International Journal of Heat and Mass Transfer 118 (2018) 758–772

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Modelling enhancement of cross-ventilation in sheltered buildings using stochastic optimization

Mohammadreza Shirzadi [a], Parham A. Mirzaei [b,*], Mohammad Naghashzadegan [a], Yoshihide Tominaga [c]

[a] Mechanical Engineering Department, University of Guilan, Rasht, Iran
[b] Architecture and Built Environment Department, University of Nottingham, Nottingham, UK
[c] Department of Architecture and Building Engineering, Niigata Institute of Technology, 1719 Fujihashi, Kashiwazaki, Japan

ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form 10 October 2017
Accepted 27 October 2017

Keywords:
CFD
Cross-ventilation
Turbulence
Optimization
Sheltered building

ABSTRACT

Accurate representation of turbulence phenomenon in Computational Fluid Dynamics (CFD) modeling of cross-ventilation around and inside buildings is a challenging and complex problem, especially under the sheltering effect of surrounding buildings. Steady Reynolds Averaged Navier-Stokes (RANS) models are broadly used in many practical applications. However, these models mainly fail to predict accurate distribution of flow characteristics in the cavity formed between the buildings, and hence miscalculate the attributed cross flow and airflow rate through buildings. In this study, a novel and systematic methodology is proposed to enhance the accuracy of the $k-\varepsilon$ model for the urban study applications such as cross-ventilation in the sheltered buildings.

A microclimate CFD model for a case study of a cross-ventilation experimental work by Tominaga and Blocken (2015) was firstly constructed and validated. In the next step, the closure coefficients of the $k-\varepsilon$ model were modified using a stochastic optimization and Monte Carlo Sampling techniques. The probability density function (PDF) of all closure coefficients were given to the optimizer and proper objective function defined in terms of different validation metrics. The modified coefficients obtained from the developed systematic method could successfully simulates the cross-ventilation phenomena inside the building with an airflow rate prediction error less than 8% compared to the experiment while other RANS models predicted the airflow rate with up to 70% error. The effectiveness of the optimization technique was also discussed in terms of validation metrics and pressure coefficients.

1. Introduction

Buildings account for about 40% of total final energy consumption in the US and European countries [2]. Increasing rate of industrialization and urbanization, and emerging of more mega cities indicate the importance of integration of the energy saving strategies into the modern buildings [3]. Natural ventilation has been extensively used in traditional and modern buildings to improve thermal comfort and air quality [4,5], and to decrease the cooling energy demand of buildings. Moreover air quality of dwellings and comfort level of occupants can be significantly enhanced by utilizing natural ventilation strategies [6]. Nonetheless, accurate design of buildings to benefit from these natural ventilation strategies highly depends on a reliable prediction of the airflow parameters, crossing through buildings.

Different analytical and empirical models were developed in the last three decades to characterize natural ventilation in buildings. As descripted in [7], these methods include small-scale or full-scale experimental test, multi-zone and Computational Fluid Dynamic (CFD) models. In the recent years due to an exponential growth in the computational capability of the processors, application of the CFD models in wind-driven related topics such as cross-ventilation [8–10], energy prediction [11–15], pedestrian level ventilation [16,17], pollution dispersion [18], and wind-driven vehicles [19] has been noticeably surged. Most of the microclimate CFD studies adapted Reynolds-averaged Navier Stokes (RANS) as their turbulence models. The number of large eddy simulations (LES) [20–23] and unsteady Reynolds-averaged Navier Stokes (URANS) [17,24] studies are considerably less due to the limitation of these models in terms of high computational cost and complexity. Therefore, steady RANS models are recognized as reliable and low cost simulation techniques, which are commonly accepted in the wind-driven CFD studies.

* Corresponding author at: University Park, Nottingham NG2RD, UK.
E-mail address: Parham.Mirzaei_Ahranjani@nottingham.ac.uk (P.A. Mirzaei).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.107
0017-9310/

Nomenclature

ρ	density
t	time
x_i	three components of the spatial coordinate ($i = 1$, streamwise (x); $i = 2$, lateral (y); $i = 3$, vertical (z))
U_i	three components of the mean velocity vector ($i = 1$, streamwise; $i = 2$, lateral; $i = 3$, vertical)
τ_{ij}	viscous stress tensor
S_{M_i}	momentum source
μ_t	turbulent viscosity
δ_{ij}	Kronecker delta function
k	turbulent kinetic energy
P	pressure
μ_{eff}	effective viscosity
C_μ	$k-\varepsilon$ model constant
μ	molecular viscosity
ε	turbulent dissipation rate
P_k	shear production term
D	building length
U_H	inflow mean streamwise velocity at building height H
H	building height
α	power-law exponent
q	hit rate
N	number of data points
O_i	observed value
P_i	predicted value
FB	fractional bias
$FAC2$	fraction of the predictions within a factor of 2 of the observations
$NMSE$	normalized mean square error
u_i	three components of the fluctuating velocity vector ($i = 1$, streamwise; $i = 2$, lateral; $i = 3$, vertical)
σ_k	$k-\varepsilon$ model constant
σ_ε	$k-\varepsilon$ model constant
$C_{\varepsilon 2}$	$k-\varepsilon$ model constant
$C_{\varepsilon 1}$	$k-\varepsilon$ model constant
W	building width
C_p	pressure coefficient

In general, cross-ventilation researches can be classified into two categories of unsheltered or isolated (generic) building and sheltered scenarios where the effect of flow distraction caused by surrounding buildings or other environmental obstacles is also considered. Acceptable accuracy of CFD modeling of cross-ventilation for unsheltered scenario was reported in many researches. In the works presented by Ramponi and Blocken [8], Tepner et al. [9], van Hooff et al. [25], and Yusuf and Mirzaei [26] RANS and LES models were successfully applied to the unsheltered building scenario. Many studies also considered the sheltering effect of the neighborhood buildings on the airflow inside a building and around it at the pedestrian level [6,17,22,27–34]. The complexity of the turbulent flow in the case of sheltered building was demonstrated in these studies while detailed representation of surrounding environment was emphasized. The complexity of the sheltering effects in CFD simulations is still a challenging issue for CFD users and it can be concluded that the accuracy of CFD models for sheltered buildings requires significant improvement.

Due to the high complexity of URANS and LES models along with their inherent high computational cost, many of the above mentioned studies utilized RANS models for the turbulence modelling. However, these models mainly fail to predict accurate distribution of the turbulent kinetic energy (TKE), specifically for the sheltered building and street canyon airflow scenarios. As described in [35–38], the RANS turbulence models are generally showing poor accuracy in the modeling of the flow separation over the roof and the wake region behind the buildings. This is mainly due to the inaccurate prediction of the momentum diffusion in the wake region inside the street canyon and behind the buildings. Also, the RANS turbulence modes are not inherently able to simulate the unsteady fluctuations around the building, which has a noticeable impact on the momentum diffusion in the wake region behind building [35]. This major limitation in the modeling of the TKE results in an inaccurate cross-ventilation pattern inside the studied sheltered building. Despite some valuable guidelines for cross-ventilation modeling of unsheltered buildings using the RANS models, e.g. [8], a similar comprehensive study for the sheltered building scenarios cannot be addressed. A few existing studies such as [22] are based on the highly expensive and complex LES models. Although some of the existing investigations utilized the RANS models in their study for cross-ventilation of generic buildings, e.g. [27,39], the developed CFD models are mainly validated with the experimental data obtained from the unsheltered building scenarios.

Despite many modifications performed on the RANS turbulence models, e.g. *RNG* $k-\varepsilon$ [40] and Realizable $k-\varepsilon$ [41,42], their application for the atmospheric boundary layer (ABL) flow modeling does not necessary provide accurate results [43]. In addition to the poor accuracy of these RANS models in predicting the momentum diffusion, there is another limitation related to the closure coefficients used in these models. This drawback is associated with the fact that the closure coefficients are mainly obtained based on different experimental and empirical data analyses found from the fundamental and classical flow problems, e.g. homogeneous decaying turbulence, free shear flow, and fully developed channel flow [44]. Nonetheless, such flows have limited similarities with the airflow characteristics in the ABL. Therefore, it can be concluded that there is an inherent uncertainty in these coefficients, and as demonstrated in [44,45], the flow-independent values for these coefficients are unlikely to exist.

Modification of the closure coefficients has been done previously in different CFD applications. Weihing et al. [46] investigated the turbulent heat transfer phenomenon in a heated channel with periodic surface ribs in which commonly used closure coefficients of RANS models fail to predict the massively separated flow behavior and turbulent heat flux. They showed the superiority of the full differential transport closures to the eddy-viscosity closures in capturing rapidly-evolving flow and thermal field. In another work by Shams et al. [47], the limitations of the eddy-viscosity model for turbulent heat transfer prediction in low-Prandtl fluids were investigated while a set of new correlations and closure coefficients were proposed for natural and mixed convection regimes using an algebraic heat flux model (AHFM) and low-Reynolds $k-\varepsilon$ model. In the work presented by Duynkerke [48], the closure coefficients of the standard $k-\varepsilon$ model were modified based on a comparison with a LES simulation and a measurement study for neutral and stable ABL flows over a flat terrain. The value of the modified closure coefficients in this study were obtained to be $C_\mu = 0.033$, $C_{\varepsilon 1} = 1.46$, $C_{\varepsilon 2} = 1.85$, $\sigma_\varepsilon = 2.38$, and $\sigma_k = 1$. A similar study by Detering and Etling [49] was done in which modified closure coefficients were presented for mesoscale ABL simulation above flat and complex terrain. In the recent years, thanks to the increased computational power, statistical techniques have been used by some researchers to calibrate the closure coefficients of the RANS