A systematic methodology for energy modeling improvement of cross-ventilated buildings in dense urban areas

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Abstract. Cross-ventilation strategy is an efficient and reliable method, which has been used in modern zero-energy buildings and traditional buildings for reducing building energy consumption and improving indoor air quality. The accuracy of current models based on building energy simulation (BES) and computational fluid dynamics (CFD) are questionable in dense urban areas. Hence, in this paper, a systematic methodology is introduced aiming to improve the energy modeling accuracy of cross-ventilated buildings in urban areas. The methodology comprises of three main steps for validation metric definition, CFD model calibration, and BES model calibration. The CFD model calibration is based on the stochastic optimization of the closure coefficients while BES model calibration is carried out by using results of the calibrated CFD model and approximation models. The proposed method was applied to a small multi-story building surrounded by eight buildings in a neutral atmospheric boundary layer (ABL) in Rasht city, Iran. According to the results, the accuracy of the modified BES model is 60% higher than the default BES model in prediction of the cross-ventilation energy-saving potential.

1. Introduction
Emerging of megacities as a result of rapid population increase has adverse effects on building energy consumption, city ventilation, and indoor/outdoor air quality [1]. Among different approaches for analysing the interactions between buildings and their surrounding microclimate, building energy simulation (BES) tools and computational fluid dynamics (CFD) are widely used due to their higher flexibility for complex geometries and lower cost in comparison to the field and wind tunnel measurements [2].

BES tools are historically developed for isolated building condition while they utilize very simplified models for convective heat transfer coefficient (CHTC), wind pressure and velocity profiles, and thermal radiation for interpreting the effects of the surrounding microclimate on the target building. 3D distribution of airflow parameters of the urban microclimate can be obtained by CFD models and be used as input and boundary conditions for BES modes in order to achieve higher accuracies. Nevertheless, high computational cost of CFD models limits their utilization for hourly time-steps on yearly-basis thermal calculations.

Despite the popularity of BES-CFD coupled approaches, their applications in dense urban areas are still challenging. On one hand, the accuracy of BES tools in prediction of wind velocity and pressure distributions [3], discharge coefficient [4,5], and CHTCs is very low in dense urban areas. On the other hand, the CFD models struggle to provide accurate results in dense building configurations [6]. This study aims to discuss the applicability of a systematic framework introduced by the authors for increasing the prediction accuracy of coupled BES and CFD models in dense urban areas. In the proposed framework, the CFD and BES models are calibrated using different statistical approaches that are discussed in detail in the following sections.
2. Methodology

In Figure 1, the proposed framework is illustrated graphically. The framework comprises of three steps for the case study definition, CFD model calibration, and BES model calibration.

2.1. Step 1: Case study and validation metric definition

In this step, important parameters and flow features, which have considerable impact on the building thermal performance are identified. Then, available experimental (on-site or wind tunnel measurements) or high-fidelity CFD (e.g., LES) data relevant to the studied case are determined in order to define validation metrics for CFD and BES calibrations.

2.2. Step 2: CFD model Calibration

This step comprises of calibration of the closure coefficients of the turbulence model. As shown in Figure 3, a Monte-Carlo Sampling technique is utilized in order to generate a database of the CFD models based on the probability distribution functions (PDF) of the turbulence closure coefficients. Then, a stochastic optimization model, which is coupled with the CFD solver and Monte-Carlo Sampling model is used to obtain the best values of the closure coefficients, which show the highest CFD accuracy. More details about the CFD calibration can be found in [7].

2.3. Step 3: BES model Calibration

In the final step, the calibrated CFD model and also available high-fidelity or experimental data are utilized in order to calibrate the BES model as shown in Figure 2. The focus of the proposed methodology is to improve the modeling accuracy of BES model for prediction of the local wind velocity profile around the building surfaces, surface wind pressure and CHTC distributions over the exterior walls, and the crossing airflow rate through the building openings.

A proper design of experiment (DOE) method such as adaptive Latin Hyper Cube sampling (LHS) is utilized to generate a database of BES and CFD samples based on different variable, including building, openings, urban geometrical parameters, air temperature, wind direction and speed, etc. The calibrated CFD model is then coupled to the generated database to obtain correlations for CHTC, wind pressure and velocity, openings discharge coefficient, etc. based on appropriate Meta models such as response surface or radial basis functions. The developed Meta models are then transferred to the final BES model as input parameters. Details of this procedure are presented in [8].
3. Outlines of the BES and CFD models for the considered case study

The considered case study is a group of real-geometry of 3-story buildings, which have the same geometry with multiple openings on the second and third floors in a neutral ABL condition located in Rasht city, Iran (see Figure 4).

For CFD model calibration, experimental results from the time-averaged velocity and turbulent kinetic energy (TKE) distributions inside a sheltered cross-ventilated building were used [9]. The standard k-ε model was selected for the CFD calibration. An AMD® processor was used for CFD simulation of a generated database with 250 samples. More details about the closure coefficient calibration and CFD model development can be found in [7]. The CFD model of the real-geometry office building was created using the same setup as the calibrated CFD model while a cylindrical computational domain was created to handle different wind directions [10].

The BES model was developed based on EnergyPlus (E+) and Airflow Network (AFN) models. Then, it was coupled to the CFD model using a static coupling approach. The default value of openings’ discharge coefficients in the AFN model were replaced by an adaptive discharge coefficient correlation obtained by the calibrated CFD model. Moreover, the simplified correlation of the surface-averaged wind pressure in E+ was replaced by the local-surface wind pressure distribution by [11]. Furthermore, a modified correlation of CHTC based on the experimental measurements by [12] was used in E+ model, which was modified by the local wind velocity distribution calculated by the calibrated CFD model.

4. Result and discussion

Figure 5 compares distribution of the TKE over a vertical central plane inside the buildings number B2, B5, and B8 predicted by the standard and calibrated k-ε models. A high TKE level is predicted by the standard k-ε model near the stagnation point of B2 while the TKE is significantly under predicted in the cavities between and inside the buildings. These are well-known deficiencies of the standard k-ε model. In contrast, the TKE prediction by the calibrated k-ε model is significantly lower than the standard k-ε model near the stagnation point while a higher level of TKE is predicted inside the cavities and buildings. This resulted in different predictions for the airflow rate by these models against a wind angle of 0° as shown in Table 1. The relative error of the airflow predictions by the standard and calibrated k-ε models is about 11% and 25% for B1 and B2 buildings, which are subjected to the wind directly, but the error significantly rises to 128% and 159% for B5 and B8 buildings exiting under the sheltering effects of other buildings. The predicted value for the surface-averaged wind pressure difference over the windward and leeward façades of B5 is $\Delta C_P = 0.22$ and $\Delta C_P = 0.51$ for the standard and calibrated k-ε models, respectively while the experimental value is $\Delta C_P = 0.47$. The predicted value by the standard k-ε model is outside the range of the negative and positive extreme values in the experiment, which are respectively $\Delta C_P^{min} = 0.37$ and $\Delta C_P^{max} = 0.84$. 

\[ \begin{align*}
\Delta C_P &= 0.22 \\
\Delta C_P &= 0.51 \\
\Delta C_P &= 0.47
\end{align*} \]
In Figure 6, variation of the energy-saving (ES) potential is shown against different wind angles. The ES potential is defined as the ratio of the building energy consumption when the cross-ventilation is used to the building energy consumption when no cross-ventilation is utilized (i.e., all openings are closed). The first case is based on E+ model with default settings for the surface pressure, opening’s discharge coefficient, and CHTC. The second case is a calibrated E+ model based on the proposed methodology.

When the default E+ model is used, the calculated ES is about 80% against all wind angles. In contrast, different ES values are predicted by the calibrated E+ model against different wind angles, which are significantly lower than the prediction results by the default E+ model. The calculated ES’s by the calibrated model are 60.4%, 59.5%, and 29.9% against the wind angles of 0°, 30°, and 60°, respectively.

Against the wind angle of 60°, difference in the ES predictions by two models is about 50%, which is due to the significant deviation between the prediction results of two models for the local wind velocity profile around the building surfaces, crossing airflow rates of building openings, and wind surface pressure and CHTC distributions over the building walls.

The noticeable difference between the results shows that, even for a simple building configuration used as the case study, very low accuracy results can be obtained when default BES models are utilized for building energy calculations in dense urban areas.

### Table 1. Total airflow rate through the buildings’ openings against the wind angle of 0°

| 𝑄𝑄/𝐴𝐴_𝑉𝑉_ΗΗ | Standards | Calibrated | Error % |
|--------------|-----------|------------|---------|
|              | 𝑘𝑘 – 𝜖𝜖   | 𝑘𝑘 – 𝜖𝜖    |         |
| B2           | 4.96      | 5.59       | 25.26   |
| B5           | 1.05      | 1.67       | 128.27  |
| B8           | 1.37      | 2.33       | 159.06  |

### 5. Conclusion

A systematic methodology was introduced for increasing the accuracy of building thermal performance under urban microclimate interactions. The developed framework is based on the calibration of BES and CFD models by utilization of experimental data and different statistical methods, including design of experiment, stochastic optimization, and approximation models. A case study comprising of a multi-story office building located in a dense urban area was considered and it was shown that the energy-saving potential is significantly overestimated by the default BES and CFD models in comparison to the calibrated BES and CFD models.
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