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Article

Investigation of PM2.5 Dispersion in Din Daeng District, Bangkok, Using Computational Fluid Dynamics Modeling

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Abstract. Din Daeng is a small and densely populated district of Bangkok, with two major expressways and three main roads in the area. PM2.5 concentration in Din Daeng district often exceeds both the daily and annual standards of the National Ambient Air Quality Standards. Computational Fluid Dynamics (CFD) was applied to investigate the effects of the metropolitan characteristics and traffic volumes on the dispersion of PM2.5. The turbulent flow was analysed using the Standard k-ε model. There were two scenarios in this simulation study. One was to investigate the consequences of having the expressways. The other was to examine the influence of the city lockdown due to the COVID-19 pandemic. The presence of the expressways in Din Daeng district was demonstrated to increase PM2.5 concentrations by approximately 3.4 times compared to the case without the expressways. In addition, the city lockdown substantially reduced PM2.5 concentration by almost 49% compared to that during the normal period.

Keywords: PM2.5, Din Daeng District, Bangkok, computational fluids dynamics.

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1. Introduction

Air pollution is currently a big issue in Thailand, especially in Bangkok. Bangkok has faced a severe dust cover phenomenon in recent years. Also known as $PM_{2.5}$, dust particles with a diameter of 2.5 microns or smaller are approximately one-quarter of the diameter of human hair [1]. When $PM_{2.5}$ enters the human body, it affects the function of numerous organs, whether it is a rash or skin inflammatory disease. Furthermore, long-term exposure to $PM_{2.5}$ raises the risk of coronary heart disease and lung illness, in addition to lung cancer [2]. Thailand regulates daily exposure of $PM_{2.5}$ to not exceeding 50 micrograms per cubic meter [3].

Air pollutants from industrial facilities, open burning (such as garbage burning, agricultural waste open burning, etc.), and vehicles are the sources of $PM_{2.5}$ in Bangkok. Vehicles are the primary source of pollution [4, 5], contributing 72.5% of $PM_{2.5}$ in Bangkok. Trucks contribute the highest amount of 28%, followed by pickup trucks (21%), personal vehicles (10%), buses (7%), motorcycles (5%), and vans (1.5%) [6]. According to statistics on registered vehicles in Bangkok, every year there is an increasing tendency. The number of vehicle registrations grew by 2.46% in 2021 compared to 2020 [7].

Another factor leading to high $PM_{2.5}$ concentration in Bangkok might be the city characteristics. There are numerous tall buildings, such as hotels, commercial malls, and residences (e.g., condominium complexes). In addition, most streets are quite narrow. Some places have tall structures of the sky train over the urban canyon, resulting in inadequate ventilation.

There are two expressways and three main roads in Din Daeng district. As a result, the $PM_{2.5}$ concentration in Din Daeng is high. From 2019 to 2021, the annual average $PM_{2.5}$ concentrations were 32, 21, and 33 $\mu g/m^3$ [8], which exceeded Thailand's national air quality standard (over 25 micrograms/m^3) [9].

The investigation of $PM_{2.5}$ dispersion may be accomplished using a variety of methods, including field measurement, wind tunnel, and numerical method such as Computational Fluid Dynamics (CFD) modeling. In comparison to the previous two methods, the benefit of CFD is allowing to test scenarios with less time and resources. As a result, CFD was preferred in as a suitable method for the investigation of $PM_{2.5}$ dispersion in this study.

2. Methodology

2.1. Study Area

Din Daeng is one of Bangkok's fifty districts. The location is as shown in Fig. 1. It has a total area of 8.354 square kilometers and a population of 112,814 [11]. Most of the area is composed of residential buildings, government offices, educational institutions, and commercial areas. The buildings are not particularly tall. However, the building density is high, and the streets are relatively narrow.

The studied area is approximately 2 square kilometers covering Bangkok's air quality monitoring station (b56). There are three main roads: Din Daeng, Pracha Songkhro, and Mitmaitri Roads. In addition, there are two expressways: Chalerm Mahanakorn and Si Rat Expressways. The focused area is shown in Fig. 2.

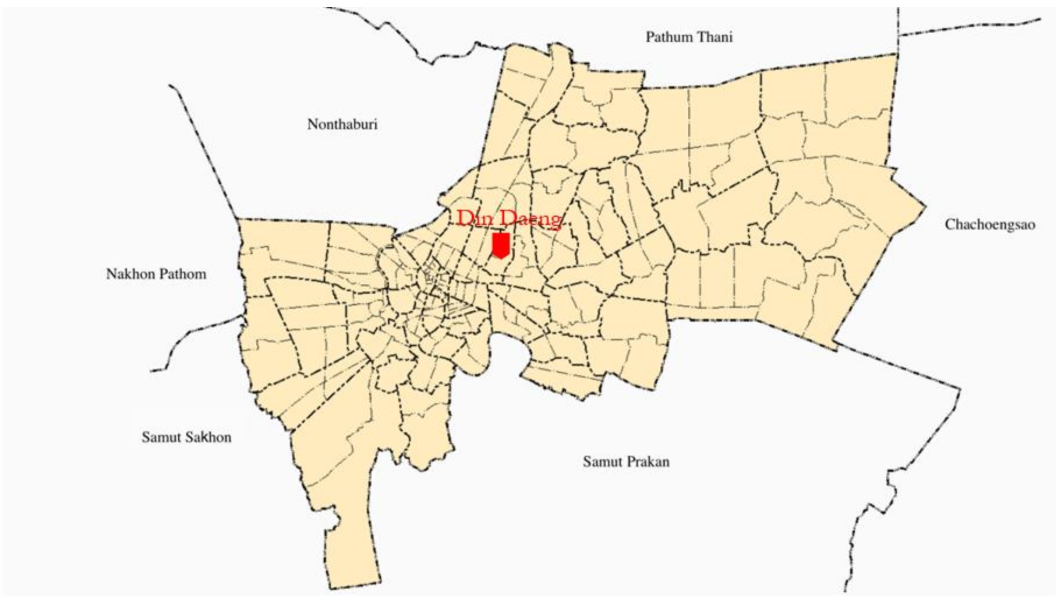

Fig. 1. Din Daeng District [12].

Fig. 2. Focused area for the investigation of PM2.5 dispersion in Din Daeng.

2.2. Model Simulation

2.2.1. Computational geometry and meshes

Geographic and urban planning data from the Department of City Planning and Urban Development, Bangkok Metropolitan Administration (BMA), were used to generate the geometry including the buildings as displayed in Fig. 3. Then, the buildings were combined and subtracted from the geometry to create the computational domain of the fluid as shown in Fig. 4. Based on the study by Pardyjak and Brown (2002) [13], the distance at which the building has no effects on velocity profiles is equivalent to 1.25 times the height of the tallest building on that side (Hmax). In this study, the vertical and lateral boundaries were 1.25 times of Hmax. The height of the tallest building in the focused area was about 136.5 m. Thus, the height of the domain was about 307.1 m. In addition, after the mesh sensitivity study the suitable grid size was 15 m and the total number of grids was approximately 3.8 million cells.

2.2.2. Boundary condition

The 'Velocity Inlet' was used for the inlet boundary condition in which the mean wind velocity and temperature were specified [14, 15]. The wind direction was perpendicular to the inlet. The 'Pressure Outlet' was applied for the outlet boundary condition in which the pressure was specified as atmospheric pressure. The lateral and upper boundaries were defined as symmetrical boundaries. Building walls and ground surfaces were defined as stationary walls with a no-slip condition. For asphalt roads, the ground surface temperature was higher than the atmospheric temperature for around 12-14 °C [16].

The Discrete Phase Model (DPM) was used to simulate $PM_{2.5}$ dispersion. For the boundary condition of $PM_{2.5}$, it was introduced to the system by being emitted from the road surface [17] and carbon was the primary element [18]. The emission can be calculated from Eq. (1) [19].

$$Emission\ rate\ \left(\frac{kg}{s}\right) = \frac{\sum Q_i \cdot f_i \cdot l}{3600} \tag{1}$$

where Q_i is the traffic volume of each vehicle type (veh/h), f_i is the emission factor of each vehicle type (kg/(km·veh)), and l is the length of road (km). The emission factor and the total traffic volume of each vehicle type are shown in Table 1 and Table 2.

Fig. 3. The geometry of the focused area.

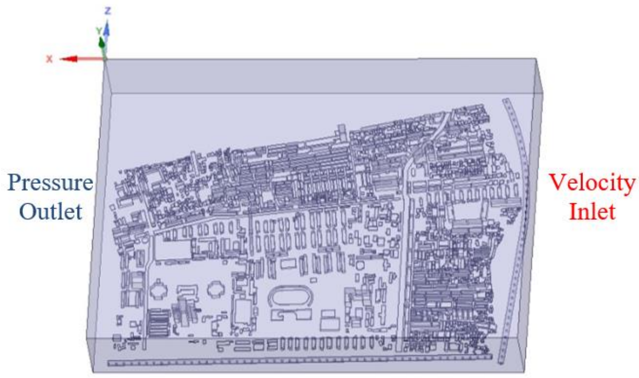

Fig. 4. The computational domain of the focused area.

Table 1. Emission factor of each vehicle type [20, 21].

Type (i)	$PM_{2.5}$ emission factor (g/km)
Three - Wheeler	0.0114
Passenger car	0.0011
Bus	0.0354
Heavy commercial vehicles	0.0783

Table 2. The total traffic volume of each vehicle type [22].

Type (i)	Total traffic volume (Vehicles)			
	Normal period		Lockdown	
	10 AM – 12 PM	1 – 4 PM	10 AM – 12 PM	1 – 4 PM
Three - Wheeler	157	235	128	192
Passenger car	13,001	16,555	10,650	13,551
Bus	399	598	326	489
Heavy commercial vehicles	194	234	159	192

2.2.3. Governing equations

The governing equations of fluid dynamics, which described a substance's dynamics within the controlled volume of this study, were consisted of mass, momentum, and energy equations. The following are the details of these equations:

The mass conservation or continuity equation can be written as:

$$\frac{\partial \rho}{\partial t} + \Delta \cdot (\rho \vec{v}) = 0 \tag{2}$$

where ρ is density, t is time, and $\vec{v}$ is the fluid velocity.

The momentum conservation can be written as:

$$\frac{\partial}{\partial t}(\rho \vec{v}) = -[\nabla \cdot \rho \vec{v}\vec{v}] - \nabla P + [\nabla \cdot \bar{\bar{\tau}}] + \rho \vec{g} \tag{3}$$

where P is static pressure, $\bar{\bar{\tau}}$ is the stress tensor, and $\rho \vec{g}$ is the gravitational body force.

The stress tensor is given by:

$$\bar{\bar{\tau}} = \mu[(\nabla \vec{v} + \nabla \vec{v}^T)] \tag{4}$$

where μ is dynamic viscosity.

Energy conservation can be written as:

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho \vec{v} e) + \frac{\partial \rho K}{\partial t} + \nabla \cdot (\rho \vec{v} K) + \nabla \cdot (\alpha_{eff} \nabla e) + \rho g \cdot \vec{v} \tag{5}$$

where e is the internal energy, K is kinetic energy, g is the gravitational acceleration, and α_{eff} is the effective thermal diffusivity. The kinetic energy is given by:

$$K = \frac{|\vec{v}|^2}{2} \tag{6}$$

Reynolds-averaged Navier-Stokes equations (RANS) were used to investigate time-averaged motions in turbulent fluid flows in this study. The RANS equation may be used to investigate the effect of pollutant dispersion in street canyons [23-25]. RANS may be represented by a single equation (e.g., Spalart-Allmaras model) or two equations (e.g., k-ε models and k-ω models).

The Standard k-ε model, RNG k-ε model, and Realizable k-ε model are the three varieties of k-ε models. The k-ε models are commonly used in fluid flow simulations [26] and in the investigation of pollutant dispersion in street canyons [27, 28]. So et. al. (2005) and Huang et. al. (2008) [29, 30] demonstrated that the Standard k-ε model is effective in studying pollutant dispersion in street canyons. Therefore, the Standard k-ε model was used in this study. It is composed of the following equations:

Turbulent kinetic energy (k):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k \vec{v}) = \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right] + 2\mu_t E_{ij} E_{ij} - \rho \varepsilon \tag{7}$$

Turbulent dissipation rate (ε):

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon \vec{v}) = \frac{\partial}{\partial x_i}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right] + C_{1\varepsilon}\frac{\varepsilon}{k} 2\mu_t E_{ij} E_{ij} - C_{2\varepsilon}\rho \frac{\varepsilon^2}{k} \tag{8}$$

where E_{ij} is the rate of deformation, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants and equal to 1.44 and 1.92, respectively. σ_k and σ_ε are the turbulent Prandtl numbers for k and ε, and equal to 1.0 and 1.3, respectively. μ_t is eddy viscosity and can be written as:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{9}$$

where C_μ is equal to 0.09.

Two scenarios were investigated to determine the effects of urban structures, traffic volume, and other factors on the dispersion of $PM_{2.5}$. The first scenario was the influence of the expressways. In this scenario, $PM_{2.5}$ concentrations when the expressways were included and removed from the computational domain were compared. Without the expressways, the major emission source was from the traffic flows on the three main roads in Din Daeng district. The input parameters were based on the traffic volume and meteorological data on 27th January 2020. Furthermore, the second scenario was the influence of the city lockdown due to the COVID-19 pandemic which directly affected the traffic volume through the district [31]. $PM_{2.5}$ concentrations were compared between a normal period and a lockdown period simulated in similar weather conditions. The input parameters for the normal period and the lockdown period were based on the traffic volume and meteorological data on 25th January 2021 and 27th January 2020, respectively. (January is in the dry season when $PM_{2.5}$ pollution is usually extreme.)

3. Results and Discussions

3.1. Model Validation

Model validation is the process of verifying a model by comparing the simulated results with the relevant experimental data (same conditions). In this study, the data from the simulation were compared with the measured data from Bangkok's air quality monitoring station (b56). The data were taken at a height of 2.5 meters off the ground [32] where the air quality monitoring apparatuses were installed.

The model validation results are shown in Fig. 3, the trend of $PM_{2.5}$ concentrations obtained from the air quality monitoring station tends to increase in the afternoon (1 PM – 4 PM) due to higher emission rate. This agrees well with the values from the simulation which tend to increase as well. As a result, the CFD model can be used to predict the dispersion of $PM_{2.5}$ in this study.

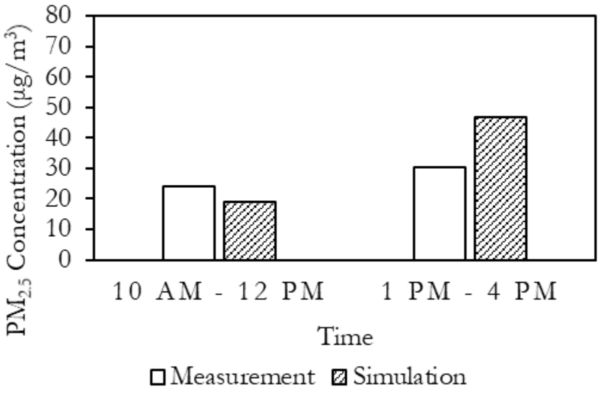

Fig. 5. Comparison of simulated and measured PM2.5 concentration (based on 25th January 2021 data).

3.2. The Influence of the Expressways

3.2.1. The influence of the expressway on $PM_{2.5}$ dispersion at the air quality monitoring station (b56)

There are two expressways, i.e., Chalerm Mahanakorn and Si Rat Expressways, passing over Din Daeng district. These may affect $PM_{2.5}$ concentration and air ventilation in the area. Fig. 6 illustrates the effects of the expressways in Din Daeng district on $PM_{2.5}$ concentration at the air quality monitoring station (b56). It was measured at the height of 1.5 meters, representing human breathing level [33]. In addition, the total traffic volume with and without the expressways as well as the wind speeds during 10 AM – 12 PM and 1 PM – 4 PM are shown in Table 2. The results show that the presence of the expressway increases the concentration of $PM_{2.5}$ by approximately 3.4 times compared to the case without the expressways. Although the total emission rate is higher during 1 PM – 4 PM, $PM_{2.5}$ concentrations are lower in both cases as compared to those during 10 AM – 12 PM. This might be due to the increased air ventilation caused by the higher wind speed.

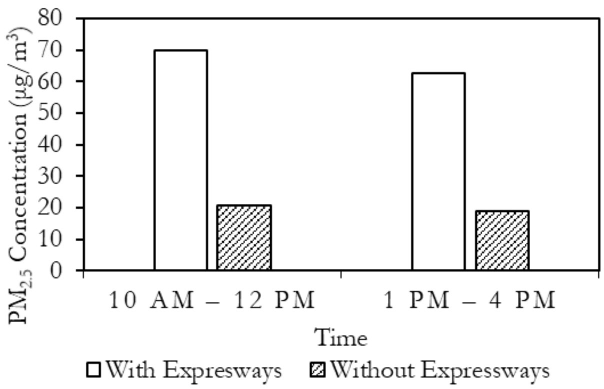

Fig. 6. The effects of expressways on $PM_{2.5}$ concentration at the air quality monitoring station in Din Daeng district (simulated based on the traffic volume and meteorological data on 27th January 2020).

Table 3. Total emission and wind speed based on the traffic volume and meteorological data on 27th January 2020.

Time	Wind speed (m/s)	Total emission rate (kg/s) with expressways	Total emission rate (kg/s) without expressways
10 AM – 12 PM	0.43S	2.10e-5	8.93e-6
1 PM – 4 PM	0.78S	3.15e-5	1.34e-5

Note: S denotes the south wind or the wind blowing from the south.

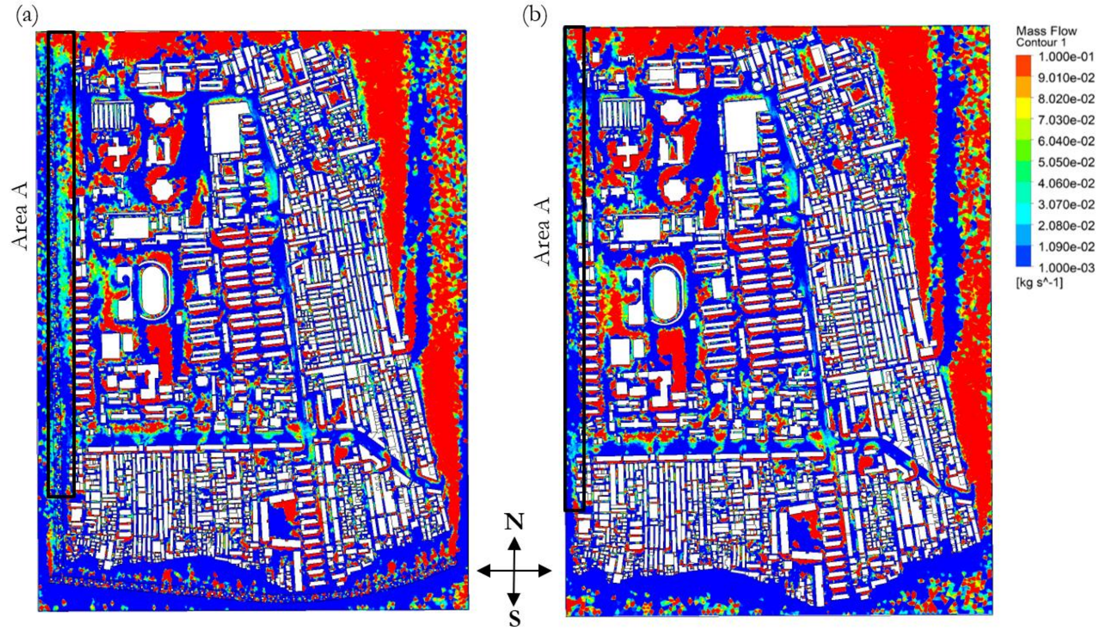

Fig. 7. $PM_{2.5}$ dispersion in Din Daeng district (simulated based on traffic volume and meteorological data on 27th January 2020 at 1-4 PM): (a) with expressways and (b) without expressways.

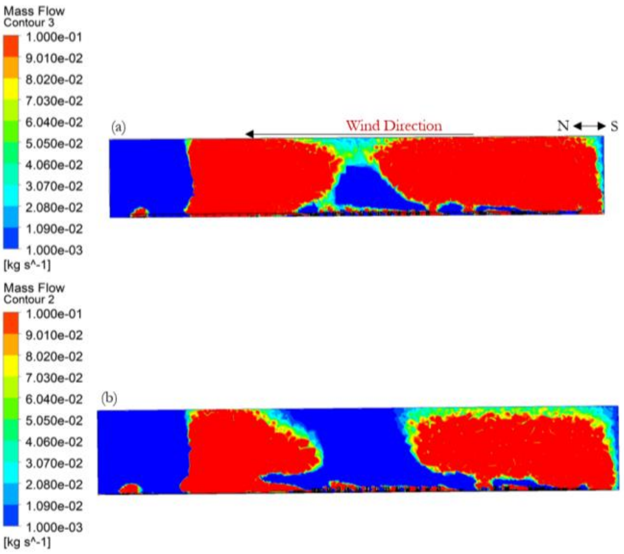

Fig. 8. $PM_{2.5}$ dispersion in Din Daeng district illustrated on a cross-sectional plane at the area with buildings near the expressways (area A in Fig. 7) (simulated based on traffic volume and meteorological data on 27th January 2020 at 1-4 PM): (a) with expressways and (b) without expressways.

The influence of the expressways on $PM_{2.5}$ dispersion at a height of 1.5 meters around the nearby buildings in Din Daeng district is shown in Fig. 7. With the expressways (Fig. 7(a)), $PM_{2.5}$ concentration around the buildings close to the expressways (area A in box) is mostly greater than that without expressways (Fig. 7(b)). The buildings in this area are mostly residential flats and houses. This might be due to the focused area (i.e., area A) is surrounded by taller buildings and expressways, causing $PM_{2.5}$ accumulation in that area. In addition, when the emission rate increases (i.e., 1PM – 4PM) and the wind blows northward, $PM_{2.5}$ concentration is increased in most area and disperses more to the north. This can be illustrated in Fig. 8 which presents a cross-sectional view of the area with buildings near the expressways.

3.3. The Influence of the City Lockdown due to COVID-19 Pandemic

Bangkok City lockdown during January to February year 2021, due to the COVID-19 pandemic, resulted in the reduction of traffic congestion in the metropolitan area [31]. The effects of the city lockdown on $PM_{2.5}$ concentration were investigated in this study. Fig. 9 shows the comparison of $PM_{2.5}$ concentrations at the air quality monitoring stations (b56) during the normal and lockdown periods. It was found that $PM_{2.5}$ concentrations during the lockdown period are less than the values during the normal period: about 73% lower during 10 AM – 12 PM and about 25% lower during 1 PM – 4 PM. This might be due to the decrease in the total emission rate during the lockdown period. In addition, the high wind speed (see Table 3) particularly in the afternoon (1 PM – 4 PM) of the normal period might result in better ventilation and lower $PM_{2.5}$ concentration, despite the higher emission rate in the afternoon. Furthermore, consider the trend of $PM_{2.5}$ concentrations during the lockdown period during which the temperature and wind speed are lower compared with the condition during the normal period. The increase of temperature and wind speed in the afternoon during the lockdown period might not sufficiently promote the atmospheric convection to reduce $PM_{2.5}$ accumulation [34]. Thus, $PM_{2.5}$ concentration during the lockdown period is increased with the emission rate.

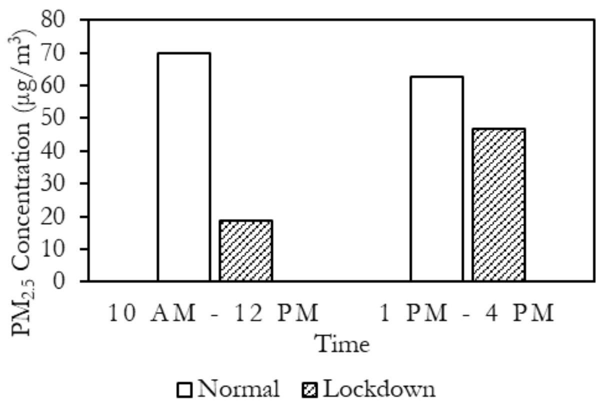

Fig. 9. The effects of the city lockdown due to the COVID-19 pandemic on $PM_{2.5}$ concentration at the air quality monitoring station in Din Daeng district (based on the traffic volume and meteorological data on 27th January 2020 (normal period) and on 25th January 2021 (lockdown)).

4. Conclusions

This study was aimed to investigate the dispersion of $PM_{2.5}$ in Din Daeng, one of Bangkok's most densely populated districts with high $PM_{2.5}$ concentration (often well above the national standard). Furthermore, the presence of the expressways through the area increases the volume of traffic and, thus, $PM_{2.5}$ emission in the area. CFD modeling is used in this study to investigate $PM_{2.5}$ dispersion and to identify the solutions for reducing $PM_{2.5}$ pollution.

The investigation results showed that the presence of the expressways increases the traffic volume passing through the area and increases $PM_{2.5}$ concentration by approximately 3.4 times compared to the case with no expressways. In addition, with the presence of the expressways, more $PM_{2.5}$ is accumulated around the nearby buildings which are surrounded by taller buildings and the expressways. These result in higher $PM_{2.5}$ concentration in that area compared to the case with no expressways. Furthermore, the city lockdown due to the COVID-19 pandemic seems to significantly impact the concentration of $PM_{2.5}$, i.e., $PM_{2.5}$ concentration is decreased by approximately 49% from the normal period. It is also shown that the meteorological condition, such as wind speed, wind direction, and temperature, has a significant effect on $PM_{2.5}$ concentration. For example, despite a high emission rate, sufficiently increasing wind speed and temperature can result in lower $PM_{2.5}$ concentration. Therefore, with a stagnant air and low temperature condition especially in an area surrounded by tall buildings, a policy to control the traffic volume, and thus the emission rate, might be needed to reduce $PM_{2.5}$ concentration.

Although the CFD model is able to predict the trend of $PM_{2.5}$ concentration, this study still has a limitation due to insufficient data from the measurements. More actual data for both model validation and input parameters would improve the predictability of the CFD model in this study.

Table 4. Total emission and meteorological data during the normal period and lockdown (based on the traffic volume and meteorological data on 27th January 2020 and on 25th January 2021, respectively).

Time	Total emission rate (kg/s)		Wind speed (m/s)		Temperature (°C)	
	normal period	lockdown	normal period	lockdown	normal period	lockdown
10 AM – 12 PM	2.10e-5	1.72e-5	0.43S	0.20S	32.77	30.57
1 PM – 4 PM	3.15e-5	2.59e-5	0.78S	0.45S	33.28	32.55

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