THE PREDICTION OF PM2.5 DISPERSION IN BANGKOK (PATHUMWAN DISTRICT) USING CFD MODELING

Miss Punyisa Chaisri

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การทำนายการแพร่กระจายของฝุ่น PM2.5 ในกรุงเทพมหานคร (เขตปทุมวัน) โดยใช้การจำลองพลศาสตร์ของไหลเชิงคำนวณ

น.ส.ปุญญิศา ชัยศรี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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By	Miss Punyisa Chaisri
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Thesis Advisor	Assistant Professor PIMPORN PONPESH, Ph.D.

Accepted by the FACULTY OF ENGINEERING, Chulalongkorn University in Partial Fulfillment of the Requirement for the Master of Engineering

.... Dean of the FACULTY OF ENGINEERING

(Professor SUPOT TEACHAVORASINSKUN, Ph.D.)

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.... Chairman

(Assistant Professor SUPHOT PHATANASRI, Ph.D.)

.... Thesis Advisor

(Assistant Professor PIMPORN PONPESH, Ph.D.)

.... Examiner

(PHUET PRASERTCHAROENSUK, Ph.D.)

.... Examiner

(Associate Professor SOMPONG PUTIVISUTISAK, Ph.D.)

.... External Examiner

(Assistant Professor Tonkid Chantrasmi, Ph.D.)

ปุญญิศา ชัยศรี : การทำนายการแพร่กระจายของฝุ่น PM2.5 ในกรุงเทพมหานคร (เขตปทุมวัน)โดยใช้การจำลองพลศาสตร์ของไหลเชิงคำนวณ. (THE PREDICTION OF PM2.5 DISPERSION IN BANGKOK (PATHUMWAN DISTRICT)USING CFD MODELING) อ.ที่ปรึกษาหลัก : ผศ. ดร.พิมพ์พร พลเพชร

รูปแบบเมือง สภาพอุตุนิยมวิทยา และแหล่งกำเนิดมลพิษ เป็นปัจจัยสำคัญที่ส่งผลต่อความเข้มข้นและการแพร่กระจายของสารมลพิษภายในพื้นที่ที่มีอาคารขนาบถนน การแพร่กระจายของฝุ่น PM2.5 ในเขตปทุมวัน กรุงเทพมหานคร ที่มีลักษณะของพื้นที่ที่มีอาคารขนาบถนน ถูกทำนายโดยใช้แบบจำลองพลศาสตร์ของไหลเชิงคำนวณ การไหลและการแพร่กระจายของฝุ่น PM2.5 ถูกวิเคราะห์โดยใช้แบบจำลองความปั่นป่วนชนิด standard k-ε ความเข้มข้นของฝุ่น PM2.5 ถูกศึกษาภายใต้สภาวะต่างๆ เพื่อแสดงให้เห็นถึงผลของรูปแบบเมืองในพื้นที่ศึกษา ลักษณะทางอุตุนิยมวิทยา และการล็อกดาวน์เนื่องจากโควิด-19 ต่อความเข้มข้นของฝุ่น PM2.5 แบบจำลองเชิงตัวเลขได้รับการตรวจสอบด้วยข้อมูลที่วัดได้จากสถานีตรวจวัดคุณภาพอากาศของสำนักสิ่งแวดล้อม กรุงเทพมหานคร การลดลงของอัตราการปล่อยมลพิษในช่วงล็อกดาวน์ทำให้ความเข้มข้นฝุ่น PM2.5 ลดลงร้อยละ 25.24 จากเวลาปกติ นอกจากนี้ รูปแบบของเมืองที่มีโครงสร้างรถไฟฟ้าจะเพิ่มความเข้มข้นของฝุ่น PM2.5 บริเวณใต้รถไฟฟ้าร้อยละ 21.6 และพื้นที่ห่างจากรถไฟฟ้าร้อยละ 7.05 นอกเหนือจากนี้ ต้องคำนึงถึงสภาพอากาศ โดยเฉพาะความเร็วและทิศทางลมด้วย สุดท้าย ผลลัพธ์ที่ได้จากการจำลองจะถูกนำมาใช้เพื่อเสนอแนวทางในการลดความเข้มข้นของฝุ่น PM2.5

สาขาวิชา	วิศวกรรมเคมี	ลายมือชื่อนิสิต	
ปีการศึกษา	2564	ลายมือชื่อ อ.ที่ปรึกษาหลัก	

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Punyisa Chaisri : THE PREDICTION OF PM2.5 DISPERSION IN BANGKOK (PATHUMWAN DISTRICT)USING CFD MODELING. Advisor: Asst. Prof. PIMPORN PONPESH, Ph.D.

City configuration, meteorological conditions and emission source are the important factors affecting the concentration and dispersion of pollutants within urban street canyon. The dispersion of PM2.5 in Pathumwan district, Bangkok which has a characteristics of street canyon was predicted using a Computational Fluid Dynamics (CFD) model. Flow and dispersion of PM2.5 were analyzed using standard k-ε turbulence model. The concentrations of PM2.5 were investigated under different conditions to demonstrate the effect of city configuration in study area, meteorological characteristics, and lockdown due to COVID-19 on PM2.5 concentration. The numerical model was validated with the measured data from the air quality monitoring station of the Environment Bureau, Bangkok. The reduction of emission rate during lockdown period causing the PM2.5 concentration decreased by 25.24 percent from normal time. Besides, the city configuration with the skytrain structure increases PM2.5 concentration at the area under the skytrain by 21.6 percent and at the area away from the skytrain by 7.05 percent. Moreover, meteorological conditions must also be taken into account especially wind speed and direction. Finally, the results obtained from simulation will be used for proposing the guidelines to reduce the concentration of PM2.5.

Field of Study: Chemical Engineering		Student's Signature ....
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Punyisa Chaisri

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CHAPTER I

INTRODUCTION

1.1 Introduction

Nowadays, Bangkok is facing the air pollution problems that are getting more severe, especially particulate matter (PM) problem. This particulate matter problem is concerned as an important issue due to it can cause the adverse health effects. Fine particulate matter or PM2.5 (PM with an aerodynamic diameter of less than 2.5 micrometers) has an impact on the respiratory system since it can pass through the respiratory tract and deep into the lungs. Then, accumulate there by diffusion and damage other parts of the body through air exchange in the lungs [1]. Furthermore, PM2.5 is also an important contributor to impaired visibility.

Particulate matter can be emitted from two types of sources which are natural sources such as regional wind-blown dust, biogenic emissions and sea salt. The other source is human-made sources such as industry, power generation, mining, construction and motor vehicles [2]. For Bangkok, traffic emission is a major source of particulate air pollution [3]. Since Bangkok is an urban area and also the capital city of Thailand, rapid urban growth causes a fast increase in vehicle population and continues to increase every year lead to traffic congestion. In 2020, there are 834,835 new registered vehicles in the city (292,295 passenger cars; 19,033 buses and trucks; 415,760 motorcycles; and others) [4]. Overcrowded traffic and incomplete combustion of fuel result in the emission of a lot of PM2.5 in an urban area. In addition, the dispersion of pollutants emitted from the vehicle is greatly influenced by the structure of the buildings [5]. In an urban area, most city configurations consist of a relatively narrow street with buildings lined up continuously along both sides called street canyon [6], causing poor ventilation leads to the accumulation of PM2.5 within the city. Furthermore, the influence of the ratio of building height (H) to street width (W) called aspect ratio (H/W) and wind direction [7], ambient building structure and roof shape [8], building spacing and setback configurations [9] can greatly affect the dispersion of PM2.5 in the street canyon too.

Pathumwan, one of the districts of Bangkok, is a street canyon because it is a central business district that consists of large shopping malls along both sides of the road which is quite narrow. Besides, there are tall buildings in the university area and residential area which is the shophouses next to each other along both sides of the road. For the traffic in Pathumwan district, there are a lot of cars pass-through all day. The number of vehicles is related to PM2.5 in ambient. So, a large number of vehicles in Pathumwan district result in a high PM2.5 concentration [10]. Annual average concentrations of PM2.5 in Pathumwan were 28.25, 27.58 and 25.17 $\mu g/m^3$ in the year 2018 2019 and 2020, respectively [11] which exceeded Thailand's national air quality standard annual limit of 25 $\mu g/m^3$.

To control or reduce the concentration of PM2.5 and air pollution effectively, knowledge and understanding about PM2.5 dispersion which is influenced by source, wind direction, meteorological characteristics and city configuration that are specific to the area are necessary to make policy decisions to solve the PM2.5 problem.

For the investigation of the influence of city configuration on flow structures and pollutant dispersion, there are numerous methods and tools include field measurement, physical modeling in wind tunnel and using computational calculations such as computational fluid dynamics (CFD) model. Since field measurement is time-consuming and difficult to keep the parameters the same when the measurement needs to be repeated and the wind tunnel experiment generally takes quite a lot of time and resources compared to computational simulation. Hence, the computational fluid dynamics model is therefore certified as an effective method for investigating the influence of variables on airflow and pollutant dispersion [12, 13] and it has been applied in this research as well.

1.2 Objectives of Research

1.2.1 Develop a suitable of computational fluid dynamics (CFD) model to evaluate the dispersion of PM2.5 in Pathumwan district.

1.2.2 Investigate the influence of city configuration on PM2.5 dispersion using the CFD model.

1.2.3 Propose the guidelines to reduce the concentration of PM2.5 using data from the model.

1.3 Scope of Research

1.3.1 Collect the necessary information which consists of

1.3.1.1 The data of PM2.5 emission sources and PM2.5 concentrations in Pathumwan district at different times.

1.3.1.2 Geographical data of Pathumwan district such as the configuration or characteristics of the city.

1.3.1.3 Meteorological data such as temperature, wind speed and direction.

1.3.2 Investigate and test the mathematical model (standard k-ε model) that is suitable for the transport phenomena of the system.

1.3.3 Validate the model by comparing the model's prediction results with the actual measurement results (PM2.5 concentration and temperature) and if there is a discrepancy, the model will be modified or developed until it can explain or predict the results correctly.

1.3.4 Investigate the influence of city configuration on PM2.5 dispersion.

1.3.5 Propose the guidelines to reduce the PM2.5 concentration.

CHAPTER II

THEORY AND LITERATURE REVIEWS

2.1 Description of the study area

Pathumwan district is located in the city center and covers an area of 8.37 square kilometers. A large part of the district area is taken up by the campus of Chulalongkorn University and large shopping malls, which causes this area to become the street canyon due to the roads are flanked by tall buildings continuously on both sides especially Rama I road. Since Pathumwan is a central business, commercial, service and tourism district, the traffic in this area is always crowded and often faces traffic jam.

For the traffic at Samyan intersection, there are a lot of cars pass-through around 80,000-88,000 vehicles/day while the traffic volume at Pathumwan intersection is around 50,000-69,000 vehicles/day. Chaloem Phao Junction has a traffic volume around 32,000-39,000 vehicles/day and traffic volume at Henri Dunant intersection is 48,000-64,000 vehicles/day [14]. A large number of vehicles cause a lot of PM2.5 emissions, results in high PM2.5 concentrations in Pathumwan.

2.2 PM2.5

PM2.5 is a fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller. Most of PM2.5 in the atmosphere as a result of complex reactions of chemicals such as sulfur dioxide and nitrogen oxides, which are pollutants emitted from power plants, industries and automobiles. Some are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires [15].

Of all air pollution measures, PM2.5 is believed to pose the greatest risk to health. Due to its small size, it can remain suspended in the air for long periods and can get deep into the lungs and some may even get into the bloodstream. This can cause respiratory illnesses such as asthma, bronchitis, and emphysema. For short-term symptoms to high levels of particulate matter include irritation of the eye throat and nose, irregular heartbeats, asthma attacks, coughing, chest tightness, and shortness of breath. Moreover, there are also environmental effects such as reduced visibility, damage of materials, acid deposition and increased ozone levels [16].

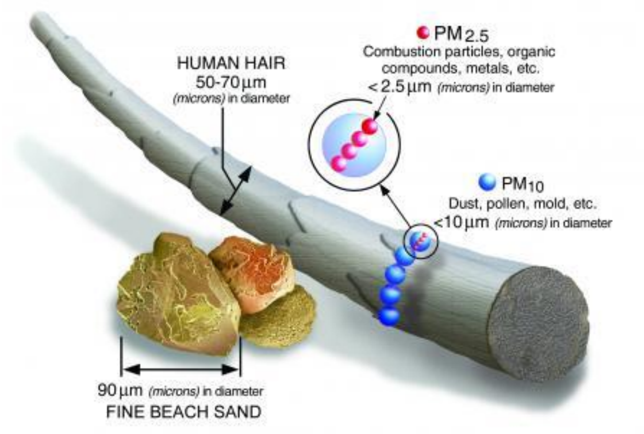


Figure 1 Size comparisons for PM particles [15]

2.3 Street canyon

The term street canyon refers to a relatively narrow street flanked by buildings continuously on both sides. However, a broader definition of the term has been applied by allowing for some openings on the walls of the canyon.

2.3.1 Canyon geometry and classification

A street canyon will be a symmetric canyon, if the buildings flanking the street have approximately the same height. The dimension of a street canyon is expressed by its aspect ratio, H/W (the ratio of building height to street width) and L/W (the ratio of building length to street width) (Figure 2). Based on the values of aspect ratios, street canyons can be classified as listed in Table 1. On the other hand, a street canyon will be asymmetric canyon if there are significant differences in building height. Asymmetric canyon can be classified into two categories depending on the height of the upwind (H_A) or downwind (H_B) buildings (Table 1) with respect to the wind direction [17].

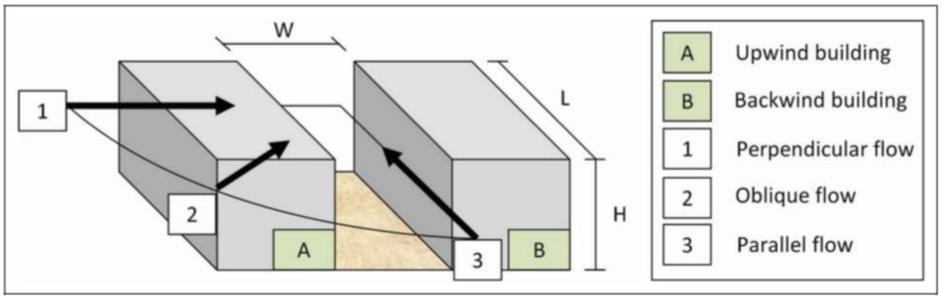


Figure 2 Geometry of a street canyon [17]

Table 1 Classification of street canyons.

Aspect ratio	Classification
$H/W \leq 0.5$	Avenue canyon
$0.5 < H/W < 2$	Regular canyon
$H/W \geq 2$	Deep canyon
$L/W \leq 1$	Short canyon
$1 < L/W < 5$	Medium canyon
$L/W \geq 5$	Long canyon
$H_A > H_B$	Step-down canyon
$H_A < H_B$	Step-up canyon

2.3.2 Wind direction

When the roof level or background wind direction is perpendicular to the street, a vertically rotating wind flow is created with a centered primary vortex inside the street canyon. The up-wind side of the canyon is usually called leeward, and the down-wind side is called windward as shown in Figure 3.

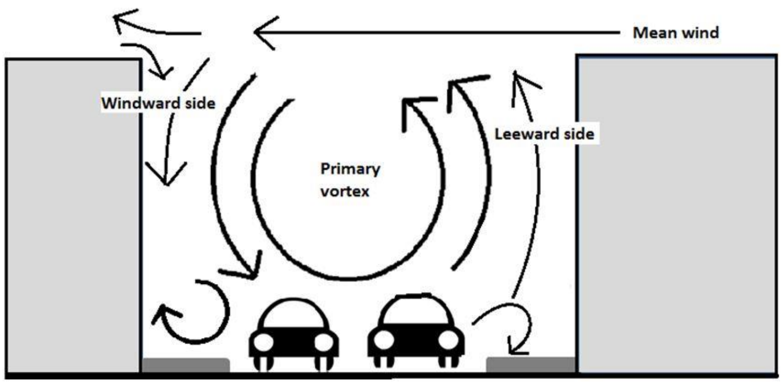


Figure 3 Wind flow in the street canyon [18]

Based on the aspect ratio, different flow regimes are defined in street canyons. The flow regimes when the aspect ratio increases are (a) isolated roughness flow, (b) wake interference flow and (c) skimming flow (Figure 4).

In the case of wide canyons (H/W < 0.3), the buildings are well spaced and act as isolated roughness elements, there is a sufficient distance for air to flow before encountering the downwind (or backwind) building. When buildings become more closely (H/W≈ 0.5), the air flow has insufficient distance to readjust before encountering the downwind building, resulting in wake interference flow. For regular canyons (H/W≈1), the bulk of the synoptic flow skims over the canyon producing the skimming flow which is characterized by the formation of a single vortex within the canyon [19].

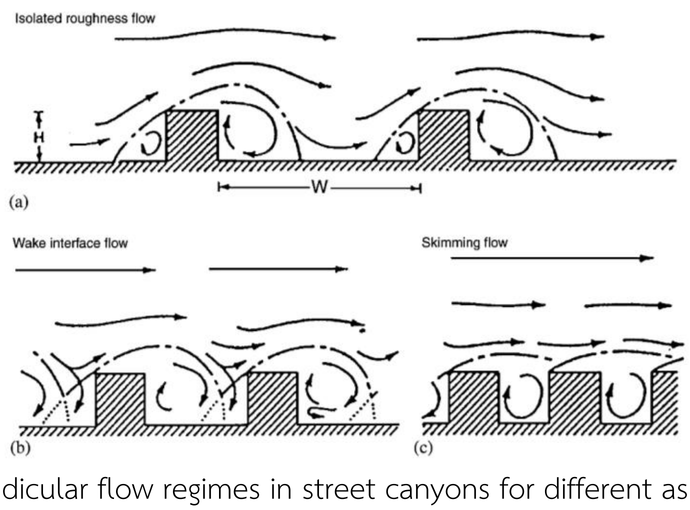


Figure 4 Perpendicular flow regimes in street canyons for different aspect ratios [20]

In case of oblique flow, it induces a helical vortex with a corkscrew type action along the length of canyon. Since the angle of incidence on the windward wall is similar to the reflection angle of the wall, resulting in the formation of helical vortex across the canyon.

When the flow is parallel to the street axis, the flow within the street canyon is in the same direction as the flow above the roof and the mean vertical velocity is almost zero. A channelization effect is seen where winds tend to be channeled and accelerated through the canyon. Since the street width is non-uniform, a venturi effect occurs when winds flow through small openings, further enhancing the wind velocity.

For a deep street canyon (H/W≈ 2), two vortices are developed where an upper vortex is driven by the ambient air flow at roof level and a lower vortex is weakly driven in the opposite direction by the upper vortex. For a higher aspect ratio (H/W≈3), a third weak vortex might be also formed vertically aligned in a deep street canyon and the strength of the lower vortices is relatively weak compared to vortex at roof level [17].

2.3.3 Wind speed

A low wind speed (less than 1.5-2.0 m/s) does not produce a vortex within the street canyon so the air inside canyon is almost stagnant, which in turn reduces air ventilation. Hence, low wind speed has no significant effect on the flow structure and pollutant dispersion no matter direction the wind blows from. On the other hand, when the wind speed above the canyon is more than 1.5-2.0 m/s, the vortex is formed.

For high wind speed above roof level, the multiple vortices will become only one vortex due to the intensification of upper vortex. The intensification of a vortex helps the pollutants enable to disperse out of the street canyon more effectively, resulting in the enhancement of air quality [17].

2.3.4 Thermal effects

In daytime, the atmospheric condition is affected by temperature, where the solar radiation will heat up ground surfaces, building facades and building roofs which in turn heats up the ambient temperature in the vicinity of the buildings and leads to thermally unstable conditions. The stability condition of atmosphere and different heated building walls contribute to the changes of air flow and pollutant dispersion in the street canyons.

2.3.4.1 Thermal stability

The thermal stability can be categorized as stable, neutral (isothermal) and unstable based on Richardson number, Ri

$$Ri = \frac{gH(T_{ref} - T_W)}{(T_{ref} + 273)U_{ref}^2} \quad \text{(Eq. 1)}$$

where g is the gravitational acceleration, H is the building height, U_{ref} is the reference wind speed, T_{ref} is the reference temperature and T_W is the wall temperature.

Ri = 0 corresponds to neutral case, Ri < 0 corresponds to unstable case and Ri > 0 corresponds to stable case. Furthermore, the characteristic of the flow based on Ri can also be determined as follows:

Laminar flow becomes turbulent when Ri < R_c

Turbulent flow becomes laminar when Ri > R_T

where R_c is the critical Richardson number for the onset of turbulence and R_T is the critical Richardson number for the termination of turbulence. The typical values of R_c and R_T are 0.21-0.25 and 1.0, respectively.

The thermal stability has significant effects on the flow structure and pollutant dispersion. The primary vortex formed in between buildings becomes weaker when under stable atmosphere. The low intensity of the vortex will create stagnation of the flow at the bottom of canyon, which in turn prevents the pollutant from being transported upward. In contrast, the intensity of the vortex becomes stronger when atmospheric conditions are unstable as a result of the enhancement of turbulence and thus help in better pollutant removal. Hence, the pollutant concentration for stable case is much higher compared to neutral and unstable cases.

2.3.4.2 Different wall heating conditions

Different wall heating is caused by different incident angle of solar radiation, which leads to a different surface location of the wall being heated. In the case of ground surface or leeward wall being heated up, the intensity of the primary vortex is strengthened due to the upward motion of the air near the heated leeward wall or ground surface, resulting in better air quality. For windward wall heating, the primary vortex is split into two due to the buoyancy force on the windward wall, which opposed the circulation of the primary vortex resulting in reduction of air quality [17].

2.3.5 Pollutant dispersion

The dispersion of pollutants in a street canyon depends on the rate of exchanging air vertically between the street and the above-roof level atmosphere and laterally with connecting streets.

Perpendicular and oblique wind exhibit higher pollutant concentration on the leeward side compared to the windward side. The increased pollutant concentration on leeward side is due to the accumulation of pollutants carried from the source to leeward wall by the wind vortex. In the case of parallel flow, the pollutant concentration is identical on both of the leeward and windward walls. For all wind directions, the pollutant concentrations decrease along with height above the ground on both sides of the street [17, 19].

2.4 Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation. CFD applies numerical methods called discretization to develop approximations of the governing equations of fluid mechanics in the fluid region of interest. CFD techniques have been increasingly applied to the simulation of atmospheric problems since CFD models can provide a useful method for the investigation of the air flow in complex street configurations as well as for the assessment and prediction of air pollution dispersion in the city.

The CFD simulation process consists of three main steps, including pre-processing, solver and post-processing.

1) Pre-processing is the first step in building and analyzing a flow model. It includes the preparation of geometry, creating and applying a suitable computational mesh, setting up the material properties, initial and boundary conditions.
2) Solving is the step that the CFD solver will first approximate numerically the unknown flow variables, then discretizes the governing flow equations using these approximations and finally solves the resulting system of algebraic equations.
3) Post-processing is the final step in CFD analysis. It involves the organization and interpretation of the predicted flow data and the production of CFD images and animations. Besides, the results can be analyzed by different methods such as contour plots, vector plot, streamlines or data curve for appropriate graphical representations and report.

FLUENT is one of the most popular CFD codes. Hence, ANSYS Fluent from ANSYS Inc. was chosen to be used in this study. It provides comprehensive modeling capabilities for a wide range of incompressible and compressible, laminar and turbulent fluid flow problems. Steady-state or transient analyses can be performed. In ANSYS Fluent, a broad range of mathematical models for transport phenomena is combined with the ability to model complex geometries.

2.5 Mathematical model

The mathematical model used for the prediction of PM2.5 dispersion in this study are as follows:

2.5.1 Governing equations

The governing equations are based on the conservation of mass, momentum and energy as shown in Eq. 2-4.

2.5.1.1 Mass Conservation Equation

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \qquad \text{(Eq. 2)}$$

where ρ is the fluid density and u_i is the flow velocity.

2.5.1.2 Momentum Conservation Equation

The momentum conservation (Navier-Stokes) equation or Newton's second law can be written as follows:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g \qquad \text{(Eq. 3)}$$

where p is the static pressure, μ is the molecular viscosity and ρg is the gravitational body force.

2.5.1.3 Energy Conservation Equation

$$\frac{\partial \rho e}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i e) + \frac{\partial \rho \mathrm{K}}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i \mathrm{K}) + \frac{\partial}{\partial x_i}(u_i p) = \nabla \cdot \left(\alpha_{eff} \nabla e\right) + \rho g u_i \qquad \text{(Eq. 4)}$$

where e is the thermal energy, K is the kinetic energy, g is the gravitational acceleration and α_{eff} is the effective thermal diffusivity defined as the sum of laminar and turbulent thermal diffusivities.

The kinetic energy, K, is given by

$$\mathrm{K} = \frac{|u_i|^2}{2} \qquad \text{(Eq. 5)}$$

2.5.2 Reynolds Averaged Navier-Stokes (RANS) Equation

The Reynolds averaged Navier-Stokes (RANS) equations are a mathematical model of turbulent flow that introduces additional terms in the governing equations that need to be modeled in order to include the turbulence effects [21]. Due to the high Reynolds number and the city configuration resulting in turbulent flow in the system, so the RANS equations are employed for the mean flow field in the street canyon. The RANS equations can be calculated from the conservation equation of mass and momentum by substituting the flow variables with the mean and fluctuation which can be expressed by Eq. 6 and 7.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho \overline{u_i}) = 0 \qquad \text{(Eq. 6)}$$

$$\frac{\partial}{\partial t}(\rho \overline{u_i}) + \rho \overline{u_j} \frac{\partial \overline{u_i}}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)\right] + \rho g + \frac{\partial}{\partial x_j}\left(-\rho \overline{\acute{u}_i \acute{u}_j}\right) \qquad \text{(Eq. 7)}$$

where $\overline{u_i}$ and $\overline{u_j}$ are the mean velocity components in the different directions, $\acute{u}_i$ and $\acute{u}_j$ are the fluctuating velocity components in different directions. The added Reynolds stresses $\left(-\rho \overline{\acute{u}_i \acute{u}_j}\right)$ term made it impossible to solve the two conservation equations because of the extra variable. This requires the turbulence model to help in the calculation.

2.5.3 Turbulence model

The RANS equations are modeled by various two-equation turbulence models such as k-ε models and k-ω models [22].

The common method for the simulation of turbulent flow and pollutant dispersion in street canyon is the k-ε two-equation model due to their robustness and efficiency [5, 22]. Xie et al. [8] reported that the standard k-ε turbulence model is the most optimum turbulence model among k-ε model variants (standard, RNG and Chen-Kim) for calculating the pollutant dispersion in street canyon. Therefore, the standard k-ε turbulence model was selected for this study and its equation can be written as follows:

Transport equations for the standard k-ε model

Turbulent kinetic energy (k) transport equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \bar{u}_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \qquad \text{(Eq. 8)}$$

Turbulent dissipation rate (ε) transport equation:

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon\bar{u}_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \qquad \text{(Eq. 9)}$$

where k is the turbulent kinetic energy, ε is the turbulent dissipation rate, G_k represents the generation of turbulent kinetic energy due to the mean velocity gradients. G_b is the generation of turbulent kinetic energy due to buoyancy. $C_{1\varepsilon}$, $C_{2\varepsilon}$ and $C_{3\varepsilon}$ are constants. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, respectively.

The turbulent (or eddy) viscosity, μ_t, is computed by combining k and ε as follows:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \qquad \text{(Eq. 10)}$$

where C_μ is a constant.

The term G_k, representing the production of turbulent kinetic energy due to the velocity gradients, is defined as

$$G_k = -\rho\overline{u_i' u_j'}\frac{\partial \overline{u_j}}{\partial x_i} \quad \text{(Eq. 11)}$$

The generation of turbulence due to buoyancy (G_b) is given by

$$G_b = \beta g_i \frac{\mu_t}{Pr_t}\frac{\partial T}{\partial x_i} \quad \text{(Eq. 12)}$$

where Pr_t is the turbulent Prandtl number for energy and g_i is the component of the gravitational vector in the ith direction. For the standard k-ε turbulence model, the default value of Pr_t is 0.85. The coefficient of thermal expansion, β, is defined as

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p \quad \text{(Eq. 13)}$$

The model constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_{μ}, σ_k and σ_ε have the following default values:

$C_{1\varepsilon}$ = 1.44, $C_{2\varepsilon}$ = 1.92, C_{μ} = 0.09, σ_k = 1.0, σ_ε = 1.3

For $C_{3\varepsilon}$ constant, it is calculated according to the following relation:

$$C_{3\varepsilon} = tanh\left|\frac{v}{u}\right| \quad \text{(Eq. 14)}$$

where v is the component of the flow velocity parallel to the gravitational vector and u is the component of the flow velocity perpendicular to the gravitational vector.

$C_{3\varepsilon}$ will become 1 for buoyant shear layers for which the main flow direction is aligned with the direction of gravity. For buoyant shear layers that are perpendicular to the gravitational vector, $C_{3\varepsilon}$ will become zero.

2.5.4 Pollutant trajectories

The Discrete Phase Model (DPM) was used to simulate particles trajectories. The trajectory of a discrete phase particle is predicted by integrating the force balance on the particle. This force balance equates the particle inertia with the forces acting on the particle, and can be written (for the x direction in Cartesian coordinates) as

$$m_p \frac{du_p}{dt} = m_p \frac{u-u_p}{\tau_r} + m_p \frac{g_x(\rho_p-\rho)}{\rho_p} + F_x \qquad \text{(Eq. 15)}$$

where m_p is the particle mass, u is the fluid phase velocity, u_p is the particle velocity, ρ is the fluid density, ρ_p is the density of the particle, F_x is an additional force, $m_p \frac{u-u_p}{\tau_r}$ is the drag force, and τ_r is the particle relaxation time calculated by:

$$\tau_r = \frac{\rho_p d_p^2}{18\mu} \frac{24}{C_d Re} \qquad \text{(Eq. 16)}$$

Here, μ is the molecular viscosity of the fluid, d_p is the particle diameter, and Re is the relative Reynolds number, which is defined as

$$Re \equiv \frac{\rho d_p \left|u_p-u\right|}{\mu} \qquad \text{(Eq. 17)}$$

When the flow is turbulent, ANSYS Fluent will predict the trajectories of particles using the mean fluid phase velocity, $\bar{u}$ and instantaneous value of the fluctuating gas flow velocity, $\acute{u}$ to predict the dispersion of the particles due to turbulence.

$$u = \bar{u} + \acute{u} \qquad \text{(Eq. 18)}$$

2.6 Literature reviews

Zhang, H., et al. (2015) [5] analyzed the influences of the relative height of buildings on both sides of the street canyon on the air flow field and pollutant concentration field when the direction of wind is perpendicular to the street. Besides, the effects of non-isolated street canyon and aspect ratio on the flow field and the distribution of the pollutants were also studied. By using the numerical simulation method, the results showed that the pollutant dispersion in street canyon is greatly influenced by the street canyon structure. For the case that the height of the leeward building is lower than that of the windward building, a clockwise vortex was formed inside the canyon. It resulted that the concentration of pollutants on the leeward side was higher than the windward side. Dominant airflow flited the top of the street canyon causing the velocity of the vortex was relatively small, so the pollutant dispersion was weaker. In contrast, when the height of leeward building is higher than that of windward building, a counterclockwise vortex was formed inside the canyon while in the upper part of the windward building formed a clockwise vortex. Due to the special air movement inside street, it was difficult to spread out the pollutants and the pollutant concentration on the windward side was higher than the leeward side. In the case of aspect ratio, the increase of aspect ratio increased pollutant concentration. For the non-isolated street canyon, the pollutant was more difficult to spread out compared with the isolated street canyon.

Crowther, J.M. and A.G.A.A. Hassan. (2002) [7] simulated the effects of canyon geometry and wind direction on pollutants distribution by using PHOENICS CFD software package with a standard k-ε turbulence model. The results indicated that the pollutant concentration increased when the aspect ratio increased. For wider canyon (low aspect ratio), the exchange of air between street level and above roof-level was sufficient to dilute the pollutant concentration within street. If the street canyon become deeper (high aspect ratio), air exchange was restricted led to high street-level concentration. In addition to the aspect ratio, street length also affected the pollutant concentration. Reducing the street length helped to reduce street-level pollution in street canyon. Besides, pollutant dispersion was also significantly affected by the variability in wind direction. For wind direction normal to the street, the concentrations at the leeward side were greater than at the windward side. When the wind was parallel to the street, the pollutant concentrations along the street on both sides were identical and higher in the middle of the street. The concentration reached a minimum value when the wind was oblique.

Xie, X., Z. Huang, and J.-s. Wang. (2005) [8] investigated the effects of building geometry and ambient building structures on pollutant dispersion. All the calculations were performed using the PHOENICS code with the standard k-ε turbulence model. The flow field can be influenced not only by the configuration of street buildings but also the configuration of ambient buildings. When the height of leeward building of the upstream street was enhanced, the clockwise vortex in the studied canyon was coupled with the clockwise vortex in the upper region. As a result, the vortex in the studied street become distortional and the vortex center moved upward so the fluxion in the street canyon weakened, resulting in the high pollutant concentration. In another case, when the height of leeward building of the upstream street and the windward building of the downstream street were enhanced at the same time, the vortex center would become higher and the fluxion in the street canyon become weaker. Hence, the street canyon which high buildings flanked on both sides of street had the highest concentration. For the investigation of the effect of building geometry, the results showed that the spaces between buildings increased the quantity of the new air entered the street canyon. So, more pollutants were transported out of the canyon.

Wang, P., et al. (2011) [23] investigated the impact of solar radiation on air flow structure and pollutant dispersion in street canyon using the CFD technique. In the simulation, the temperature difference between the air and the ground surface and building facade was set to 10 °C. The results indicated that heating from building wall surfaces and ground led to strong buoyancy forces as the air was heated by the wall surface when receiving direct solar radiation. This thermally induced buoyancy had a significant role in determining flow fields within street canyon. When the leeward side of the buildings and the ground were heated, the airflow structure and pollutant dispersion patterns were similar to that without solar radiation, the buoyancy flux added to the upward advection flux along the wall strengthening the original vortex. This effect intensified the pollutant dispersion and caused the pollutant concentration in street canyon to decrease. On the other hand, solar heating had an important impact on the air flow structure when the windward side was heated. It produced an upward buoyancy flux that opposed the downward advection flux along the wall then the flow structure was divided into a clockwise top vortex and a reverse lower vortex inside the canyon. As a result, the pollutants were accumulated at the windward side and the pollutant concentrations in the canyon increased.

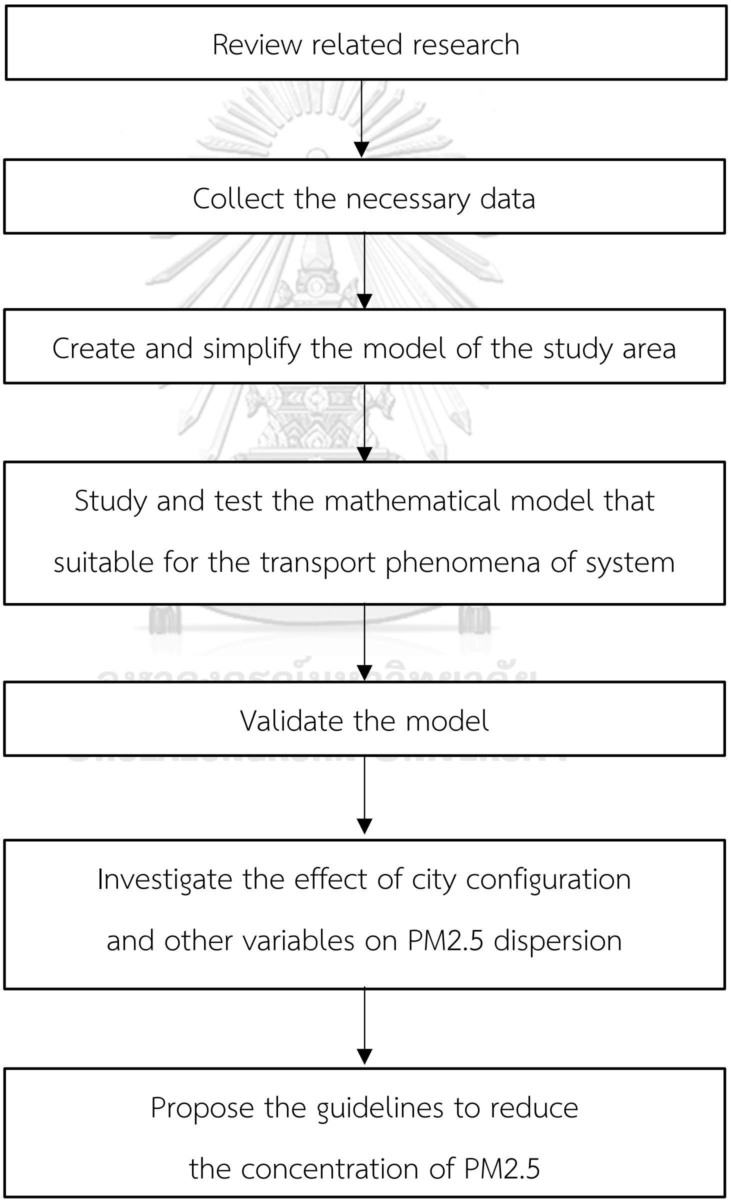
Walaipan Yeemadarlee. (2018) [10] studied the impact of traffic flow on PM2.5 emissions at two traffic junctions which are Pathumwan intersection and Odeon Circle Yaowarat roundabout. The PM2.5 concentrations were collected 12 hours/day within working hours on weekdays and weekends. While the traffic flow and number of vehicles were recorded by video recorder (CCTV) at the same date and time. The results showed that the highest PM2.5 concentration was found in Pathumwan intersection that had the number of vehicles more than in Odeon Circle Yaowarat roundabout. From the relationship between PM2.5 concentrations and traffic conditions, the linear regression of Pathumwan intersection showed a significant relationship between PM2.5 and traffic flow and number of vehicles, r=0.84. While the linear regression of Odeon Circle Yaowarat roundabout, r=0.48, did not show a significant relationship between PM2.5 and traffic volume.

CHAPTER III

METHODOLOGY

3.1 Research methodology

The research methodology for the simulation of air flow field and PM2.5 dispersion in Pathumwan district shows in following flowchart.



3.2 Physical model configuration

The study area in Pathumwan district has an area of around 1.95 square kilometers, covering the area with Bangkok's air quality monitoring station and the area with high aspect ratio which is the shopping center area with the skytrain structure. The scope of focused area is in yellow frame shown in Figure 5.

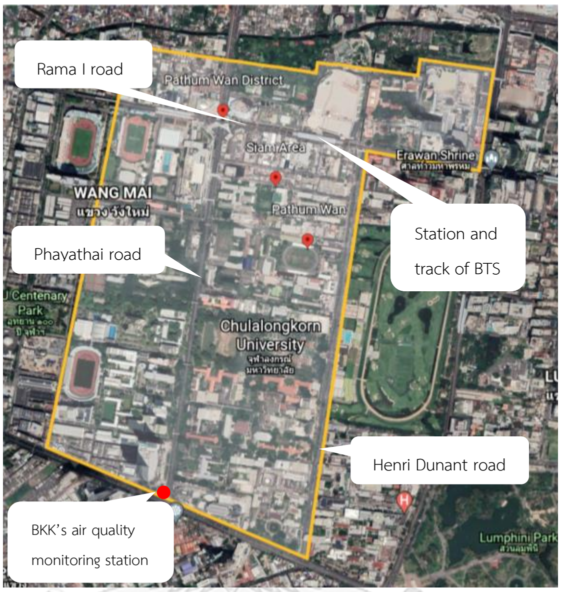


Figure 5 The scope of focused area in Pathumwan district.

3.3 Simulation setup

3.3.1 Computational domain

Lateral and upper boundaries of the domain were placed about 1.25 times of Hmax far from the study area, where Hmax is the highest height of the building on each side. Since the distance of 1.25 times of the building's height is the reattachment length that velocity profile does not affected by the building [24].

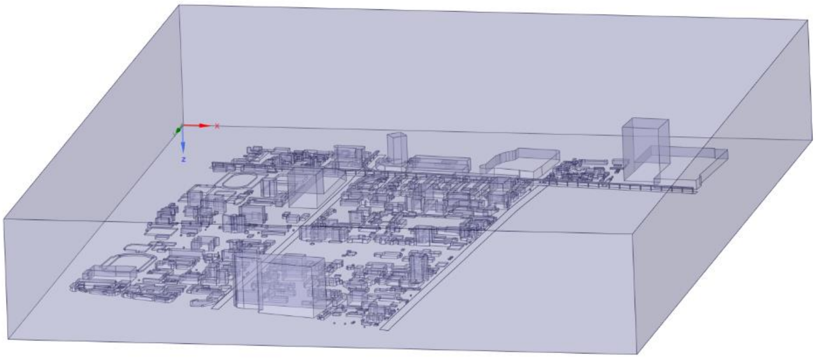
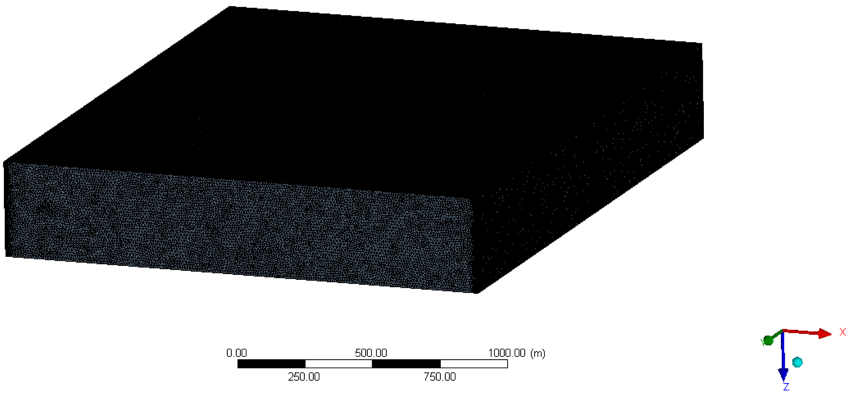


Figure 6 Computational domain for the CFD simulation.

3.3.2 Mesh

The mesh was made of about 4.8 million elements, with the element size of 10 m. For the edge sizing, element size along the roadside was set to 2.5 m which equals to the shortest distance between the road and the building and element size at the corner of enclosure was set to 3.5 m which equals to the lowest building. The value of skewness and aspect ratio are 0.23 and 1.86, respectively.



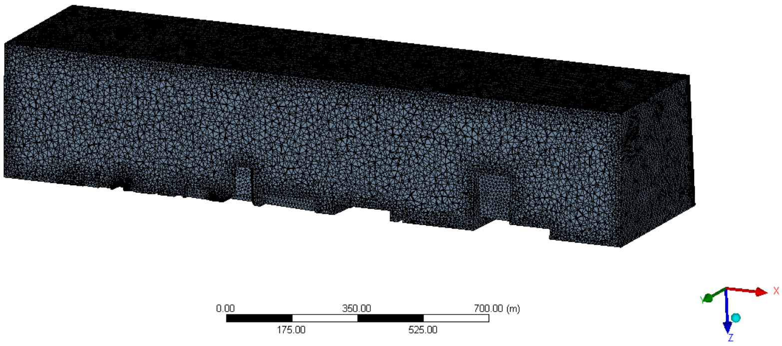


Figure 7 Detail of the mesh.

3.3.3 Boundary conditions

Steady-state simulations were performed using ANSYS 19.2 with the RANS standard k-ε turbulence model. At the inlet boundary, the temperature, wind velocity and direction were specified using the data from the Bangkok's air quality monitoring station at the study period. The turbulence specification method was specified as K and Epsilon which turbulent kinetic energy (k) and turbulent dissipation rate (ε) were calculated by the Eq. 19 and 21.

$$k = \frac{3}{2}\left(u_{avg} I\right)^2 \qquad \text{(Eq. 19)}$$

$$I = 0.16\left(Re_{D_H}\right)^{-1/8} \qquad \text{(Eq. 20)}$$

where u_{avg} is the mean flow velocity and I is the turbulence intensity.

$$\varepsilon = \frac{k^{3/2}}{l} \qquad \text{(Eq. 21)}$$

The turbulence length scale (l) is given by

$$l = \frac{0.07 D_H}{C_\mu^{3/4}} \qquad \text{(Eq. 22)}$$

where D_H is the hydraulic diameter.

The outlet boundary was set as the pressure outlet which equals the atmospheric pressure. Symmetry condition was applied for the upper and lateral boundaries. Stationary wall and no-slip condition were applied to the ground surfaces and building walls, where the temperature can be specified. The maximum temperature difference at midday between the air and the road surface can reach 12-14 °C, with a road surface made from asphalt [25]. Then, the temperature of road (T_R) was set to 13°C higher than the air. For the traffic exhausts, a Discrete Phase Model (DPM) was used for simulating the PM2.5 injection and dispersion [26]. Carbon which is the major element in PM2.5 [27] was set to inject at the road surfaces with a particle diameter of 2.5×10^{-6} m (PM2.5). The mass flow rate of PM2.5 emitted from the source was calculated by the following equation [28]:

$$Emission\ rate\ (\frac{kg}{s}) = \frac{\sum Q_i \cdot f_i \cdot l}{3600} \quad \text{(Eq. 23)}$$

where Q_i is the traffic volume of a type i motor vehicle (veh/h), f_i is the emission factor of the type i motor vehicle (kg/(km·veh)) and l is the length of the road (km).

The emission factors of each vehicle types are shown in Table 2 [10].

Table 2 PM2.5 emission factors for mobile sources.

Vehicle type	**Emission factor (g/km)**
Two wheeler	0.0035
Three wheeler	0.0114
Passenger car	0.0011
Heavy commercial vehicles	0.0783

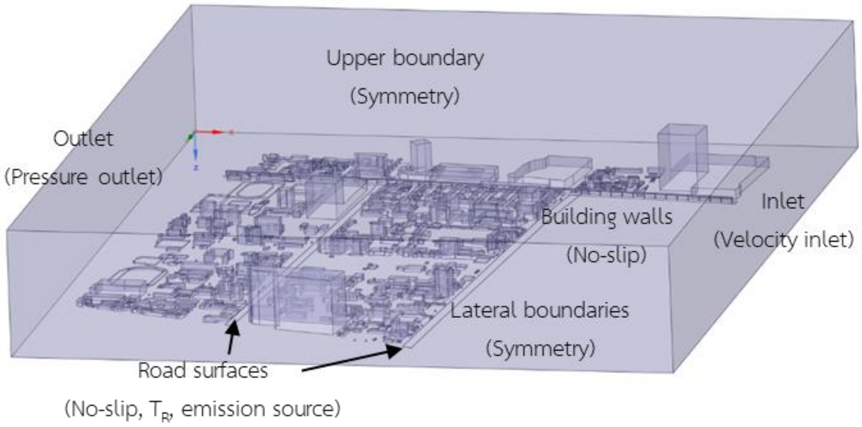


Figure 8 Boundary conditions for the CFD simulation setup.

3.4 Investigation of the effect of city configuration and other variables on PM2.5 dispersion

The investigation of the effect of city configuration and other variables on PM2.5 dispersion was divided into 4 cases, which are the effect of skytrain structure in the focused area, the effect of lockdown, the effect of distance from road and the influence of tall building on PM2.5 concentration. These cases have different city configuration, meteorological conditions and different number of vehicles which are the important factors that affect the air flow and PM2.5 dispersion in the street canyon. Besides, the change in PM2.5 concentration during the morning, noon and evening were also investigated to study the influence of the change in meteorological conditions and emission rate during the day on PM2.5 concentration.

3.5 Propose the guidelines to reduce the PM2.5 concentration

From the investigation of the effect of city configuration and variables on PM2.5 dispersion, it will lead to the guidelines to reduce the concentration of PM2.5 in the study area to not exceed the daily standard of 50 $\mu g/m^3$.

CHAPTER IV
RESULTS AND DISCUSSION

4.1 Model validation

The numerical model was validated with the measured data from the air quality monitoring station of the Environment Bureau, Bangkok which located in front of Samyan Mitrtown. The results from simulation were compared with the measured data at a height of 2.5 m based on the principle of installing an air sampling station [29].

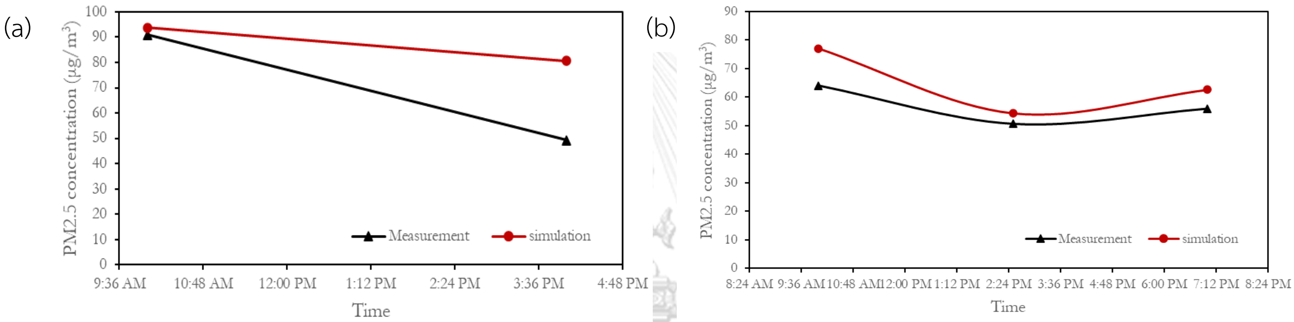


Figure 9 Validation results of PM2.5 concentration on (a) 14 Jan 2019 (normal time), (b) 21 Jan 2021 (lockdown).

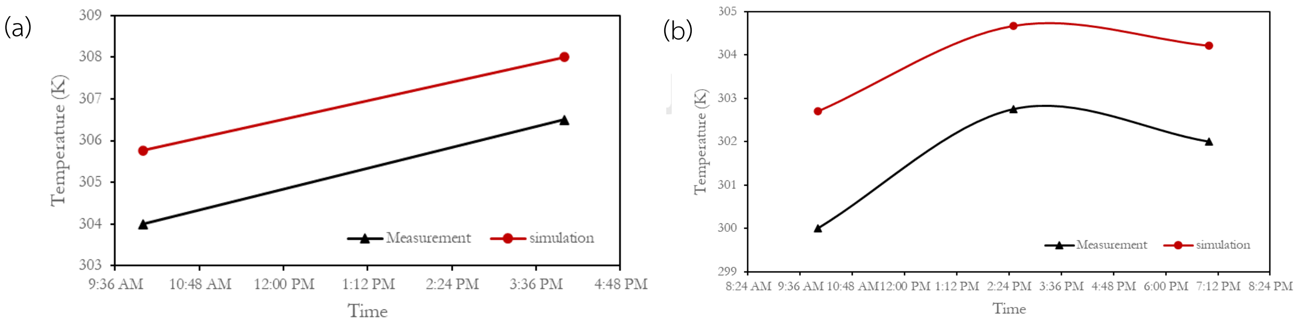


Figure 10 Validation results of temperature on (a) 14 Jan 2019 (normal time), (b) 21 Jan 2021 (lockdown).

The validation shows that the numerical model can be used for predicting the pollutant dispersion within the street canyon since the validation results of PM2.5 concentration and temperature profiles in Figure 9 and 10, respectively, show good agreement. For Figure 9(a)-(b), the simulated PM2.5 concentrations at normal time and lockdown period were divided by the correction factor of 30 and 35, respectively, before being compared with the measured data. In addition, the limitation on meteorological data from the air quality monitoring station at normal time causing only 2 data-point present in the validation plots.

4.2 The effect of skytrain structure on PM2.5 concentration

Since there is a high-rise building area with the skytrain structure in Pathumwan district, the stations and track of skytrain located between tall buildings causes poor ventilation leads to the accumulation of pollutants. So, the effect of skytrain structure on PM2.5 concentration in the focused area at normal time (14 Jan 2019) must be investigated.

4.2.1 The effect of skytrain structure on PM2.5 concentration at the air quality monitoring station area

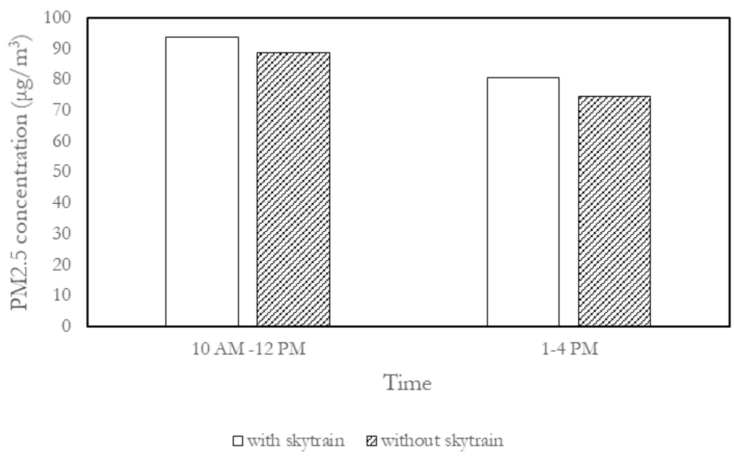


Figure 11 Effect of skytrain structure in Pathumwan district on PM2.5 concentration at the air quality monitoring station area (simulated based on the traffic volume and meteorological data on 14 Jan 2019).

Table 3 Emission rate and meteorological data around air quality monitoring station, Phayathai road on 14 Jan 2019.

Time	Wind speed (m/s)	Wind direction	Temperature (K)	Emission rate (kg/s)
10 AM – 12 PM	0.2	←	305.8	9.89e-06
1 – 4 PM	0.31	←	308.0	1.48e-05

Figure 11 shows the comparison of PM2.5 concentration at the air quality monitoring station area between with and without skytrain structure in Pathumwan district. It is found that the presence of the skytrain structure in Pathumwan district increases PM2.5 concentration at the air quality monitoring station area, which is away and in the south direction from the skytrain structure, by about 7.05 percent. In addition, the PM2.5 concentration at 1-4 PM is lower than at 10 AM-12 PM although the emission rate is higher because wind speed at 1-4 PM is higher so it helps the pollutants enable to disperse out better than low wind speed. Moreover, the high temperature will help reduce pollutant concentration since the heated air will rise vertically and strengthen pollutant dispersion.

4.2.2 The effect of skytrain structure on PM2.5 concentration at the area under the skytrain

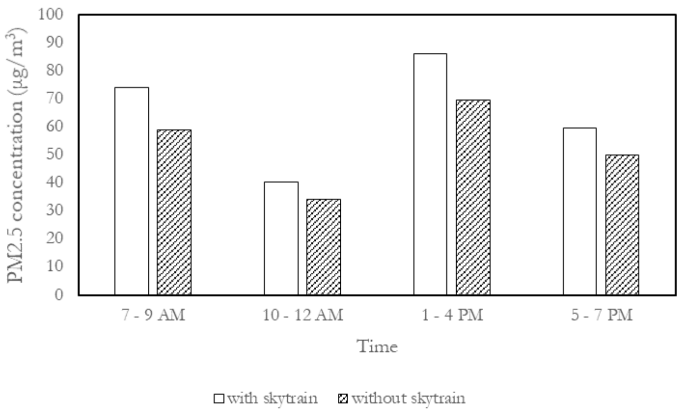


Figure 12 Effect of skytrain structure on PM2.5 concentration at the area under skytrain (simulated based on the traffic volume and meteorological data on 14 Jan 2019).

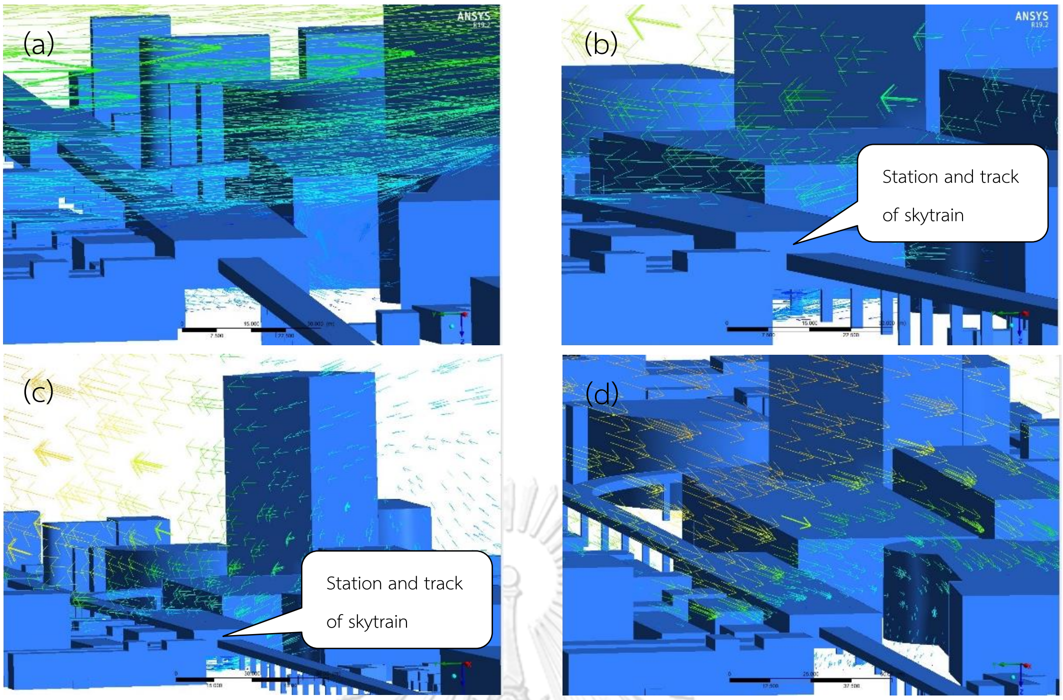


Figure 13 Airflow fields around the skytrain structure on Rama I road during (a) 7-9 AM, (b) 10AM – 12PM, (c) 1-4 PM and (d) 5-7 PM.

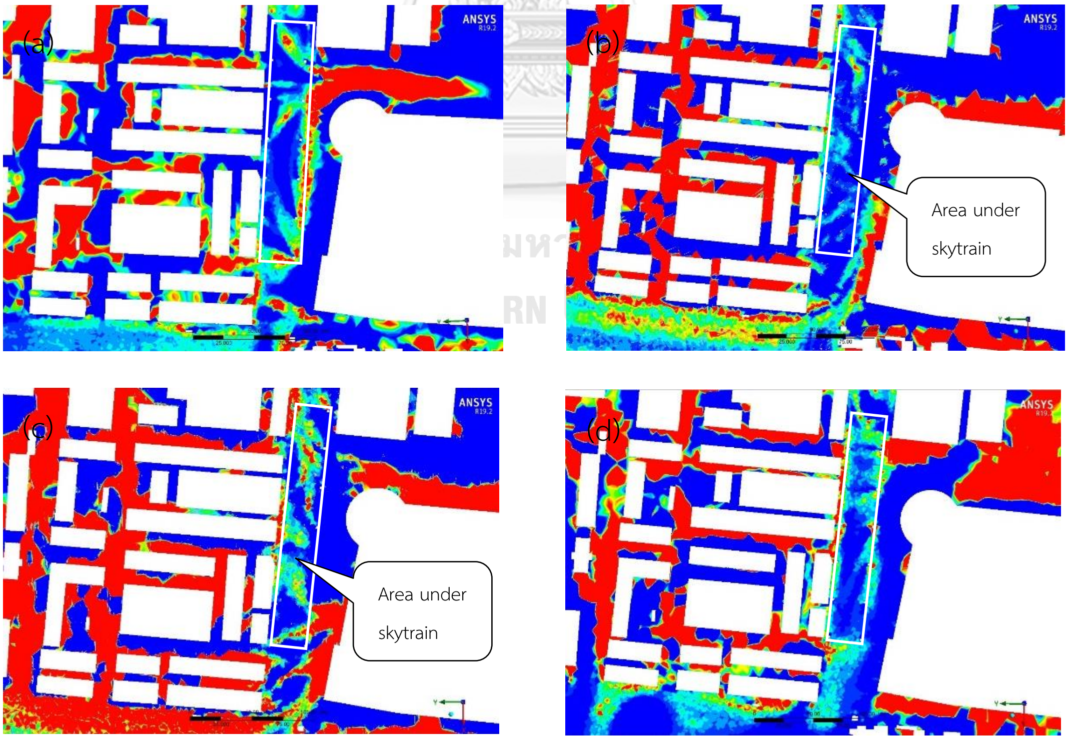


Figure 14 PM2.5 concentration contour at the area under the skytrain on Rama I road during (a) 7-9 AM, (b) 10AM – 12PM, (c) 1-4 PM and (d) 5-7 PM.

Table 4 Emission rate and meteorological data around Rama I road on 14 Jan 2019.

Time	Wind speed (m/s)	Wind direction	Temperature (K)	Emission rate (kg/s)
7 – 9 AM	0.04	↑	302.9	6.24e-06
10 AM – 12 PM	0.08	←	306.3	6.47e-06
1 – 4 PM	0.13	←	309.1	9.71e-06
5 – 7 PM	0.07	→	307.9	6.64e-06

The PM2.5 concentration at the area under skytrain between with and without skytrain structure is shown in Figure 12. It can be seen that PM2.5 concentration in the case with skytrain increased by 21.6 percent from the case without skytrain. Due to the stations and track of skytrain are the construction that obstruct the flow of air and the surroundings of skytrain are tall buildings of shopping malls, thus making the ventilation worse. The highest concentration of PM2.5 occurs at 1-4 PM which is the period with the highest emission rate compared to other periods. Besides, the wind at 1-4 PM flows parallel to the street under the track of skytrain (as shown in Figure 13(c)), so the pollutants will be carried by airflow along the street and not disperse out causing high concentration. Next, 7-9 AM is the period with the second highest concentration. Although it is the period with the lowest emission rate but due to the lowest wind speed causing the wind that flows perpendicular to the Rama I road under the skytrain can carry less pollutant away from the canyon. So, the pollutants accumulate and lead to high pollutant concentration. Besides, temperature at the period of 7-9 AM is the lowest. So, the influence of thermal effect that will reduce the concentration of pollutant is less than other cases. For the period of 5-7 PM, there are higher emission rate and lower wind speed than 10 AM - 12 PM causing higher concentration of PM2.5.

4.3 The effect of the city lockdown due to COVID-19 pandemic on PM2.5 concentration

Since lockdown directly affects the number of cars which is the emission source of PM2.5, so the different numbers of car between normal time and lockdown period will affect the concentration of PM2.5 in the focused area. Thus, the effect of lockdown on PM2.5 concentration is also investigated.

4.3.1 The effect of city lockdown on PM2.5 concentration at air quality monitoring station area

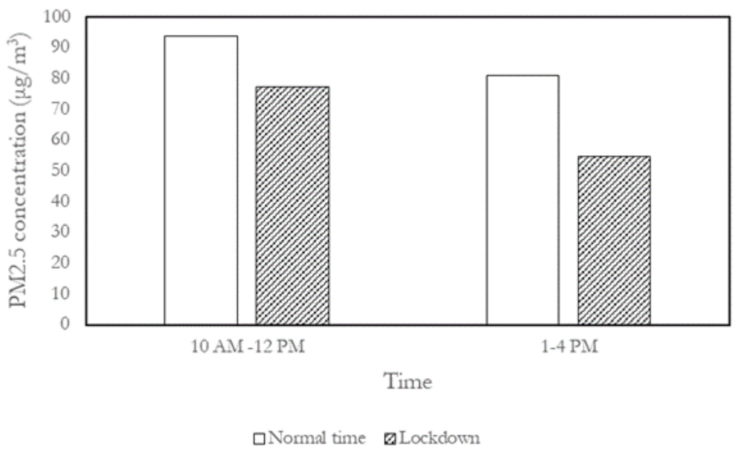


Figure 15 Comparison of PM2.5 concentration at the air quality monitoring station area during the normal time and the city lockdown period (simulated based on the traffic volume and meteorological data on 14 Jan 2019 and 21 Jan 2021, respectively).

Table 5 Emission rate on Phayathai road around the air quality monitoring station area during normal time and lockdown period.

Time	Emission rate (kg/s)	
	Normal	Lockdown
10 AM – 12 PM	9.88836E-06	7.88603E-06
1 – 4 PM	1.48325E-05	1.1829E-05

The comparison of PM2.5 concentration at air quality monitoring station area during the normal time and the city lockdown period is shown in Figure 15. It can be seen that the PM2.5 concentrations at normal time are higher than lockdown period. From Table 5, the emission rate during the lockdown period is reduced by 20.25 percent from the normal time and the PM2.5 concentration is reduced by 25.24 percent. As the lockdown directly affects the traffic volume reduction, the emission of PM2.5 is reduced, so the concentration of PM2.5 is reduced from normal time.

4.4 PM2.5 concentration at various distances from the road

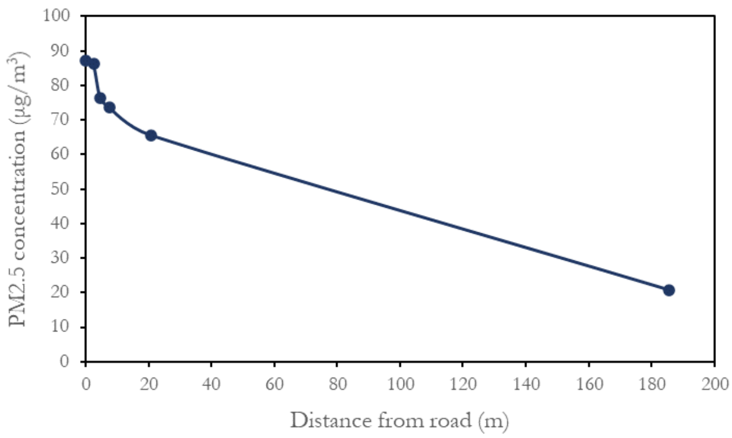


Figure 16 PM2.5 concentration at various distances from Rama I road (simulated based on the traffic volume and meteorological data on 14 Jan 2019 during 1-4 PM).

Figure 16 shows PM2.5 concentrations at various distances from Rama I road. It is shown that roadside area (distance from road is zero) has the highest PM2.5 concentration. This is because it is closest to the emission source, and the concentration of PM2.5 decreases as the distance from the road increases. At a distance of 5 meters from the road, the PM2.5 concentration is reduced by 12.3 percent.

4.5 The influence of tall building on PM2.5 concentration

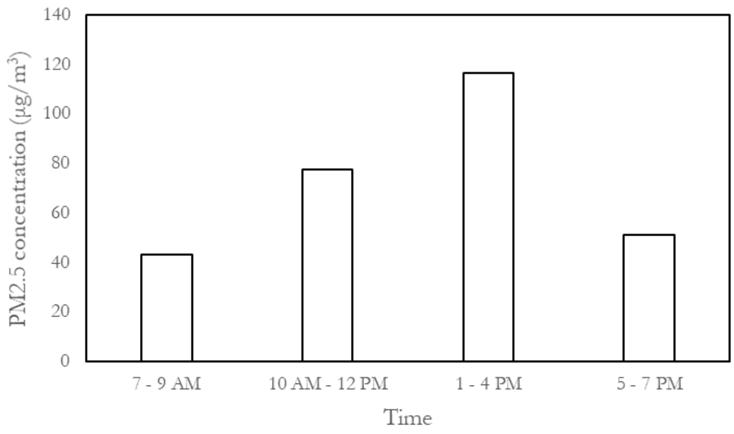


Figure 17 PM2.5 concentration at the tall building opposite MBK building (simulated based on the traffic volume and meteorological data on 14 Jan 2019).

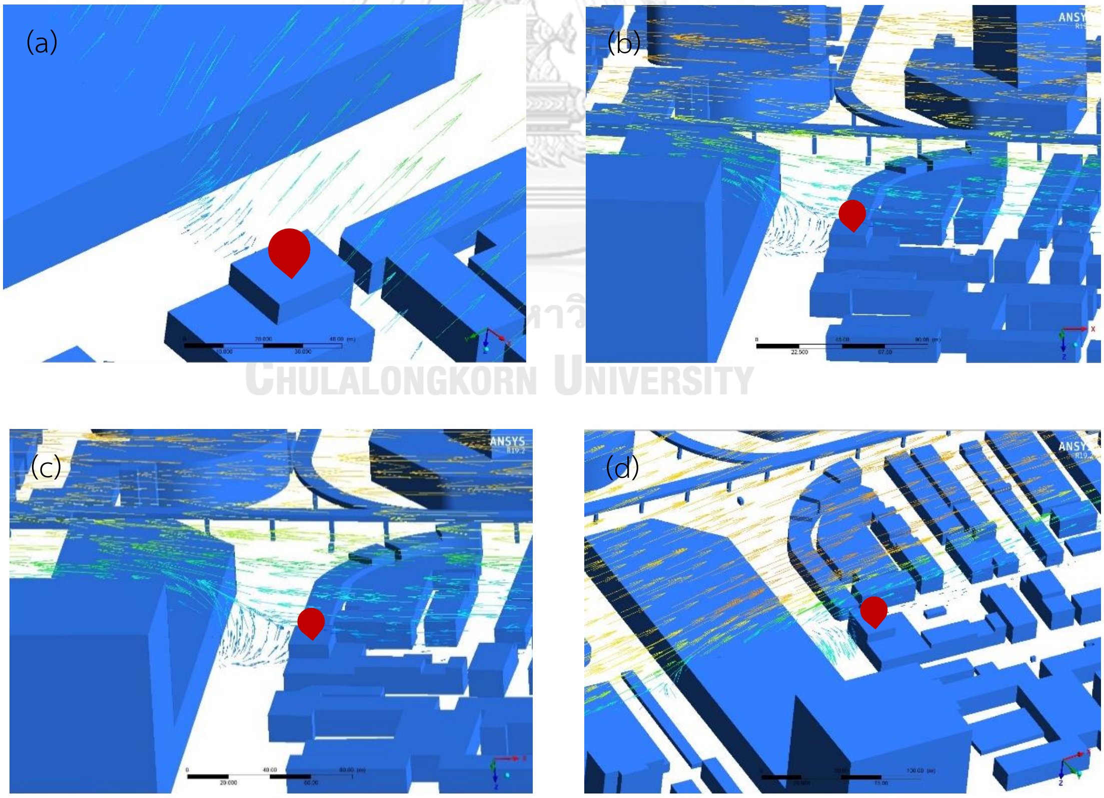


Figure 18 Airflow fields on Phayathai road in front of MBK building during (a) 7-9 AM, (b) 10AM – 12PM, (c) 1-4 PM and (d) 5-7 PM.

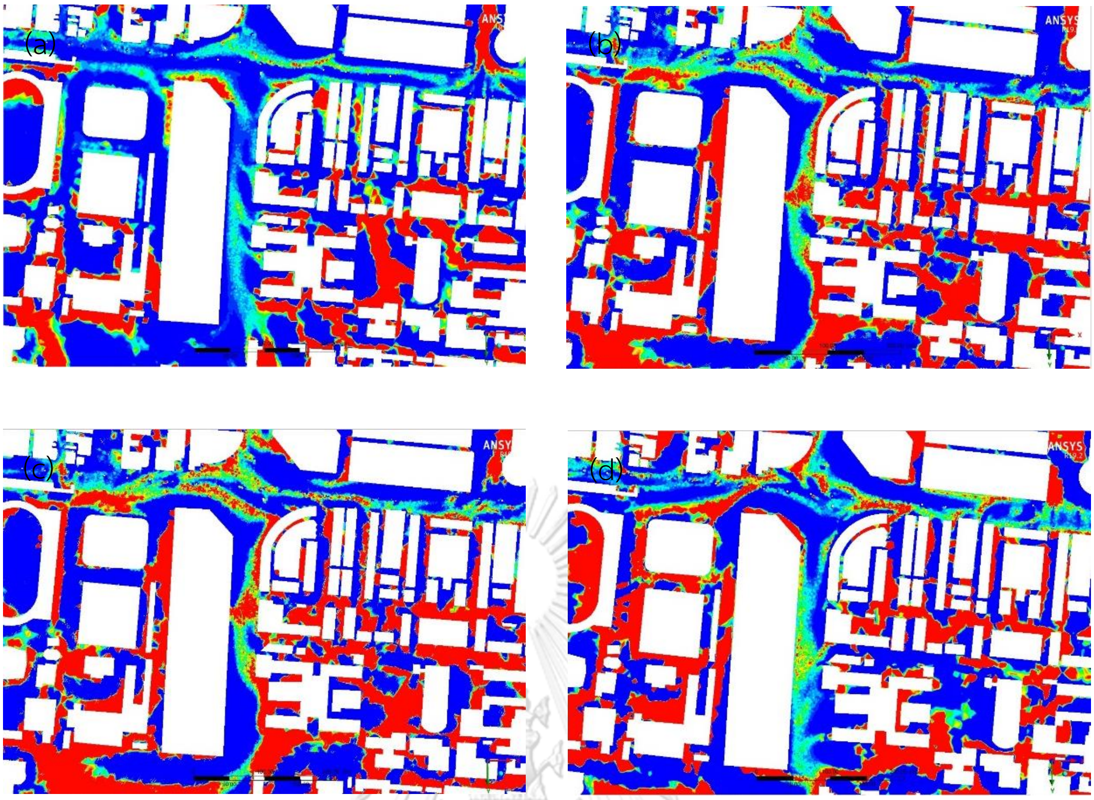


Figure 19 PM2.5 concentration contour on Phayathai road in front of MBK building during (a) 7-9 AM, (b) 10AM – 12PM, (c) 1-4 PM and (d) 5-7 PM.

Table 6 Emission rate and meteorological data at the opposite side of MBK, Phayathai road on 14 Jan 2019.

Time	Wind speed (m/s)	Wind direction	Temperature (K)	Emission rate (kg/s)
7 – 9 AM	0.02	↑	304.0	6.78886E-06
10 AM – 12 PM	0.04	←	306.4	9.88836E-06
1 – 4 PM	0.05	←	309.0	1.48325E-05
5 – 7 PM	0.09	→	306.7	9.60695E-06

Figure 17 shows the concentration of PM2.5 at the tall building opposite MBK building. The highest concentration of PM2.5 occurs at 1-4 PM which is the period with the highest emission rate. Next is the period of 10 AM – 12 PM with the second highest emission rate. In addition, the wind direction during 10 AM – 4 PM flows perpendicular to the street, so MBK building will obstruct the flow of air. Then, the vortex is formed and carries the pollutants from MBK side to the opposite side (as shown in Figure 18(b)-(c)). Thus, the PM2.5 concentration at the tall building opposite MBK is high. The period that has the lowest concentration is 7-9 AM due to the lowest emission rate. Moreover, the wind at this period flows parallel to the street, so there are no buildings to obstruct the airflow. From Figure 18(a), it shows that although the wind speed at 7-9 AM is low, but there is some air flows upward and removes some pollutants out of the canyon. For the period of 5-7 PM, despite having a high emission rate but the high wind speed makes the concentration relatively low.

CHAPTER V
CONCLUSIONS

The dispersion of PM2.5 in street canyon is influenced by many factors such as city configuration, emission source and meteorological characteristics. For the city configuration in the focused area, there are many tall buildings in the shopping mall and university areas, and the skytrain structure located between high-rise buildings. These constructions obstruct the airflow, so it is difficult for the pollutants to be spread out causing the accumulation of pollutants. As a result, the PM2.5 concentration in the case with skytrain is higher than without skytrain. The presence of skytrain structure increases PM2.5 concentration at the area under the skytrain by 21.6 percent and at the area away from the skytrain (i.e., around the air quality monitoring station) by 7.05 percent. In addition to the city configuration, emission source is also important to the concentration of PM2.5. The lockdown period affects the traffic volume reduction, so the emission of pollutants also decreases since motor vehicles are a major source of particulate air pollution in Bangkok. Thus, the concentration of PM2.5 during the lockdown period is reduced by 25.24 percent. Besides, the distance from road where the pollutants are emitted is directly related to the concentration of PM2.5. The farther from the road, the less the concentration will be. For the meteorological characteristics, both temperature, wind speed and direction affect the dispersion of PM2.5 especially wind speed and direction. The higher wind speed, the lower concentration of PM2.5. Despite this, the direction of the wind and the building configuration that the wind flows through must also be taken into account. If the wind flows perpendicular to the street located between tall buildings, the vortex will form and carry pollutants to the upwind building, causing the pollutant concentration at leeward side to be high. For the temperature, PM2.5 concentration decreases with increasing temperature since the heated air will rise vertically and strengthen pollutant dispersion.

From the results of this study, it can lead to the proposing the guidelines to reduce the concentration of PM2.5 in Pathumwan district or in an area with similar city configuration. The relation between the distance from road and PM2.5 concentration can be used for building construction design. Since the building's orientation affects the PM2.5 concentration, so the concentration at the sidewalk in front of the building is still high due to it is located near the emission source and influenced by the building blocking the dispersion of pollutants. Thus, the roadside buildings should be spaced from the road to facilitate ventilation and reduce pollutant accumulation. Furthermore, the lockdown showed a significant reduction in PM2.5 concentration associated with reduction in the number of vehicles. This can lead to the issuing of policies regarding traffic control during the period with low wind speed and low temperature, which is the period that causes high pollutant accumulation.

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VITA

NAME	Punyisa Chaisri
DATE OF BIRTH	13 Jun 1996
PLACE OF BIRTH	Bangkok
INSTITUTIONS ATTENDED	Graduated in bachelor's degree from Faculty of Science in Chemical Technology, Chulalongkorn University in 2019.
HOME ADDRESS	Saimai, Saimai, Bangkok 10220