NUMERICAL SIMULATION OF WIND PRESSURE DISTRIBUTION IN URBAN BUILDINGS OF RANDOM STAGGERED ARRAYS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

Malaysia-Japan International Institute of Technology
Universiti Teknologi Malaysia

JUNE 2015

To my beloved mother and father

ACKNOWLEDGEMENT

First and foremost, I praise God the Almighty for providing me this opportunity and granting me the capability to proceed successfully. I would like to offer my sincere thanks to all of the people without whom I would not be able to complete my thesis: Dr. Sheikh Ahmad Zaki bin Shaikh Salim, my main supervisor for his continuous guidance and expertise; Dr. Mohamed Sukri bin Mat Ali, my co-supervisor whose expertise and assistance are most appreciated.

I want to express my thanks to these respectful people who have shared their knowledge and constructive criticisms through our numerous, insightful discussions: Assoc. Prof. Dr. Aya Hagishima and Dr. Naoki Ikegaya of Kyushu University; Dr. Azli Abd Razak of Universiti Teknologi MARA (UiTM) Shah Alam; and, Prof. Emeritus Dr. Norio Arai and Prof. Dr. Masataka Shirakashi of Malaysia-Japan International Institute of Technology (MJIIT). Needless to say, the completion of my thesis would be far-fetched without the spiritual support and useful advises of my beloved parents and family, esteemed colleagues in *i*Kohza Wind Engineering of MJIIT and friends.

Last but not least, I would like to extend my gratitude to MJIIT for funding me in the course of my study. Their support for the betterment in education is an indication that the price of knowledge is invaluable.

ABSTRACT

In typical urban areas where buildings are built in clusters, wind pressure distribution of buildings is influenced by the interference effects from neighbouring buildings, which consequently affect wind-induced ventilation in buildings. This study was aimed to investigate the relationship between two geometric parameters of idealized urban arrays and mean pressure distribution. Hence, numerical investigation was conducted using large-eddy simulation (LES) on six idealized urban cases. The first geometric parameter was packing density λ_p which is the ratio of planar area of buildings to the total surface area, and was used to designate six building arrays, between sparse and dense urban conditions i.e. $0.044 \leq \lambda_p \leq 0.391$. The second geometric parameter was used to incorporate the heterogeneity of urban surfaces, defined by aspect ratio of building α (i.e. the ratio of frontal area to planar area of a building). Nine types of square-based buildings which were arranged randomly in staggered arrangement, have different values of α ranged between 0.84 (low-rise building) and 3.76 (high-rise building). Current results show that in denser arrays (i.e. $\lambda_p \geq 0.250$), pressure drag which was calculated through mean pressure differences between windward and leeward sides of buildings, is dominated by high-rise buildings by up to 55%. Besides, effects of packing density are significant on low-rise buildings (i.e. $\alpha \leq 2.64$) since the interference effects are likely to intensify when distances between adjacent buildings become less mainly at height z below the building height average h_{ave}. In addition, a linear relationship between α and averaged mean pressure difference is observed in all packing densities, particularly for high-rise buildings (i.e. $\alpha \geq 3$). The results obtained from this study are exclusive to random staggered arrays, but the findings are an important addition to understanding wind pressure distribution in idealized arrays resembling real urban condition.

ABSTRAK

Dalam kawasan bandar yang tipikal di mana bangunan dibina secara berkelompok, taburan tekanan udara dipengaruhi oleh gangguan daripada keadaan bangunan yang berdekatan dan memberi kesan terhadap pengudaraan dalam bangunan. Penyelidikan ini bertujuan untuk mengkaji kaitan antara dua parameter geometrik bagi kawasan bandar ideal dan taburan tekanan udara. Oleh itu, simulasi berkomputer menggunakan model turbulen LES dijalankan bagi enam kes bandar ideal. Parameter geometrik pertama ialah kepadatan bandar λ_p iaitu nisbah antara luas tapak bangunan dengan luas lot kawasan bangunan. Ia mewakili kawasan bandar yang berkepadatan rendah ke kepadatan yang tinggi iaitu $0.044 \leq \lambda_p \leq 0.391$. Parameter geometrik kedua mewakili ketidaksekataan ketinggian bangunan dan dinamakan sebagai nisbah aspek bangunan, α (nisbah antara luas tapak bangunan dengan luas permukaan hadapan bangunan). Sembilan jenis bangunan bertapak segi empat sama yang disusun secara rawak dalam susun atur yang dinamakan *staggered*, mempunyai nilai α yang berbeza iaitu dari 0.84 (bangunan rendah) hingga 3.76 (bangunan tinggi). Hasil daripada LES menunjukkan bagi kes bandar yang padat (iaitu $\lambda_p \geq 0.250$), daya seretan yang dikira melalui perbezaan purata tekanan di antara permukaan bangunan bahagian hadapan dan belakang didominasi oleh bangunan-bangunan tinggi sehingga 55%. Selain itu, kesan kepadatan bangunan adalah ketara bagi bangunan rendah (iaitu $\alpha \leq 2.64$) mungkin kerana gangguan terhadap pergerakan udara menjadi kritikal apabila jarak di antara bangunan berkurangan terutamanya pada ketinggian z kurang dari purata ketinggian bangunan h_{ave}. Tambahan pula, hubungan yang linear antara nilai α dengan perbezaan purata tekanan udara telah diperolehi, terutamanya bagi bangunan tinggi (iaitu $\alpha \geq 3$) dalam semua kes λ_p. Data yang diperolehi adalah khusus kepada kajian bangunan yang dinamakan *random staggered arrays*, namun ini adalah penting bagi pertambahan kajian mengenai kesan taburan tekanan udara dalam kawasan bandar ideal yang menyerupai kawasan bandar yang sebenar.

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LIST OF SYMBOLS

λ_p	-	Packing density
α	-	Aspect ratio of a building
C_p	-	Wind pressure coefficient
A_P	-	Planar area of a building
A_T	-	Total surface area
A_F	-	Frontal area of a building
σ_h	-	Standard deviation of building height
h_{ave}	-	Building average height
h_{max}	-	Maximum building height
C_d	-	Drag coefficient
u_i	-	Velocity component where i = 1, 2, or 3
p	-	Pressure
ν	-	Kinematic viscosity at sea level = 1.046×10^{-5} m^2/s
ρ	-	Air density at sea level = 1.225 kg/m^3
$\overline{P}$	-	Total time-averaged pressure
ν_e	-	Eddy viscosity
C_S	-	Smagorinsky constant
$\overline{D_{ij}}$	-	Time-averaged strain velocity
D_{ij}	-	Strain velocity
$\overline{p}$	-	Time-averaged pressure
h	-	Standard block height = 25 mm
T, T_b	-	Characteristic time scales
u_*	-	Surface friction velocity
U_b	-	Bulk velocity (i.e. average velocity)
L_x	-	Streamwise length of the computational domain
L_y	-	Lateral length of the computational domain

L_z	-	Vertical length of the computational domain
Re	-	Reynolds number
Re*	-	Roughness Reynolds number
z	-	Vertical distance
z_0	-	Roughness length
$\overline{U}$	-	Spatially averaged streamwise velocity
$\overline{p_f}$	-	Mean pressure on the front side (windward) of a building
$\overline{p_b}$	-	Mean pressure on the back side (leeward) of a building
$\overline{\Delta p}$	-	Mean pressure difference between the front and back sides of a building
$\overline{\Delta p_m}$	-	Mean pressure difference at the middle of a building
$\overline{p_{m,f}}$	-	Mean pressure at the middle of a front side of a building
$\overline{p_{m,\mathrm{b}}}$	-	Mean pressure at the middle of a back side of a building
$\overline{\Delta P_{\max}}$	-	Maximum mean pressure difference
H_i	-	Block i of random staggered array where i = 1, 2, 3, 4, 5, 6, 7, 8, and 9
$\overline{u'w'}$	-	Reynolds stresses
τ_0	-	Surface shear stress
A_S	-	Surface area
F_p	-	Pressure drag
γ	-	Pressure-to-drag ratio
U_{ref}	-	Reference velocity
β	-	Ratio of pressure drag of individual blocks to the total pressure drag of an entire block array
β_i	-	Ratio of pressure drag

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CHAPTER 1

INTRODUCTION

1.1 Introduction

The development of urban areas has always been associated with its impact on the environment and living condition of people living in a city. The energy demand in a city is costly and linked to the continuous supply of electricity to commercial and residential buildings running on air-conditioning systems (Santamorius *et al.*, 2001). In this regard, natural ventilation or wind-induced ventilation is a far cheaper and cleaner alternative to mechanical ventilation i.e. the air-conditioning system since it saves on energy and cost. With the increasing demand of energy in proportional with the global population, natural ventilation is a practical approach to promote energy saving and environmental-friendly city.

According to the Department of Economic and Social Affairs of the United Nations, almost half of the global population approximated at 7 billion in 2010 lives in urban areas, and this is expected to keep growing. This process is known as 'urbanisation' which results in more people migrating to cities, thus more activities conducted to sustain living. The increase of anthropogenic activities (e.g. transportation, consumption of electricity, waste disposal, etc.) in an urban area affects living condition of its inhabitants. As a consequence from emissions of heat and gas, a microclimate change known as urban heat island (UHI) ensues, when the averaged temperature in a city is higher than in its surrounding area (Chow and Roth, 2006; Sarkar and Ridder, 2010).

The continuous development of urban areas and growing urban population are two other possible indicators that the effects of UHI are getting alarming. The increased temperature which leads to a living discomfort of urban inhabitants has forced them to use more energy for cooling. So, this research has taken a subtle approach by studying wind-induced ventilation in urban buildings. The usage of heating, air conditioning, and ventilation (HVAC) systems is an example of expensive consumption of energy, such as in a tropical country like Malaysia (Saidur *et al.*, 2007) and countries located in temperate climate regions like the USA and UK (Perez-Lombard *et al.*, 2007). By utilizing the wind-induced ventilation in a building particularly in tropical climate, the thermal load of the air-conditioning system will be reduced hence less energy consumed to operate it.

This study is therefore an important effort of investigating the effects of surrounding buildings in an urban area on wind-induced ventilation. Although its positive impact may not be substantial and immediate, it is a promising investment without expensive spending on planning and maintenance. In the future, with the optimization of wind-induced ventilation, it is expected that a well-ventilated city will lead to a sustainable environment and living condition with less dependency on mechanical ventilation.

1.2 Problem Statement

The effectiveness of wind-induced ventilation in urban buildings could assist with the reduction of energy consumption by mechanical ventilation systems. Therefore, the amount of heat released by the system into the urban environment may become less. Not only that, it may also become the driving force for the transport of heat and gas away to the atmosphere.

In an urban area where buildings are built in a cluster with random spacing, sheltering effects from neighbouring buildings are non-negligible. This has an impact on wind pressure distribution around the buildings and ultimately, the effectiveness of wind-induced ventilation. The relationship between wind pressure distribution and the sheltering effect is therefore important. In this regard, a geometric parameter, packing density (λ_p) which is the ratio of planar area of buildings to the total urban surface area was used to quantify the sheltering effect. In addition, the heterogeneity of a typical urban surface, featured by the variation in building height, is nonetheless imperative to this research. Therefore, another geometric parameter namely building's aspect ratio (α i.e. ratio of frontal area to the planar area of a building) was analysed and discussed in relation to wind pressure distribution.

In this study, the problem was investigated through computational fluid dynamics (CFD) simulation. Several case studies of urban areas, each defined by λ_p, were simulated using numerical configurations from previous numerical studies which had been validated in the preliminary simulation of this study. CFD results obtained were then used to estimate and study the effectiveness of wind-induced ventilation in urban buildings through detailed analysis of wind pressure distribution.

1.3 Research Objectives

Based on the problem statement above, there are three main objectives of this study:

(i) To provide a database of wind pressure distribution of buildings in urban areas defined by different values of packing density;

(ii) To estimate the effect of packing density on wind-induced ventilation in urban buildings;

(iii) To study the relationship between wind pressure distribution and aspect ratios of buildings.

1.4 Research Question

Based on the objectives stated above, three research questions were developed in this study:

(i) How significant is the effect of packing density on pressure distribution of buildings?

(ii) What is the relationship between packing density of urban arrays and wind-induced ventilation?

(iii) What is the relationship between wind pressure distribution and aspect ratios of buildings?

1.5 Scope of the Study

The scope of this study is defined through the geometric parameters used to investigate wind-induced ventilation in building arrays. Firstly, to demonstrate the effects of packing density, six values of λ_p were investigated in this study: 4.40%, 8.20%, 17.0%, 25.0%, 30.9%, and 39.1%. Secondly, the type of urban areas used was also fixed in terms of the arrangement of buildings and distribution of buildings' heights. These two conditions are essential to keep the direction of this study in the right path.

1.6 Significance of the Study

The importance of estimating wind-induced ventilation in an urban area is significant to a building design which in fact can influence the comfort of its inhabitants and may likely pose an impact on the overall urban microclimate (Yamamoto, 2006). Furthermore, this study can contribute to the existing literature on wind-induced ventilation in urban buildings.

1.7 Limitations of the Study

The estimation of wind-induced ventilation was based on the wind pressure distribution on urban buildings but the effect of thermal buoyancy was excluded primarily because buoyancy-driven ventilation is studied more effectively when indoor and outdoor conditions are considered (Andersen, 2003). The urban buildings modelled and used in this study are solid-walled blocks and therefore, this study was not intended to analyze the internal flow and its properties inside the buildings.

1.8 Thesis Structure

The rest of the thesis is structured as follows. Literature review on wind-induced ventilation is summarized and discussed in Chapter 2. In Chapter 3, methodological approaches used in this study are explained. Several sub-chapters on numerical settings, boundary conditions, CFD techniques etc. are organized for a detailed and comprehensive elaboration. This also includes preliminary results for validation and comparison purposes. In Chapter 4, results of the second-stage CFD simulation are presented. This chapter is included with thorough analysis and discussion which are imperative to the objectives outlined in this study. Lastly, in Chapter 5, conclusions of the study and recommendations for further works are presented.

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