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Analysis of thermal field within an urban canyon with variable thermophysical characteristics of the building's walls

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Abstract. In a typical urban configuration, a microclimatic analysis has been carried out. Using a CFD method, a N-S oriented urban street canyon, with a given H/W ratio, has been examined. The standard k–ε turbulence model has been used to simulate a three-dimensional flow field and to calculate the thermo-fluid dynamics parameters that characterize the street canyon. In this study has been analyzed the thermal flow field when the walls of the building change the properties of solar radiation absorption, in particular for α=0.2 and α=0.8. Solar radiation considered is that of 21/07 in Milan in two different hours: at 11:00 a.m. and at 02:00 p.m. The study shows the importance of the thermophysical properties of a wall, in the development of the thermal field and flow field. This is a very important topic, in terms of improvement of well-being and the quality of the air within the cities, through the choice of materials and colors of the facades of buildings.\

1. Introduction

Roughly 25% of the final energy consumption, including all energy delivered to the final consumers (excluding deliveries for transformation and network losses) in the EU is used for residential and 15% for commercial buildings. Heating represents 70% of the residential energy consumption (European Commission Energy, 2009). Therefore there is a great energy saving potential by minimizing the energy demand for space heating and cooling of buildings. Today about 50% of the world population lives in urban areas, increasing to about 70% by 2050.

The urbane climate is strongly influenced by its geometry and surface materials. The urbane temperature increases respect to surrounding areas. The increased heat gains are due to higher absorption of solar radiation on dark surfaces such as asphalt, the reduced energy losses during the night due to buildings that block thermal radiation to the cold sky, the lack of evapotranspiration as well as lower convective heat losses due to wind sheltering by buildings. Waste heat from buildings, industry and transportation further contributes to the urban warming. Besides the higher air temperatures, higher radiative gains, to the building and lower convective heat losses from the building also increase the space cooling.

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This paper studies a particular urban context, an urban canyon, where the characteristics properties of facades are changed trough the absorption coefficients. In effect thermal conditions in street canyons are important topics of urban microclimate, that influences the buildings energy demand and has a large impact on the thermal comfort and health of the people [1]. Surface temperature distribution and air circulation play an important role on heat exchanges between the building and canyon air, that in turn influence pedestrian comfort and the energy demand of buildings [2 -6].

Moreover, the technical characteristics of the used materials determine to a high degree the energy consumption and comfort conditions of individual buildings as well as of open spaces [7, 8]. Many studies have been carried out to understand better the optical and thermal characteristics of materials as well as their impact on the city climate [9-15] and systematic ambient temperature differences above various types of materials have been reported.

The albedo of cities is seriously decreased compared to the surrounding rural areas mainly because of the irregular building structure. Cantat [16] has shown that the albedo in Paris is almost 16% lower than in the surrounding rural areas. Aida and Gotoh [17] have assessed the decrease of the urban albedo because of the geometrical characteristics of urban canyons. It is found that urban configuration with canyon width about twice the width of buildings gives the lowest albedo at all zenith angles. Also, Aida [17] has reported that under clear weather conditions, the absorption of urban structures is increased to about 20% compared to a flat surface of the same material. The use of materials presenting high reflectivity to the solar radiation and high spectral emissivity, cool materials, contribute to increasing the urban albedo and it is considered to be one of the more promising and powerful techniques to mitigate the heat island phenomenon [18].

In this study, using a commercial CFD code (Ansys Fluent), several 3D numerical tests have been performed on an isolated street canyon, to evaluate how the flow field changes within the canyon at different surface properties of facades.

2. CFD numerical model

In this section the CFD numerical model that we have used to perform the simulations, is outlined. Using the commercial CFD code Ansys Fluent 14.0 [19], 3D double precision, pressure based version, the steady RANS equations have been solved in combination with the standard k- ε model.

To evaluate the impact of thermal effects, the natural convection module has been activated by setting incompressible ideal gas model for air density. Based on the best practice guidelines by Franke et al. [21] and Tominaga et al. [23], the computational domain has been extended beyond the built area by 5H in the North, West and South direction, of 15H in the East direction, as can be observed in Figure 1, in the next chapter. The upper boundary condition is located at distance of 5H above the building roofs. These dimensions have been chosen to take into account of the blockage ratio and to ensure the flow re-development behind the building region. The temperature surfaces has been obtained as result of the heat transfer calculations, setting up: the solar load module, the temperature of undisturbed air (303 K), and the internal temperature of buildings (299 K). To simulate the ground influence, the computational domain has been extended 5 m below the ground level. The ground has been simulated setting the following parameters: density = 1000 kg/m^3; specific heat = 1000 J / kg·K; thermal conductivity = 2 W/ m·K; temperature at −5 m = 288 K; emissivity = 0.9; solar radiation absorptivity (direct visible and infrared) = 0.8. The radiation exchanges has been evaluated setting up the S2S radiation model, in which the energy exchange parameters are accounted by a geometric function, i.e., view factor, and activating the solar ray tracing in the solar load model, provided in ANSYS Fluent version 14.0.0. Transient heat conduction in ground and walls has been analyzed in [24]. This study finds that these effects are important to calculate heat fluxes, but not for surface temperatures which influence the natural convection flow fields. Furthermore, the materials characteristics have been reported in [21, 23]: i.e., the building walls have: density = 1000 kg/m^3;

specific heat = 1000 J/ kg·K; thermal conductivity = 0.15 W/ m·K; thickness = 0.30 m; internal air temperature = 299 K; emissivity = 0.9; solar radiation absorptivity (direct visible and near infrared) = 0.8. To ensure a high quality of the computational grid, it is fully structured and the shape of the cells has been chosen hexahedral. The velocity profile has been set giving a uniform velocity magnitude at the velocity inlet boundary, the turbulence intensity at 10% and the roughness length z0 = 0.05 m . As the flow approaches the built area the velocity inlet profile is fully-developed before reaching the buildings [24] and it can be represented by Equation (2.1), where u* is the friction velocity, K is the Von Karman constant (0.4) and z is the height coordinate. This equation represents the wind velocity profile of the inlet flow, when the wind approaches the buildings. In another study [24], it is shown that the profile reaches the asymptotic velocity when it reaches about 4 m in height.

The aerodynamic roughness value z_0 has been set in relation to the roughness parameters in the ground surface boundary conditions (Ramponi and Blocken [25]): the sand-grain roughness height *Ks* and the roughness constant *Cs*. According to the best practices guideline for the CFD simulations by Franke et al. [21] and Tominaga et al. [23], setting Ks = 1 m and Cs = 0.5, we obtain z_0 = 0.05 m (Blocken et al. [26], ANSYS Fluent User's Guide [19]), that has been considered an appropriate value to represent the roughness of the outer region (Blocken et al. [26], Norris and Richards [27]).

$$u(z) = \frac{u^*}{K} \ln\left(\frac{z + z_0}{z_0}\right) \qquad (2.1)$$

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, as shown in Equation (2.2) [21].

$$u^* = k^{0.5} C_\mu^{0.25} \qquad (2.2)$$

Where C_μ = 0.09.

The numerical model used for the computation of the temperature and velocity fields inside the canyon has been validated by reproducing the experimental data reported by Ueara et al. [28], showing a satisfactory degree of agreement, as discussed in Bottillo et al [24].

3. Results

In this study, considering different ambient wind conditions, several simulations have been performed on an isolated urban canyon, in order evaluate the effects on the flow field and heat exchange processes within the canyon. The analyzed urban canyon has the following characteristics: it is placed in Milan, Italy (longitude: 9.18, latitude: 45.47, UTC:+1), it has an aspect ratio H/W = 1 and L/W = 5, the orientation is N–S, the buildings width and height are 20 m, the street width is 20 m and the street length is 100 m. A steady state simulation has been carried out with the ambient temperature and solar radiation at 11.00 a.m. and at 02:00 p.m. of 21 July in Milan, as given by the software meteorological file. As previously mentioned, the computational domain has been extended beyond the built area by 5H in the North, West and South directions, of 15H in the East direction.

To evaluate the relationship between the wind flow field and the temperature field within the canyon, varying the value of the absorption coefficients, we compare the values of heat exchange coefficient h_c, turbulent kinetic energy k, wall temperatures T_{wall} and the intensity of the wind speed u. All these variables are calculate on vertical lines on three different plans, as can be observed in Figure 1, with XZ coordinates: the north plane is placed ten meters from the north limit of the building, the central plane is situated at the middle of the canyon and the south plane is ten meters from the south limit. Specifically the turbulent kinetic energy and wind speed are calculated on lines 0.4 m distant from the façades, while the wall temperatures and the heat exchange coefficients are evaluated on the building façades themselves.
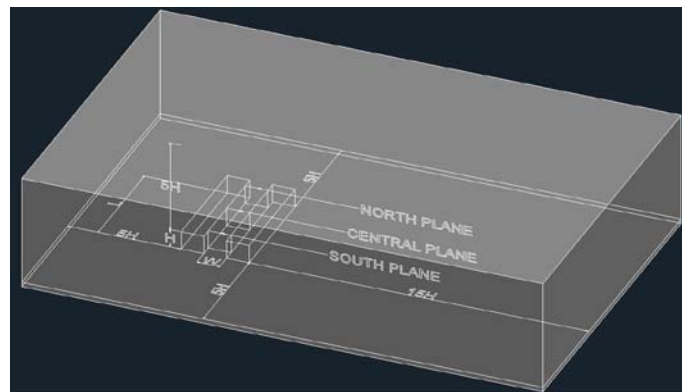
Figure 1. Computational domain.

In previous works [24, 29, 30] we have analyzed the importance of considering a 3D model on the thermal effects and on the formation of the vortices within the canyon. It can be noted in Figure 2, specifically in the central plane, the formation of a rotating vortex, which have effects on the values of the parameters analyzed in these studies and also on the thermal comfort within the canyon. The formation of the vortex within the canyon implies moreover negative effects on the air quality, due to the stagnation of air pollutants in the lower parts of the street canyon. At last, the increase in temperature has a negative effect, in summer, on the thermal comfort for people living inside the building, and on energetic consumption of air conditioning systems.
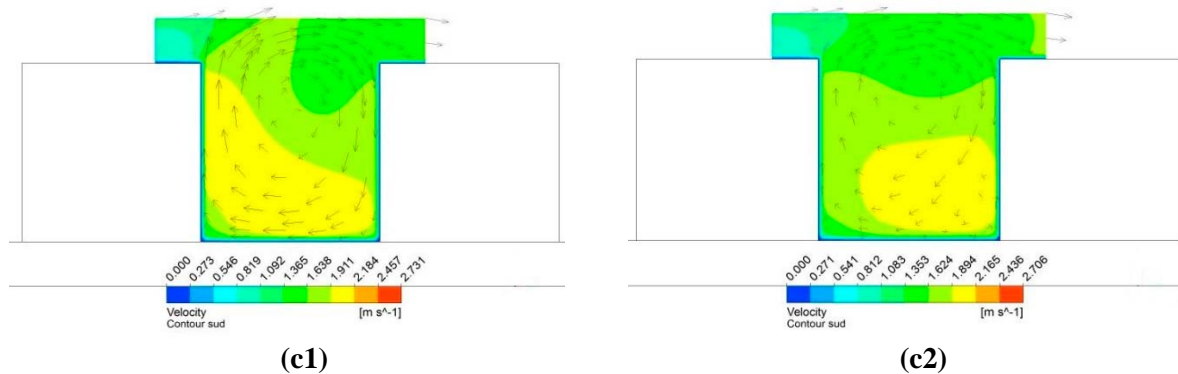
(c1)   **(c2)**
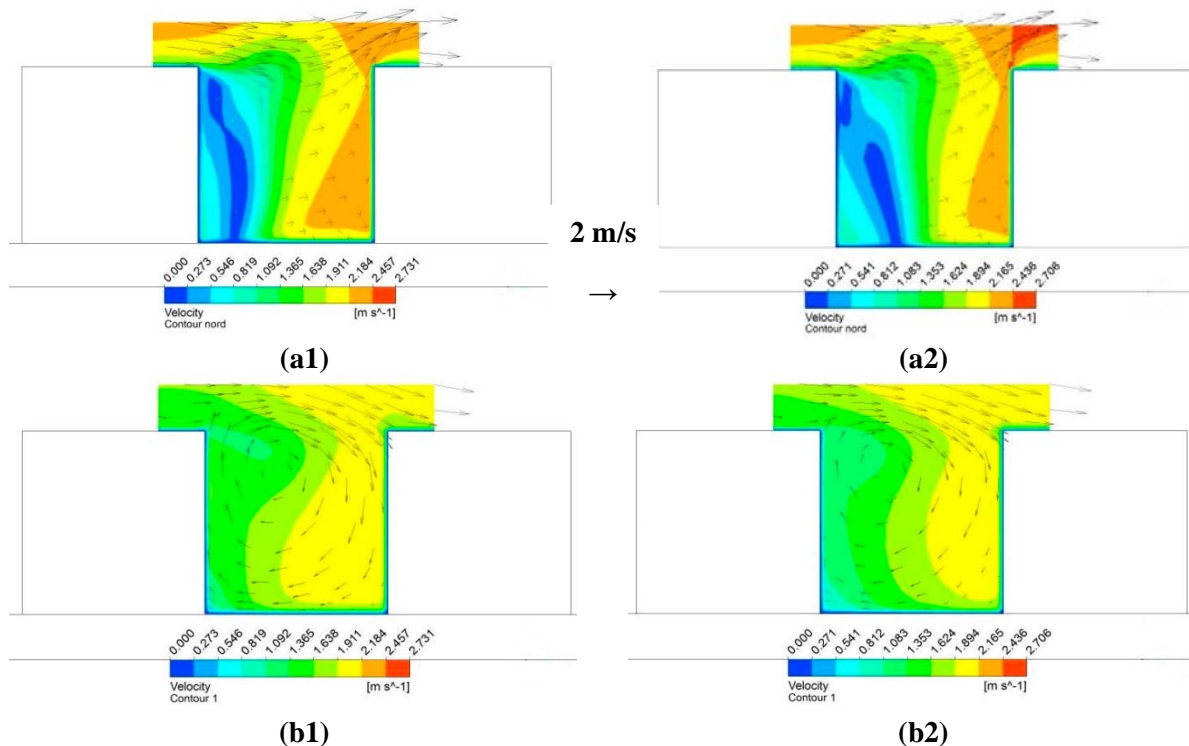
Figure 2. XZ velocity vectors on North plane (a); Central plane (b); South plane(c); at 11:00 (subscript 1) and 14:00 (subscript 2).

Considering the various aspects outlined by the previous works, in this study we consider the wind direction of 45° NW and the velocity magnitude of the wind is 2 m/s. Thus the windward façade is always the which ones towards the east direction, i.e. the right façade (WW) in Figure 3. As reported in [24, 26, 29] the values of the convective heat transfer coefficient are not very sensitive to wind direction, so that a wind direction of 45° N can represent a wide range of wind directions between 0° and 60°. This conclusion allow us to perform a parametric analysis on the average values of convective heat transfer coefficient, based on results of 3D CFD simulations characterized by an average wind direction. In Figure 3 it can be observed the configuration of the analyzed urban canyon at 11:00 a.m. and at 02:00 p.m., in particular the direction and the magnitude of the wind and the geometrical parameters H and W.
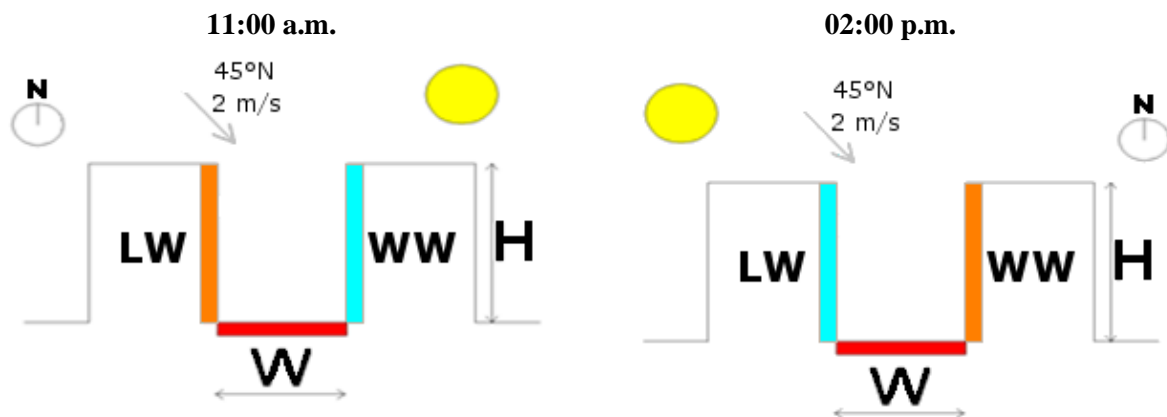
Figure 3. Configuration of the analyzed urban canyon at 11.00 a.m. and at 02:00 p.m.

In this study the parameters, which have been previously described, have been calculated varying the absorption coefficients of the leeward façade (LW) and the windward façade (WW), while the ground absorption coefficients remain always fixed, in different ways: in SIM A have been considered α of both façades equal to 0.8; instead in SIM B α = 0.2 for both façades; in SIM C the α of the leeward façade is 0.2, while for windward façade and for the ground are 0.8; at last, in SIM D, has been taken in account α = 0.2 for the windward façade and α = 0.8 for the leeward façade and for the ground (Table 1).

	α Ground	α LW Façade	α WW Façade
SIM A	0.8	0.8	0.8
SIM B	0.8	0.2	0.2
SIM C	0.8	0.2	0.8
SIM D	0.8	0.8	0.2

Table 1. Presentation of the simulations carried out in this study, varying the absorption coefficients α.

In the next tables, i.e. Table 2, Table 3, Table 4, Table 5, the values of h_c, k, T_{wall}, u, for each simulation are presented. For each simulation carried out, have been considered these parameters on the North, Central and South planes, which have been calculated on the windward façade and on the leeward façade, at 11:00 a.m. and at 02:00 p.m.

SIM A_$α_{WW}$ = 0.8_$α_{LW}$ = 0.8			
WINDWARD FAÇADE at 11:00 a.m.			
	h_c [W/m²K]	k [m²/s²]	T_{wall} [K]	u [m/s]
North	13.79	0.33	308.2	1.82
Central	10.03	0.16	309.32	1.61
South	9.02	0.12	310.19	1.39
WINDWARD FAÇADE at 2:00 p.m.			
North	13.72	0.33	321.19	1.81
Central	10.56	0.19	324.67	1.52
South	9.57	0.14	326.64	1.41
LEEWARD FAÇADE at 11:00 a.m.			
North	10.42	0.2	325.04	0.59
Central	10.80	0.21	324.55	1.1
South	9.71	0.15	326.5	1.5
LEEWARD FAÇADE at 2:00 p.m.			
North	8.76	0.13	309.37	0.52
Central	9.44	0.16	310.00	0.88
South	8.53	0.12	310.87	1.29

Table 2. Values of the convective heat transfer coefficient (h_c), turbo-kinetic energy (k), wall temperature (T_{wall}) and velocity magnitude (u) calculated on the windward and leeward façades at 11:00 a.m. and at 02:00 p.m., relatively to the SIM A.

It can be noticed, as expected, the similar values of T_{wall} when the façades are in shadow, else if the absorption coefficients are different. In fact both the windward façade at 11:00 a.m. and the leeward façade at 02:00 p.m., have been calculated a wall temperature comprised between 307 and 311 K, as it's possible to observe in the tables below. Upon the facades in shadow a temperature decrease of 2-3 K has been observed when the absorption coefficient was reduced from 0.8 to 0.2.

As reported in tables 2-5, when the absorption coefficient in the WW façade changes from 0.8 to 02 an important decrease of the T_{wall} temperature can be noticed (11K). The same consideration can be noted about T_{wall} calculated on the leeward façade, when it's exposed to sun radiation. This aspect has important consequences on the street canyon microclimate and, on other hand, also on the thermal fluxes which enter in the buildings.

A further consideration refers to the absence of a mutual thermal interaction between the two façades, when the absorption coefficients are changed.

SIM B_α_{WW} = 0.2_α_{LW} = 0.2				
WINDWARD FAÇADE at 11:00 a.m.				
	h_c [W/m^{2}K]	k [m^2/s^2]	T_{wall} [K]	u [m/s]
North	13.77	0.33	307.08	1.81
Central	9.89	0.15	307.51	1.57
South	8.89	0.12	308.53	1.39
WINDWARD FAÇADE at 2:00 p.m.				
North	13.76	0.33	311.44	1.81
Central	10.14	0.17	313.06	1.53
South	9.23	0.12	314.50	1.40
LEEWARD FAÇADE at 11:00 a.m.				
North	9.83	0.17	313.72	0.54
Central	10.30	0.19	313.35	0.99
South	9.30	0.14	314.82	1.40
LEEWARD FAÇADE at 2:00 p.m.				
North	8.68	0.13	307.90	0.51
Central	9.37	0.15	307.90	0.87
South	8.52	0.12	309.06	1.30

Table 3. Values of the convective heat transfer coefficient (h_c), turbo-kinetic energy (*k*), wall temperature (T_{wall}) and velocity magnitude (*u*) calculated on the windward and leeward façades at 11:00 a.m. and at 02:00 p.m., relatively to the SIM B.

Considering SIM A and SIM C at 11:00 (in Table 2 and in Table 4), i.e. when the leeward façade it's exposed to sun radiation, the windward façade, which is in shadow and with α = 0.8 fixed, does not change significantly his wall temperature, when the absorption coefficient on leeward façade is varied from 0.8 (SIM A) to 0.2 (SIM B). In contrast with expectations, the values of T_{wall} calculated on the windward façade does not increase when on leeward façade α = 0.2, but remain quite constants between 307 and 310 K.

SIM C_α_{WW} = 0.8_α_{LW} = 0.2				
WINDWARD FAÇADE at 11:00 a.m.				
	h_c [W/m^{2}K]	k [m^2/s^2]	T_{wall} [K]	u [m/s]
North	13.77	0.33	307.08	1.81
Central	9.89	0.15	307.51	1.57
South	8.89	0.12	308.53	1.39
WINDWARD FAÇADE at 2:00 p.m.				
North	13.73	0.33	321.14	1.81
Central	10.56	0.19	324.64	1.52
South	9.58	0.14	326.63	1.41
LEEWARD FAÇADE at 11:00 a.m.				
North	9.83	0.17	313.72	0.54
Central	10.31	0.19	313.34	0.99
South	9.31	0.14	314.82	1.40
LEEWARD FAÇADE at 2:00 p.m.				
North	8.76	0.13	307.82	0.52
Central	9.44	0.16	307.95	0.88
South	8.53	0.12	309.34	1.29

Table 4. Values of the convective heat transfer coefficient (h_c), turbo-kinetic energy (*k*), wall temperature (T_{wall}) and velocity magnitude (*u*) calculated on the windward and leeward façades at 11:00 a.m. and at 02:00 p.m., relatively to the SIM C.

The same consideration can be made between SIM A and SIM D at 02:00 p.m., i.e. when the windward façade it's exposed to sun radiation, and the T_{wall} of the leeward façade are included between about 308 and 311 K.

SIM D_α_{WW} = 0.2_α_{LW} = 0.8				
WINDWARD FAÇADE at 11:00 a.m.				
	h_c [W/m^{2}K]	k [m^2/s^2]	T_{wall} [K]	u [m/s]
North	13.81	0.33	308.15	1.82
Central	10.04	0.16	309.35	1.61
South	9.02	0.12	310.23	1.38
WINDWARD FAÇADE at 2:00 p.m.				
North	13.75	0.33	311.41	1.81
Central	10.14	0.17	313.06	1.53
South	9.23	0.12	314.5	1.40
LEEWARD FAÇADE at 11:00 a.m.				
North	10.42	0.20	325.06	0.59
Central	10.81	0.21	324.53	1.11
South	9.71	0.15	326.50	1.50
LEEWARD FAÇADE at 2:00 p.m.				
North	8.68	0.13	308.32	0.51
Central	9.37	0.15	309.86	0.87
South	8.52	0.12	311.33	1.30

Table 5. Values of the convective heat transfer coefficient (h_c), turbo-kinetic energy (k), wall temperature (T_{wall}) and velocity magnitude (u) calculated on the windward and leeward façades at 11:00 a.m. and at 02:00 p.m., relatively to the SIM D.

4. Discussion

As expected the variations of absorption coefficient from 0.2 to 0.8 have a strong effect on the wall temperatures. This aspect has important consequences on the street canyon microclimate and, on other hand, also on the thermal fluxes which enter in the buildings.

As far as microclimate is concerned, changes in the wall temperature imply changes in the mean radiant temperature and thus in thermal comfort. As regards the thermal loads, diminutions of the absorption coefficient lead to reductions in the solar load. In particular at steady state the reduction of the absorption coefficient from 0.8 to 0.2 brings to a 11 K decrease of the wall temperature and then a decrease of the entering thermal flux.

In fact the thermal fluxes through the wall, in steady case, depend proportionally on the difference of temperature between the inner and the outer surfaces of the façade considered. Thus an increase of about 11 K between the different cases, when α = 0.2 and α = 0.8, produces as consequence an important increase of the thermal fluxes across the wall, with the worsening of the summer cooling load that implants must to counteract and a consequent higher energy consumptions.

According to results obtained, changes in the physical properties of one of the walls do not significantly affect the temperatures of the opposite wall. Moreover, changes in the absorption coefficient have a slight, but not negligible, effect on the CHTC coefficient. For example when the absorption coefficient changes from 0.2 to 0.8, the wall temperature increase of 11K, so that the natural convection influence of the flow field is more important and the CHTC coefficient can increases of about 5%.

5. Conclusions

In this study a numerical simulation method has been used to investigate the values of the convective heat transfer coefficient h_c, the turbo-kinetic energy k, the wall temperature T_{wall} and the velocity magnitude u, within an urban canyon with the geometrical ratio H/W = 1, varying the absorption coefficient α on the windward and leeward façades. These values have been calculated at two different hours: at 11:00 a.m. and at 02:00 p.m. of 21 July, in Milan (Italy). Four simulations have been presented, in which the ground absorption coefficient is fixed and equal to 0.8, instead $α_{WW}$ and $α_{LW}$ varying between 0.8 and 0.2, as it can be observed in Table 1.

Moreover it has been shown that the façades in shadow have similar values of T_{wall}, even if the absorption coefficients are changed. When the façades are sun-heated, i.e. at 11:00 a.m. for the leeward façade and at 02:00 p.m. for the windward façade, it can be noted an important difference between the value of T_{wall} when the absorption coefficient is equal to 0.8 and when it is equal to 0.2 and that causes important different in thermal loads and on the values of the mean radiant temperature.

Regarding to the other parameters considered in this study, it can be observed that the average velocity within the canyon isn't essentially modified from the initial configuration, which is represented from SIM A, but slight but not negligible variation on the CHTC coefficient are produced by the absorption coefficients changes.

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