Solar Energy 170 (2018) 470–485

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Review

Numerical coupling model to compute the microclimate parameters inside a street canyon

Part II: Experimental validation of air temperature and airflow

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ARTICLE INFO

Keywords:
Numerical coupling model
Street canyon
CFD model
Air temperature
Wind velocity
Turbulent kinetic energy
Experimental campaign

ABSTRACT

Software and hardware systems have evolved rapidly in recent years. The numerical microclimate simulation is becoming an important tool for providing better information and analysis of thermal comfort, thermodynamic behaviors and energy consumption for a large range of urban configurations. This research is conducted over two parts. In the first part (Athamena et al., 2018), we have presented the development of a new numerical model based on full dynamic coupling process between the thermo-radiative software "Solene" and the CFD model "Code_Saturne". The surface temperatures' output results of coupled simulations were compared with the measurements data obtained during the EM2PAU[1] experimental campaign. The comparisons showed that the coupling model reproduced the wall and ground surface temperatures quite well. This second part discusses the experimental validation concerning the air temperature and airflow results. Foremost, the measurement devices used during the EM2PAU experiment to measure air temperatures and average wind velocities inside the street canyon are detailed. Next, we present the inlet boundary conditions for the thermodynamic model. Following the same method used for surface temperatures, we have submitted the numerical results of air temperature, wind velocity and turbulent kinetic energy to an assessment with the statistical parameters and experimental data. The results indicate that the coupling model simulates the air temperatures and mean wind velocities at local scale adequately. On the others hand, the comparisons for turbulent kinetic energy highlight unsatisfactory results which are probably due to an erroneous representation of the inlet profiles of $\boldsymbol{k}$ and $\boldsymbol{\varepsilon}$ based on the theoretical formulations.

1. Introduction

This decade has been marked by the advent of a new generation of urban spaces known as Ecodistricts or sustainable neighborhoods. To design an Ecodistrict, several aspects need to be addressed. First, it is imperative to successfully integrate buildings into their environments. Then, we must take into account the microclimate and comfort in their multiple aspects: thermal, visual and acoustic; and finally, how the different flux -water and waste in particular- will be mastered (Athamena, 2012). In Ecodistricts, the outdoor thermal comfort becomes a central issue for the public authorities and the project managers such as architects and urban planners. These actors are called upon to design and propose measures and actions to characterize and anticipate the thermal comfort situations of their urban propositions.

Thermal comfort is a very interdisciplinary domain, which includes many aspects in various scientific fields such as physical building sciences, physiology, and psychology of pedestrians, to name a few. The numerical simulation technique has become an essential mean in the treatment of the complexity, heterogeneity and non-linearity of urban climatic systems. It is more flexible and less expensive than

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[1] Etude Micro-Météorologique sur la Propagation Acoustique en milieu Urbain.

https://doi.org/10.1016/j.solener.2018.05.015
Received 21 November 2017; Received in revised form 4 May 2018; Accepted 5 May 2018

measurement campaigns because of the control of computation parameters. In addition, advances in computer technology have led to an increased and improved ability to model and simulate complex physical and physiological conditions. Nowadays, many new numerical tools have been developed. These tools are being commonly applied to assess thermal comfort efficiency of many urban configurations (Ali-Toudert and Mayer, 2006, 2007; Du et al., 2014; Karakounos et al., 2018).

Despite their success and efficiency, these numerical models allow us to generally simulate only one or two parameters with numerous assumptions. To limit the hypotheses and improve the quality of results, several attempts to couple various numerical models were carried out recently (Robitu et al., 2006; Zhu et al., 2007; Bouyer et al., 2011; Barbason and Reiter, 2014; Liu et al., 2016; Yang et al., 2017; Yamamoto et al., 2018).

In 2006, a coupling platform between Solene (TR) and Fluent (CFD was developed by Robitu et al. (2006) to evaluate the influence of vegetation and water pond on urban microclimate of public places. The simulations were carried on for a typical hot clear sunny day of summer, July the 15th, for Fleuriot Square in Nantes, France. The researchers remarked that the computing time of coupled simulations was long, even when using workstations, about one week for only one evaluation. They noticed also that the scrupulous description of the urban scene is time consuming and supposed that the development of satellite imaging may reduce this problem. In this study, the numerical results were compared with the published results in similar cases which did not allow a precise verification of the quality of their numerical output results.

The evaluation of the benefits of the coupling simulations in the estimation of building energy consumption are studied by Bouyer (2009) and Bouyer et al. (2011). To reach their objective, the researchers developed Solene building thermal model as a sub-model inside the thermo-radiative model. They then coupled Solene (TR) with Fluent (CFD) to evaluate the microclimate parameters and the energy demand of one building, arranged inside urban fragment consisting of two main blocks, during one week in winter and one week in summer. The results showed the real benefits of using the microclimatic coupling technique to more accurately assess the building energy consumption in urban context. The benefits are observed especially in the thermo-radiative balance evaluation, which seems to contribute, regardless of the season, as a heat gain in the balance and in the convective heat flux which was strongly urban airflow dependent. As perspectives, Bouyer (2009) suggested that the future researches should have the experimental validation as a guideline before proposing the coupling of microclimate models. Close collaboration between numerical modelers and experimenters would be desirable to fill gaps or reveal particular points where the two domains must complement each other. The same perspectives were reported by Chen et al. (2009), Fan and Ito (2012) and Gros et al. (2012).

Indeed and as is often specified in the literature, knowledge of energy exchange phenomena in an urban context requires the crossing of approaches related to experimentation, simulation and remote sensing (Mestayer and Anquetin, 1994). Arnfield recalls that the numerical simulation, a method perfectly adapted to deal with the complexity and the no-linearity of urban climate systems, has been speedily developing in the scientific community, but, without immediate and rigorous validation of models, or, if necessary, too light (Arnfield, 2003).

The practical aspect of this research aims to help architects and urban planners in their effort to designs more comfortable outdoor spaces by providing them robust tool and sound recommendations. To achieve this goal, we propose to develop a numerical coupling model between two free access software: the CFD model, Code_Saturne (developed by EDF[2]) (Benhamadouche et al., 2002 and Archambeau et al., 2004) and the TR model, Solene (developed by CRENAU[3] laboratory) (Groleau and Miguet, 1998; Miguet, 2000 and Groleau, 2000). The developed numerical exchange method is based on the full dynamic coupling strategy proposed by Zhai et al., 2002 and considered by them as the more reliable and efficient method for coupling CFD and thermal models.

The scientific aspect aims then to approve the robustness and efficiency of the full dynamic coupling strategy by submitted the output results of coupled simulations (surface and air temperatures, mean wind velocity and turbulent kinetic energy) to a detailed validation with the data measurement obtained during the EM2PAU in-situ campaign. The goal of this validation is (i) to check the computational cost and quality of the output results and (ii) to verify the impact of the origin of the input data on the accuracy of coupled results.

To better explain the coupling model methodology, the experimental campaign, the detailed input data and the validation process, we were compelled to divide this research into two related parts. In the first paper (Part I) (Athamena et al., 2018), the methodology of the model based on full dynamic coupling process between the thermo-radiative software “Solene” and the CFD software “Code_Saturne” was detailed. The surface temperatures’ output results of coupled simulations were compared with the measurements data obtained during the EM2PAU in-situ campaign. The simulation results showed a good consistency with daytime measurements for all surfaces as well as nighttime measurements’ disagreements for the canyon soil due to inappropriate choices of physical properties for ground materials.

In this paper, we present the second part of the experimental validation with regard to air temperature and airflow. In Section 1, we will be presenting a quick overview of the principle of the numerical coupling model developed. In Section 2, the EM2PAU In-situ experiment is briefly described. Also, the measurement instruments used during the experiment to measure air temperatures and wind velocities inside the street canyon are presented. The physical boundary conditions modelled from the measurement data specific to the thermodynamic simulation carried out by Code_Saturne are detailed in Section 3.

The 4th Section is devoted to the validation of results. As in surface temperature, we submitted the instantaneous and hourly numerical results of air temperature, mean wind velocity, and turbulent kinetic energy to a “global” validation with the statistical parameters proposed by Chang and Hanna (2004) and “detailed” with the experimental data. Sensitivity tests of the impact of inlet boundary conditions on thermodynamic results are also performed and discussed in this unit. Thus, we list the most impacting input data that affect the quality of coupled simulation and we discuss optimal solutions to reduce the computational cost.

The findings of this study will then be used for further studies aiming to characterize the outdoor thermal comfort for more realistic geometries of Ecodistricts.

2. The numerical coupling model

In urban CFD simulations, homogeneous values of surface temperature are habitually used to compute wind, air temperature and turbulence in the canopy layer (Ramponi et al., 2015 and Liu et al., 2017). On the other hand, a single reference of wind velocity and uniform values are generally used to compute wall and ground temperatures in thermo-radiative models (Idczak et al., 2010 and Hénon et al., 2011). The numerical coupling model developed in this study aims to eliminate these hypotheses by creating a two way information exchange platform between Solene and Code_Saturne software, at each time-step of computation.

The new model is based on the robustness full dynamic coupling strategy (Zhai et al., 2002; Athamena et al., 2018), where the surface temperatures calculated by Solene’s thermo-radiative balance of are introduced in Code_Saturne as boundary conditions. The thermodynamic simulation, carried out by Code_Saturne, computes air temperature and convective exchange coefficients, which are reintroduced in Solene as input data as shown in Fig. 1. The coupling between Solene

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