Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1211

# INFLUENCE OF THE GEOMETRICAL PARAMETERS OF URBAN CANYONS ON THE CONVECTIVE HEAT TRANSFER COEFFICIENT

by

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*In this study, a microclimate analysis has been carried out starting with a particular urban configuration, "the street canyon". The analysis, conducted by performing numerical simulations using the finite volumes commercial code ANSYS FLUENT studies how the thermal and flow field are affected by the effect of the solar radiation, varying the ratio H/W. Furthermore, a thermo fluid dynamic analysis of natural convection effects and of 3-D characteristics of the flow field on the heat transfer coefficient, has been carried out. The check of the urban microclimate through this type of study, can be helpful to find solutions at thermal comfort and energy saving.*

Key words: *urban canyon, solar radiation, CFD, urban microclimate*

## Introduction

The well-being and quality of life of each of us also depend on the climatic conditions environment where we live [1]. Considering that about 50% of the world population live in urban areas [2], it is natural and necessary to study the characteristics of the microclimate of our urban areas. In particular, the climatic conditions and urban environment appear closely related to the morphological characteristics of the city (and the parts of this). In many cases, urbanization can affect the local climate of a city more intensely and faster than the global warming giving rise to the phenomenon of the so-called urban heat island (UHI). This study will concentrate on the analysis of a particular urban configuration: the urban canyon. The geometry of the urban canyon is often described by a single parameter, the canyon aspect ratio (*H/W*), which is defined as the ratio of the building height, *H,* to the width between buildings, *W*. In literature several authors have studied the street canyons, through numerical simulations [3], wind tunnel experiments [4-6], measurement campaigns [7], and comparison between numerical model and measurements campaign on a canyon scale model [8]. In literature, there are typically two-dimensional studies [3, 9]. The 3-D effects are considered in other studies [4, 5] but an array of cubical buildings is simulated, and in this case, the flow is channeled and it maybe supposed that the tridimensional effects are less important. In this paper, using a commercial CFD code (ANSYS FLUENT), an isolated street canyon is considered, to evaluate how the flow field

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1212

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

changes within the canyon at different *H/W* ratio and to highlight the importance of considering tridimensional effects on convective heat transfer inside the canyon.

In some papers, not only the canyon but also the urban configuration around the canyon, are studied numerically [10, 11]. In [12] the effects of the radiative properties of the surfaces materials on canyon surfaces temperatures and their importance for heat island mitigation are evaluated. In the study of urban microclimate in an urban canyon the convective heat transfer coefficients (CHTC) analysis, for external surfaces of the building, play a key role. The analysis of thermal and the flow fields in an urban canyon provides the surfaces values of parameters like CHTC and friction velocity that are required by UHI models [13, 14].

The thermal field and flow field inside an urban canyon are two basic parameters for the analysis of heat exchanges between confined environment and open space. In this particular study, we analyze, just how they are affected by the ratio *H/W* while *L/H* is fixed. The analysis of the flow and thermal field inside of the canyon has been performed with a CFD simulations conducted during summer days, because, during this period, weather conditions affect human activity much more than during the winter season. The thermal field is determined by setting up the solar radiation module, the ambient conditions and thermophysical properties values of the buildings and the ground.

**The CFD numerical model**

The simulations have been performed with the commercial CFD code ANSYS FLUENT 14.0, 3-D double precision, pressure based version and the steady RANS equations have been solved in combination with the standard *k-ε* model. The governing equations can be expressed:

– momentum equation

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \frac{\mu}{\rho} \frac{\partial^2 \bar{u}_i}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_j} \left( \overline{u'_j u'_j} \right) + f_i \tag{1}$$

– continuity equation

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{2}$$

– heat conservation equation

$$\bar{u}_i \frac{\partial \bar{T}}{\partial x_i} + \frac{\partial}{\partial x_i} \left( K_T \frac{\partial \bar{T}}{\partial x_i} \right) = 0 \tag{3}$$

where $\bar{u}_i$ is the average speed of air-flow, $\overline{u'_j u'_j}$ – the Reynolds stress, $\rho$ – the air density, $\mu$ – the molecular viscosity, $f_i$ – the thermal-induced buoyant force, $\bar{T}$ – the potential temperature, and $K_T$ – the heat diffusivity. The standard *k-ε* model has been used to solve the turbulence problem. The turbulence kinetic energy, *k*, and its rate of dissipation, *ε*, are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho\varepsilon \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial\varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{k}(G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon}\rho \frac{\varepsilon^2}{k} \tag{5}$$

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1213

where $G_k$ is the generation of turbulence kinetic energy due to the mean velocity gradients, $G_b$ – the generation of turbulence kinetic energy due to buoyancy, $C_{1\varepsilon}$, $C_{2\varepsilon}$, and $C_{3\varepsilon}$ are the constants, and $K_T$ and $\mu_t$ expressions are reported in the standard $k$-$\varepsilon$ model of ANSYS FLUENT 14.0, 2011, $\sigma_k$ and $\sigma_\varepsilon$ are the turbulent Prandtl numbers for $k$ and $\varepsilon$, respectively. To evaluate the impact of thermal effects, the incompressible ideal gas module has been used for air density.

In this model the standard wall functions (SWF) are used to save computing time.

The formula used to evaluate the CHTC coefficient is reported following:

$$CHTC = \frac{q}{T_{\text{wall}} - T_{\text{ref}}} \quad (6)$$

where $q$ is the convective heat flux, $T_{\text{wall}}$ – the wall temperature, and $T_{\text{ref}}$ – the reference temperature defined in the boundary conditions.

In [15] it is shown that in urban canyons the SWF give CHTC that agree with low Reynolds number modeling, if natural convection effects are moderate and when the Richardson number, Ri, is not much higher than one. In the present paper the Richardson number is not larger than 3, then the SWF are used. The aim of this paper is to compare the microclimate for different cases using the same models with the same limitations. In particular, different geometrical configuration are analyzed differing the *H/W* parameter.

*Computational domain*

To calculate the thermal effects, the natural convection module has been activated by setting an incompressible ideal gas model for air density. The analyzed urban canyon has the following geometrical characteristics: the aspect ratio $H/W = 0.5$, $H/W = 1$, and $H/W = 2$ (fig. 1), the orientation is north-south, the width and height of the building are 20 m, the street length is 100 m and the street width is 20 m.
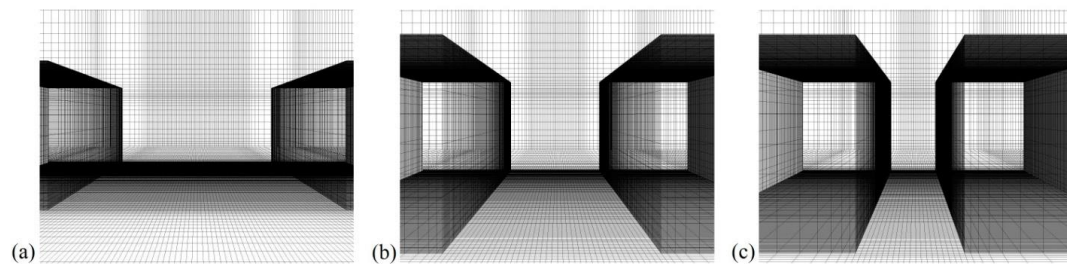


**Figure 1. Canyon with (a) $H/W = 0.5$, (b) $H/W = 1$, (c) $H/W = 2$**

Based on the best practice guidelines by Franke *et al.* [16] and Tominaga *et al.* [17], the dimensions of the computational domain have been chosen in relation to the buildings height, *H*, fig. 2: the distance between the side walls of the buildings and the north, east and south planes is $5H = 100$ m, instead the west plane is $15H = 300$ m from the westerly building. The distance between the roofs of the buildings and the upper plane is $5H = 100$ m. The building's dimensions determine the different domain extension behind the built area. When the flow direction is transversal to the canyon length, the obstacle size is maximum, and the flow re-development requires a distance of $15H$ from the buildings to the outflow bounds. Instead, when the flow is parallel to the canyon axis, the obstacle size is minimum, and the distance behind the built area is $5H$. The domain dimension over the buildings has been chosen
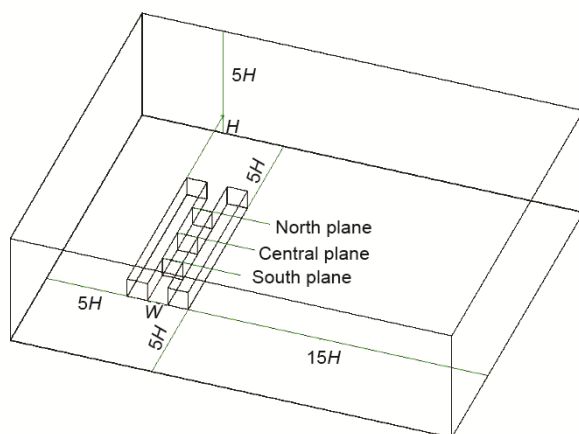
1214

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

**Figure 2. Computational domain**

to take into account the blockage ratio, defined as the ratio of the area blocked by the buildings to the total cross-section area. This parameter depends on the obstacles size and wind direction: when the building obstacle area is minimum, the blockage ratio assumes the value of 2%, instead of when the wind impacts transversally to the canyon direction, it assumes the maximum value of 5.5%. To ensure a high quality of the computational grid, it is fully structured, and the shape of the cells has been chosen hexahedral, fig. 1. To simulate flow fields, in the area of interest, 40 cells per cube root of the building volume has been used and 20 cells per building separation [16]. For the vertical resolution of the canyon 20 cells have been used. Furthermore, the grid has been arranged so that the evaluation height for pedestrian comfort is located higher than the 3rd grid from the ground surface.

*Boundary conditions*

In this simulation, the surfaces temperatures have been obtained as the result of the heat transfer calculations, setting up: the temperature of the undisturbed air, the solar load module, and the temperature inside of the buildings (299 K). To evaluate the soil influence, the calculation domain has been extended 5 m below the ground level. The ground has been simulated with the following thermophisical characteristics: thermal conductivity = 2 W/mK, temperature at −5 m = 288 K, density = 1000 kg/m$^3$, specific heat = 1000 J/kgK, solar radiation absorptivity (visible and infrared) = 0.8, and emissivity = 0.9. The radiation exchanges have been calculated setting up the S2S radiation model, in which the energy exchange parameters are considered by a geometric function, *i. e.*, view factor, and activating the solar ray tracing. The zero static pressure on the outlet plane and zero gradients of all variables at the top and lateral sides of the domain are setting. Transient heat conduction in ground and walls has been analyzed in [18]. This study finds that thermal inertial effects are important to calculate heat fluxes and the temperatures of the inner layers, but not for surface temperatures which influence the natural convection flow fields. In [18] it is shown that the differences between the surfaces temperatures of the steady-state and the transient case are a few percent of the air surface temperature difference so that only steady-state simulation have been carried out. Furthermore, the materials characteristics have been reported in [16, 17]. The building walls have: thermal conductivity = 0.15 W/mK, specific heat = 1000 J/kgK, density = 1000 kg/m$^3$, internal air temperature = 299 K, thickness = 0.30 m, and emissivity = 0.9. In [18] it has been verified that as the flow approaches the built area the inlet velocity profile is fully-developed before reaching the buildings and it can be represented by eq. (7), where $u^*$ is the friction velocity, $K$ – the Von Karman constant (0.4), $z$ – the height co-ordinate, and $z_0$ – the aerodynamic roughness and its value is 0.05 m that can be considered an appropriate value to represent the roughness of the land covered with low vegetation and small isolated obstacles [19]. This equation represents the wind velocity profile of the inlet

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1215

flow when the wind approaches the buildings. In another study [18], it is shown that the wind profile reaches the asymptotic velocity when it reaches about 4 m in height:

$$u(z) = \frac{u^*}{k} \ln\left( \frac{z + z_0}{z_0} \right)$$  (7)

The friction velocity value has been obtained by the correlation with the calculated value of the turbulent kinetic energy, $k$, at the first node above the ground, [16]:

$$u^* = k^{0.5} C_\mu^{0.25}$$  (8)

where $C_\mu = 0.09$. On the buildings façades and the ground inside the canyon the roughness length is zero.

*Model validation*

The validation of the mathematical model used in our study has been carried out through the comparison with the wind tunnel experiment performed by Uehara *et al.* [4]. The experiment has been characterized by a flow direction transversal to rows of blocks and, at the measurement location, the flow appeared totally canalized. A numerical validation test has been performed on our street canyon model, which has been scaled by the reduction factor 1/200 and where the wind direction has been considered totally transversal to the canyon direction. The comparison between the data obtained with the wind tunnel experiments and the numerical test has been carried out for the vertical profile of normalized horizontal velocity $u/u_0$ and $(T - T_f)/(T_a - T_f)$, evaluated on a central vertical line within the street canyon. The agreement between the numerical model and the wind tunnel experiments is satisfactory inside the canyon as shown in [18] where the experimental and numerical model results are plotted and they agree well inside the canyon.

**Results**

The *H/W* ratio is a very important value to define air-flow and temperature fields inside the canyon. For this reason, six simulations were performed: three at 11:00 a. m. on July 21, with *H/W* = 0.5, 1, 2, fig. 1; three at 02:00 p. m. on on July 21, for the same value of *H/W*. The canyon is made by two twin buildings with $H = 20$ m, $W = 20$ m, and $L = 100$ m, is north-south oriented, placed in city of Milan, Italy (latitude = 9.18, longitude = 45.47, UTC+1). In each simulation, fixed values of ambient wind velocity magnitude and wind direction and undisturbed air temperature, have been considered ($u_0 = 2$ m/s, wind direction = 45°N and undisturbed air temperature 303 K). The velocity value of 2 m/s has been chosen because the effect of natural convection is still important [5]. As found in [18, 20, 21], the values of CHTC are not very sensitive to wind direction neither for isolated buildings [21] nor inside canyons [18, 20].

As reported in [21], the values of CHTC on the windward (WW) façade in a standalone building, do not show variations in a wide range of wind directions. In particular, in [21] is shown that the CHTC are relatively insensitive to wind direction within the interval 0° +60° from the normal to the WW façade. Important changes are found for wind directions almost parallel to the façade.

Then, in [20] several simulations were performed by varying the wind directions. Particularly for three different wind directions: 20°, 45°, and 70° from the canyon axis. As

can be seen in tab. 1 [20] the average values of the CHTC on WW and leeward (LW) façades are similar for three directions. In [18] instead, have been performed a 2-D simulation and a 3-D simulation with wind direction perpendicular to the canyon axis. The average value of CHTC on LW and WW are different from the values for other wind directions [20]. Particularly lower values of the CHTC and comparable with the values reported in [22, 23] for 2-D canyons are found. Then, the wind direction strongly affects the thermal and dynamical effects within the canyon for wind directions close to the perpendicular to the canyon axis. There is also a large range of wind directions between 70° and 20° from the canyon axis where the influence of the wind direction is low. So that a wind direction of 45° from the canyon axis can represent a wide range of wind directions between 0° and 60°.

To consider the relationship between the wind flow field and temperature field inside the canyon, the values of heat exchange coefficient, $h_c$, turbulent kinetic energy, $k$, wall temperatures, $T_{wall}$, and the intensity of the wind speed, $u$, are considered. All variables are calculated on vertical lines on three different planes, with XZ co-ordinates, fig. 2. The north plane is situated ten meters from the north limit of the building, the central plane is located in the middle of the canyon, and the south plane is ten meters from the south limit. While wall temperatures and heat exchange coefficients are calculated on lines that are situated on the building façades, the turbulent kinetic energy and wind speed are considered on the first node.

Thermal effects considerably modify flow fields inside the canyon. As shown in [20], in which the flow field is analyzed inside an urban canyon similar to the one of this paper, when the natural convection is not considered, a single aerodynamic vortex can be formed in the canyon. When natural convection is switched on two counter-rotating vortices of which one is aerodynamic, and the other one is thermal are often formed in the canyon. These effects are reported in several papers for instance [3].

Results of calculated simulation, always considered with natural convection, are consistent with the cited simulation, as is visible from fig. 3, in which the wind velocity vectors are represented, calculated in south vertical plane with different *H/W* at 02:00 p. m.
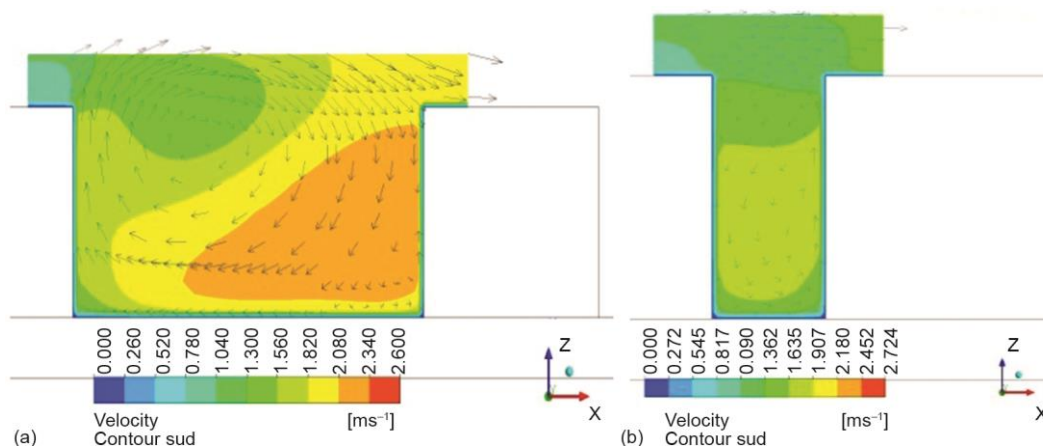


**Figure 3. Wind flow field on XZ south plan with *H/W* = 2 and 0.5; (a) south plane, *H/W* = 0.5 at 02:00 p. m., (b) south plane, *H/W* = 2 at 02:00 p. m.** (*for color image see journal web site*)

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1217

As can be seen from fig. 3, in south plane with $H/W = 0.5$ we only have one vortex while in south plane with $H/W = 2$ is evident in the bottom WW façade the presence of a second vortex due to convective aspects.

*Average values of CHTC inside of the canyon*

Table 1 shows surface averaged values of $h_c$ in the WW and LW façade for the three values of $H/W$ ratio and the values for the same configurations for the 2-D studies implemented by [22, 23]. In particular, the results relevant to a numerical computation performed for a 2-D canyon, with natural convection switched on, using a wall temperature of 30 °C and an incoming air temperature of 20 °C [23], are displayed in tab. 1

**Table 1. Values of the $h_c$ parameter on the WW at 02:00 p. m. and LW façade at 11:00 a. m. in present study and on others studies present in literature.**

| | $H/W = 0.5$ | | $H/W = 1$ | | | $H/W = 2$ | |
|---|---|---|---|---|---|---|---|
| | [23] | Present study | [23] | [22] | Present study | [23] | Present study |
| WW | 3.55 | 11.57 | 3.16 | 3.08 | 11.28 | 2.03 | 9.91 |
| LW | 2.41 | 10.51 | 2.38 | 2.22 | 10.29 | 1.83 | 9.28 |

A result obtained by Saneinejad *et al.* [22] using a 2-D configuration with $H/W = 1$, the natural convection switched off, wind velocity 2 m/s, incoming air temperature 20 °C and wall uniform temperatures 30 °C is also reported. As regards the values of $h_c$ in relation to the $H/W$ from tab. 1 is seen that there is a slight decrease with the increase of $H/W$ which becomes more evident between $H/W = 1$ and 2.

The average values of CHTC on the LW façade are always lower than those of the WW façade coherently with the other papers in the literature, but in our case, the difference is lower. The same trend was found by Allegrini *et al.* [23] with a much higher decrease of $h_c$. In our case, we arrive at 10% in Allegrini's case also to 30%. The results of Allegrini *et al.* [23] and Saneinejad *et al.* [22] show much lower values of CHTC than those obtained in this study and this appears to be because considered a bi-dimensional case.

As it can be seen in [18, 20, 22-24], the flow field inside the urban canyon in the 2-D simulations is different from the flow corresponding to 3-D simulations for wind directions not normal to the canyon axis. In particular, in the 2-D case, the flow field is characterized by a skimming flow and, for the same external air velocity, the values of the wind velocity inside the urban canyon are lowered than in the 3-D case. Of course, the values of the CHTC are lower.

*The 3-D effects inside the canyon*

Tables 2 and 3 show values of dynamic and thermal variables relatively to the WW and LW façade at 11:00 a. m. and 02:00 p. m. for the three values of $H/W$ ratio.

The results reported in tabs. 2 and 3 are obtained by simulations in a 3-D domain, fig. 2, and 3-D effects on the flow are evident in the formation of a spiral flow, made by the combination of a vertical descendent vortex and the longitudinal component of wind speed, as was demonstrated in various studies [5, 20].

1218

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

The presence of the longitudinal velocity component has an important effect on the characteristics of the flow field, and determines much greater values of CHTC than those typical of the 2-D field, as shown in tab. 1. Notice that such a longitudinal component plays a fundamental role also when the wind is almost transversal to the canyon [20].

This longitudinal velocity component significantly changes the vortex structure and the flow field along the entire length of the canyon respect to 2-D analysis [18, 20, 21].

Tables 2 and 3 show that the CHTC and turbulent kinetic energy and local velocity values may have considerable variation along the canyon axis.

**Table 2. Values of the parameters on the WW façade at 11:00 a. m. and at 02:00 p. m.**

| Windward façade at 11:00 a. m. | | | | | | |
|---|---|---|---|---|---|---|
| Ratio | Plane | $h_c$ [Wm$^{-2}$K$^{-1}$] | $k$ [m$^2$s$^{-2}$] | $T_{wall}$ [K] | $u$ [ms$^{-1}$] | $u_z$ [ms$^{-1}$] |
| $H/W = 0.5$ | North | 12.48 | 0.28 | 307.71 | 1.44 | 0.19 |
| | Central | 10.34 | 0.19 | 308.53 | 1.52 | −0.04 |
| | South | 9.81 | 0.15 | 308.55 | 1.69 | −0.40 |
| $H/W = 1$ | North | 13.79 | 0.33 | 308.20 | 1.82 | 0.14 |
| | Central | 10.03 | 0.16 | 309.32 | 1.61 | −0.46 |
| | South | 9.02 | 0.12 | 310.27 | 1.39 | −0.47 |
| $H/W = 2$ | North | 13.32 | 0.30 | 307.99 | 1.88 | 0.11 |
| | Central | 8.77 | 0.11 | 310.19 | 1.38 | −0.36 |
| | South | 7.41 | 0.08 | 312.09 | 1.18 | −0.26 |
| Windward façade at 02:00 p. m. | | | | | | |
| $H/W = 0.5$ | North | 12.50 | 0.28 | 323.55 | 1.44 | 0.23 |
| | Central | 11.04 | 0.23 | 325.69 | 1.49 | 0.16 |
| | South | 11.19 | 0.22 | 325.37 | 1.63 | -0.08 |
| $H/W = 1$ | North | 13.72 | 0.33 | 321.19 | 1.81 | 0.20 |
| | Central | 10.56 | 0.19 | 324.67 | 1.52 | -0.20 |
| | South | 9.57 | 0.14 | 326.64 | 1.41 | -0.09 |
| $H/W = 2$ | North | 13.18 | 0.30 | 319.44 | 1.87 | 0.16 |
| | Central | 9.06 | 0.12 | 324.51 | 1.33 | -0.11 |
| | South | 7.50 | 0.09 | 327.85 | 1.22 | 0.29 |

These variations of CHTC and *k* can be connected with the 3-D nature of the flow field as seen from fig. 4. In de Lieto Vollaro A. *et al.* [24] and by fig. 4, it can be seen that at the North plane the flow field structure is the same for each *H/W* parameter and different from that on the other planes. In particular, the direction of the flow field in North plane is characterized by the external velocity field, and the velocity vectors have the predominant component perpendicular to WW façade. This creates a strong re-circulation and thus a turbulent kinetic energy increase. Moreover, as can be seen from tabs. 2 and 3 the turbulent kinetic energy is strongly correlated with the values of CHTC. It can, also, be seen that CHTC coefficient and *k* vary in

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1219

**Table 3. Values of the parameters on the LW façade at 11:00 a. m. and at 02:00 p. m.**

| Ratio | Plane | $h_c$ [Wm$^{-2}$K$^{-1}$] | $k$ [m$^2$s$^{-2}$] | $T_{\text{wall}}$ [K] | $u$ [ms$^{-1}$] | $u_z$ [ms$^{-1}$] |
|---|---|---|---|---|---|---|
| Leeward façade at 11:00 a. m. |
| $H/W = 0.5$ | North | 10.16 | 0.22 | 325.64 | 1.11 | 0.75 |
| | Central | 11.16 | 0.19 | 324.27 | 0.77 | 0.28 |
| | South | 10.21 | 0.18 | 325.71 | 1.44 | 0.72 |
| $H/W = 1$ | North | 10.40 | 0.21 | 324.38 | 1.11 | 0.59 |
| | Central | 10.78 | 0.20 | 323.90 | 0.59 | 0.20 |
| | South | 9.69 | 0.15 | 325.82 | 1.50 | 0.69 |
| $H/W = 2$ | North | 11.38 | 0.24 | 320.65 | 1.07 | 0.34 |
| | Central | 8.64 | 0.13 | 324.10 | 0.27 | 0.09 |
| | South | 7.82 | 0.10 | 326.39 | 1.27 | 0.43 |
| Leeward façade at 02:00 p. m. |
| $H/W = 0.5$ | North | 8.77 | 0.13 | 309.59 | 0.91 | 0.58 |
| | Central | 9.99 | 0.17 | 309.50 | 0.69 | 0.22 |
| | South | 9.15 | 0.14 | 309.95 | 1.27 | 0.50 |
| $H/W = 1$ | North | 8.76 | 0.13 | 309.37 | 0.52 | 0.05 |
| | Central | 9.44 | 0.16 | 310.00 | 0.88 | 0.32 |
| | South | 8.53 | 0.12 | 310.87 | 1.29 | 0.33 |
| $H/W = 2$ | North | 10.87 | 0.21 | 308.26 | 0.30 | –0.01 |
| | Central | 7.85 | 0.10 | 310.88 | 1.05 | 0.10 |
| | South | 6.78 | 0.07 | 312.63 | 1.23 | 0.00 |

similar ways, while CHTC and the local velocity value on the wall may vary in opposite ways, in particular in LW façade. Also in [21] it is shown that on the WW façade of an isolated building the local values of the CHTC are better correlated with $K$ than with the local velocities.

From central plane to the south plane, the aerodynamic vortex coming from the roof is fully-developed, figs. 3 and 4. In particular, it is seen that for $H/W = 0.5$ the second natural convection vortex which rotates in the opposite direction is not evident, but the CHTC and the turbulent kinetic energy are higher when the wall is radiated by the Sun. Instead for $H/W =1$ the second vortex due to convective aspects on the central plane appears in bottom WW façade. For $H/W = 2$ on the central and south planes the second vortex occupies a large part of the canyon. It is, therefore, clear the importance of natural convection in the formation of the opposite vortex. From tabs. 2 and 3 it can be seen that variations of the CHTC values there are along the canyon axis and this variations also depend on the $H/W$ parameter.

In particular, the CHTC values on WW façade decrease along the canyon axis and this decrease is more accentuated varying $H/W$. For $H/W = 0.5$ and 1 the CHTC variations along the canyon are about of 30%, while for $H/W = 2$ the variations are about 50%. Instead, on LW façade, those changes are much less marked for $H/W = 1$ and 0.5 and are considerable only for $H/W = 2$, tab. 3.

The results, therefore, seem that there is a strong correlation between the local values of the CHTC and $H/W$ parameter. In the LW façade for $H/W = 2$ the variations for CHTC
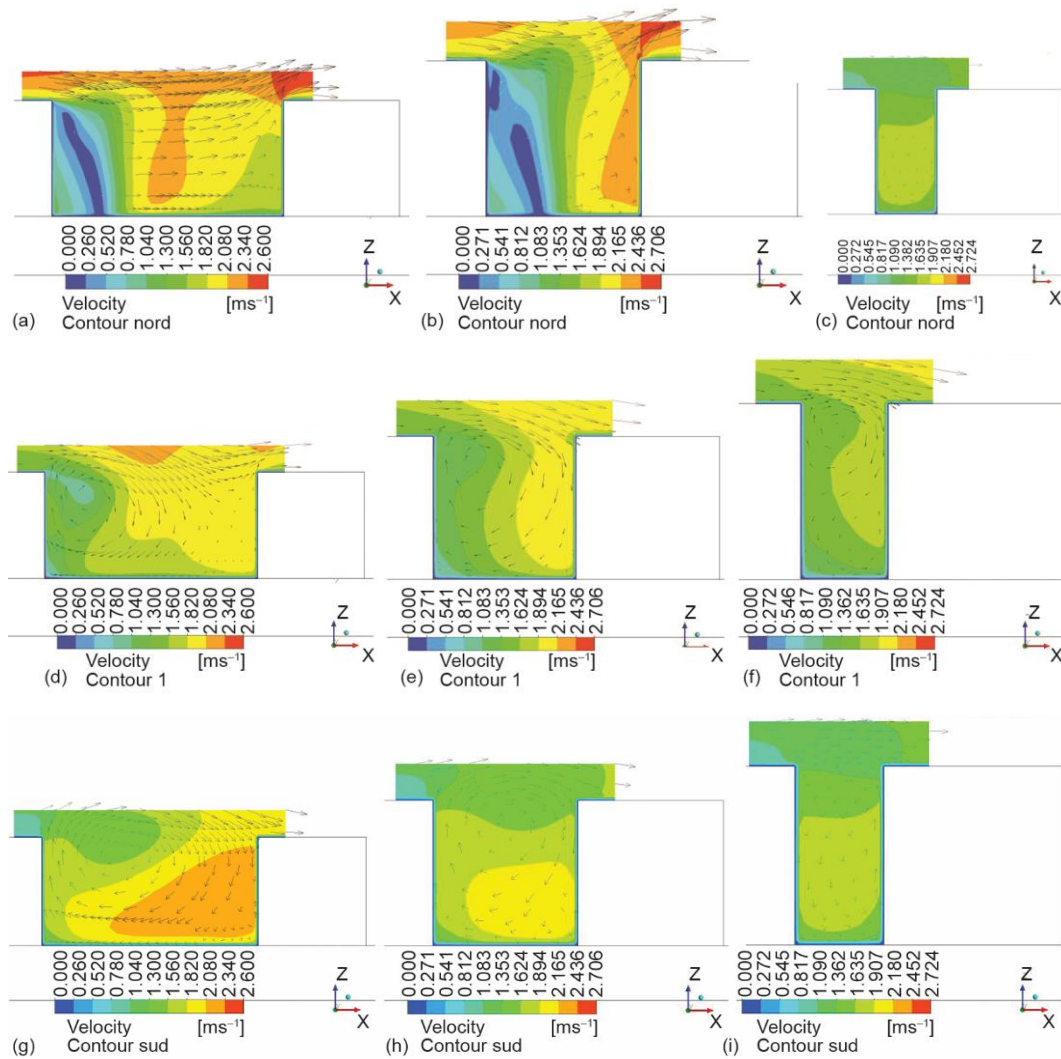
1220

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223



**Figure 4. Wind flow field on XZ north, central, and south plan with *H/W* =0.5, 1, and 2; (a) north plane, *H/W* = 0.5 at 02:00 p. m., (b) north plane, *H/W* = 1 at 02:00 p. m., (c) north plane, *H/W* = 2 at 02:00 p. m., (d) central plane, *H/W* = 0.5 at 02:00 p. m., (e) central plane, *H/W* = 1 at 02:00 p. m., (f) central plane, *H/W* = 2 at 02:00 p. m., (g), south plane, *H/W* = 0.5 at 02:00 p. m., (h) south plane, *H/W* = 1 at 02:00 p. m., (i) south plane, *H/W* = 2 at 02:00 p. m.** (*for color image see journal web site*)

is near 40% instead in the WW façade for *H/W* = 2 the variations get to 50% form south plane to north plane.

The values of $T_{wall}$ depend on various variables: primarily the amount of building surface under irradiation, the wind speed intensity, *u*, turbulences of the flow field in the proximity of the building façades described by *k*, and the thermal exchange coefficient, $h_c$, between the façade and air inside the canyon. The 3-D effects of the flow field appear important for the $T_{wall}$ values. As shown in tab. 2, $T_{wall}$ increases when *H/W* increase and can have strong variations along the canyon axis: usually, $T_{wall}$ of the north plane is lower than at the other two planes and,

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

1221

in some cases, it differs consistently. Contemporarily there is also a reduction of thermal exchange coefficient, and this determines a reduction of the capacity for the façades to exchange heat and to lower their surface temperature. In tab. 2 at 02:00 p. m., $H/W = 2$, north plane and south plane surface temperatures differ for more than 8 K. This difference is probably due to the strong variations of kinetic energy that determines the effectiveness of the thermal exchanges.

The dependence of various variables on height, $z$, was also analyzed. For the CHTC, $u$ and $K$ parameters the dependence of $z(m)$ exists with increasing $z$ but is little remarkable, while for $T_{wall}$ the variations seem important. Figures 5 and 6 report the $T_{wall}$ parameter on WW and LW façade on the central plane at 11:00 a. m. and 2:00 p. m. Figures 5 and 6 show that for both the WW and LW façade, the $T_{wall}$ in the bottom part of the canyon are higher than the average temperature so that in the pedestrian part of the canyon the mean radiant temperature is higher and this has a negative effect on the human thermal comfort.
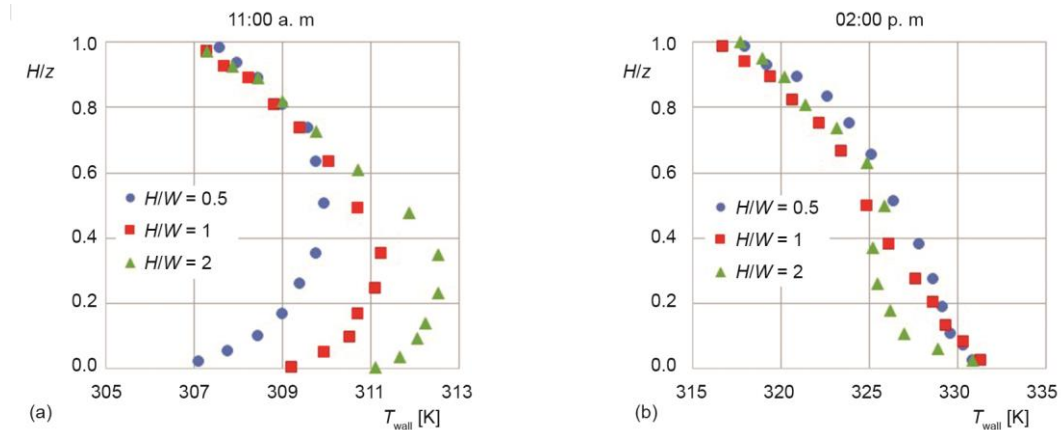


**Figure 5. Trends of $T_{wall}$ parameter calculated on the WW façade on the central plane within the canyon at 11:00 a. m. and at 02:00 p. m.**
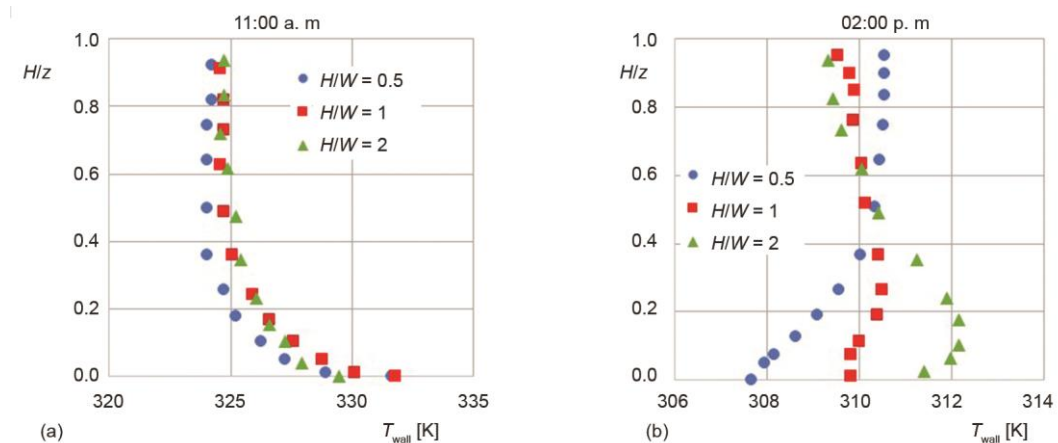


**Figure 6. Trends of $T_{wall}$ parameter calculated on the LW façade on the central plane within the canyon at 11:00 a. m. and at 02:00 p.m**

1222

Vallati, A., *et al.*: Influence of the Geometrical Parameters of Urban …
THERMAL SCIENCE: Year 2019, Vol. 23, No. 2B, pp. 1211-1223

## Conclusions

In this numerical study, many different configurations of a 3-D urban canyon have been considered by varying the geometric ratio *H/W* for two different hours of the day, with the aim to analyze the variations of the thermo fluid dynamic parameters, *i. e. h_c*, *k*, *T*$_\text{wall}$, *u*, by varying the geometry of the canyon.

The simulations and analysis presented in this paper show that the CHTC coefficient depend on various parameters linked together in a complex way: on the geometric characteristics of the canyon, on incoming solar radiation that influence the natural convention phenomena, and on the urban canyon 3-D characteristic that cause variations on the thermal exchange along the canyon axis

The analysis show that remarkable variations on the thermal exchange and on the CHTC coefficient are found along the canyon axis, for different solar irradiation and geometrical caracteristic (*H/W*).

Particularly, in the WW and LW façades the CHTC values for *H/W* = 2 strongly decrease between the inlet and the outlet of the canyon, in the WW façade this variations is about 50% in the LW façade the variations is about 40% maximum. In general it can be said that, the variations of CHTC coefficient along the canyon axis increase with the *H/W* ratio.

The analysis show that the *T*$_\text{wall}$ parameter increase when *H/W* increase and can have strong variations along the canyon axis. This phenomenon is directly connected to the natural convection effects and then to the CHTC coefficient. It is evident in the LW façade while it is less noticeable on WW façade where the forced convection effects are more relevant.

These variations on the CHTC coefficients along the canyon axis should be taken in to account to evaluate the thermal loads in the buildings on the canyon.

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1223

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