様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

# 科学研究費助成事業　　研究成果報告書

令和　４ 年　 ９ 月　 １ 日現在

機関番号：１５４０１
研究種目：若手研究
研究期間：2020～2021
課題番号：２０Ｋ１４８８９

研究課題名（和文）Stochastic Model Optimization for Improving the Accuracy and Rapidity of Urban Airflow CFD Simulations

研究課題名（英文）Stochastic Model Optimization for Improving the Accuracy and Rapidity of Urban Airflow CFD Simulations

研究代表者

シルザディ　モハンマッドレザ（Shirzadi, Mohammadreza）

広島大学・先進理工系科学研究科（工）・研究員

研究者番号：４０８６８７３３

交付決定額（研究期間全体）：（直接経費）　　3,300,000円

研究成果の概要（和文）：レイノルド平均ナビエ-ストーク（RANS）乱流モードに基づく計算流体力学（CFD）モデルは、計算コストが低いため、都市大気シミュレーションに頻繁に使用されます。 ただし、ストリートキャニオンの弱風域では精度はそれほど高くありません。 RANSの閉鎖係数のデフォルト値は、他のフィールドから採用されていますが、都市の気流シミュレーションには完全には適していません。 したがって、この研究では、都市CFDシミュレーションの計算精度と速度を大幅に向上させる新しい確率的最適化手法を使用して、RANSの閉鎖係数の最適値を見つけるための体系的なアプローチを提案しました。

研究成果の学術的意義や社会的意義
This research results help the CFD users to increase the accuracy of their numerical prediction and finally can improve the reliability of practical designs in urban applications in cities to have more sustainable and safe cities.

研究成果の概要（英文）：The computational fluid dynamics (CFD) models based on the Reynold-averaged Navier-Stoke (RANS) turbulence modes are frequently used for urban air simulations because of their low computational cost. However, their accuracy is not so high in the weak wind regions in street canyons. The default values of the RANS’ closure coefficients are adapted from other fields, which are not perfectly suitable for urban airflow simulations. Hence, in this study, a systematic approach was proposed to find the optimum values for the RANS’ closure coefficients by using a novel stochastic optimization method to significantly improve the computational accuracy and rapidity of urban CFD simulations. Different benchmarks, ranging from simple buildings to buildings in an actual city were considered to demonstrate the applicability of the proposed framework.

研究分野：wind engineering

キーワード：Urban airflow simulation　Stochastic optimization　Accuracy improvement　CFD　Calibration

## 1. 研究開始当初の背景

Increasing applications of computational fluid dynamics (CFD) in different aspects of urban studies, including pedestrian level wind comfort, building energy, pollution dispersion, and urban heat island, reflects on the importance of this powerful approach in research and practical engineering applications. Current CFD tools for such studies are generally based on the Reynolds-averaged Navier-Stokes (RANS) models and large eddy simulation (LES) approach in which the Navier-Stokes equations are resolved in time and space.

As shown in Figure 1, the performance of urban airflow CFD simulation models, in terms of accuracy, rapidity (computational speed), and their feasibility for engineering applications are quite different while each mode requires a different tempo-spatial resolution. The RANS accuracy is lower than LES, but it has a higher computational speed which is about one order of magnitude higher than LES and higher feasibility. In fact, the very high complexity of detailed boundary condition implementation and mesh generation, in addition to enormous computational cost make LES infeasible for urban airflow simulations. Since in practical engineering applications, several calculation cases for multiple wind directions are required, utilization of LES becomes more limited and challenging. One drawback of RANS for urban airflow simulations is the low accuracy of two-equation RANS turbulence models in the prediction of mean-flow quantities in weak wind regions inside the street canyons and behind buildings. In general, this inaccuracy is resulted from the inaccuracy related to the turbulent-viscosity hypothesis and derived equations for the turbulent parameters, which consist of several unknown coefficients approximated with the observation of a few fundamental flows, including homogenous isotropic decaying turbulence, fully developed channel flow, and simple shear flow. Nonetheless, there is a marginal similarity between these fundamental flows and airflow around buildings in the atmospheric boundary layer (ABL).

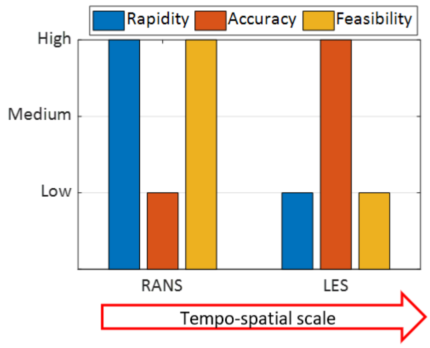

**Figure 1** Comparison of urban CFD models

## 2. 研究の目的

Considering the low accuracy of RANS models in addition to their popularity and practicality in practical engineering problems, an important question that should be answered is: *Is it possible to optimize RANS parameters based on urban airflow physics in an affordable and applicable manner to obtain a significant improvement in RANS CFD accuracy and rapidity?* Hence, the primary objective of this research is to improve the accuracy and rapidity of urban airflow CFD simulations. In specific, a systematic framework for improving the accuracy of two-equation RANS turbulence models will be proposed in which different statistical and approximation models, machine-learning tools, and optimization solvers are utilized to optimize the RANS closure coefficients based on urban airflow physics.

## 3. 研究の方法

A schematic of the proposed framework for RANS CFD model calibration is shown in Figure 2. The framework consists of two main steps. The first step includes four sub-steps: 1-1) Case study definition, 1-2) Determination of focused output parameters, 1-3) High-quality data acquisition, 1-4) Validation metrics calculation for focused output parameters. Through these sub-steps, required data for the closure coefficients calibration are organized systematically by conducting a series of CFD simulations, acquiring high-quality data from different resources, and performing statistical analyses.

In sub-step 1-1, after preparation of the CFD model, e.g., geometry generation, boundary condition implementation, and applying CFD solver settings in accordance with the guidelines by [1,2], a suitable zero equation, one-equation, or two-equation turbulence model will be selected although two-equation models are more popular in urban flow simulations. In sub-step 1-2, the focused output parameters of the CFD model should be chosen for the calibration purpose. For instance, for pedestrian comfort studies, the focused parameters are wind velocity distribution and/or pollution concentration at the pedestrian level, or for building energy evaluations, the focused parameters are wind surface pressures over building walls and/or crossing airflow rate. In sub-step 1-3, high-quality data should be provided to define suitable validation metrics required for the turbulence model calibration obtained from Step 2. At this stage, different sources, including wind tunnel measurement and large eddy simulation (LES), can be used depending on the focused output parameters and the aimed level of accuracy.

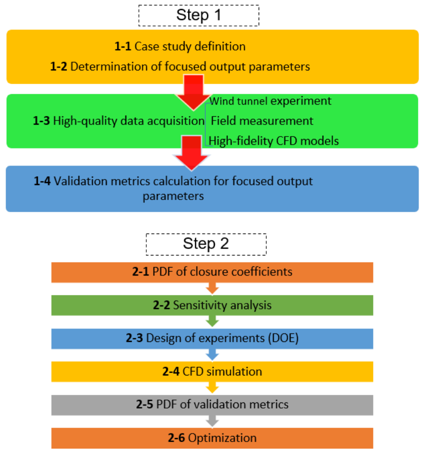


**Figure 2 Framework of RANS CFD models calibration**

After obtaining the required high-quality data, in sub-step 1-4, validation metrics should be employed to quantitatively investigate the level of agreement between the CFD and high-quality datasets. The most common validation metrics for environmental and urban flow studies are those proposed by [3], including the hit rate $q$, fraction of the predictions within a factor of 2 of the observations ($FAC2$), fractional bias ($FB$), and normalized mean square error ($NMSE$).

The second step of the proposed framework includes six sub-steps. In this step, closure coefficients of the selected turbulence model are considered as variables in an optimization process to find the best agreement between the CFD and the acquired high-quality datasets. Hence, the optimization variables are the closure coefficients while the objective function is defined based on a combination of the selected validation metrics. In sub-step 2-1, PDFs of all the closure coefficients are obtained according to available information about the history of model development and experimental data in the literature. As a general consideration, a uniform PDF is a suitable choice as there is not enough statistical information about the closure coefficients of RANS turbulence models. After calculating the PDF of the closure coefficients, in sub-step 2-2, a sensitivity analysis is required to identify the most effective closure coefficients on the CFD accuracy. Sensitivity analysis can be conducted using a simple model such as the one-factor-at-a-time method (OFAT) or a complex one such as Latin Hypercube sampling [4]. In sub-step 2-3, a suitable design of experiment (DOE) method, e.g. Monte Carlo Sampling (MS), is utilized to generate a database for CFD samples according to the PDF of the closure coefficients. Then, the CFD samples are solved in sub-step 2-4, and in sub-step 2-5, CFD results are post-processed to obtain the PDF of the selected validation metrics as well as their mean value and standard deviation. Finally, in sub-step 2-6, an optimization solver is used to find the best set of the closure coefficients according to the calculated validation metrics of the CFD database. An appropriate objective function is defined to minimize the deviation of the validation metrics and their ideal values. For more reliable calibration, stochastic optimization (reliability-based) algorithms can be used in which the objective function involves two terms to minimize (1) the deviation between the mean value of the validation metrics and ideal values, and (2) the standard deviation of the validation metrics. The second term enhances the reliability of the calibration process via reducing the uncertainty of the validation metrics caused by the uncertainty of the closure coefficients.

## 4. 研究成果

The performance of the proposed calibration framework is investigated using three different case studies[5]. A schematic of each case is presented in Figure 3. Case 1 is an isolated high-rise building placed in an unstable ABL. Case 2 is a sheltered building model subjected to a cross-ventilation flow through two openings on its windward and leeward façades. Case 3 consists of a group of 31 low-rise buildings with the same dimensions in a regular arrangement with a planar area ratio of 0.4, which represents a highly-dense urban area.

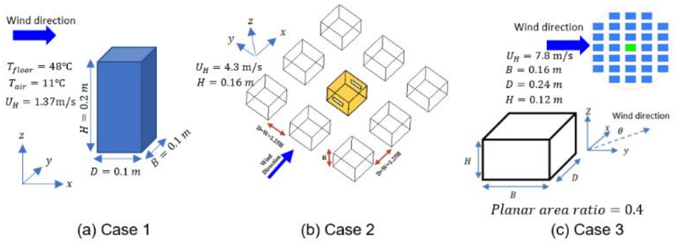


**Figure 3: Schematic of case studies**

In Figur 4, the distribution of turbulent kinetic energy (TKE) around the high-rise building is compared against the experimental measurements over a central vertical plane ($y/H = 0$) and a horizontal plane near the ground ($z/H = 0.025$). The results of the CFD model with the default closure coefficients over the vertical and horizontal planes exhibit two well-known deficiencies of two-equation turbulence models, i.e., a high level of TKE around the windward wall and above the roof, and a significant underprediction of TKE and momentum diffusion inside the wake region behind the building. The calibrated model shows significant improvement in the prediction of TKE level in comparison with the reference model. The TKE level in front of the windward wall is lower than the reference model while it is noticeably higher in the wake region behind the building.

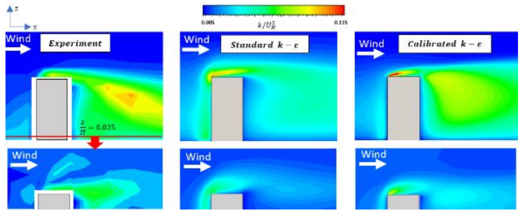

**Figure 4 TKE around the high-rise building**

For Case 2, the vertical profiles of the streamwise velocity over a central vertical plane inside the building model is shown in Figure 5. As it can be seen from the experimental results, a clear windward jet is formed at $x/H = 0.16$ and at $z/H = 0.4$ with a velocity of $U/U_H = 0.1$. In contrast, for the standard k-ε model, the streamwise velocity is almost zero over the vertical line at $x/H = 0.16$ and the model fails to reproduce the windward jet, which is the main feature of the cross-ventilation. The calibrated model successfully predicts the windward jet with a velocity of $U/U_H = 0.12$ at $x/H = 0.16$ and $z/H = 0.4$, which is close to the experimental result. Furthermore, the vertical profiles of the streamwise velocity over the vertical plane far from the windward opening and near the ground show a better agreement between experiments and the calibrated model. Nevertheless, the streamwise velocity at the upper part of the target building is underestimated by both models. It should be noted that the relative deviation between the airflow rate prediction by the standard k-ε model and the experiment is about 100%, while it noticeable decreases to 8% using the calibrated model.

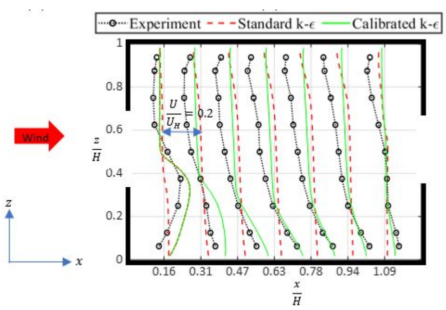


**Figure 5: streamwise velocity over a vertical central plane inside the building**

In Figure 6, the profiles of the surface wind pressure coefficient ($C_P$) along a central line over windward and leeward façades and roof of the target building are plotted against the 0° wind angle for Case 3. Over the windward and leeward façades, between $0 \leq z/H \leq 0.5$, both CFD models underestimate $C_P$ while the calibrated k-ε model calculates more accurate results between $0.5 \leq z/H \leq 1$. In these regions, the standard k-ε model's predictions are far from the experimental results. The superiority of the calibrated k-ε model is more clearly demonstrated by looking at the $C\_P$ variation over the roof, where the pressure recovery along the roof is very well predicted by the calibrated model and a close agreement is obtained with the experimental results. In contrast, a uniform pressure distribution is calculated by the standard k-ε model, which is significantly higher than the experimental result.

Another example of the application of the proposed calibration method for a practical engineering case is explained in the following. The calibration method was used for a case study of the pedestrian level wind environment around high-rise buildings to minimize the high-speed regions [6]. In this study, a multi-fidelity shape optimization framework is proposed for the pedestrian-level wind environment (PLWE). In the proposed framework, low-fidelity computational fluid dynamics (CFD) models based on steady Reynolds-averaged Navier–Stokes equations (RANS) models and high-fidelity CFD models based on large-eddy simulation (LES) are efficiently integrated into the optimization process to improve the optimization reliability while maintaining its computational speed in an affordable range for practical engineering applications. The optimization solver is coupled with an approximation model generated by low-fidelity CFD samples obtained using a design of experiments (DOE) technique. The optimal candidates are then evaluated according to the degree of improvement of the objective function compared to the reference case. If the degree of improvement shows significant deviations between the low-fidelity and high-fidelity models, suitable corrections and modifications are applied to improve the reliability of the optimization process. The applicability of the proposed method was investigated in terms of minimizing the high-wind-speed area, as the optimization objective, around a high-rise building considering (a) uniform urban blocks and (b) real urban blocks with different frequency distributions of wind directions associated with two different local wind climates.

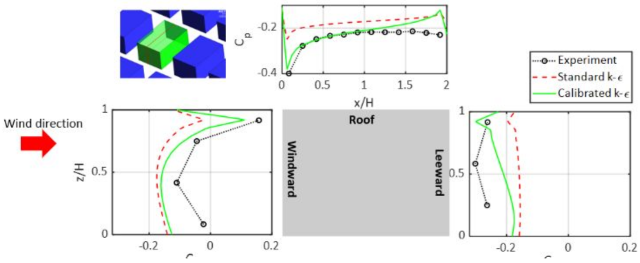

**Figure 6: surface wind pressure coefficient over building surfaces**

Figure 7 shows the distribution of the amplification factor (K) for the optimum building geometry. The distribution of K is calculated by the default RLZ k-ε model (low-fidelity model), calibrated RLZ k-ε model based on the coefficients by (Calibration-1), the final calibrated RLZ k-ε model (Calibration-2), and LES. A comparison between K calculated by the RLZ k-ε model shows a notable underprediction of the high-wind speed areas by the RLZ k-ε model, especially in front of the building near the corners and sidewall. Utilization of the closure coefficients improved the prediction accuracy of the low-fidelity model; however, the area of high-wind speed is lower than that in the case of the LES. Calibration-2, which was obtained using OFAT sensitivity analysis, shows a significant improvement in the prediction of the high-speed wind regions, which is comparable with the LES results in most regions.

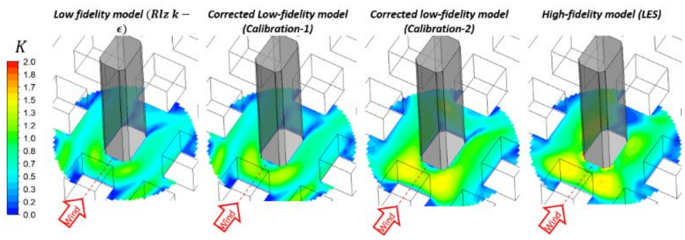

**Figure 7: Distribution of the amplification factor ($K$)**

## References

[1] Y. Tominaga, A. Mochida, R. Yoshie, H. Kataoka, T. Nozu, M. Yoshikawa, T. Shirasawa, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, J. Wind Eng. Ind. Aerodyn. 96 (2008) 1749–1761.

[2] J. Franke, A. Hellsten, H. Schlünzen, B. Carissimo, Best Practice Guideline for the CFD Simulation of Flows in the Urban Environment. COST Action 732: Quality Assurance and Improvement of Microscale Meteorological Models, Hamburg, Ger. (2007).

[3] M. Schatzmann, COST 732 model evaluation case studies: approach and results, Meteorological Inst., 2010.

[4] D.C. Montgomery, G.C. Runger, N.F. Hubele, Engineering statistics, John Wiley & Sons, 2009.

[5] M. Shirzadi, P.A. Mirzaei, Y. Tominaga, RANS Model Calibration Using Stochastic Optimization for Accuracy Improvement of Urban Airflow CFD Modeling, J. Build. Eng. (2020) 101756.

[6] M. Shirzadi, Y. Tominaga, Multi-fidelity shape optimization methodology for pedestrian-level wind environment, Build. Environ. 204 (2021) 108076.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　0件／うち国際共著　0件／うちオープンアクセス　0件）

| 1．著者名 | 4．巻 |
|---|---|
| Shirzadi Mohammadreza、Mirzaei Parham A.、Tominaga Yoshihide | 13 |
| 2．論文標題 | 5．発行年 |
| CFD analysis of cross-ventilation flow in a group of generic buildings: Comparison between steady RANS, LES and wind tunnel experiments | 2020年 |
| 3．雑誌名 | 6．最初と最後の頁 |
| Building Simulation | 1353～1372 |
| 掲載論文のDOI（デジタルオブジェクト識別子） | 査読の有無 |
| 10.1007/s12273-020-0657-7 | 無 |
| オープンアクセス | 国際共著 |
| オープンアクセスではない、又はオープンアクセスが困難 | － |

| 1．著者名 | 4．巻 |
|---|---|
| Shirzadi Mohammadreza、Mirzaei Parham A.、Tominaga Yoshihide | 32 |
| 2．論文標題 | 5．発行年 |
| RANS model calibration using stochastic optimization for accuracy improvement of urban airflow CFD modeling | 2020年 |
| 3．雑誌名 | 6．最初と最後の頁 |
| Journal of Building Engineering | 101756～101756 |
| 掲載論文のDOI（デジタルオブジェクト識別子） | 査読の有無 |
| 10.1016/j.jobe.2020.101756 | 無 |
| オープンアクセス | 国際共著 |
| オープンアクセスではない、又はオープンアクセスが困難 | － |

| 1．著者名 | 4．巻 |
|---|---|
| Tominaga Yoshihide、Shirzadi Mohammadreza、Inoue Sho-ichi、Wakui Tomoharu、Machida Takashi | 180 |
| 2．論文標題 | 5．発行年 |
| Computational fluid dynamics simulations of snow accumulation on infrared detection sensors using discrete phase model | 2020年 |
| 3．雑誌名 | 6．最初と最後の頁 |
| Cold Regions Science and Technology | 103167～103167 |
| 掲載論文のDOI（デジタルオブジェクト識別子） | 査読の有無 |
| 10.1016/j.coldregions.2020.103167 | 無 |
| オープンアクセス | 国際共著 |
| オープンアクセスではない、又はオープンアクセスが困難 | － |

| 1．著者名 | 4．巻 |
|---|---|
| Shirzadi Mohammadreza、Mirzaei Parham A.、Tominaga Yoshihide | 209 |
| 2．論文標題 | 5．発行年 |
| LES analysis of turbulent fluctuation in cross-ventilation flow in highly-dense urban areas | 2021年 |
| 3．雑誌名 | 6．最初と最後の頁 |
| Journal of Wind Engineering and Industrial Aerodynamics | 104494～104494 |
| 掲載論文のDOI（デジタルオブジェクト識別子） | 査読の有無 |
| 10.1016/j.jweia.2020.104494 | 無 |
| オープンアクセス | 国際共著 |
| オープンアクセスではない、又はオープンアクセスが困難 | － |

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　0件）

| |
|---|
| 1．発表者名<br>Mohammadreza Shirzadi，富永禎秀 |
| 2．発表標題<br>CFD analysis of cross-ventilation of a sheltered building: Comparison between SRANS and LES |
| 3．学会等名<br>2020年度日本建築学会大会学術講演梗概集（関東） |
| 4．発表年<br>2020年 |

| |
|---|
| 1．発表者名<br>富永禎秀，Mohammadreza Shirzadi |
| 2．発表標題<br>ステレオ PIV による境界層流中におかれた高層建物モデル後方循環流の計測 |
| 3．学会等名<br>2020年度日本建築学会大会学術講演梗概集（関東） |
| 4．発表年<br>2020年 |

〔図書〕　計0件

〔産業財産権〕

〔その他〕

新潟工科大学 風・流体工学研究センター
https://www.niit.ac.jp/windcenter/

6．研究組織

| | 氏名<br>（ローマ字氏名）<br>（研究者番号） | 所属研究機関・部局・職<br>（機関番号） | 備考 |
|---|---|---|---|

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

| 共同研究相手国 | 相手方研究機関 |
| --- | --- |