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Simulation of Urban Microclimate with SOLENE-microclimat - An Outdoor Comfort Case Study

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ABSTRACT

There are numerous physical phenomena that occur in an urban microclimate which need to be taken into account for simulating outdoor comfort. However, very few tools are dedicated towards this cause. The objective of this article is to present the assessment of the impacts of different urban strategies on a simulated neighbourhood microclimate. The neighbourhood is located in Prague, Czech Republic, and its microclimate was simulated using a simulation tool called SOLENE-microclimat. It consists of a coupling of a thermo-radiative model, a thermal building model and a computational fluid dynamics model (CFD). One of its purposes is to simulate the impact of urban built environment on outdoor comfort. The obtained simulation results are based on two variable parameters: surface albedo and presence of trees. These results include variations in surface, air temperatures, wind speeds and the Universal Thermal Climate Index (UTCI) in the given urban area. The analysis shows that both variations have a significant impact on the urban microclimate. The potential use of this simulation tool for urban built environment is discussed along with its limitations. Such kind of studies can be important for city planning, i.e. providing thermal comfort in urban built environment and mitigating urban heat island.

Author Keywords

SOLENE-microclimat; urban microclimate; simulation; outdoor comfort; CFD; thermo-radiative model; city planning; built environment; urban heat island.

1 INTRODUCTION

An urban microclimate, which can be characterized by the urban heat island (UHI) phenomenon, results from radiative, heat and water exchanges between the deep soil, the urban surfaces and the atmosphere [7]. There is a significant impact of urban built environment on outdoor comfort and the energy consumption in buildings [4]. Therefore, for assessing outdoor comfort, it is important to consider the various physical phenomena which take place in an urban environment. Researchers and professionals use existing simulation tools to assess thermo-aerial comfort of the outdoor environment in built environment. However, there are only few such tools available. Many of them have been listed in the master thesis of Jan Vatter [21] including their advantages and disadvantages.

In presented case study, the simulation tool called SOLENE-microclimat was used. It was developed for conducting microclimate simulations evaluating and energy consumption of buildings, but we do not study in this paper this last feature. The modelling and meshing of urban geometry is performed with external software which allows accurate reproduction of complex urban shapes and user influenced configuration of the mesh. Benjamin Morille has listed the main characteristics of SOLENE-microclimat in his paper [16] along with examples of project for which it was used. SOLENE-microclimat simulates: solar radiation and its impacts on urban surfaces, wind distribution and its impacts, effect of vegetation and water bodies and energy demand of buildings for cooling, in the entire 3D modelled urban environment.

It was originally developed by CRENAU (Centre de Recherche Nantais Architectures Urbanités) which is a research laboratory in Nantes, France. It was created as a research tool hence it is almost entirely configurable. But this can also be a disadvantage as it has no user-interface and also no official user-manual, so the user has to obtain all the information about this tool from researchers who are working with it or from publications and doctoral theses devoted to it.

This article presents SOLENE-microclimat and its modules in detail followed by a case study evaluating, during the hottest days in a year, variations of outdoor climate comfort in a modelled urban neighbourhood, located in Prague, Czech Republic. Two variations were included:

Variation1: Change in albedo values of walls, roofs and sidewalks (simulated light or dark colours).

Variation2: Presence of row of trees in streets surrounding the central block of the neighbourhood.

The results of surface temperatures, air temperatures, wind speeds and UTCI were analyzed for two sidewalk areas [3]. The main objective of this case study was to present effects of albedo and trees on thermal comfort in the streets.

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2 METHODOLOGY

2.1 SOLENE-microclimat

As discussed earlier, SOLENE-microclimat is a simulation tool for urban microclimate simulation. It consists of thermo-radiative model, a CFD model and a thermal building model. It is developed by CRENAU which is a part of the joint research centre AAU (Ambiances, Architectures, Urbanités). Numerous publications and four theses were devoted to it, developing its models [22, 18, 5, 11].

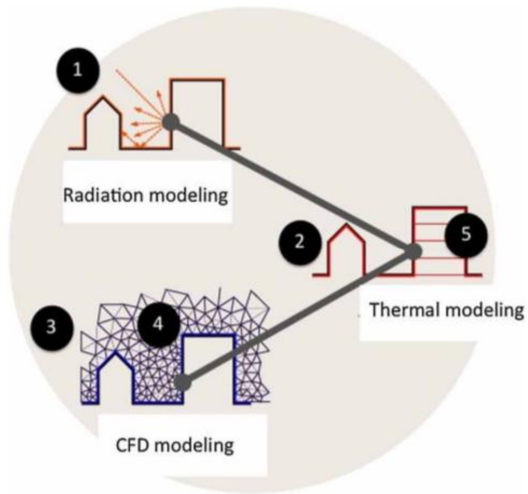

Figure 1. The coupled modules in SOLENE-microclimat [13].

The phenomena that are taken into account in this simulation tool are illustrated in the Figure 1:

1. Radiative transfer: short-wave direct, diffuse and reflected solar radiation; long-wave radiations exchanged between surfaces and sky.
2. Radiation effects on urban surfaces : conduction and storage of the heat in walls and soils.
3. Wind propagation (CFD model) and convective exchanges.
4. Evapotranspiration from natural surfaces such as vegetation (trees, grass, green roofs and walls) and water surfaces or humidification systems.
5. The energy balance for a building in simulated area.

Point 1 corresponds to the historical SOLENE radiative model, whereas Points 1+2 correspond to the thermo-radiative model based on SOLENE and Points 1+2+3+4+5 correspond to the so called SOLENE-microclimat model [13].

The following sections describe the thermo-radiative and CFD models that have been coupled for simulating outdoor microclimate. The simulation tool is still under development and new features, which were not used for the case study presented in this article, are currently in the process of being incorporated. Bernard proposed a methodology for modelling the impact of UHI, according to geographical indicators characterizing the urban surroundings, on the used weather data [2]. A more precise ground model and a new humidified ground model are currently under development.

Thermo-Radiative Model

SOLENE was first developed for the simulation of natural light in both the urban morphologies and the indoor architectural spaces by the CERMA (Centre de recherche méthodologique d'architecture). It took into account the direct solar radiation, diffused sky luminous radiation, and the inter-reflections [15].A thermo-radiative model was developed to include the possibility for calculating the outdoor comfort. It was described and validated by Hénon [9]. The greenery models were also validated in the research done by Malys [12]. This was also validated by the data acquired during FluxSAP hydro-climatological experimental campaign [14].

The sky vault is represented by a meshed sphere to depict anisotropic solar radiation (see Figure 2). Direct and diffused solar fluxes used for the simulations can be obtained from in-situ measurements or from weather data or it can be calculated by using the sky model developed by Perez [17]. Two parameters are used to define nebulous sky: the degree of purity of the sky and its luminosity, commonly represented by ε and Δ, respectively. Sky thermal radiation is assumed to be isotropic.

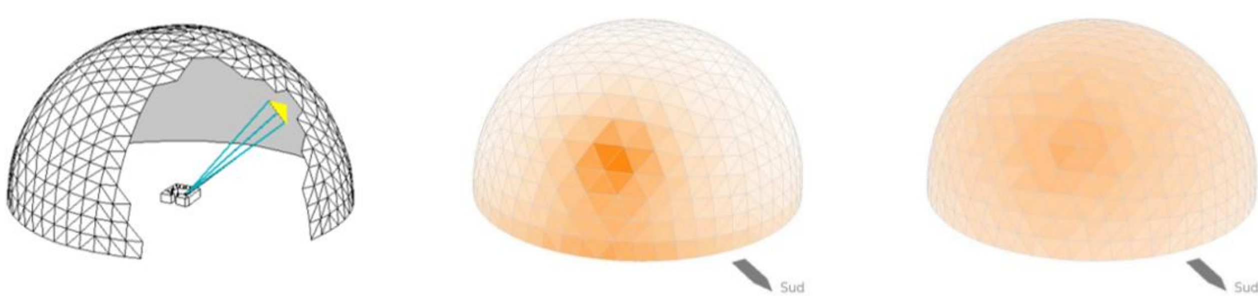

Figure 2. Hemispherical geometry representing the sky (left), distribution of luminance for a clear sky (middle) and for a covered sky (right) ε = 1; Δ = 0,35 [6].

At each time step of the simulation and for each mesh of the urban surfaces, the absorbed solar radiation is calculated. It is composed of direct and diffused solar radiations from the sun and the sky, plus the reflected fluxes which are related to the albedo of the other surfaces and are considered as isotropic. The multiple reflections are computed by the radiosity method which primarily requires the computation of geometrical form or view factors between all meshes of the urban scene [9].

Thermal radiation is taken into account and calculated with the radiosity method too. For each mesh, the absorbed infrared flux is calculated as the difference between the fluxes received from the sky and that from the reflections on the other meshes, minus the fluxes reflected and emitted by the mesh itself. Only one reflection is considered for the infrared radiation, because emissivity of urban surfaces is mostly around 90%, and it saves considerable computational time [11]. The radiation emitted by a mesh was calculated with the Stefan–Boltzmann law, which required the knowledge of the surface temperature. It was determined by the thermal balance of each mesh describe by Henon [9], iterated until the surface temperatures converge.

The sensible heat flux involved in the thermal balance is determined by the temperature difference between the surface and the air, multiplied by the convective heat transfer coefficient which depends on the wind speed. Air temperature and wind speed can be taken from weather data, or can be determined more precisely by the coupling of the thermo-radiative model with the CFD model.

CFD Model

The CFD model coupling with Thermo-radiative model is Code_Saturne, developed by EDF (Électricité de France and available online as open source since 2007. It is primarily used to calculate wind speed distribution in the whole 3D scene. It's coupling with the thermo-radiative model enable the calculation of energy and moisture transportation, in order to determine physical characteristics of air and its interactions with urban surfaces.

The technique used for the simulation is the numerical wind tunnel which creates in a virtual environment an atmospheric wind tunnel used for experiments on small models. The simulations are computed on an open domain, where the upper air layer is already decoupled from the model. The laterals faces, according to wind direction, are inlet and free outflow. The conditions set for the inlet of the numerical wind tunnel for an urban environment are characterized by the wind profile (eq 2) and the turbulence parameters k_{in} and ε_{in} (eq 3 and 4) [5].

$$v_{in}(z) = v_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \quad (2)$$

$$k_{in} = I{v_{ref}}^{2} \quad (3)$$

$$\varepsilon_{in}(z) = C_{\mu}^{3/4}\frac{k^{3/2}}{kz} \quad (4)$$

With v_{ref} the wind speed from the weather data at z_{ref}= 10m for most stations; α = 0.36, land parameter for downtown area; I = 0.3, the turbulence intensity; C = 0.09, the turbulent viscosity constant and k = 0.41 the Von Karman constant.

The dimensions of the numeric wind tunnel depended on the box enclosing the zone of the interest. Blocking effect appears in the case of borders of the numeric wind tunnel and the urban geometry are too close. However, increase of number of meshes extends significantly the calculation time. A compromise needs to be found. Few publications propose different proportions between the dimensions of the numeric wind tunnel and the zone of interest [1, 6, 19]. To have the shortest calculation time, we chose the smallest ratio (see Figure 3).

2.2 Case Study

The urban area studied is close to the city centre of Prague, Czech Republic and was built in 19^{th} Century. It is a typical city block consisted of circa 6 storeys houses surrounded by broad streets. Ten blocks constitute the modelled area, which has a total surface area of 138135 m². The height to width ratio of streets is mainly ranging between 0.7 and 1.2. The proportion of built-up area is 46%, and 41% if we don't take into account the construction inside the blocks. On average, buildings have six floors, so the proportion of floor area is 246%.

The urban materials simulated here were typical in the 19th century (see Table 1). Nowadays, most of attics are used as flats therefore thermally insulated. Top layers were given for sidewalk, road and courtyard, soil completed the ground compositions in the thickness of 2m. For each material, the conductivity, thermal capacity and density is given.

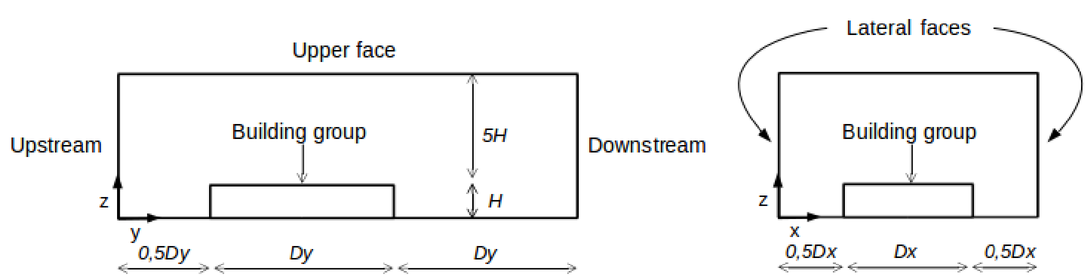

Figure 3. Dimensions and boundary conditions of the considered domain.

Figure 4. View of the central block. Source Google maps.

The simulation was carried out for the hottest eleven consecutive days (3rd to 14th August 2015) based on the weather data specified below. Since the weather data do not contain direct and indirect solar flux, Perez model of sky included in SOLENE-microclimat was used. Perez parameters were selected as: $\varepsilon = 0.12$ and $\Delta = 0.63$, as they correspond to a clear sky.

The coupling with the CFD model is activated only for the last 22 hours because CFD requires a lot of calculation power. The first ten days are without coupling, only the thermo-radiative model is running. These ten days without coupling allow the warming up of the scene, to load correctly surfaces with energy. Some simulations conducted by Benjamin Morille have shown that with this method, results are enough close of those obtained with coupling all days.

Wall	Material	Thickness [m]	Emissivity
Facade	Mortar	0,3	0,9
	Brick	0,6	
Roof	Tile	0,02	0,9
	Insulation	0,15	
Park	Dirt	2	0,9
Courtyard	Concrete	0,1	0,9
Sidewalk	Pavement	0,06	0,9
Road	Asphalt	0,2	0,9

Table 1. Material compositions of exposed surfaces

Weather data

The input weather data was obtained from the Prague airport weather station, therefore they didn't correspond to values that existed inside the city with the UHI impact on air temperature. The doctoral thesis work of Bernard is supposed to correct this, but the required data are only available for French cities [2]. This doesn't affect the significance of the results presented here because the objective was to assess the difference of outdoor comfort between scenarios, not absolute values for each one.

For the last 22 hours, the wind blew from the east for most of the hours but for few of them it blew from the south. Because of the wind tunnel dimension condition mentioned before, a space should have been provided in the north for the downstream wind that came from the south to prevent blocking effect. This meant more calculation time for only few time steps. To avoid this, those few wind direction were modified from south to east.

Variations

Two simple variations were considered. First one is an albedo variation for sidewalks, building roofs and facades, concerning all the urban area. Chosen values corresponded to architecture that can be found in Prague. Facade could have light or dark colour paintings, roof could be composed of clay tile or slate, and stones for sidewalk pavement could be gray or black. Albedo values are:

- High albedo variation: facades: 0.7; roofs: 0.3; sidewalks: 0.3; roads: 0.1.
- Low albedo variation: facades: 0.3; roofs: 0.05; sidewalks: 0.1; roads: 0.1.

The second variation was an employment of two rows of trees for each street along the central block. Rows of trees were modelled without trunks, as blocks of 6x10m placed five meters above sidewalks, over their entire length. Their leaf area density (LAD) was configured to 1 m^2/m^3 [5]. Green roofs and green walls were not used in this case study because it is generally rare to find them on old buildings.

	High albedo	Low albedo
Without tree	V1	V2
With trees	V3	V4

Table 2. Combination of Variations

2.3 Calculations

Coupling method

The coupling between CFD and thermo-radiative models can be done in several ways. Bouyer detailed three possibilities in his article [6]. The full dynamic coupling consists of iterating until the strict convergence between CFD and thermo-radiative model is obtained. However this requires high computational time. In quasi dynamic coupling, there is just a single iteration between CFD and thermo-radiative models, but this can be insufficient for strictly representing the transfer of heat and moisture. In his research presented in his article [6], Bouyer used an intermediate coupling method where the resolutions of momentum, continuity, and turbulence equations were disabled after the initializing process. Velocity and turbulence fields were pre-processed for each wind direction and velocity. Then, for each time step during the iterative process, only transport equations for energy and moisture were solved. This enables to save consequently the computation cost. The air fluxes were not disturbed by the heat transfers from the wall surfaces but it can be assumed that the external convective heat transfer coefficient depends only on the wind velocity distributions that are close to the walls [6]. For the case study presented in this article, the same quasi dynamics coupling, without iteration for a convergence of the surface temperature was used. This made it less accurate but faster than simulations of Bouyer.

Convective heat transfer coefficient

In order to calculate the convective heat flux, the difference of temperature between air and surface is multiplied with convective heat transfer coefficient (CHTC). This depends on the wind speed and few formulas exist to solve it. While developing SOLENE-microclimat, correlation found by Jayamaha [10] was preferred (eq.5).

$$CHTC = 5.85 + 1.7 * v \quad (5)$$

For the wind speed values, there are three possibilities. The first is to use the value directly from weather data for all meshes. The second is the wind velocity profile according to the equation (2), which considers the height of each mesh. However, for both solutions, the impact of the environment is not taken into account. The third uses the wind speed value at each point calculated by the CFD model. Malys compared these possibilities to assess the building energetic consumption[13].

For the case study presented in this article, it was decided that for the first ten days, there would be no coupling and only the thermo-radiative model would run. The CHTC was fixed to 11 which was the average value determined with Jayamaha formula (eq. 5), using the wind speed values from weather data for all time steps before coupling. Air temperature values used to calculate the convective heat flux for this period were taken from the given weather data. Then, for the final 22 hours, the wind speed value of each mesh were used and a personalized CHTC was obtained for each mesh using Jayamaha's formula.

3 RESULTS

Each simulation generated a lot of data. For each time step the following results can be visualized:

- For each surface mesh: Short waves received (direct, diffuse from the sky vault, reflected on other urban surfaces), parts absorbed or reflected; long wave exchanges (with the sky vault and with the urban scene); Surface temperature; Latent heat flux (for vegetation).
- For each volume mesh (if coupling with CFD): Intensity and direction of wind; Air temperature; Relative humidity.

To visualize all the results dynamically, the software ParaView was used. In order to assess pedestrian comfort, two specific areas were chosen for comparison: one sidewalk in the western street of the central block, and another sidewalk in the southern street of the central block (see Figure 5). Results presented in the graphs and analyzed below are average values from those areas. Air temperatures and wind speeds were taken from the first tetrahedron above the ground surface. The hours were given in real solar time.

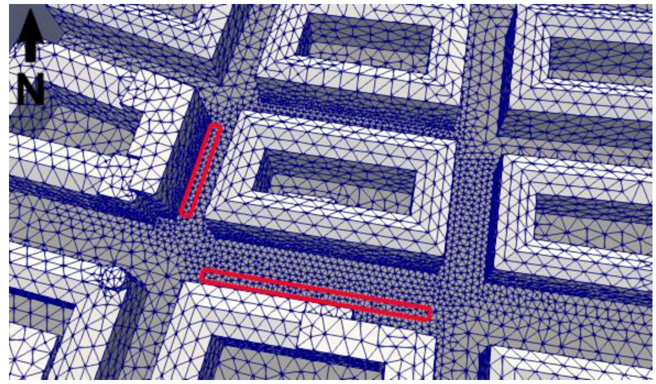

Figure 5. Areas chosen for comparison: two sidewalks in the southern and western street around the central building.

3.1 Surface Temperature

The differences in surface temperatures between both streets are significant. In the southern street, the area chosen was in the shade for most of the day. It received direct solar radiation only in the morning, a significant difference of temperature was noted between with and without trees at this moment (at 9h: V1-V3=7.3°C; V2-V4=10°C) but not for the rest of the day (Figure 6).

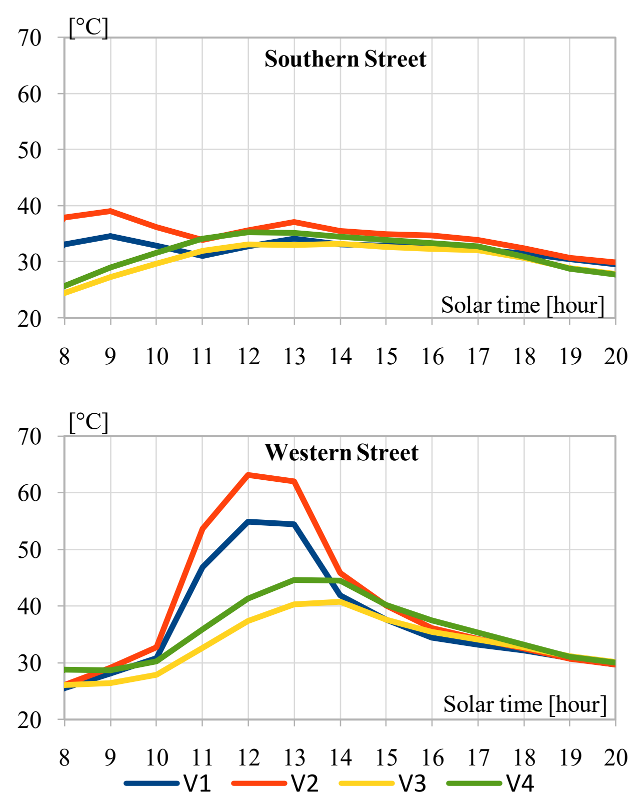

Figure 6. Surface temperatures on the last day of simulation

As compare to South street area, the maximal value of surface temperature in the western street was higher (at 12h:

V2=63.1°C). Without tree, it received most of the solar irradiation between 11h and 12h.The ground accumulated heat and its surface temperature increased. The presence of trees stopped direct solar irradiation, hence the temperature difference was significant (at 12h: V1-V3=17.5°C; V2-V4=21.7°C). The impact of the change in albedo values was also observed (at 12h: V1-V2=8.2°C; V3-V4=4°C) but it was less significant than the impact of trees.

3.2 Air Temperature

In the southern street, the temperature increased regularly throughout the day, without any large variations. This was because the area was in the shade. For the same reason, the difference between the cases with and without trees was mostly constant all throughout the day. The difference occurs because other parts of the neighbourhood are exposed to solar radiation without trees, which increased the air temperature globally (avg.: V1-V3=1°C; V2-V4=1.5°C). In the western street, there was a peak in the difference between the cases with and without trees (at 13h: V1-V3=2°C; V2-V4=2.5°C).This was because the surface temperature of the previous time step was at maximum. Due to the coupling method, the surface temperature of a given time step influenced the air temperature of the next one. Plus, at 13h, the wind speed was particularly low compare to the rest of the day (without trees: at 13h=1.6m/s; avg.=3m/s). The wind speed has a preponderant influence on air temperature when surface temperatures are high.

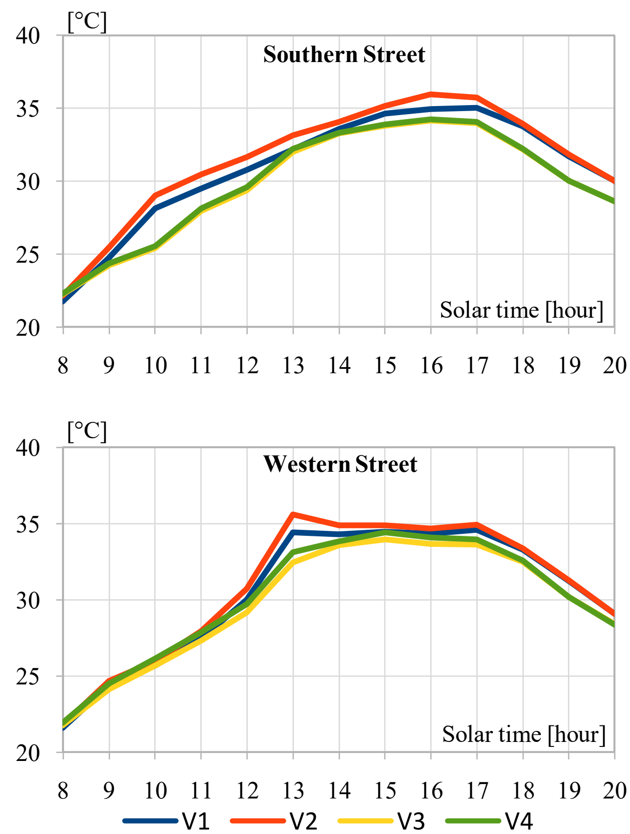

Figure 7. Air temperatures on the last day of simulation

For both streets, the impact of albedo variation was not significant with the presence of trees. But it was significant without the presence of trees, when the sun radiates a part of the street, from 10h to 13h for the western street and from 8h to 17h for the southern street, whose south-facing buildings were particularly exposed.

3.3 Wind Distribution

The wind distribution along a sophisticated geometry is a complex phenomenon and its analysis requires to consider several parameters. Southern street has a lower wind speed compared to Western street due to complexity in wind distribution and since the top left street is shorter than the bottom right (wind entry points are indicated by arrows on Figure 8).

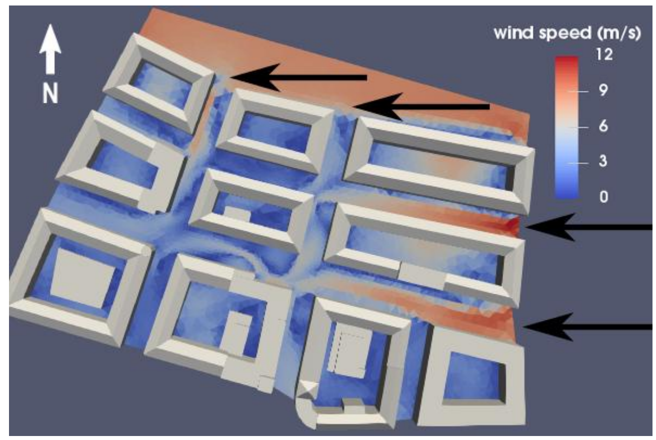

Figure 8. Wind distribution without tree at 15h. Wind original direction is from East.

For both streets the wind speed was slightly reduced with the presence of trees (avg.: West street: -11%, South street: -7%). Trees were an obstacle to the wind, because they were in sufficient number and leafy. This little loss of cooling due to wind was largely compensated by blocking of the solar irradiation.

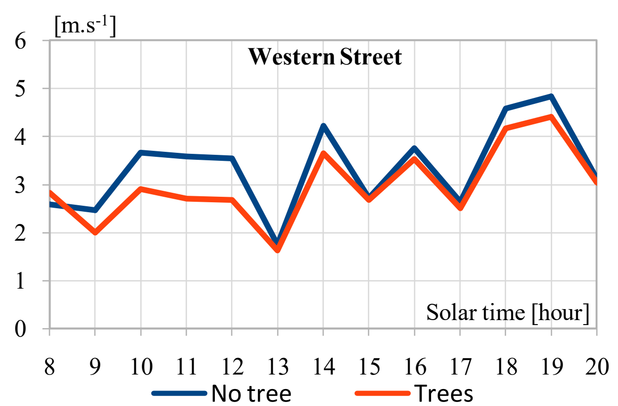

Figure 9. Wind speed on the last day of simulation.

3.4 UTCI

There exists two type of comfort index, the simple models which considers only environmental parameters (WCT, AT, ET*, etc.) and the two-node models which takes into account the processes concerning the human body: heat generation and heat losses (PMV, SET*, UTCI, etc) [21]. It was decided to study the UTCI which was developed to provide accurate predictions for important applications, validated all around the world and adapted for local conditions [3]. UTCI is defined as the air temperature of the reference condition described in Blazejczyk article causing the same model response as the actual condition. It differs from other two-node comfort indexes because it includes a multi-node model of human thermo-regulation based on the Fiala model [8].

To calculate the UTCI, input parameters air temperature, vapour pressure, wind speed and mean radiant temperature are required. To determine the mean radiant temperature, a cylinder depicting human body was used which consists of 25 faces and a height of 1,75 m. For each mesh of the area that was under consideration, the long wave exchanges between the cylinder faces and all the surfaces, including the sky, were calculated as well as shortwave flux directly from the sun and from the surfaces after reflexions [22]. For vegetation cases, trees shaded the cylinder. The rest of inputs parameters were directly taken from simulation results. The calculation method of UTCI was taken from the original F90 UTCI source code of Peter Broede [20].

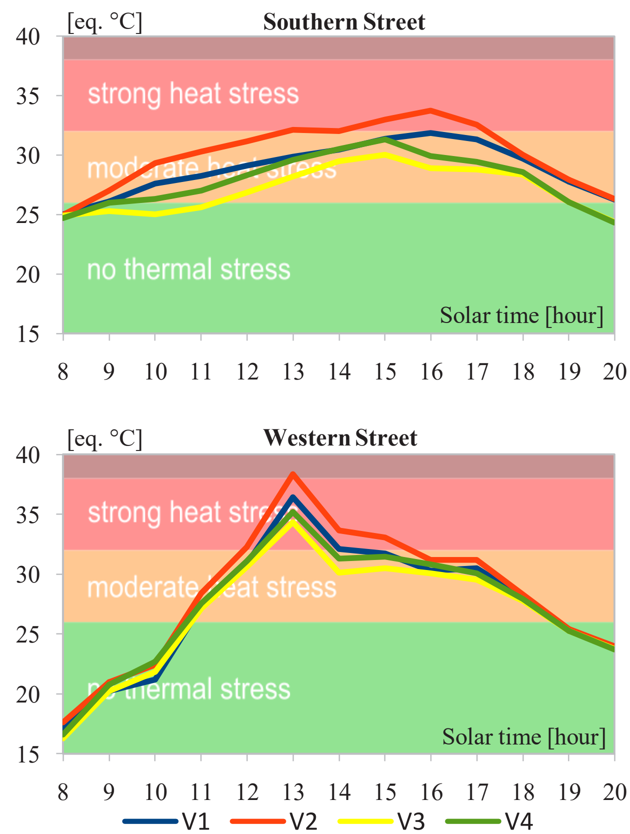

Figure 10. UTCI on the last day of simulation

The results of UTCI are quantitative, since they are given as equivalent temperature, and qualitative, due to a sensation scale. This characteristic, plus taking into account the interaction of the climatic components, makes it a good tool to communicate the results to laymen. Compared to air temperature, differences between scenarios are more visible. Results were following mostly same paths, but with some variation. For the western street, the UTCI decreased after the peak at 13h compare to air temperature. It was mainly because the sun stopped to irradiate this part of the street, which did not affect the air temperature, but it did affect the global comfort. In the southern street, the difference between V3 and V4 was more visible. It is explainable with the influence of surface temperature surrounding a person on his well-being. Surface temperatures of the south-facing building were higher on V4.

4 DISCUSSION AND CONCLUSION

The analysis shows that high albedo surfaces and vegetations can have a significant impact on the urban microclimate. More generally, SOLENE-microclimat can be a useful simulation tool for assessing outdoor comfort. The powerful coupling between the thermo-radiative and the CFD model can simulate many physical phenomena that are involved in an urban microclimate, in order to describe human sensations. The advanced parameterizations and accurate reproductions of complex urban shapes have made it a unique and reliable tool which is able to simulate many situations with a large degree of freedom in modelling and processing. Results obtained from the simulation tool are numerous and give many possibilities for analyses and assessments of urban comfort. The graphical representation in 3D is a big advantage for sharing results with laymen.

The case study, which was a simple example of what can be done with this simulation tool, already revealed interesting information about the urban comfort. It is possible go further, for example, for assessing the impacts of albedo variation for each type of surface (sidewalk, roof, facade) and for determining precisely which sidewalk should be covered with trees to obtain a good investment to impact ratio for improving the outdoor comfort. With a good parameterization the simulations conducted by SOLENE-microclimat are a useful decision-making tool for urban planners. The coupling method and days of simulation should be chosen carefully and must be taken into account during the assessment of results.

From the application point of view, SOLENE-microclimat was created and mostly used for research purposes; therefore it has some obstacles for its use by non-specialist. It does not have a graphic interface and there are no official documentations to act as a user guide. Guidance is mainly provided by the researchers and engineers who are working with it.

One specific issue posed a challenge for this study. In the results of the simulations, some localized temperature values were abnormally high. In a study made by Laurent Malys, similar local outliers were also observed. He supposed that it is because of the confinement effects due to the recirculation near brightened-up walls [13]. This could also be explained because the natural convection was not taking into account. If there is no forced convection (wind speed = 0), the energy wouldn't be carried by the air and the temperatures would rise. This was a problem of the coupling method used for the simulation, but the large majority of values were coherent.

The current version of SOLENE-microclimat does not take into account the water balance in the urban soil. This is an important aspect of the urban microclimate because it involves the evapotranspiration process which impacts the humidity and air temperature. We can configure the rate of saturation in the soil but it does not evolve along simulations because SOLENE-microclimat has not been coupled with a proper hydrological model yet. However, this shortcoming does not demean the interest in this tool. It is a comparative tool so all simulation cases are configured with the same issue. Hence, a team at ECOTEN is working on developing different hydrological models for urban soils, for different level of knowledge of the ground composition.

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