

INFLUENCE OF COOL MATERIALS ON BUILDING ENERGY DEMAND AT DISTRICT SCALE

Adrien Gros¹, Petroula Alexaki², Emmanuel Bozonnet^{*1}, and Christian Inard¹

*1 LaSIE, La Rochelle University
Pole science et technologie
Avenue Michel Crépeau
17000 La Rochelle
France*

*2 Grenoble INP
11, rue des Mathématiques
38402 Saint Martin d'Hères
France*

ABSTRACT

Since 2007, more than half of world population lives in urban areas and its activity leads to an increase of building energy demand notably in summer. The temperature rise of densely built areas is mainly due to landscaping and anthropogenic heat fluxes such as air conditioning systems. Acting on urban landscaping, building density, surface albedo or green area can mitigate the urban heat island with direct and indirect improvement of building energy performances.

In the present study, a new numerical approach was developed to assess the building energy demand including microclimate interactions on buildings. The different physical phenomena are computed at the district scale with different meshes, for the surfaces and the volumes, of the tridimensional numerical mockup. The urban microclimate is assessed thanks to specific models developed for the outdoor airflows, the longwave and shortwave radiative exchanges. The thermal behaviour of buildings is computed by a model developed on the basis of the weighting factor method which saves computation time. Then, a coupling method was implemented in order to match the results from the various meshes. The thermal balances are computed simultaneously for the whole district cells, including indoor and outdoor balances, for each time step.

A case study was selected and studied: a district located in Nantes, France, named Pin Sec district. A parametric study is carried out considering cool materials. The results are displayed as the cooling demand of buildings for each case studied. The impact of cool material areas on both building energy demand and urban microclimate are clearly shown through the results obtained.

KEYWORDS

Zonal model, district scale, urban microclimate, building energy demand, weighting factor method

1 INTRODUCTION

Between 1950 and 2007, the urban population has grown from 30% to 50% of the world population. The associated growth of the urban area has amplified urban microclimate. The modification of the local wind fields and the increase of the heat transfers between walls, ground and air, changed the microclimatic parameters at local scale. The most known urban microclimate aspect engendered is the Urban Heat Island (UHI). It is characterised by higher temperatures in urban area than in rural area, leading to an increase of the cooling energy demand in the towncenter (Santamouris et al. 2001) . The use of air-conditioning systems to maintain indoor inhabitant comfort, reject anthropogenic heat fluxes in the atmosphere. The result is a negative feedback that increases the UHI and the building energy demand. The building energy demand management have to be more efficient with limiting the air-conditioning systems use. Modification of urban landscaping, such as building morphology, surface albedo or green areas, can mitigate UHI, which consequently reduces energy demand.

The simulation of the different physical processes in urban areas can be used to compute the building energy demand. Traditionally the thermal dynamic building tools are used to optimise the energy consumption of building by computing annual or seasonal building energy demand. The meteorological data files used are generally issued from standard data (as the airport) and are not representative of the urban microclimate conditions. The outdoor physical phenomena are generally very briefly described and the interaction with the urban environment is not taken into account. Microclimatic models enable to compute precisely all the physical processes in the urban areas (Martilli 2007). But the building indoor description is generally very simplified and CPU times needed to achieve simulation are too high to simulate the building energy demand during a year or a season.

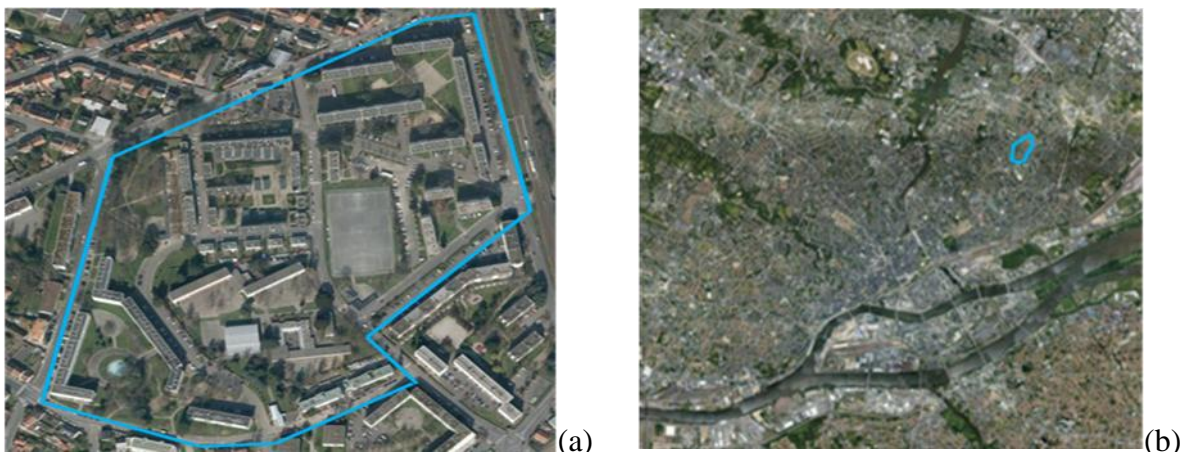
We propose in this paper an intermediate model dealing with the local urban climate with building energy demand at the district scale. The goal of this model is to couple the climatic field of the urban canopy with thermal fluxes inside buildings. The detailed description of all the physical processes inside and outside the building are not adapted to annual prediction of energy consumption at the district scale. Thus a simplified model of the urban canopy based on zonal model is used. Initially developed to compute temperature fields in canyon street (Bozonnet et al. 2005; de la Flor and Domínguez 2004), this method was improved to be applied on any urban geometric configuration. A reduced thermal building model based on the weighting factor method (Depecker et al. 2001; Rousseau 1978) is used to compute the building thermal load.

In the first part, the meshes used in order to simulate the canopy, as well as buildings are described. In the last part, a case study i.e a district located in Nantes, France, named Pin Sec district, is used to compute the building energy demand during the summer season. A parametric study is carried out considering cool materials. Cool materials are characterised by high albedo and emissivity (Santamouris et al. 2011). By decreasing the solar irradiance absorbed by the facades, cool materials allow reducing the surface temperatures and thus minimizing the UHI intensity and the cooling load associated. The results are displayed as the cooling demand of buildings for each case studied.

2 URBAN DISTRICT MESH FOR URBAN FLUXES

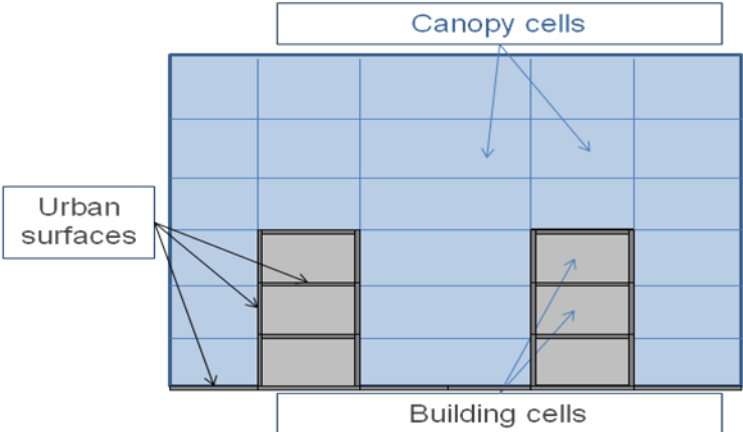
An adapted meshing was developed to model at the district scale. The Pin Sec district located in the North-East of Nantes city centre, in France (Figure 1), is used to illustrate the meshes developed. Pin Sec is a residential district of 136.000 m² composed of 40 residential buildings, 4 scholar buildings, 1 scholar gymnasium, 2 sport buildings and 11 utility buildings.

Figure 1 : Topview (a) and localisation (b) of Pin Sec district in Nantes, France



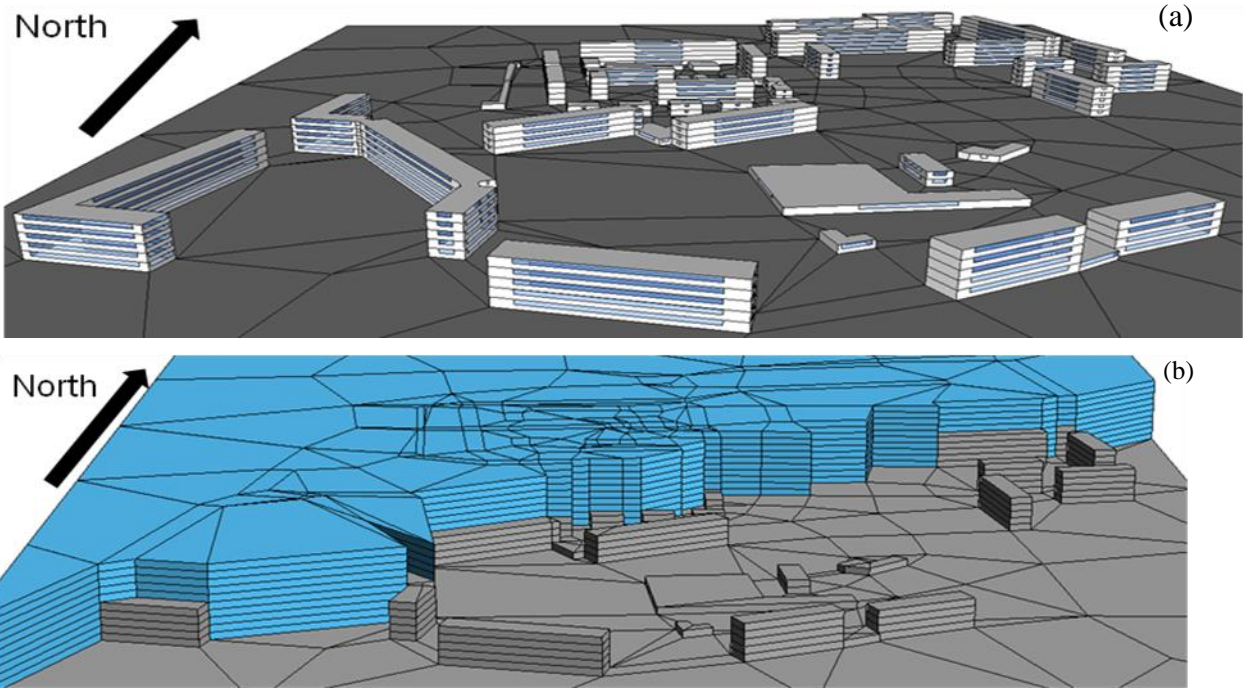
The district is split into two domains, the urban canopy, divided in canopy cells and the building divided in building cells (Figure 2). The canopy cells are used to compute the outdoor air temperature and the building cells are used to compute the power needed to maintain a given temperature set point. The urban surfaces are the interfaces between the canopy cells and building cells. They are used to calculate the surface outside temperatures of the ground and the buildings walls.

Figure 2 : Representation of the different physical domains



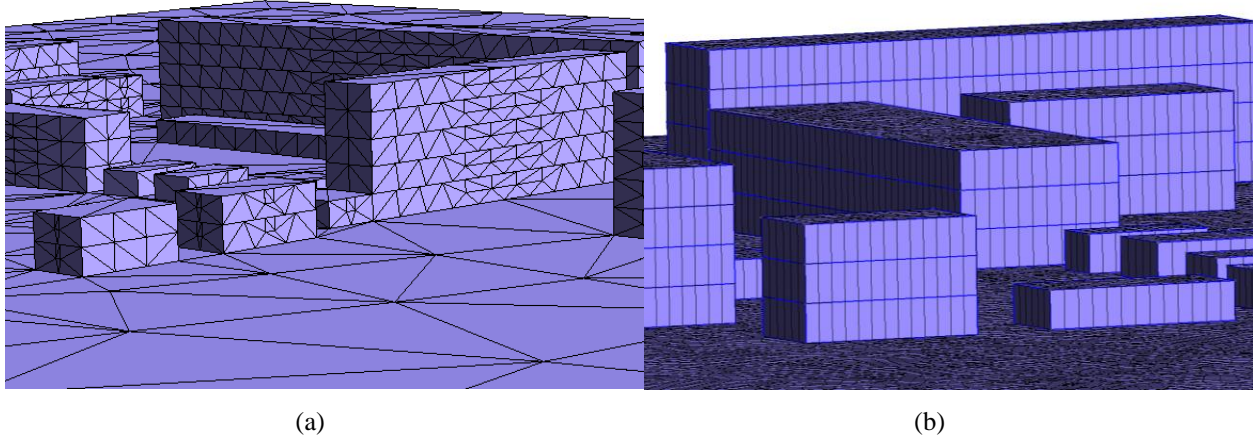
The coupled model allows computing surfacic physical values (surface temperatures) and volumic physical values (outdoor air temperatures and heating/cooling powers). Thus, two categories of mesh have to be distinguished: the surfacic mesh and volumic mesh. For the surfacic mesh, the discretization is chosen like in the building thermal dynamic simulation. Each wall with different orientation and physical properties are defined by its own node. Thus the Pin Sec district is composed of 1551 surfaces (Figure 3 (a).) with surfaces ranging from 50 m² to 1000 m². In the volumic mesh, each floor of a building represents a building cell with a height equal to 3 m. The canopy cells are built by extrusion of the ground urban surface. To simplify the simulation, height of the building cells and canopy cells are equal and fixed to 3 m i.e the height of a floor. Thus the Pin Sec district is composed of 3122 canopy cells and 149 building cells (Figure 3 (b)).

Figure 3 : District surfacic (a) and volumic (b) model



Some physical phenomena need a more precise mesh. To compute solar irradiance received by each wall, it is necessary to determine the mask effect created by the urban environment. Each urban surface is split into triangles to obtain 15 887 submeshes (Figure 4 (a)). To compute the airflow around the building a more precise mesh is used too. The volumic district model is meshed with a regular hexahedral meshing. Thus, the Pin Sec district is composed of 13 584 688 hexahedra (Figure 4 (b))

Figure 4 : Surfacic (a) and volumic (b) submesh



3 URBAN CANOPY MODEL

3.1 Temperature field simulation

The canopy cells are composed of five or six faces indexed n . These faces are either an interface with another canopy cell or an urban surface.

Each face is crossed by mass and heat fluxes. The temperature of the canopy cell $T_{e,k}^t$ at time t can be computed thanks to the thermal balance (Equation (1)) with V_k , the cell volume [m^3], C_p , the air specific heat [$J/(kg.K)$], ρ the air density [kg/m^3], $\phi_{k,n}$ the heat flux through the face n [W] and ϕ_s the heat production in the cell [W].

$$\rho C_p V_k \frac{dT_{e,k}^t}{dt} = \sum_n \phi_{k,n} + \phi_s \quad (1)$$

For a face in contact with urban surface i at the temperature $T_{se,i}^t$ the flux through the face is defined by:

$$\phi_{k,n} = h_{cs,i} A_i (T_{se,i}^t - T_{e,k}^t) \quad (2)$$

Where A_i is the area of the urban facet i [m^2].

Else if the face n is an interface with another cell at the temperature $T_{e,j}^t$, the heat flux through is defined by:

$$\phi_{k,n} = C_p Q_n (T_{e,j}^t - T_{e,k}^t) \quad (3)$$

Where, Q_n is the mass flow through the face n [kg/s].

To respect the mass conservation the air mass flow sum of each canopy cell must be equal to zero.

3.2 Flow field simulation

The Computational Fluid Dynamic models are often used to simulate the flow field in urban areas and to study pedestrian comfort or outdoor air quality. These models are very precise but the computing time and the power necessary is not adapted to achieve annual or seasonal simulation. To simplify the flow field computation, the urban aerodynamic model QUIC (Pardyjak and Brown 2003) is used. This model is based on empirical laws developed by Rockle (1990) to provide flow fields which comply with continuity equation (Kaplan and Dinar 1996; Kastner-Klein et al. 2004). The velocities calculated are then used to compute the air mass flows through each canopy cell interface. The QUIC aerodynamic simulation is used to compute the velocity components u , v or w for the facet of each hexahedral submesh aligned in the x , y or z directions. The air mass flow $Q_{f,p}$ [kg/s] through the facet p is given by:

$$Q_{f,p} = \rho V_{f,p} A_{f,p} \quad (4)$$

Where $A_{f,p}$ is the area [m²] and $V_{f,p}$ the normal velocity [m/s] of facet p .

Each interface from canopy cells can be represented as facet set oriented in the x , y or z direction corresponding to the hexahedral meshing. The air mass flow through the interface is the sum of each air mass flow through each corresponding facet.

$$Q_n = \sum_{p=0}^{N_p} Q_{f,p} \quad (5)$$

4 THERMAL BUILDING MODEL

4.1 Building demand model

To simplify the calculation building energy load, the weighting factor method is used. This method consists in computing all the thermal processes inside building cells for a unit excitation. The weighting factor W^n_E is the discrete value of the thermal load induced by the unit excitation E_u , n hours after the excitation. The thermal load Q^t_E [W] induced by a excitation E^t is expressed with the convolution product (equation (6)).

$$Q^t_E = \sum_{n=0}^{\infty} W^n_E E^{t-n} \quad (6)$$

To compute the total thermal load of a building cell, three categories of unit excitation are considered:

- T_c , the temperature set point of the building cell,
- E_{clo} , the solar irradiance through the windows incoming in the building cell,
- $T_{se,j}$, the outdoor surface temperature of the walls

Thus the power P^t [W] needed to maintain the temperature set point is computed as the sum of the thermal load induced by each excitation, the internal gain Q^t_{int} and the thermal load due to the air exchange with a canopy cell k

$$P^t = \rho C_p V \frac{dT_c^t}{dt} + \rho C_p D_v (T_c^t - T_{s,k}^t) - Q^t_{int} - Q^t_{E,clo} - Q^t_{T_c} - \sum_{j=1}^{N_p} Q^t_{T_{se,j}} \quad (7)$$

Where, D_v is the ventilation air flow [m³/s] in the building cell due to the infiltration and the mechanical ventilation.

4.2 Thermal surface model

The urban surfaces are interface between urban canopy and building. The surface temperature calculation allows coupling the outdoor air temperature with indoor thermal load simulation. A thermal balance is used to compute the outdoor surface temperature $T_{se,i}^t$ of the urban surface i .

$$\varphi_{cs,i}^t + \varphi_{ps,i}^t + I_{GLO,i}^t = I_{CLO,i}^t \quad (8)$$

The conductive heat flux is calculated by using the response factor method (Depecker et al. 2001; Mitalas and Stephenson 1967).

$$\varphi_{ps,i}^t = \sum_{n=0}^{\infty} Y_i^n \cdot T_{si,i}^{t-n} - \sum_{n=0}^{\infty} Z_i^n \cdot T_{se,i}^{t-n} \quad (9)$$

If the urban surface is a building wall, weighting factors are defined to calculate the conductive heat flux with excitation defined in the previous section (Gros 2013). Thus the conductive heat flux is calculated by:

$$\varphi_{ps,i}^t = \varphi_{int}^t + \varphi_{E,clo}^t + \varphi_{Tc}^t + \sum_{j=1}^{N_p} \varphi_{Tse,j}^t - \sum_{n=0}^{\infty} Z_i^n \cdot T_{se,i}^{t-n} \quad (10)$$

With

$$\varphi_E^t = \sum_{n=0}^{\infty} YW_E^n E^{t-n} \quad (11)$$

The convective heat flux is calculated by using the outdoor air temperature of the canopy cell in contact with the surface:

$$\varphi_{cs,i}^t = h_{cs,i} (T_{s,k}^t - T_{se,i}^t) \quad (12)$$

The direct solar irradiance $I_{b,i}^t$ and the diffuse solar irradiance received by the urban surface i are calculated by using the solar irradiation simulation software SOLENE (Miguet and Groleau 2002). The overall surfaces of the urban scene form a closed envelope, including the sky as a hemisphere with an infinite radius (Bozonnet et al. 2005). By using the view factors between the urban surfaces, the radiosity method can be used to compute the total irradiance considering the multiple reflexion $I_{CLO,T,i}^t$ (Equations 13 and 14).

$$J_{CLO,i}^t = \rho_{CLO,i} (I_{b,i}^t + I_{d,i}^t + \sum_{j=1}^{N_s} F_{ij} J_{CLO,j}^t) \quad (13)$$

$$I_{CLO,t,i}^t = \frac{J_{clo,j}^t}{\rho_{CLO,i}} \quad (14)$$

Considering the urban surface as black body, the longwave irradiance reflections are neglected. The view factors are then used to compute the longwave irradiance received by each urban surface through a linear model.

$$I_{GLO,i}^t = h_{rs} F_{ij} (T_{se,j}^t - T_{se,i}^t) \quad (15)$$

5 CASE STUDIES

5.1 Description

The coupled model is applied to the Pin Sec district in Nantes, to study the influence of the cool painting. The goal is to study the impact of different cool painting application on the cooling energy demand corresponding to the period from 1st May to the 30th September. The building walls are composed of 20 cm of concrete and 10 cm of insulation and double-glazed windows. Cool paints are applied to increase the reflectivity from 0.3 to 0.9 and to maintain a high emissivity of 0.9. The coupled model is used to simulate the energy demand of the Pin Sec district for 4 different cases. The first case is without cool painting (case A), the second case concerns cool paint only on building vertical walls (case B), the third is with cool paint only on the roofs (case C) and the last case gathers case B and C (cool paint on roofs and vertical walls, case D).

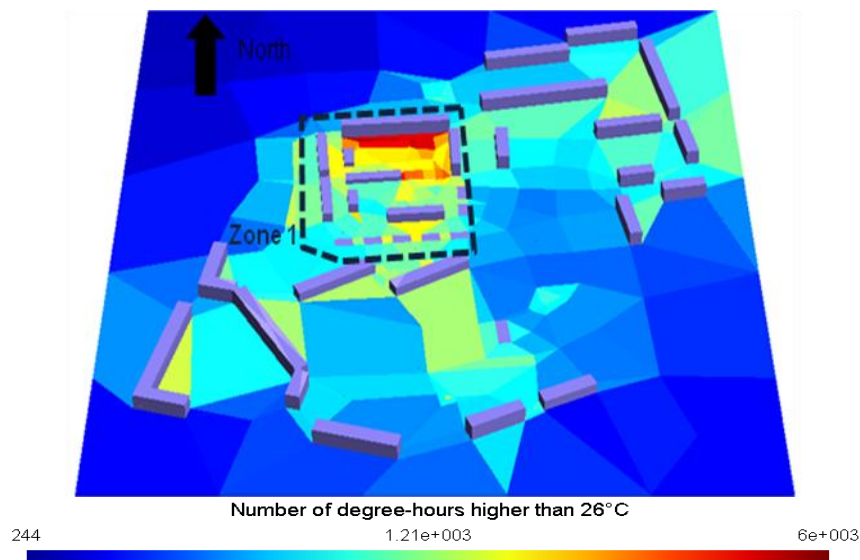
Table 1: Description of studied cases

Case A	Case B	Case C	Case D
Without cool paint	With cool paint on building vertical walls	With cool paint on building roofs	With cool paint on building roofs and walls

5.2 Microclimatic aspect

The coupled model allows computing the air temperature of each canopy cell for each hour of the year. These results can be aggregated to calculate for each canopy cell, the number of degree-hours [D-h] higher than the indoor temperature set point (26°C). This process allows determining which cells are the most influenced by the urban environment. The canopy cells located in the centre of the district have the highest values, reaching values of 6000 D-h higher than 26°C (zone 1 Figure 5).

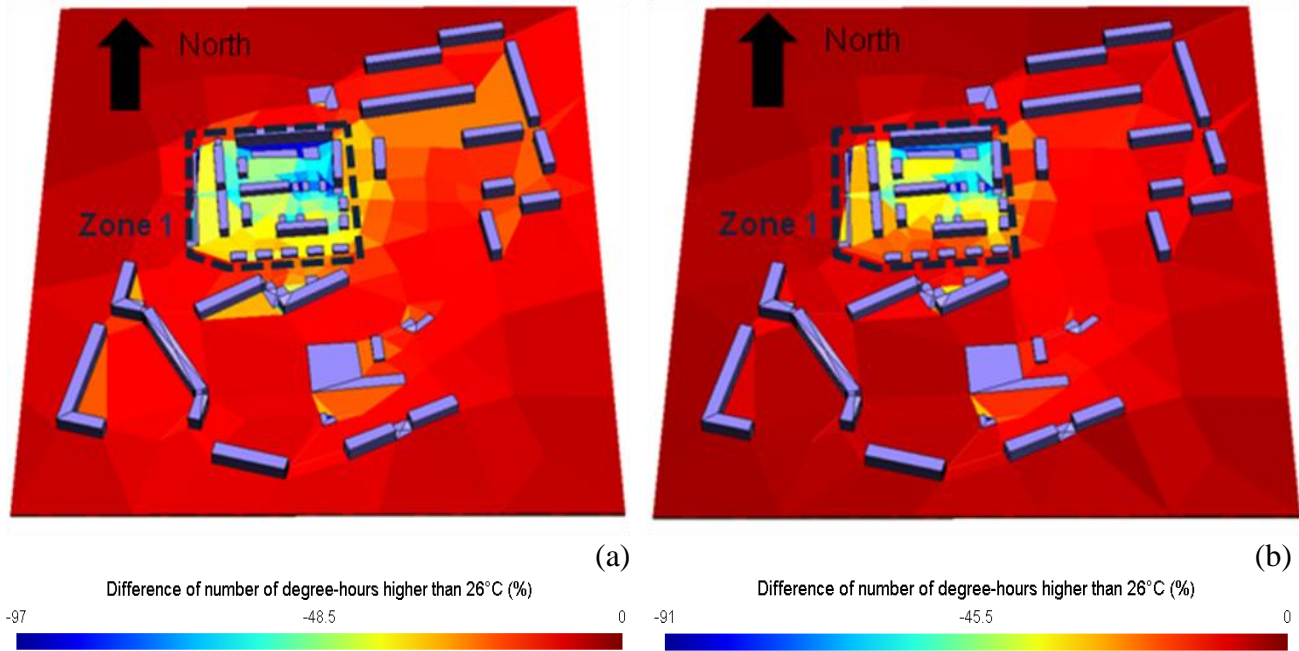
Figure 5 : Degree-hours number of urban cells (3m < Z < 6m)



The canopy cells located in the district side have the smallest values close to 243 D-h higher than 26°C. The values located on the boundaries of the studied domain are equal to the meteorological data used for the simulation. Thus the more the canopy cells are located in high density area, the more the number of degree-hours is high. Thus the numbers of degree-hours increases for canopy cells located in high density areas.

The differences between the number of degree-hours for case A and B or C respectively for canopy cells located between 0 m and 3 m due to the cool paint application are shown in Figure 6. The more sensitive zones correspond to the denser zones. Indeed, in zone 1 (Figure 6) the contact surface between canopy and urban area is more important than in the other zones. The air is more influenced by the surface temperatures and thus by cool paint. As presented on the Figure 6, the use of cool paint on facades (case B) is the most efficient way to decrease UHI effects. It allows a more important decrease (97% for case B, and 91% for the case C) and a better distribution in the whole district.

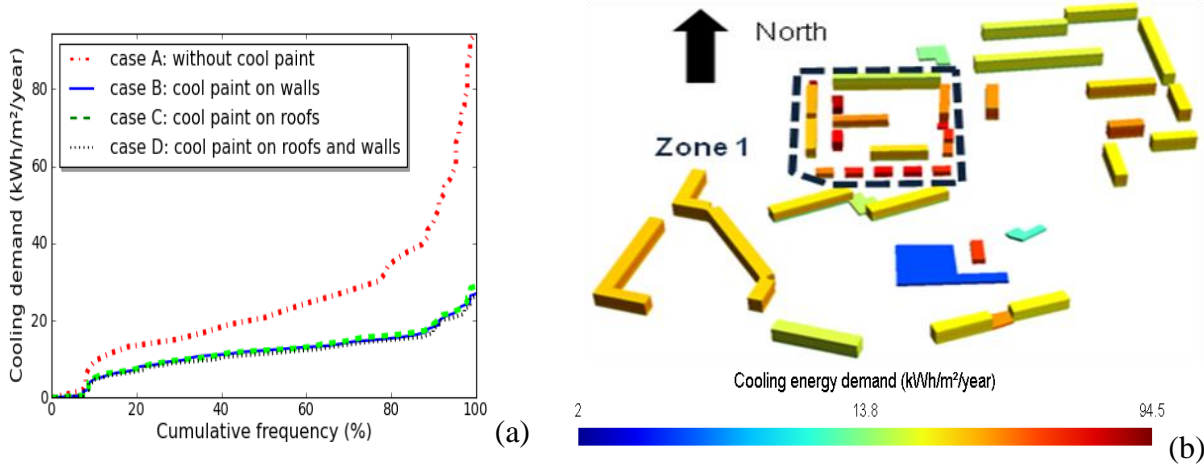
Figure 6 : Difference of number of degree-hours for urban cells ($0m < Z < 3m$) between case A and B (a) and case A and C (b)



5.3 Building demand impact

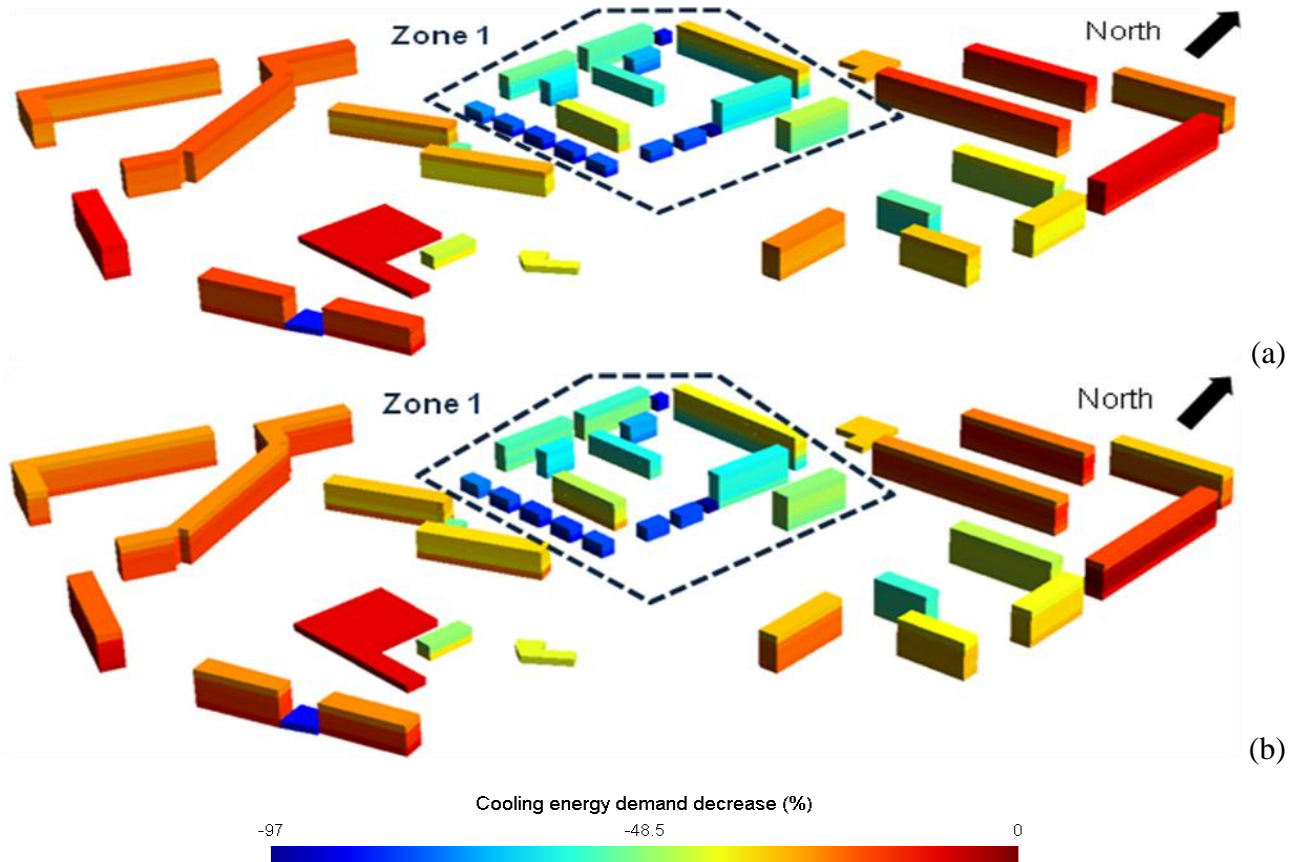
Figure 7 (a) shows cumulative frequency of cooling demand for the four cases. For case A, 8% of building cells, corresponding to the 11 utility buildings are not air conditioned. 60 % of building cells have cooling need ranging from 15 kWh/m²/year to 40 kWh/m²/year and 32% ranging from 40 kWh/m²/year to 87 kWh/m²/year. Figure 7 (b) shows cooling energy demand distribution in the district. The areas with the most important cooling energy demand are located in zone 1, in accordance to the result presented in Figure 5.

Figure 7 : Cooling demand cumulative frequency for the cases A, B, C and D (a) and tri-dimensional energy demand representation of the district for case A (b)



Using cool paint reduces the disparity of cooling energy demand between the different buildings. All the cooling energy demands are ranged from 0 to 20 kWh/m²/year. For both cases of cool paint either on the roofs or on the walls, the decrease is the same but the spatial distribution changes. The use of cool paint on roofs favours the decrease of energy demand of the last floor of the buildings (Figure 8 (b)), and the use of cool paint on facades favours the decrease of energy demand of the intermediate floors of the buildings (Figure 8 (a)). Energy demand decrease is not uniform in the district. It is more important in zone 1, corresponding to the most important decrease of the number of degree-hours higher than 26°C (Figure 6). Furthermore, the buildings with the higher energy demand of case A, are those with the higher cooling energy decrease due to the cool paint (cases B, C and D).

Figure 8 : Energy demand decrease between case A and B (a) and between case A and C (b)



6 CONCLUSIONS

In this paper, a model based on the coupling between building energy model and urban canopy at a district scale is presented. This coupled model highlights the microclimatic effect on the building energy demand. It was used to study the impact of different cool paints on the Pin Sec district in Nantes, France. Then, the impact of cool paints on building energy demand and urban microclimate could be assessed. The calculation of the Degree-hours inside the urban canopy shows zones where energy demand is less important. The densest built areas are the most sensitive ones to the urban microclimate impact: the cooling energy demands are the most important and the cool paint use is the most efficient. Whatever the cool paint method used, the decrease of cooling energy demand is roughly equal to 78%. Using cool paint on facades seems the most efficient to reduce the UHI effects. By applying cool paint on the facades of a given building enables reducing the energy demand of surrounding buildings. Applying cool paint on the roofs has less impact on the urban microclimate than when applied on walls. It seems that it is not necessary to combine roof and wall cool painting. Indeed the benefits of cool paints seem to reach a threshold. So, to further decrease cooling demand it's necessary to work on removing indoor heat by using an appropriate ventilation strategy. Finally in order to improve the cool paint effect at the district scale, it could be interesting to carry out a parametric study in order to determine how each building influences the urban microclimate.

7 ACKNOWLEDGEMENTS

The authors are grateful to the Poitou-Charentes Region and the ADEME (French Environment and Energy Management Agency) for the financial support of this study.

8 REFERENCES

- Bozonnet, E., Belarbi, R., and Allard, F. (2005). "Modelling solar effects on the heat and mass transfer in a street canyon, a simplified approach." *Solar Energy*, 79(1), 10–24.
- Depecker, P., Menezo, C., Virgone, J., and Lepers, S. (2001). "Design of buildings shape and energetic consumption." *Building and Environment*, 36(5), 627–635.
- De la Flor, F. S., and Domínguez, S. A. (2004). "Modelling microclimate in urban environments and assessing its influence on the performance of surrounding buildings." *Energy and Buildings*, 36(5), 403–413.
- Gros, A. (2013). "Modélisation de la demande énergétique des bâtiments à l'échelle d'un quartier." Thèse de Doctorat, université de La Rochelle.
- Kaplan, H., and Dinar, N. (1996). "A lagrangian dispersion model for calculating concentration distribution within a built-up domain." *Atmospheric Environment*, 30(24), 4197–4207.
- Kastner-Klein, P., Norman, O. K., and Clark, J. V. (2004). "Modeling of flow and dispersion characteristics in typical urban building configurations with the fast-response model QUIC." *13th Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Assoc.*
- Martilli, A. (2007). "Current research and future challenges in urban mesoscale modelling." *International Journal of Climatology*, 27(14), 1909–1918.
- Miguet, F., and Groleau, D. (2002). "A daylight simulation tool for urban and architectural spaces—application to transmitted direct and diffuse light through glazing." *Building and Environment*, 37(8-9), 833–843.
- Mitalas, G. P., and Stephenson, D. G. (1967). "Room thermal response factors." *ASHRAE Trans.:(United States)*, 73.

- Pardyjak, E. R., and Brown, M. (2003). *QUIC-URB v. 1.1: Theory and User's Guide*. LA-UR-07-3181.
- Rockle, R. (1990). "Bestimmung der Stomungsverhältnisse im Bereich komplexer Bebauungsstrukturen." der Technischen Hochschule Darmstadt,, Germany.
- Rousseau, S. (1978). "Simulation numérique du comportement thermique des locaux d'habitation. Evaluation de l'influence de la radiation solaire, des conditions climatiques et des paramètres caractéristiques du bâtiment."Thèse de Doctorat, INSA de Lyon.
- Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., and Assimakopoulos, D. . (2001). "On the impact of urban climate on the energy consumption of buildings." *Solar Energy*, 70(3), 201–216.
- Santamouris, M., Synnefa, A., and Karlessi, T. (2011). "Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions." *Solar Energy*, 85(12), 3085–3102.