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Analysis of convective heat transfer at building facades in street canyons

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Abstract

The natural convection effects on the flow structures and the heat processes have been analysed in an urban canyon. Predictions of convective heat transfer are essential in building and environmental studies on urban heat islands and building energy performance. An important part of the heat exchange between buildings and the ambient surrounding is due to convective and radiative heat flows. An idealized 2D urban canyon with Height/Width (H/W) equal to 1 were evaluated. The aim of this study is to quantify the influence of different wind intensity to the convective heat transfer coefficient when the walls were heated.

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Keywords: urban heat island; CFD; convective heat transfer coefficients; building; street canyon

1. Introduction

The rapid urbanization and economic growth of cities causes different worsening to human health regarding both thermal comfort and exposure to pollutant. In urban areas, the environmental is influenced by 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. In order to evaluate the thermal flow field depending on different variable, researches on urban areas are needed [1–8]. Frequently, the variation of urban thermal field leads to indirect energy efficiency effect. As a matter of facts, the increase of air temperature due to the urban heat island effect (UHI) [9] leads to an increase of building energy demand. Many studies are focused on the performance of building analyzing the efficiency of different building envelope and plants [10–22]. However, the rapid urbanization

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can lead to the variation of urban fabric around the building taken into account. This fact leads to a modification of the environment thermo-fluid dynamic field and a consequent variation of the building and plant performances.

In order to reduce the thermal worsening, especially during the summer, the technique of urban heat island mitigation techniques can be used to reduce the temperature differences from urban and rural area. Often cool materials are the simplifier solution to this purpose [23–27].

Computational fluid dynamics (CFD) can be used to predict the thermal flow field inside urban areas, varying different conditions such as wind direction and intensity, solar radiation, geometrical layout, and so on.

In this paper the thermal flow field condition was analysed in an idealized urban canyon, defined as the space between building that line up continuously on both sides of the street [28]. Results on convective heat transfer coefficient at building façades are analysed depending on wind intensity and heated walls.

Nomenclature

U	velocity, m/s	T	air temperature, °C
u*	friction velocity, m/s	T_a	ambient air temperature, °C,
y_0	roughness length, m	T_g	ground temperature, °C
κ	von Karman coefficient	U_{2H}	velocity at altitude of 2H, m/s
ε	turbulence dissipation rate, m^2/s^3	H	building height, m
k	turbulence kinetic energy, m^2/s^2	W	street width, m
Rb	bulk Richardson number	ΔTG	temperature difference between ground and air, °C
g	acceleration due to gravity, m/s^2	ΔTB	temp. difference between building walls and air, °C

2. Methodology

The work consists of the following steps, such as:

- Analysis of the Uehara wind tunnel experiment setup in order to validate the numerical model;
- Applying of the validated numerical model to the idealized urban canyon setup and comparison with the Uehara wind tunnel experiment;
- Analysis of the thermal flow field and the convective heat transfer coefficient at building façades in depending of wind intensity and heated walls.

3. Numerical model

The idealized 2D street canyon is shown in Fig. 1, where all the dimensions of the model domain are related to the building height H. The distances from the building and the domain boundary are made in according to the AIJ guidelines [29].

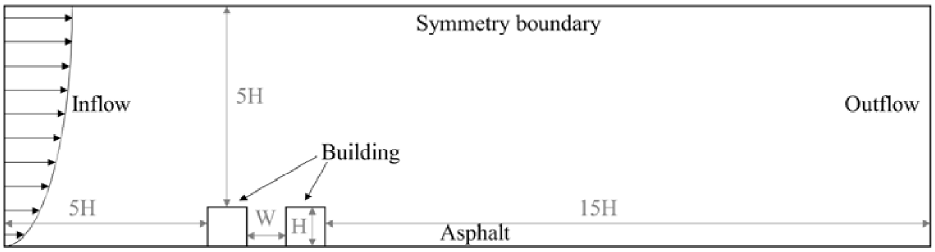


Fig. 1. Schematic diagram of the computational domain.

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 and are refined near the wall in order to resolve the non-equilibrium wall functions. This is useful in complex flows involving separation, reattachment, and impingement where the mean flow and turbulence are subjected to severe pressure gradients and change rapidly [30].

At the inlet it was implemented the velocity, the turbulence dissipation rate and the turbulence kinetic energy in according with the Eq. (1–3).

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

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

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

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

No slip boundary condition is employed at ground and building surfaces. Symmetry boundary condition is defined at the top of the domain considering that additional increasing of altitude does not change the thermo-fluid dynamic conditions. Fixed temperature boundary conditions are employed on the wall and ground surfaces.

4. Model validation

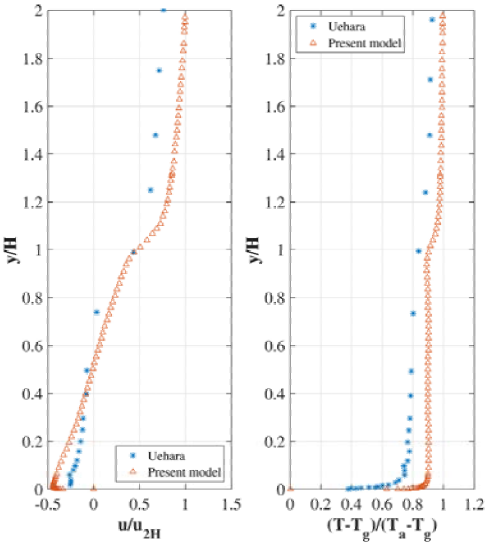
4.1. Uehara wind tunnel experiment setup

The numerical model validation was assessed reproducing the model implemented in the wind tunnel experiment performed by Uehara [31]. This model is constituted with 10 buildings with an aspect ratio H/W equal to 1. The difference temperature between the ground and the air temperature was imposed to 2 °C and the wind speed inlet at the height of 2H was imposed to 2.52 m/s. These values allow to have a model with a bulk Richardson number of –0.21 defined by the Eq. (4):

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

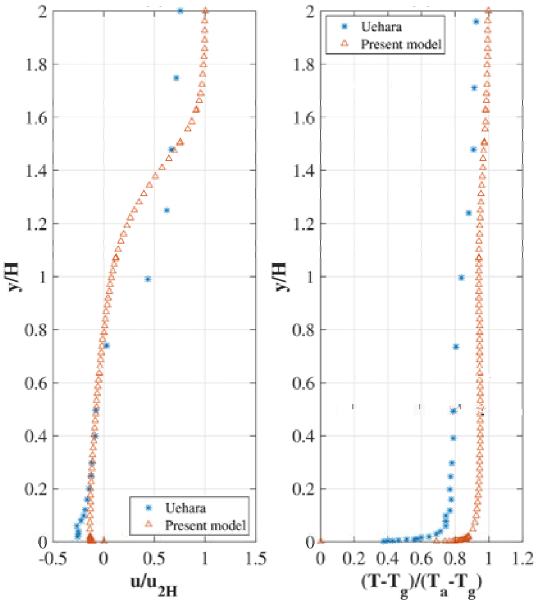
Fig. 2 shows the comparison between the measured data performed by Uehara at Rb = –0.21 and the calculated value from the CFD model. Fig. 2(a) reported the normalized velocity, while Fig. 2(b) the normalized temperature profile in the centerline of the canyon. The temperature calculated with the numerical model is slightly lower than the experimental data. The horizontal velocity over the building top (y/H > 1) is higher than the experimental data, due to the difference from the logarithmic laws and the realistic velocity profile in the inlet boundary condition. Inside the urban canyon there is an instauration of a great vortex deeply investigated in fluid-dynamic [32]. In this cavity the horizontal velocity is comparable with the experimental data and the differences are attributed to the use of 2D model instead a three-dimensional model.

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



(a) (b)

Fig. 2. Comparison between the simulated data and the observed data by Uehara (2000) along the centerline of the 2D geometry referred to the Uehara experimental setup: (a) vertical profile of normalized horizontal velocity; (b) vertical profile of normalized temperature.



(a) (b)

Fig. 3. Comparison between the simulated data and the observed data by Uehara (2000) along the centerline of the canyon geometry taken into account: (a) vertical profile of normalized horizontal velocity; (b) vertical profile of normalized temperature.

4.2. Present geometry setup

Using the model validated in the previous paragraph, Fig. 3 shows the comparison between the measured data performed by Uehara and the calculated value from the CFD model shown in Fig. 1. 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 Fig. 4. Brown [33] demonstrated the presence of fluid detachment in the first building. For this reason, the inflection point of the vertical velocity profile in the idealized urban canyon setup is at an y/H equal to 1.3 differently for the Uehara wind tunnel experiment setup shown in Fig. 2 where there is at about an y/H equal to 1.

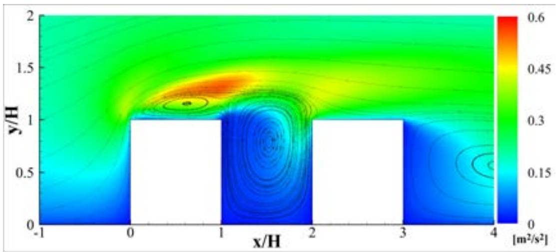


Fig. 4. Flow field and spatial contour of turbulence kinetic energy for the model validation setup.

5. Results and discussion

Fig. 5 shows the velocity streamline and spatial temperature contour of the idealized urban canyon taken into account. Considering an air temperature of 20 °C, different simulation were performed using a velocity of 2.5 m/s (Fig. 5(a, c, e) and 4.5 m/s (Fig. 5(b, d, f)), 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.

It is worth to notice that the heating of ground and building façades causes an instauration of a second vorticity inside the urban canyon (Fig. 5(c–f)) due to the buoyancy effects. With a low velocity, the extension of the second vorticity is greater than in the case of 4.5 m/s because there is a more forced convection inside the street canyon. The presence of a great second vortex allow to have a higher temperature than in the case of a velocity of 4.5 m/s due to more air mixing in the street canyon. 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.

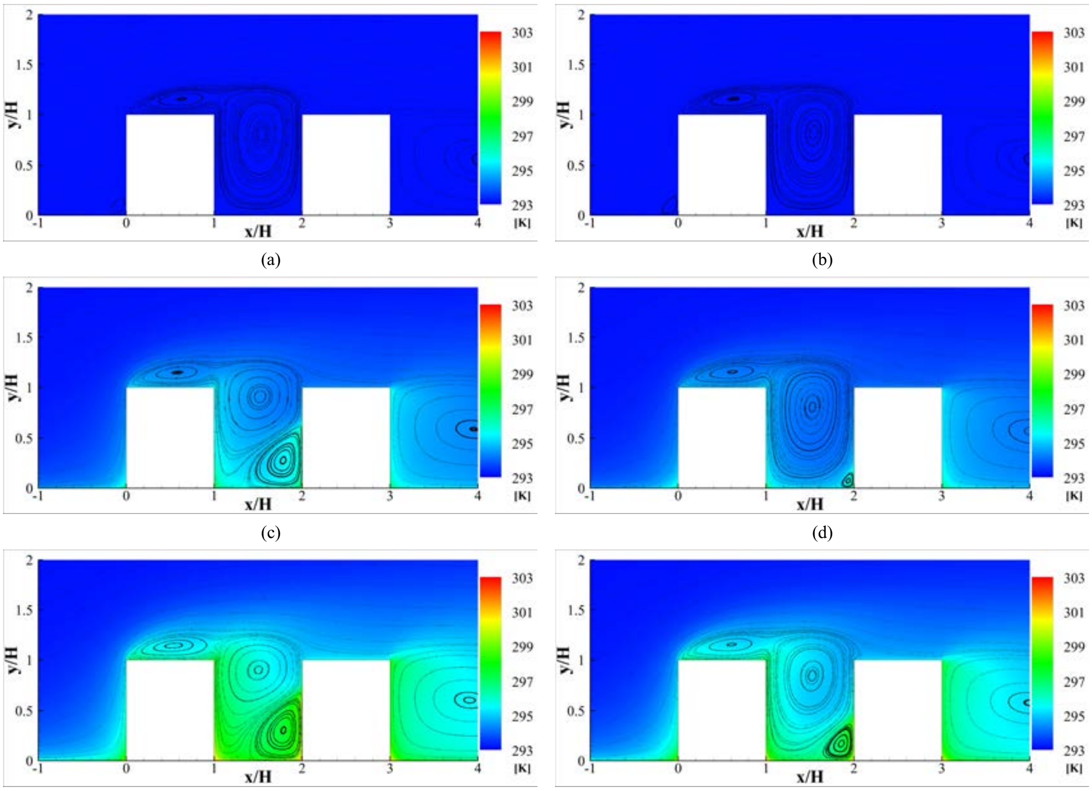
Fig. 6 shows the vertical profile of the convective heat transfer coefficient (CHTC) varying the air velocity and the ground and building temperature. The values are referred to the upwind line (red line), the downwind line (blue line) and the line in which the flow approach the buildings (green line), called approach line. The CHTC related to the upwind line have low values up to 7 W/(m^2 K), while in the downwind line and the approach line these values reach 18 W/(m^2 K) because high velocity is found when the flow impact the façade. In the approach line there are higher CHTC values than in the downwind line caused by the direct flow impacting on the building façade without bumping with any obstacles. The presence of more walls heating causes more evident differences of the CHTC from upwind to downwind because there is high temperature values inside the canyon.

Considering the results shown in Fig. 5e regarding the case of 2.5 m/s and ΔTG = 30 ΔTB = 20, the presence of two extended vortexes inside the canyon can suggest high CHTC values. Unlike the latter the CHTC values inside the urban canyon are comparable with $y/H < 0.5$ and high values are evident at the building top where there is an influence of the external flow field. As a matter of fact, in the Figure 6d there are the higher CHTC values than in Fig. 6(b) due to the presence of a velocity of 4.5 m/s.

In the building energy performances, the choice of the appropriate CHTC values are done using the standard ones in the ISO 6946 [34], calculated as:

$$CHTC = 4 + 4 \cdot v \tag{5}$$

where v is the wind velocity in the surface proximity.

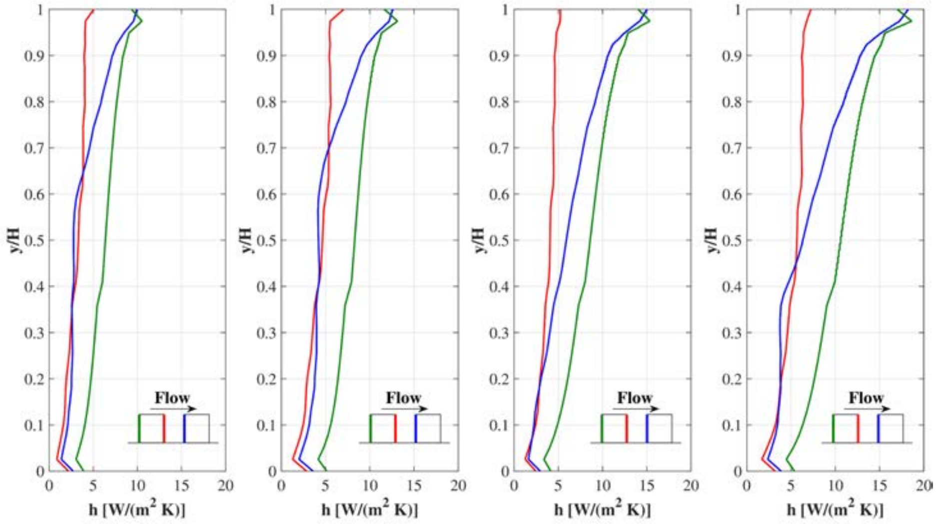


(a) (b)

(c) (d)

(e) (f)

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, (c) 2.5 m/s ΔTG = 15 ΔTB = 10, (d) 4.5 m/s ΔTG = 15 ΔTB = 10, (e) 2.5 m/s ΔTG = 30 ΔTB = 20, (f) 4.5 m/s ΔTG = 30 ΔTB = 20.



(a) (b) (c) (d)

Fig. 6. Vertical profile of the heat transfer coefficient in the green, red and blue façades: (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=20, (d) 4.5 m/s ΔTG = 30 ΔTB = 20.

Table 1 shows the percentage differences between the mean CHTC simulated at the building walls (see Fig. 6) and calculated from Eq. (5). Usually in the building energy performances calculation is imposed the wind velocity far from the building due to the impossibility estimation of the velocity inside the urban fabric. For this reason, in the Eq. (5) is imposed the wind velocity υ as 2.5 and 4.5 m/s for each cases. Inside the urban canyon, there are meaningful differences with values up to 82.9 % for the upwind wall. Furthermore, the atmospheric boundary layer considered with the velocity vertical profile shown in Eq. (1), cause a velocity variation in the proximity of the ground with consequent decrease of the CHTC values up to 61.3 % from the standard ones.

These results suggest that the ISO 6949 do not consider the thermo fluid-dynamic effects around buildings. The influences of the vorticities analysed in Fig. 5 are not well described with a linear correlation shown in Eq. (5). The values in the Table 1 suggest that there is the need to better choice the CHTC values for each building wall depending on the environmental surrounding.

Table 1. Percentage difference between the CHTC simulated and calculated form the ISO 694.

Case study	Mean upwind CHTC	Mean downwind CHTC	Mean approach CHTC
2.5 m/s ΔTG = 15 ΔTB = 10	–78.2 %	–72.0 %	–55.1 %
4.5 m/s ΔTG = 15 ΔTB = 10	–69.3 %	–62.4 %	–41.8 %
2.5 m/s ΔTG = 30 ΔTB = 20	–82.9 %	–71.5 %	–61.3 %
4.5 m/s ΔTG = 30 ΔTB = 20	–76.5 %	–67.0 %	–52.2 %

6. Conclusions

In this paper the thermal flow field and the heat transfer coefficient were analysed in an idealized urban canyon. The analysis are made depending on wind intensity and heated ground and building surfaces. After a two-step model validation method, the instauration of vorticity and the consequent temperature field were evaluated inside the street canyon. The analysis highlights that the presence of a great second vortex allow to have a higher temperature inside the urban canyon due to more air mixing phenomenon. 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.

The heat transfer coefficient calculated on the upwind and downwind line has significantly different values, due to the flow field and the heating. In the building energy performances, the choice of the appropriate CHTC values are done using the standard ones in the ISO 6946. There is a meaningful differences from the CHTC simulated and calculated form the legislation suggesting that there is the need to better choice the CHTC values depending on the environmental surrounding. As a matter of fact, building energy consumption changed with the use of different CHTC up to 30 % for isolated buildings and 80 % for buildings in urban settings [35].

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