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ON THE DRAG FORCE DISTRIBUTION OVER ARRAYS OF CUBICAL BUILDINGS: WIND TUNNEL EXPERIMENTS

Riccardo Buccolieri[1], Hans Wigö[2], Mats Sandberg[2] and Silvana Di Sabatino[3]

[1]Dipartimento di Scienze e Tecnologie Biologiche ed Ambientali, University of Salento, Lecce, Italy
[2]Faculty of Engineering and Sustainable Development, University of Gävle, Sweden
[3]Department of Physics and Astronomy, University of Bologna, Italy

Abstract: In this paper we discuss the distribution of drag force along aligned arrays of cubes of different packing density. The distribution is evaluated via wind tunnel measurements performed on individual cubes located along the middle column of the array using a balance provided by a standard load cell. Results are compared with the drag force estimated by a pressure-derived method and clearly show a change of the distribution of the drag force. The force is uniform at low packing densities, while mostly acting on first rows of the arrays at large packing densities. This work leaves room for research tailored to a better parameterization of urban effects in dispersion models.

Key words: *drag distribution; standard load cell; cubic building arrays.*

INTRODUCTION

The air flow pattern and the penetration of ambient air (dilution capacity) within a group of buildings is dependent on the building packing density. Changes in air flow pattern and dilution capacity are both reflected in a corresponding change of the drag force distribution.

Here we discuss the distribution of the drag force within several aligned arrays of cubes of different packing density. Differently from our previous study (Buccolieri et al., 2017) where the drag force was measured on the whole array, here the drag force is measured on individual cubes located along the middle column of each array. This approach allows us to quantitatively evaluate the change of the drag distribution for different packing density.

The important aspect of 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 within numerical mesoscale models. We expect that in the future the drag force distribution obtained for different wind directions (providing a sort of ”drag force rose”) can be the basis for a first order modelling of the dispersion of pollutants within an urban area. For improving this approach, there is also a need for exploring the effect of the drag force distribution on the turbulent exchange in the vertical direction.

DESCRIPTION OF PHYSICAL MODELS

Measurements were carried out in a closed-circuit boundary layer wind tunnel with a working section of 11m long, 3m wide and 1.5m high located at the Faculty of Engineering and Sustainable Development at the University of Gävle (Sweden). An isolated cube and seven aligned arrays of cubes with height H=0.06m were considered. The lot area was a square with a side length of 13H (0.78m). The lot area was kept constant, while the planar area index λ_p changed by varying the number of cubes on that. The λ_p investigated were: 0.028, 0.0625, 0.11, 0.25, 0.44, 0.56, 0.69 (Figure 1).

A boundary-layer (BL) flow in the wind tunnel was achieved considering two different conditions for the fetch. In the first case the entire fetch was covered with cubes of 0.04m representing roughness elements (“BL roughness” hereinafter), while in the second case the fetch was smooth with no roughness elements (“BL no roughness” hereinafter). The distance between the final row of roughness elements and the front of the lot area was approximately 0.4m. The roughness area in the working section of the wind tunnel had a total length of 8m made of spires in the first part and then of 0.04m cubes (roughness elements).

The experiments were performed with one reference wind velocity $U_{ref}(H)$ [ms^{-1}] corresponding to 500 revolutions per minute (rpm) of the fan that drove the wind tunnel. The velocity was measured with a TSI hot-film anemometer in the middle of the empty circular disk where the cubes were attached (see next section). Mean velocity and relative turbulence intensity profiles up to z/H=2.5 were:

$$\frac{U(z)}{U_{ref}(H)} = 0.9\left(\frac{z}{H}\right)^{0.16} \quad \frac{I(z)}{I(H)} = 2.4\left(\frac{z}{H}\right)^{-0.06} \quad \text{(BL roughness)} \tag{1}$$

$$\frac{U(z)}{U_{ref}(H)} = \left(\frac{z}{H}\right)^{0.16} \quad \frac{I(z)}{I(H)} = 1.4\left(\frac{z}{H}\right)^{-0.45} \quad \text{(BL no roughness)} \tag{2}$$

The drag force and pressure measurements were performed separately on one individual (target) cube placed along the middle column of the array (Figure 1). That is only one target cube was subjected to the measurement. Thus to evaluate the drag distribution along each array, 1) the target cube was fixed on the wind tunnel floor and positioned at the first row of the array, 2) the first measurement was taken, 3) the surrounding cubes of the array were moved so that the target cube was at second row of the array, 4) the second measurement was taken and so on, until the target cube was positioned at the last row of the array. This procedure was followed for all the arrays investigated.

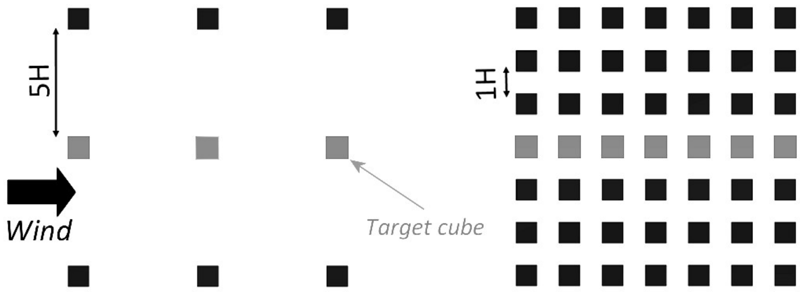

Figure 1. Example of two arrays of λ_p = 0.028 (left) and λ_p = 0.25 (right) with indication of the target cubes (grey) subjected to measurements. The lot area was 13H x 13H, with H=0.06m

INSTRUMENTATION AND MEASUREMENT SET-UP

Drag force measurements on individual cubes

The drag force acting on the individual target cube was directly measured using the standard load cell method described in Buccolieri et al. (2017). The target cube was connected to the load cell via two thin rods that went through a small opening in the turntable. There was an air gap of 1mm between the cube and the turn table. The load cell was mounted on a stable tripod standing on the floor of the laboratory hall (Figure 2) so that the cube was mechanically isolated from the wind tunnel and that the measured force was only due to air resistance. In the standard load cell the horizontal force, caused by the air movement, is transformed into vertical tensile and compressive force at its edges. Here they were Vetek 108AA with glued strain gauges 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. 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 60 seconds. The force was read when the sliding average was stable.

The load cell measured the force in one direction since it was mounted in parallel with the main wind flow, which means that only the drag force along the flow direction was measured. The load cell has 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 ± 7%. For details refer to Buccolieri et al. (2017).

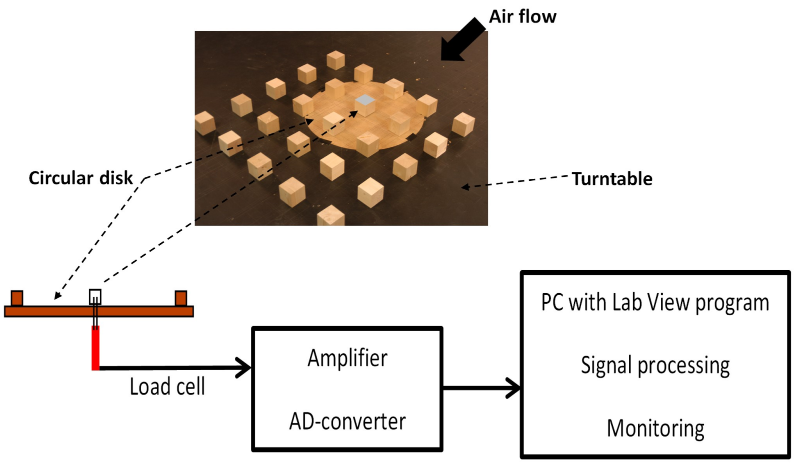

Figure 2. Array attached to the circular disk, with indication of the target cube (grey) connected to the load cell

Pressure measurements on individual cubes

The static pressure was measured via pressure taps of 0.8 mm diameter placed at the windward and leeward façades of the target cube (Figure 3). Since the distribution was symmetrical, the pressure was measured at one half of the façades. The tap opening was oriented perpendicular to the wall.

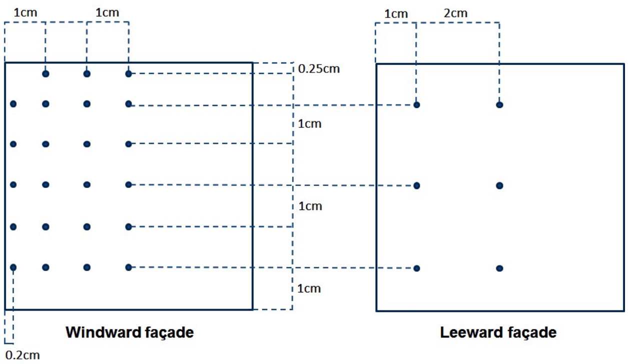

Figure 3. Pressure taps position at windward and leeward façades

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 1000 Hz and the final reported pressure was the average over 30 seconds. Due to the acceleration of the air flow towards the edges, on the windward façade of the cube the static pressure varied a lot. Therefore some pressure taps were also placed near the edges of the wall. The area was then divided into 40 sub-areas (A_i with i=1 to 40) according to where the taps were located. The force was then calculated as follows:

$$F_{windward} = \sum_{i=1}^{n} p_i \times A_i \qquad F_{leeward} = \sum_{i=1}^{n} p_{average} \times A_{leewrad} \tag{3}$$

where the measured pressure p_i is assumed to be constant over the entire sub-area A_i. Please note that on the leeward façade of the building (area $A_{leeward}$) the pressure distribution was almost uniform so the force was calculated from the average pressure $p_{average}$. The (form) drag force acting on the cube along the flow direction was finally calculated as:

$$F_{pressure} = F_{windward} - F_{leeward} \tag{4}$$

RESULTS

The change of drag distribution along the arrays

Figure 4 shows the distribution of drag force (normalized by the force on the isolated single cube) along all the packing densities investigated for the BL no roughness case (results for the BL roughness case show a similar behaviour). Please note that (i) both the standard load cell and pressure-derived method provide the form drag force along the wind direction and (ii) for each array the number of measured points is equal to the number of target cubes subjected to measurements (see Figure 1).

First, it should be noted that the standard load cell method and the pressure-derived method provided the same results, suggesting that the standard load cell method, which is simpler to set-up, could be used for quick evaluations of the drag force within similar kind of arrays. Second, the analysis directly confirms what we retrieved from the drag force measured over the whole array in Buccolieri et al. (2017), that is the "centre" of gravity" of the force moves towards the front when the packing density increases (Britter and Hanna, 2003). In fact, while for the lowest packing densities the force is almost equally distributed along the array, with increasing packing density most of the force is exerted by the first rows of the array.

In particular, measurements on individual cubes allows to quantitative assess such drag distribution. At λ_p=0.11 the force along the array is half of that at the first cube, while at λ_p=0.25 the force is almost totally exerted by the first cube. As discussed in Buccolieri et al. (2017) the latter case corresponds to a change in the evolution of the curve of the drag force (acting on the whole array) which may be due to the fact that the array starts to behave as one single unit and the total drag force is no longer proportional to the number of cubes. The effect of an increase of the frontal area is in fact cancelled out by the reduction of mean wind velocity and drag when λ_p increases under large λ_p condition.

Analysis of pressure distribution at individual cubes

Figure 5 shows pressure contours at the windward façade of the target cube located at the first row of the array. Pressure values and distribution at lower λ_p (0.028 and 0.0625) are larger and similar to those of the isolated cube, confirming that a wake interference flow generated by quasi-independent cubes occurs and the total drag force can mostly be seen as the sum of the drag force of the individual cubes. With increasing building packing density the pressure distribution becomes more uniform and the pressure on the front façade also becomes lower.

CONCLUSIONS

An experimental investigation of the drag force distribution along aligned arrays of cubes characterized by different packing densities is presented. The analysis shows a change of the distribution of the drag force within the array, with most of the force acting on first rows of the arrays at larger packing densities. This implies that, even if the buildings are evenly distributed, the distribution of the drag force over the city is not necessarily evenly distributed. This has consequences on the appropriate choice of the reference area for the calculation of the drag coefficient C_D commonly employed in dispersion models.

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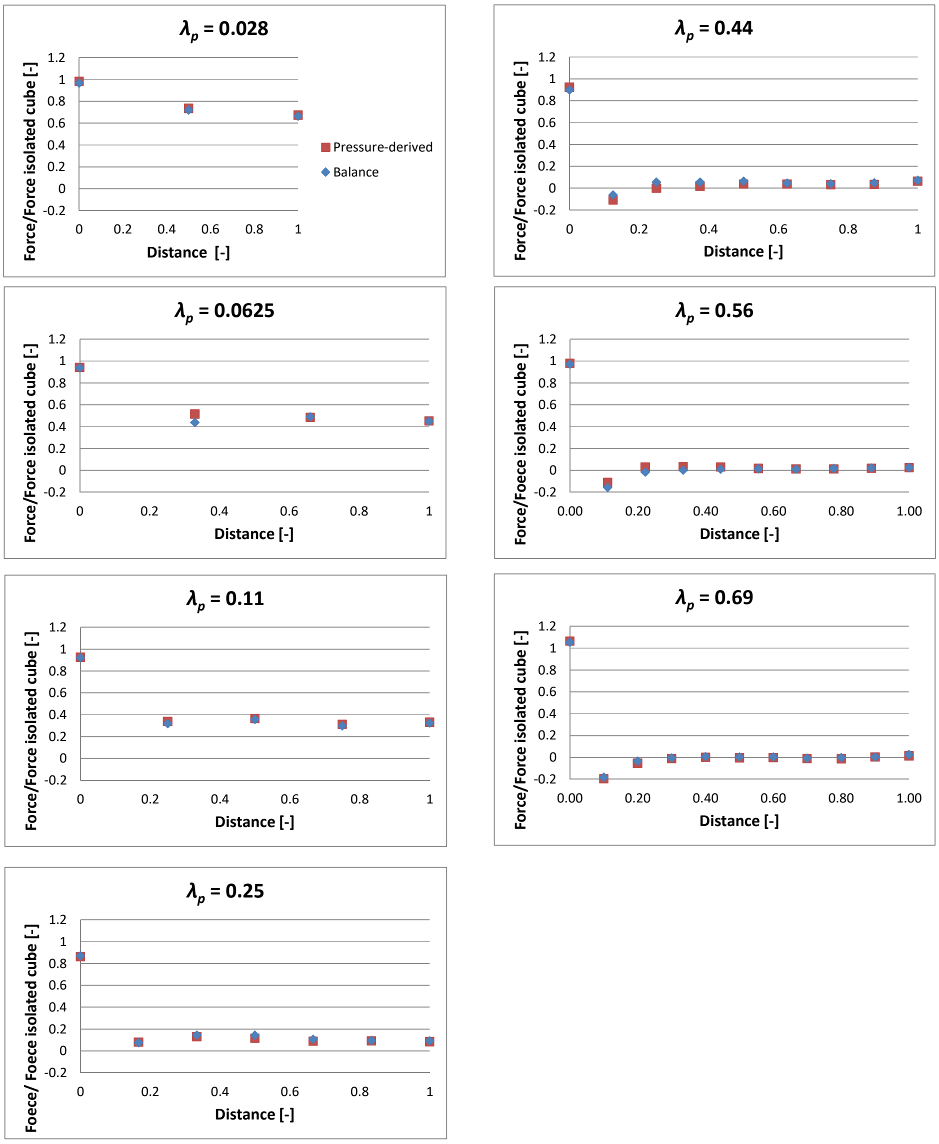

Figure 4. Distribution of drag force (normalized by the force on the isolated cube), BL no roughness case. The *x*-axis represents the distance from the first cube of the array ("0") to the last one ("1") along the wind direction

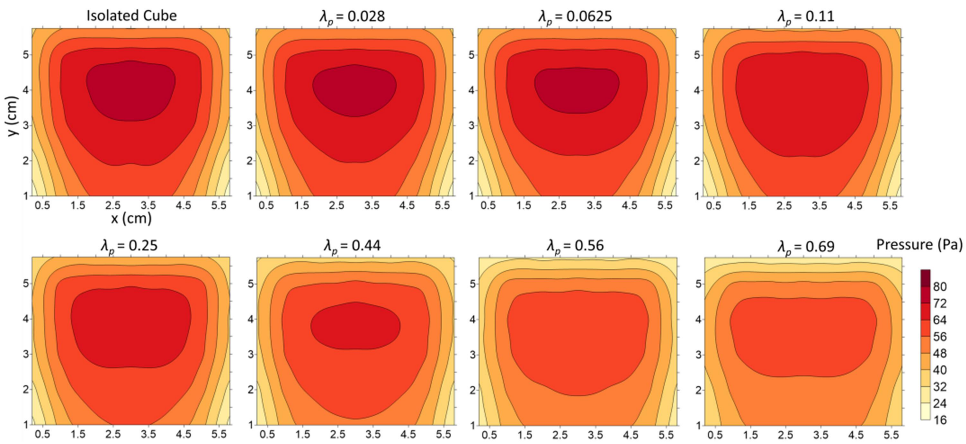

Figure 5. Pressure contours at windward façade of the first cube, BL no roughness case