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1	The drag force distribution within regular arrays of cubes and its
2	relation to cross ventilation – theoretical and experimental analyses
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15	
16	Abstract
17	A novel set of wind tunnel measurements of the drag force and its spatial distribution
18	along aligned arrays of cubes of height H and planar area index λ_p (air gap between
19	cubes) equal to 0.028 (5H) to 0.69 (0.2H) is presented and analysed. Two different
20	types of measurements are compared: one type where the drag force is obtained using
21	the standard load cell method, another type where the drag force is estimated by
22	measuring the pressure difference between windward and the leeward façades. Results
23	show that the drag force is nearly uniformly distributed for lower λ_p (0.028 and 0.0625),
24	it decreases up to 50% at the second row for $\lambda_p=0.11$, and it sharply decreases for larger
25	λ_p (from 0.25 to 0.69) where the force mostly acts on the first row. It follows that for the
26	lowest λ_p the drag force typically formulated as a drag area corresponds to the total
27	frontal area of the array, whereas for large λ_p the drag area corresponds to the area of the
28	first row. By assessing the driving pressure for ventilation from the drag force, the
29	analysis is extended to estimate the cross ventilation as an example of application of this
30	type of measurements.
31	

32 **Keywords:** drag distribution; standard load cell; cubic building arrays; drag area;

33 interference factor; cross ventilation

34

35 **1. Introduction**

Several studies of the modification of the flow due to an array of obstacles exposed to a boundary layer flow have been carried out in the past. These studies can be broadly subdivided into two main categories. One category is based on the classical fluid mechanical approach where the focus is on the evolution of the approaching velocity profile when passing through the array. Usually the array is long enough that an equilibrium is established. An excellent recent example of this approach is given by Thomas et al. (2017), where references to similar studies are provided.

The other category is where the main concern is the ventilation of the array taking 43 into account individual buildings. In this case the focus is on understanding how both 44 the whole array interacts with the approaching wind and how the individual buildings 45 interact with the airflow through the array. The overarching goal of this paper is to 46 contribute to this understanding. This paper is essentially a continuation of our previous 47 48 work (Buccolieri et al., 2017), where the total drag force was measured in a wind tunnel by using a standard load cell. The focus was to study the effect on the drag force of 49 different building packing density of an array consisting of buildings (represented by 50 cubes) of equal size and shape. A novel method for assessing the distribution of the drag 51 force was introduced by formulating the total drag force as a drag area and then 52 matching this area with the physical façade area of the buildings. One scope here is to 53 validate this method by directly measuring the distribution of the drag force within the 54 array using the same standard load cell method. To provide insight into the quality of 55 the measurements and confidence for the obtained results, the drag force is also 56 assessed by an independent method based on measurements of the surface pressure at 57 the windward and leeward façades of the buildings. 58

The results are analysed from the perspective that the introduction of an array in a given turbulent flow is a perturbation of a reference case which we have chosen to be the isolated cube. The introduction of new buildings to the reference case increases the resistance (drag) and less air (less flow rate) penetrates into the array compared to the reference case. Therefore it takes a longer time for the approaching air to pass through the array. This delay has been quantified by Antoniou et al. (2017) for a region within
Nicosia in Cyprus by predicting the mean age of air in the city. The delay has a
consequence for air quality because the local mean age of air is directly proportional to
the concentration in case of homogeneous emissions, see Eq.10 in Buccolieri et al.
(2010). Low flow rate penetrating into the array means that less flow available for
ventilation of the buildings.

The argument above helps clarifying that the drag is an important parameter linked to 70 both air quality within the array and ventilation potential available for buildings in a 71 given neighbourhood or city. There are several wind tunnel studies reporting on 72 pressure distribution measurements at building façades as well as estimate of the drag 73 force either pressure-derived or using a balance. Cheng and Castro (2002) and Cheng et 74 al. (2007) estimated the drag force on individual cubes within an array by calculating 75 the integral of the pressure difference between the front and the back façades of the 76 cube. Other studies, relevant to the field of wind load on structures, utilized pressure 77 78 measurements to evaluate the pressure distribution on individual buildings (Kim et al., 2012; Tecle et al., 2013). Zaki et al. (2011) employed surface pressure measurements of 79 80 the form drag on building arrays featured by both vertical and horizontal randomness as well as different packing densities demonstrating a significant effect of building height 81 variation on aerodynamic parameters when the planar area index is larger than 17%. Li 82 et al. (2015) confirmed the dependence of building shape and position within the array 83 on the drag coefficient by surface pressure measurements. A comprehensive dataset of 84 wind pressure for isolated low- and high-rise buildings, as well as for non-isolated low-85 rise buildings, is available from the Tokyo Polytechnic University (wind.arch.t-86

87 kougei.ac.jp/system/eng/contents/code/tpu).

Cheng et al. (2007), Hagishima et al. (2009) and Zaki et al. (2011) directly measured 88 the drag force using a balance. Cheng et al. (2007) showed that the drag force exerted 89 on cube arrays and derived from measured Reynolds stresses can be underestimated by 90 as much as 25% compared to drag directly measured using a balance. Hagishima et al. 91 (2009) measured the drag force directly by a designed floating raft in a wind tunnel to 92 investigate the aerodynamic effects of various building arrays showing that both wind 93 direction and the height non-uniformity of buildings affect aerodynamic parameters 94 significantly. 95

More recently, few studies have reported measurements of the drag force distribution 96 within building arrays, as done in this paper. Chen et al. (2017) used a standard load cell 97 within arrays consisting of buildings with both the same height and different heights. 98 From the recorded drag force the vertical transport by both advection and turbulence 99 expressed as an exchange velocity was predicted based on methods presented in 100 Bentham and Britter (2003) and in Hamlyn and Britter (2005). Li et al. (2018) reported 101 wind tunnel measurements of the drag distribution within irregular arrays consisting of 102 buildings of different shapes but with the same height. The drag force was estimated 103 from the pressure difference between the windward and leeward facades of the 104 buildings and directly by using floating rafts. They presented drag force distributions 105 and an extensive discussion of estimation of measurements errors and how to conduct 106 this type of measurements is presented. 107

In this context, the novelties of the present paper are briefly summarised:

- a comprehensive dataset of recorded drag force including both the total drag force of

the whole array (shown in Buccolieri et al., 2017) and the distribution of the drag force

within the array for a large span of building packing densities has been created. The

112 dataset includes also data obtained from pressure measurements at the wind- and

113 leeward façades of the buildings;

- original analyses are presented showing that an interference between buildings exists

and this needs to be quantified in the derivation of the drag force by introducing the

- wall to wall distance as interference parameter in addition to building area density;
- a further validation of the novel method presented in Buccolieri et al. (2017) for

assessing the drag force distribution starting from the drag force measurements of the
whole array is provided;

- an application of the potential usefulness of the dataset is provided by estimating the
 potential for wind-driven cross ventilation. It is shown that measuring the drag force is
 much simpler than measuring the pressure in several points.

123

124 **2. Description of wind tunnel experiments**

125 **2.1.** The physical models

Measurements were carried out in a closed-circuit boundary layer wind tunnel with a working section 11m long, 3m wide and 1.5m high at the University of Gävle (Sweden) (Fig. 1a). An isolated cube and seven aligned arrays of cubes of planar area index (ratio between the planar area of buildings and the lot area) λ_p from 0.028 to 0.69 were

130 considered. The cube height H was equal to 0.06m. The lot area was a square with a

side length of 13H(0.78m) (see Fig. 3a later in the text).

Drag force and pressure measurements were performed separately on one individual cube ("target cube" hereinafter) placed along the middle column of the array (Fig. 1b). Please note than when the number columns was even (as for example for λ_p =0.0625 in

the figure), the measurements were performed along one of the two columns

constituting the middle of the array. The target cube was kept fixed on the wind tunnel

137 floor while its position within the array was changed by moving the other cubes.

138 Initially the target cube was located in the first row. In the next step the cubes from the

last row were moved to the front so that the target cube was located in the second row

of the array. This procedure was repeated until the target cube was positioned in the lastrow of the array.

The employed geometries are the same as used in our previous paper (Buccolieri et al., 2017), i.e. the lot area was kept constant (the denominator in λ_p) and the number of cubes was increased to represent neighbourhoods of different λ_p . In this approach there may exist conditions where flow adjustment occurs and conditions where the flow is still evolving. These experiments intend to reproduce conditions in which the surrounding terrain is almost uniform and there is a considerable transition from a given roughness to a new roughness where the flow within the array may be still evolving.





Fig. 1 a) Sketch of the wind tunnel. b) Example arrays with planar area index λ_p =0.0625 and 0.25, with indication of air gap between cubes and the target cubes (roof s highlighted in grey) placed in the centre of the turntable along the centre of the arrays.

155 **2.2.** The boundary-layer flow

A boundary-layer (BL) flow in the wind tunnel was achieved considering two 156 different conditions for the fetch: (i) the entire fetch was covered with cubes of 0.04m 157 side length representing roughness elements ("BL roughness" hereinafter); (ii) the fetch 158 was smooth with no roughness elements ("BL no roughness" hereinafter). The distance 159 between the final row of roughness elements and the front of the lot area was 160 approximately 0.4m. The roughness area in the working section of the wind tunnel had 161 a total length of 8m made of spires in the first part and then of 0.04m cubes (roughness 162 elements). 163 The boundary layer thickness δ was about 0.15m (2.5H) in the "BL no roughness" 164

165 case and about 0.8m (13.3*H*) in the "BL roughness" case, as estimated by taking the

height at which the velocity was equal to 99% of the free stream velocity. The blockage

167 coefficient ($\Phi = A_{model, proj.} / A_{wind_tunnel}$, where $A_{model, proj.}$ [m²] is the projected area of the

168 cube along the main wind direction and A_{wind_tunnel} is the cross-sectional area of the

measurement section in the wind tunnel), was about 0.1% which fulfils the requirements
of the VDI 3783 guidelines (2004).

The experiments were performed with one reference wind velocity U(H) [ms⁻¹] at the 171 cube height H, corresponding to 500 revolutions per minute (rpm) of the fan that drove 172 the flow in the wind tunnel. The independence of the drag force on the reference 173 velocity was tested in the previous work (Buccolieri et al., 2017). The error is within 174 $\pm 5\%$ of the measured value. Undisturbed mean velocity and relative turbulence intensity 175 profiles approaching the array (which are in equilibrium with the roughness in the 176 fetch), both normalised by the corresponding value at H=0.06m up to z/H=2.5, are (Fig. 177 2): 178

179
$$\frac{U(z)}{U(H)} \approx \left(\frac{z}{H}\right)^{0.16}$$
 (1)

180
$$\frac{I(z)}{I(H)} \approx \left(\frac{z}{H}\right)^{-0.06}$$
 (BL roughness) (2)

181
$$\frac{I(z)}{I(H)} \approx \left(\frac{z}{H}\right)^{-0.46}$$
 (BL no roughness) (3)

182



183 184

Fig. 2 a) Boundary layer (BL) wind velocity (left) and relative turbulence intensity (right)
 incoming profiles in the wind tunnel for rpm = 500. The profiles have been fitted using power laws in Eqs. 1, 2 and 3.

The velocity was measured with a TSI hot-film anemometer in the middle of the empty circular disk where the target cube was attached (see subsection 2.3). The turbulence intensity was calculated as the standard deviation of the velocity fluctuations divided by the mean velocity. Tab. 1 summarizes the cases investigated.

- 192
- 193

194 **Table 1**

Summary of all test cases investigated in the wind tunnel. U(H), I(H) and Re are the incoming

mean flow velocity and turbulence intensity at building (cube) height H and the Reynolds number, respectively.

No. of cubes	λ_p	Air gap between buildings (in the transversal and longitudinal directions)	Centre to centre distance between buildings (in the transversal and longitudinal directions)
1	-	Isolated cube	
3x3	0.028	5H	6H
4x4	0.0625	3 <i>H</i>	4H
5x5	0.11	2 <i>H</i>	3 <i>H</i>
7x7	0.25	1H	2H
9x9	0.44	0.5H	1.5H
10x10	0.56	0.33H	1.33H
11x11	0.69	0.2 <i>H</i>	1.2H

 $U(H) \text{ [ms^{-1}]} - I(H) \text{ [\%]} - Re \text{ [-]}$

BL roughness	BL no roughness
5.2 - 27.6 - 20,800	9.5 - 7.1 - 38,000

Note: the Reynolds number, based on the height of the cube H and the incoming undisturbed
reference flow velocity U(H) at cube height H, is lower in the "BL roughness" case as a
consequence of the smaller U(H).

201

202 2.3. Drag force measurements

The drag force F_D (balance) acting on the individual target cube was directly 203 measured using the standard load cell method described in Buccolieri et al. (2017). 204 Specifically, the target cube was connected to the load cell via two thin rods that went 205 through a small opening in the turn table. There was an air gap of 1mm between the 206 cube and the turn table. The load cell was mounted on a stable tripod standing on the 207 floor of the laboratory hall (Fig. 3) so that the cube was mechanically isolated from the 208 wind tunnel and the measured force was only due to air resistance. To measure the drag 209 force distribution within the array, the force was singularly measured on the cubes 210 located along the centre of the array (along the wind direction). 211

In the standard load cell the horizontal force, caused by the air movement, was

transformed into vertical tensile and compressive force at its edges. Here it was Vetek

108AA with glued strain gauges (Vetek, 2016) which measured the forces and provided

an electrical output signal. The signal was then amplified through the Amplifier,

converted to digital through the 16 bit AD-converter and finally read by the Lab View

program (Fig. 3). In the program the signal offset (zero) and gain could be adjusted

before further processing. The signal from the load cell was sampled at 1000Hz and

then a mean value was calculated every second. Due to turbulence the measuring signal

still fluctuated and further signal processing was necessary. To obtain stable

measurements a sliding average was considered using 60s. The force was read when thesliding average was stable.

The load cell measured the force along the flow direction since it was mounted in parallel with the main wind flow. The load cell had an internal compensation that balances out the torque. Therefore, it measured the net force in the flow direction regardless of where the force acted on the cube. The accuracy was tested and the total measurement uncertainty is specified as the reading \pm 7%. Further details, including the calibration procedure, are given in Buccolieri et al. (2017).

229



230 231 232

Fig. 3 Pictures showing an example of the array built in the wind tunnel and attached to the circular disk, with indication of the target cube connected to the load cell.

233

234 **2.4.** Pressure measurements and drag force estimation

The static pressure at windward and leeward sides was measured via pressure taps placed at the façades of the target cube (Fig. 4a,b). The diameter of the tap openings was 0.8mm and the opening was oriented perpendicular to the wall. The pressure was measured only at one half of the façades. All pressure taps were connected to a multiplexer (scanner valve), which transferred each pressure to the Furness FCO12 pressure transducer. The signal was sampled with 1000Hz and the final reported

- pressure was the average over 30s. The area was then divided into 40 sub-areas (A_i with
- i=1 to 40) according to where the taps were located (Fig. 4c).
- The drag force, acting perpendicular on the windward side of the target cube, was
- then calculated as follows:
- 245 $F_{D_windward}$ (pressure) = $\sum_{i=1}^{n} p_i \times A_i$ (4)
- where the measured pressure p_i was assumed to be constant over the entire sub-area A_i .
- On the leeward side of the target cube (area $A_{leeward}$) the pressure distribution was
- almost uniform so the force was calculated from the average pressure $p_{average}$ as
- 249 follows:

250
$$F_{D_leeward}$$
(pressure) = $p_{average} \times A_{leeward}$ (5)

- 251 Sensitivity tests using Eq. 4 for calculating $F_{D_leeward}$ (pressure) showed a percentage
- difference lower than 2%.
- The total drag force F_D (pressure) acting on the target cube, along the flow direction,
- 254 was finally calculated as:

255
$$F_D(\text{pressure}) = F_{D_{windward}}(\text{pressure}) - F_{D_{leeward}}(\text{pressure})$$
 (6)

- The direction of the force was determined by the sign of the pressure.
- 257





Fig. 4. a, b) Pressure taps position at windward and leeward façades of the target cube.
c) Sub-areas of the windward façade employed for the calculation of the drag force via the pressure-derived method.

It should be noted that Eq. 6 represents an integration based on a finite number of 265 sampling points. One can expect the result to be dependent on the number of sampling 266 points and the location of the sampling points, since due to the acceleration of the air 267 flow towards the edges, on the windward side of the building the static pressure varies a 268 lot across the surfaces (see. Fig. 9 later in the text). Therefore, as shown in Fig. 4a, after 269 several tests (not shown here) with different number of sampling points on both the 270 windward and leeward façades, some pressure taps were also placed near the edges of 271 the wall, resulting in good agreement between the calculated (by the pressure-derived 272 method) and measured (with the balance) drag force (see Fig. 7 later in the text). 273 274

3. Drag area and cross ventilation

276 **3.1. The drag area**

The drag coefficient based on the drag force F_D generated by the target cube, the reference velocity U(H) and the physical frontal area of the cube A_{Cube} is defined as:

279
$$C_D = \frac{F_D}{\frac{1}{2}\rho U(H)^2 A_{Cube}}$$
 (7)

With the aim of determining the effective area of cubes generating the drag force, we use the definition of the drag area (Buccolieri et al., 2017) by setting the drag coefficient equal to 1 and solving for the area. The drag area of the target cube (A_D) becomes:

283
$$A_D = \frac{F_D}{\frac{1}{2}\rho U(H)^2}$$
 (8)

The rationale for introducing a drag area is that it can be compared with the physical area of the cubes in the array. The drag coefficient becomes the ratio between the drag area and the physical area of the cube:

$$287 C_D = \frac{A_D}{A_{cube}} (9)$$

288 Regarding the magnitude of the drag area there are two extreme cases:

- *Long distance between the cubes (low* λ_p *) No interference between the cubes*
- 290 The cubes behave as independent bodies and the total drag force acting on the whole
- array $(F_{D \ total})$ is equal to the number of cubes N multiplied by the drag force F_D
- 292 generated by the single target cube:

$$P_{D_total}(\text{for low }\lambda_p) = NF_D$$
(10)

which, by Eq. 8, leads to the total drag area of the array $(A_{D_{total}})$:

295
$$A_{D_total}(\text{for low }\lambda_p) = \frac{F_{D_{total}}}{\frac{1}{2}\rho U(H)^2} = N \frac{F_D}{\frac{1}{2}\rho U(H)^2} = NA_D$$
 (11)

296 Short distance between the cubes (large λ_p) – Strong interference between the cubes) 297 The extreme case is when total force F_{D_total} is on the cube at the front ($F_{D_front_cube}$) 298 which, by Eq. 8, leads to total drag area:

299
$$A_{D_total}(\text{for large } \lambda_p) = \frac{F_D}{\frac{1}{2}\rho U(H)^2} = \frac{F_{D_front_cube}}{\frac{1}{2}\rho U(H)^2} = A_{D_front_cube}$$
(12)

To generalize, if F_D^i is the drag force generated by cube *i* within the array and A_D^i is

the corresponding drag area, the total drag force exerted by the whole array is equal to:

302
$$F_{D_total} = \sum_{i=1}^{N} F_{D}^{i}$$
 (13)

and the total drag area A_{D_total} (see Eq. 8) becomes:

304
$$A_{D_total} = \frac{\sum_{i=1}^{N} F_D^i}{\frac{1}{2}\rho U(H)^2} = \sum_{i=1}^{N} A_D^i$$
 (14)

By dividing the total drag area by the total physical frontal area for each λ_p , $\frac{A_{D_total}}{\text{Frontal area}}$, it can be evaluated which is the most appropriate reference area (drag area)

to be used for the calculation of the drag coefficient C_D , i.e. when the ratio tends to one.

308

305

306

309 3.2 Assessment of wind-driven cross ventilation based on the drag force

Wind-driven natural ventilation of buildings occurs either as cross ventilation or single-sided ventilation (Etheridge and Sandberg, 1996). Single- sided ventilation occurs when all openings are located on one side (Warren, 1977). Cross ventilation occurs when there are openings on different sides of a building.

Cross ventilation has been studied by several authors using different approaches. 314 Some examples are provided by Karava et al. (2007, 2011), Chu and Chiang (2014) and 315 Shetabvish (2015). More recently Shirzadi et al (2018) have investigated cross 316 ventilation for buildings embedded in arrays using computational fluid dynamics. 317 When the pressure inside the building is uniform (Kobayashi et al., 2010), cross 318 319 ventilation is assumed to be driven by the difference of the static pressure between outside and inside of the building which generates a velocity through the openings. If 320 321 the building is a bluff body, the drag force is generated by the pressure difference between the windward and the leeward façades . 322

323 In the present paper, in order to assess the potential for cross ventilation it is assumed here that the cubes in the investigated arrays are provided with two openings opposite to 324 each other (Fig. 5) and for simplicity the area of both openings are taken to be equal. By 325 entrainment into the air stream flowing into the room there is a gradual expansion of the 326 air stream. If the distance L, to the leeward wall, is larger than about six times the linear 327 dimension of the opening, the cross section of the air flow have expanded so it is larger 328 than the opening in the leeward wall. Then the whole air stream cannot continue straight 329 through the opening on the opposite side. This is the prerequisite for the pressure inside 330 the building to be uniform. 331



Fig. 5. A cube with two openings located opposite to each other.

The flow rate $Q_{opening}$ [m³s⁻¹] through the opening is, by assuming that the velocity profile is uniform across the opening, given by:

$$338 \quad Q_{opening} = A_{opening} U_{opening} \tag{15}$$

The velocity in the opening, $U_{opening}$, is driven by the pressure difference $|\Delta \bar{p}_{Out-In}|$ between outside of the building and the inside of the building according to the orifice equation (Etheridge and Sandberg, 1996):

342
$$U_{opening} = C_{discharge} \sqrt{\frac{2|\Delta \bar{p}_{Out-In}|}{\rho}}$$
 (16)

343 where $C_{discharge}$ is the discharge coefficient which takes into account several factors as e.g. area contraction of the stream tube when passing through the opening and losses. 344 For the opening on the windward façade $\Delta \bar{p}_{out-In} = (\bar{p}_{windward} - \bar{p}_{inside})$ and for 345 the opening on the leeward façade $\Delta \bar{p}_{Out-In} = (\bar{p}_{inside} - \bar{p}_{leeward})$. The unknown 346 quantity is the pressure \bar{p}_{inside} within the cube which we assume to be constant within 347 the cube. This condition is fulfilled if the openings are not too large. The pressure 348 variation inside a building related to the size of the openings is shown in Kobayashi et 349 al (2010). This pressure inside the cube is obtained from the flow balance that dictates 350 that the flow rates through both openings are the same. For simplicity, we set the 351

discharge coefficients for the openings on the windward and the leeward façades the same. This implies that the pressure difference across both openings is the same and the pressure within the cube is equal to the average of the pressure on the windward and the leeward façades. Therefore, the pressure difference across both openings becomes equal to half the pressure difference between the leeward and the windward side:

357
$$\Delta \bar{p}_{Out-In} = \frac{1}{2} \left(\bar{p}_{windward} - \bar{p}_{leeward} \right)$$
(17)
358 This pressure difference can be assessed from the drag force F_D (balance) measured

with the standard load cell and the physical surface area of the cube F_D (balance) as follows:

361
$$(\bar{p}_{windward} - \bar{p}_{leeward}) \approx \frac{F_D(\text{balance})}{A}$$
 (18)

Inserting this into Eq. 16 the velocity through the opening $U_{opening}$ in relation to the reference velocity U(H) can be written as:

$$\frac{U_{opening}}{U(H)} = \frac{C_{discharge} \sqrt{\frac{F_D(balance)}{\rho A}}}{U(H)}$$
(19)

The discharge coefficient $C_{discharge}$ reported in the literature varies a lot. This is due 365 to that apart from different conditions at the tests, the discharge coefficient takes into 366 account many factors. In many practical applications the discharge coefficient is an 367 adjustment factor that links flows at complex conditions to the orifice equation. 368 According to Karava et al. (2004) the discharge coefficient varies between 0.14-0.65 369 and according to Cruz and Viegas (2016) it varies between 0.47-0.81. In our assessment 370 a precise estimation of the discharge coefficient is not available and thus we set it equal 371 to 1 because the whole analysis is only an order of magnitude estimate. This implies 372 that we, if the orifice equation is valid, overestimate the potential. After setting the 373 discharge coefficient equal to 1, Eq. 19 leads to: 374

375
$$\frac{U_{opening}}{U(H)} = \frac{\sqrt{\frac{F_D(\text{balance})}{\rho A}}}{U(H)} = \frac{1}{\sqrt{\rho A}} \frac{\sqrt{F_D(\text{balance})}}{U(H)}$$
(20)

Please note that if an estimate of the discharge coefficient is available, this can the
easily be taken into account by multiplying Eq. 20 by the new discharge coefficient and
the results will be qualitatively similar to those presented in subsection 4.4 (see Fig. 10
later in the text).

Eq. 20 is used here to evaluate the potential for cross ventilation driven by a static 380 pressure difference. The façade area $A = H^2$ is constant while the reference velocity at 381 roof height U(H) is dependent on the type of boundary layer generated (roughness 382 elements in the fetch or not). According to Eq. 20 the velocity in the opening $U_{opening}$ 383 approaches zero when the force approaches zero, which occurs when the difference in 384 mean pressure (Eq. 18) approaches zero. Now other mechanisms for exchange of air 385 between the interior of the building and the ambient come into play (Haghighat et al., 386 1991). One mechanism is the penetration of turbulent eddies through the openings and 387 another one is flow driven by pressure fluctuations. Pressure fluctuations are generated 388 by e.g. vortex shedding (Zu and Lam, 2018). These mechanisms give rise to penetration 389 phenomena with strong variations in time and therefore the exchange between the 390 indoor and the ambient cannot always be estimated from the flow rate in the opening 391 based on the velocity field (air exchange rate). Instead the exchange must be based on 392 an exchange of a passive contaminant present indoor. This exchange is retained from 393 concentration data. This exchange rate is the purging flow rate (Etheridge and 394 Sandberg, 1996) and is maximized by the air exchange rate. An example of predicting 395 the purging flow rate from concentration data can be seen in Kobayashi et al (2018). 396 It should be noted that there is a direct relation between the velocity in opening 397 $U_{opening}$ according to Eq. (20) and the assessment of the in-canopy velocity U_C 398 according to Bentham and Britter (2003) relation (2): 399

400
$$U_C = \sqrt{2}U_{opening}$$

(21)

This relation is obtained from the relation (2) in Bentham and Britter (2003) by substituting the left hand side with the drag force and in the right hand side setting the drag coefficient equal to 1. Eq. 21 implies that it is possible to read off the variation in in-canopy velocity from the variation in the velocity through an opening and vice versa.

406 **4. Results**

407 4.1. Evaluation of the drag distribution

408 4.1.1 Interaction between the approaching flow and the array

Fig. 6a shows a sketch of the flow pattern when the wind approaches the array. For
the approaching wind the array constitutes a resistance consisting of a blockage by
cubes generating a drag force, while for the air stream passing through the street

canyons the resistance is generated by a friction against the surfaces forming the street 412 canyons. At the frontal façades of cubes there are stagnation points and for the air 413 stream passing along the street canyons there are corresponding retardment points 414 defined as the points with the highest static pressure (Sandberg et al., 2004). Due to the 415 increased resistance only a fraction of the approaching flow can penetrate into the array 416 because the street canyons have a lower flow capacity (Hang et al, 2010) than the 417 surrounding non occupied terrain. The fraction (dashed line in the figure) that does not 418 entrain into the array continues above the array. At the downstream end of the array 419 there is a corresponding change from a higher to a lower resistance that causes the flow 420 capacity downstream to increase. This change generates a downward flow at the 421 downstream end of the array. Fig. 6b shows the evolution of the static, dynamic and 422 total pressure in the approach flow continuing through the street canyon. 423



Fig. 6. Flow towards the cubes in the front row. a) Sketch of the flow pattern and b) pressure
coefficient by static, dynamic and total pressure along the line indicated in a) (adapted from
Sandberg et al., 2004).

429

430 **4.1.2** Interaction between the cubes and the boundary layer

For an isolated cube a shear boundary layer is developed and by flow separation a 431 characteristic flow pattern is generated around the cube with a wake on the leeward 432 side. With respect to a reference pressure the isolated cube experiences a positive 433 434 pressure on the windward side and a negative pressure in the wake on the leeward side. The difference between these pressures generates a drag force on the cube. For an array 435 of cubes, the introduction of surrounding cubes creates an air gap around all cubes 436 located within the interior region of the array. The air gaps constrain the flow and 437 consequently the windward and leeward pressures to be changed relative to an isolated 438

cube. There are many physical phenomena that may affect the drag force on individual 439 cubes which depends on their location within the array. The velocity in the wake is less 440 than the free stream velocity and therefore the cube behind the first cube will be 441 sheltered and subsequently exposed to a lower velocity than the first cube. The result is 442 a lower drag force. If the cubes come very close to each other the cube downstream will 443 be fully submerged within the wake of the first cube which results in a force directed 444 opposite to the wind direction. The second cube may also affect the cube upstream by 445 that the location of the point of separation on the sides of the upstream cube is changed. 446 If the cubes are very close to each other there may be no separation from the first cube. 447

The introduction of surrounding cubes will thus lead to an interference. Based on 448 field measurements and modelling results, Oke (1988) identified three flow regimes for 449 wind direction perpendicular to the street axis in neutral stratification. For widely 450 spaced buildings (aspect ratio between the building height H and the street width W < 451 0.3), the flow fields associated with the buildings do not interact (isolated roughness 452 flow regime). At closer spacing (0.3 < H/W < 0.7) the wake behind the upwind building is 453 disturbed by the recirculation created in front of the windward building (wake 454 455 interference flow regime). Further reducing spacing (H/W>0.7) results in the skimming flow regime, where a stable recirculation is developed inside the canyon and the 456 ambient flow is decoupled from the street flow. 457

The degree of interference can be expressed as an "interference factor" defined as $F_D/F_{D_isoltaed_cube}$, i.e. the ratio between drag force of the target cube surrounded by cubes and the drag force generated by an isolated cube. There are thus three cases: 1) no interference (interference factor = 1); 2) Sheltering (interference factor < 1); 3) Amplification (interference factor > 1).

463

464 4.1.3 Measured drag distribution

Fig. 7 shows the interference factor for the cases with a boundary layer generated with roughness elements in the fetch. The cases with a boundary layer generated with no roughness elements in the fetch exhibit a similar behaviour. Both the drag forces measured by the balance and the pressure difference are presented. The balance measured the total contribution to the drag due to the form drag and friction. By definition the drag based on the pressure difference is the form drag. The cube is a bluff
body so we expect the form drag to dominate.

From the figure it can be argued that the standard load cell method and the pressure-472 derived method provided similar distribution of the drag force within the array. This 473 provides confidence in the measurements. Only the target cube located at the first row 474 showed a normalized drag force based on the pressure about 10% larger than the drag 475 force based on measurements by the balance. It is likely that this difference is due to 476 that the pressure is measured in a finite number of points. Secondly, results confirm that 477 the change in distribution of the drag force when changing the building packing density 478 is in accordance with assessment of the distribution of the drag force based on 479 measurements of the total drag force of the whole array reported in (Buccolieri et al., 480 2017). For further details see also the next subsection. 481

At the lowest packing density $\lambda_p=0.028$ (air gap between the cubes is 5H) there is no 482 interference. And at $\lambda_p=0.11$ (air gap 2H) the interference factor is 0.5, while at $\lambda_p=0.25$ 483 (air gap 1H) the force is almost totally exerted by the first cube. As discussed in 484 Buccolieri et al. (2017) the latter case corresponds to a maximum drag force generated 485 486 by the whole array (see Fig. 6 of their paper). With further increase of λ_p , the drag force slightly decreases until it becomes almost constant. One can claim that at $\lambda_p=0.25$ the 487 array start to behave as one single unit. The effect of an increase of the frontal area is in 488 fact cancelled out by the reduction of mean wind velocity (see Buccolieri et al., 2010). 489 At $\lambda_p = 0.44$ the air gap is 0.5H and the drag force on the cube located downstream of the 490 cube at the front of the array becomes negative. We interpret this as that the second 491 cube now is submerged (Gowda and Sitheeq, 1990) in the boundary layer generated by 492 the cube at the front. However it remains to verify this by flow visualization. A further 493 detail is that starting with $\lambda_p=0.11$ the drag force on the cube at the front is less than on 494 an isolated cube. This we interpret as that the cube downstream affect the drag force 495 exerted on the cube at the front. However for the largest packing density $\lambda_p=0.69$ (air 496 gap (0.2H) there is an amplification of the drag force on the front cube in the row that we 497 cannot explain. Associated with the change in the distribution of the drag force with 498 changing packing densities there is a change in the air flow pattern. In Figure 7 of 499 Buccolieri et al (2010) it is shown that starting from packing density $\lambda_p=0.44$ there are 500 recirculation zones within the array. 501





503

Fig. 7. Profiles of $F_D/F_{D_isolated_cube}$ (interference factor) generated by the target cubes, BL roughness case. The x-axis represents the distance from the first target cube of the array ("0") to the last target cube ("1"), see Fig. 1.

508 4.2. Assessment of the drag area

In Buccolieri et al (2017) the drag area distribution was assessed from the total drag

510 force recorded over the whole array by calculating the ratio: Total drag area/Frontal

area, i.e. the ratio between the total drag area retrieved from the total drag force and thephysical frontal area of the whole array (see their Eq. 13).

Here the same relation is employed but using the drag force measured on the individual target cube. The total drag area is thus estimated by adding the drag forces measured with the balance generated by the single target cubes and the physical frontal area is the total frontal area of the target cubes. Two extreme cases of the frontal area are chosen, i.e., the physical frontal area of all the middle column of the array and the physical frontal area of the first (upstream) target cube. Each cube has a frontal area equal to 0.036m².

The comparison is shown in Fig. 8. First it can be noted that the drag distribution 520 obtained from current measurements on individual cubes is similar to that obtained from 521 measurements over the whole array. This suggests that, when estimating the drag area 522 generating the drag force, the single middle column is representative of the whole array 523 for each λ_p , indicating that our choice of isolated array well represents the drag force 524 exerted by a portion of the city of a given λ_p . Second the figure shows that, as expected 525 by the drag force distribution shown in Fig. 7, for low packing density the total frontal 526 area is the most appropriate reference area (drag area) since the ratio is close to one, 527 whereas for large packing densities the frontal area of the first row only is the one to be 528 used as the appropriate reference area. 529 530



531

Fig. 8. Drag area/Frontal area as a function of the planar area index λ_p when using the frontal area of the first cube or of the first row of cubes (full rhombus and square, respectively) and the frontal area of the middle column or of all the cubes (empty rhombus and square, respectively) in the a) "BL roughness" and b) "BL no roughness" cases. Note: square symbols refer to drag force measurements over the whole array (Buccolieri et al., 2017).

538 **4.3** Pressure distribution on the surface of target cubes

To show the spatial distribution of pressure, Fig. 9 shows the pressure contours on 539 the windward side of the first, central and last target cubes for the BL roughness case 540 obtained by interpolating the measured pressure. Results for the BL no roughness 541 follow a similar behaviour. We remind here that the pressure was measured (i) on the 542 same target cube as the drag force was measured by the balance; and (ii) on one half of 543 the side only (see Fig. 4), and therefore eventual asymmetries in the horizontal direction 544 is not revealed which of course is a limitation. The stagnation point is the point with the 545 546 highest pressure and from this point the air approaching the façade is distributed over the façade. For an isolated cube the stagnation point lies on the vertical symmetry line. 547 However when a cube is lying in the front row of an array the location of the stagnation 548

point is probably affected by the amount of air pressed into the street canyon, formed bytwo neighboring rows.

Fig. 9 shows that for all packing densities the first cube (i.e. the cube at the upstream 551 first row of the array) has qualitatively the same pressure distribution as for the isolated 552 cube. Further, the pressure distribution for the lowest packing density ($\lambda_p=0.028$) is 553 qualitatively similar for all cubes in the row, that is the interference between the cubes 554 is low in this case. This is in contrast to the case with the highest packing density 555 $(\lambda_p=0.69)$ where the pressure distribution on the cube at the centre and at the end of the 556 row is almost uniform. The general trend is that with increasing packing density the 557 gradient of the pressure distribution on the wall diminishes for the central and last 558 cubes. This is due to the fact that with increasing packing density the width of the air 559 gap between the cubes diminishes and this constrains the air motion. Because the 560 pressure distribution is a footprint of the air motion along the wall, this results in a more 561 uniform pressure distribution. 562

BL roughness





569

Fig. 9. Pressure contours on the windward façade of the first, central and last target cubes for each packing density λ_p , BL roughness case.

570 4.4. Assessment of the potential for cross ventilation

The potential for cross ventilation is shown in Fig. 10 as the ratio between the 571 velocity at the opening $U_{opening}$ and the reference velocity U(H) at the height of the 572 cube according to Eq. 20. This velocity ratio is dependent on the square root of the drag 573 force multiplied with an expression which only varies with the type of boundary layer, 574 generated either with no roughness elements in the fetch or with roughness elements in 575 the fetch. We remind here that in Eq. 20 the force measured by the balance 576 F_D (balance) is employed. 577 The figure shows that for the first (upstream) target cube the velocity ratio becomes 578

about the same for both types of boundary layers and is approximately about 0.8.

Overall for cubes located downstream the velocity ratio with increasing packing density 580 shows a similar qualitative behaviour as that found for the drag force (see Fig. 7). 581 Specifically, when the packing density is $\lambda_p=0.25$ the velocity ratio has dropped to 582 approximately 40% and by further increasing the packing density to $\lambda_p=0.44$ the 583 velocity ratio drops to 20%. This shows that, as expected, cross ventilation is very much 584 affected by the packing density. One can expect that single sided ventilation is less 585 sensitive to the packing density because the ventilation is mainly generated by 586 fluctuations. On the other hand single sided ventilation is in general much less than 587 cross ventilation. For the same object the relation between cross ventilation and single 588 sided ventilation has been studied in wind tunnel tests reported in Hayati et al. (2018). 589 590



Fig. 10. Cross ventilation assessment through the ratio of velocity at the opening $U_{opening}$ and the reference velocity U(H). The x-axis represents the distance from the first target cube of the array ("0") to the last target cube ("1"), see Fig. 1.

595

596 **5. Conclusions**

597 The drag force distribution generated by regular arrays of cubes was measured in a 598 wind tunnel. The force was measured using both a standard load cell and indirectly 599 estimated by measuring the static pressure at windward and leeward façades. The

- measurements with the two methods coincide within 10%. The drag force is presented
 as an interference factor by dividing the measured drag force with the drag force from
 an isolated cube. The main findings of the paper are summarized below:
- for the lowest packing density, the drag force is almost uniformly (within 15%)
- distributed between the cubes within the array. With increasing packing density the
- 605 force exerted on the fraction of the cubes located downstream of the first row
- progressively diminishes, and for the highest packing densities the whole force is
- exerted on the first row, primarily. At the largest packing densities the force on the
 second row is negative i.e. directed opposite to the wind direction;
- as the packing density increases the interaction between the buildings changes from a
- collection of weakly interfering rows to become a single array, and finally as one row
- only. This implies that for very low packing densities the total frontal area is the most
- appropriate reference area (drag area) whereas for large packing densities the most
- appropriate reference area is the frontal area of the first row;
- the methodology previously presented in Buccolieri et al (2017) is further verified
- demonstrating that the distribution of the drag force within the array can be derived
- from the total drag force, using a combination of the total drag force expressed as a dragarea and the physical frontal area of the cubes.
- 618 the potential for cross ventilation is quantified as the velocity through a ventilation
- opening which is proportional to the square root of drag force. It is shown that there is a
- direct relation between the velocity through a ventilation opening and the in canopy
- velocity. This is an observation that has not previously pointed out.
- the recorded pressure contours on the façades of the cubes is a footprint of the air
 motions in the air gap between the cubes showing that with increasing packing densities
 the gradient of the pressure decreases.
- 625 Measuring the drag force correctly is not only relevant for the field of wind load on
- structures, but also for the derivation of improved description of the effect of the city
- 627 within atmospheric mesoscale models. Several mesoscale studies of the drag force
- generated by arrays of buildings have been carried out with different methods. For
- example, Gutierrez et al. (2015) implemented a mechanical drag coefficient formulation
- depending on packing density following Santiago et al. (2010) into the Building Effect
- 631 Parameterization + Building Energy Model system coupled with mesoscale Weather

- Research Forecasting model. The mesoscale model was applied over New York
- obtaining an improvement of accuracy of mesoscale model in predicting surface wind
- speed in complex urban area. We expect that in the future the drag force distribution
- obtained for different wind directions (providing a sort of "drag force rose"), which may
- lead to very significant changes in the total drag imposed by the surface (Claus et al.,
- 637 2012a,b; Santiago et al., 2013), can be the basis for a first order modelling of the
- dispersion of pollutants within an urban area.
- 639

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- 646

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