A novel approach to CFD analysis of the urban environment

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Abstract. The construction of cities, with their buildings and human activities, not only changes the landscape, but also influences the local climate in a manner that depends on many different factors and parameters: weather conditions, urban thermo-physical and geometrical characteristics, anthropogenic moisture and heat sources. Land-cover and canopy structure play an important role in urban climatology and every environmental assessment and city design face with them.
Inside the previous frame, the objective of this study is both to identify both the key design variables that alter the environment surrounding the buildings, and to quantified the extension area of these phenomena. The tool used for this study is a 2D computational fluid dynamics (CFD) numerical simulation considering different heights for buildings, temperature gaps between undisturbed air and building's walls, velocities of undisturbed air. Results obtained allowed to find a novel approach to study urban canopies, giving a qualitative assessment on the contribution and definition of the total energy of the area surrounding the buildings.

1. Introduction

With further understanding of human health, nature and environment protection, people are more concerned about the relationship between buildings and the surrounding environment [1]. Due to rapid urbanization in developing countries, environmental issues have gained increasing attention in cities with all kind of climates, especially for the metropolis [2]. Therefore, the interest in the microclimate around buildings in urban areas has increased as it affects, among other things, outdoor and indoor thermal comfort [3-5], energy use for heating and cooling [6], the dispersion of air pollution and all the other parameters that can affect the anthropogenic heat [7-8]. In the urban environment, a comfortable climate is important for well-being [9-10].

Great problems in the assessment of urban climatology are due to heterogeneity, especially in land-cover and canopy structure and so many problems are due to the building design [11-15].

The objective of this study is to evaluate the influence of a single isolated building to identify the key urban design variables that influence the urban canopy, and evenly to obtain a correlation that allows giving indications about influence that a building could produce in the surrounding environment. To do this, 2D computational fluid dynamics (CFD) numerical simulations, using standard k–ε turbulence model of individual buildings have been performed, varying alternately some geometric parameters and environmental conditions.

This approach allows both to identify, in a simple and unique way, the extension of the area influenced by the building and to calculate the difference in total energy between disturbed and undisturbed areas surrounding the building.

The novel aspect of this approach is mainly due to the introduction of only one energy parameter to take into account the building influence on its surrounding environment.

In this way, it is also possible a comparison among different urban settlements characterized with different environmental microclimate, in terms temperature, in order to define possible actions to reduce energy consumption and to find out the weight that each of them can have on the urban microclimate change, to highlight urban critical issues. This can lead to defining a strategy of urban actions (creation of green areas, restricted traffic areas, etc.) and architectural (different materials applications, cool roofs, green roofs, cool pavements, etc.) to improve the microclimate of the considered area; by this way, qualitative results can be reached in a quicker time respect to current approaches.

The study also reports a correlation between the average height of the buildings and the extension of the relative influenced area that could be easily improved, following the proposed approach, also to groups of buildings.

2. A background on Computational Fluid Dynamics for urban areas

In the last years a lot of studies were developed [16-18] on external building ventilation with CFD models, as this approach could allow to deepen phenomena that are objectively difficult to investigate experimentally, thus lowering significantly the costs of the study. However, almost all those are unsteady analyses with macro models of 1km×1km mesh and steady analyses at daytime with micro models [19-21]. Unsteady analysis with a micro model is not so spread because the calculation for the solar radiation requires a lot of computational time and resources [22].

The state of the art of microclimate residential studies led to the definition of two main categories for its approach: lumped parameters [23-24] and distributed parameters method [25–26]. Currently, most calculations cases mesh the surfaces and air into the same size, which lead to long calculating time and few practical applications some other researches give assumed surface temperatures as boundary conditions of CFD simulation, instead of calculating both the quantities with the equations in CFD simulation, which may lead to serious inaccuracy. Using measured surface temperatures for CFD calculation may be reliable, but it may also require many detailed boundary conditions. Therefore, the research about how to reduce the calculating time without reducing the accuracy for numerical simulation of the thermal environment around buildings is needed.

3. Model Description

Computational fluid dynamics (CFD) modelling is based on the numerical solution of the governing fluid flow, which is derived from basic conservation and transport principle: (a) the mass conservation (continuity) equation and (b) the three momentum conservation (Navier–Stokes) equations in x, y, z. The air around the buildings can be regarded as an incompressible turbulent inert flow, and the air density is assumed to be constant. These assumptions are reasonable for most lower atmosphere environments as described by Sini et al. [27]. Besides, the turbulence produced by the buoyancy effect is not included because the convective thermal effect around the building is not taken into consideration in the present study. So it has been considered only the turbulence provided by the forced convection. For the two-dimensional problem of an isolated building, the standard k–ε turbulence model governing equations (continuity (1) and momentum (2)) can be expressed as follows:

$$\frac{\partial \overline{U}_i}{\partial x_i} = 0 \qquad (1)$$

$$\overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{P}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\upsilon \frac{\partial \overline{U}_i}{\partial x_j} - \overline{u_i u_j} \right) \qquad (2)$$

k and ε transport equations in the standard k–ε turbulence model:

$$\overline{U}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\nu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \upsilon_t \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_i}{\partial x_i} \right) \frac{\partial \overline{U}_i}{\partial x_i} - \varepsilon, \tag{3}$$

$$\overline{U}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\upsilon_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{\varepsilon}{k}\left(C_{\varepsilon 1} \upsilon_t \left(\frac{\partial \overline{U}_i}{\partial x_j} + \frac{\partial \overline{U}_j}{\partial x_i} \right) \frac{\partial \overline{U}_i}{\partial x_j} - C_{\varepsilon 2 \varepsilon} \right) \tag{4}$$

where

$$\overline{u_i u_j} = \frac{2}{3} k \delta_{ij} - \upsilon_t \left(\frac{\partial \overline{U}_i}{\partial x_i} + \frac{\partial \overline{U}_j}{\partial x_j} \right) \tag{5}$$

$\upsilon_t = C_\mu \left(k^2 / \varepsilon \right)$, k is the turbulent kinetic energy, ε denotes the turbulent dissipation rate. The constants for k–ε turbulence model are summarized in Table 1.

Table 1. Constants for k–ε turbulence model

| C_μ	σ_k	σ_ε	C_{z1}	C_{z2}
0.09	1.00	1.22	1.44	1.92

Figure 1 shows the computational building block configuration, where a two-dimensional computational domain is considered. The inlet boundary is placed at a distance ten times that of the building height (H) upstream of the building, where the velocity inlet boundary condition is applied, and similarly the outlet boundary is placed at a distance ten times that of the building height (H) downstream of the building, where pressure outlet boundary condition is applied. The definition of the extension for the control fluid domain was done by following the guidelines for CFD simulations already known in the literature [28].

The velocity inlet boundary condition is chosen at the inflow boundary with a constant profile and a static pressure of 0 Pa with respect to the reference pressure is imposed as outlet boundary condition. It is used to force the flow in the direction normal to the outlet without any backflow. A free-slip wall condition is applied at the upper boundary.

The domain is discretized by using an orthogonal grid. Since the geometry is relatively simple, a block-based hexahedral mesh is used to enhance the quality of the mesh. The grid lines are refined near the solid surfaces (ground, rooftops, and building walls) and the spacing between grid lines is gently stretched at increasing distances from the solid surfaces, where all inflation ratios of the mesh are kept about 1.05.

Extensive tests of the independence of the meshes have been developed with increasing mesh numbers until further refinement is shown to be less significant, to ensure an independence of the results from grid size. The physical domain and cells number were changed according to the size of the building. A typical computational domain when H = 10 m is 300x100 m, to which it corresponds a computational grid of about 50 000 cells. The sketch of the grid mesh is reported in Figure 1: the grid chosen was fine when closer to building and ground and then expanded further away. The expansion ratio in this non-uniform grid system is about 1.1.
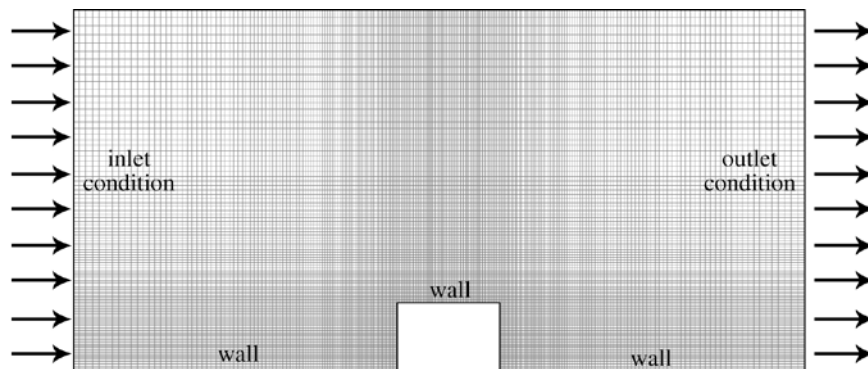
Figure 1. Computational domain and grid

The commercial CFD code ANSYS 14.5 was used in this research. The 2D steady RANS equations are solved in combination with the realizable k-ε turbulence model. The realizable k-ε turbulence model is chosen because of its generally good performance for wind flow around buildings [29]. The governing equations were discretized using a finite volume method and the Density Based method was used to solve the equations. The numerical solver employs a structured, non-orthogonal, fully collocated, cell-centered, finite volume approach for the discretization of the computational domain, and the velocity vector is decomposed into its Cartesian components. Physical diffusive cell fluxes are approximated using a conventional second-order central differencing scheme, and the SIMPLE algorithm [30] is used for pressure correction. Pressure interpolation is standard and second order discretization schemes are used for both the convection terms and the viscous terms of the governing equations [30].

The convergence target based on root mean square is set to 10^{-7}. The quantities of interest, such as velocity and turbulent kinetic energy were monitored at several grid points during the solving process to check stable levels before convergence is met.

4. Methodology

There is not a clear set of variables to study the urban morphology and climatology [31-32]. Therefore, the choice of variables is influenced by the following factors: those identified by the researchers as critical to understanding the urban canopy environment [31-35]; factors ignored in previous researches; variables that can be readily manipulated by designers at the concept design stage.

In this work three critical variables has been identified as major variables to be analyzed: wind speed (V_∞); temperature difference between the undisturbed air and the building surface temperature (ΔT); height of the buildings.

This study assumes the width (W) of the building constant as it is, in real cases, very small respect to the extension of the zone influenced by the building.

The temperatures of ground and building surfaces play an important role in the thermal environment around buildings and so in the canopy layer. They influence the air distribution significantly and the simulation needs them as thermal boundary conditions. The following assumptions are adopted to develop the heat balance model of ground and building surfaces:

- The walls of the buildings have uniform thermal characteristics (windows are neglected for simplification);
- The temperature inside buildings and the ground temperature has been set to be always constant and equal to 303 K, thus the simulation of the thermal environment around buildings focuses on the outdoor air temperature.

Two different temperature differences between the undisturbed air and the building surface temperature (ΔT) have been imposed, to represent summer, winter and spring conditions. In this study,

the contribute of radiation was not considered, also if it is known to be an important factor in the study of the urban environment. For this reason, to emphasize the presence of the temperature, it has been chosen $\Delta T = +5$ K and -5 K.

Even though the geometry of the flow configuration is rather simple, the flow is physically quite complex, with multiple separation regions and vortices, as widely described in the ASHRAE [36]. The study on the height of the buildings H and of its influence on urban canopy layer was conducted by simulating gradually increasing heights. Starting from a minimum height of buildings up to H = 5 m, we analysed buildings up to H = 30 m height, with variations of H in each simulation of about 5 m. As shown below, the parameter H is proved crucial to assessing the extent of the urban environment extension.

Moreover, in this work have been analysed three different speed regimes, 0.1, 0.5, 1 m/s, chosen to represent typical speed that can be found in a typical urban environment.

Summarizing, using the model described in the previous sections, we carried out a series of CFD simulation studies to assess the impact of the previously defined parameters on the building influence extension. Three macro cases have been simulated:

- Case 1: fixing the building height H and the temperature difference ΔT (free stream temperature-building temperature), the undisturbed velocity V_∞ has been varied from 0.1 m/s to 1 m/s;
- Case 2: fixing the building height H and the velocity V_∞, the temperature difference (free stream temperature-building temperature) ΔT has been varied from –5 K to +5 K;
- Case 3: fixing the temperature difference ΔT (free stream temperature-building temperature) and the velocity V_∞, the buildings height H has been varied from 5 m to 30 m.

5. The urban scale analysis

Since the velocity and temperature difference seem to be the major responsible for the energy balance in an urban area, these variables have been used as parameters to evaluate the energy balance, during the numerical simulations. An energy indicator defined as a function of the velocity and the temperature difference has been introduced:

$$E_{ENV} = f(E_K, E_P, Q) \quad [J] \tag{6}$$

where E_K is the kinetic energy, E_P is the potential energy and Q is the total heat. From a theoretical point of view, it would be more accurate to distinguish this index into two parts, one for the summer and one for the winter period. But in this paper a practical approach has been chosen and the part relating to the temperature difference has been considered in its absolute value (6) and so a unique energy index can be used. More, in the calculation of E_{ENV} the term relating to the potential energy, has not been considered, as its influence contribution appears to be negligible.

The environment energy (E_{ENV}), that is the energy in the urban canopy layer, is calculated on a surface with origin in the center of the building and has a certain extension that to have to be determined. This extension is calculated as follows:

- (for the zone) above the building, the point in which the variation of the undisturbed velocity with the height does not exceed 0.03% has been identified;
- for the downstream zone of the building, however, a distance calculated between the center of the building and the point at which the variation of speed undisturbed with the height remains constant (0.5%) as one moves away from the body in a direction parallel to the current (see Curve B in Figure 2) is defined. Figure 2 shows the velocity profiles as you move away from the building (for example, V1, V2, ...) and a point in which the speed (V4) is approximately equal (0.5%) to the previous one (V3). This trend is any way shown precisely in Figure 2, where velocity profiles as a function of distance from the building are presented.

The environment energy should be compared with a value calculated in an undisturbed area, where it is not affected from the presence of buildings. By this way, it is possible to have a quantification of the

influence of the urban building considered. Thus, this quantification would be considering the variation of the E_{ENV}, and then the change of total energy.
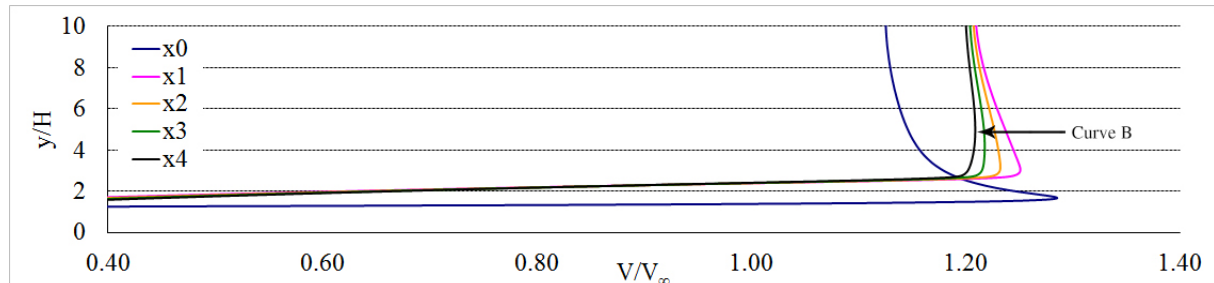

Figure 2. Velocity variation with height

6. Results

6.1. Case 1

Building height H and temperature difference ΔT have been fixed, while varying the free stream velocity V_∞ between 0.1 m/s and 1 m/s. In this case, the building height H is set at 5 m and then at 10 m, its width is 15m, and the temperature difference ΔT between the free stream air and the walls of the building is equal to 5 K (summer situation). In particular, the air temperature was set at 298 K and the temperature of the building at 303 K. As shown in Figure 3, the variations of the ratio E_{ENV}/H with velocity are minimal and scarcely appreciable. Further testing has been done by varying the height H of the building, from 5 m to 10 m. Also in this case the variations of the ratio E_{ENV}/H with velocity are minimal and slightly appreciable.
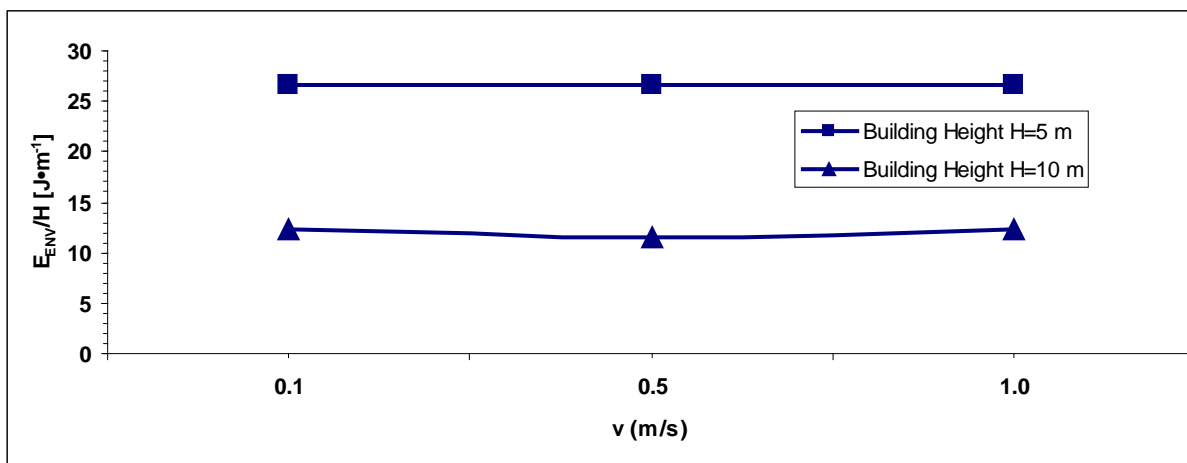
Figure 3. Evolution of E_{ENV}/H as function of free stream velocity (H = 5 m)

In Table 2 the values of the E_{ENV}/H ratio in function of the free stream velocity are reported, for both the cases in which there is the presence of buildings, called Disturbed (indicated with D_s), and in which it is not affected by the presence of buildings, called Undisturbed (indicated with U_n). The Undisturbed area was calculated considering the influence of the Disturbed area, but eliminating any kind of influence due to the building. So the simulation was developed with the same boundary conditions of the one with the building, but eliminating the presence of the building.

Table 2. E_{ENV}/H values in function of V_∞

	H = 5 m		H = 10 m	
V_∞ [m/s]	E_{ENV}/H [J/m] D_s	E_{ENV}/H [J/m] U_n	E_{ENV}/H [J/m] D_s	E_{ENV}/H [J/m] U_n
0.1	26.56	21.58	12.31	10.04
0.5	26.56	21.58	11.54	10.04
1	26.57	21.58	12.34	10.04

The difference in values between the D_s area and the U_n one are evident: as expected, in the presence of buildings, the value of E_{ENV} grows significantly, as the total energy in this area is higher. So, we can conclude that as the free stream velocity V_∞ increases, the parameter E_{ENV}, and hence the extension of the building influence area, does not vary substantially

6.2. Case 2

In this case, the building height H and the velocity V_∞ have been fixed, while varying the temperature difference ΔT from -5 K to $+5$ K. The building height H is set at 5 m, its width is 15 m and the undisturbed air velocity is equal to 0.1 m/s.
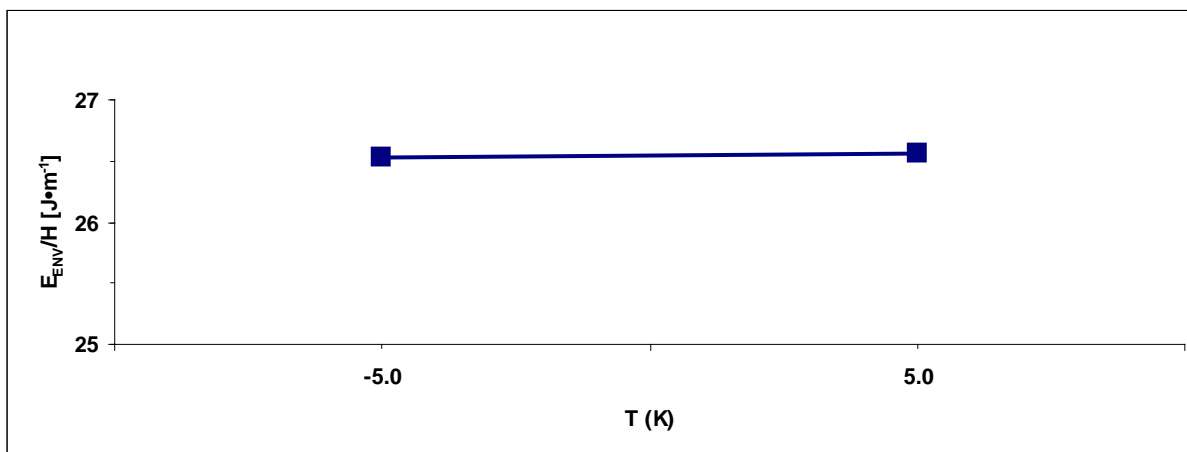
Figure 4. Evolution of E_{ENV}/H as a function of ΔT.

As shown in Figure 4, the variations of the ratio E_{ENV}/H in function of the ΔT are minimal and slightly appreciable, and we can conclude that the parameter E_{ENV} does not vary substantially with the variation of the temperature difference between undisturbed air and the walls of buildings, and hence the extension of the urban heat island does not vary. Even in this case (Table 3) the values of the ratio E_{ENV}/H as a function of the temperature difference, both for the area where there is the presence of buildings, called D_s, and for the area without buildings, called U_n, are reported.

Table 3. E_{ENV}/H values in function of ΔT

ΔT [K]	E_{ENV}/H [J/m] D_s	E_{ENV}/H [J/m] U_n
+5	26.56	21.58
-5	26.53	21.58

Also, in this case, the difference in values between the D_s area and the U_n area is clearly visible. As expected, in the presence of buildings the value of E_{ENV}/H increases significantly, as the total energy present in this area surrounding the building is higher.

6.3. Case 3

The temperature difference ΔT and the velocity V_∞ have been fixed, while varying the buildings height H from 5 m to 30 m. The temperature difference ΔT between the undisturbed air and the walls of the building is equal to 5 K, its width is 15 m and the undisturbed air velocity is equal to 0.1 m/s.

Table 4. A comparison of E_{ENV} values for a city/rural condition

H [m]	E_{ENV}/H [J/m] D_s	E_{ENV}/H [J/m] U_n
5	26.56	21.58
10	12.31	10.04
15	5.60	4.58
20	3.88	3.42
25	2.56	2.35
30	1.12	1.02

As expected, even in this case the difference is clearly visible between the values of the D_s area and the U_n area: in presence of buildings, the value of E_{ENV}/H increases significantly, as in previous cases. Figure 5 and Table 4, shows that increasing the building height, the value of E_{ENV} decreases with some potential law, found in:

$$E_{ENV} = a \cdot H^{(b+1)} \tag{7}$$

being a numerical coefficient equal to 470.6 and b an exponent equal to -1.66. A comparison between the analytical and numerical correlation found is reported in Figure 5.
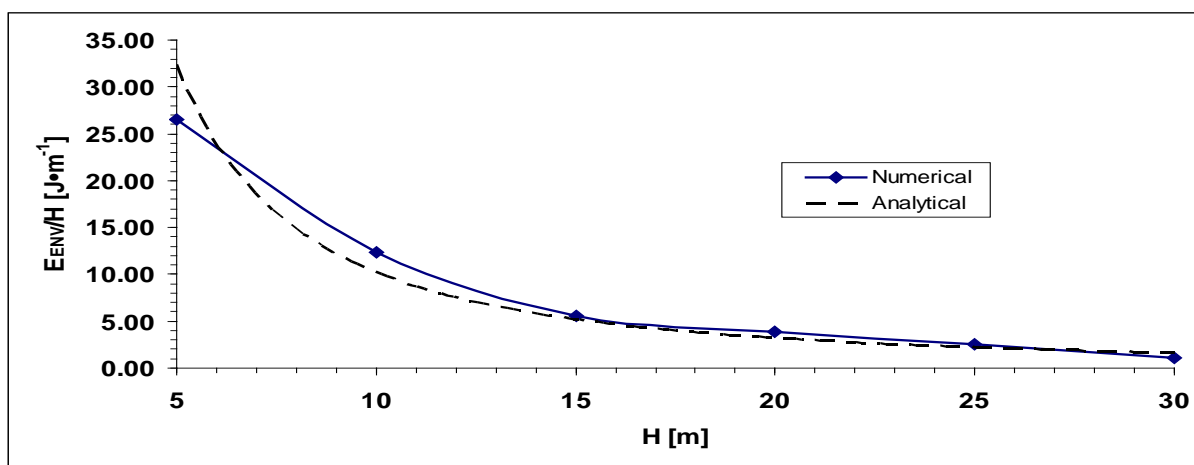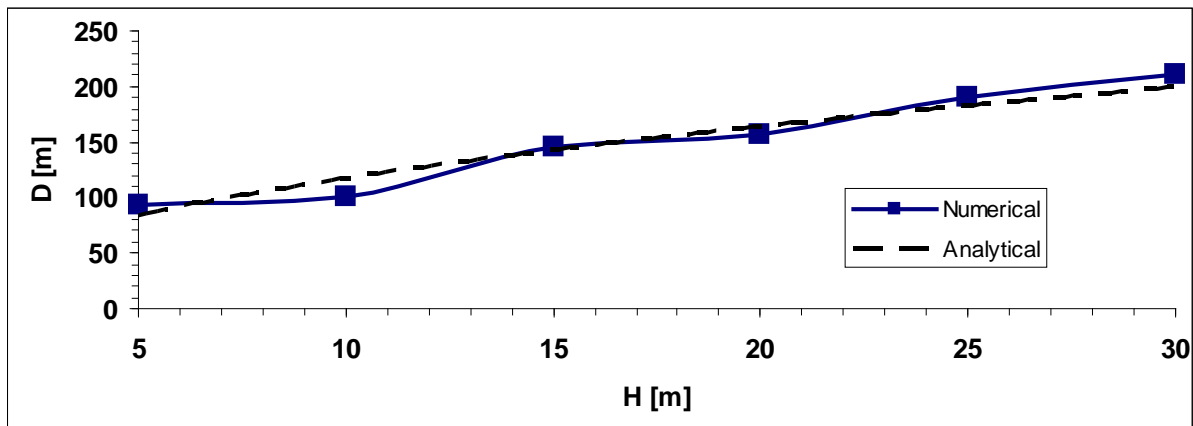

Figure 5. Analytical and numerical correlation comparison for the E_{ENV}/H

This correlation shows that an increase of the height of the buildings produces a decrease of the factor E_{ENV}/H with a potential law. Being $E_{ENV} = f(D)$ a function of the extension (D) of the area surrounding the building, increasing the height of building, the extension of the influenced area increases. This means that it is also possible to find a correlation that links D and the average height of the buildings. In this case the correlation becomes:

$$D = c \cdot H^d \tag{8}$$

with c e d coefficients respectively 38.9 e 0.48. A comparison between the analytical and numerical correlation found is reported in Figure 6.

Figure 6. Analytical and numerical correlation comparison for D.

In this way, it is possible to have both a qualitative value, using E_{ENV}, and a quantitative value linked to the extent, by D, of the disturbed urban environment, considered.

7. Discussion and conclusions

Results obtained allowed to find a correlation between the average height of buildings H and the external building environment total energy E_{ENV}. This parameter allows to give a qualitative assessment on the contribution of the total energy of the urban environment. The next step was then to give a quantitative assessment, tying this parameter to the extension of the influence of the single building, D, and also to find in this case a correlation linking the D to the average height of buildings. With these correlations, it is possible to characterize quickly and easily an influence due to the buildings, in terms of total energy and geometric extension.

With this approach it is also possible a comparison among different urban environment in order to define possible actions to reduce energy consumption and to find out the weight that each of them can have on the urban microclimate change, to highlight urban critical issues.

This could lead to defining a strategy of urban actions (creation of green areas, restricted traffic areas, etc.) and architectural (different materials applications, cool roofs, green roofs, cool pavements, etc.) to improve the microclimate of the considered area.

Then next step will be to create a complete model that, in the frame of the presented approach, could take into account other parameters like radiation, evapotranspiration, transmission and absorption of the buildings, etc.. in order to develop a guide line of possible actions to mitigate city impact on environment.

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