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Energy Procedia 101 (2016) 1018 – 1025

Energy Procedia

71st Conference of the Italian Thermal Machines Engineering Association, ATI2016, 14-16 September 2016, Turin, Italy

Numerical study of buoyant flows in street canyon caused by ground and building heating

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Abstract

The urban areas discomfort is related to the increase of local temperatures, which is induced by the large concentration of the built environment, road pavement and the high construction materials thermal capacitance. The particular configuration of buildings arrangement amplifies the population vulnerability and the exposure to pollution. These conditions can be related to the "urban fabric" density, road geometrical characteristics, buildings features and, finally, to the lack of wide-open spaces. An important part of the heat exchange between buildings and the ambient surrounding is due to convective and radiative phenomena. Computational fluid dynamics (CFD) is often used to predict flow structures in urban areas for the determination of pollutant dispersion, human comfort or heat fluxes. During daytime building façades and ground surfaces are heated by solar radiation and thereby they induce buoyancy, which changes the flow field around buildings significantly. A computational fluid dynamics (CFD) model is developed and used to investigate the thermo-fluid dynamic effects inside and above a street canyon. In this study different simulations have been performed and validated, investigating the micro-climatic condition, such as thermal and air velocity fields.

Keywords: Urban Heat Island; CFD; Thermo-fluid dynamic effects; Building; Street canyon.

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doi:10.1016/j.egypro.2016.11.129

1. Introduction

In the cities, human health is related to the urban fabric. As a matter of fact, thermal comfort and exposure to pollutant are related to different causes: height of building; weight of roads; absence or presence of vegetation; pavement and building material; wind intensity and consequent natural ventilation; and so on. Different researches on urban areas [1-8] and especially to the indirect energy efficiency effect caused by the variation of urban thermal field [9-19] are done in order to investigate the environmental effect to the buildings. The variation of the urban fabric caused by the rapid urbanization of cities leads to the modification of the environment thermo-fluid dynamic field and a consequent variation of the building and plant performances. Different studies are focused to reduce the thermal worsening with the use of urban heat island mitigation techniques [18-20]. Computational fluid dynamics (CFD) can used to analyse the thermal flow field condition around the buildings in order to investigate the causes of the temperature increase inside urban canyons [21].

In this study it was analysed the thermo-fluid dynamic effects inside and above a street canyon considering an idealized two-dimensional urban canyon.

Nomenclature

Rb	bulk Richardson number
g	acceleration due to gravity [m/s^2]
T_a	ambient air temperature [°C]
T_g	ground temperature [°C]
U_{2H}	velocity at altitude of 2H [m/s]
H	building height [m]
W	street width [m]
ΔTG	temperature difference between ground and air [°C]
ΔTB	temperature difference between building walls and air [°C]

2. Numerical model

The idealized 2D street canyon is shown in Figure 1 where all the dimensions of the model domain is related to the building height H. The distances from the building and the domain boundary are in according to the AIJ guidelines [22].

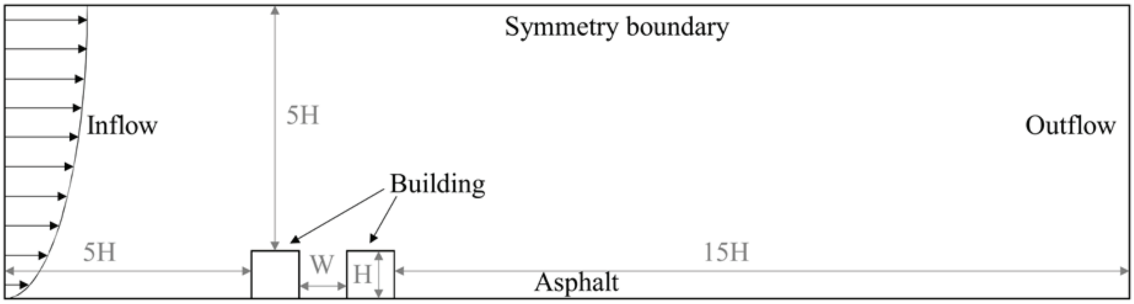

Fig. 1. Schematic diagram of the computational domain.

The mathematical model considers the *k-ε* turbulence model with Renormalization Group (RNG) theory in order to solve the Reynolds-averaged Navier-Stokes (RANS) and energy transport equations. The model equations are discretized using a second-order scheme with finite volume method solved by the CFD code Fluent. The mesh of the computational domain is constituted of 89511 quadrilateral elements resulting from a grid independence study shown in Figure 1a considering the variation of the Reynolds number calculated inside the urban canyon. The mesh chosen have an error of about 6% compared to the finer mesh. The mesh is refined near the wall, in order to resolve the non-equilibrium wall functions [23] as shown in Figure 2b. No slip boundary condition is employed at ground and building surfaces. Fixed temperature boundary conditions are employed on the wall and ground surfaces.

At the inlet it was implemented the atmospheric boundary layer (ABL) profiles of velocity, turbulence dissipation rate and turbulence kinetic energy in according with the equation 1-2-3 [24]:

$$U(y) = \frac{u^*}{\kappa} \log\left(\frac{y + y_0}{y_0}\right) \tag{1}$$

$$\varepsilon(y) = \frac{u^{*3}}{\kappa \cdot (y + y_0)} \tag{2}$$

$$k = \frac{u^{*2}}{\sqrt{C_{mu}}} \tag{3}$$

where the roughness length is 0.03m, the von Karman coefficient κ is 0.4 and the coefficient C_{mu} is 0.09.

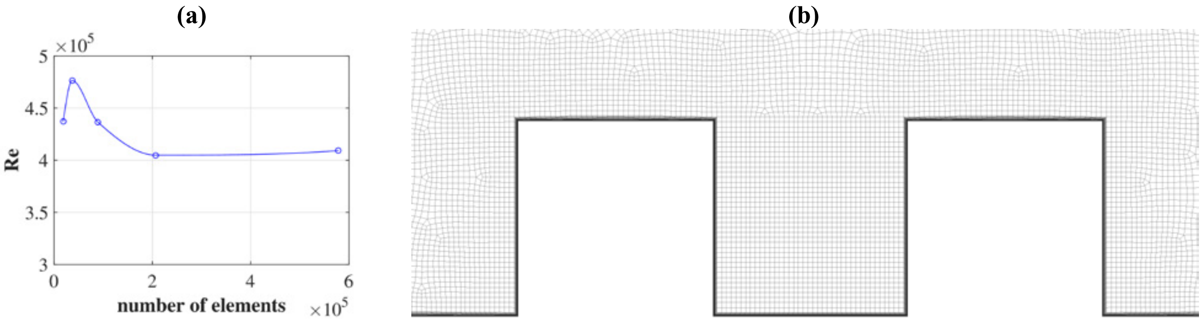

Fig. 2. Mesh and grid independence of the computational domain.

3. Model validation

The numerical model validation was assessed reproducing the model implemented in the wind tunnel experiment performed by Uehara [25]. In the 2D numerical experimental case ten row of buildings of an height of 20 m were considered and the boundary conditions are settled in order to have a model with a bulk Richardson number of -0.21 defined as:

$$Rb = \frac{g \cdot H \cdot (T_a - T_g)}{(T_a + 273.15) \cdot U_{2H}^2} \tag{4}$$

Figure 4 shows the comparison between the measured data performed by Uehara at *Rb=-0.21* and the calculated value from the CFD model. Figure 4a and 4b are related to the Uehara wind tunnel experimental model, while Figure 4c and 4d are related to the idealized urban canyon considered in the present study (Figure 1). Figure 4b shows that the temperature calculated with the numerical model is slightly lower than the experimental data. Figure 4a shows that the horizontal velocity over the building top (y/H>1) is higher than the experimental data, due to the difference of the velocity inlet profile. Inside the urban canyon the horizontal velocity is comparable to the experimental data and the differences are attributed to the use of 2D model instead a three-dimensional model. The velocity inside the urban canyon (y/H<1) is comparable to the experimental data due to the instauration of a great vorticity deeply investigated in fluid-dynamic [26]. In Figure 4a and 4b, the present model validation is compared with other studies [5,27,28]. It is worth to notice that the present model have approximately the same velocity and temperature profile compared to the other studies.

As shown in Figure 4c and 4d, the CFD velocity and temperature vertical profile in the canyon centerline are different from the Uehara wind tunnel experiment setup due to the presence of fluid detachment in the first canyon as shown in Figure 3. Brown [29] demonstrated the presence of fluid detachment in the first building.

As demonstrated above, the model is considered valid to simulate the thermal-condition inside the urban canyon.

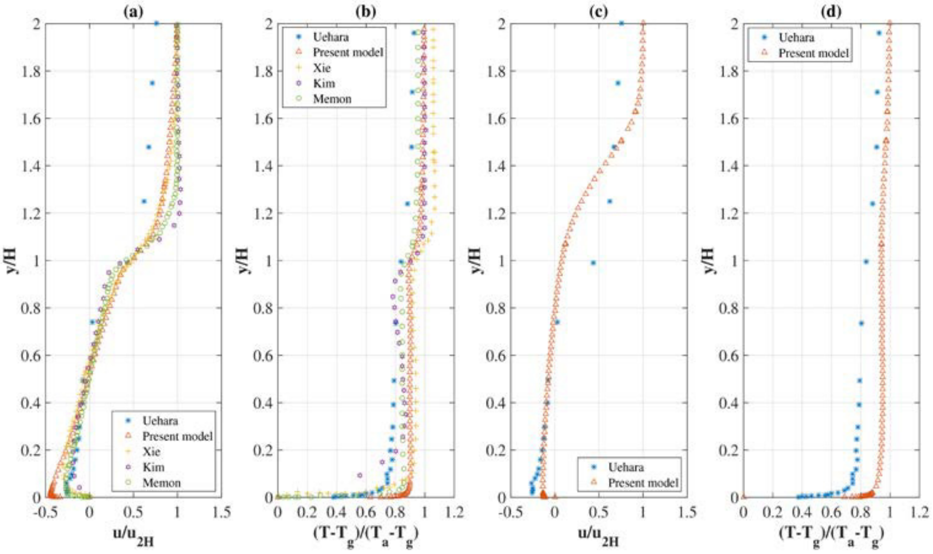

Fig. 4. Comparison between the simulated data and the observed data by Uehara (2000): (a) and (b) are related to the Uehara model setup; (c) and (d) are related to the idealized urban canyon model setup.

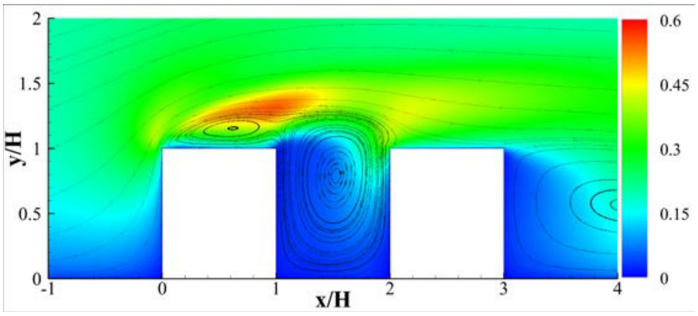

Fig. 3. Flow field and spatial contour of turbulence kinetic energy for the model validation setup

4. Results and discussion

In Figure 5-6-7-8-9 the velocity streamline and the spatial temperature contour of the idealized urban canyon taken into account are shown. Considering an air temperature of 20°C, different simulations were performed using a velocity of 2.5 m/s and 4.5 m/s, and a temperature difference between ground and air (ΔTG) of 0°C, 15°C and 30°C, and between building façades and air (ΔTB) of 0°C, 10°C and 20°C.

In Figure 5 are shown the case in which ΔTG=0 and ΔTB=0. It is possible to notice that with different velocity there is only one main vortex inside the street canyon and a detachment in the first building roof.

Figure 6 shows results when ΔTG=0 and different ΔTB are present. Increasing the building façades temperature there is an instauration of a second vortex at the bottom part of the canyon. When the air velocity outside the canyon is 4.5 m/s, the main vortex remains with a large dimension with a consequent lower air temperature inside the canyon than in the case of 2.5 m/s. As a matter of fact, the presence of two countercurrent vortexes allow to maintain for more time the air heated particles inside the urban canyon as shown in Figure 6c where there is an high temperature near the right wall differently from the left wall. Furthermore, the air temperature near the left wall is more homogenous because there isn’t the influence of the second vortex.

Figure 7 shows results when ΔTB=0 and different ΔTG are present. It is worth to notice that increasing the ground temperature does not involve the instauration of a second vortex. This suggest that the second vortex is induced only when the building façades are heated.

Figures 8 and 9 shows results with a mutual application of different ΔTG and ΔTB. The vorticities established inside the canyon are related to the heating of building façades as mentioned above. The combination of ground and building façades heating can rise the air temperature inside the urban canyon. As expected, the higher air temperature is shown when ΔTB and ΔTG have the maximum values (Figure 9c).

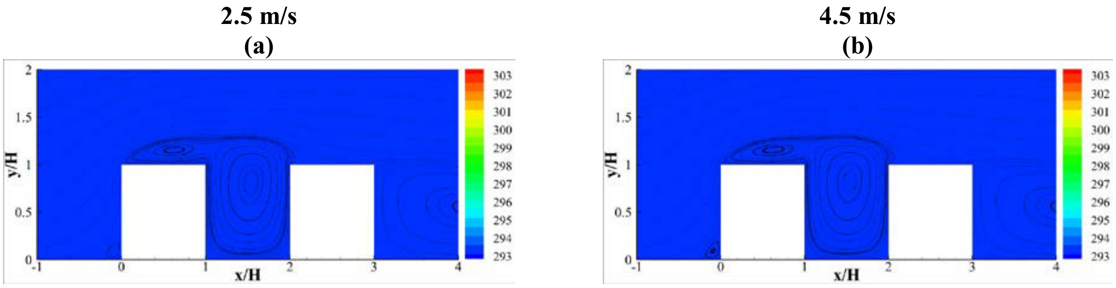

Fig. 5. Velocity streamline and spatial temperature contour of the idealized urban canyon: (a) 2.5 m/s ΔTG=0 ΔTB=0, (b) 4.5 m/s ΔTG=0 ΔTB=0

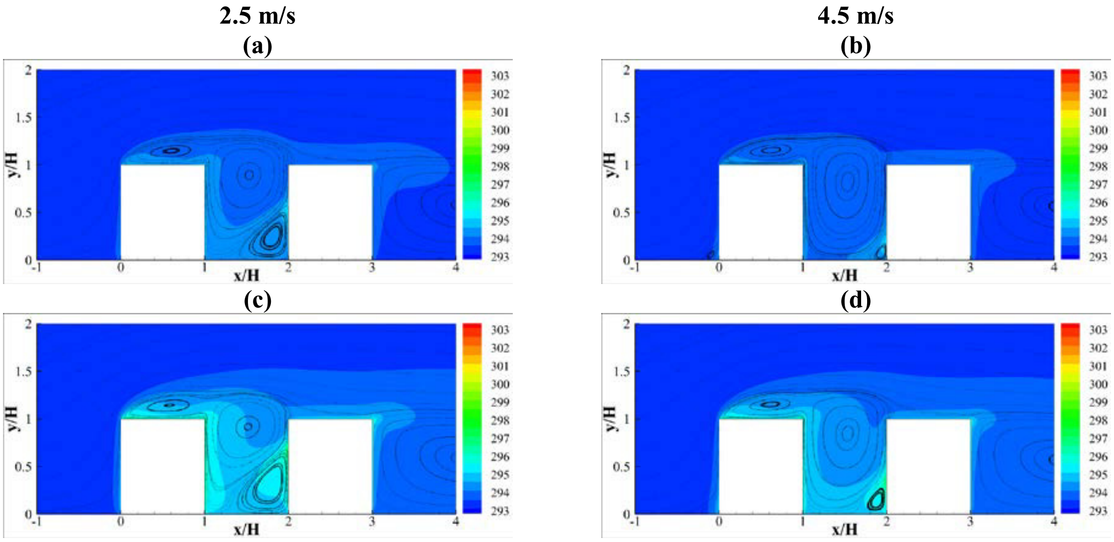

Fig. 6. Velocity streamline and spatial temperature contour of the idealized urban canyon: (a) 2.5 m/s ΔTG=0 ΔTB=10, (b) 4.5 m/s ΔTG=0 ΔTB=10, (c) 2.5 m/s ΔTG=0 ΔTB=20, (d) 4.5 m/s ΔTG=0 ΔTB=20

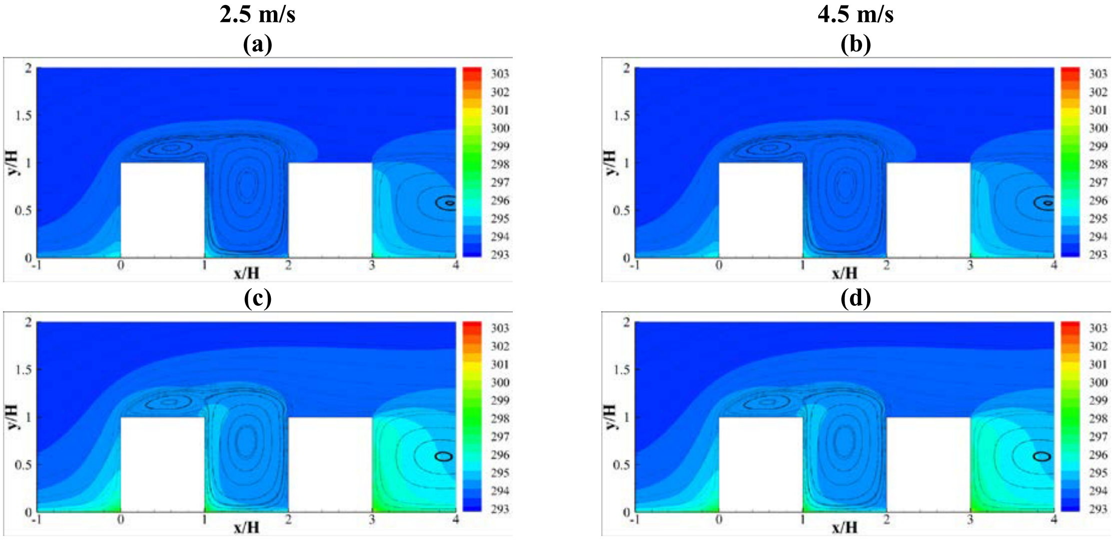

Fig. 7. Velocity streamline and spatial temperature contour of the idealized urban canyon: (a) 2.5 m/s ΔTG=15 ΔTB=0, (b) 4.5 m/s ΔTG=15 ΔTB=0, (c) 2.5 m/s ΔTG=30 ΔTB=0, (d) 4.5 m/s ΔTG=30 ΔTB=0

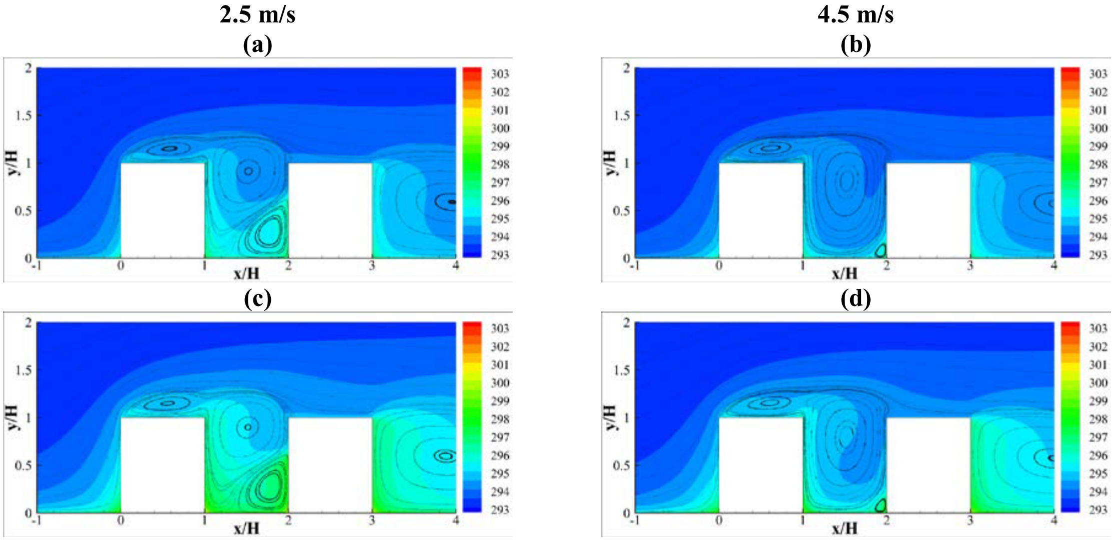

Fig. 8. Velocity streamline and spatial temperature contour of the idealized urban canyon: (a) 2.5 m/s ΔTG=15 ΔTB=10, (b) 4.5 m/s ΔTG=15 ΔTB=10, (c) 2.5 m/s ΔTG=30 ΔTB=10, (d) 4.5 m/s ΔTG=30 ΔTB=10

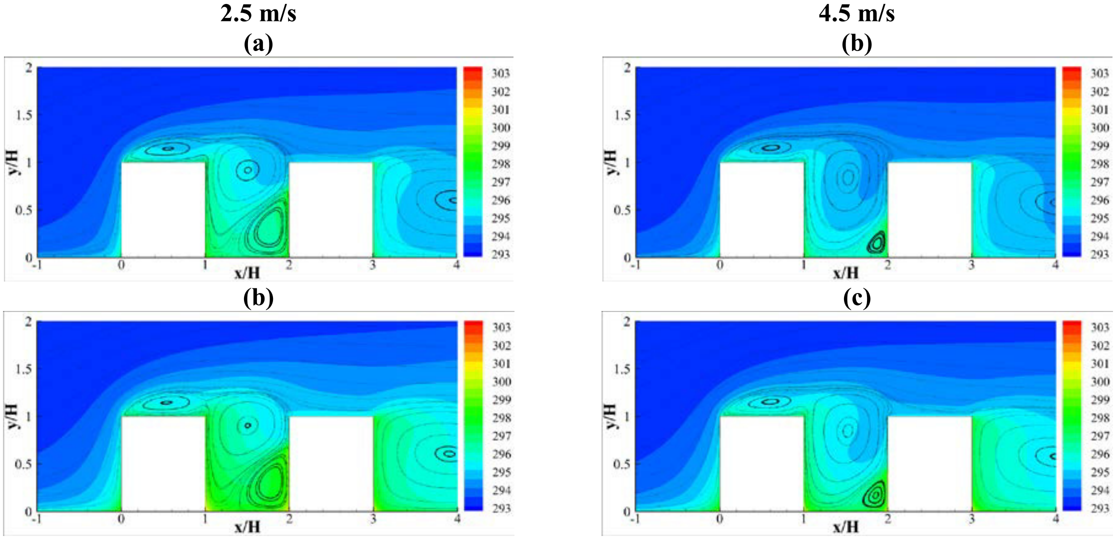

Fig. 9. Velocity streamline and spatial temperature contour of the idealized urban canyon: (a) 2.5 m/s ΔTG=15 ΔTB=20, (b) 4.5 m/s ΔTG=15 ΔTB=20, (c) 2.5 m/s ΔTG=30 ΔTB=20, (d) 4.5 m/s ΔTG=30 ΔTB=20

For all the scenarios, it was analyzed the bulk Richardson number that represents the importance of natural convection relative to the forced convection. By varying its numerical value ($0.1 \leq Rb \leq 10$), mode of convection heat transfer is altered from forced to mixed to natural. In particular, the natural convection is negligible when $Rb \leq 0.1$, forced convection is negligible when $Rb \geq 10$. Therefore, $0.1 < Rb < 10$ is used to describe the effect of both natural convection and forced convection [30].

Table 1 shows the mean bulk Richardson number (Rb) calculated inside the urban canyon ($y/H \leq 1$). It is worth to notice that when only the building façades are heated the thermal convection inside the urban canyon is forced, while in the other scenarios there is the compresence of both natural and forced thermal convention. This fact justifies the results shown in Figure 6 where there is the presence of forced convection that allow to have two vortexes inside the urban canyon. The ground heating allows to have the natural convection inside the urban canyon as shown in Table 1 where the bulk Richardson number is upper the value of 0.1. In this case there isn't the establishment of a second vortex as shown in Figure 7.

Table 1. Bulk Richardson number of the different scenarios.

ΔTG	0	0	0	15	15	15	30	30	30
ΔTB	0	10	20	0	10	20	0	10	20
Rb with 2.5 m/s	0	0.048	0.099	-0.813	-0.752	-0.703	-1.611	-1.538	-1.493
Rb with 4.5 m/s	0	0.011	0.023	-0.254	-0.242	-0.229	-0.506	-0.494	-0.477

5. Conclusions

In this paper the thermal flow field was analysed in an idealized urban canyon. Results are analysed depending on the wind intensity and heated ground and building surfaces. The analysis highlights that the heating of building façades causes a second vortex inside the canyon and the thermal convection inside the urban canyon is forced. Furthermore, there is a low intensity of the second vortex when the outside air velocity have an high value. With the instauration of a second vortex, there is an high air temperature inside the urban canyon caused by a more air mixing phenomenon. Ground heating can lead high temperature of the upwind building wall due to the air mass transport caused by the main vorticity. Furthermore, the increase of the bulk Richardson number suggest that natural convection effects are attributed to the ground heating.

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