IMPACT OF HIGH-RISE BUILDING SHAPES ON WIND FLOW CHARACTERISTICS AND ENERGY POTENTIAL

By

EHSAN MOKHTARI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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Chairman : Wan Srihani binti Wan Mohamed, PhD
Faculty : Design and Architecture

This research project aims to study the design of high-rise buildings and investigate how wind affects energy absorption by developing an aerodynamic optimization procedure (AOP) and using Computational Fluid Dynamics (CFD) in COMSOL Multiphysics. The goal of the study is to optimize building shape for wind energy exploitation. The electricity sector is a significant source of carbon dioxide emissions and contributes to global climate change. Wind energy has become a potential source of low-carbon energy production in recent years. The shape of buildings is a significant factor in aerodynamics, providing an opportunity for wind power control and wind energy proliferation. In a smart sustainable city, building costs can be reduced without affecting structural elements. By optimizing building shape in the early stages of design, it is possible to control wind-induced loads and responses, as well as reduce energy demand in high-rise buildings where resource consumption is higher than in low-height buildings.

The research includes four case studies with the same height but different cross-section plans (circular and rectangular), and analyzed based on wind velocity maximization. The study used three-dimensional CFD simulation of wind loading on tall buildings to optimize building shape. The results showed an improved performance of circular models compared to rectangular models in terms of aerodynamic characteristics. The corner modification in buildings could be an asset for generating potential electricity by incorporating wind turbines. The validation procedure is primarily achieved from the development of a robust technique of inflow generation, called Air Flow over an Ahmed Body, which will be used to generate the wind velocity field in the simulation.

The accomplished research generally offers progress in numerical techniques of climate responsive design, improving the urban built environment in terms of resilience and sustainability. The research will provide valuable insights for architects, engineers, and building developers to design and optimize high-rise buildings for wind energy

exploitation, reducing the carbon footprint and improve the energy efficiency of the building.

Keywords: Aerodynamics, Computational Fluid Dynamics (CFD), High-rise Buildings, Shape Modification, Wind Energy

SGD: Goal 7: Affordable and Clean Energy

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

IMPAK BENTUK BANGUNAN PENCAKAR LANGIT TERHADAP ALIRAN ANGIN DAN POTENSI TENAGA

Oleh

EHSAN MOKHTARI

Ogos 2022

Pengerusi : Wan Srihani binti Wan Mohamed, PhD
Fakulti : Rekabentuk dan Senibina

Sektor elektrik adalah sumber utama pelepasan karbon dioksida yang menyumbang kepada perubahan iklim global. Sejak kebelakangan ini, tenaga angin terus menjadi sumber yang berpotensi untuk penghasilan sumber tenaga karbon rendah. Beban dan tenaga angin yang dieksploitasi sangat bernilai di kebanyakan bangunan tinggi, oleh itu pendekatan terhadap respons angin pada peringkat awal reka bentuk bangunan bukan sahaja dapat mengawal beban dan tindak balas yang disebabkan oleh angin, tetapi juga dapat mengurangkan permintaan tenaga terutamanya kepada bangunan tinggi berbanding bangunan rendah di mana penggunaan sumber lebih tinggi daripadanya. Reka bentuk bangunan merupakan faktor penting dalam aerodinamik, yang menghasilkan peluang untuk mengawal kuasa angin dan percambahan tenaga angin dan kesannya dapat mengurangkan kos sesuatu bangunan tanpa melibatkan elemen struktur bangunan tersebut dalam sesuatu kelastarian bandar pintar.

Kedua, mitigasi aerodinamik dan percepatan telah mendorong kebanyakan penyelidik untuk menyelidiki pelbagai bentuk bangunan, namun, eksploitasi terhadap angin adalah masalah yang lebih penting kerana ia berkaitan dengan pengurangan penggunaan tenaga dan juga penjanaan tenaga seperti elektrik. Pengoptimuman bentuk telah dikaji oleh kebanyakan penyelidik sama ada dengan mengubah orientasi, ketinggian, dimensi, lokasi, atau sudut. Senario ini dapat menghasilkan pelbagai persembahan aerodinamik dengan mengubah setiap item. Oleh itu, projek ini bertujuan untuk mengembangkan prosedur pengoptimuman aerodinamik (AOP) dimana ia dapat meningkatkan penyerapan kepada tenaga angin dengan menggunakan Computational Fluid Dynamics (CFD) dalam perisian Multiphysics Comsol yang merupakan persekitaran interaktif untuk memodelkan dan mensimulasikan masalah saintifik dan kejuruteraan dan seterusnya mensimulasikan angin berdasarkan Persamaan K-Epsilon. Ia membolehkan antara muka pengguna berasaskan fizik konvensional dan sistem gandingan persamaan pembezaan separa (PDE). Mengenai model turbulensi yang digunakan, Sebagian besar penelitian dilakukan menggunakan model turbulensi RANS. Prosedur yang dicadangkan diguna pakai untuk mengoptimumkan sudut bangunan menggunakan simulasi CFD tiga dimensi yang sangat digunapakai dalam bidang ini kerana faedah ekonominya dibandingkan dengan kaedah konvensional, termasuk ujian terowong angin. Empat kajian kes dipilih dengan ketinggian yang sama dan rancangan penampang yang berbeza (bulat dan segi empat tepat) dan seterusnya dianalisis berdasarkan pemaksimuman kecepatan angin. Kedua, kajian penyelidikan ini tentang pengaruh sudut kejadian angin terhadap ciri aliran angin di sudut bangunan tinggi. Analisis menunjukkan peningkatan prestasi ciri aerodinamik dalam model pekeliling yang dibincangkan dalam bab-bab berikutnya. Pengoptimuman bentuk secara aerodinamik adalah teknik, di mana bentuknya diubahsuai dengan memotong sudut seperti chamfered, bulatan sudut atau menambahkan sedikit bahan di sudut. Oleh kerana kos pemasangan, teknik ini lebih sesuai dan berkesan untuk bangunan bertingkat tinggi dibandingkan bangunan rendah. Pengubahsuaian sudut di bangunan dapat menjadi aset yang dapat digunakan untuk menghasilkan elektrik oleh turbin angin. Prosedur pengesahan sebagai objektif terakhir penyelidikan ini terutama dicapai melalui pengembangan teknik penjanaan aliran masuk yang kuat, yang disebut Air Flow over a Ahmed Body. Oleh kerana perisian ini telah dipersetujui oleh piawaian umum dalam turbulensi aliran udara, perisian ini disahkan sendiri berdasarkan kaedah pengesahan ini. Secara umum, penelitian yang dilakukan dalam tesis ini memberikan kemajuan dalam teknik reka bentuk iklim berangka, yang meningkatkan daya tahan dan kelestarian lingkungan binaan bandar.

Kata kunci: Aerodinamik, pengiraan dinamik bendalir, bangunan pencakar langit, pengubahsuaian bentuk, tenaga angin

SDG: Matlamat: Tenaga Mampu Milik dan Bersih

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Wan Srihani binti Wan Mohamed, PhD
Senior Lecturer
Faculty of Design and Architecture
Universiti Putra Malaysia
(Chairman)

Roslina binti Sharif, PhD
Senior Lecturer
Faculty of Design and Architecture
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 18 April 2024

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UPM	Universiti Putra Malaysia
°C	degree celsius
CFD	Computational Fluid Dynamic

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

In today's world, the scarcity of non-renewable resources and the use of renewable resources for energy conservation issues are attracting the attention of many scientists. Wind characteristics for energy conservation and power generation are one of the main key points in ensuring human health and thermal comfort as well as lowering air pollution at the pedestrian level (Hang et al., 2012; Zhang, Kwok, Liu & Niu, 2015). The limited land resources of modern architecture have led to the emergence of skyscrapers of various shapes and heights (Esmaili et al., 2007). Each urban area has its own roughness and typical wind characteristics as urban roughness increases with the increase in height and wind speed (Elshaer, Gairola, Adamek, & Bitsuamlak, 2017). This demonstrates that the urban environment has the potential to conserve wind energy and provide energy efficiency which, in turn, can reduce energy loss, air pollutants, and carbon emissions (Walker, 2011). The ultimate impact of shrinking carbon emissions will bring economic growth to urban areas of big cities. Regarding the reduction of energy consumption, Directive 2010/31/EU is adopting an approach at an early stage in the design of buildings to take advantage of renewable energy facilities such as wind power (Directive 2010/31/EU of the European Parliament of the European Union and Committee of 19 May 2010 on Energy Performance of Buildings).

Technologies such as wind turbines and locations such as building roofs have been used to exploit wind power (Abohela, Hamza, & Dudek, 2013; Larin, Paraschivoiu, & Aygun, 2016; Stathopoulos et al., 2018). Wu, Bangga and Cao (2019) utilized a synthetic method combining computational fluid dynamics (CFD) simulation and double multi-stream tube method to estimate a wind turbine performance. In a similar study, the operational efficiency of a vertical axis wind turbine (VAWT) was evaluated under environmental turbulence intensity condition (Lee, Tsao, Tzeng, & Lin, 2018). Their results showed that vertical wind had a clear effect on the power output when horizontal wind speeds were within a certain range. These results can be employed as a reference for selecting aerodynamic properties, output efficiency, CFD simulations and vertical wind turbine position.

Omid Esmaili (2007) claims that the combination of building shape, height, and composition may cause human discomfort that cannot be accommodated by inducing strong wind currents near the ground. In his treatise, a popular situation of urban planning was covered that amplified the ground wind speed over a tall building of 56-story (Esmaili et al., 2007). Concerns about the quality of urban public spaces have been raised by Sigrid Reiter (2009), who focused on the progression of CFD and computational fluid dynamics (Reiter, 2010). Providing a simple graphical tool, he developed a new methodology for quantifying wind speeds around buildings. The study results can serve as a simple design tool for architects and urban planners to consider wind in the design of the built environment. It was also proved that numerical modelling has become a high-performance tool that provides useful guidelines for designers and city planners. Studies on wind speed estimation in urban environments show that street canyons have a major impact upon wind flow in cities and wind speeds are evident only over the ridges of isolated single building roofs. Therefore, it is difficult to generalize methods for estimating wind resources in urban environments based on the diversity of factors. Scaling factors can also be a viable solution if the correctness of their use is well known (Walker 2011). Thordal, Bennetsen, and Koss (2019) explained the important aspects to consider when applying CFD simulations to wind loads on tall structures. In this study, the main parameters of the atmospheric boundary layer were considered to determine whether the upstream wind flow was sufficiently generated in the numerical simulations. Computational Wind Tunnel (CWT) tests were conducted, and the influence of wind loads on the design of low-to mid-rise buildings was demonstrated. The survey results showed that wind pressure was much greater than the other factors in the CWT tests (Avini, Kumar, & Hughes, 2019). For efficient harvesting of wind energy, Hassanli, Hu, Kwok, and Fletcher (2017) proposed opening strategies for a double-skin facade (DSF) system. It was demonstrated that the flow within the cavity can be enhanced over a wide range of incident wind angles.

Bharat and Ahmed (2012) discussed the urban influence on the increase and decrease of wind velocities, as well as the shift of wind directions arising from the overriding weather phenomenon. This paper highlighted such influences on special weather scales ranging from tens of kilometers to meters and even less in size. Wind modelling was then performed with the aid of WAsP software to record wind loads around the building complex areas. Ahmed and Bharat (2012) proposed the mitigation scenarios of adverse wind effects to achieve the desired level of pedestrian amenity for heights below 50 meters. These scenarios were followed with no intention of compromising the architectural design. Sunderland, Mills, and Conlon (2013) carried out an approach based on urban climate research to examine the impact of varying degrees of surface roughness on the wind field between and above the buildings. However, this approach was shown to be able to assess the potential for microturbine energy production with sufficient accuracy. Regarding the dependency of wind power on environmental conditions and CO2 gas emissions in the atmosphere, Dorsey-Palmateer (2019) found various types of wind generation.

The effect of twisted wind flows on the pedestrian-level wind (PLW) field (Weerasuriya, Tse, Zhang, & Li, 2018) in an urban environment. Weerasuriya et al. (2018) highlighted four twisted wind flows of different magnitudes and employed directions of yaw angles to find wind speed variations resulting from characteristics of twisted wind profiles at the pedestrian level. However, building a facade or shape was not the focus of this study. Using a two-step approach, Trikootam and Hornikx (2019) analyzed the impact of wind on distant sound propagation over various generic urban sections in downward atmospheric refraction. They first simulated the wind field using computational fluid dynamics (RANS-CFD) and then adopted the mean wind field approach in computational acoustics (PSTD-CA). It was concluded that the wind effect is significantly influenced by the urban topology near the receiver and source; thus, the broadband effect is small in the absence of wind in a downward refracting atmosphere. Laboratory simulations have shown that tall mass timber buildings subjected to extreme wind storms, such as tornadoes, could be susceptible to probable damage as a result of increased deflection (Bezabeh, Gairola, Bitsuamlak, Popovski, & Tesfamariam, 2018). Enhancing pedestrian wind comfort has been assessed in practical instances based on a fusion of several criteria (Jacob and Sagaut, 2018). It was discovered that common criteria for pedestrian comfort led to varying conclusions, conditional on accessibility to data of high spatiotemporal resolution. The current study is a step forward to the latest advances in wind power exploitation, analyzing different forms of tall buildings of the same height in terms of wind power absorption. The towers vary in their cutting plans with two rectangular and two circular cross-sections. The optimum shape for maximizing the wind speed is to be investigated, and it has a linear relationship with the wind absorption.

1.2 Problem Statement

Malaysia is a developed country with many skyscrapers in all regions, which can be constructed to reduce energy consumption. The environment surrounding a skyscraper primarily influences energy consumption. Outside temperature, wind, humidity, and solar radiation are among the environmental variables that affect the amount of energy required for heat transmission or air circulation around a building. The wind aerodynamic design can be generally controlled in towers of more than 40 stories (Daemei, Khotbehsara, Nobarani, & Bahrami, 2019). Wind can provide a renewable, clean, and unending source of power generation when it is potentially provisioned at the early stage of building design. In this sense, skyscrapers can contribute to the discharge of nonrenewable resources such as coal, oil, groundwater, and natural gases. The devastating impact of fossil fuels on the environment has made many designers harness energy from renewable, free, and natural resources rather than from non-renewable ones. Conversion to the use of mechanical and electrical energy, reduction of energy consumption, and provision of wind turbines for wind power play a key role in sustainable development target housing. Concerns about the discharge of energy resources and the issue of energy conservation have led to technological advances in reducing the energy consumption of buildings. The use of wind energy is more advantageous in high-rise buildings, as the flow of wind is accelerated at high altitudes.

For instance, the first skyscraper for testing the best technical solutions for energy savings was experimentally established in Manchester. The energy consumption of the tower was limited by the efficient use of 7,000 solar panels and wind turbines that generate approximately 10% of the energy required by high-rise buildings.

To elaborate more about the word high-rise, the majority of international organizations, such as the CTBUH (Council on Tall Buildings and Urban Habitat (CTBUH)) define a skyscraper as a building that reaches or exceeds the height of 150 m and 30 floors.

According to the findings of a recent study, Malaysia has shown low readiness for energy conservation from solar power (Teoh, Go, & Yap, 2020). The construction of houses with low energy consumption as well as the construction of energy efficient skyscrapers is currently accepted and intended all around the world. However, the importance of the shape of the building, especially the corners, for wind absorption has demonstrated that changing the appearance can be another efficient strategy to meet the targets of sustainable development. There is evidence on the correlation between building geometry and local wind flows and climate (Van Druenen, Van Hooff, Montazeri, &

Blocken, 2019; Kabosova, Kmet, & Katunsky, 2020). The wind experienced in any local region is strongly dependent on topography and other factors. In tropical climates, instantaneous wind speed and direction are determinants of high-rise building design because the average wind speed may vary in direction with height. Towers generally have different floor plans, and four case studies with different flatness were considered for this study in Penang, Malaysia. Although the optimization of high-rise building shapes has been the topic of several studies, they have mostly focused on pressure as the key characteristic of wind flow around buildings. Additionally, the investigation of the effect of wind on the energy absorption of tall buildings has been overwhelmed in the wind climate of the tropics. There is also a lack of numerical research on the issue of the wind load assessment of skyscrapers. To fill these gaps, this work will focus on the generation of wind energy potential as a renewable resource to improve the energy efficiency and system performance of tall buildings in Peninsular Malaysia, a tropical region.

1.3 Significance of Study

Wind power harnesses the breeze to the productive end of the generated electricity. It is one of the greenest energy sources, and its societal, economic, and environmental benefits are being increasingly recognized by all people. (Herbert, Iniyan, Sreevalsan, & Rajapandian 2007). Wind energy, as a safe and environmentally friendly power, diminishes the use of petroleum derivatives as the starting point of ozone-harming substances that contribute to dangerous atmospheric deviation as the oldest challenge to the environment. (Blaabjerg and Ma, 2017).

Wind energy is not exclusively endless and accessible in all areas, yet it does not pollute the environment, implying that it additionally aids in the decrease of energy imports just as neighborhood business. Focusing on the practical turn of events, wind energy can effectively deliver power more than other sustainable assets because of its agreeability with no falling apart impact. In the view of previously mentioned reasons, wind power abuse by means of wind turbines is of fundamental significance (Koetket et al., 2018). This is because of the high working energy prerequisites and reliance on artificial lighting and cooling, which are the main concerns that unfavorably influence the climate of high rises. This explains the negative aspects of metropolitan life that are hostile to ecological systems, as perceived by many researchers. Enthusiastic research is being conducted to reduce high-mount energy, maintenance costs, and future primary energy demands (Godoy-Shimizu et al., 2018). However, skyscrapers that fill the city skyline can potentially provide a means of extending renewable energy by installing wind turbines on the roofs. However, the flow area above high-rise building roofs has not received much consideration, and the outcomes have mostly been applied to low-rise roofs.

This study is important because it will provide designers and architects with a useful tool for predicting the feasibility of urban wind for utilization in specific urban environments. In the long run, their predictions can be evaluated in comparison with on-site measurements of wind energy and speed, thereby balancing the estimated and actual outcomes of wind power generation (Chen, Hong, & Piette, 2017). This thesis emphasizes how wind speed can be boosted in towers by shape modification, especially in the critical parts of corners, which have a powerful effect on wind flow characteristics. To this end, four buildings of the same height were adopted as case studies in the tropics. To precisely specify the incremental rate of wind velocity, Komtar Tower located in Penang and three others within its neighborhood, diverse in roof plan, were considered to evaluate their reaction to the corner modification.

1.4 Hypothesis

This study formulated the following research hypotheses:

1. The shape of a building affects the characteristics of wind flow around tall buildings.
2. There is a positive association between the wind speed and energy potential, which can be obtained from the design of high-rise buildings.
3. The aerodynamic changes in the corners of high-rise buildings are related to wind characteristics.
4. The circular tower plans outperform the rectangular ones in terms of energy exploitation for wind turbine installation.
5. Chamfered and softened edges are more promising in the high-rise building design of the tropics.

1.5 Constraints

This project analyzes the wind load and flow around tall buildings and excludes consideration of the wind turbine effect on the flow. Regarding the current situation of the site, the available wind resources were obtained, and no other empowered winds were investigated. The quantity of the wind outperforms the quality in terms of wind velocity enhancement; therefore, wind quality is not analyzed in this thesis, and the focus is on the wind quantity.

1.6 Main Objectives

The research methodology used in this study was simulation. The impact of wind on high-rise buildings in Malaysia differs that from in other parts of the world, and this is the focus of the present research. The main objective of this thesis is to determine the optimized shape among four case studies in Malaysia using simulations to absorb wind energy and increase wind velocity around tall buildings. This shows how detailed modified corners can have the potential to increase wind speed, especially at higher altitudes.

1.7 Specific Objectives

The present study aims to close these research gaps through the following specific research objectives.

To study the current design and shape of high-rise buildings.

To investigate and evaluate the effect of wind on the energy absorption of high-rise buildings in the tropics.

Recommended criteria for future high-rise building designs and shapes

To develop aerodynamic optimization procedures that can identify the optimal building appearance of the selected reinforcement type.

1.8 Thesis Chapter Outline

This thesis is organized into five chapters.

Chapter one has so far introduced the problem under investigation, stated the objectives of research, formulated study hypotheses, and examined the significance of engaging the reader in the research project.

Chapter Two contains background information about the topic under investigation, providing a review of the current design of towers and familiarity with previous work related to the research project. Indicating the niche in the existing work, the current study is linked to the literature.

Chapter three discusses the study design, including the nature of the work, simulation procedure, model construction, and data analysis. The study analytical tool, criteria for the selected aerodynamic optimization procedure (AOP), and validation process are also described.

Chapter four reports the simulation results accompanied by related figures, tables, and charts. This justifies the study results in response to each research hypothesis. The findings of the present study were then compared with those of previous studies.

Chapter five summarizes the study and concludes the paper.

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