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HÖGSKOLAN I GÄVLE

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

ON THE DRAG FORCE DISTRIBUTION OVER ARRAYS OF CUBICAL BUILDINGS

WIND TUNNEL EXPERIMENTS

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atmosphere

2017 TRAVEL AWARD FOR YOUNG INVESTIGATORS

Background and aim of the work

Measuring the drag force in wind tunnel

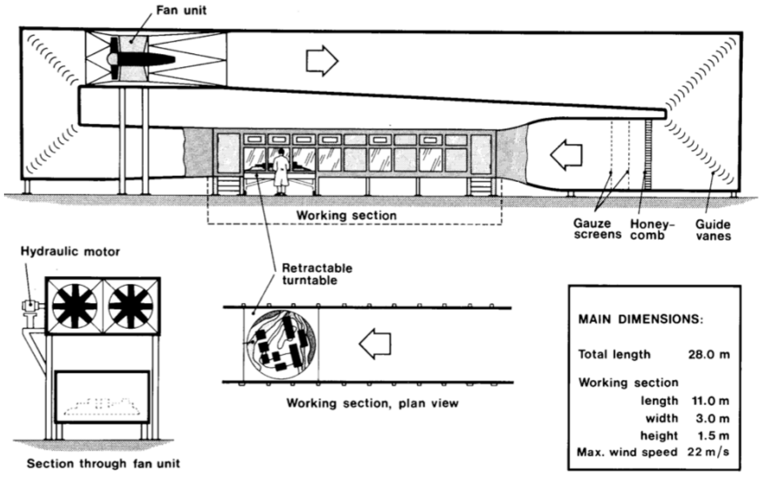
- **Description of the effect of the city** within numerical mesoscale models

- **The "center" of gravity" of the force will move towards the front when the packing density is increasing** (*Britter and Hanna, 2003; Annual Review of Fluid Mechanics 35, 469-496*). Consequences on the **appropriate choice of the reference area** for the calculation of C_D

- **The aim is to discuss wind tunnel measurements of the drag force measured with a direct method**

Description of physical models

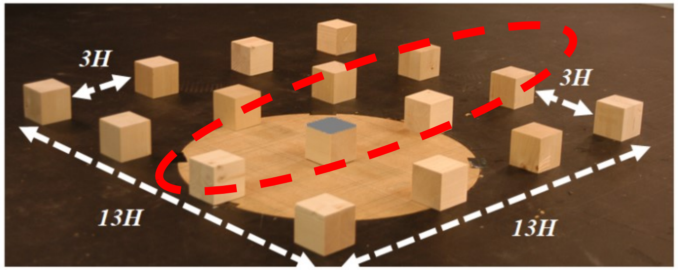
- **Wind tunnel experiments** at the Faculty of Engineering and Sustainable Development at the University of Gävle (Sweden)



- **Closed-circuit boundary layer wind tunnel**: 11m (l) x 3m (w) x 1.5m (h)

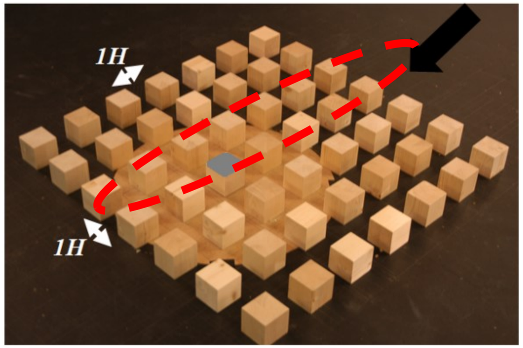
- **1 reference wind velocity U_{ref}** (measured with a TSI hot-film anemometer at the cube height *H*): *independence tested and confirmed in previous work (Buccolieri et al., 2017; Environmental Fluid Mechanics 17, 373-394).*

λ_p=0.0625



λ_p=0.25

Air flow



Drag force and pressure measurements were performed separately on individual (target) cubes

- ***H*=0.06m**
- **$\lambda_p = \lambda_f$ = 0.028 to 0.69**

Description of physical models

- **Two different conditions for the fetch**
  - ✓ the entire fetch was covered with the roughness elements ("**BL roughness**")
  - ✓ the fetch was smooth with no roughness elements ("**BL no roughness**")

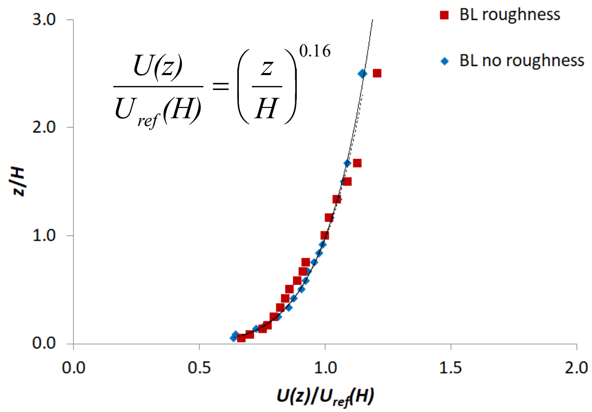
- **Reynolds number** = $H^2 x U_{ref}(H)/\nu$ = 38,000 (BL no roughness)
  20,800 (BL roughness)

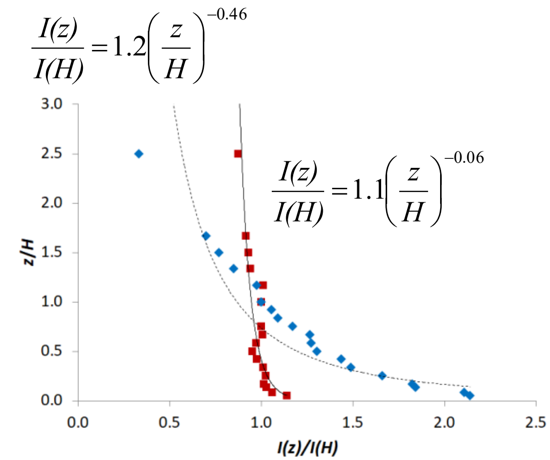
Reynolds independence condition; sufficient to maintain a turbulent flow throughout

- **Blockage coefficient**

$$\Phi = A_{model,proj.} / A_{wind\_tunnel} = 0.1\%$$ *fulfils the requirements of the VDI 3783 guidelines*

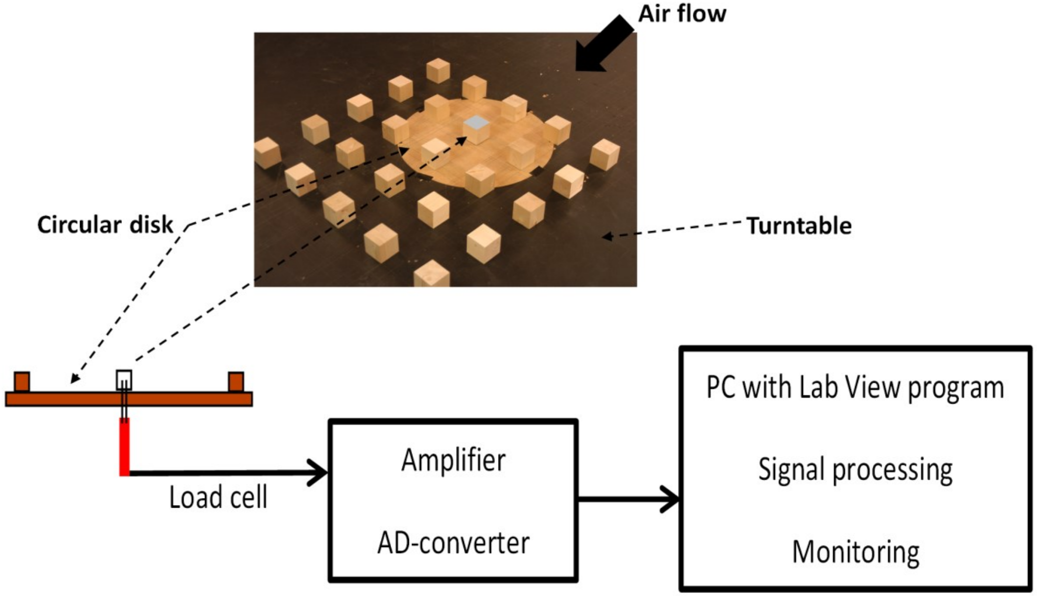
$A_{model,proj.}$: projected area of the cube along the main wind direction
A_{wind_tunnel}: cross-sectional area of the measurement section in the wind tunnel





Instrumentation and measurement set-up

DRAG FORCE measurements on the TARGET CUBE



- **The cube was above a circular disk**, which was placed in the centre of and at the level of the turntable

- **The cube was connected to the load cell**, which was mounted on a stable tripod standing on the floor of the laboratory hall

- **The load cell measured the force in one direction** (i.e. along the flow direction) since it was mounted in parallel with the main wind flow

Instrumentation and measurement set-up

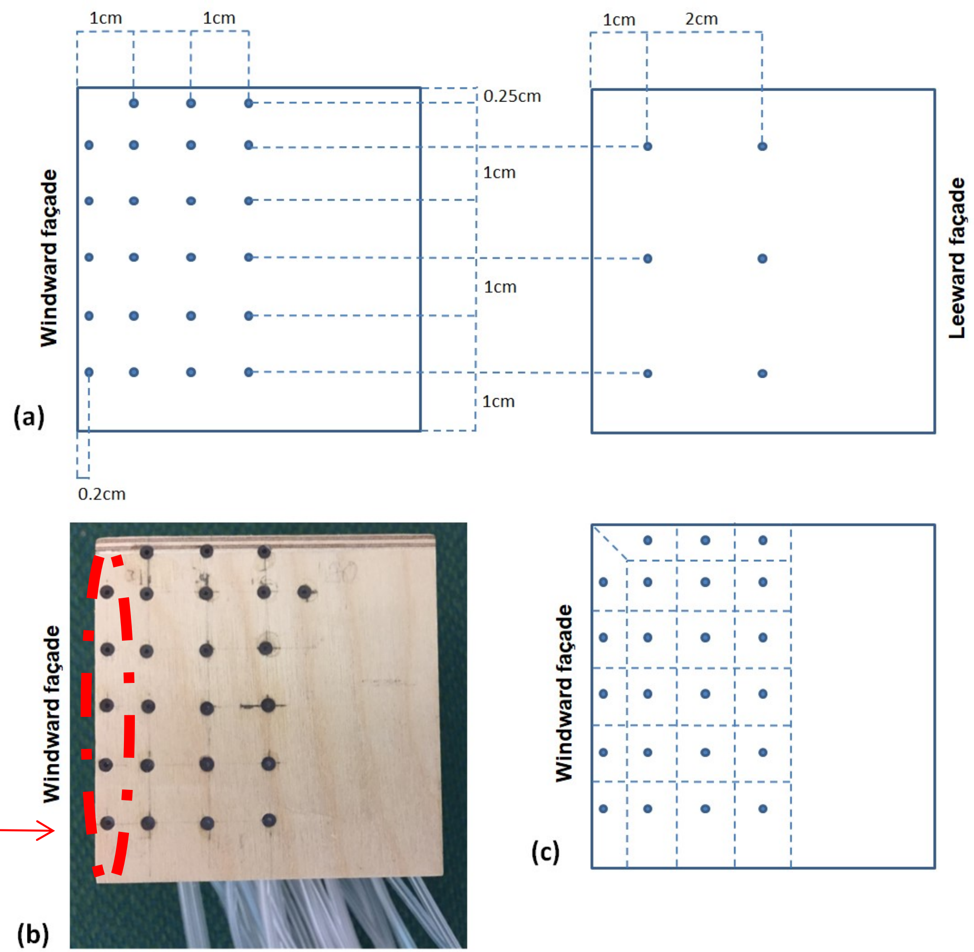
PRESSURE measurements on the TARGET CUBE

- Static pressure measured via **pressure taps** of 0.8mm diameter

- Pressure taps 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

Extra pressure taps near the edges of the wall



Instrumentation and measurement set-up

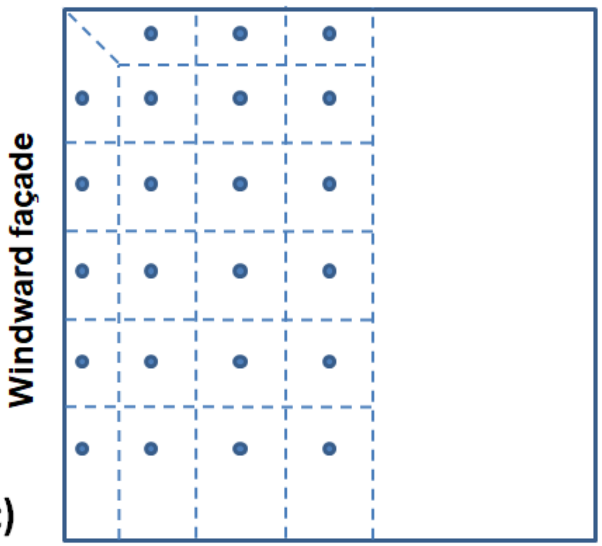
PRESSURE measurements on the TARGET CUBE

- **WINDWARD**: The area was divided into 40 sub-areas (A_i with i=1 to 40) according to where the taps were located

$$F_{windward} = \sum_{i=1}^{n} p_i \times A_i$$

(the measured pressure p_i is assumed to be constant over the entire sub-area A_i)

c)



- **LEEWARD** (area $A_{leeward}$)

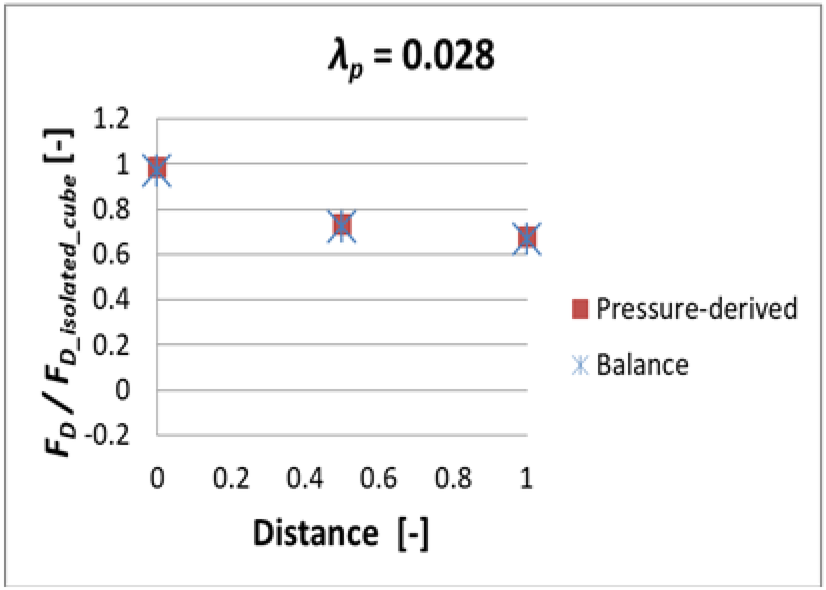
$$F_{leeward} = p_{average} \times A_{leewrad}$$

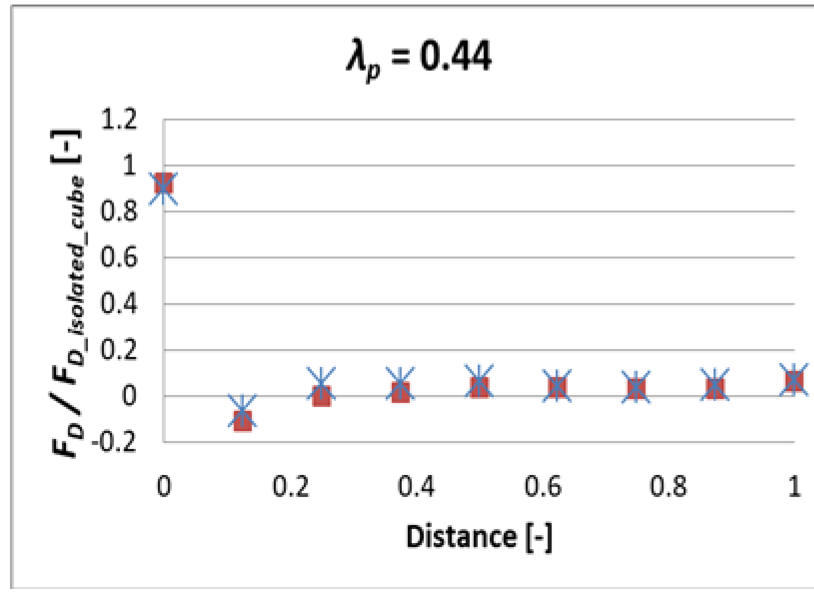
drag force along the flow direction

$$F_{pressure} = F_{windward} - F_{leeward}$$

Results

the drag force distribution



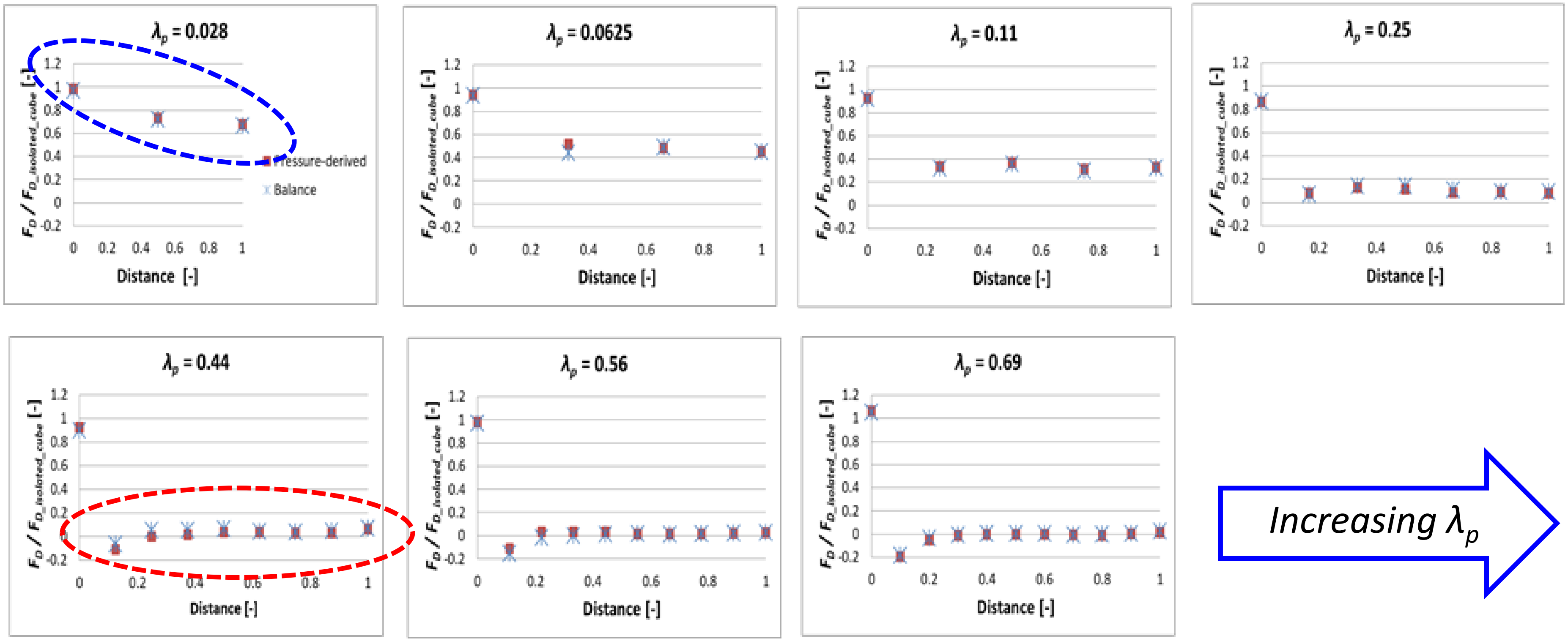


BL no roughness case (results for the BL roughness case show a similar behaviour)

The standard load cell method, which is simpler to set-up, could be used for the evaluation of the drag force within similar kind of arrays

Results

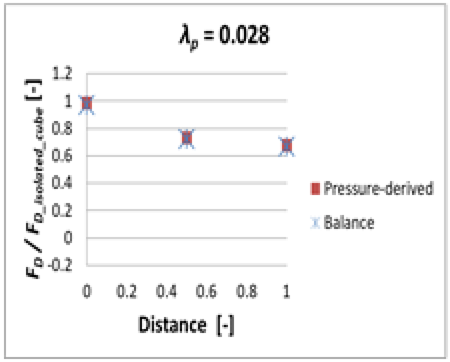
the drag force distribution

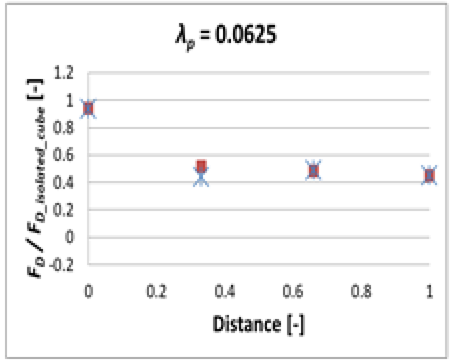


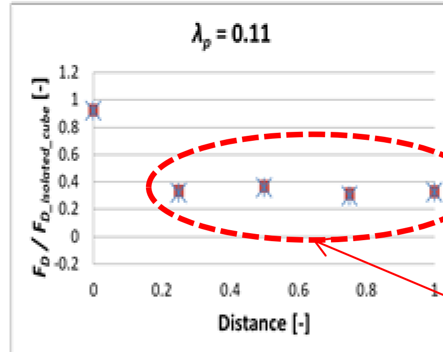
- **Lowest packing densities**: *the force is almost equally distributed along the array*
- **With increasing packing density** *most of the force is generated by first rows*

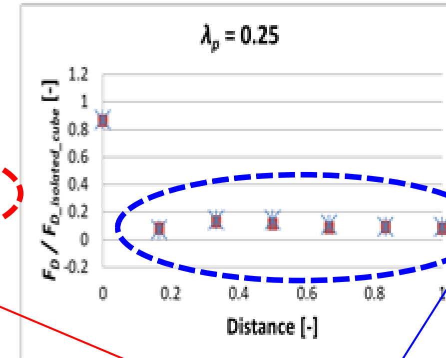
Results

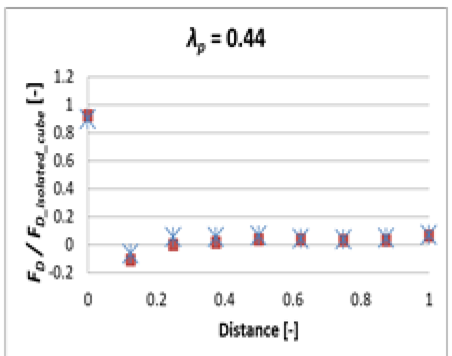
the drag force distribution

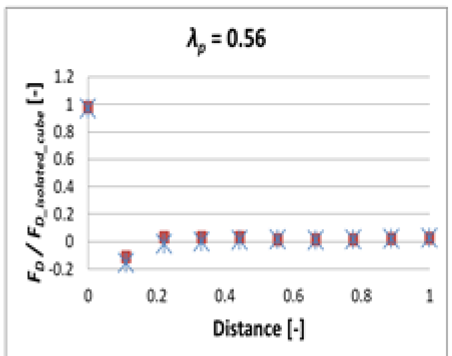


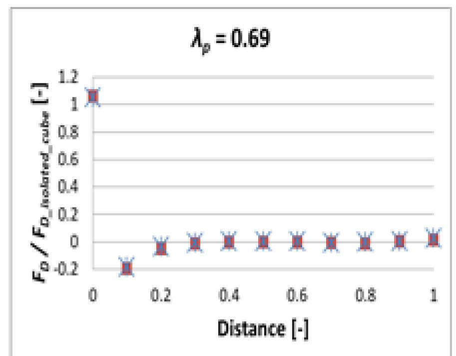










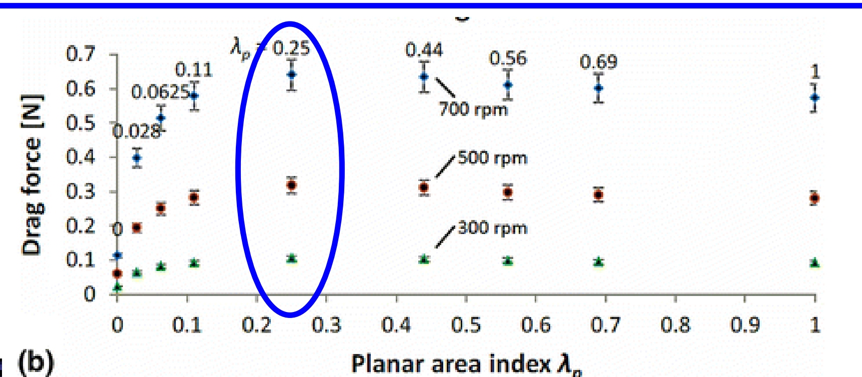


The force is half of that at the first cube

The force is almost totally generated by the first cube

The array starts to behave as one single unit and the total drag force is no longer proportional to the number of cubes

Buccolieri et al., 2017



Results

effective rows of cubes generating the drag force

HOW MANY CUBES (or rows of cubes) GENERATE THE DRAG FORCE?

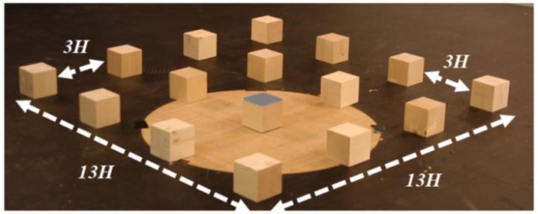
drag area A_D ⟶ the effective size of the object as it is "seen" by the fluid flow around it

$$A_D = C_D A$$

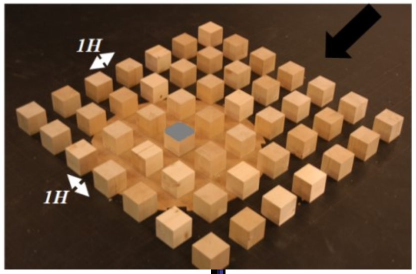
Standard procedure: *set the area equal to the area of the projection of the body on a plane normal to the stream*. This procedure results in area equal to the frontal area of one cube or row. BUT:

- Low packing density (cubes well separated): *drag area close to the total frontal area of all cubes*

λ_p=0.0625



λ_p=0.25



- GENERAL: **the appropriate drag area depends on the packing density**

HOW MANY CUBES (or rows of cubes) GENERATE THE DRAG FORCE?

drag force on the cube

Set the drag coefficient equal to one and solve for the area

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

C_D for the target cube

$$C_D = \frac{A_D}{A_{Cube}}$$

physical frontal area

CASE 1 - *N* independent cubes (low λ_p)

$$F_{D\_total} = NF_D \longrightarrow A_{D\_total} = NA_D$$

CASE 2 - large λ_p

$$F_{D\_total} = F_{front\_cube} \longrightarrow A_{D\_total} = A_{D\_front\_cube}$$

Results

effective rows of cubes generating the drag force

HOW MANY CUBES (or rows of cubes) GENERATE THE DRAG FORCE?

GENERAL CASE

$$F_{D\_total} = \sum_{i=1}^{N} F_D^i$$

$$A_{\mathrm{D\_total}} = \frac{\sum_{i=1}^{N} F_D^i}{\frac{1}{2}\rho U_{ref}^2(H)} = \sum_{i=1}^{N} A_D^i$$

normalized by the drag area of the isolated cube ($A_{D\_isolated\_cube}$)

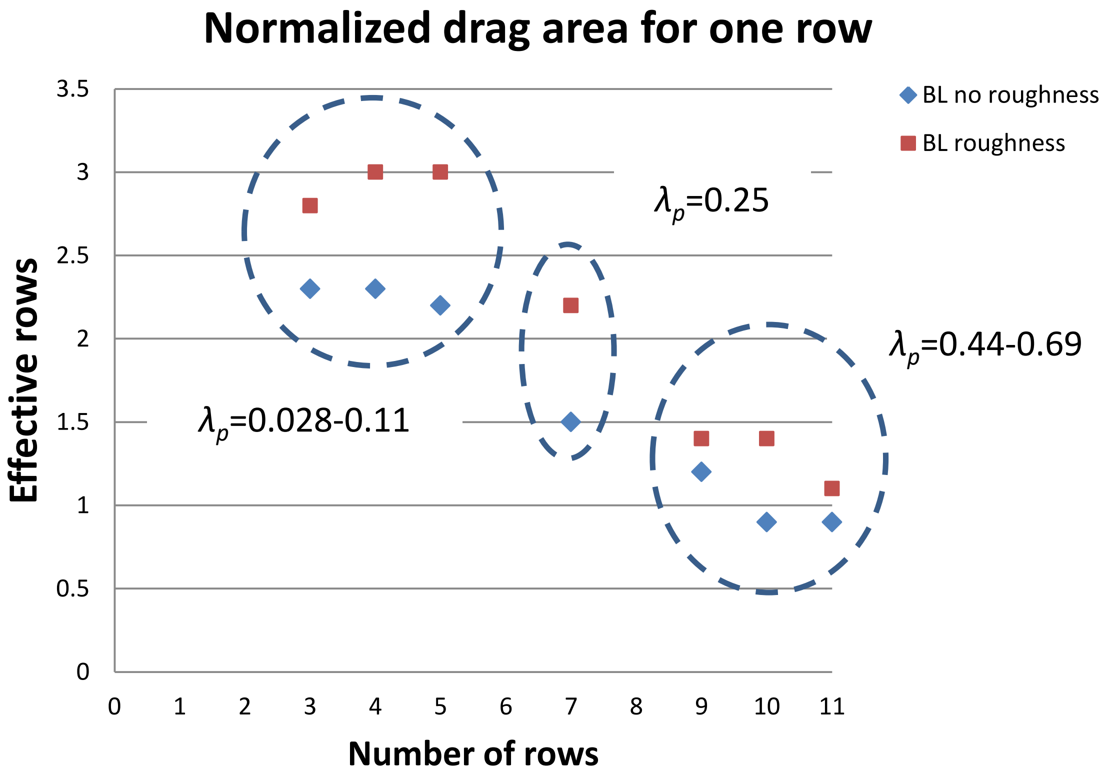
$$N_{effective}(\lambda_p) = \frac{\text{Total drag area}}{\text{Drag area of isolated cube}} = \frac{A_{\mathrm{D\_total}}(\lambda_p)}{A_{D\_isolated\_cube}} = \frac{\sum_{i=1}^{N} A_{\mathrm{D}}^i}{A_{D\_isolated\_cube}}$$

- **Assessment of rows of cubes which are effective in generating the drag force**
- It can be employed for *regular arrays of buildings subjected to perpendicular approaching wind provided that the drag force of upstream to downstream rows is known*

Results

effective rows of cubes generating the drag force

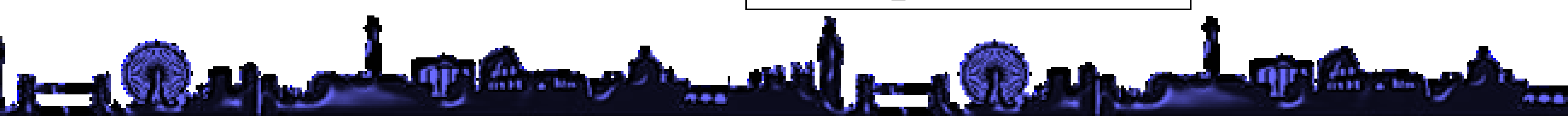
HOW MANY CUBES (or rows of cubes) GENERATE THE DRAG FORCE?



NEXT STEP: Link the drag area A_D to λ_p for the calculation of C_D or other parameters, under several wind directions (no drag force measurements required)

$$A_{D\_total} = \frac{F_{D\_total}}{\frac{1}{2}\rho U^2_{ref}(H)} \propto f(\lambda_p)$$

$$C_D \propto f(A_D\_total)$$



Conclusions

- A novel technique (based on a standard load cell) is set-up to **directly measure the drag force in wind tunnel**
- A comprehensive **dataset of drag force measurements**
- **Change of the distribution of the drag force within the array, with most of the force acting on first rows of the arrays at higher packing densities**
- Consequences on the estimation of C_D employed for parameterizing urban effects in dispersion models. **Based on the measured drag force, we propose**
  - **recommendation on the choice of the appropriate reference area** for the calculation of C_D

THANKS FOR

YOUR ATTENTION!

PUBLISHED: Buccolieri, R., H. Wigö, M. Sandberg and S. Di Sabatino, 2017**: Direct measurements of the drag force over aligned arrays of cubes exposed to boundary-layer flows**. *Environmental Fluid Mechanics*, **17**, 373-394

IN PREPARATION: Buccolieri, R., H. Wigö, M. Sandberg and S. Di Sabatino, in preparation. **Experimental determination of the drag force distribution within regular arrays of cubes**