12th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes

UNIVERSITY OF SALENTO (ITALY)

UNIVERSITY OF BOLOGNA (ITALY)

UNIVERSITY OF CAMBRIDGE (UK)

The Influence of Buoyancy on Flow and Pollutant Dispersion in Street Canyons

RICCARDO BUCCOLIERI *Dipartimento di Scienza dei Materiali - University of Lecce (ITALY)*

BEATRICE PULVIRENTI *DIENCA - University of Bologna (ITALY)*

SILVANA DI SABATINO *Dipartimento di Scienza dei Materiali - University of Lecce (ITALY)*

REX BRITTER *Department of Engineering – University of Cambridge (UK)*

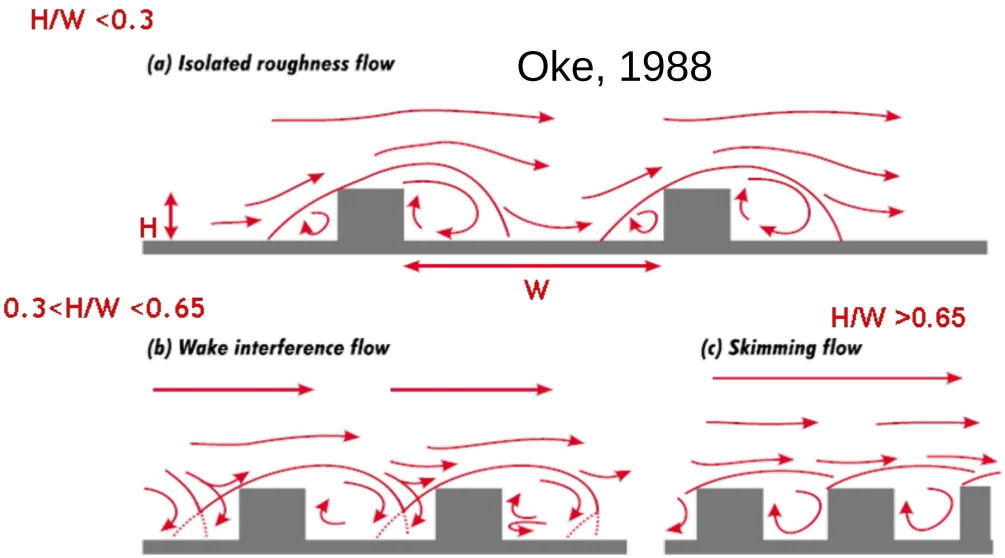
Outline

- **I**ntroduction
- **Approach**
- **R**esults
  - flow field
  - temperature field
  - concentration field
- **S**ummary and **C**onclusions

Introduction

STREET CANYON

- city basic geometry unit
- geometries which affect flow and turbulence fields
- ***aspect ratio***, W/H



Oke, 1988

Introduction

Our past work - *Mechanical forcing*

STUDY OF FLOW AND DISPERSION IN STREET CANYONS

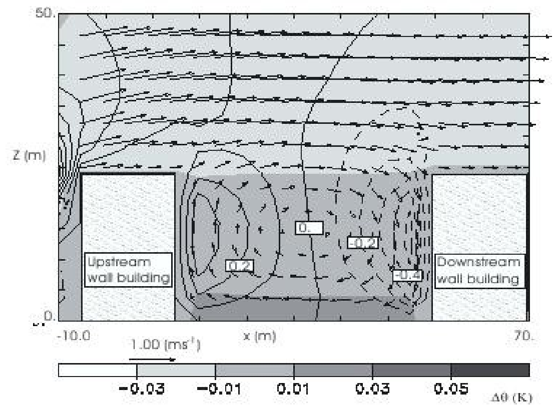
- Study of the **effects of ambient wind direction** on pollutant dispersion by means of the commercial CFD code FLUENT using *k*-*ε* turbulence models and the advection-diffusion method
- Study of the **influence of building geometry** on pollutant dispersion
- **Validation/Comparison of CFD predictions** with results from an integral dispersion model such as ADMS-Urban
- Validation/Comparison of CFD predictions with wind tunnel measurements

Literature – Examples
Heat effects

➢**BOHNENSTENGEL et al.** (Metereologiske Zeitschrift, 2004) studied the problem numerically

➢*Mechanical forcing dominates the circulation inside a street canyon,*
➢*but this forcing is influenced by the large-scale thermal stability*

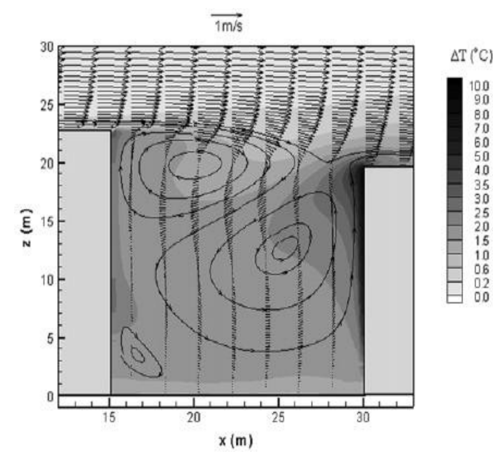
➢**They do not give model details or limits for the presence of the effects, nor they study the effects of thermal gradients on dispersion**



➢**LOUKA et al.** (Water, air and soil pollution, 2002) studied the problem by open field experiments and numerically (based on experimental results performed on a street canyon in Nantes)

➢*Windward heating: a thin boundary layer develops locally within a few centimeters from the heated wall, modifying the vortex*

➢*Thermal effects important for air quality in the street,* but **they do not obtain the concentration profile modification**

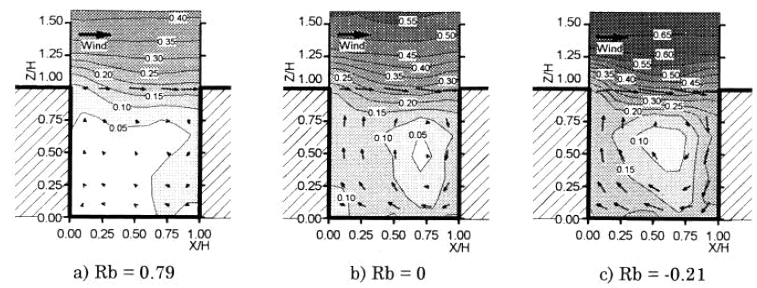


Literature – Examples
Heat effects

➢**UEHARA et al.** (Atmospheric Environment, 2000) parameterised the problem with the Richardson number

➢They introduced a negative Ri number when the leeward wall is heated (unstable condition) and Ri positive when the windward wall is heated (stable condition)

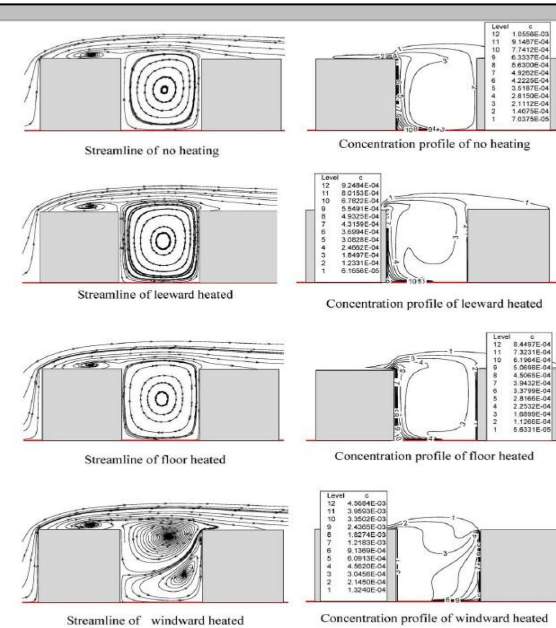
➢*Enhancement of the primary vortex when the leeward is heated*



➢**XIE et al.** (Building and Environment, 2005; Atmospheric Environment, 2007)

➢2D numerical study on flow and pollutant dispersion.

➢They found a *strong influence of thermal gradients on the wind and pollution dispersion*, as shown by the figure



Literature – Examples Heat effects

- **SOLAZZO and BRITTER** (Boundary-Layer Meteorology, 2007) studied differential temperatures between the canyon bounding facets, the spatial temperature distribution within the canyon and the temperature of the air above the canyon.

- *Vortex within the canyon produced a temperature distribution spatially uniform, Tcan.* The variation of *Tcan* with wind speed, surface temperatures and geometry was extensively studied.

- *A simple parameterisation was proposed to evaluate the temperature within the cavity:*

$$T_c = 0.11 \frac{H}{W} \left(T_w - T_{amb}\right) + T_{amb}$$

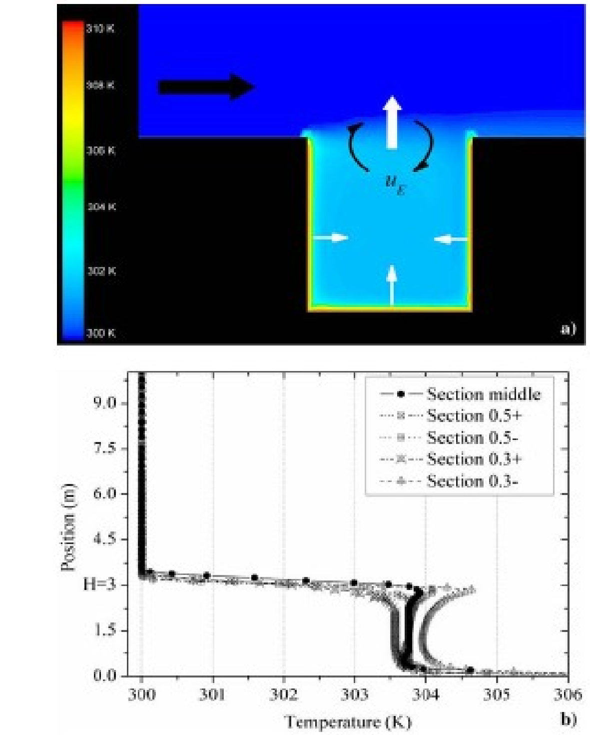
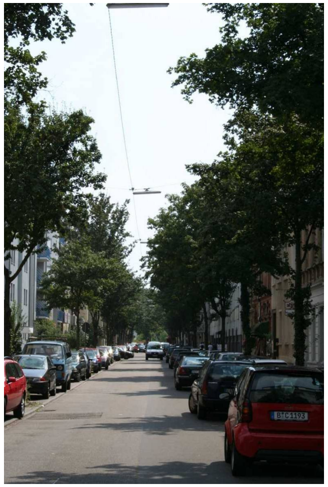


Fig. 6 (a) Temperature contours for the simulated case with $H/W = 1$, $U_{IN} = 5.0\,\mathrm{m\,s^{-1}}$, $T_w = 310\,\mathrm{K}$. The meaning of the arrows is the same as in Fig. 1. (b) Temperature profiles within the canyon for five vertical sections: the mid-section and four sections (0.3+ and 0.5+) near to the downstream facet (respectively 0.3 m and 0.5 m from the downstream facet) and 0.3− and 0.5− near to the upstream facet (at the same distances)

- **NO DETAILS ON METHODOLOGY**
- **INCREASE OF MORE STUDIES**

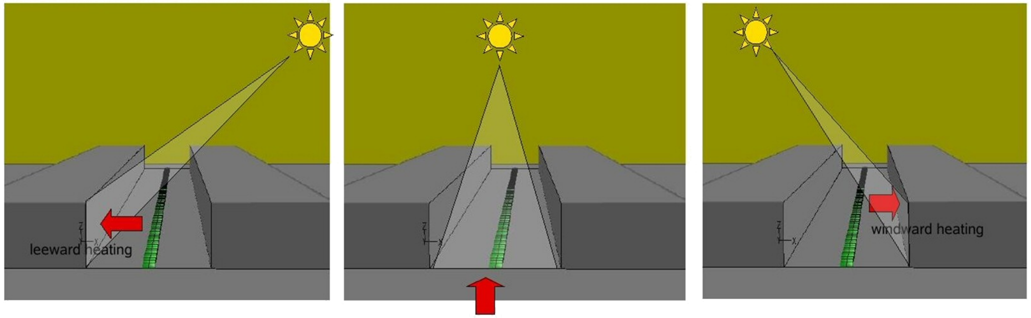
Approach

Impact of ground and wall heating on flow and pollutant dispersion in a street canyon



- **Thermal effects** affect street canyon flow and pollutant transport
- They are generally due to **solar radiation** on building walls and ground surface that heats up air in the vicinity
- The role of **buoyancy forces** within street canyon is particularly relevant under **calm wind conditions**, when downward inertial forces are often compensated by an upward flow due to the buoyancy

heating at: **ground level, leeward and windward** (ΔT=10°C)



Approach
buoyancy modelling

- When heating the building walls or ground, the **air density changes** due to the air temperature increase.

- **Buoyancy forces** are incorporated in the momentum equation

- The model for buoyancy forces the **Boussinesq's hypothesis** is adopted (the density and the other physical parameters do not change, except for the density in the buoyancy forces term).

- The **rate change in the air density** due to an increase in temperature is:

$$\frac{\rho_w - \rho_a}{\rho_a} = -\beta\left(T_w - T_a\right)$$

β: thermal expansion coefficient → $\beta = -\frac{1}{\rho_a}\frac{\rho_w - \rho_a}{T_w - T_a} \approx 3.3 \cdot 10^{-3} K^{-1}$

ρ_a and T_a: ambient density and temperature

ρ_w and T_w: wall density and temperature

- From momentum equation, Ri allows to estimate the effect of the thermal radiation on the flow in the street canyon.

Richardson number

$$Ri = \frac{\left[g\left(T_w - T_a\right)H\right]}{T_a {u_0}^2} = \frac{Gr}{\mathrm{Re}^2}$$

g: gravitational acceleration

H: building height

u_0: ambient wind velocity

Approach

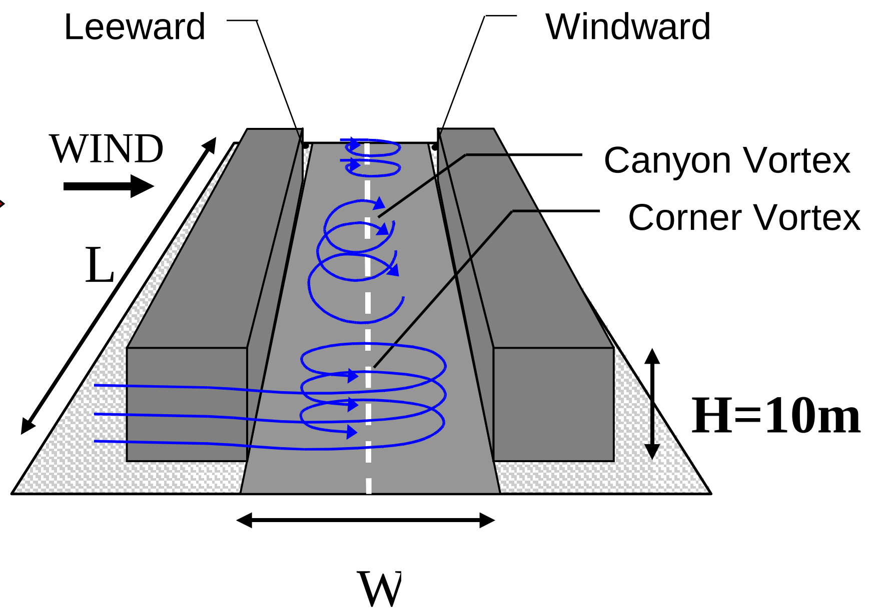
outline of the cases investigated

Skimming flow

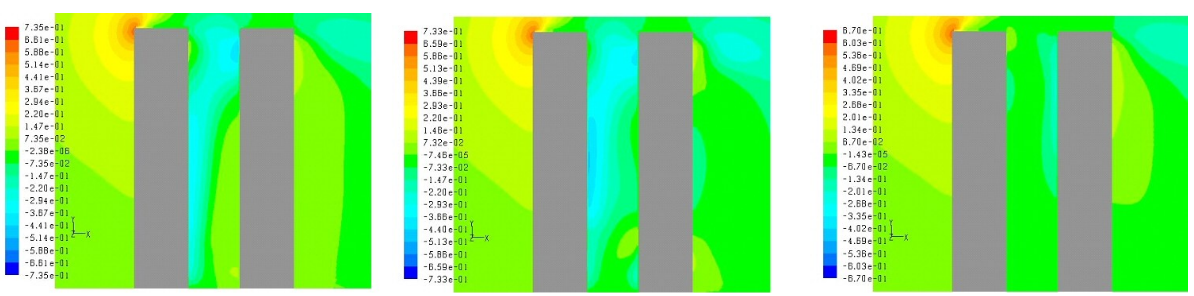
Wake interference flow

- 4 street canyon aspect ratios: **W/H=0.33-0.5-1 2**

- to avoid unrealistic three-dimensional effects, depending on L/H, a ratio **L/H=20** is chosen (after performing sensitivity tests)



Plane: z/H=0.5



W/H=1, L/H=10

Y velocity component: leeward heating (left), ground heating (middle) and windward heating (right)

A large amount of air enters in the canyon from the lateral openings. Then, the problem becomes strongly three-dimensional, and the expected single vortex structure is not observed even in the middle of the canyon

Approach

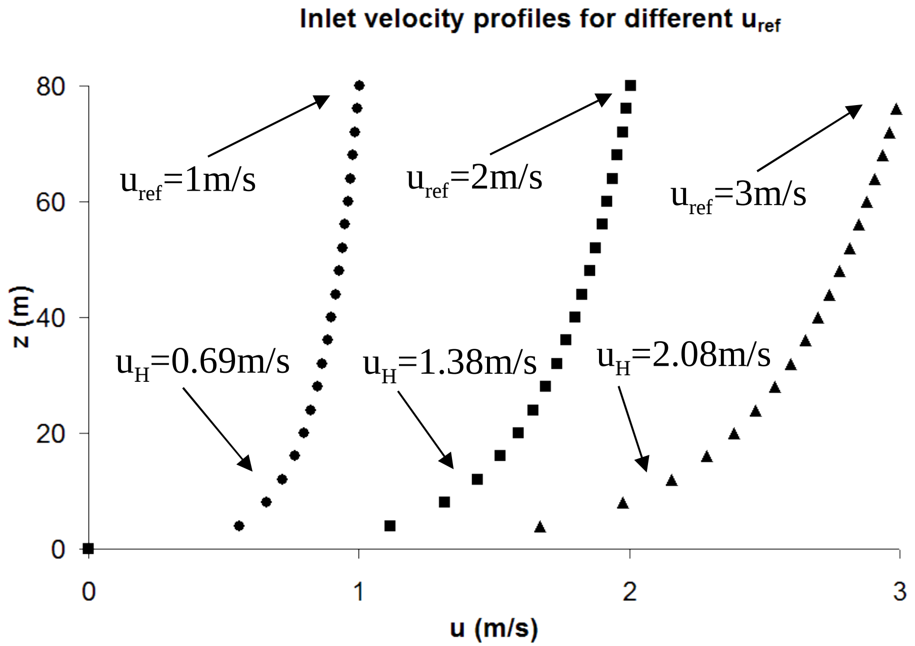
outline of the cases investigated

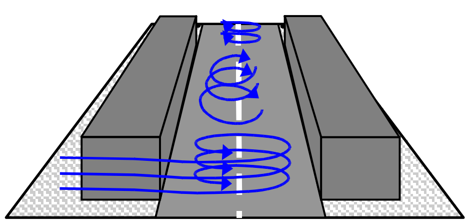
Richardson number

$$Ri = \frac{[g(T_w - T_a)H]}{T_a u_o^2} = \frac{Gr}{Re^2}$$

u_{ref} (m/s) at domain height	Ri
1	**3.27**
2	**0.82**
3	**0.36**

u_H (m/s) at building height	Ri_H
0.69m/s	**6.82**
1.38m/s	**1.70**
2.08m/s	**0.76**





Approach
numerical modeling

- CFD code FLUENT
- grid: hexahedral elements
  - ~1,000 000
  - δ_x=0.02H, δ_y=0.1H, δ_z=0.025H
- RANS-Equations
- turbulence closure schemes
  - standard *k-ε*
- second order discretization schemes
- Boussinesq approximation

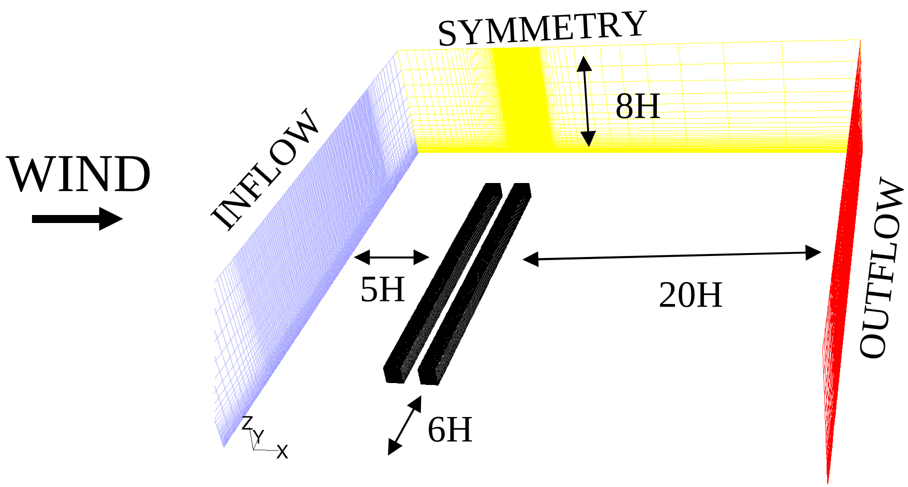
- dispersion: advection-diffusion method
- line source (*l*=*L*) along the street canyon centerline

$$c^+ = \frac{c\,u_{ref}\,H}{Q/l}$$

c: calculated concentration

u_{ref}: reference velocity at the top of the domain

Q=10 g/s: strength of line source



INLET

$$u(z) = \frac{u_*}{\kappa}\ln\left(\frac{z+z_0}{z_0}\right) \quad k = \frac{u_*^{\,2}}{\sqrt{C_\mu}}\left(1-\frac{z}{\delta}\right) \quad \varepsilon = \frac{u_*^{\,3}}{\kappa z}\left(1-\frac{z}{\delta}\right)$$

*u**: friction velocity

κ=0.40: von Kàrmàn constant

z_0*=0.1 m:* roughness length

C_μ = 0.09

δ: boundary layer height

Approach
numerical modeling

Computational times: about 12 hours with a *Dual AMD Opteron™ Processor 2000Mhz – 1024 KB Cache – 2 GB RAM*

Wall function: one of the difficulties of computation of natural convection by the standard $k - \varepsilon$ model is the validity of the wall function method, which is based on the local equilibrium logarithmic velocity and temperature assumptions. The **logarithmic wall functions** were originally derived for **forced-convection flows** and do not hold for natural convection boundary layers.

↓

fine grids close to the wall when Grashof numbers (Gr) are high

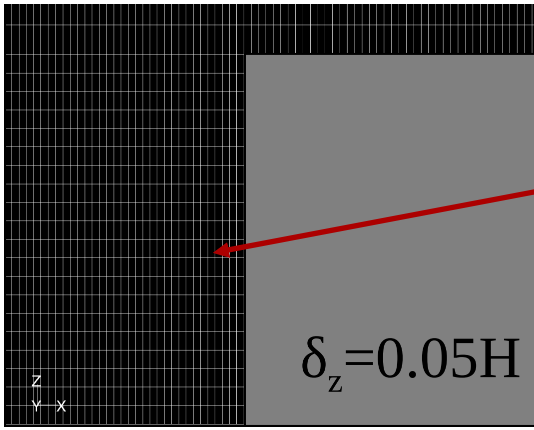
M. Holling and H. Herwig, 2005. Asymptotic analysis of the near-wall region of turbulent natural convection flows. J. Fluid Mech., 541, 383–397.

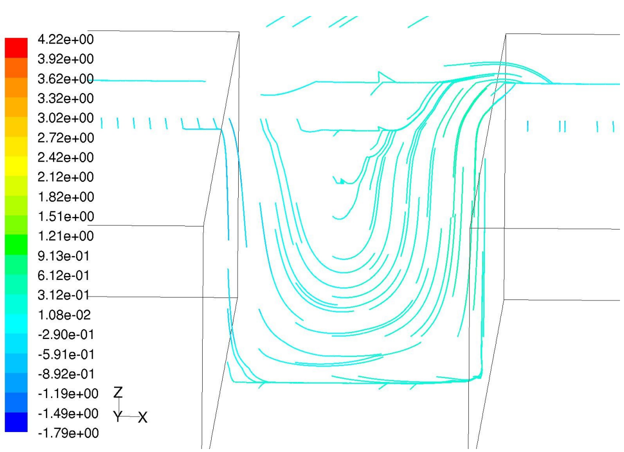
W/H=1
windward heating - Ri=3.27

Approach
numerical modeling

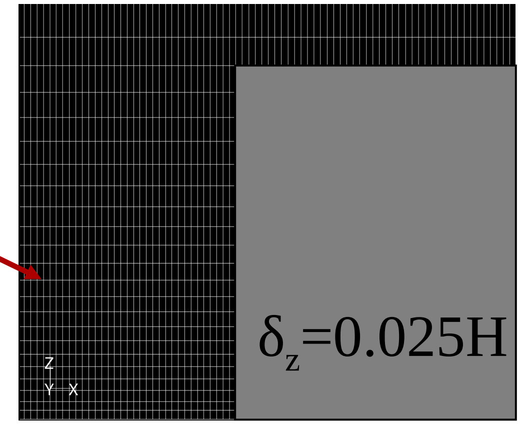
After introducing the dispersion…..

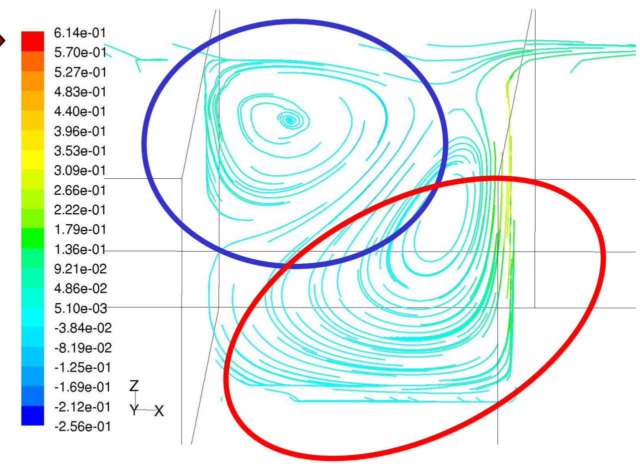
Mesh inside the canyon





- **grid not sufficient to capture thermal and dispersion effects together**
- flow structure unrealistically altered: **large vertical velocity component** is observed over the top of the buildings

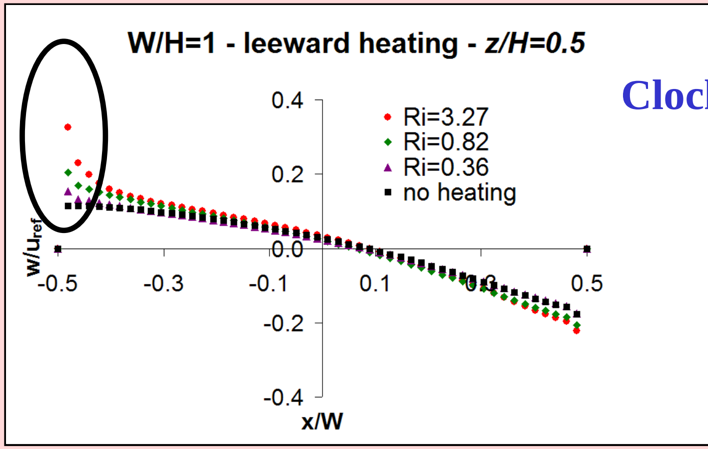




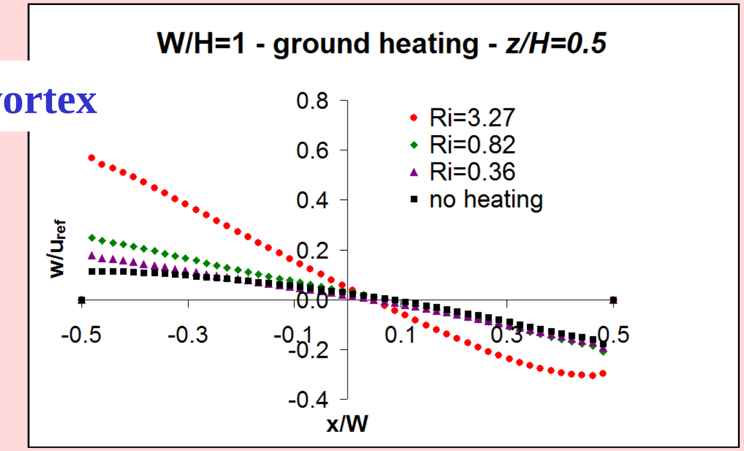
clockwise and anti-clockwise vortex

Results
flow field – influence of Ri

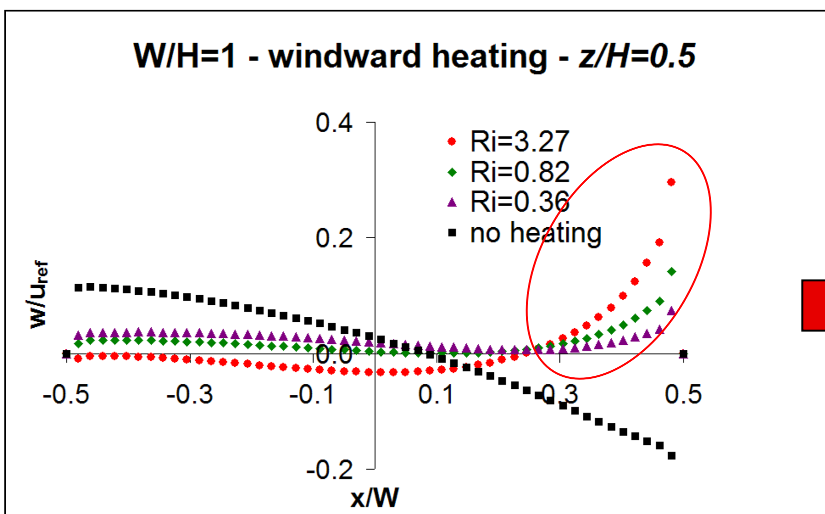
W/H=1



Clockwise vortex



Slight buoyancy effect for all the aspect ratios and the Ri considered



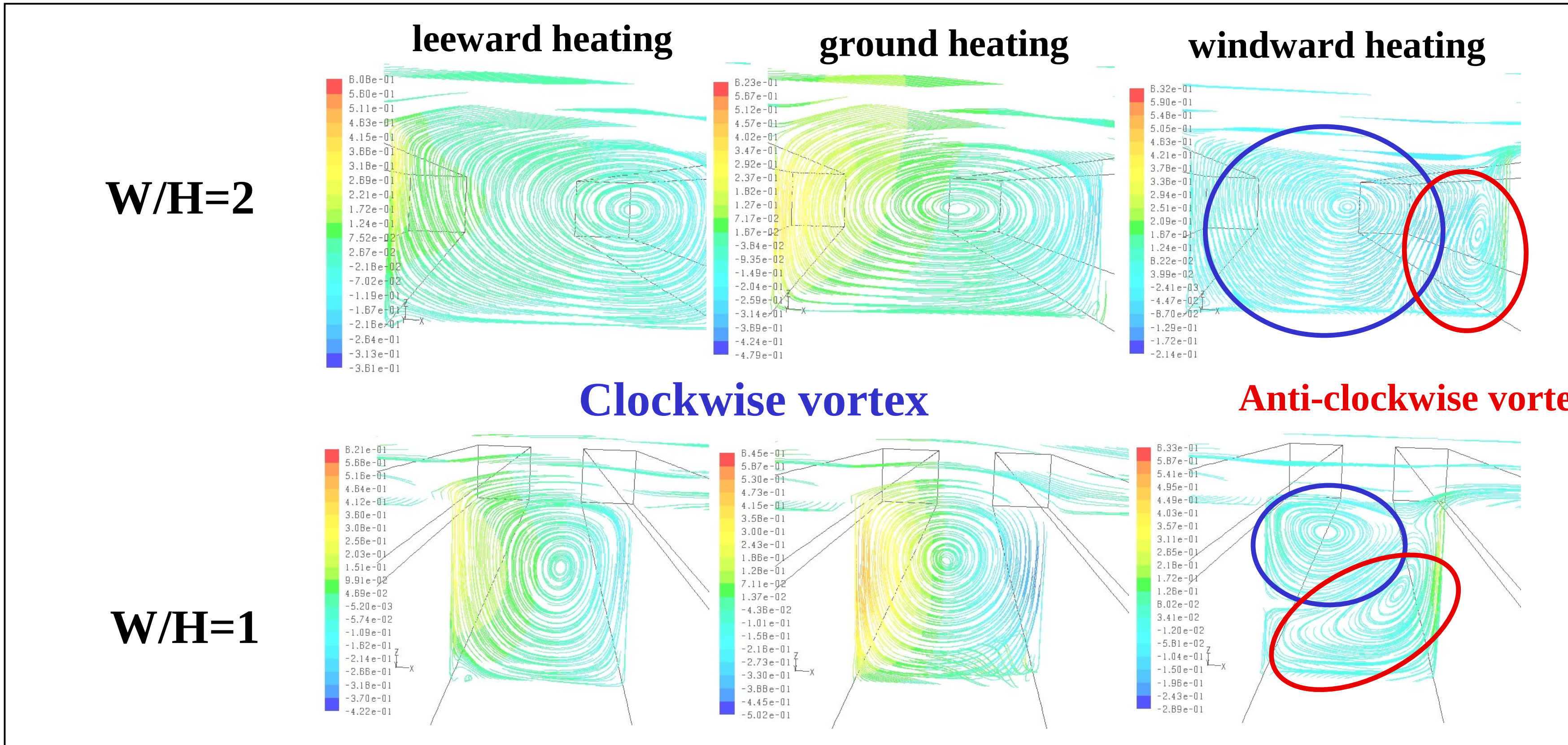
Anti-clockwise vortex more pronounced at higher Ri for all aspect ratios

Results

flow field – influence of heating

Ri=3.27, u_{ref}=1m/s

z velocity component, middle (y=0) of the canyon



weak dependence on the aspect ratio (the vortex is enhanced by the buoyancy)

vortex weaker as the aspect ratio increases (larger vertical velocity could break the vortex at smaller aspect ratios)

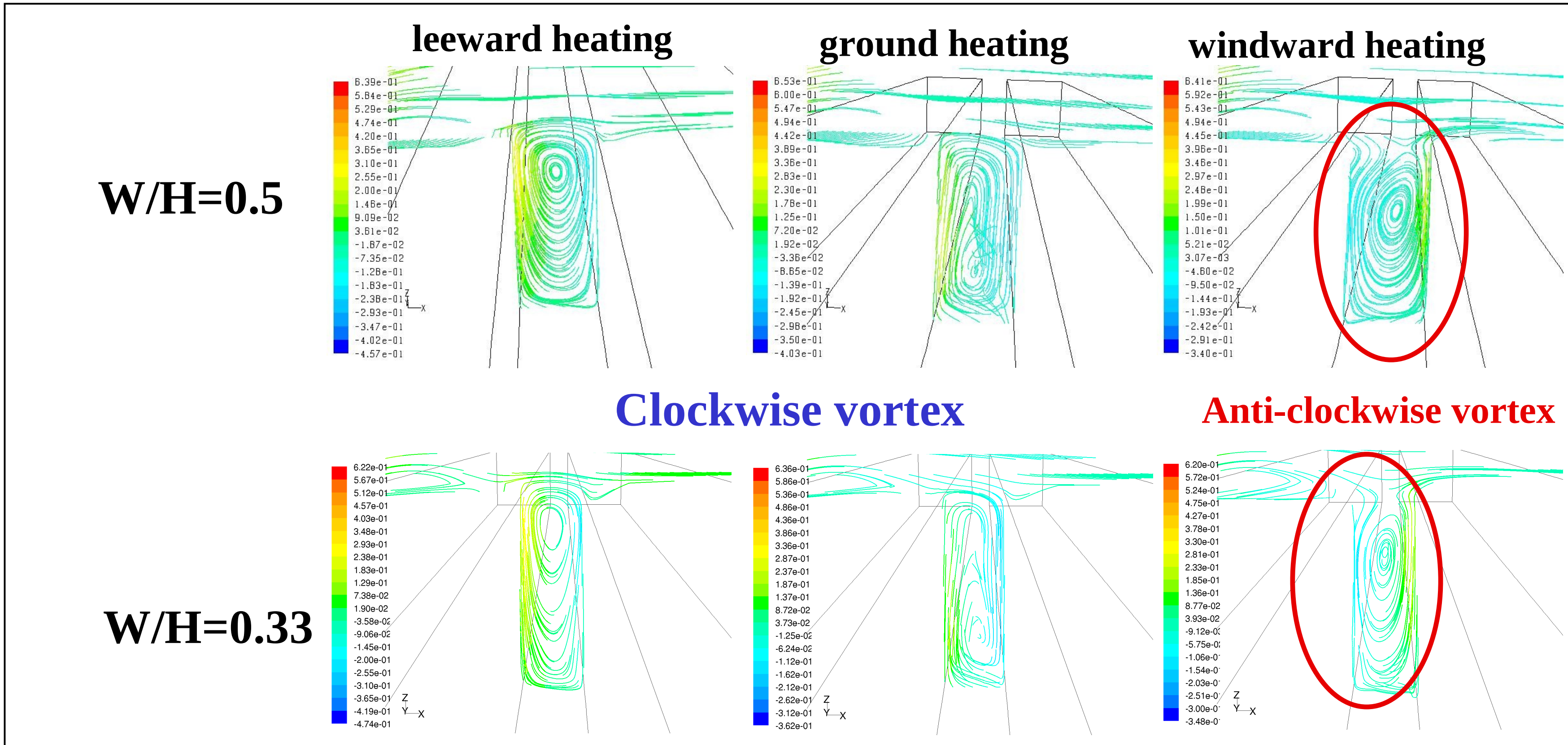
- **clockwise vortex suppressed by the anti-clockwise vortex as W/H decreases**

Results

flow field – influence of heating

Ri=3.27, u_{ref}=1m/s

z velocity component, middle (y=0) of the canyon



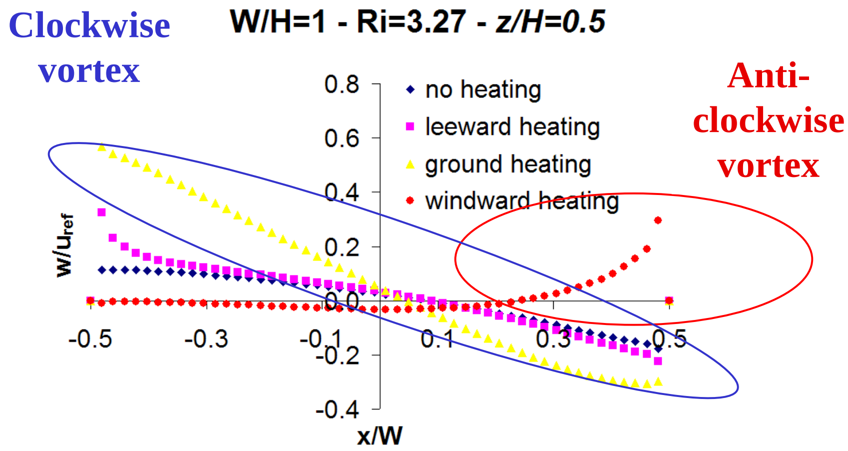
weak dependence on the aspect ratio (the vortex is enhanced by the buoyancy)

vortex weaker as the aspect ratio increases **(**larger vertical velocity could break the vortex at smaller aspect ratios)

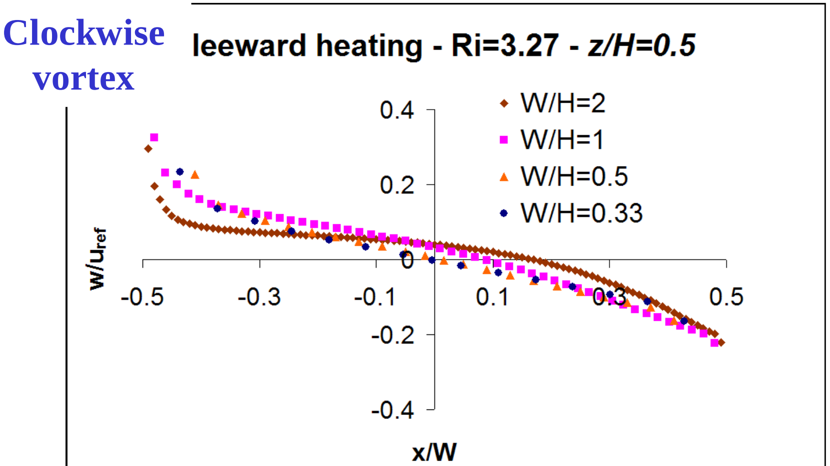
Results

flow field – influence of heating/W/H

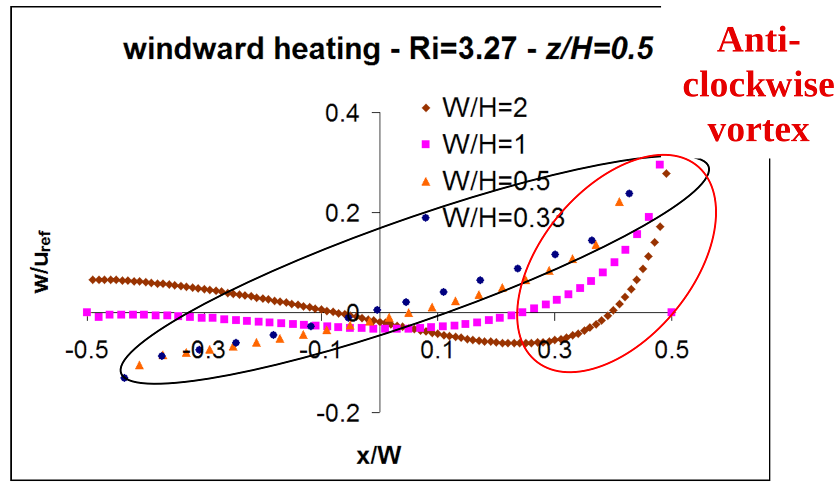
Ri=3.27, u_{ref}=1m/s



- Contribution to buoyancy due to different heated walls
- Strong effect for windward heating



weak dependence on the aspect ratio (the clockwise vortex is enhanced by the buoyancy)



- **clockwise vortex suppressed by the counter-rotating vortex as W/H decreases**
- **counter-rotating vortex dominant at W/H=0.5 – 0.33**

Results
flow field – sensitivity to W/H

middle of the canyon

Ri=3.27
u_{ref}=1m/s

<table>
<tr><th>W/H \ Heating</th><th>No heating</th><th>Leeward</th><th>Ground</th><th>Windward</th></tr>
<tr><td>2</td><td colspan="3" rowspan="4">One clockwise vortex</td><td rowspan="2">Two vortex: clockwise and anti-clockwise</td></tr>
<tr><td>1</td></tr>
<tr><td>0.5</td><td rowspan="2">One anti-clockwise vortex</td></tr>
<tr><td>0.33</td></tr>
</table>

Ri=0.36
u_{ref}=3m/s

<table>
<tr><th>W/H \ Heating</th><th>No heating</th><th>Leeward</th><th>Ground</th><th>Windward</th></tr>
<tr><td>2</td><td colspan="3" rowspan="4">One clockwise vortex</td><td>One clockwise vortex</td></tr>
<tr><td>1</td><td rowspan="2">Two vortex: a clockwise above a small anti-clockwise</td></tr>
<tr><td>0.5</td></tr>
<tr><td>0.33</td><td>Two vortex: a small clockwise above a anti-clockwise</td></tr>
</table>

Results
temperature field – flow field

Ri=3.27, u_{ref}=1m/s

middle (y=0) of the canyon

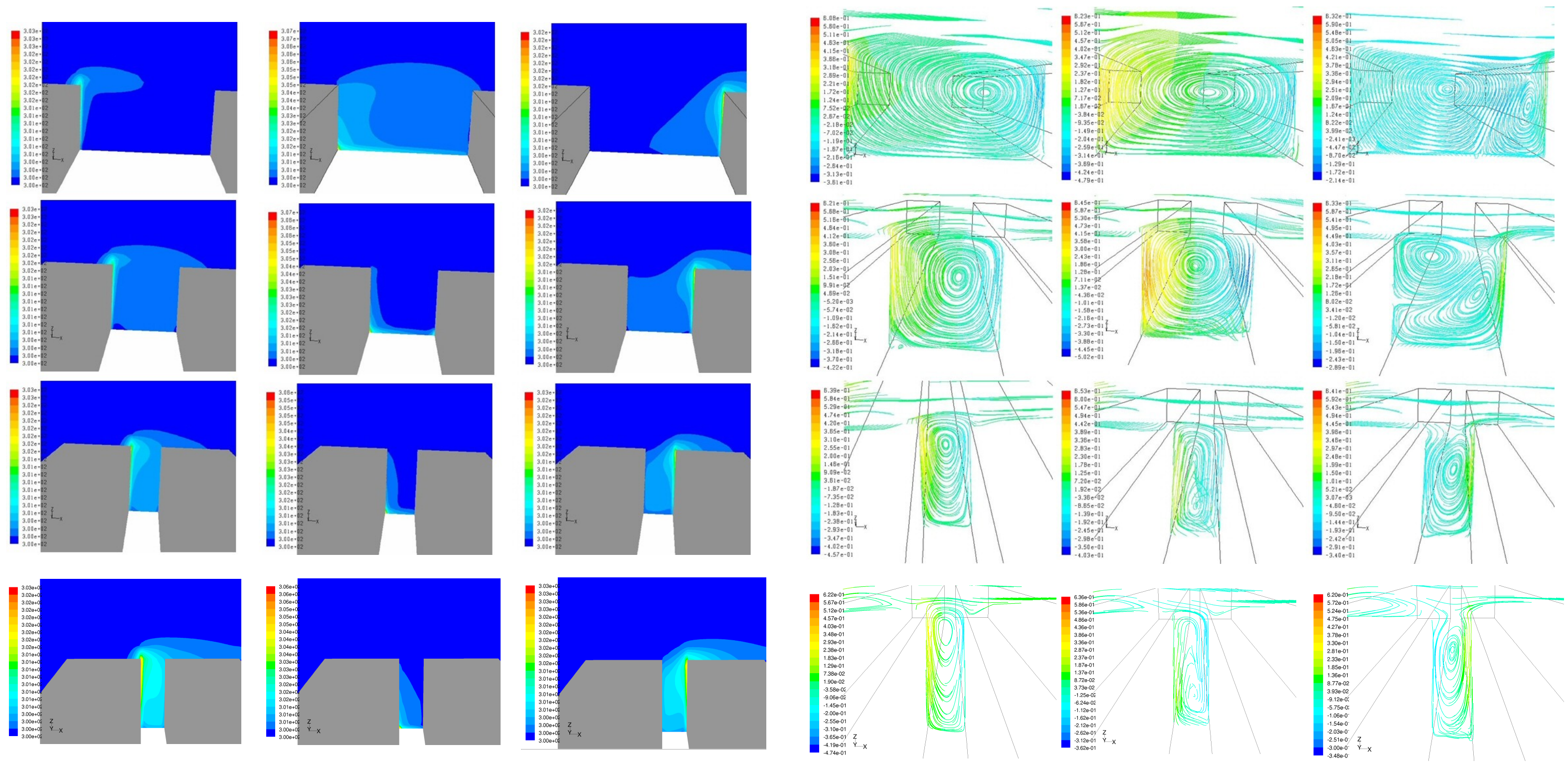
	leeward h.	ground h.	windward h.	leeward h.	ground h.	windward h.

W/H=2

W/H=1

W/H=0.5

W/H=0.33



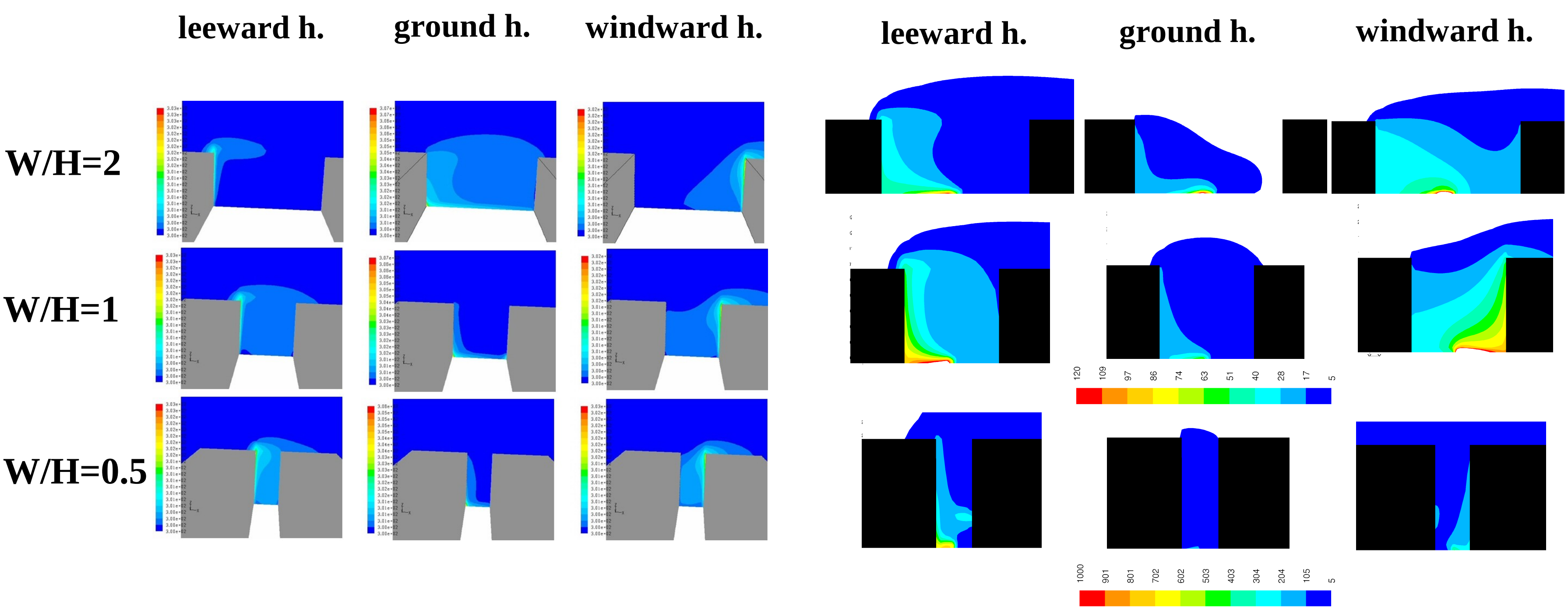
Temperature **Flow field**

Results

temperature field – concentration field

Ri=3.27, u_{ref}=1m/s

middle (y=0) of the canyon



Temperature

Concentration

Summary and Conclusions

combined buoyancy and mechanically induced forces → **wind flow structure** and **pollutant dispersion** characteristics in street canyons

FLOW

DISPERSION

Leeward heating

for all the Ri and W/H

- **clockwise canyon vortex enhanced**
- **its centre shifted towards the windward**

↓

lower concentrations with respect to the no heating case

Ground heating

for all the Ri and W/H

- **clockwise canyon vortex maintained**
- larger vertical velocity occur **increasing the exchange with the top flow**

↓

very lower concentrations with respect to the no heating case

Windward heating

- cooler air from the bottom of the canyon leads to **a second vortex close to the windward wall**
- the **anti-clockwise vortex** appears **at larger aspect ratios W/H when Ri is higher**

↓

larger pollutant concentrations near the windward wall rather than at the leeward

THANK YOU FOR
YOUR ATTENTION!