Abstract

The present work deals with the determination of outdoor thermal comfort using a decoupled approach. Unlike the existing tools that model the coupling between surface heat transfer and air temperature, we present here a method advantageously allowing for the usage of the available features of EnergyPlus for the calculation of surface temperatures, the effect of vegetation and retrieving the outdoor solar fluxes. Isothermal air velocities are computed separately using openFOAM. The method allows for an hourly determination of comfort at ground level over the year with the computed ambient parameters.

Key Innovation

- Using EnergyPlus to simulate outdoor comfort.
- Hourly air velocity field with openFOAM.

Practical Implications

The method described here allows the seasonal evaluation of outdoor comfort for design variants with an overnight run on a desktop computer.

Introduction

A limited number of tools allow for the detailed determination of the urban micro-climate, such as the recognized ENVI-met by Bruse and Fleer (1998) and Solene by Gros et al. (2016). These validated approaches are based on the coupling of heat transfer on surfaces with non-isothermal fluid dynamics, however at the cost of a high computational expense, reaching days of CPU time. At the other end of the geometrical scale, the Town-Energy-Balance model (TEB) by Masson (2000) allows the simulation of urban climate using a 1D canyon-street model.

At early stages of construction projects, the available level of detail is low and iterations are often required in the design process: The aforementioned tools hence become practically unaffordable or are too coarse to assess accurately the effects of street planning. The work proposed here is a de-coupled approach, providing for a simplified evaluation of surface temperatures and air velocities in the outdoor built environment, using the open-source software EnergyPlus and openFOAM respectively for building energy simulation (BES) and computational fluid dynamics (CFD).

Tweaking EnergyPlus for Outdoors

The usage of the available features of EnergyPlus allows for the determination of outdoor surface temperatures and irradiation by validated methods. Heat transfer through or between the elements composing the urban environment such as ground, walls and vegetation are succinctly described in the paragraphs that follow and the comparison of results with the existing literature is exposed.

Geometry and Zoning

Building energy simulation softwares are obviously able to determine the surface temperatures of external walls depending on outdoor boundary conditions:
this feature will be used to obtain outdoor surface temperatures and solar irradiation. The trick used here relies in constructing one "building" model that encompasses the urban environment considered.

From an existing building, the surrounding built environment is added in the building model as a single, large, unconditioned zone, with its bottom floor in contact with the ground (see Figure 2). A similar method was used by Allegrini et al. (2012) with TRNSYS for the determination of the influence of surrounding buildings on energy use, however without discretizing the ground or including vegetation in the model.

![Figure 2: Principle of integration of the surrounding environment into EnergyPlus’ model, with \((T_s, \varphi_s)\) the temperature and incident solar flux on surfaces.](image)

An illustration of this method is provided in Figure 3 using one of EnergyPlus’s example files as building model file.

![Figure 3: Geometry integrating the original building model with neighbouring constrictions and discretised ground in a single building model.](image)

This method advantageously allows for the usage of the available features in EnergyPlus, such as the addition of shadings or the simulation of low vegetation. The properties of the different surfaces are modified in order to match the desired materials, e.g. building walls, windows, roofs, pavement or road surface, as depicted on Figure 2. A sensitivity study of the thickness of ground "wall surface" above the added zone showed that from 2 [m] thickness, it has little influence on the results obtained.

Latent heat transfer to the ambiance from ponds, lawns or trees is not accounted for. However, as far as vegetation is concerned, the shading effect was proved to be the major contributor to cooling rather than water evaporation Morakinyo et al. (2020); Tsoka et al. (2018). What is more, the evapotranspiration level depends much on the leaf area index, stomatal resistance and rainfall. Those parameters are often not known with an adequate level of detail, be it in meteorological files or plant description. Trees are hence integrated as mere shading objects.

No influence of the outdoor surface temperature on the local outdoor air temperature is considered, as in classical BES. This strong modeling assumption allows to reduce the computational expense to a few hours only for a yearly simulation, mainly spent on solar calculations.

Noticeably, in this very proof of concept a single zone is added, however there is no obstacle to adding multiple, conditioned zones that would represent different buildings.

**Transient Conduction**

Heat storage in the environment’s surfaces (walls, roofs, ground) is modelled with EnergyPlus’ integrated wall model. The "Conduction Transfer Function" algorithm is used to represent conduction through the walls and ground as per Ceylan and Myers (1980). Other algorithms such as the finite difference method are, as of now, not compatible with EnergyPlus’s EcoRoof model for vegetated roofs.

**Radiation**

Short wave radiation is computed using the solar shading routine integrated in EnergyPlus. The latter takes into account radiation as follows:

- Reflection on windows is specular.
- Reflection from walls is diffuse (see Figure 4).

![Figure 4: Specular and diffuse reflection on windows and walls.](image)

A ray-tracing method calculates the beam and sky-diffuse components of solar radiation reflected on each of the model’s surfaces, including the effect of neighbouring wall surfaces (e.g. the surrounding buildings) and mere shading objects such as trees in the present case.

The default model for outdoor long wave heat transfer is linearized in EnergyPlus. It is separated in three fluxes (p. 87 of DOE (2020)):

- the radiation between the walls and the ground
- the radiation between the walls and the sky
- the radiation between the ground and the sky

Each radiant flux is calculated through the estimated
view factor of the considered surface with the ground
and sky, obtained from the tilt angle $\phi$ corresponding
to the angle between the surface and the ground:

$$F_{\text{gnd}} = 0.5(1 - \cos(\phi)) \quad \text{and} \quad F_{\text{sky}} = 0.5(1 + \cos(\phi))$$

(1)

For a horizontal surface, $F_{\text{gnd}} = 1$ and $F_{\text{sky}} = 1$. For
a vertical surface, both view factors are worth 0.5.

The contribution of radiation with the sky vault is then split between sky and “air” with coefficient $\beta$:

$$\beta = \sqrt{0.5(1 + \cos(\phi))}$$

(2)

The radiation with “air”, a proxy for the surfaces
of the surrounding environment, is then weighted by
$(1 - \beta)F_{\text{sky}}$ and the contribution of sky is weighted by
$\beta F_{\text{sky}}$.

The long wave radiant flux is then linearized:

$$h_{r,\text{ground}} = \frac{\epsilon \cdot \sigma \cdot F_{\text{ground}} \cdot (T_{\text{surf}}^4 - T_{\text{air}}^4)}{T_{\text{surf}} - T_{\text{air}}}$$

(3)

$$h_{r,\text{sky}} = \frac{\epsilon \cdot \sigma \cdot F_{\text{sky}} \cdot \beta \cdot (T_{\text{surf}}^4 - T_{\text{sky}}^4)}{T_{\text{surf}} - T_{\text{sky}}}$$

(4)

$$h_{r,\text{air}} = \frac{\epsilon \cdot \sigma \cdot F_{\text{sky}} \cdot (1 - \beta) \cdot (T_{\text{surf}}^4 - T_{\text{air}}^4)}{T_{\text{surf}} - T_{\text{air}}}$$

(5)

This calculation method is simplistic given the complexity of urban environments, however, the recently added feature of EnergyPlus allowing to provide user-defined view factors of the building’s outdoor surfaces to the surroundings described in Luo et al. (2020) is a promising prospect. The study by Evins et al. (2014) proposes an alternative improvement of the existing model in EnergyPlus, with upgraded bulk view factors and surrounding temperatures for the determination of energy consumption.

**Convection**

The convection on the external surfaces are represented with EnergyPlus’ integrated model, the DOE-2 model. The calculation takes into account the surface roughness of the material and the tilt angle of the surface.

Interestingly, if the local air velocities are known, they can be added by the user, using the SurfaceProperty:LocalEnvironment object in order to enhance the description of the local convective heat transfer coefficient.

**Vegetation**

Originally used as a model for vegetated roofs, EnergyPlus’s built-in EcoRoof model is used to represent low vegetation or lawns. The model, illustrated on Figure 5, requires detailed characteristics for each type of vegetation and performs a heat and mass balance depending for instance on the plant’s stomatal resistance, its leaf area index, rainfall and soil humidity. It can be used on for horizontal surfaces only.

On this particular point, a drawback of the approach is that only one such object can be defined in EnergyPlus’ simulation setup and hence whatever the number of different vegetated surfaces defined, a unique vegetation temperature is calculated.

**Comparisons with the literature**

In this section comparisons of the results obtained with the model are made with the existing experimental and numerical literature, contributing to assess its relevance.

**High & Low Vegetation**

The developed tool was used to compare vegetated and non-vegetated streets as set per the setup shown on Figure 6. Its surface temperatures can be observed on Figure 7, which presents an average reduction of 8 [K] when comparing vegetation to mineral ground. The references Musy et al. (2017, 2014) using the software SOLENE and on-site measurements show results of the same magnitude, with a reduction of 7 to 11 [K] in similar streets in presence of trees.
The references Musy et al. (2017, 2014), also propose results for surfaces covered with low vegetation, with temperatures varying between 18.8°C and 21°C around noon. In a similar geometrical setup, the developed tool showed higher values of surface temperatures, varying between 20°C and 30°C. Even though absolute values are different, which is probably related to different outdoor boundary conditions and materials, around 10 [K] temperature reduction between the mineral and vegetated ground is obtained in both studies.

Regarding high vegetation, i.e. trees, the day/night "obstruction" effect of trees against sun and sky vault can be observed, as the simulated average surface temperature surrounding the trees is hotter during the night than in streets without trees. This observation was correlated to the fact that the long wave radiant flux towards the sky is weakened by the presence of trees: Figure 8 shows the longwave radiant flux of a street with and without tree.

Figure 8: Longwave radiant flux with/without trees.
Noticably, the results obtained are highly dependent on the vegetation size and of its leaf density.

Canyon Street
A brief study of the "canyon street" phenomenon was led, evaluating different width to height ratios. According to Stewart and Oke (2012); Morakinyo et al. (2020), the surface temperature in a narrow street is lower than in a large street during day time, owing to the shading effect. The phenomenon is reversed at night and the narrow street tends to stay hotter than the larger one, as the sky view factor of the ground is reduced by the buildings façades. This phenomenon can be observed on Figure 9 presents the temperatures of discretised patches of the street over time, obtained with the model for various width to height ratios.

Figure 9: Temperatures over time for various H/L ratios of a canyon street.

Albedo
Variations of the ground’s and surrounding building’s albedo were simulated. The effect of albedo variation on temperature are presented in Figure 10 and show a very high influence on the surface temperature with a difference of 47°C between the lowest and highest albedo tested, ranging from 0.1 to 0.9. Reference Kyriakodis and Santamouris (2018) used the software ENVI-Met to conduct a study on the influence of the albedo, and obtained very similar results with a decrease of 9 [K] with a variation of albedo from 0.04 to 0.35, and a decrease of 6 [K] with a variation of albedo from 0.04 to 0.17 in a second study, which compares well with the orders of magnitude of temperature reduction plotted on Figure 10 for similar increases of albedo.

Summary of the results
The results obtained exhibit a satisfactory behaviour compared to the experimental and numerical literature and will be considered as sufficient for the proof of concept presented in the sequel:

- The phenomenon is well reproduced in terms of dynamics and amplitude of the surface temperatures compared to Musy et al. (2014).
- Reflection is correctly taken into account and visible between buildings and ground, influenced by the albedo of each surface, similarly to Musy et al. (2014). Specular reflection of the solar flux on glazed facades was also observed.
- Radiant flux is inhibited with decreasing width to height ratio or trees, owing to the reduced sky view factor in presence of trees, in narrow streets or close to buildings. Similar results can be observed in Musy et al. (2014).
- Shading from buildings and trees is correctly represented. Building walls are opaque, whereas trees transmit 20-30% of the solar flux to the ground, as per Toudert and Mayer (2005).

Computation of Air Velocities
The human body being very sensitive to air movement (Höppe, 1999), computing the outdoor velocity field cannot be spared for the determination of comfort. For the sake of conciseness, a brief description of the method and hypotheses made in order to obtain the velocity fields is provided here. The widely used
Figure 11: Mesh dimensions according to the highest building height $H$.

and validated OpenFOAM (Jasak et al., 2007) open-source CFD software is used throughout the study. In order to achieve computational affordability, the influence of outdoor surfaces on outdoor air temperature and humidity is not taken into account. The isothermal CFD computations are hence decoupled from the BES part and may run independently.

Meshing a Digital Wind Tunnel

In the present work, a numerical wind tunnel experiment approach was used, allowing to study a given urban context under various incoming wind directions and intensities and reducing the meshing effort. The general mesh set-up is configured to enforce all the general guidelines for environmental flow problems (Franke and Baklanov, 2007; Tominaga et al., 2008), mainly related to computational domain dimensions (see Figure 11) and relative grid parameters: grid sizes, expansion ratios, local densities, as well as convergence criteria and relaxation factors.

Performing CFD simulations for several wind incidences without sharing the computational burden is computationally expensive. In order to decrease the overall computational cost, a meshing methodology partly inspired by Toparlar et al. (2015) is applied. A single hexahedral domain is meshed for six different in- and outflow directions, leading to a unique mesh, assembled from two components Walther et al. (2020): a central cylindrical mesh with the urban area to investigate, as in Kastner and Doğan (2019), enclosed within a rectangular mesh forming the wind tunnel. A coherent meshing of the outer discretizations at the domains allows for relative rotations of the subdomains, as shown on Figure 12, keeping a conformal mesh interface. For every desired wind incidence, the remeshing process is hence replaced by a simple rotation and stitching of the rectangular and cylindrical submeshes.

Unlike in Kastner and Doğan (2019), the outer parallelepipedal domain was kept, mainly in the purpose to set up boundary conditions directly from OpenFOAM libraries, without additional development.

The resulting mesh in the context of the case study has following features: the mesh size is in the order of magnitude of $\sim 10^7$ cells, with elements as small as $\sim 0.5$ [m].

Figure 12: Mesh rotations for wind incidences from North to East, every 30°.

Simulation set-up

Using the recommendations by (Franke and Baklanov, 2007; Tominaga et al., 2008), the main numerical hypothesis for the isothermal air flow simulations are the following:

- The chosen CFD approach is the RANS (Reynolds Averaged Navier-Stokes) framework, with a SIMPLE steady-state solver.
- The turbulence is handled with a $k-\omega$ SST model, a good trade off between precision in near wall areas (inner part of the boundary layer, where a $k-\omega$ formulation is used), and a stable and rather fast resolution in the main freestream, with a $k-\varepsilon$ behaviour.
- The inlet velocity profile reproduces the atmospheric boundary layer, hence a logarithmic velocity profile is used (varying with the altitude $z$), together with corresponding profiles for turbulent variables.
- The ground roughness is representative of urban areas, whereas the sides and top boundaries of the domain are defined with a "slip" boundary condition.
- The buildings surfaces are treated with appropriate rough wall functions.
- The median meteorological velocity is used as inlet reference velocity at $z = 10$ m for each wind direction.
- The convergence criteria are of $10^{-4}$ on the residual quantities.

The site’s wind data is processed into 12 equal bins representing 30°, the first one being centred on North. Twelve wind directions are hence simulated and serve the reconstruction of the hourly air velocity fields, similarly to Delpech et al. (2005); Toparlar et al. (2015). An example of result is presented on Figure 13. The computational expense is limited to an overnight run on a robust desktop computer.

Case study

Brief Presentation

The case study is the urban space in front of Strasbourg’s main train station where a large esplanade with high and low vegetation was landscaped (see Figure 14. The surrounding are composed mainly of

\[ \frac{\partial}{\partial t} \rho + \nabla \cdot (\rho \vec{v}) = 0 \]

\[ \frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \otimes \vec{v}) + \nabla \phi = \nabla \cdot \vec{f} \]

\[ \frac{\partial}{\partial t} (\rho e) + \nabla \cdot (\rho \vec{v} e + \vec{v} \cdot \nabla \rho e) = \nabla \cdot (\vec{f} \cdot \rho e) + \nabla \cdot (\kappa \nabla \Tilde{\varepsilon}) + W_{\text{source}} \]

\[ \frac{\partial}{\partial t} (\rho \phi) + \nabla \cdot (\rho \vec{v} \phi) = \nabla \cdot (\vec{f} \phi) + \rho_{\text{source}} \]

\[ \kappa = \nu + \frac{C_{\mu}}{\min(Re, 1)} \nu_{t} \]

\[ \frac{\partial}{\partial t} \rho_t \varepsilon + \nabla \cdot (\rho_t \vec{v} \varepsilon) + \nabla \cdot (\rho_t \phi \varepsilon) = \nabla \cdot \left( \nu_{t} \nabla \varepsilon \right) + \frac{C_{\mu}}{\min(Re, 1)} \varepsilon \nabla \cdot \vec{v} \]

\[ \frac{\partial}{\partial t} \rho_t \omega + \nabla \cdot (\rho_t \vec{v} \omega) + \nabla \cdot (\rho_t \phi \omega) = \nabla \cdot \left( \nu_{t} \nabla \omega \right) + \frac{C_{\mu}}{\min(Re, 1)} \omega \nabla \cdot \vec{v} \]

\[ \frac{\partial}{\partial t} \rho_t \mu + \nabla \cdot (\rho_t \vec{v} \mu) + \nabla \cdot (\rho_t \phi \mu) = \nabla \cdot \left( \nu_{t} \nabla \mu \right) + \frac{C_{\mu}}{\min(Re, 1)} \mu \nabla \cdot \vec{v} \]

\[ \varepsilon = \frac{\mu_t}{C_{\mu} \rho} + \frac{\omega^2}{C_{\mu} \rho} \]

\[ \mu = \frac{\mu_t}{C_{\mu} \rho} \]

\[ \omega = \frac{\omega_t}{C_{\mu} \rho} \]

\[ \kappa = \nu + \frac{C_{\mu}}{\min(Re, 1)} \nu_{t} \]

\[ \frac{\partial}{\partial t} \rho_t \varepsilon + \nabla \cdot (\rho_t \vec{v} \varepsilon) + \nabla \cdot (\rho_t \phi \varepsilon) = \nabla \cdot \left( \nu_{t} \nabla \varepsilon \right) + \frac{C_{\mu}}{\min(Re, 1)} \varepsilon \nabla \cdot \vec{v} \]

\[ \frac{\partial}{\partial t} \rho_t \omega + \nabla \cdot (\rho_t \vec{v} \omega) + \nabla \cdot (\rho_t \phi \omega) = \nabla \cdot \left( \nu_{t} \nabla \omega \right) + \frac{C_{\mu}}{\min(Re, 1)} \omega \nabla \cdot \vec{v} \]

\[ \frac{\partial}{\partial t} \rho_t \mu + \nabla \cdot (\rho_t \vec{v} \mu) + \nabla \cdot (\rho_t \phi \mu) = \nabla \cdot \left( \nu_{t} \nabla \mu \right) + \frac{C_{\mu}}{\min(Re, 1)} \mu \nabla \cdot \vec{v} \]

\[ \varepsilon = \frac{\mu_t}{C_{\mu} \rho} + \frac{\omega^2}{C_{\mu} \rho} \]

\[ \mu = \frac{\mu_t}{C_{\mu} \rho} \]

\[ \omega = \frac{\omega_t}{C_{\mu} \rho} \]
1950’s to 1970’s buildings. The ground level in this area, composed of an open place including mineral pavement with lawns and connecting streets will be the area of interest in this case study.

The 3D geometrical model used in the sequel is presented on Figure 15.

Computation of a comfort index

The corrected and open source version of the Physiological Equivalent Temperature (PET) comfort index found in Walther and Goestchel (2018) is chosen as the outdoor comfort index. Based on a mathematical model of human physiology, it consists of an equivalent operative temperature, much resembling a typical indoor environment (\( \sim 50\%\) relative humidity and low air velocity), that would provoke the same physiological response as the actual environment.

Four environmental parameters are required for the computation of the body’s physiological reaction to its environment: the air temperature and relative humidity will be taken from the local meteorological file, whereas the radiant temperature and air velocity fields originate from the method described here.

For this first proof of concept, a simplified radiant temperature field is calculated:

- The longwave contribution to the radiant temperature is supposed to originate mainly from the local ground surface temperature, shown on Figure 16. This exceedingly coarse assumption will be enhanced in future works, using view factors between octagons representing individuals as in SOLENE Musy et al. (2014).
- The "solar" radiant temperature \( T_r^* \) integrating the shortwave contribution is calculated after Helbig et al. (2013) from the solar flux distribution (an example of which is given on Figure 17) at normal incidence:

\[
T_r^* = \sqrt{\bar{T}_r^4 + \frac{\alpha \varphi f_p}{\sigma \varepsilon}} \tag{6}
\]

where \( T_r \) is the radiant temperature computed with the longwave radiation contribution and \( f_p \) is a projection factor depending on the solar altitude angle, allowing to convert the flux received on the ground to the one on a cylinder representing an individual. Variables \( \alpha, \varphi, \sigma, \varepsilon \) are respectively the solar absorptivity of the individual, solar flux at normal incidence, Boltzmann constant for radiation and the emissivity.

The surface temperatures for the case study are presented on Figure 16. Obviously, the surface temperature of the lawns (in yellow) is the same for all parcels: this relates to the fact that EnergyPlus’ EcoRoof object does not handle several locations for vegetated surfaces (the large temperature difference between mineral ground and lawns makes the effect of tree shading invisible on this Figure graph, it is nevertheless present). The solar fluxes obtained are presented on Figure 17 and show the influence of trees and buildings.
observe the influence of more elevated air velocities in the wind stream and higher surface temperatures close to buildings.

Figure 18: PET comfort level at 8 AM in January. The average PET between 5 AM and 11 PM during the hottest week of the year (mid-July) is is plotted on Figure 19 where one can observe the effect of the lawns and trees.

Figure 19: Average PET comfort level during the hottest week.

Conclusion & Perspectives

The present work proposes a simplified approach for the evaluation of outdoor comfort, using state-of-the-art models for building simulation and computational fluid dynamics. The coupling of outdoor air temperature and relative humidity with building surfaces is neglected and allows for a relatively low computational effort compared to non-isothermal models, as well as simulating longer periods of time.

A high level of geometrical detail can thus be modeled, keeping it affordable to perform sensitivity or parametric studies of the parameters, e.g. for uncertain material properties or design variations. Compared to the approach developed concurrently in Kastner and Doğan (2019), based on a similar principle, the present method does not rely on a commercial 3D CAD software.

The main results may be summarised as follows:

- Dynamics and amplitude of surface temperatures were compared to the literature and are well reproduced, including shading effects for short wave radiation and sky view factor obstruction for long wave radiation.
- Single patches of low vegetation can reliably be modeled, however the EcoRoof model is not able to compute more than one surface temperature for vegetation, which is a drawback.
- Trees are taken into account as shading objects.
- The hourly wind patterns are reproduced by interpolation from a set of CFD simulations.
- The method allows for the computation of a comfort index at an hourly time step over the year.

As a perspective, the ongoing developments of the tool include:

- The integration of local convective coefficient on surfaces as a by-product of the isothermal CFD simulation,
- Improving the long wave radiation model by providing surface to surface view factors as per Luo et al. (2020) as well as a view factor based MRT calculation for the computation of comfort,
- Adding thermal zoning and conditioning for neighbouring buildings, which will allow for the estimation of energy consumption of the area.
- As a more challenging prospect, a "ping-pong" coupling strategy between building surface temperatures and local air temperature is currently explored. Indeed, using the isothermal air flow at hand from the CFD simulations, a steady-state, local heat and mass balance at each cell of the mesh can be performed. Solving this system yields the steady state cell temperature, neglecting the effect of temperature gradients on air flow. The comparison to measured data for validation purposes would also be valuable.

References


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