J. Wind Eng. Ind. Aerodyn. 142 (2015) 149–163

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

A Cartesian grid refinement method for simulating thermally stratified urban environments

Dionysios Angelidis [a,c,*], Vasiliki D. Assimakopoulos [b], George Bergeles [c]

[a] St. Anthony Falls Laboratory, Department of Civil Engineering, University of Minnesota, 2 Third Avenue SE, Minneapolis, MN 55414, USA
[b] National Observatory of Athens, Institute of Environmental Research and Sustainable Development, I.Metaxa & V.Pavlou, 15236 Athens, Greece
[c] Laboratory of Innovative Environmental Technologies, School of Mechanical Engineering, National Technical University of Athens, Zografos Campus, 15710 Athens, Greece

ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form
8 February 2015
Accepted 23 March 2015

Keywords:
Urban environment
Atmospheric stability
Street canyon
Thermal stratification
Cartesian grid refinement
m-ADI solver

ABSTRACT

The capability to accurately simulate thermally stratified environments highly depends on the numerical model which governs the physical problem, but also on the temporal and spatial discretization resolution. This paper presents a multi-resolution Cartesian mesh refinement method for solving the incompressible Navier–Stokes equations, while the standard k–ε turbulence model is employed to resolve stratified turbulent flows. Hanging nodes are used to facilitate the implementation of high order discretization schemes and the algebraic system of the discretized differential equations is solved with a generic modified Alternating Direction Implicit (m-ADI) method developed to resolve locally refined grids. The overall performance of the new flow solver is initially evaluated against experimental data related to the laminar flow past a square cylinder for Reynolds numbers, defined based on the mean ambient wind speed and the characteristic length scale, of $87 \le Re \le 250$ and neutral thermal stratification. The unsteady character of the flow field is successfully predicted and the grid refinement approach enables accurate low cost and low blockage simulations. The flow solver is applied to simulate the flow over thermally stratified idealized urban areas. Good agreement with experimental measurements, where the bulk Richardson number was defined based on the mean wind speed at the top of the reference street canyon, is obtained for $-0.21 \le R_b \le 0.78$ while the grid refinement method allowed simulation of the experimental setup in detail, including all the roughness elements and the idealized street canyons. The numerical calculations indicate that even weak thermal stability can lead to laminarization of the induced flow field; reducing at the same time the potential for air mixing and results to air degradation. Even though the recirculation patterns are influenced under weak thermal stratification, extreme thermal instability within the region of $-16 \le R_b \le -64$ with $Re = 6800$ results to the development of two counter-rotating vortices of equivalent kinetic energy. However, the linear correlation of the average kinetic energy at the roof-level with the R_b number indicates that the buoyancy forces determine the air mixing levels.

1. Introduction

Urban air pollution is an ongoing problem with significant impacts on human health and climate. The still increasing urban population and traffic volume put further pressure on the densely built and poorly ventilated urban areas that suffer from stagnant conditions, areas of high pollutant concentrations and the urban heat island effect. Understanding flow and dispersion in urban streets is therefore of paramount importance for the systematic air quality monitoring, management and planning (Carpentieri and Robins, 2010). The wind field and pollutant dispersion characteristics within clusters of buildings have been the subject of numerous studies. Initially, Gaussian plume models (Hout van den and Baars, 1988; Benson, 1992) were developed and used for concentration estimation because they were simple, quick and required minimum computational power. However, they could not reconstruct the complex wind field between building configurations.

Computational fluid dynamics (CFD) codes are able to predict relatively accurately the wind field, the pollutant dispersion patterns and the convective heat transfer. Scaperdas and Colvile (1999) used the StarCD code to appraise the significance of air quality measurements at an intersection of typical street canyons and a few years later (Assimakopoulos et al., 2003) used the microscale model MIMO to investigate the influence of 2D building geometrical

* Corresponding author.
E-mail address: dennis.angelidis@gmail.com (D. Angelidis).

http://dx.doi.org/10.1016/j.jweia.2015.03.012
0167-6105/

configurations on the atmospheric pollutant dispersion. The standard k–ε turbulence model was also implemented by Xie et al. (2005), who studied the pollutant dispersion from vehicle exhausts in a 2D urban street canyon. They found this model to be optimum against the RNG (Yakhot and Orszag, 1986) or the Chen and Kim (1987) modified k–ε models. Xie et al. (2006, 2007) used the commercial CFD code FLUENT to investigate the natural ventilation potential of 2D idealized street canyons and concluded that the different k–ε models provide comparable results for buoyancy induced flows. The same software was used by Buccolieri et al. (2009) who studied the effects of avenue-like tree planting on flow and pollutant dispersion of traffic exhausts in urban street canyons (Cheng et al., 2009). Angelidis et al. (2012) performed 3D URANS simulations to calculate the time scale characteristics of turbulent flows in organized cubic idealized buildings and recently, Allegrini et al. (2014) investigated the performance of CFD simulations for buoyant flows in urban street canyons. They concluded that the accuracy of the results for the flow profiles inside the street canyon highly depends on the grid resolution and the capability to predict the shear layer accurately. LES calculations can provide accurate simulations in typical street canyons and allow the reproduction of the fluctuating pollutant concentration (Tominaga and Stathopoulos, 2011). Recent works demonstrate that mesh adaptivity for RANS or LES calculations can enable accurate multi-resolution simulations in and around urban areas (Aristodemou et al., 2009; Nezis et al., 2011). However, the accuracy of LES calculations highly depends on the computational grid's resolution as the filter width defines the resolved scales.

The previous works indicate that even though CFD calculations can provide important physical insight of the flow mechanisms in and around urban areas, multi-resolution calculations could enable high fidelity simulations on large computational domains with low computational cost. Hence, the purpose of this work is to present a fully unstructured Cartesian flow solver that provides the capability of adaptive mesh refinement around regions of special interest. The solution of the incompressible Navier–Stokes equations, coupled with the standard k–ε turbulent model, on locally refined grids allowed to get physical insight of the complex mechanisms induced in thermally stratified environments. Concerning the numerical methodology, a fully unstructured grid layout is adopted in order to avoid any flux mismatch or pressure discontinuity issues across fine/coarse interfaces (Papadakis and Bergeles, 1999; Anagnostopoulos, 2003). The formulation of the discrete equations facilitates the utilization of high order discretization schemes and the method can be extended to solve the governing equations on non-isotropically refined 2D or 3D grids. The fully unstructured implementation and the storage of all the dependent variables in one-dimensional vectors give the potential of optimum load balance in parallel calculations. Moreover, the concept of the Alternating Direction Implicit (ADI) method (Peaceman and Rachford, 1955) is extended to the new modified Alternating Direction Implicit (m-ADI) solver; the latter enables the employment of the Tridiagonal Matrix Algorithm (TDMA) (Atkinson, 1989) on locally refined meshes. The flow solver is validated against the unsteady flow around a square cylinder. Finally, the cases of flow under stable, weak and strong unstable conditions over idealized urban canyons are investigated with the new solver.

The structure of the current paper is as follows: The first part is devoted to describing the mathematical model and the discretization of the governing equations on unstructured Cartesian grids. The algorithmic part is completed with the description of the modified Alternating Direction Implicit (m-ADI) solver adapted for resolving unstructured meshes. After validating the flow solver against the unsteady flow around a square cylinder, the effect of weak thermal stratification, including both stable and unstable conditions, within idealized symmetric street canyons, is studied. The current work finally investigates the effect of extreme thermal stratification over idealized urban areas and the air mixing potential which is governed by the buoyancy forces.

2. A local grid refinement model to simulate stratified urban environments

Two decades ago (Coelho et al., 1991) presented a two-dimensional numerical model for solving the Navier–Stokes equations on unstructured grids. They adopted strong coupling between all the dependent variables between overlapping grids with different refinement levels and they demonstrated the capability of accurate and fast numerical calculations. Chen et al. (1997) introduced the idea of structured adaptive mesh refinement (S-AMR) and solved the governing equations on overlaid structured grids. By doing so, grids belonging to different levels are decoupled and resolved iteratively, while under-relaxation is required when transferring information between the various levels of grid refinement. In the work of Papadakis and Bergeles (1999), the incompressible Navier–Stokes equations were discretized on a staggered grid layout and the strong coupling between successive levels of refinement ensured the robustness of the algorithm. The computational efficiency of the grid refinement method was quantified and found to be in line with Coelho et al. calculations. Theodorakakos and Bergeles (2001) developed an adaptive mesh refinement methodology and utilization of hanging nodes facilitated the implementation of higher-order discretization schemes. Their work was then extended to perform two-phase Volume Of Fluid (VOF) flow calculations on grids adapted around moving liquid drops (Theodorakakos and Bergeles, 2004). Based on the previous works, Anagnostopoulos (2003) proposed an efficient method according to which no restriction of the arrangement and the aspect ratio of the control volumes exists. Thus, inclusion of adaptive refinement criteria provided additional flexibility to the calculations. Most recent Cartesian grid refinement approaches are based on hierarchical locally refined algorithms (Chetverushkin et al., 2008). Structured adaptive mesh refinement strategies, where several nested and overlapped patches employ hierarchically refined blocks, are managed with the most popular open source packages, like PARAMESH (MacNeice et al., 2000) and SAMRAI (Griffith et al., 2007) toolkits. Vanella et al. (2010) demonstrated the robustness of such an approach for fluid–structure interaction problems and either transitional or turbulent flow regimes, coupling LES with locally refined grids. Recently, an Adaptive Mesh Refinement (AMR) flow solver, based on a hybrid staggered/non-staggered unstructured grid layout, was developed to perform 3D LES calculations for wind turbine simulations (Angelidis and Sotiropoulos, 2015).

2.1. Mathematical model

In the present study the Reynolds-Averaged Navier Stokes equations (RANS) are discretized on 2D structured or unstructured Cartesian grids, adopting a collocated grid arrangement for the velocity components and a finite volume discretization scheme. The governing equations are successfully coupled and resolved using the SIMPLE algorithm and the Rhie–Chow pressure correction formulation (Rhie and Chow, 1983). Thus, the mass conservation is

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

and the momentum equation is derived as

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial(\overline{u_i}\,\overline{u_j})}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial \overline{\tau_{ij}}}{\partial x_j} - \frac{\partial}{\partial x_j}\overline{u_i' u_j'} + f_{Bi} \tag{2}$$