MODELING AND ANALYZING FLOW TO PRODUCE STRATIFIED FLOW BY EXERTING IT OVER THREE DIMENSIONAL COMPLEX TERRAINS

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ABSTRACT

The aim of this project is to produce stratified flow based on numerical model by exerting a flow over three dimensional complex terrains. The main reason this stratified flow is rarely found in the many engineering practical experiments is due to the difficulties to initiate stratified flow in the initial state of the flow. This factor is assessed and various setups of the model are examined to consider the accuracy attained.
The flow performance is tested over a number of terrain types: skyscrapers, trees and mountains. The standard k-ε (epsilon) turbulent model has been used in CFD setup to help the simulation processes. The mesh discretization has been analyzed for sensitivity change and to obtain grid independent. The velocity value with different magnitudes has been given to each model.
The simulation is shown to perform well for all terrain types. The result shows that flow is stratified leaving each terrains. The stratified flow produced by exerting flow over each terrain types has different velocity distribution profile. The results also shows that the velocity distribution behind each terrain is slowly stable by the distance increases and will resume to its initial velocity distribution profile at certain distance.

Keywords: terrain, stratified flow, CFD

I. Introduction

Stratified flow is a flow that consists of layers in which flow velocity for each layers has different value. The term "stratified flow" is commonly used to denote the flow of "stratified fluid", or more correctly "density-stratified fluid". In such fluids the density (mass per unit volume) varies with position in the fluid, and this variation is dynamically important[1].

Researches and extensive investigations about stratified flow have emerged due to its important practical applications in the area of power, mechanical and civil engineering, oceanography, meteorology. Many articles which are related to stratified flow may be found in existing literatures; both theoretical and experimental investigations have been carried out by several researchers[2-10]. Study about stratified flow has been recently driven by atmospheric considerations more than others although subject of stratified flows is relevant to many engineering fields. The study of stratified flow has wide broad of reasons. In term of oceanography as well as meteorology, stratified flow has been studied analytically and monitored experimentally. In this case fluids (stratified flow) will generate wakes when the flow passes an obstacle. The daily example of this phenomenon in application can be seen in stratified flow over orography which generates vortices or *lee vortices*[11]. The most famous case is Melbourne eddy, where the lee vortices re-circulates the air and carries pollutant in its flow and thus has important consequences for local air quality. Orography vortices are also linked with initiation and intensification of severe weather. Recent study in Colorado shows that vortices are responsible in initiation of severe storms, floods, and tornado. In another example, study of flow which passes the Mt Alp suggest that wakes may interact with upper-level troughs produce synoptic-scale lee cyclones. In mechanical engineering aspect, stratified flow can be related to wind power examination. The study about this has been performed by Paul Stangroom[7].

None of the fluid flows in uniform velocity. There are several factors which influence the flow to become stratified, anyway there is no absolute reason why flow becomes stratified. Air flowing on earth is very complex. There are many factors which influence the flow of air, for example the influence from earth itself such as complex terrains. Complex terrains compose earth surface and give significant effects to flowing air (wind). The influence of the terrain and surface roughness are considerable in the inner region of the boundary layer[13,14,16,17]. The roughness of an area is determined by

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the size and distribution of the roughness element it contains. The variation in terrain height, due to mountains, valleys or building has effect on the flow creating features such as separation, recirculation and variable pressure gradient. The velocity profile of a flow will change as long as obstacles exist. However, this effect only occurs near to the obstacle whereas at far region from obstacle, flow remains unaffected. Flow that moves over obstacle will accelerate on the crest and generate maximum velocity value. Separation caused by obstacle, produces stratified flow behind the obstacle. But distance also determines how far the stratification can be occupied. Stratification is also determined by its physical properties such as viscosity, pressure and heat. The viscosity has an influence to the flow regime which is related to the Reynolds numbers[12)].

Scientists and researchers have been doing many practical experiments regarding effects of stratified flow which may occur for certain cases. The use of wind tunnel has been increasingly performed to analyze and examine many prototypes for aerodynamic reasons. But numbers of computational methods are also being popular to study a flow. Bert Blocken in research of Numerical Simulation of Wind Flow around Building tried to examine a flow over building with different formation of building [4)]. He also gave angle variation of wind attack. He analyzed wind rises at the ground level because of flow past a high-rise building. The similar research was conducted by Andreas Bechmann (2006) in research of Large-Eddy Simulation of Atmospheric Flow over Complex Terrain [3)]. He examined the wind power and analyzed velocity distribution behind the obstacle. He added more obstacles in his research that was askervin hill in England and he used LES model in CFD sets up. In association of examining wind power and analyzing flow over complex terrains accompanied with stratification effects, there was Paul Strangroom (2004) in his research of CFD Modeling of Wind Flow over Terrain [7)]. Paul added more numerical models into his research and compared the results with wind tunnel data. He also collected real data of wind flow to set real condition in his research. The data itself were taken using several anemometers. Several scientists who performed almost similar research, were Allan Russell (2009), Alexander Baklanve and Branko Grisigino (2007), Richard Dewey (2005), Maarten H.P Abaum and David P. Marshall (2004) [2,17,8,6)]. Those people related their research with numerical models by using different types of obstacles.

Using of CFD in modeling a flow has become popular. CFD is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems involving fluid flows. CFD is fundamentally derived from Navier Stoke Equation. In CFD, it is possible to model several types of flow. However in CFD, the velocity of flow at initial state is always uniform. The modeling for stratified flow is still under developments but different methods have been proposed. Most of these methods are good in maintaining a sharp interface at conserving mass. This is crucial since the evaluation of the density, viscosity and surface tension in based on the values averaged over the interface. Therefore, normally an obstacle is used during simulation to produce stratified flow.

The use of obstacle always is followed by turbulent regime. In CFD, there are several turbulent models which can be used to examine a flow. The standard k-ε model is the simplest “complete models” of turbulence and it allows two equation model in which the solution of two separated transport equations allows the turbulent velocity and length scales to be independently determined. The standard *k-ε* model of turbulence has become the workhorse of practical engineering flow calculation. Robustness, economy and reasonable accuracy for wide range of turbulent flows explain its popularity in industrial flow [20)].

II. Modeling

1. Standard K-ε turbulent equations

The standard k-ε model is a semi-empirical model based on model transport equations for the turbulent kinetic energy *(k)* and its dissipation rate *(ε)*. The turbulent kinetic energy *(k)* and its dissipation rate *(ε)* are obtained from the following equations[18)]:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right]+G_k+G_b-\rho\varepsilon-Y_M+S_k \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+C_{1e}\frac{\varepsilon}{k}(G_k+C_{3e}G_b)-C_{2e}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \qquad (2)$$

$$\mu_t=\rho C_\mu\frac{k^2}{\varepsilon} \qquad (3)$$

$$k=\frac{3}{2}(u_{avg}I)^2 \qquad (4)$$

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$$\varepsilon = C_{\mu^{3/4}} \frac{k^{3/2}}{\ell} \tag{5}$$

$$I = \frac{u'}{u_{avg}} = 0.16\,(\mathrm{Re}_L)^{-1/8} \tag{6}$$

$$\ell = 0.07\,L \tag{7}$$

2. Terrain Types

Three terrain types are used to accomplish the purposes. Terrains are created in software *GAMBIT*[20]. Selection in creating terrain is according to the object on earth which currently relates to many researches about stratified flows. These terrain types are listed as follows:

a. Skyscrapers

The skyscrapers are created with a 1:100 scale. They are subsequently arranged with certain distance from one to another. The skyscrapers are created in form of cube which contains 3 different sizes. The skyscrapers are illustrated as follows:

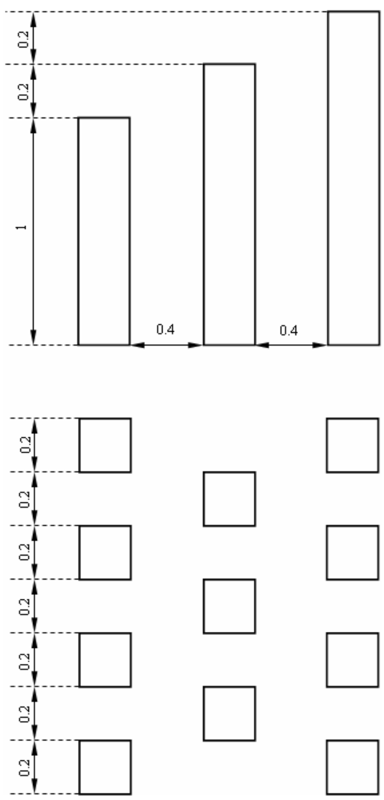

Fig. 1 Skyscrapers in orthogonal drawing

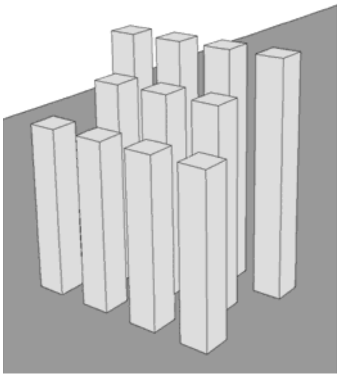

Fig. 2 Skyscrapers model in three dimensional view

b. Trees

The trees are created with a 1: 25 scale. They are arranged almost resemblance the skyscrapers formation which was previously made as the first terrains. The trees also contain three different sizes and are illustrated as below:

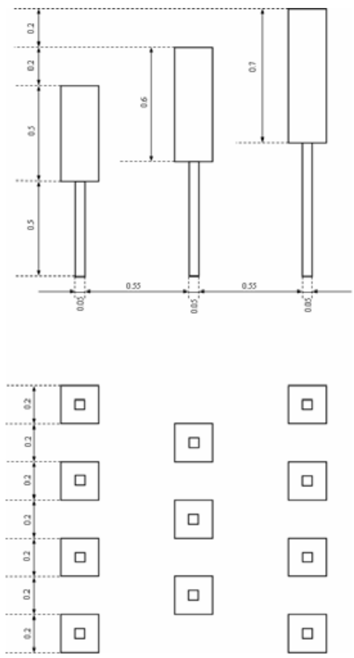

Fig. 3 Trees in orthogonal drawing

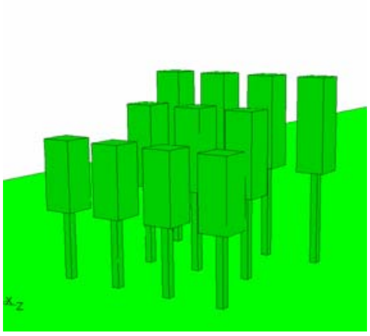

Fig. 4 Trees model in three dimensional view

c. Mountains

The mountainous terrains are created with a 1:2000 scale. The mountains also constitute of three different sizes and are arranged adjacent one to another. The mountain itself is illustrated as follows:

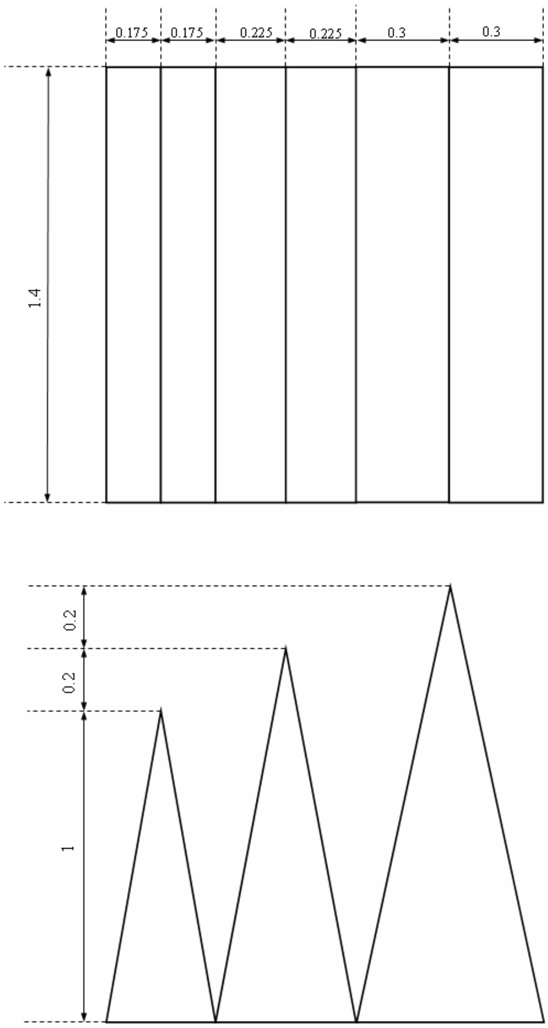

Fig. 5 Mountains in orthogonal drawing

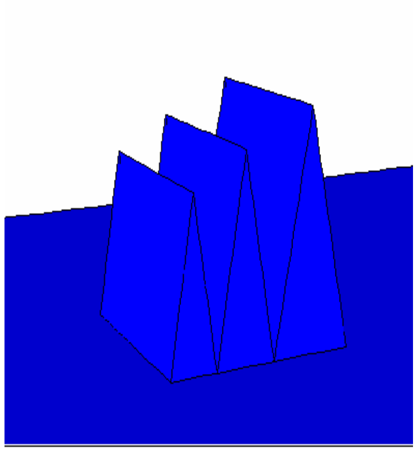

Fig. 6 Mountains model in three dimensional view

3. Grid Sensitivity

A widely used term in numerical modeling is 'grid independence'. When spatial discretization errors are zero, the grid is said to be independent, and if more nodes are added to the domain, no improvement in the accuracy of the result will occur.

The skyscrapers are used to accomplish the purpose of grid independent. The model is meshed with tree different grid sizes that are 0.1, 0.15 and 0.2. Each size is then numerically calculated. Calculation is performed with same parameters and boundary condition settings.

The velocity data is then plotted to achieve the purpose of grid independence. Figure 6 shows the result attained.

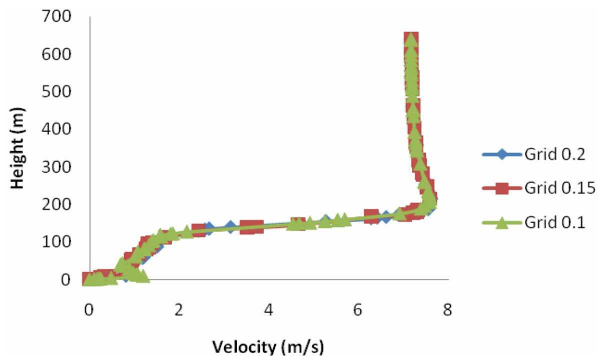

Fig. 7 Velocity distributions at 10 m from skyscrapers

The difference of velocity data between each grid is shown in the following table.

Table. 1 Average differences in grid independence

Grid Compared	Percentage of Difference
Grid 0.15 – Grid 0.1	1.55%
Grid 0.2 – Grid 0.1	3.13%
Grid 0.2 – Grid 0.15	2.3%

From these results, the full simulation is performed with the setup grid 0.1.

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III. Results

The numerical processes have been performed to obtain stratified flow by exerting a flow over three different terrain types. Velocity variation has been given with different values which are 25 km/h, 40 km/h, 55km/h, 70km/h and 85km/h.

Term of stratified flow was defined as variation of velocity distribution of each layers of flow. The results show similar characteristic occurs where velocity distribution varies against altitude. The stratification is seen behind the obstacles and marked with different colour of velocity's contour.

Acceleration and deceleration occurs for each models. Wake region occurs behind the obstacle (near to the foot) where the flow is chaotic, not stable and swirls. Leaving the obstacle, flow starts to resume normal and becomes stable so that the obstacle effects no longer exist at certain distance from the obstacle.

Increment of velocity value for skyscrapers models reached 15%, where as trees and mountains terrains reached 19.7%, 17% respectively.

Velocity reduction reaches 100% for each velocity variations and it occurs on surface of the obstacles Surface of the obstacles exerts frictional forces to the flow, consequently fluids particles are attached to the surface making them impossible to move. This can be seen clearly along the surface in which velocity value is zero. Zero value is represented by dark blue color.

Following figures show the velocity distribution of:

a. Skyscrapers terrain

a
b
c
d
e

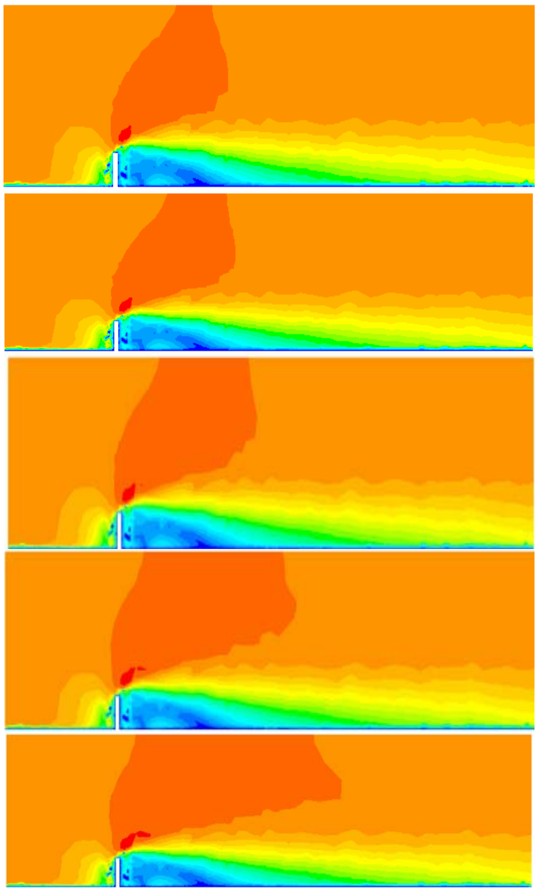
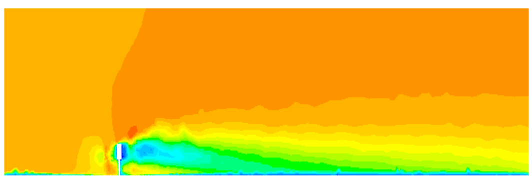


Fig. 8 Contour of velocity of skyscrapers terrain. a) V = 25km/h, b) V = 40km/h, c) 55km/h, d) V = 70km/h, e) V = 85 km/h

b. Trees terrain

a



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b

c

d

e

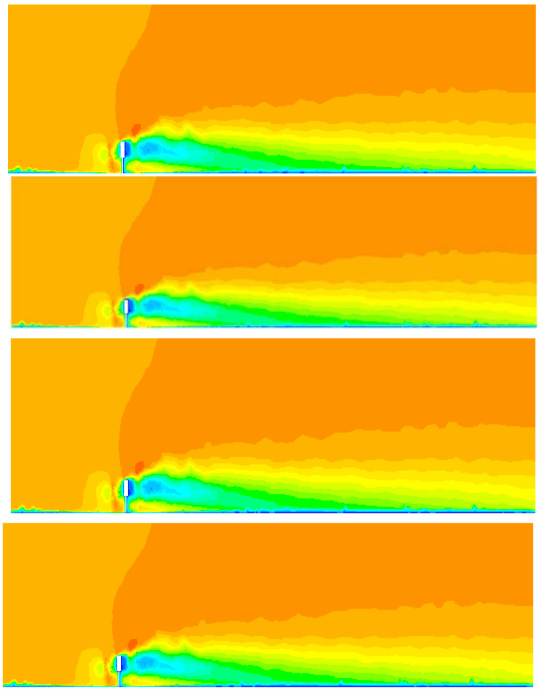

Fig. 9 Contour of velocity of trees terrain. a) V = 25km/h, b) V = 40km/h, c) 55km/h, d) V = 70km/h, e) V = 85 km/h

c. Mountain terrain

a

b

c

d

e

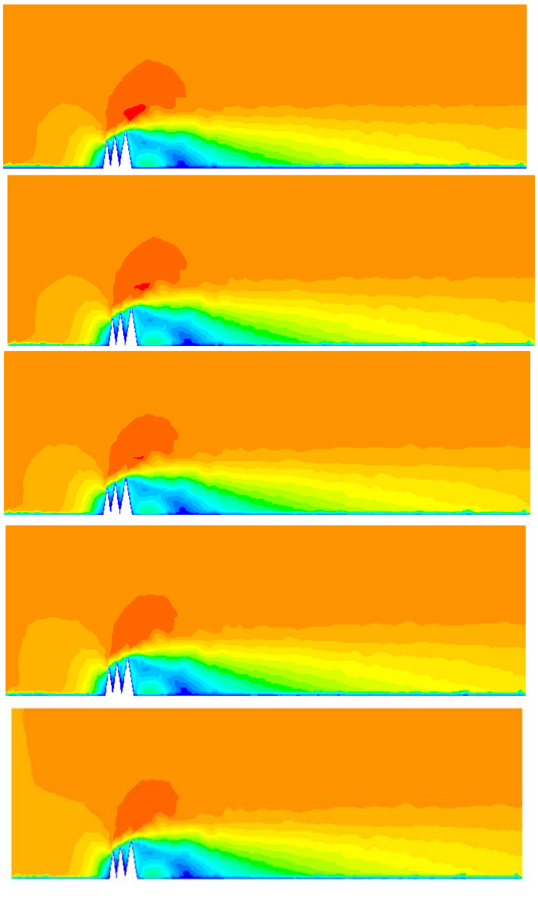

Fig. 10 Contour of velocity of mountains terrain. a) V = 25km/h, b) V = 40km/h, c) 55km/h, d) V = 70km/h, e) V = 85 km/h

IV. Discussion

The stability of flow's stratification was different for each terrain types. Geometrical shape and obstacles formation have an important role in determining the flow pattern leaving the obstacle. However stratification seems to resumes its initial velocity distribution that is to be uniform. It is assumed that velocity distribution will be uniform at certain distance from the obstacle.

For skyscrapers terrain, flow accelerates on the top. The region, where the flow changes to be strong, is bigger while higher velocity value is applied. This phenomenon only occurred for skyscrapers terrain.

For trees and mountains terrains, the velocity variation has no significant effects. This can be seen obviously in trees terrains. Effects of velocity variation for mountain terrains are more relevant for retardation which is caused by mountain itself. The area in front of mountain is more likely to be affected by the velocity variation.

V. Conclusion

This research shows a complete numerical simulation of flow over three dimensional complex terrains. The CFD process and methodology has been thoroughly examined including the mesh sensitivity. The suitable turbulence models for a flow analysis have been selected. The use of standard k-ε (epsilon) model has been newly automated for practical engineering use, so that analysis of flow over complex terrain regions can be quickly and simply performed by non-expert CFD users. As such, the study can be used for further related research particularly about stratified flow.

The results obtained by numerical analysis showed that:

(1) Grid sensitivity tests show resulting errors of more than 1%. This is assumed to be one of the main sources of error and the fact that the CFD results are within 3% of full scale data is still promising.
(2) In the real condition, mountains give the best satisfaction as the stratification still exists until 37 km away from the mountains, but the velocity distribution is just about stable within 4 km from the mountains.
(3) Velocity variations which have been given to the flow have no effects in the stratification. Velocity variations are assumed to be related in turbulent characteristics.
For trees terrains, velocity variations seem to have no effect at all in the flow nor to turbulent characteristics. Similar results are obtained for each velocity variations
(4) Flow over mountains generates more wakes area compared with flow over skyscrapers. However, flow over skyscrapers generates bigger area where velocity increment occurs.
(5) All the work in this project has been performed on Notebook using a single processor machine. Limitations in memory have limited the grid resolution, and is hence the main source of error.
This usage of Notebook shows how accessible CFD models are to general users and the need for specialist workstations has effectively been removed.

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