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Computational Fluid Dynamics Analysis for Evaluating the Urban Heat Island Effects

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Abstract

The quality of the thermal environment within the built environment is dependent by local climate and urban design features. Therefore, the scientific knowledge on urban design and microclimate are fundamental for obtaining a tolerable thermal environment at the neighborhood scale. Such problematic interested the huge part of the world population that lives in urban area, which is currently about 50% and it is expected will increase to 66 % by 2050.

The specificity of the urban climate is frequently associated with the urban heat islands phenomenon, which refers to the elevated temperatures within the city areas compared to the rural surroundings. In this context a typical urban geometry is represented by the so called “urban canyon “that denotes an ideal infinite urban street confined by buildings on both sides

In this study an urban geometry, constituted by three urban street canyons with a canyon aspect ratio H/W of 1.0, has been examined. CFD simulations were performed to evaluate the fields of temperature and velocity of the air within the urban canyons and their surroundings. Several scenarios were examined considering alternatively the leeward or the windward walls hitted by the sunrays, while the opposite façade was shaded, as well as varying the reflective properties of the surfaces and the wind velocity. The results of simulations evidence that the adoption of materials of the building envelope with high albedo coefficient guarantees a decrease of the temperatures at least of 1.5°C. Therefore, an increase of the knowledge of urban climate may provide valuable contribution to promote energy efficiency in the built environment.

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Keywords: Urban Heat Island, Street canyon, CFD simulation

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1. Introduction

The percentage of the world population, which lives in urban area, has crossed the threshold value of 50%, a proportion that is expected to increase to 66 % by 2050 [1].

Many of these people lives in 28 mega-cities with 10 million inhabitants or more, that host 453 million people (12 % of the world's urban dwellers); among them, sixteen are located in Asia, four in Latin America, three in Europe three in Africa and two in Northern America. Moreover, the world is projected to have 41 mega-cities by 2030. Urban areas offer most economical resources in comparison with rural area, but otherwise, for satisfying the citizen requirements, they involve high-energy consumptions, which in turn increase the emission of global warming gases and pollutants.

Nomenclature

C_p = air specific heat at 300 (J kg^{-1} K^{-1})
F_r = Froude number
I_g = solar irradiation (W/m^2)
H = height of street canyon (m)
H/W = canyon aspect ratio
k = turbulent kinetic energy (m^2 s^{-2})
K = Von-Karman constant
q* = net all-wave radiation flux (Wm^{-2});
q_F = anthropogenic heat flux (Wm^{-2})
q_H = turbulent sensible heat fluxes (Wm^{-2})
q_E = turbulent latent heat fluxes (Wm^{-2})
T = air temperature (°c)
U = air velocity intensity (m s^{-1})
u^* = friction velocity (m s^{-1})
z =height from the ground, (m)
z_0 = inflow roughness length scale (m)
α = solar radiation absorptivity
δ = atmospheric boundary layer depth (m)
ε =turbulence dissipation rate (m^2 s^{-2})
Δq_S = net uptake or release of energy by sensible heat changes (Wm^{-2})
Δq_A = net horizontal advective heat flux (Wm^{-2}).
ΔT_{u-r} = urban/ rural temperature difference (°c)
μ =dynamic viscosity (kg $m^{-1}s^{-1}$)
Ψ_0 = shadow factor
ψ_s = sky view factor
Ψ_m = integrated stability function for momentum

Therefore, cities are one of the major players where sustainable policies should be directly or indirectly actuated, and therefore they have to contribute in achieving the major policy objectives in terms of sustainable and parsimonious practices. Thus, actions are needed at urban level to ensure that cities will be able to fulfil their potential in the actuation of sustainable policies, and at the same time to guarantee comfortable environmental climate.

Eurostat [2] have defined the Degree of Urbanization (DEGURBA) in order to identify real urban structures with a high concentration of population, these are cities (densely populated areas), towns and suburbs (intermediate density areas), rural areas (thinly populated areas).

In densely populated urban areas, it is observed an increase of air temperature, near the ground (canopy layer), respect to the rural surroundings, due to a difference in cooling between urban and rural areas. This phenomenon, known as urban heat island (UHI), is taking growing prominence among the scientific community [3, 4, 5].

The urban heat island development is affected by several factors: anthropogenic heat, humidity and pollutants, as well as the effect of impermeable surfaces, which reduce the evapotranspiration.

Another not negligible feature is the solar reflectance since it determines how the solar irradiation is reflected, and absorbed by the surfaces as well as the obstructed view of sky with the consequently trapping of radiation heat within the buildings [5]. Moreover, low albedo coefficients as well as high-insulated building envelope leads to high daytime surface temperatures, [6].

The mutual influence of UHI and urban layout as well as thermal comfort has been analyzed, along with mitigation technologies [7, 8]. For instance, the solar reflectance of building envelopes and urban pavement represents an important optic-energetic property to mitigate the summer UHI effect [9,10,11].

Building simulations barely consider the effective microclimate within the built environment even if it is well known that air temperature and humidity nearby to the buildings, at the urban canopy layer (UCL), may significantly differ from that of the urban boundary layer (UBL).

The Computational Fluid Dynamics (CFD) analysis allows performing comparative analysis of the urban heat island effect based on different scenarios. Many researchers used widely the CFD in urban physics for investigating the wind flow field [12], the effect of natural ventilation [13,14] thermal environment in urban areas [15,16], as well as pollutant dispersion [17].

However, numerical studies, as opposed to observational studies have the drawback to apply several simplifications, since the urban microclimate physics is very multifaceted.

In the present study, the microclimate of an ideal multi street canyon is investigated through CFD simulations. In particular, the presence of building surface temperature higher than the air within the canyon, due to the effect of solar irradiation and anthropogenic heat is inspected with the aim to evaluate the fields of velocity and temperature within the canyon.

Several scenarios were examined considering alternatively the leeward or the windward walls, hitted by the sunrays, while the opposite façade was shaded, as well as varying the reflective properties of the surfaces and the wind velocity.

This research would contribute to increase the knowledge on urban microclimate and provide strategical suggestions for planners, designers, and urban decision makers to document, mitigate and improve the thermal environment of cities.

2. Literature Overview

2.1. Street canyon

A street canyon geometry represents an ideal infinite urban street confined by buildings on both sides with wind incidence perpendicular to the street axis. [18].

The geometry of an urban canyon is usually described by its aspect ratio H/W [19, 20], where H is the height and W the width of the canyon. A canyon is classified as regular when it has an aspect ratio approximately equal to 1.0 and modest little opening along the sides. In symmetric urban canyons, the buildings bounding the street have approximately the same height

Aspect ratios below 0.5 are typical of the so-called avenue canyons, while values higher than 2.0 are representative of narrow canyons. Finally, the length (L) of the canyon indicates the distance between two major intersections, subdividing street canyons in short ($L/H<3$), medium ($L/H<7$) and long canyons ($L/H>7$).

As regard wind direction, the up-wind side of the canyon is named leeward side, and the downwind is named windward side [18].

In case of perpendicular flow, the airflow within the canyon is characterized by the growth of one or more vortices inside the canyon. Aspect ratio (H/W) between 0.65 and 1.6 origins a single vortex, while higher aspect ratio causes the development of a wake interface or multiple vortices [21,22]. In addition, the appearance of small weak vortices at the bottom corners of the canyon may arise.

However, in presence of vertical surface inside the canyon with temperature higher than the air, e.g. surface heated by the solar irradiation, an upward airflow is established close to that surface. The canyon air flow regime results, therefore, from the interaction between the thermally induced and circulatory flows.

The air flow regime within the canyon is determined by buoyancy effects for wind velocities below of 2.0 and 3.0 m·s[1] [19, 23]. A reliable parameter frequently used for describing the balance between inertial and buoyancy forces is the Froude number (F_r). Froude number close to unit designates the transitions between the two-flow regimes because it depends on both wall temperature and wind velocity [23].

The urban geometry primarily affects the airflow regime within the street canyons rather than the climate of the boundary layer [24, 25]

Another, crucial query for air quality and pollution dispersion modelling is whether, or how much of the vortex circulation, is a recirculation of air within the canyon. An air mixing will occur even with a well-developed vortex since the air is entrained (ejected) at the top of the canyon due to the intermittent penetration of eddies or downward (upward) by the stream lines or the mixing in the shear layer [26].

2.2. Urban Heat Island

The development of the UHI is associated with the energy balance of the urbanized area. In particular, the dimensions and spacing of buildings, namely the urban geometry, the radiative properties of urban materials, i.e. solar reflectance, thermal emissivity, as well as the heat capacity, influence the energy absorption and the emitted long-wave radiation back to the sky from a given surface. The urban energy balance is defined as [27]:

$$q^* + q_F = q_H + q_E + \Delta q_S + \Delta q_A \quad [\mathrm{Wm^{-2}}] \tag{1}$$

where

q^* is the net all-wave radiation flux;
q_F is the anthropogenic heat flux from heat released by combustion of fuels (e.g., traffic, building HVAC systems);
q_H and Q_E are the turbulent sensible and latent heat fluxes, respectively
Δq_S is the net uptake or release of energy by sensible heat changes in the urban ground-canopy-air volume
Δq_A is the net horizontal advective heat flux.

During daytime, experimental investigations have highlighted that the surfaces within the urban canyon reach temperatures higher, up to 20 °C, than the air over the height of the built area (UBL)[19,28].

Especially at night, the air above urban centres is typically warmer than air over rural areas, thereby the UHI determine an urban/ rural temperature difference (ΔT_{u-r}) occurs energy balance differences

Two empirical relationships between the UHI intensity and the aspect ratio (*H/W*) or as a function of the sky view factor were presented by OKE [27]:

$$\Delta T_{u-r} = 7.54 + 3.97 \cdot ln\left({}^{H}/_{W}\right) \tag{2}$$

$$\Delta T_{u-r} = 15.27 - 13.88 \cdot \psi_s \tag{3}$$

$$\psi_s = cos\left(atan\left({}^{2H}/_{W}\right)\cdot\right) \tag{4}$$

Stewart and Oke introduced the Local Climate Zone (LCZ), to standardize the classification of urban and rural field sites for observational UHI studies [29]. A LCZ is defined as "regions of uniform surface cover, structure, material and human activity, it can span hundreds of meters to several kilometres in horizontal scale.

3. Methodology

3.1. CFD Simulations

The flow field inside the urban canyon has been calculated by solving the two-dimensional, steady-state, Reynolds-Averaged Navier–Stokes (RANS) equations through the FLUENT code. In steady-state RANS modelling, the flow properties are fragmented into their mean and fluctuating components by Reynolds decomposition.

Fluent code offers several turbulence schemes including multiple variations of the k-ε models, as well as k-ω models, and Reynolds stress turbulence models [30].

In street canyon flow and thermal stratification studies, the standard k-ε turbulence model is commonly adopted. [8].This turbulence model supposes that the Reynolds stresses are isotropic, and therefore it is sufficient to take account of two additional equations: one for the kinetic energy, "k" and another for the dissipation rate, "ε".

Fluent code allows calculating the net radiation setting up solar model which is based on the position on the earth's surface (latitude and longitude), the model orientation with respect to North, the time of day, the season, and established conditions for clear or cloudy weather.

As solver, the pressure-based algorithm "Simple", which exploits a relationship between velocity and pressure corrections to enforce mass conservation and obtain the pressure field, was used.

However, in street canyon and thermal stratification studies, the standard k-ε turbulence is the model most commonly used.

To evaluate the impact of thermal effects, the natural convection module has been activated by setting an incompressible ideal gas model for air density. Air is approached as an ideal compressible gas with a specific heat *Cp= 1,005* J $kg^{-1}K^{-1}$. Air density is calculated referring to an isobaric transformation, while the dynamic viscosity" μ is defined as follows:

$$\mu(T) = \mu_0 \cdot \sqrt{(T / 300)} \quad (5)$$

with $\mu_0 = 1.85\ 10^{-5}$ kg $m^{-1}s^{-1}$ (at 300 K).

According to Monin-Obukhov [31] and Solazzo [32] the inflow air velocity is defined by a logarithmic profile as a function of the height from the ground, z

$$U(z) = \frac{u^*}{k}\left[ln\left(\frac{z}{z_0}\right) - \psi_m\right] \quad (6)$$

In addition to the velocity profile, at the boundary inlet surfaces the profiles of the turbulent kinetic energy *k* and of the turbulence dissipation rate ε have been specified in order to start the iterative calculations.

$$k = \frac{u_*^2}{\sqrt{C_\mu}}\left(1 - \frac{z}{\delta}\right) \quad (7)$$

$$\varepsilon = \frac{u_*^3}{K \cdot (z + z_0)}\left(1 - \frac{z}{\delta}\right) \quad (8)$$

Where $u*$ is the friction velocity, K Von-Karman constant , δ is the atmospheric boundary layer depth, z_0 the inflow roughness length scale and Ψ_m is the integrated stability function for momentum obtained through the diagram of Golder [33]

A finite-difference numerical solution technique based on integration over the control volume is used to solve the model equations with appropriate boundary conditions. It is indispensable to mention that final converged steady-solutions is obtained by solving iteratively the unsteady transport equations with very large pseudo-time steps. According to the guidelines of Franke et al. (2007) [34] the results can be considered as converged when the residuals have a value lower than 10^{-5}.

4. Studied urban geometry

The studied urban geometry consists of four line of buildings, with fixed canyon aspect ratio H/W of 1.0, building's height H =10.0 m and building's width W= 10.0 m , the façade orientation is E-W.

The main features of the investigated geometry are tightly packed buildings of 1 to 3 stories tall, few or no trees, little or no green space, concrete, steel, stone and glass construction materials, diurnal temperature range is medium. Features that allow to classify this urban area as a compact low-rise zone, namely LCZ 3, following the Local Climate Zone (LCZ) classification proposed by Stewart and Oke (2012).

4.1. Calculation domain and Mesh of calculus

As regard to the computational domain Franke [31] suggests that the top of the domain should be at least 5·H (H is the height of the tallest building) above the roof of the buildings, the distance between the buildings and the outlet should be 15· H, otherwise Tominaga [32] suggests that a distance of 10·H can be sufficient. Figure 1 depicts the dimensions of the calculation domain.

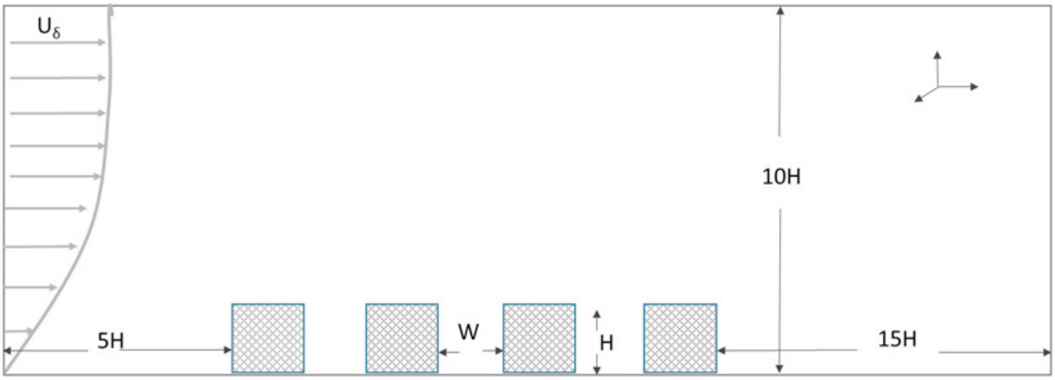

Fig. 1. dimensions of the calculation domain

The computational grid used was composed by a quadrilateral mesh with variable dimensions in order to improve the accuracy of the calculation. The cell dimensions are 0.03x0.03 m close to the building façade, 0.125 x 0.125 m within the urban canyons and 1.0 x 1.0 m in the rest of the domain. Globally, the mesh is constituted by 30200 cells.

Furthermore, the Standard Wall Function of Fluent was used to bridge the viscosity-affected region between the wall and the fully-turbulent region.

4.2. Operative and boundary conditions

The steady state simulations have been carried out with different wind directions and velocities as well the reflective coefficients of the surfaces within the urban canyon. Moreover, it was investigated the behavior of the urban canyon considering alternatively the leeward walls, or the windward walls, warmed by the sunrays, while the opposite façade was shaded.

The value of horizontal solar radiation is assumed to be 960 W/m^2, which correspond with a sunny day (27 July at 13:00 at of 37.5° Latitude , and 15.5° Longitude), and the ambient temperature T_a was fixed to 303 K.

The energy fluxes incident on each surface have been calculated as following:

$$q^* = \psi_0 \cdot \alpha \cdot I_g + q_F \quad (9)$$

Where: α is the solar radiation absorptivity, I_g the solar irradiation [W/m^2], Ψ_0 the shadow factor and q_a the anthropogenic heat radiation exchanges. This last term has been fixed by 25 W/m^2 [27]. The sensible heat storage and the net heat advection were neglected in this study.

Table 1 summarizes the main features of the six simulated scenarios.

Table 1. Main features of the simulated scenarios

Scenario		A_1	A_2	B_1	B_2	C_1	C_2
Wind velocity U_δ at z= 10 m;	m/s	6.0	6.0	6.0	6.0	2.0	2.0
Heated Wall		leeward	windward	leeward	windward	leeward	windward

Solar Irradiation (facade)	W/m^2	420	420	420	420	420	420
Solar Irradiation (roof and road)	W/m^2	960	960	960	960	960	960
Absorptivity (roof and facade)	%	70	70	20	20	70	70
Absorptivity (road)	%	90	90	90	90	90	90
Anthropogenic heat	W/m^2	25	25	25	25	25	25
Shadow factor	%	50	50	50	50	50	50

5. Discussion and results

The flow patterns inside the urban canyon has been calculated by solving the two-dimensional, steady state, Reynolds-Averaged Navier–Stokes (RANS) equations through the FLUENT code.

The CFD simulations allow calculating the flow field and the temperature within the calculation domain.
As an example figure 2 shows the flow field in two scenarios, A_2 and B_2, which differ for the albedo coefficient of the surfaces, that are 0.7 and 0.2 respectively.

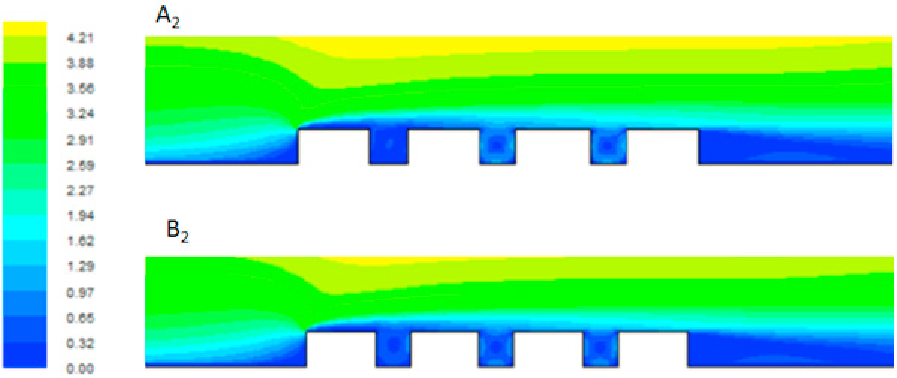

Fig. 2. Flow patterns in the scenarios A_2 and B_2

It can be observed, as the geometry of the street canyon is that one typical of the skimming flow, which occurs when the wind velocities are high, and consequently the convective effect dominates over the buoyancy effect.

In this flow regime, the air flow skims over the street canyon without go through the canyon, where a single stable vortex is established. However, the turbulence may generate smaller vortices at the canyon bottom.

Some differences emerge between the subsequent canyons, where an increase of the airflow inlet is detected, although it is quite modest.

In the following figures 3, 4 and 5, the flow and the temperature fields within the central street for the different scenarios are compared. Globally, all the examined scenarios are characterized by flow regimes fairly different.

Observing the fields of velocity and temperature for the scenarios A1 and A2, it becomes evident that when the irradiated surface is windward, the incoming air encounters the irradiated facade and it is rapidly heated, then its temperature further increases due to the heat exchanged with the ground surface. Thereby, the thermal energy is rapidly transferred to the leeward façade and the center of the canyon. So on, the air close to the surface is heated and it moves upwind, reinforcing the existent eddy. Therefore, the buoyancy reinforces the recirculation of the air flow and the counter rotating vortex increases its momentum.

Otherwise, when the leeward facade is hitted by the solar radiation, the incoming airflow first meets the cold façade and then the ground surface as well as the irradiated wall, which do not succeed to increase its temperature significantly. In this circumstance, the incoming cold air constrains the transmission of the heat flux to the center of the canyon.

The buoyancy effect is feeble and the vortex intensity is much weaker than the scenario A1, consequently the vertical exchanges between the far away air and the air in the canyon increase.

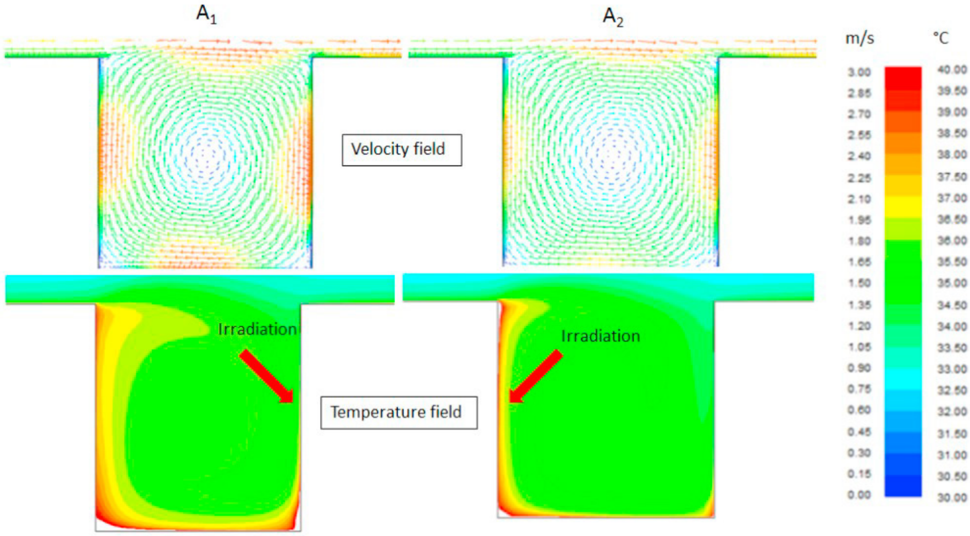

Fig. 3 Temperature and Wind Field in central canyon – scenarios A1 and A2

For the scenarios B_1 and B_2, the airflow within the canyon does not showed significative differences in comparison with the scenarios A_1 and A_2, confirming the different air patterns when the warmed façade is that one leeward or windward. Otherwise essential differences emerges in the temperature distribution, indeed the lower values imposed to the surfaces' albedo modify the radiative energy balance within the canyon.

Substantially, a decrease of the temperatures at least of about 1.5 °C is detected; these lower temperatures, which descend by the adoption of the reflective materials, allow reducing the pedestrian thermal discomfort within the urban canyon.

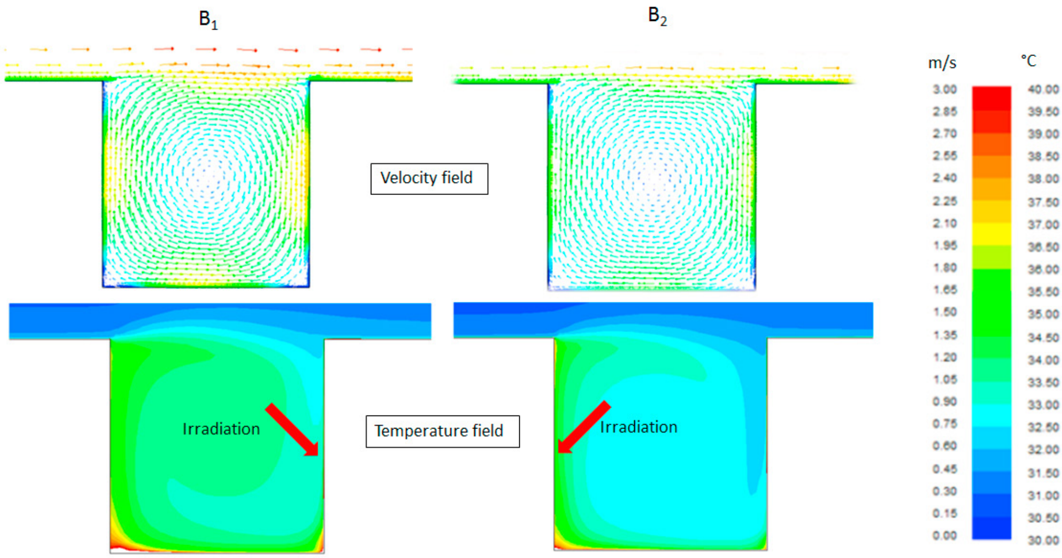

Fig. 4 Temperature and Wind Field in central canyon – scenarios B1 and B2

The last examined scenarios (C_1 and C_2), characterized by the lowest wind velocity ($U_\delta = 2.0$ m/s), disclose a rather different flow field inside the street canyon in comparison with the other scenarios. Particularly, in the case of windward heated wall, the buoyancy forces produce a second counter rotating vortex [11]. Thus two vortices, characterized by distinct air velocities, co-exist inside the canyon. The shear stress forces at the canyon top induces the greater air circulation, the main vortex, while weaker air velocities characterize the lower vortex. Consequently, a stagnant zone appear in the right corner of the street with temperatures higher than 35°C, which could be dangerous for the human health.

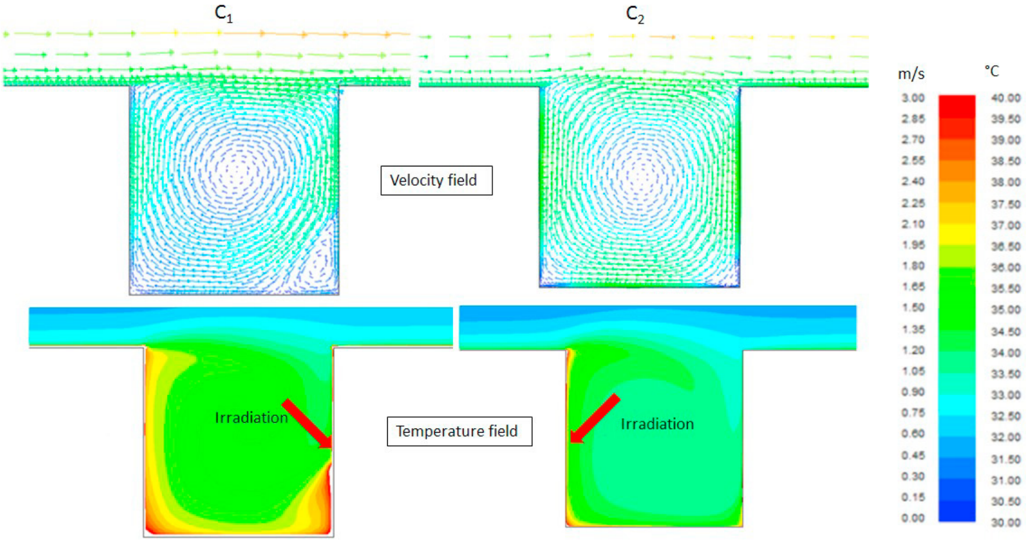

Fig. 5 Temperature and Wind Field in central canyon – scenario C_1 and C_2

In conclusion, it is possible to highlight that the heated windward wall produces a higher retention rate due to the above detected vortex splitting effect.

6. Conclusions

In this study, the microclimate of an ideal multi street canyon is investigated through CFD simulations. In particular, the presence of building surface temperature higher than the air within the canyon, due to the effect of solar irradiation and anthropogenic heat is inspected with the aim to evaluate the fields of velocity and temperature within the canyon. The paper demonstrates the effectiveness of the walls made of reflective materials for mitigation of the urban heat island effects. The increase of the surface albedo reduces the amount of heat stored during the daytime; limit the air temperatures within the canyon allowing to reach a decrement of temperature of about 1.5°C.

Moreover, the results indicate that the scenario where the leeward wall is heated, it is most efficient to disperse the entrainment or auto-produced thermal energy within street canyon out of it. This outcome may be effective also in reference with the dispersion of pollutant out of the street canyon.

Therefore, the knowledge of the characteristics of the urban micro-climate may provide valuable contribution for a most precise evaluation of the building energy needs and to promote energy efficiency in the built environment.

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