Passive scalar diffusion in and above urban-like roughness under weakly stable and unstable thermal stratification conditions

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Abstract

Wind-tunnel experiments were conducted to investigate passive scalar diffusion behaviour in and above urban-like roughness under various thermal stratification conditions. Staggered arrays of rectangular blocks with aspect ratios of 0.96 or 1.92 were used to model the urban canopies. Weakly stable and unstable thermal stratification conditions were created by controlling the temperature of the wind-tunnel floor and the airflow. Above the modelled urban roughness, vertical profiles of the velocity and temperature were measured by a laser Doppler anemometer and a cold-wire thermometer, respectively. The estimated Obukhov length was found comparable or larger than the boundary-layer thickness, indicating very weak stratification. Passive-scalar diffusion was studied by emitting ethane gas from a point source on the wind-tunnel floor. Thermal stratification had substantial effect on diffusion even in the vicinity of the source where mechanical mixing by the model blocks was presumed to eliminate the stratification effect.

Keywords: Diffusion, Surface roughness, Thermal stratification, Urban canopy, Wind tunnel

1. Introduction

In urban air pollution problems, prediction of pollutant diffusion from emission sources is important. Many numerical models for diffusion prediction have been developed, but such models need to be validated against field or laboratory

5 data. In atmospheric diffusion, wind-tunnel experiments provide validation data
6 under controlled conditions.

7 In the real atmosphere, thermal stratification usually occurs and affects the
8 diffusion behaviour. Although mechanical mixing is considered to reduce the
9 stratification effect in urban geometries, many wind-tunnel experiments revealed
10 non-negligible effects of stratification. Representative studies are reviewed in the
11 following. Experiments over smooth surfaces with small values (much less than
12 the threshold 1-5 proposed by Robins 2003) of the roughness Reynolds number
13 are omitted.

14 Shirakata et al. (2002) used various vorticity generators and roughness ele-
15 ments to generate turbulence and stratification profiles that reproduced diffusion
16 behaviour observed in the field for the Pasquill–Meade stability classes (Pasquill
17 1961; Meade 1959). Hort and Robins (2002) studied diffusion from the top of
18 cylindrical tanks over a rough surface under neutral and stable stratification con-
19 ditions. Similarly, Yassin (2013) simulated diffusion from a stack on an isolated
20 building immersed in a boundary layer over a rough surface under neutral, stable,
21 and unstable stratification conditions. Robins et al (2001) studied the diffusion of
22 dense gas over a rough surface under stable stratification conditions. Their study
23 provided a more detailed characterization of the turbulence field than did other
24 studies involving diffusion. Uehara et al. (1997, 1998, 1999) studied recirculation
25 and diffusion in street canyons under neutral, stable, and unstable stratification
26 conditions. The street canyons they studied were not two-dimensional, but were
27 located between the walls of buildings on opposite sides of a corridor along an
28 inline array of simulated three-dimensional buildings. Xie et al. (2013) have re-
29 ported both numerical models and wind-tunnel results simulating the boundary
30 layer over arrays of buildings, but they provided little information about the wind-
31 tunnel experiments. Uehara et al. (2007) conducted simulations of diffusion from
32 line sources in a reduced-scale model of a real urban area under neutral, stable,
33 and unstable conditions, but their comparison with field observations was confined

to results under neutral stratification conditions. Yassin et al. (2005) conducted a similar investigation of diffusion from point sources under various stability conditions.

Field experiments using large modelled building arrays have been reported (Inagaki and Kanda 2008, 2010; Yee and Biltoft 2004; Gailis and Hill 2006). However, the inevitable variability of meteorological conditions and the limited number of measurement locations have made it difficult to draw general conclusions.

This paper presents a wind-tunnel study of passive scalar diffusion from a ground source in modelled urban geometries under neutral, stable, and unstable ambient thermal stratification conditions. The ground-level emission assumes tail-pipe emission from road vehicles, especially hot spots at road crossings. The surface roughness is the same as in Kanda et al. (2011) except that their real-city models are replaced with arrays of parallelepiped blocks. Kanda et al. (2011) demonstrated that the results of wind-tunnel diffusion experiments and field monitoring agreed well for four different urban areas under neutral stratification condition. In effect, this paper adds to Kanda et al. (2011) thermal stratification as another parameter affecting diffusion.

2. Experimental methods

The experiments were conducted in the Atmospheric Diffusion Wind Tunnel at the National Institute for Environmental Studies in Japan (Fig. 1; Ogawa et al. 1981). The wind tunnel was of the closed-circuit type, with a test section 24 m long, 3.0 m wide, and about 2.2 m high. The wind speed U_0 at the test-section entrance was fixed at 1.5 m s^{-1} . A higher wind speed, such as $U_0 = 3.5 \text{ m s}^{-1}$ adopted by Kanda and Yamao (2011) (hereinafter denoted as KY), was desirable for the purpose of securing a fully turbulent boundary-layer flow, but to create distinctly different stratification conditions within the capacity of the wind tunnel, a lower speed was required. We note that the chosen wind speed of $U_0 = 1.5 \text{ m s}^{-1}$

ITEM

TYPE	SINGLE RETURN
CONTRACTION RATIO	5:1
<TEST SECTION>	
DIMENSION	3 ^m X (2 ~ 2.4) ^m (adjustable) X 24 ^m
WIND VELOCITY	0.2 (0.1) ~ 10.0 m/sec
FLOW TEMPERATURE	32 (15) ~ 87 °C
FLOOR TEMPERATURE	7 ~ 112 °C
<FAN>	
TYPE	SINGLE STAGE AXIAL FLOW FAN
DIAMETER	2.2 m
SPEED	max 770 rpm
RATED MOTOR POWER	90 kW

Figure 1: Overview of the wind tunnel. The test-section size is 24 m long, 3.0 m wide, and about 2.2 m high. The seeding particles for the laser Doppler anemometry were generated at “A” for the neutral and unstable cases, and at “B” for the stable cases. A higher-resolution figure can be found in Ogawa et al. (1981).

62 was a little above a threshold U_0 of 1.0 m s^{-1} , below which the time-averaged
63 properties of the wake flow behind a two-dimensional hill model (63° slope angle)
64 depended on U_0 under neutral stratification conditions (Kanda et al. 2013). As
65 described in KY, the downwind acceleration of the flow due to the boundary-layer
66 growth was expected to have negligible effect on the experimental results. The
67 coordinates (x, y, z) were defined such that x was the windward coordinate with its
68 origin at the source described later in this section, y was the horizontal crosswind
69 coordinate with its origin at the centre line of the wind tunnel, and z was the
70 vertical coordinate with its origin at floor level.

71 Thermal stratification was created by controlling the temperature of the recir-
72 culating air and that of the 3×3 -m floor panels in the test section. The temperature
73 T_∞ of the recirculating air was measured at the mid-height of the test-section en-
74 trance, and the temperatures T_f of the floor panels were measured at 6 evenly
75 spaced points on each panel by thermocouples embedded immediately below the
76 top surface of the panel. In the cases of unstable stratification, the floor panels
77 were heated to 40°C and the recirculating air was maintained at 15°C . In the cases
78 of stable stratification, the floor panels were cooled to 15°C and the recirculat-
79 ing air was heated to 40°C . The upper temperature 40°C was chosen so that the
80 secondary circulation induced by the temperature difference on the walls and the
81 ceiling was negligibly weak and the glycerine mist for the velocity measurement
82 did not evaporate while flowing through the heat exchanger in the underground
83 section of the wind tunnel. The neutral cases were conducted in the winter, and
84 the air-conditioning of the wind-tunnel building maintained both the floor pan-
85 els and the recirculating air at 16°C . On both sides of the test section, outer 1-m
86 tall and inner 0.45-m tall partitions were installed to isolate the experimental area
87 from the secondary circulation (Ogawa et al. 1981). The effective width of the
88 test-section between the inner partitions was therefore about 1.8 m. Because the
89 width was only twice as large as the boundary-layer thickness, there could have
90 been some crosswind variation in the flow properties.

Table 1: Experimental conditions and parameter values. The bulk Richardson number Ri_b is defined by $Ri_b = 19.6(T_\infty - T_f)\delta/(T_\infty + T_f)U_\infty^2$.

stability	Stable		Neutral		Unstable	
T_∞ (°C)	40		16		15	
T_f (°C)	15		16		40	
δ (m)	0.6–0.7		0.8–0.9		0.8–0.9	
H (mm)	48	96	48	96	48	96
U_∞ (m s ⁻¹)	1.60	1.64	1.59	1.62	1.58	1.61
u_* (m s ⁻¹)	0.070	0.090	0.104	0.116	0.128	0.146
u_*/U_∞	0.044	0.055	0.065	0.072	0.081	0.091
T_* (K)	0.54	0.47	–	–	-0.86	-0.59
L_{OB} (m)	0.7	1.4	–	–	-1.4	-2.7
Ri_b (m)	2.3	2.2	–	–	-3.0	-2.9
$\partial T/\partial z(z = H/2)$ (K m ⁻¹)	68	50	–	–	-29	-24

Two types of roughness elements were placed on the wind-tunnel floor, one in the upwind part and the other in the downwind part. The upwind roughness elements consisted of flat aluminium bars fitted with vertical rectangular plates (Fig. 2 in KY). The height h from the base of the bar to the top of the plates was either 20 or 40 mm. The bars were placed at 0.2-m intervals in the x direction, and the plates were placed in a staggered formation (the two rows of dashed lines toward the left edge of Fig. 2 represent the last two bars). In the following discussion, upwind roughness is denoted by the height in centimetres, i.e., h_2 and h_4 for roughness elements with a height h of 2 cm and 4 cm, respectively.

The downwind roughness element was an urban-canopy model consisting of rectangular wooden blocks with a square horizontal cross section, a horizontal side length L of 50 mm, and a height H of 48 or 96 mm. The number of test cases was six, as indicated in Table 1. For the 48-mm blocks, the upwind rough-

Figure 2: Plan view of the urban canopy model. The grey squares represent the blocks making up the canopy model. The long-dash lines upwind of the canopy model represent the vertical plates that are the roughness elements. The circled cross indicates the point where the vertical velocity profiles were measured. The open circle indicates the location of the source on the wind-tunnel floor. The plume concentration was measured at the crosswind sections indicated by the short-dash lines. L and D indicate the length of a block side and the length of a side of a lot containing one block, respectively.

ness was $h/2$, and for the 96-mm blocks, the upwind roughness was $h/4$. These combinations were associated with the least fetch required for adjustment of the turbulence properties after the roughness change investigated in KY. The plan area ratio λ_p was defined by

$$\lambda_p = \frac{L^2}{D^2}, \quad (1)$$

where D^2 (0.01 m^2) was the lot area per block. The value of λ_p was therefore 0.25. The wooden blocks were arranged in a staggered formation as shown in Fig. 2. The blocks were placed piece-by-piece on the wind-tunnel floor panels so that the floor panels whose temperatures were controlled to within $\pm 1^\circ\text{C}$ by the built-in water jacket, were exposed to the ambient air in places where there were no blocks. The blocks were laid on the previous day of each experimental run, and the thermal condition in the wind tunnel was made to stabilize for at least two hours after activating the heat exchange system and air flow. The surface temperature of

116 the blocks was not measured although the blocks were expected to have been in a
117 thermal equilibrium with the ambient air during the measurements. The roughness
118 Reynolds number Re_* based on the roughness length 3.4 mm estimated in KY was
119 larger than 15, and hence the flow over the roughness elements could be regarded
120 as sufficiently turbulent.

121 Immediately downwind of the test section entrance, a 0.18-m high castellated
122 fence and five 0.9-m high Counihan-type spires (Counihan 1969; Robins 1979)
123 were installed (Fig. 3). The large eddies generated by these elements increased the
124 thickness of the boundary layer to a little below the height of the spires. Because
125 the large eddies decayed slowly downwind, the boundary layer was inherently
126 in transition. Fully developed boundary layers could have been created without
127 the spires, but the spires were installed because one of the purposes of this study
128 was to characterize the turbulence field under similar geometrical and thermal
129 conditions to those employed in the previous studies conducted in the same wind
130 tunnel (Uehara et al. 1997, 1998, 1999, 2000, 2007; Kanda et al. 2011, 2013).

131 Although the spires were used to enhance the boundary-layer thickness, it
132 would still be a concern if the development distance to the test area was suffi-
133 cient particularly in the stable-stratification cases. Detailed downwind develop-
134 ment could not be measured in our study due to the limited stretch of the optical
135 fibers for the laser Doppler anemometry, but past studies support that our distance
136 ≈ 11 m was sufficient. In the meteorological wind tunnel at Colorado State Uni-
137 versity, Ohya et al. (1997) found that the streamwise homogeneity was achieved
138 approximately at 23.5 m from the entrance of the test section (1.8-m wide and 1.8-
139 m high) of which the floor was cooled from 12.2 m downwind of the entrance in
140 order to establish stable stratification comparable to or stronger than our cases. In
141 a different wind tunnel at Kyushu University, Ohya (2001) reported that boundary
142 layers were fully grown at 9 m from the entrance of the test section (1.5-m wide
143 and 1.2-m high).

144 The turbulent velocity field was measured with a three-channel laser Doppler

Figure 3: Wind-tunnel test section. (a) Side-view sketch. The vertical:horizontal scaling is 2:1. (b) Spires and fence. (c) Bird's-eye view from a downwind location.

145 anemometer (LDA) (Dantec Co., Ltd. in Denmark). Details of the measurement
 146 techniques are given in KY. The vertical profiles of velocity were measured at a
 147 point located a distance $3D$ downwind of the source (described later) and imme-
 148 diately behind a block (see Fig. 2). Profiles in the region upwind of the canopy
 149 model are presented in KY for the neutral cases but were not measured in this
 150 study for the stable and unstable cases. It should be noted that the alignment of
 151 the laser beams was adjusted every time a different thermal condition was set up
 152 to compensate for the distortion of the metal frame holding the laser heads. The
 153 components in the (x, y, z) direction of the mean and perturbation velocity are de-
 154 noted by (U, V, W) and (u, v, w) , respectively. The standard deviation of (u, v, w)
 155 is denoted by $(\sigma_u, \sigma_v, \sigma_w)$. Approximate uncertainty range of the mean velocity
 156 value was 0.05 m s^{-1} . The seeding particles were a mist of glycerine generated by
 157 evaporating liquid glycerine and circulating the condensed particles in the wind
 158 tunnel. This seeding method required a large volume of glycerine and risked
 159 damage to the ball bearings of the main fan, but enabled accurate measurement of
 160 velocity fluctuations of all the length scales existing in the wind tunnel. The lo-
 161 cation of mist generation was immediately downwind of the urban canopy model
 162 in the neutral and unstable cases (A in Fig. 1) and immediately downwind of the
 163 heat exchange unit in the stable cases (B in Fig. 1) to avoid total evaporation be-
 164 fore the mist reached the test section. In the stable cases, the glycerine evaporator
 165 was installed in the upper part of the wind-tunnel section ($5 \times 5 \text{ m}$) because the
 166 mist from the upper part of the underground section of the tunnel came around the
 167 wind-tunnel corners and filled the lower part of the test section on the upper floor.
 168 The bias behaviour was not a concern in the neutral and unstable cases because
 169 the glycerine mist went through the fan and a damper that mixed the air across the
 170 wind-tunnel section before it entered the heat exchange unit. Because the amount
 171 of glycerine required to fill the wind tunnel was fairly large due mainly to depo-
 172 sition on the large surface area especially in the heat exchangers (parts 23 and 24
 173 in Fig. 1) and partly to the relatively low sensitivity of our LDA system, the mesh

174 screens at the test-section entrance were covered with streaks of descending con-
175 densed glycerine after three consecutive vertical profile measurements. To prevent
176 additional turbulence generation and non-uniformity in the airflow, the glycerine
177 deposited in the wind tunnel was evaporated by heating the recirculating air to
178 90°C and was discharged through a ventilation pump for several hours after two
179 vertical profile measurements. Because of this procedure, only two vertical profile
180 measurements were possible per week.

181 Temperature was measured using a cold-wire probe (55P01, DISA, Denmark)
182 consisting of a platinum-plated tungsten wire with a diameter of 5 μm and a length
183 of 3 mm. The wire was placed parallel to the wind about 5 mm downwind of the
184 cross volume of the LDA laser beams. The electric resistance of the wire was
185 calibrated offline against the reading of a quartz thermometer (DMT-624, Tokyo
186 Denpa Co., Ltd., Japan) at various values of the mainstream temperature. The
187 sampling frequency was fixed at 200 Hz. The mean, perturbation, and standard
188 deviation of temperature are denoted by T , θ , and σ_θ , respectively.

189 The turbulent vertical heat flux $\overline{w\theta}$ was calculated by taking into account the
190 separation Δl of 5 mm between the cross volume of the LDA laser beams and the
191 cold-wire probe. Based on the frozen turbulence hypothesis, $\overline{w\theta}$ was defined as
192 the maximum value of $\overline{w(t)\theta(t + \tau)}$ as the delay τ was varied by small steps. The
193 delay τ giving the maximum of $\overline{w(t)\theta(t + \tau)}$ was found to be approximately the
194 same as $\Delta l/U$.

195 For the diffusion experiments, ethane diluted by nitrogen was emitted from a
196 hole 13 mm in diameter that was located on the floor of the wind tunnel 12.3 m
197 downwind of the test-section entrance and 0.975 m downwind of the upwind edge
198 of the urban canopy model. The origin of x was defined as the centre of this hole.
199 The hole was filled with glass beads and then covered with a stainless steel mesh
200 to prevent interference with the airflow above it. The glass beads also enhanced
201 heat exchange between the ethane and the floor panel. The emission flow rate Q_v
202 of the diluted ethane was $3.33 \times 10^{-6} \text{ m}^3 \text{ s}^{-1}$ (0.2 L min^{-1}), equivalent to a vertical

203 velocity of 0.025 m s^{-1} at the exit of the hole. The dilution ratio r and the emission
204 rate $Q = rQ_v$ of ethane were chosen to keep the concentration within the dynamic
205 range of the hydrocarbon detector.

206 The concentration of ethane in the region downwind from the source was mea-
207 sured by drawing air through a sampling rake to a flame ionization detector (FID,
208 Kimoto Electric Co., Ltd. in Japan) calibrated using standard gas. The dashed
209 lines in Fig. 2 indicate the x positions where the yz -section of the concentration
210 field was measured. At each rake position, measurement was continued until the
211 accumulated average became nearly constant. The sampling rate was 1 Hz, and
212 the typical measurement time was 5 min. More details of the concentration mea-
213 surement technique are given in KY.

214 3. Velocity and temperature field

215 3.1. Mean quantities

216 Figure 4 shows the vertical profiles of U and T . Inside the canopy ($z < H$), U
217 was approximately zero for all the conditions, the indication being that the mea-
218 surement point was in the wake region of a block with very weak mean flow. The
219 value of U increased rapidly near the canopy top, and then followed a logarithmic-
220 like relation up to approximately the middle of the boundary layer. The boundary-
221 layer thickness δ , defined as the height where U reached about 98% of the ambient
222 value of U_∞ listed in Table 1, was about 0.6–0.7 m in the stable and neutral cases
223 and 0.8–0.9 m in the unstable cases. Because determination of δ was not a major
224 concern in our study and also because of the limitation of duration of the mea-
225 surement mentioned previously, the measurement interval at large z was a rather
226 coarse 0.1 m and the resolution of δ was low.

227 The mean temperature T was normalized as $(T - T_f)/\Delta T$, where $\Delta T = 25^\circ\text{C}$
228 was the temperature difference between the wind-tunnel floor and the inlet air. The
229 temperature changed rapidly near the canopy top, and then followed a logarithmic-

230 like relation. Inside the canopy, thermal stratification existed just as it did above
231 the canopy.

232 We do not present further analysis on the profiles of U and T particularly in
233 the region where they appeared to exhibit logarithmic-like relations because our
234 measurements were limited to a single horizontal point in and above modelled
235 urban canopy where considerable horizontal inhomogeneity has been known to
236 exist (Cheng and Castro 2002).

237 3.2. *Turbulent fluctuations and fluxes*

238 Figure 5 shows the vertical profiles of the standard deviations (velocity fluctu-
239 ations) σ_u , σ_v , and σ_w . The velocity fluctuations were scaled by U_∞ rather than by
240 the more physically relevant friction velocity u_* because determination of u_* could
241 have large uncertainties. We clearly observed the velocity fluctuations increase as
242 the stratification changed from stable to neutral to unstable.

243 Figure 6 shows the vertical profiles of σ_θ , the Reynolds stress $\overline{uw}$, and the
244 turbulent heat flux $\overline{w\theta}$. As was the case with velocity fluctuations, σ_θ was larger
245 for unstable stratification than for stable stratification.

246 The Reynolds stress $\overline{uw}$ was small inside the canopy, but became abruptly very
247 negative at the canopy top. Above the canopy, there was a constant-stress layer
248 where the magnitude of $\overline{uw}$ was approximately constant. The magnitude of $\overline{uw}$ in
249 the constant-stress layer became larger as the stratification changed from stable to
250 neutral to unstable and also as the canopy height H became larger. The thickness
251 of the constant-stress layer became larger as the stratification changed from stable
252 to neutral to unstable, but the top height of the layer appeared to be unaffected by
253 the change in H .

254 The heat flux $\overline{w\theta}$ was negative, zero, and positive for stable, neutral, and un-
255 stable stratification, respectively, with some exceptions inside the canopy. We
256 could not determine if the exceptions were evidence of genuine tendencies or
257 were merely experimental errors. The magnitude of $\overline{w\theta}$ was relatively small in-

(a-1)

(a-2)

(b-1)

(b-2)

Figure 4: Vertical profiles of (a) the mean streamwise velocity U and (b) the mean temperature T . The sub-labels 1 and 2 denote canopy heights $H = 48$ mm and $H = 96$ mm, respectively. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively. The horizontal dotted lines indicate the canopy top $z = H$.

Figure 5: Vertical profiles of standard deviations of velocity components: (a) σ_u , (b) σ_v , and (c) σ_w . Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively. The horizontal dotted lines indicate the canopy top $z = H$.

Figure 6: Vertical profiles of (a) standard deviation σ_θ of temperature, (b) momentum flux $\overline{uw}$, and (c) heat flux $\overline{w\theta}$. Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively.

side the canopy for both stable and unstable cases. Because heat flux must be continuous across the canopy top, there should be locations with relatively large $\overline{w\theta}$ inside the canopy so that the horizontally averaged heat flux matches at the canopy top. For the stable stratification, $\overline{w\theta}$ was approximately constant in the constant-stress layer, but for unstable stratification, $\overline{w\theta}$ increased up to $z/L \approx 10$ and decreased rapidly above that height. For experiments without spires and a fence at the test-section entrance, it is known that $\overline{w\theta}$ decreases monotonically with z under unstable stratification conditions (e.g., Nagata et al. 2011). We considered the increase of $\overline{w\theta}$ for $z/L \lesssim 10$ under unstable stratification conditions to have been caused by the larger energetic eddies generated by the spires and fence, whereas for the stable stratification, large eddies were suppressed. Finally, there appeared to be negligible dependence of $\overline{w\theta}$ on H .

Fluctuations σ_u , σ_v , σ_w , and σ_θ were compared with field observation results in the surface atmospheric boundary layer summarized in Stull (1988). For the comparison, scaling parameters were defined as follows.

$$u_* = \sqrt{-\overline{uw}_{CS}}, \quad (2)$$

$$T_* = -\frac{\overline{w\theta}_{CS}}{u_*}, \quad (3)$$

$$L_{OB} = -\frac{T u_*^3}{g \kappa \overline{w\theta}_{CS}}, \quad (4)$$

where the subscript ‘CS’ denotes the constant-stress layer and L_{OB} is the Obukhov length. Tables 1 and 2 list the values of the scaling parameters and the scaled fluctuations. We observe that the values of L_{OB} are comparable or larger than δ , indicating very weak thermal stratification.

In field observations, the Obukhov length L_{OB} was used in the following similarity relations for the convective boundary layer (Stull 1988).

$$\sigma_w/u_* = 1.9 (-z/L_{OB})^{1/3}, \quad (5)$$

$$\sigma_\theta/T_* = -0.95 (-z/L_{OB})^{-1/3}. \quad (6)$$

Table 2: Scaling quantities based on the flux measurements, and scaled variances in the constant-stress layer. The values of z indicate the measurement heights considered representative of the constant-stress layer. In the case of stable stratification and $H = 96$ mm, the values were averages at $z = 130$ mm and $z = 180$ mm. The horizontal wind speed fluctuation σ_h was defined by $\sigma_h = (\sigma_u^2 + \sigma_v^2)^{1/2}$. Columns ‘Stull’ represent values of the similarity relations in the surface atmospheric boundary layer summarized in Stull (1988), recapitulated here as Eqs. 5 and 6.

stability	Stable			Neutral			Unstable			
H (mm)	48	96	Stull	48	96	Stull	48	Stul	96	Stull
L_{OB}	0.7	1.4					-1.4		-2.7	
z (mm)	100	130/180		100	180		140		180	
σ_u/u_*	1.93	1.95	2.4	2.06	2.02	2.5	1.91		1.92	
σ_v/u_*	1.51	1.58	1.6 ^{a)}	1.45	1.59	1.7–2.5	1.50		1.62	
σ_h/u_*	2.45	2.51	2.9	2.52	2.57	2.9				
σ_w/u_*	1.26	1.26	1.6	1.18	1.28	1.0–1.6	1.18	0.8	1.20	0.9
σ_θ/T_*	1.92	1.95	2.0	–	–	–	-1.86	-2.0	-2.20	-2.3

a) calculated as $\sqrt{\sigma_h^2 - \sigma_u^2}/u_*$

274 As shown in Table 2, most of the fluctuations in our experiments were smaller
 275 than those obtained by Eqs. 5 and 6 except for σ_w for the unstable cases which
 276 were higher, and σ_w for the neutral cases for which the experimental values were
 277 within the wide range of the field results.

278 For the unstable cases, convective velocity scale w_* defined by

$$w_* = \left(\frac{g}{T} \overline{w\theta}_{cs} \delta \right)^{1/3}, \quad (7)$$

279 may be of interest. Assuming $\delta = 0.85$ m, we found $w_*/u_* = 1.14$ and 0.92
 280 for $H = 48$ mm and $H = 96$ mm, respectively. These values are considerably
 281 smaller than the threshold 2.9 (Fedorovich 2004) for the distinction between shear
 282 and shear-free convection. Therefore, the established unstable stratification was
 283 confirmed again to be very weak.

284 3.3. Integral length scales

285 Integral length scales represent the sizes of turbulent eddies. Under Taylor's
 286 frozen turbulence hypothesis, an Eulerian integral length scale L_i^x is defined by

$$L_i^x = U(z)T_i^x = U(z) \int_0^\infty \rho_i(z, \tau) d\tau, \quad (8)$$

287 where the subscript i denotes the velocity component u , v , or w , where T_i^x is the
 288 Eulerian integral time scale, and where the auto-correlation $\rho_i(z, \tau)$ is given by

$$\rho_i(z, \tau) = \frac{\overline{u_i(z, t + \tau)u_i(z, t)}}{\overline{u_i^2}}, \quad (9)$$

289 where u_i is either u , v or w . In the following, we omit z and consider a partial
 290 integral

$$I_i(\tau) = \int_0^\tau \rho_i(\tau') d\tau'. \quad (10)$$

291 We note that Taylor's hypothesis has been shown to fail for free-shear flows in
 292 many experiments (Pope 2000), and the length scale (8) should be distinguished
 293 from the proper one defined by the spatial correlation.

294 Ideally, T_i^x should be obtained as the limiting value of $I_i(\tau)$ as τ becomes large.
 295 However, the measured $I_i(\tau)$ did not always behave as a function approaching a
 296 constant value for two reasons: (1) the uncertainty of $\rho_i(\tau)$ at large τ was large
 297 (equivalent to the uncertainty of the velocity spectrum at low frequencies), the
 298 result being irregular variations of $I_i(\tau)$ at large τ , and (2) $\rho_i(\tau)$ had a distinct
 299 negative lobe for $i = v$ and w at z sufficiently elevated from the top of the roughness
 300 elements, the result being a decrease of $I_i(\tau)$ after a maximum.

301 To determine T_i^x unambiguously, we adopted the following procedure. If $\rho_i(\tau)$
 302 had a distinct negative lobe (determined subjectively from the plot of $I_i(\tau)$), T_i^x
 303 was defined at the first zero of $\rho_i(\tau)$, i.e., at the maximum of $I_i(\tau)$. Otherwise, T_i^x
 304 was calculated as the average of $I_i(\tau)$ in an appropriate interval. This interval was
 305 determined as follows. First, an initial guess T_0 of T_i^x was defined as (see Pope
 306 2000)

$$T_0 = S_i(0)/4\overline{u_i^2}, \quad (11)$$

307 where $S_i(0)$ is the value at $f = 0$ of the one-sided power spectrum $S_i(f)$ of ve-
 308 locity fluctuation calculated by the maximum entropy method. Then, assuming
 309 an exponentially decaying form $\rho_i(\tau) = \exp(-\tau/T_0)$, an averaging interval $[\tau_0, \tau_1]$
 310 was set such that $\rho_i(\tau_0) = 0.01$ and $\rho_i(\tau_1) = 0.001$ where 0.01 and 0.001 could
 311 be any other set of sufficiently small numbers. Finally, the time scale T_i^x was
 312 calculated as the average of $I_i(\tau)$ in $[\tau_0, \tau_1]$, i.e.,

$$T_i^x = \frac{1}{\tau_1 - \tau_0} \int_{\tau_0}^{\tau_1} I(\tau) d\tau. \quad (12)$$

313 If we regard $\rho_i(\tau)$ ill-bahaved when $\rho_i(\tau)$ did not have a distinct negative lobe and
 314 the difference between T_0 and T_i^x was larger than 10%, ill-bahaved $\rho_i(\tau)$ often
 315 occurred in $z/H \gtrsim 2$ for the neutral and unstable cases and independent of z/H
 316 for the stable cases.

317 We note that repeating the above procedure with the right-hand side of Eq. 12
 318 as a new initial guess T_0 until the difference from T_0 becomes sufficiently small is

319 theoretically faulty. For example, if we assume an auto-correlation

$$\rho_i(\tau) = e^{-\tau/T_0} + \epsilon \xi(\tau), \quad (13)$$

320 where $\xi(\tau)$ is a random function with a small amplitude ϵ , then Eq. 12 becomes

$$T_i^x = 0.996T_0 + \epsilon \int_{2T_0 \ln 10}^{3T_0 \ln 10} \int_0^\tau \xi(\tau') d\tau' d\tau. \quad (14)$$

321 For a simple case of $\epsilon = 0$, Eq. 14 becomes $T_i^x = 0.996T_0$, quite acceptable con-
322 sidering the experimental errors. However, repetitive procedure implies solving

$$T_i^x = \frac{\epsilon}{0.004} \int_{2T_i^x \ln 10}^{3T_i^x \ln 10} \int_0^\tau \xi(\tau') d\tau' d\tau, \quad (15)$$

323 which is independent of the unperturbed auto-correlation $e^{-\tau/T_0}$. Hence, the repet-
324 itive procedure was not adopted.

325 Figure 7 shows the vertical profiles of L_u^x , L_v^x , and L_w^x . Co-plotted in Fig. 7 are
326 the integral length scales for the neutral-stability experiment with $U_0 = 3.5 \text{ m s}^{-1}$
327 and with the urban-canopy models replaced by the upwind roughness bars in KY:
328 the black and cyan markers indicate experiments with and without, respectively,
329 the spires and fence at the test-section entrance. We first note that, in the neutral
330 cases, the maximum values of L_u^x were much larger ($L_u^x \approx 1.1\delta$) than those ($L_u^x \approx$
331 0.3δ) reported in previous studies (e.g., Robins 1979; Shirakata et al. 2002). As
332 is apparent from the difference between the blue and black markers in Fig. 7,
333 the large L_u^x maxima were caused by the spires and fence. However, because
334 the previous studies reporting $L_u^x \approx 0.3\delta$ also installed spires, the large L_u^x of
335 our results can be attributed to the particular geometry of our spires, which rather
336 excessively generated large energetic eddies of a size comparable to the boundary-
337 layer height. In a preliminary experiment with smoke visualization, such large
338 eddies were actually observed behind the spires. Although the spire shape and
339 configuration were similar to those employed in Counihan (1969), the large height
340 (0.9 m) compared to $\delta = 0.7\text{-}0.8 \text{ m}$ at the measurement location or geometrical
341 errors due to the polystyrene body and the steel angle bars (see Fig. 3) could have

Figure 7: Vertical profiles of integral length scales: (a) L_u^x , (b) L_v^x , and (c) L_w^x . Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively. The black and cyan markers indicate the results in KY with and without, respectively, the spires and fence at the test-section entrance under roughness conditions where the upwind roughness bars (h2 for $H = 48$ mm, and h4 for $H = 96$ mm) extend into the region of urban-canopy models.

caused the large eddies. It should be noted that, with a triangular spire rather than an elliptic-wedge spire as employed in this study, Counihan (1969) found a conspicuous maximum of σ_u around the middle height of the boundary layer.

The integral length scales L_i^x increased as stratification changed from stable to neutral to unstable. Above the canopy top, L_i^x increased monotonically with z for all the components of the stable cases and for the v and w components of the neutral cases, but L_i^x had maxima for all the components of the unstable cases and for the u component of the neutral cases although the scatter of the data was large. The large scatter when the L_u^x values are large was probably due to the measurement duration, which was not sufficiently long to reflect the long correlation time of the eddies with large L_u^x .

Particularly noteworthy were the very large maxima of the v and w components for the unstable stratification case. The difference from the neutral cases for these components was much larger than was the case for the u component, which was predominantly controlled by the vorticity generated by the spires and fence. The locations and magnitudes of the maxima represented the locations and sizes of the turbulent eddies that were generated by both mechanical and convective forcings. Also, the difference of L_i^x ($i = u, v$) due to the canopy height H was substantially large (large differences in the overall magnitude, and in locations and magnitudes of the maxima) for the unstable stratification conditions, whereas the differences for neutral and stable stratification were relatively small (small difference in the profile shape and the overall magnitude). Hence, the morphology of the turbulent eddies was sensitive to the canopy geometry when convective forcing contributed to their generation.

4. Concentration Field

We examined the turbulent diffusion of a passive scalar in the presence of the urban canopy. In KY, diffusion under neutral stratification was studied by focusing on the effect of surface roughness conditions upwind of the urban canopy

models. It was found that the concentration field near the source (x less than a few multiples of L) was little affected by the upwind roughness condition if the upwind fetch (distance between the upwind edge of the urban-canopy model and the source at $x = 0$) was sufficiently large, but the concentration further downwind was affected considerably. The upwind fetch needed to eliminate the effect of the upwind roughness condition was much larger than that required for the adjustment of the second-order moments of turbulent velocity fluctuations. The upwind roughness bars h2 and h4 for the $H = 48$ mm and $H = 96$ mm urban-canopy blocks, respectively, employed in this study were found in KY to require the shortest fetch among the various bar heights tested for velocity field adjustment for each type of block, but the effect of the upwind roughness should appear in the concentration field at x greater than a few multiples of L . Hence, the results presented below should be viewed with this consideration in mind.

Figure 8 shows the concentration field in the yz -plane at $x = 2L$ and $18L$. To draw the contours, the measured values were interpolated onto a regular grid by the natural-neighbour interpolation method implemented in the ngmath library (<http://ngwww.ucar.edu/ngmath/>) of the NCL/NCAR Graphics package (NCAR 2012). The labelled values are a normalized concentration C_n defined by

$$C_n = \frac{CU_\infty L^2}{Q}, \quad (16)$$

where C is the measured raw concentration in the volume mixing ratio. The fact that the spread of the plume became larger with H and as the stratification changed from stable to neutral to unstable was consistent with the change of the relevant velocity fluctuations σ_v and σ_w (see Fig. 5). The axis of the plume deviated to negative y for stable stratification. The deviation was due to the asymmetry in the thermal and geometrical conditions of the large wind tunnel and occurred with smaller amplitude even for the neutral cases of KY. In preliminary experiments, the magnitude of the deviation was found to become larger for larger ΔT . Because the deviations were always in the opposite directions for stable and unstable

Figure 8: Contours of the normalized concentration C_n of ethane at two positions (x): lower panel $x = 2L$ (contour interval 0.3) and upper panel $x = 18L$ (contour interval 0.02). Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The stratification is (a) stable, (b) neutral, and (c) unstable.

cases with respect to the neutral cases, we suspect that secondary circulations that could not be removed completely by the installed internal walls were the cause of the deviations. This is one of the reasons why we restricted our experiments to relatively weak stratification.

Figure 9 shows the vertical profiles of C_n at the centerline $y = 0$. At $x = 2L$, for all the conditions, C_n had a maximum at a little below the model half height. This in-canopy peak appeared to persist to $x = 4L$, $4L$, and $8L$ for unstable, neutral, and stable conditions, respectively, for $H = 48$ mm (Fig. 9a), and to $x = 2L$, $8L$, and $12L$ for unstable, neutral, and stable conditions, respectively, for $H = 96$ mm (Fig. 9b). The persistence of the peak for the stable stratification implies suppressed vertical mixing below the model height. Difference due to the canopy height could not be deduced confidently with the vertical resolution of our measurement.

The crosswind profiles of C_n at $z = 0.1L$ and $x = L$ or $2L$ are shown in Fig. 10. The thick horizontal lines indicate the locations of the blocks immediately upwind of the measurement line. At $x = L$, C_n was almost uniform in $|y| < 1.5L$ because the block immediately downwind of the source mixed the tracer gas efficiently. Asymmetry about $y = 0$ was observed clearly under the stable stratification condition even in the near-source region. At $x = 2L$, channelling effect (e.g., Robins et al. 2002) could be observed; C_n was nearly uniform across an upwind opening and decayed stepwise across an upwind blockage.

The concentration field $C(y, z)$ in the yz -plane at each x was fitted to a modified standard form (Hunt and Weber 1979):

$$C = C_0 \exp \left[-\frac{(y - y_0)^2}{2\sigma_y^2} - \left(\frac{Az'}{\sigma_z} \right)^s \right], \quad (17)$$

where C_0 is the maximum concentration at the x of concern, $\sigma_y(x)$ and $\sigma_z(x)$ are the y - and z -direction plume widths, respectively, as functions of x , and y_0 is the y coordinate of the plume axis. The modified vertical coordinate z' was introduced

Figure 9: Vertical (z) profiles of the normalized concentration C_n for $H = 48$ mm (a) and 96 mm (b). The grey dashed lines indicate the canopy top. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively.

(a-1)

(a-2)

(b-1)

(b-2)

Figure 10: Crosswind (y) profiles of the normalized concentration C_n at $z = 0.1L$ and $x = L$ (a) or $x = 2L$ (b). The thick horizontal lines indicate the locations of the blocks immediately upwind of the measurement line. Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively.

423 here to account for the well-mixed canopy region

$$z' = \begin{cases} z - d & (z > d), \\ 0 & (z \leq d), \end{cases} \quad (18)$$

424 where d is a fitting parameter that is a result of both advection and diffusion inside
 425 the canopy, and is assumed to change with the downwind distance x . As mixing
 426 inside the canopy proceeds, d tended to H within experimental errors, which was
 427 reasonable considering the vigorous mixing in $z \leq H$. The coefficient A is defined
 428 as

$$A = [\Gamma(3/s)/\Gamma(1/s)]^{(1/2)}, \quad (19)$$

429 where Γ represents the gamma function defined by

$$\Gamma(s) = \int_0^\infty t^{s-1} e^{-t} dt. \quad (20)$$

430 For reasons discussed in KY, we set $s = 1.5$. Strictly speaking, the value of s is a
 431 function of stability, but it was assumed constant because the parameter determi-
 432 nation became less robust if s was set as another free parameter. The parameters
 433 C_0 , σ_y , σ_z , y_0 , and d were determined by the Nelder–Mead method. A large un-
 434 certainty in the determined parameters occurred for unstable stratification where
 435 the concentration field was skewed considerably as shown in Fig. 8. To reduce
 436 this uncertainty, the values of d determined for the neutral cases were adopted for
 437 non-neutral cases. Note that the parameter values determined in this way were
 438 not that different from those determined with d as an optimization parameter as to
 439 alter the qualitative features discussed below.

440 Figure 11 shows the downwind variation of C_0 for non-neutral cases. To pro-
 441 vide a comparison with the values for neutral stratification, C_0 was normalized
 442 as

$$\frac{C_0 U_H / Q}{C_{0,\text{neut}} U_{H,\text{neut}} / Q_{\text{neut}}}, \quad (21)$$

443 where U_H was the wind speed at the canopy top $z = H$, and the subscript ‘neut’
 444 denotes values for neutral stratification. For the shorter canopy with $H = 48$ mm,

Figure 11: Downwind evolution of the maximum concentration C_0 in the yz -plane relative to the value in the corresponding neutral case: (a) $H = 48$ mm, and (b) $H = 96$ mm. The blue and red markers indicate stable and unstable stratification, respectively.

the difference from neutral cases increases monotonically with the downwind distance x . This behaviour is consistent with the intuitive picture that the relative importance of thermal stratification is small in the vicinity of the source where the eddies generated by the canopy blocks have a dominant influence on diffusion, but becomes larger downwind as the plume grows beyond the size of individual blocks. However, for the taller canopy with $H = 96$ mm, the difference from the neutral cases did not depend much on the downwind distance. This result is contrary to intuition because mechanical mixing is considered to be more vigorous for the taller canopy. However, as shown in Fig. 5, turbulence intensity was actually smaller for the taller canopy due to more effective shear-sheltering. Also, the taller canopy blocks are expected to generate taller eddies that would be more susceptible to stratification.

Figure 12 shows the downwind growth behaviours of σ_y , σ_z , and d . As noted in the case of Fig. 8, the plume widths grew with x more rapidly as the stratification changed from stable to neutral to unstable. At $x = 2L$, the measurement line immediately downwind of the source, the changes of σ_y and σ_z due to the strati-

Figure 12: Downwind growth of the plume widths (a) σ_y and (b) σ_z and d (b). Columns 1 and 2 denote canopy heights H of 48 mm and 96 mm, respectively. The grey markers in (b) represent d/L . The blue, green, and red markers indicate stable, neutral, and unstable stratification, respectively.

Table 3: Briggs formulas for plume widths over urban roughness.

Stability class	σ_y (m)	σ_z (m)
C	$0.22x(1 + 0.0004x)^{-1/2}$	$0.20x$
D	$0.16x(1 + 0.0004x)^{-1/2}$	$0.14x(1 + 0.0003x)^{-1/2}$
E-F	$0.11x(1 + 0.0004x)^{-1/2}$	$0.08x(1 + 0.0015x)^{-1/2}$

461 fication condition were small because vigorous turbulent mixing inside the urban
462 canopy reduced the effect of thermal stratification. We observed that the changes
463 of σ_y and σ_z at $x = 2L$ became larger for $H = 96$ mm than for $H = 48$ mm, a
464 result consistent with the explanation of the results in Fig. 11.

465 We observed that stable stratification affected mainly σ_y , but had smaller effect
466 on σ_z . It is worthwhile to compare our results with the Briggs formulas (Briggs
467 1973) representing field experiments over urban roughness. Table 3 lists the for-
468 mulas for the Pasquill–Gifford stability classes C (weakly unstable), D (neutral),
469 and E-F (weakly to moderately stable). In these formulas, change in stratifica-
470 tion from neutral to stable at relatively small x , where the power-law term can be
471 regarded as unity, had more effect on σ_z (43% reduction) than on σ_y (31% reduc-
472 tion). Similarly, for the change from neutral to unstable stratification, the change
473 of σ_z (43% increase) was larger than the change of σ_y (25% increase). Because
474 in an open space without considerable blockage, such as urban canopy, thermal
475 stratification should affect primarily vertical motions, it is reasonable that the rela-
476 tive change in σ_z was larger than the change in σ_y . In our experiments, the relative
477 difference in the magnitudes of σ_w between stable and neutral conditions (Fig. 5c)
478 was comparable to the relative difference in the magnitudes of σ_v (Fig. 5b). Also,
479 the relative difference in the magnitudes of L_w^x between stable and neutral con-
480 ditions (Fig. 7c) was comparable to the relative difference in the magnitudes of
481 L_v^x (Fig. 7b). Therefore, our result that the growth rate of σ_z for stable stratifica-
482 tion was so close to that for neutral stratification cannot be explained readily by

483 conventional knowledge. Note that, in preliminary experiments with the urban-
 484 canopy models replaced with the upwind roughness elements, we had observed a
 485 distinct difference in the growth rates of σ_z between stable and neutral stratifica-
 486 tion conditions. Note that these preliminary experiments were conducted in the
 487 presence of considerable secondary circulation because the temperature difference
 488 ΔT was large. Whether our current result was due to experimental errors or was
 489 caused by some mechanism peculiar to stable stratification cannot be determined
 490 with the available experimental data. Further investigation will be necessary to
 491 elucidate the cause of this behaviour.

492 Additional aspect of the diffusion behaviour can be examined in terms of the
 493 vertical entrainment velocity w_e defined by

$$w_e = \frac{d}{dx} \left(\frac{Q}{\sqrt{2\pi}\sigma_y C_0} \right). \quad (22)$$

494 By analysis of diffusion experiments (quasi-two-dimensional geometry using line
 495 sources) in three different wind tunnels under neutral stratification conditions with
 496 rough surfaces, Britter et al. (2003) found

$$w_e = \alpha_E u_{*}, \quad (23)$$

497 where the entrainment coefficient α_E was 0.65 ± 0.05 . It should be noted that,
 498 in the analysed three wind-tunnel studies (Robins et al. 2001a; Havens et al.
 499 2001; Snyder 2001), the zero-plane displacement was assumed zero because the
 500 roughness elements had negligible horizontal section area (small λ_p). Britter et al.
 501 (2003) also deduced $\alpha_E = 0.63 \pm 0.05$ for the near-neutral conditions of the Prairie
 502 Grass field experiment. In our experiments with three-dimensional plumes, it was
 503 found that $1/\sigma_y C_0$ changed linearly with x in $x \geq 12L$. Table 4 lists the values
 504 of α_E obtained as the slope of $Q/\sqrt{2\pi}\sigma_y C_0$ against x in $x \geq 12L$. For the stable
 505 and neutral stratification conditions, the values of α_E were found to be smaller
 506 than those reported by Britter et al. (2003). The small difference in α_E between
 507 stable and neutral conditions in contrast to the much larger value for the unstable

Table 4: Vertical entrainment velocity

stability	Stable		Neutral		Unstable	
H (mm)	48	96	48	96	48	96
w_e (m s ⁻¹)	0.044	0.055	0.061	0.071	0.115	0.159
w_e/u_*	0.49	0.46	0.47	0.45	0.75	0.90

condition is an alternative expression of the diffusion behaviour discussed in the previous paragraph.

5. Summary and discussions

An urban geometry was simulated in a wind tunnel using staggered arrays of parallelepiped blocks. By controlling the temperature of the recirculating air and the test-section floor, weakly stable and unstable stratification conditions were established such that the Obukhov length was larger than the boundary-layer thickness. Vertical profiles of the velocity components and temperature were measured at a point in the lee of a block using laser-Doppler anemometry and a cold-wire thermometer. Despite the weak stratification, velocity and temperature fluctuations were found to be sensitive to stratification. Passive-scalar diffusion from the wind-tunnel floor was studied using ethane as a tracer gas. Even in the proximity of the source, where diffusion occurred mostly in the urban-canopy region, the spread of the tracer-gas plume was found to be highly dependent on the degree of stratification.

The important features of our study are: (i) stable, neutral, and unstable stratification was realized in the same urban-canopy geometry, (ii) the seeding particles for the LDA measurement were dispersed as uniformly as possible, and (iii) the tracer gas for the diffusion study was emitted from the wind-tunnel floor. The first aspect (i) has been realized in the past for a single-block (Yassin 2013) or hill geometry (Ohba et al. 2002), but not for an urban-canopy geometry. The reason is

529 probably that laying hundreds of blocks on a bare wind-tunnel floor is a laborious
530 task. We emphasize that we still used simpler roughness elements in the upwind
531 region of the urban-canopy models. As mentioned in Section 4, insufficient adjust-
532 ment of the velocity field across the roughness change could have non-negligible
533 effects on the diffusion behavior. Numerical studies such as Boppana et al. (2014)
534 would be a viable approach to this problem.

535 The second aspect (ii) is essential to make correct measurements. In prelimi-
536 nary experiments, we once introduced seeding particles from a perforated vertical
537 pipe located a little downwind of the spires. When compared with the measure-
538 ment data using this paper's method of seeding, the velocity fluctuation was con-
539 siderably smaller because the narrow and non-uniform seeding could not capture
540 the large-scale eddies. As for the third aspect (iii), we note that a similar experi-
541 ment on a smooth surface would not be appropriate because the emission velocity
542 would be comparable to or larger than the velocity of the airflow near the source.
543 In our experiments, velocity mismatch near the source did exist, but vigorous
544 mechanical mixing in the canopy region rapidly spreads the tracer gas and the
545 velocity mismatch had a negligible effect as described in KY.

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