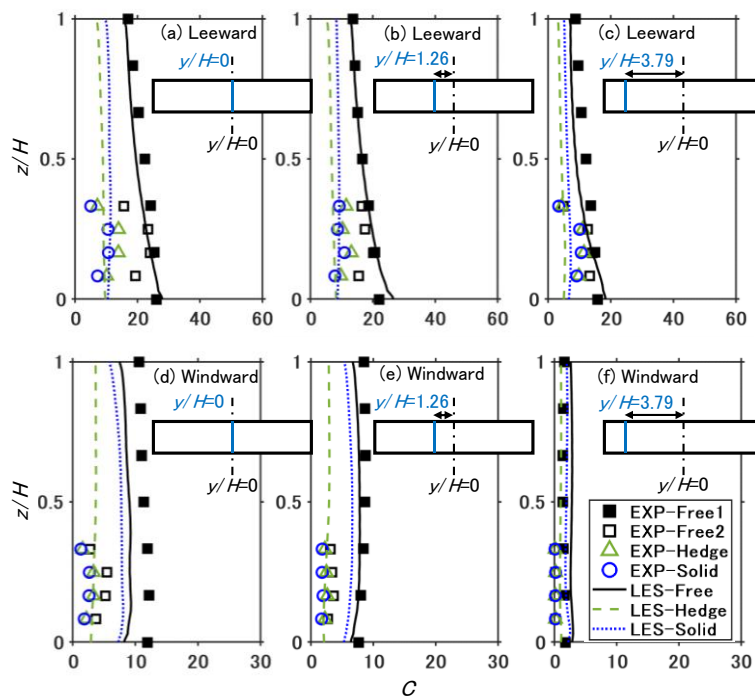
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243 Fig. 5. Distributions of the time-averaged concentration C near the leeward wall ($x/H=0.06$) and
 244 the windward wall ($x/H=1.94$) in the basic cases. The experiment data is from Gromke and Ruck
 245 (2012) [27].

246

247 In the Sections 3.1 to 3.4, the studies were based on a wind direction which was perpendicular
 248 (90 degrees) to the street. Fig. 5 shows the distributions of the time-averaged concentration C near
 249 the leeward wall ($x/H=0.06$) and the windward wall ($x/H=1.94$) in the basic cases (barrier-free,
 250 hedge barrier with $LAD=4.2 \text{ m}^2/\text{m}^3$ and solid barrier). The vertical planes were selected with the
 251 same location in the wind tunnel experiment [27]. As the simulation configurations were
 252 symmetric in the spanwise direction, the simulation results were averaged at mirror-symmetric
 253 locations. The simulation results were confirmed to be symmetrical in the spanwise direction in
 254 Appendix B. All subsequent results were presented using the same methods. The barrier-free case

255 was validated by the experimental data [27]. Although the simulated C values were smaller than
 256 the experiment, LES well reproduced the distribution patterns for both leeward and windward
 257 sides. In all cases, the C values near the leeward walls were larger than those near the windward
 258 walls. In addition, the hedge and solid barriers largely reduced time-averaged concentration from
 259 the barrier-free case, indicating that barriers were effective methods for reducing roadside
 260 pollutants. The detailed analysis can be found in Section 3.2.

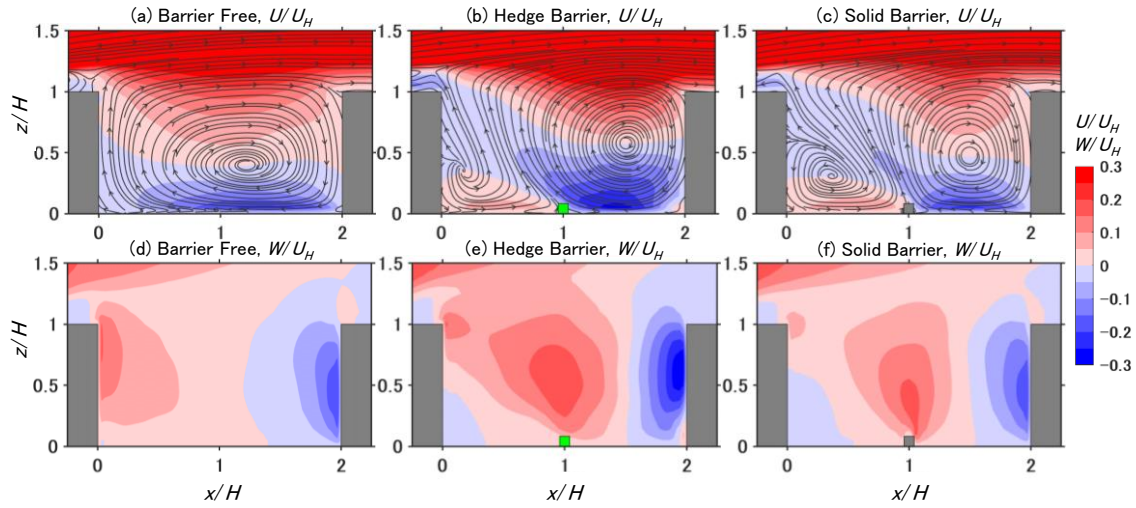


261
 262 Fig. 6. Vertical profiles of the time-averaged concentration near the leeward wall ($x/H=0.06$) and
 263 the windward wall ($x/H=1.94$) in the basic cases. EXP-Free1 indicates the experimental data from
 264 Gromke and Ruck (2012) [27]. Other experimental data are taken from Gromke et al. (2016) [14].
 265

266 Fig. 6 shows the vertical profiles of the time-averaged concentration C near the leeward wall
 267 ($x/H=0.06$) and the windward wall ($x/H=1.94$). The barrier-free data obtained in the wind tunnel
 268 experiments conducted by Gromke and Ruck (2012) [27] and Gromke et al. (2016) [14] were
 269 shown together. The two datasets showed similar values near the leeward wall, while discrepancy
 270 was found near the windward wall. In addition, the hedge and solid barriers showed similar
 271 concentration reduction in Gromke et al. (2016) [14]. Regarding the LES prediction for the
 272 barrier-free case, LES was in good agreement with Gromke and Ruck (2012) [27] on both sides
 273 of the street canyon. Furthermore, both experiment and LES showed that the concentration values
 274 in the hedge and solid barrier cases were lower than those in the barrier-free cases, indicating that
 275 LES well reproduced the barrier-induced pollutant reduction.

276

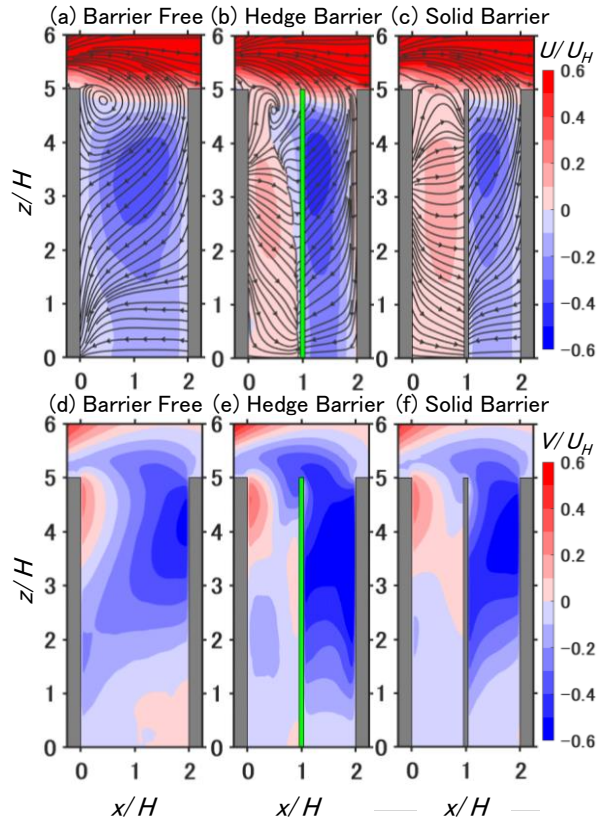
277 3.2 Flow and concentration fields of basic cases



278
279 Fig. 7. Distributions of the time-averaged streamlines, streamwise velocity U/U_H and vertical
280 velocity W/U_H in the vertical plane ($y/H=0$).
281

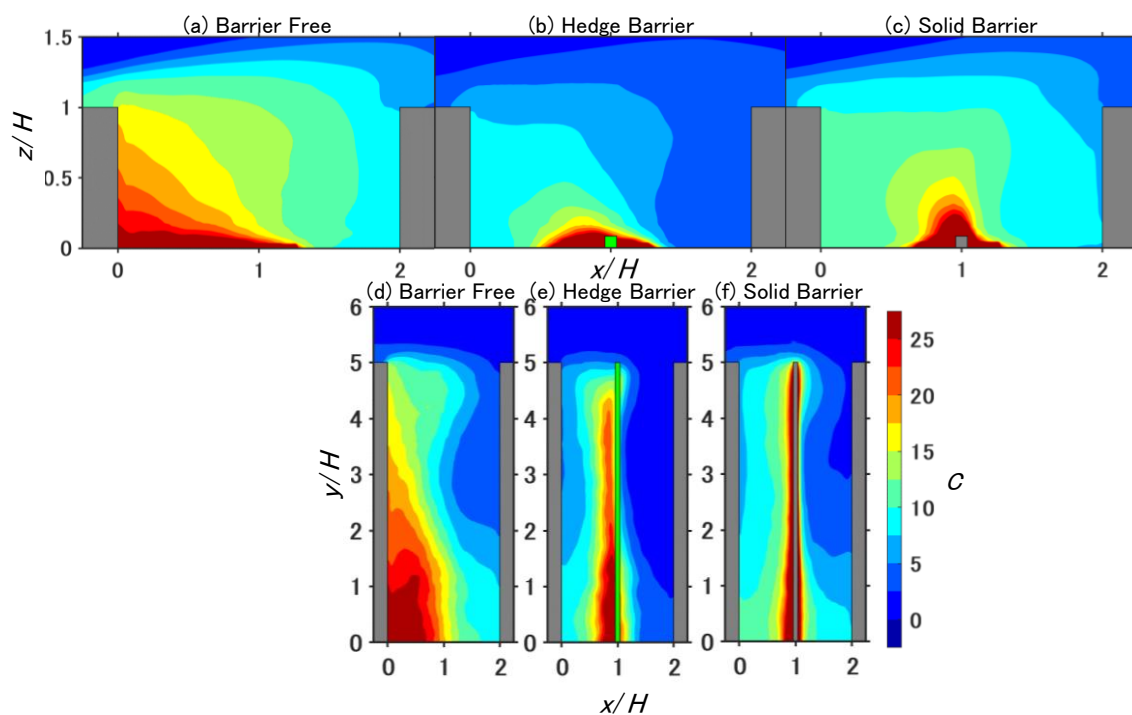
282 To find out how barriers affected the flow field in the street canyon,
283 Fig. 7 shows the distributions of the time-averaged streamlines, streamwise velocity U/U_H and
284 vertical velocity W/U_H in the vertical plane ($y/H=0$) in the basic cases (barrier-free, hedge barrier
285 with $LAD=4.2 \text{ m}^2/\text{m}^3$ and solid barrier). In the barrier-free case, a large recirculation vortex can
286 be found in the street canyon. Meanwhile, the presence of barriers forced the recirculated air flow
287 up at the middle of the canyon ($x/H=1$) and newly formed the vortices between the leeward walls
288 and the barriers, which was also observed in a street canyon with an aspect ratio of 0.75 in
289 McNabola et al. (2009) [10]. The new vortices were referred as leeward vortices hereafter, to be
290 distinct from the original vortices which were referred to as windward vortices. In both hedge and
291 solid barrier cases, the leeward vortices were in counter rotation direction with the windward
292 vortices. In addition, the windward vortices were larger than the leeward vortices. At the same
293 time, the hedge barrier case showed a stronger windward vortex compared to the solid barrier
294 case. This can be attributed to the fact that the recirculated air flow was able to pass through the
295 permeable hedge barrier but was forced over the solid barrier. Consequently, a stronger leeward
296 vortex was formed in the solid barrier case than in the hedge barrier case. In addition, although
297 the hedge barrier case generally showed larger W/U_H than the solid barrier case in the street
298 canyon, the solid barrier case showed larger W/U_H than the hedge barrier case close to the solid
299 barrier. The effect of the porosity or LAD of hedge barriers on the flow fields is further discussed
300 in Section 3.3.

301



302
 303 Fig. 8. Distributions of the time-averaged streamlines, streamwise velocity U/U_H and spanwise
 304 velocity V/U_H in the horizontal plane ($z/H=0.08$).

305
 306 Fig. 8 shows the distributions of the time-averaged streamlines, streamwise velocity U/U_H and
 307 spanwise velocity V/U_H in the horizontal plane ($z/H=0.08$), which correspond to both the barrier
 308 height and the pedestrian height. For U/U_H , negative values were simulated in the barrier-free
 309 case because of the large recirculation flow shown in
 310 Fig. 7(a). In addition, a local recirculation zone was simulated near the intersection ($x/H=0$,
 311 $y/H=5$), which brought fresh air from the side of the canyon. Meanwhile, U/U_H in hedge and solid
 312 barrier cases were generally in positive values between the leeward walls and the barriers,
 313 corresponding to the anticlockwise leeward vortices in
 314 Fig. 7(b) and (c). Further, the barriers weakened the recirculation zone near the intersection,
 315 especially in the solid barrier case. For V/U_H , hedge and solid barriers intensified the spanwise
 316 flow near the windward walls but weakened the spanwise flow near the leeward walls.



317

318 Fig. 9. Distributions of the time-averaged concentration C in the (a-c) vertical plane ($y/H=0$) and
 319 (d-f) the horizontal plane ($z/H=0.08$).

320

321 Regarding the barrier effects on the concentration fields, Fig. 9 represents the distributions of the
 322 time-averaged concentration C in the (a-c) vertical plane ($y/H=0$) and (d-f) the horizontal plane
 323 ($z/H=0.08$). In the barrier-free case, the pollutant was transported toward the leeward wall by the
 324 vertical recirculation flow and toward the inner part of the street by the spanwise flow, hence large
 325 values of C can be found near the leeward wall. The pollutant in the barrier-free case was mainly
 326 removed from the street canyon near the top of the leeward wall as studied in Zhang et al. (2022)
 327 [46]. Hedge and solid barriers greatly influenced the C distribution and significantly decreased C
 328 in the street canyon (Table 2). Meanwhile, the two counter-direction vortices in the hedge and
 329 solid barrier cases transported the pollutant toward the center of the canyon ($x/H=1$), increasing
 330 the vertical pollutant removal at the top of the street canyon. Despite this decrease of the average
 331 concentration, large C can be found along the barriers. Hence, in view of urban design issues,
 332 pollutant absorption methods [47] are expected to be combined with the barriers to achieve a
 333 better pollutant reduction effect. In addition, the solid barrier case generally showed larger values
 334 of C than the hedge barrier case. The reason could be that the windward vortex, which was
 335 stronger in the hedge barrier case than that in the solid barrier case, dominated the pollutant
 336 removal.

337

338 Table 2 summarizes the spatially-averaged concentration in the barrier-free case and the

339 concentration ratio between the analysis cases and the barrier-free case near the leeward wall
 340 ($x/H=0.06$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$), windward wall ($x/H=1.94$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$) and the whole
 341 street canyon ($0 \leq x/H \leq 2$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$). The spatially-averaged concentration is the area-
 342 weighted average concentration on the planes. In the barrier-free case, the spatially-averaged
 343 concentration near the leeward wall was about 2.7 times the value near the windward wall and
 344 1.5 times the canyon-averaged concentration. The hedge barrier reduced the spatially-averaged
 345 concentration by about 59% near the leeward wall, 64% near the windward wall and 45% for the
 346 whole street canyon compared to the barrier-free case. Although the pollutant reduction effect of
 347 the solid barrier was less than that of the hedge barrier, the solid barrier reduced spatially-averaged
 348 concentration by about 45% near the leeward wall, 20% near the windward wall and 17% for the
 349 whole street canyon.

350

351 Table 2. Spatially-averaged concentration ratio between the analysis and the barrier-free cases.
 352 The values are based on the leeward wall ($x/H=0.06$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$), windward wall
 353 ($x/H=1.94$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$) and street canyon ($0 \leq x/H \leq 2$, $-5 \leq y/H \leq 5$, $0 \leq z/H \leq 1$). The values in
 354 parenthesis indicate the spatially-averaged concentration in the barrier-free case.

| Barrier type | Leeward | Windward | Canyon |
|--|--------------|-------------|-------------|
| Perpendicular wind direction | | | |
| Free | 100.0 (13.8) | 100.0 (5.0) | 100.0 (9.0) |
| Hedge (LAD=4.2 m ² /m ³ , Width=1.5 m) | 41.1 | 36.4 | 54.5 |
| Hedge (LAD=2.0 m ² /m ³ , Width=1.5 m) | 41.0 | 36.1 | 54.1 |
| Hedge (LAD=1.0 m ² /m ³ , Width=1.5 m) | 43.1 | 36.6 | 53.2 |
| Hedge (LAD=4.2 m ² /m ³ , Width=1.0 m) | 41.4 | 34.2 | 53.2 |
| Hedge (LAD=4.2 m ² /m ³ , Width=0.5 m) | 41.8 | 35.0 | 51.8 |
| Solid (Width=1.5 m) | 55.2 | 80.7 | 83.3 |
| Solid (Width=1.0 m) | 57.2 | 80.0 | 86.8 |
| Solid (Width=0.5 m) | 59.8 | 83.1 | 87.2 |
| Oblique wind direction | | | |
| Free | 100.0 (2.5) | 100.0 (0.3) | 100.0 (1.3) |
| Hedge (LAD=4.2 m ² /m ³ , Width=1.5 m) | 69.1 | 70.2 | 132.5 |
| Solid (Width=1.5 m) | 42.0 | 39.8 | 95.9 |

355

356 3.3 Concentration flux of basic cases

357 Convective concentration flux and turbulent concentration flux are crucial for understanding the
 358 pollutant transport in urban environments [48–50]. To clarify the effect of the hedge and solid
 359 barriers on pollutant removal in the street canyon, we investigated the surface-sum concentration
 360 flux, as shown in Table 3. u' , v' , w' are the fluctuation velocities in the streamwise, spanwise and
 361 vertical directions, respectively. The pollutants were transported out of the street canyon from the
 362 vertical convective concentration flux WC and vertical turbulent concentration flux $\overline{w'c'}$ at the

363 top plane ($0 \leq x/H \leq 2$, $-5 \leq y/H \leq 5$, $z/H=1$), and also from the spanwise convective concentration flux
 364 VC and spanwise turbulent concentration flux $\overline{v'c'}$ at the side planes ($0 \leq x/H \leq 2$, $y/H=-5$ and $y/H=5$,
 365 $0 \leq z/H \leq 1$). The positive and negative values indicate the outflow and inflow concentration flux,
 366 respectively. The percentage value (ratio of each surface-sum concentration flux to the net
 367 concentration flux) was used to represent the contribution of each concentration flux. In addition,
 368 the difference of the net concentration flux between the barrier free, hedge barrier and solid barrier
 369 cases were confirmed smaller than 0.5 percent.

370

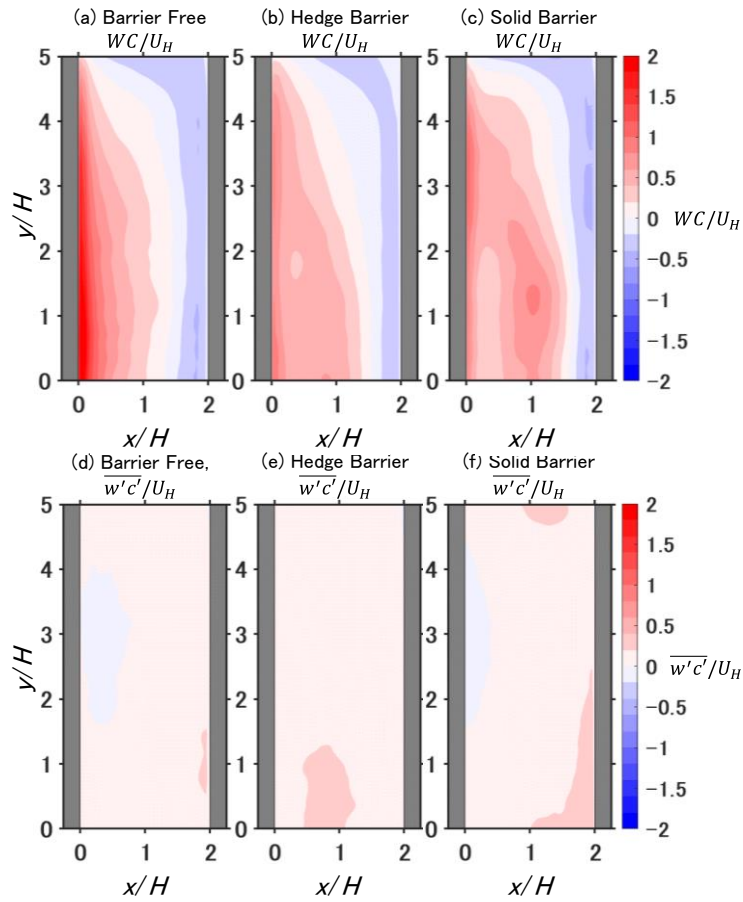
371 Table 3 Surface-sum concentration flux at the top plane ($0 \leq x/H \leq 2$, $-5 \leq y/H \leq 5$, $z/H=1$) and the side
 372 planes ($0 \leq x/H \leq 2$, $y/H=-5$ and $y/H=5$, $0 \leq z/H \leq 1$). The positive and negative values indicate the
 373 outflow and inflow concentration flux, respectively. All values are represented by percentages
 374 (ratio of each surface-sum concentration flux to net concentration flux). The values in parentheses
 375 are the nondimensionalized net concentration-flux.

| Concentration flux | Free | Hedge (LAD=4.2 m ² /m ³ , Width=1.5 m) | Solid (Width=1.5 m) |
|--------------------------------------|-------------|---|------------------------|
| WC at the top plane | 81% | 65% | 75% |
| $\overline{w'c'}$ at the top plane | 25% | 41% | 32% |
| VC at the side planes | -16% | -17% | -23% |
| $\overline{v'c'}$ at the side planes | 10% | 11% | 16% |
| Net concentration flux | 100% (1791) | 100% (1783) | 100% (1797) |

376

377 For the barrier free case, WC and $\overline{w'c'}$ at the top plane primarily determined the removal process
 378 compared to VC and $\overline{v'c'}$ at the side planes because the surface area of the top plane was larger
 379 than the side planes (Table 3). In addition, WC dominated the removal process at the top plane
 380 compared to $\overline{w'c'}$ as shown in Fig. 10 (a, d). Large positive WC occurred near the leeward wall
 381 and small negative WC occurred near the windward wall. These results were in line with the
 382 findings in two-dimensional street canyons in the previous wind tunnel experiment [51] and LES
 383 studies [52]. For the side planes, although positive VC occurred near the leeward wall, the surface-
 384 sum VC was negative because the separate flow near the building edges (Fig. 8 (a)) led to large
 385 pollutant inflow to the street canyon. At the same time, $\overline{v'c'}$ was generally positive at the side
 386 planes, especially large positive $\overline{v'c'}$ occurred near the ground.

387



388

389 Fig. 10. Distributions of the vertical convective concentration flux WC/U_H and vertical turbulent
 390 concentration flux $\overline{w'c'}/U_H$ in the top plane ($0 \leq x/H \leq 2$, $-5 \leq y/H \leq 5$, $z/H=1$) of the street canyon.

391

392 Previous LES studies found that the rooftop obstacles [52] and building façade geometrical details
 393 [53] increased $\overline{w'c'}$ at the top plane and enhanced the pollutant removal in the street canyon.

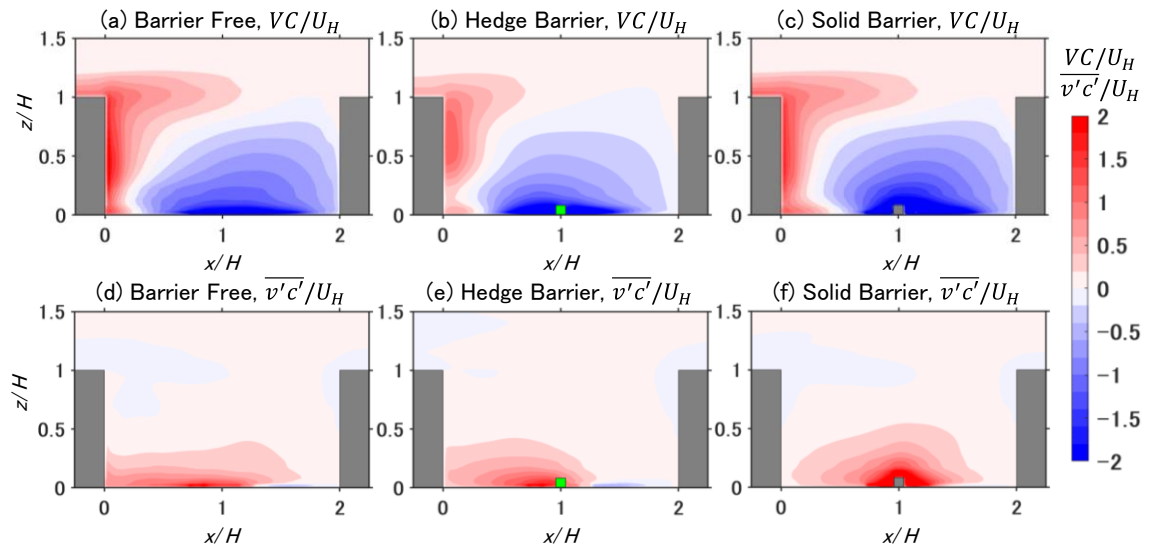
394 Similarly, the hedge and solid barriers decreased surface-sum WC and increased surface-sum
 395 $\overline{w'c'}$ at the top plane from the barrier free case as shown in Table 3. In addition, the hedge barrier

396 case showed larger surface-sum WC decrease and larger surface-sum WC increase from the
 397 barrier free case than the solid barrier case. Due to the reshaped vertical vortices (

398 Fig. 7 (a-c)), the hedge and solid barrier cases showed smaller WC near the leeward wall but
 399 larger WC above the barriers compared to the barrier free case (Fig. 10). For the side planes, the

400 hedge and solid barriers increased both inflow VC and outflow $\overline{v'c'}$ from the barrier free case,
 401 especially near the barriers (Fig. 11).

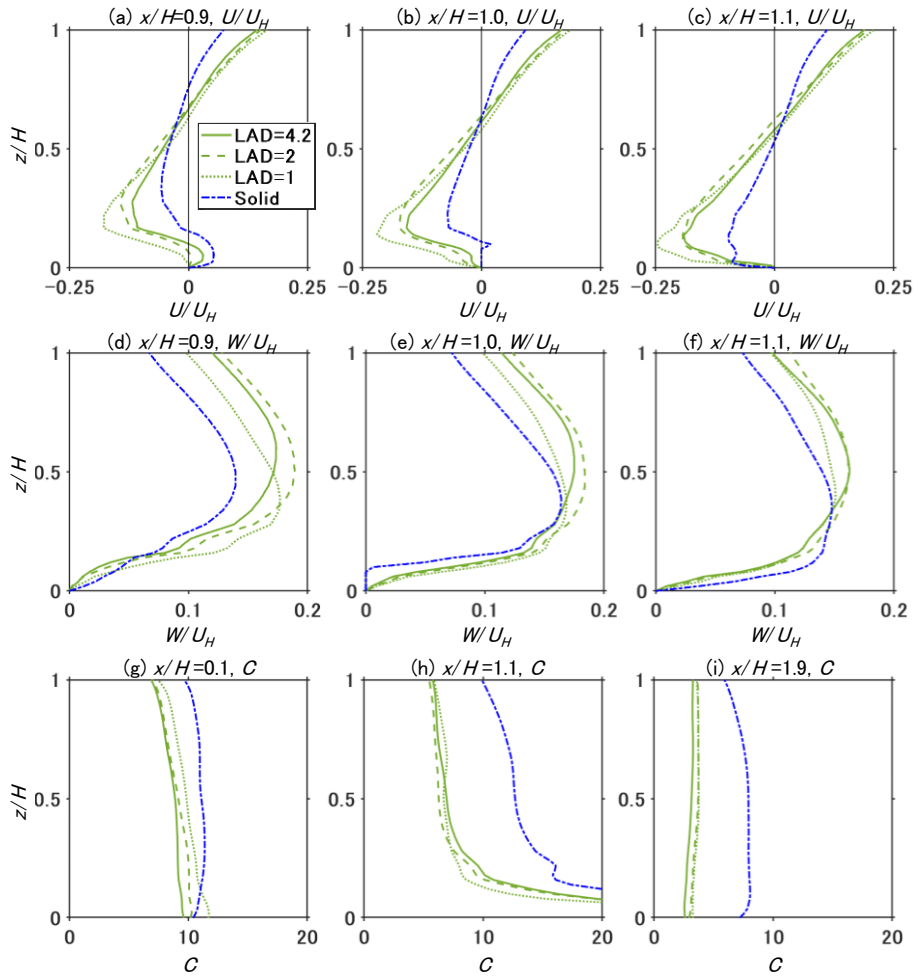
402



403

404 Fig. 11. Distributions of the spanwise convective concentration flux VC/U_H and spanwise
 405 turbulent concentration flux $\overline{v'c'}/U_H$ in the side plane ($0 \leq x/H \leq 2, y/H=5, 0 \leq z/H \leq 1$) of the street
 406 canyon.

407



409

410 Fig. 12. Vertical profiles of the time-averaged streamwise velocity U/U_H , vertical velocity W/U_H ,
 411 concentration C in the vertical plane ($y/H=0$) with different LAD.

412

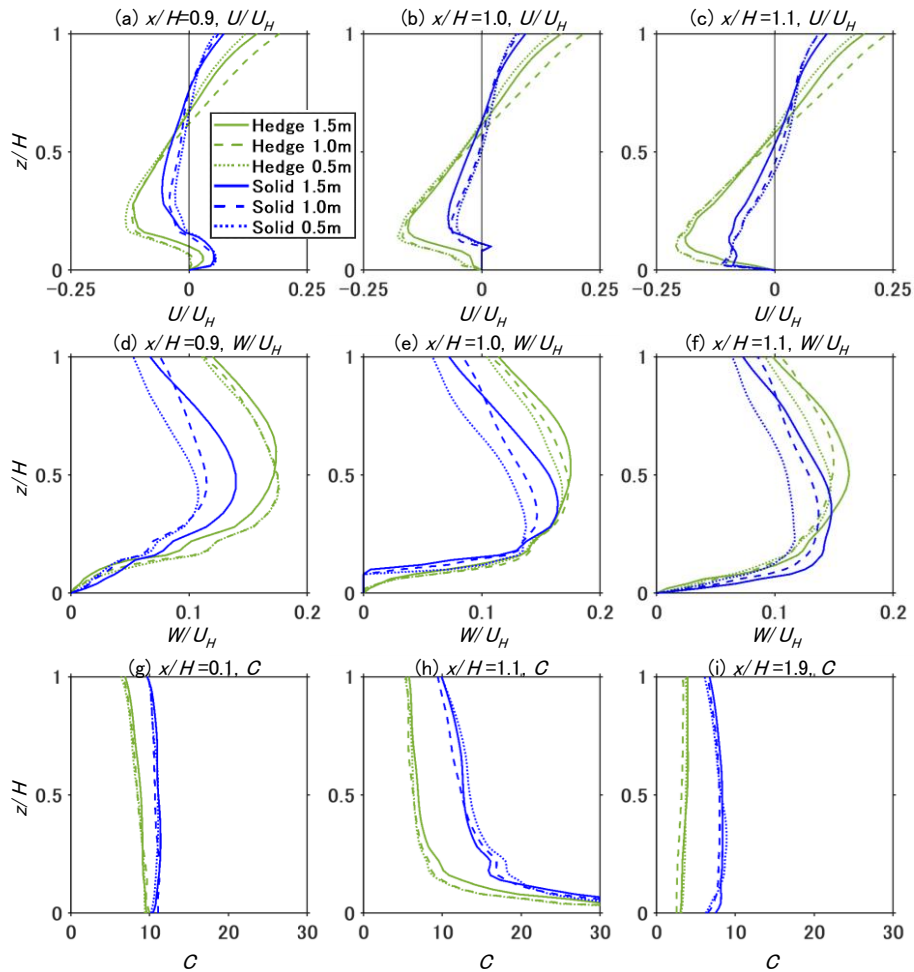
413 To understand the influence of the hedge LAD on the flow and concentration fields, Fig. 12 shows
 414 the vertical profiles of the time-averaged streamwise velocity U/U_H , vertical velocity W/U_H and
 415 concentration C in the vertical plane ($y/H=0$) for different LAD (1, 2 and $4.2 \text{ m}^2/\text{m}^3$). For
 416 comparison, the results based on the solid barrier are also shown. A decrease of LAD intensified
 417 the negative U/U_H near the ground as shown in Fig. 12 (a-c). At the same time, a decrease of LAD
 418 also increased W/U_H near the ground near the leeward side of the barrier (Fig. 12 (d)). These can
 419 be attributed to that small LAD resulted in less momentum reduction when recirculation flow
 420 passed through the hedge barriers, therefore resulted in large windward vortices and small leeward
 421 vortices as shown in

422 Fig. 7. In addition, the U/U_H differences between $\text{LAD}=4.2 \text{ m}^2/\text{m}^3$ and $\text{LAD}=2 \text{ m}^2/\text{m}^3$ were
 423 smaller than the differences between $\text{LAD}=2 \text{ m}^2/\text{m}^3$ and $\text{LAD}=1 \text{ m}^2/\text{m}^3$.

424

425 For the time-averaged concentration C , decreasing the LAD led to lower values at the center of
426 the street due to increased U/U_H (Fig. 12 (h)). Meanwhile, the stronger negative U/U_H transported
427 more pollutant toward the leeward walls and therefore increased C (Fig. 12 (g)). Regarding the
428 spatially-averaged concentration (Table 2), the hedge barrier with $LAD=1 \text{ m}^2/\text{m}^3$ showed slightly
429 higher C near the leeward wall and windward wall but smaller C for the whole street canyon
430 compared to the hedge barrier with $LAD=4.2 \text{ m}^2/\text{m}^3$. Meanwhile, the hedge barrier with $LAD=2$
431 m^2/m^3 showed comparable C to the hedge barrier with $LAD=4.2 \text{ m}^2/\text{m}^3$. As the pollutant was
432 emitted at the ground which was lower than the barrier height in the current study, the small wind
433 velocity change near the hedge barriers due to the LAD change led to small effect on concentration.
434

435 3.5 Influence of barrier width



436

437 Fig. 13. Vertical profiles of the time-averaged streamwise velocity U/U_H , vertical velocity W/U_H ,
438 concentration C in the vertical plane ($y/H=0$) with different barrier widths.

439

440 Regarding the influence of hedge and solid barrier width, Fig. 13 shows vertical profiles of time-
441 averaged streamwise velocity U/U_H , vertical velocity W/U_H and concentration C in the vertical
442 plane ($y/H=0$) with different barrier widths (0.5, 1.0 and 1.5 m). For hedge barriers, decreasing
443 barrier width resulted in similar influences on the flow and concentration fields as decreasing
444 LAD. Specifically, the negative U/U_H near the ground was enhanced and W/U_H near the leeward
445 side of the barrier was increased. In addition, decreasing hedge barrier width increased the
446 spatially-averaged concentration near the leeward and windward walls but decreased the
447 spatially-averaged concentration in the street canyon as shown in Table 2.

448

449 However, decreasing solid barrier width generally weakened both U/U_H and W/U_H in the street,
450 indicating that a thinner solid barrier led to a smaller change of the near-ground wind direction
451 from horizontal to slanting upwards. As a result, decreasing solid barrier width hindered the
452 pollutant removal at the top of the canyon and therefore increased the spatially averaged
453 concentration (Table 2) in the street canyon.

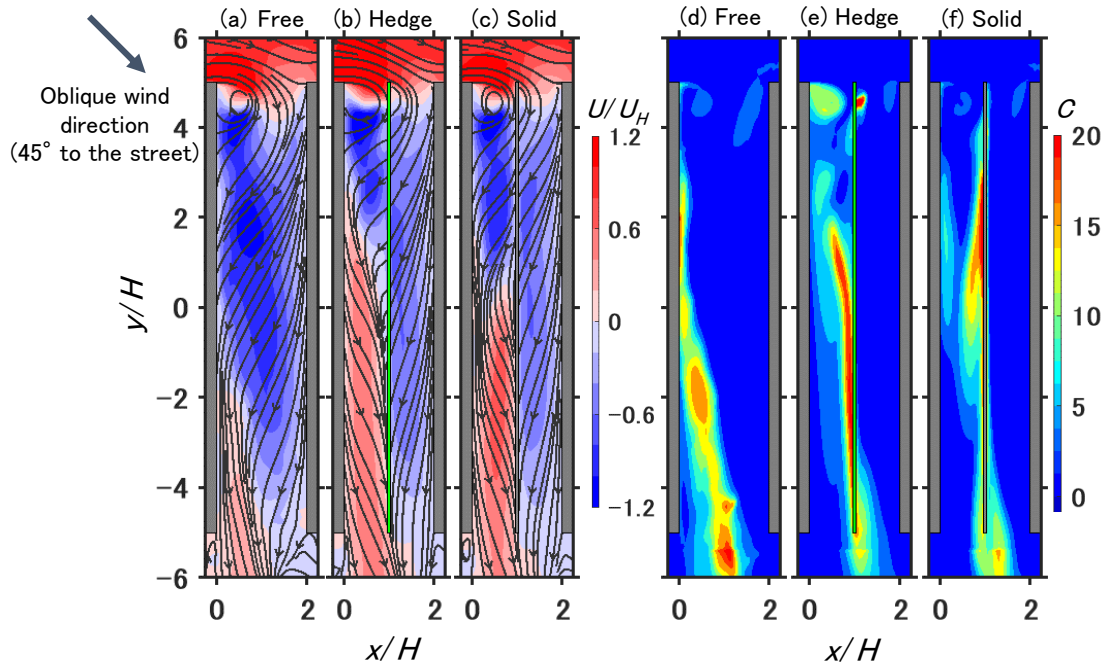
454

455 In general, increasing hedge and solid barrier width did not show significant effects on the flow
456 and concentration fields in the street canyon, indicating that the presence of a line obstacle on the
457 street ground was the dominant reason for reducing the pollutant concentration by breaking the
458 large recirculation flow (

459 Fig. 7).

460

461 3.6 Influence of oblique wind direction



462

463 Fig. 14. Distributions of the time-averaged streamlines, streamwise streamlines, velocity U/U_H
 464 and time-averaged concentration C in the horizontal plane ($z/H=0.08$) under the oblique wind
 465 direction.

466

467 To discuss the influence of wind direction, simulations of the basic cases (barrier-free, hedge
 468 barrier with $LAD=4.2 \text{ m}^2/\text{m}^3$ and solid barrier) were conducted under the oblique wind direction,
 469 which was 45 degrees to the street. Fig. 14 shows the distributions of the time-averaged
 470 streamlines, streamwise velocity U/U_H and time-averaged concentration C in the horizontal plane
 471 ($z/H=0.08$). In the barrier-free case, the oblique wind direction resulted in a large region with
 472 negative U/U_H in the street canyon (Fig. 14 (a)), therefore the pollutant was concentrated near the
 473 leeward wall (Fig. 14 (d)). In addition, the air exchange in the canyon increased in the street
 474 canyon in the oblique wind direction compared to the perpendicular wind direction. Therefore,
 475 the spatially-averaged concentration near the leeward wall, the windward wall and in the whole
 476 street canyon reduced to 18%, 6%, and 14% of values in the barrier-free case in the perpendicular
 477 wind direction, respectively (Table 2).

478

479 In the hedge and solid barrier cases, positive U/U_H regions were observed between the leeward
 480 walls and the barriers (Fig. 14 (b, c)), indicating that the barriers broke the recirculation flows
 481 into the leeward and windward vortices, similarly to the perpendicular wind directions (Fig. 8).
 482 Therefore, the leeward and windward vortices carried the pollutant along the leeward sides of the
 483 hedge and solid barriers (Fig. 14 (e, f)). Meanwhile, the permeability of the barriers resulted in

484 different streamlines near $y/H=2$ and therefore led to different locations of the high-
485 concentration area in the hedge and solid barrier cases. The hedge barrier led to higher C than the
486 solid barrier at the corner of the canyon and on the leeward side of the barrier. Regarding the
487 spatially-averaged concentration, compared to the barrier-free case (Table 2), the hedge barrier
488 reduced it by about 30% at both the leeward and windward walls, but increased it by 30% in
489 average over the whole street canyon due to the high concentration areas along the barrier.
490 However, the solid barrier reduced it by about 60% at both leeward and windward walls compared
491 to the barrier-free case, and by 4% in average over the whole street canyon. Therefore, both hedge
492 and solid barriers were effective in reducing pollutant concentrations near the building walls in
493 an oblique wind direction, and the solid barrier showed better effects than the hedge barrier.

494

495 4 Conclusions

496 4.1 Summary

497 Road barriers have been considered as effective methods to mitigate traffic pollution in urban
498 environments. Meanwhile, the effect of road barriers on the flow and concentration fields in
499 streets has not been sufficiently studied. To address this knowledge gap, this study conducted
500 large-eddy simulations on pollutant reduction effect of hedge and solid barriers in an idealized
501 street canyon. The aspect ratio of the street canyon was 0.5 and the building height was 18 m. The
502 1.5 m high barriers were placed in the middle of the street. The pollutant was emitted from the
503 line sources at ground level. After validating the LES results with wind tunnel experiments, the
504 influences of LAD and barrier width were investigated. Furthermore, the barrier effects were also
505 studied in an oblique wind direction. The major findings are summarized below:

506

507 (1) LES accurately reproduced the concentration distributions for both the leeward and windward
508 sides in the barrier-free case. In addition, LES well reproduced the barrier-induced pollutant
509 reduction. Therefore, LES was considered to be an effective method for analyzing the barrier
510 effect.

511

512 (2) For the flow fields in the street canyon, a large recirculation vortex was observed in the
513 barrier-free case. However, the road center barriers modified the recirculated air flow with
514 additional vortices between the leeward walls and the barriers. In addition, the hedge barrier
515 case showed a stronger windward vortex compared to the solid barrier case because the
516 recirculated airflow could pass through the permeable hedge barrier but was forced over the
517 solid barrier. At the same time, a stronger leeward vortex was formed in the solid barrier case
518 than in the hedge barrier case.

519

- 520 (3) For the concentration field in the barrier-free case, the pollutant was transported toward the
521 leeward wall by the vertical recirculation flow and toward the inner part of the street by the
522 spanwise flow, hence large concentration regions were found near the leeward wall. However,
523 the two counter-direction vortices in the hedge and solid barrier cases transported the pollutant
524 toward the center of the canyon and enhanced the vertical pollutant removal at the top of the
525 street canyon. The hedge barrier reduced the spatially-averaged concentration by about 59%
526 near the leeward wall, 64% near the windward wall and 45% over the whole street canyon.
527 The solid barrier was less effective: it reduced the spatially-averaged concentration by about
528 45% near the leeward wall, 20% near the windward wall, and 17% over the whole street
529 canyon.
530
- 531 (4) Decreasing the hedge LAD resulted in less momentum reduction when recirculation flow
532 passed through the hedge barriers, therefore intensified the streamwise and vertical velocity
533 in the street. The increased streamwise wind transported more efficiently the pollutant toward
534 the leeward walls and therefore increased concentration near the leeward wall. Meanwhile,
535 the increased vertical wind enhanced pollutant removal at the top of the canyon and therefore
536 decreased canyon-averaged concentration. In addition, the differences between $LAD=4.2$
537 m^2/m^3 and $LAD=2$ m^2/m^3 were smaller than the differences between $LAD=2$ m^2/m^3 and
538 $LAD=1$ m^2/m^3 . One of the reasons was considered to be that the wind velocity near the
539 barriers was small, and therefore further increasing the LAD led to little effect on velocity
540 reduction.
541
- 542 (5) Decreasing hedge barrier width resulted in similar effects on the flow and concentration fields
543 as decreasing LAD. However, decreasing the solid barrier width generally weakened the wind
544 velocity in the street. This is because thinner solid barriers led to smaller influences to change
545 the near-ground wind direction from horizontal to slanting upwards. As a result, decreasing
546 solid barrier width hindered the pollutant removal at the top of the canyon and therefore
547 increased the spatially-averaged concentration in the street canyon. In general, varying barrier
548 width from 0.5 m to 1.5 m did not show significant effects on the flow and concentration
549 fields in the street canyon because the presence of a line obstacle on the street ground was the
550 dominant reason for reducing the pollutant concentration by breaking the large recirculation
551 flow.
552
- 553 (6) In an oblique wind direction of 45 degrees to the street, the pollutant was concentrated on the
554 leeward side in the street canyon in the barrier-free case. In the hedge and solid barrier cases,
555 the barriers broke the recirculation flows into the leeward and windward vortices, similarly

556 to the perpendicular wind directions. The hedge and solid barriers reduced the spatially-
557 averaged concentration near the building walls by almost 30% and 60% compared to the
558 barrier-free case, respectively. Meanwhile, due to the high concentration regions along the
559 barrier, the hedge barrier increased by 30% the spatially-averaged concentration in the street
560 canyon and the solid barrier reduced it by about 4% compared to the barrier-free case.

561

562 In conclusion, the pollutant reduction effects of hedge and solid barriers were confirmed in both
563 perpendicular and oblique wind directions. Although the effects of the variation in the hedge LAD
564 and barrier width were not significant on the flow and concentration fields in the street canyon,
565 increasing the hedge LAD and barrier width is recommended to reduce more efficiently pollutant
566 concentrations near building walls. In addition, the hedge barrier is recommended in a
567 perpendicular wind direction to the street, and the solid barrier is recommended in an oblique
568 wind direction. The conclusions obtained in this study may help urban planners to design the
569 location and material of barriers.

570

571 4.2 Limitations of the study

572 Although this study highlighted several key aspects, some limitations should be addressed in
573 future work.

574

575 (1) Concerning the street configuration, barrier dimension and meteorological conditions, the
576 isolated street canyon employed in the current study was a generic idealized urban geometry.
577 Further studies are needed to evaluate the barrier effect in the real-world flow environment.
578 For instance, traffic-induced turbulence could significantly change the impact of the barrier.
579 In addition, although this study found that the barriers with a height of 1.5 and a width from
580 0.5 m to 1.5 m showed small differences in pollutant reduction effect, further studies are
581 needed to confirm the pollutant reduction effect from larger barriers. Moreover, the isothermal
582 boundary layer was considered, whereas solar radiation can lead to large temperature
583 differences in the street and result in buoyant flows. Therefore, the barrier effects should be
584 evaluated under different thermal conditions [54].

585

586 (2) Except of the hedge and solid barriers investigated in this study, other geometrical details in
587 the street canyon such as wind catchers [55], car parking systems [56] and elevated walkways
588 [57] can also influence the flow fields in the street and insert similar pollutant reduction
589 mechanisms to the barriers. Their urban area applicability, efficacy and limitations were
590 discussed in the literature review [6,7]. Therefore, it is of great importance to compare the
591 effects of these geometric details in order to provide urban planners with appropriate

592 recommendations for reducing pollutant concentrations. However, these geometrical details
593 have been evaluated in different street configurations and meteorological conditions such as
594 wind direction, which makes the comprehensive comparisons difficult. Therefore, further
595 studies are needed to set the same situations under the representative urban environments to
596 evaluate these geometrical details.

597

598 (3) Regarding the hedge modeling, the dry deposition effect was not considered in the current
599 study in accordance with the experiment. However, the deposition effect is dependent on the
600 pollutant species [45], particle size and density [44] and LAD [17] and may provide a more
601 comprehensive assessment of the hedge barrier volume and LAD.

602

603 (4) Chemical reactions and aerosol dynamics were not considered during the pollutant dispersion
604 in the current study, whereas they have been found to significantly influence the distribution
605 of traffic pollutants in the street canyon [58,59] and they should be considered to simulate the
606 air quality more accurately.

607

608 Declaration of competing interest

609 The authors declare that they have no known competing financial interests or personal
610 relationships that could have appeared to influence the work reported in this paper.

611

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615

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617 Chao Lin: Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft,
618 Writing - Review & Editing, Visualization

619 Ryozo Ooka: Conceptualization, Resources, Supervision, Project administration, Formal analysis,
620 Writing - Review & Editing

621 Hideki Kikumoto: Methodology, Resources, Supervision, Formal analysis, Writing - Review &
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627 Yang Zhang: Formal analysis, Writing - Review & Editing

628 Karine Sartelet: Conceptualization, Resources, Supervision, Formal analysis, Writing - Review
629 & Editing

630

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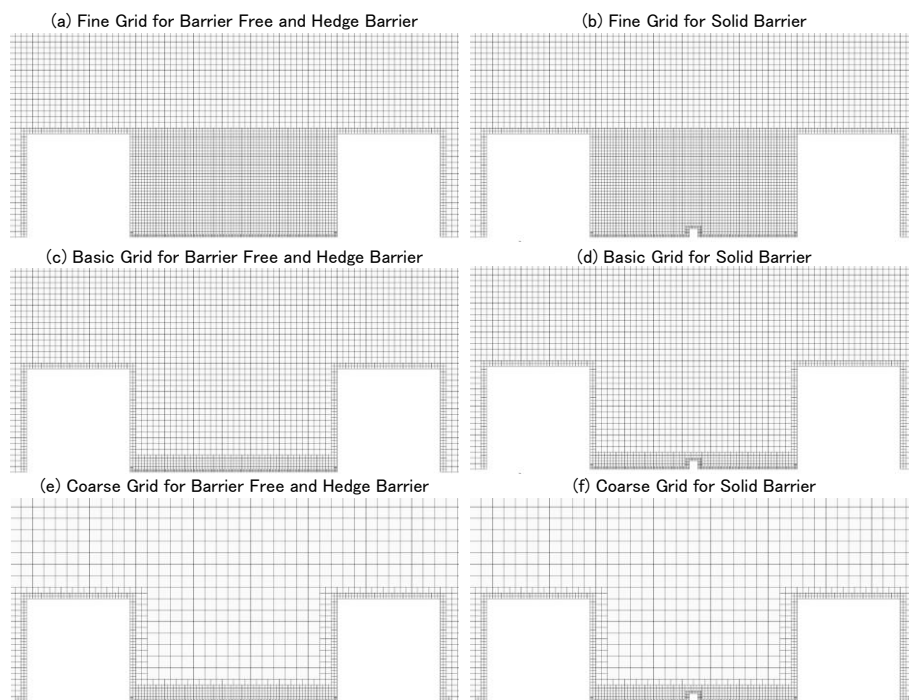
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813

814 Appendix A. Analysis on grid resolution independence



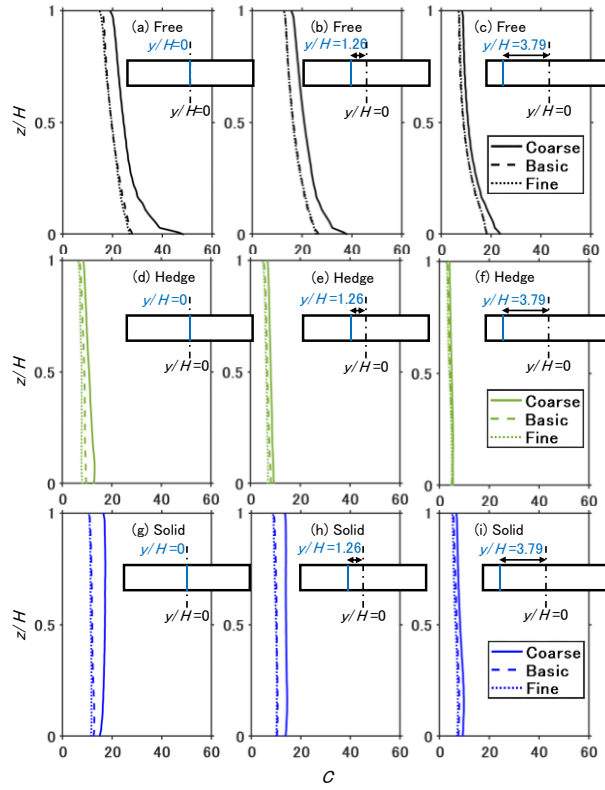
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Fig. A1. Tested grid resolutions in the street canyon.

817

818 Grid sensitivity analysis was performed using coarse (1.2×10^6), basic (1.5×10^6), and fine (1.8
819 $\times 10^6$) grids as shown in Fig. A1. The smallest grid lengths near the source were $H/72$ in all grid
820 resolutions. The largest grid lengths in the street canyon were $H/9$, $H/18$ and $H/36$ in the coarse,
821 basic and fine resolutions, respectively.

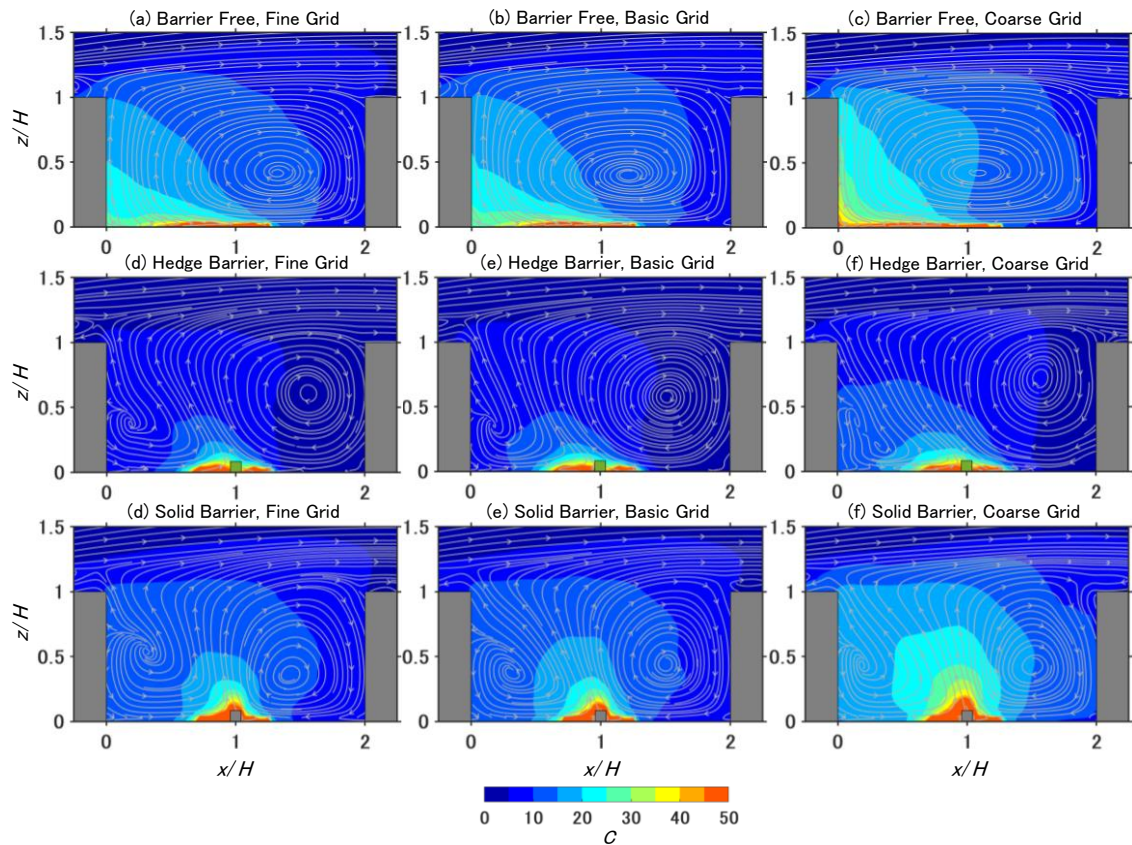


822

823 Fig. A2. Vertical profiles of the time-averaged concentration C near the leeward wall ($x/H=0.06$)
 824 with different grid resolutions. The wind direction was perpendicular to the street.

825

826 Fig. A2 compares the vertical profiles of the time-averaged concentration C near the leeward wall
 827 ($x/H=0.06$) with different grid resolutions for the barrier-free, hedge barrier and solid barrier cases.
 828 No significant discrepancy was observed between the results based on the basic and fine grids.
 829 However, the predicted mean concentration based on the coarse grid showed larger values
 830 compared to the other grid resolutions.



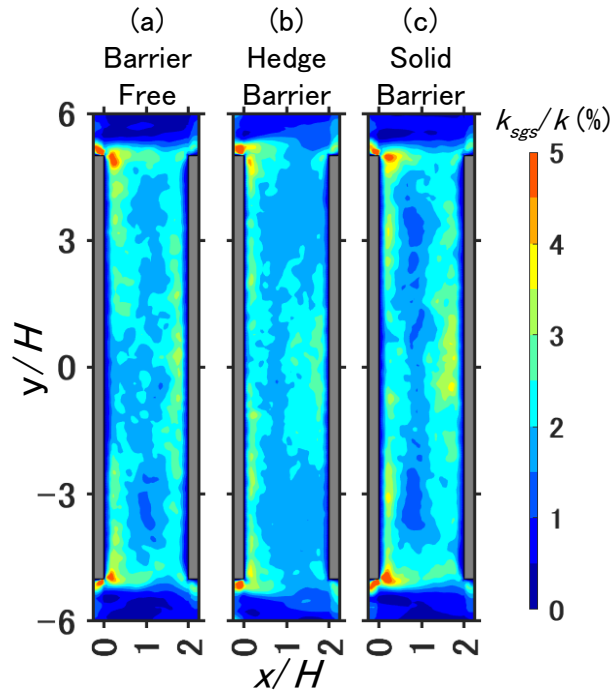
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832 Fig. A3. Distributions of the time-averaged streamlines and concentration C in the vertical plane
 833 ($y/H=0$) with different grid resolutions. The wind direction was perpendicular to the street.

834

835 Furthermore, Fig. A3 compares the distributions of time-averaged streamlines and concentration
 836 C in the vertical plane ($y/H=0$) with different grid resolutions. For the barrier-free cases, no
 837 significant discrepancy was observed between the streamlines based on different grid resolutions.
 838 For the hedge barrier cases, the vortex center of the windward vortex based on the coarse grid
 839 was higher than those based on the other grid resolutions. For the solid barrier cases, although
 840 small discrepancies were observed between the vortex centers of the leeward vortices based on
 841 different grid resolutions, the time-averaged concentration based on the basic grid and the fine
 842 grid were close and larger than those based on the coarse grid.

843



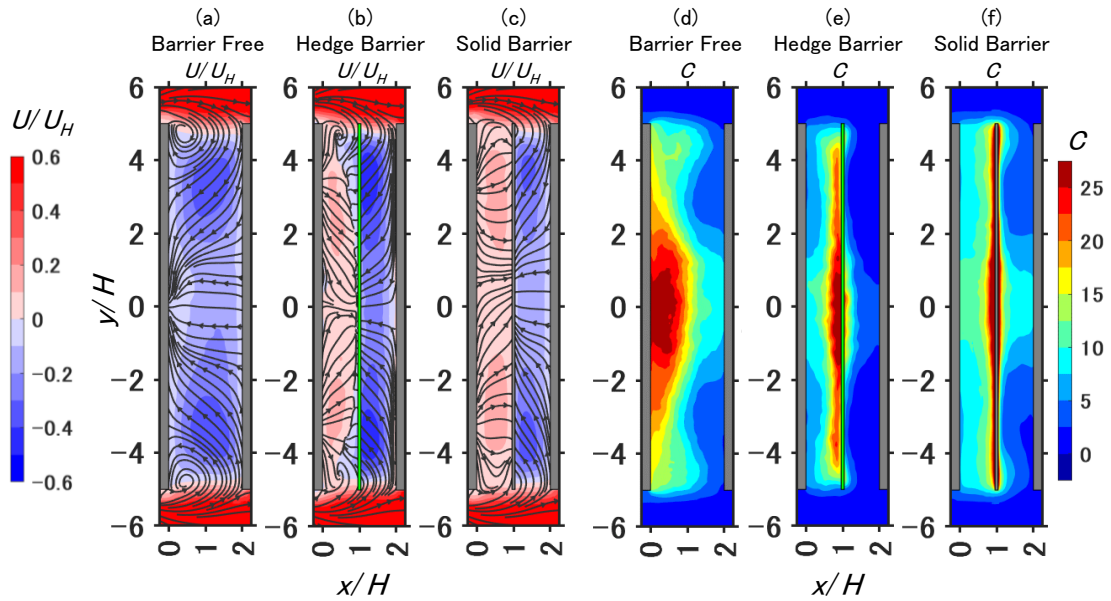
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845 Fig. A4. Distributions of the ratio of the time-averaged turbulent kinetic energy at the subgrid
 846 scale k_{sgs} and the time-averaged turbulent kinetic energy k at the resolved scale and the in the
 847 horizontal plane ($z/H=0.5$) based on the basic grid. The wind direction was perpendicular (90
 848 degrees) to the street.

849

850 In addition, Fig. A4 shows the distributions of the ratio of the time-averaged turbulent kinetic
 851 energy at the subgrid scale k_{sgs} and the time-averaged turbulent kinetic energy k at the resolved
 852 scale and the in the horizontal plane ($z/H=0.5$) based on the basic grid. The turbulent kinetic
 853 energy at the subgrid scale was calculated based on the WALE model [32] and was time-averaged
 854 during the sampling duration. Over 95% of the time-averaged turbulent kinetic energy was
 855 resolved by the LES using the basic grid. Therefore, the basic grid was adopted for the following
 856 simulations.

857



859

860 Fig. B1. Distributions of the time-averaged streamlines, streamwise velocity U/U_H and
 861 concentration C in the horizontal plane ($z/H=0.08$). The wind direction was perpendicular (90
 862 degrees) to the street.

863

864 Fig. B1 shows the time-averaged streamlines, streamwise velocity and concentration in the whole
 865 horizontal plane ($z/H=0.08$) in the street canyon. The wind direction was perpendicular (90
 866 degrees) to the street. As the sampling time was sufficient, the distributions were almost
 867 symmetric in the y -direction. For simplicity, the simulation results under perpendicular wind
 868 direction in Section 3 were averaged at mirror-symmetric locations and only half-side results were
 869 presented.