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BLACK CARBON IN PM2.5 AT ROADSIDE SITE IN BANGKOK, THAILAND

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ABSTRACT: Traffic is typically a major source of air pollution in urban areas of developing countries. The exhaust emissions include gaseous substances and particulate matter, which PM2.5 (particulate matter less than 2.5 micrometers in aerodynamic diameter) is the majority. In urban areas, the composition of PM2.5 at roadside site dominated by the carbonaceous combustion component, the major constituent wherein was represented as black carbon (BC). This study aimed to investigate the diurnal concentrations of BC related to PM2.5 by using a seven-wavelength aethalometer. Study site was located near one of congested roads in Bangkok, Thailand. The correlation between traffic volumes and BC concentrations at roadside were also discussed. Results showed that the 24-h average BC concentrations of this site were in the range of 1.5 – 15 µg/m3. The diurnal pattern of BC levels exhibited two peaks of BC concentrations occurring during 0500 to 0700 LST and 2100 to 2300 LST. The morning peak of BC evidently governed by traffic condition while the evening peak resulted from traffic associated with meteorological effect. In addition, the density of heavy-duty diesel vehicles (HDDVs) played an important role to the diurnal pattern of BC concentrations. Interestingly, the highest BC level from this study site was observed on Sunday, where the lowest was found on Monday and Friday. This involved with traffic volumes caused by particular activity around this study site.

Keywords: Black carbon, PM2.5, Heavy-duty diesel vehicle, Bangkok urban area, Air pollution.

1. INTRODUCTION

Black carbon (BC) is a major constituent of particulate matter (PM) in urban environments resulted from incomplete combustion processes of fossil fuels or burning of biomass and biofuels. BC plays an important role in climate change [1]. It has been estimated that the direct radiative forcing of BC aerosol is around 0.2-1 W/m^2, suggesting that BC is the second contributor to climate warming next to carbon dioxide [1], [2]. In addition, BC also causes harmful health effects, including several respiratory diseases and cardiovascular system [3], [4].

The rapid growth of industrialization and urbanization has created high levels of air pollution in Thailand, especially in urban areas. Vehicles and factories were stated to be major contribution to air pollution, particularly in Bangkok [5]. The Asian Development Bank [6] reported that the main source of inhalable particulate matter at roadside of Bangkok came from in-use diesel vehicles. Health risk assessments for Bangkok indicated that as much as a third of all heart disease deaths might be caused by air pollution, primarily from motor vehicles exhausts [7]. Likewise, several studies reported high levels of air pollutants, including PM and BC, at roadsides in Bangkok Metropolitan Region. The increasing severity of road transportation has the potential to greatly increase pollutant emissions, which also have the effect on health, economy and society. Nowadays, the routine automatic ambient air quality monitoring of roadside stations in Bangkok mainly focuses on parameters of NO_x, CO, O_3 and PM10, while PM2.5 was only an addition available in some monitoring stations. The measurements of BC, which are more health damaging, are not included in routine monitoring programs.

At present, BC concentrations in Thailand are only reported by researchers, and mostly related to biomass burning and its haze problem in Northern provinces of Thailand. Though BC observed in Bangkok area was noticeably traffic-related, the correlation between measured BC and traffic characteristics was not clearly stated. Thus, the purpose of this study was to investigate the diurnal concentrations of BC related to PM2.5 and traffic characteristics nearby roadside site in Bangkok area.

2. MATERIALS AND METHODOLOGY

2.1 Study area

Bangkok is the capital of Thailand, covering an area of 1569 km^2, and has a population of 6 million inhabitants [8]. In 2016–2017, there were about 9.4–9.8 million registered vehicles in Bangkok, including 65% gasoline vehicles and 25% diesel vehicles [9]. Samples of BC were collected at an automatic continuous air quality monitoring station operated by Bangkok Metropolitan Administration (BMA), namely Ratchathewi station, situated at Ratchathewi District Office. This was a roadside station located at the west-northwest side of Phayathai Road (Fig.1), which was 5 meters away from the curbside of the road and approximately 150 meters from Phayathai Intersection. Phayathai Road is one of the main roads in the center of Bangkok with high traffic density and congestion in rush hours. This road is surrounded by several commercial buildings, hospitals and educational institutes. Moreover, there is the BTS Skytrain structure covering some part of this road, especially near this monitoring station. Black carbon sampling was conducted on the rooftop of the monitoring station, which was approximately 5 meters above the ground.

Use at most three levels of headings that correspond to chapters, sections and subsections. The first level headings for chapter titles should be in 10pt, bold, justified, and upper case font. Leave one blank line before and after the first level headings, respectively.

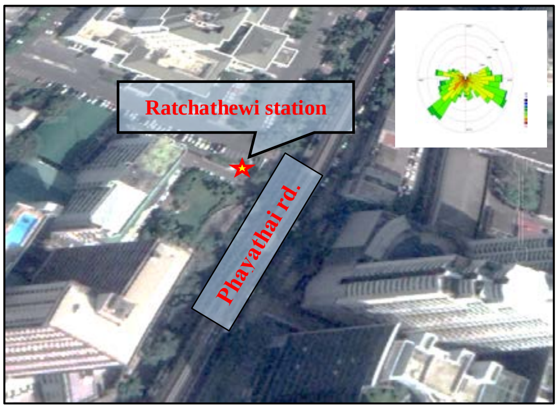

Fig.1 Location of Ratchathewi monitoring station

2.2 Samples collection and data analysis

Real-time measurements of BC concentrations were conducted at the Ratchathewi site during the dry season (January 4 – 30th, 2017). Measured data was separated into two groups of weekday (Monday to Friday) and weekend (Saturday and Sunday). Total days of measured BC data were 27 days, consisting of 19 days of weekday data and 8 days of weekend data (four Saturdays and four Sundays). However, there were some missing data during January 10 – 11th due to heavy rain.

Black carbon measurements were carried out using the equipment called aethalometer, Model AE-42 (Magee Scientific, USA) with seven different wavelengths (370, 470, 520, 590, 660, 880, and 950 nanometer). The aethalometer was equipped with a cyclone to allow only particles smaller than 2.5 µm in aerodynamic diameter. Sampled particles were collected on a quartz fiber tape. The flow rate was controlled at 2 liters/minute, and the measured cycle was set at every two minutes. Hourly averaged values from the measurement at 880 nanometer wavelength were regarded as BC mass. If measured BC data in any hour or any day were missing more than 40%, their hourly or daily averages were not calculated and presented.

Traffic volumes passing by the monitoring site were evaluated from CCTV camera obtained from Traffic and Transportation Department, Bangkok Metropolitan Administration. The number of vehicles passing in the image were manually counted for twenty minutes' duration for every hour, then, interpolated them into hourly data. Eight different vehicles; passenger car, pick-up, van, taxi, motorcycle, three-wheeler (or "Tuk Tuk"), bus and truck were categorized. Particulate matter (PM2.5) data simultaneously monitored at the same sampling sites were provided by Bangkok Metropolitan Administration (BMA).

3. RESULTS AND DISCUSSION

3.1 BC concentrations and BC/PM2.5 ratios

The daily concentrations of BC observed at Ratchathewi station were in the range of 1.5 to 15.0 µg/m^3, which their average and median were 4.5±1.9 and 4.1 µg/m^3, respectively. Secondary data of PM2.5 concentrations from BMA were in the range of 1.0 – 58.0 µg/m^3, with the average of 27.2 µg/m^3. In comparison to several studies monitoring BC nearby roadways (Table 1), BC concentrations measured in this study were somehow lower than those previously reported, e.g., the average BC concentration of 17.9±6.6 µg/m^3 observed in Bangkok area during dry season [10], the ones of 8.9±3.6 µg/m^3 monitored in Istanbul, Turkey [11], and 9.7 ± 0.8 µg/m^3 reported in London, UK [12].

However, this average BC concentration was slightly higher than those observed in Shanghai, China (3.3±2.1 µg/m^3) [13], or in Gwangju, Korea (2.4±2.2 µg/m^3) [14] and Ostrava, Czech Republic (3.5±4.1 µg/m^3) [15]. During the period of BC monitoring (January 4 – 30th, 2017), total of 557 hourly data of BC concentration were gathered, excluding missing data. The majority of BC data (76.5% of total data) were in the range of 2 – 5 µg/m^3 and the second (20.5% of total data) were found in the range of 6 – 10 µg/m^3. Those of BC data, which were smaller than 2 µg/m^3 and higher than 10 µg/m^3, were observed only 2.2 and 0.9%, respectively.

Table 1 Reported BC concentrations at different locations during dry season

Location	BC (µg/m^3)	BC/PM2.5 (%)	Ref.
Bangkok, Thailand	18±6.6	30	[10]
Istunbul, Turky	8.9±3.6	38	[11]
London, England	9.7 ± 0.8	–	[12]
Shanghai, China	3.3±2.1	5.0 – 12	[13]
Gwanju, Korea	2.4±2.2	–	[14]
Ostrava, Czech republic	3.5±4.1	–	[15]
Jiaxing, China	5.1	7.1	[16]
Guadalajara, Mexico	1.3 – 14	1.4 – 9.6	[17]
Bangkok, Thailand	4.5±1.9	18	This study

The mass fraction of BC in PM2.5 (or BC/PM2.5 ratios) in this study were ranging from 6.2 to 69.8%, the average of which was 18.0% while the median was 16.1%. These BC/PM2.5 ratios found on weekdays and weekends obviously peaked during morning hours (6:00 – 8:00) and night hours (20:00 – 21:00), while they remarkably decreased in the afternoon (15:00 – 16:00). Those peaks of BC/PM2.5 ratios in the morning and the night were related to traffic flow.

Moreover, the mass fraction of BC in PM2.5 (BC/PM2.5) of weekdays data were significantly different ($p<0.05$) from weekends data. Throughout the sampling period, the results between daytime and nighttime on weekdays and weekends did not show significant difference. The average BC/PM2.5 ratio (18.0%) from this study was clearly lower than the previous studies at roadside site in urban Bangkok (30.0 – 37.0%) [10] and in Instunbul, Turkey (38.0%) [11]. However, it was relatively higher than those found in Shanghai (5.0 – 12.0%) and Jiaxing (7.1%) of China, and in Guadalajara of Mexico (1.4 – 9 .6%) (Table 1). The fraction of BC in PM2.5 depended on pollution sources and meteorological conditions. Reddy et al. [18] mentioned that their high BC/PM2.5 ratios of Anantapur in India during winter affected by biomass burninng, while increase of non-carboneceous PM2.5 during monsoon period might decrease the ratios.

3.2 Effects of day of the week on BC concentrations

Due to the sampling site represented a roadside type, traffic emission was expected to be a major contribution of BC and PM2.5 mass. Therefore, the sampling period was assigned to obtain enough data of weekdays and weekends BC concentrations. In addition, daytime and nighttime data were separately considered in order to understand the diurnal variation of BC. Daily BC concentrations categorized as weekly pattern were averaged and illustrated in Fig.2. The average daily BC concentrations on weekdays (Monday to Friday) ranged from 4.1 to 4.9 µg/m^3, with their average of 4.4 µg/m^3. For Saturdays and Sundays, these averages were 4.4 and 5.3 µg/m^3, respectively. Surprisingly, higher BC concentrations were observed on Sundays and they were significantly higher than those on Saturdays or weekdays ($p<0.05$).

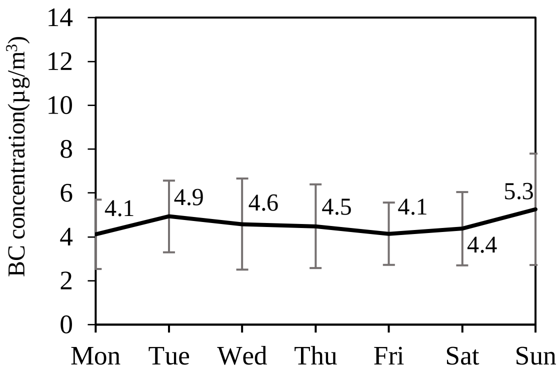

Fig. 2 The average daily BC concentrations in weekly pattern

The hourly BC concentrations during weekdays were in the range of 1.5 – 12.1 µg/m^3, and their average was 4.4±0.2 µg/m^3. During weekends, the hourly BC were in the range of 1.7 – 15.0 µg/m^3 with the average of 4.8±2.2 µg/m^3. Though the average daily BC concentration on Sundays was significantly different from others as mentioned above, there was no significant difference between hourly BC concentrations of weekdays and weekends data ($p=0.075$).

3.3 Diurnal BC concentrations

During weekdays, hourly BC concentrations recorded between daytime (06:00-18:00) and nighttime (18.00-06.00) were in the ranges of 1.8 – 12.1 and 1.5 – 9.2 µg/m^3, respectively. Their averages were 4.1 and 4.8 µg/m^3, respectively. On weekends, hourly of BC concentrations during daytime ranged from 1.8 to 15.0 µg/m^3, while those of nighttime ranged from 2.6 to 11.6 µg/m^3. The averages of weekends were 4.6 and 5.1 µg/m^3, respectively. Interestingly, these results showed that the average BC concentrations during daytime were significantly lower than nighttime ($p<0.05$). All hourly BC concentrations of weekdays and weekends were averaged, and their diurnal patterns were plotted as shown in Fig.3. Two curves of average daily BC concentrations representing weekdays and weekends data in diurnal pattern exhibited similar two peaks in the morning (5:00 – 7:00) and the night (21:00 – 23:00). During weekdays, the average hourly BC concentrations started to increase from 5:00 and reach its peak (6.2 µg/m^3) on 6:00, while the peak of weekends (6.4 µg/m^3) occurred at 7:00. In addition, some data higher than 10 µg/m^3 were mostly observed during these hours. The second peak happened in the night (21:00 to 23:00), which the evening peak of weekdays and weekends were 5.2 and 6.0 µg/m^3, respectively.

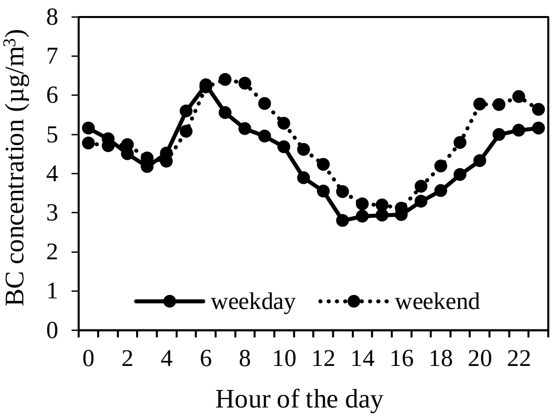

Fig. 3 Diurnal variation of BC concentrations

These two peaks of BC concentrations presented in the morning and the night, which should be related to traffic emission and the formation of boundary layer height, [10], [15]. Due to Thailand is the tropics, sunrise usually occurs during 5:00 – 6:00. The solar heat may disturb the nighttime stable layer and agitate nocturnal aerosols with some residuals near the surface. The lowest BC concentrations were found during 13:00 – 16:00 both weekdays and weekends data. The decrease after rush hours was mentioned to be associated with the atmospheric turbulent mixing and meteorological conditions [19]. Nonetheless, the diurnal pattern of BC observed at Ratchathewi station was unlike those observed in other urban cities such as London [12] and New Delhi [20] due to traffic rush hours on Phayathai road was uncommon.

3.4 Traffic characteristics on Phayathai road

Traffic volumes on Phayathai road were also counted during the same period, the traffic density ranged from 510 to 5342 vehicles/hour, resulting in the average of 2671 vehicles/hour. When weekdays and weekends data were categorized, their average densities were 2759 and 2451 vehicles/hour, respectively. The diurnal patterns of traffic flow pass through Phayathai road near the sampling station on weekdays and weekend are presented in Fig.4. The most congested traffic flows were observed during 7:00 – 8:00 and 16:00 – 17:00, which the traffic densities increased up to 3796 and 3871 vehicles/ hour, respectively.

However, Figure 4 illustrated that traffic densities during 8:00 – 16:00 were not drastically decreased in comparison with those peaks. This should be due to Phayathai road leads to Victory monument (the hub of public transportation), and several public hospitals located nearby, resulting in substantial traffic congestion almost all daytime. Besides, there were several public organization or educational institutes nearby Victory monument. Their office hours mostly ended at 16:00, resulting in traffic congestion happened since 16:00 and started to decrease after 17:00. For weekends, traffic congestion still exhibited substantially, but not the same early hours as those on weekdays. The morning traffic density during the weekends observed at 9:00 and reach the highest densities of 2844 vehicles/hour at approximately 10:00. For nighttime, their peak of 3722 vehicles/hour was found during the hour of 20:00 – 21:00.

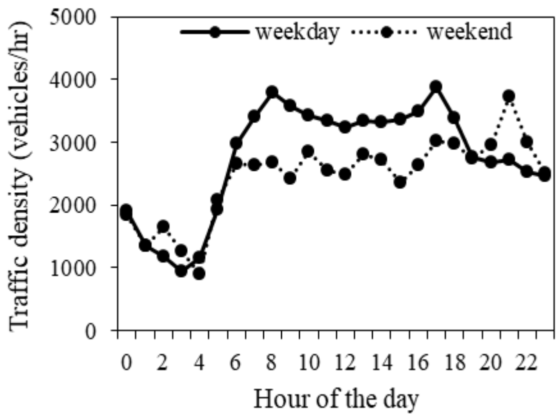

Fig. 4 Diurnal patterns of traffic density

The average traffic densities during daytime on weekdays was about 3382 vehicles/hour, which was clearly higher than the daytime average density on weekends (2675 vehicles/hour). In contrast, the average traffic densities during nighttime on weekdays (1969 vehicles/hour) was lower than that of 2185 vehicles/hour on weekends. This could be noticed that fluctuation of traffic densities on weekends were smaller than that of weekdays. Table 2 categorized traffic composition passing through this station during the same sampling period. Traffic composition affected the emission of pollutants. The vehicle fleets were dominated by private car (29-30%), taxi (25-33%) and motorcycle (21-25%), while pickup, van, Tuk–Tuk (three-wheel vehicle) and bus proportions were 8, 4, 2 and 4%, respectively. Truck show the smallest contribution of less than 1%.

Table 2 Percentage of traffic fleets composition

Vehicle type	Weekday	Weekend
Private car	30.0±4.0	29.0±3.9
Pickup	8.4±0.8	6.8±3.5
Van	4.1±0.8	3.3±0.8
Taxi	25.0±5.6	33.0±3.8
Motorcycle	25.0±13.0	21.0±6.5
Tuk–Tuk	2.0±0.2	2.2±1.0
Bus	4.7±1.7	4.0±1.1
Truck	0.4±0.1	0.6±0.0
Average (vehicles/hour)	2759±660	2451±679

The high proportions of private car, taxi, motorcycle and pickup were observed both on weekdays and weekend while the shares of Tuk–Tuk and truck were still smaller than other fleets during the week. In comparison between weekdays and weekends, the major fleets (private car, pickup, motorcycle, etc.) showed smaller proportion on weekends. While there were some fleet increased their proportions on weekends, e.g., taxi, Tuk–Tuk and truck.

3.5 Correlation between BC concentration and traffic

Figure 4 illustrated that traffic densities start to increase from pre-dawn at 4:00, similar to the increase of BC concentration in Fig. 3. However, BC concentration reached its peak at 6:00 and decreased afterward, while traffic densities still kept rising until 8:00. After the morning peak, the decrease of BC concentrations was more drastically than traffic densities. The BC concentrations lowered to the smallest during 13:00 – 16:00 (Fig. 3), but traffic densities were still substantial amount at the same hours. Therefore, the correlation between BC concentrations and traffic densities in this study could not be affirmative. Subsequently, traffic fleets were further considered and truck vehicles (Fig. 5) showed interesting correlation with BC concentrations. (Remarks: Some other fleets also showed a weak correlation, but data were not discussed here.)

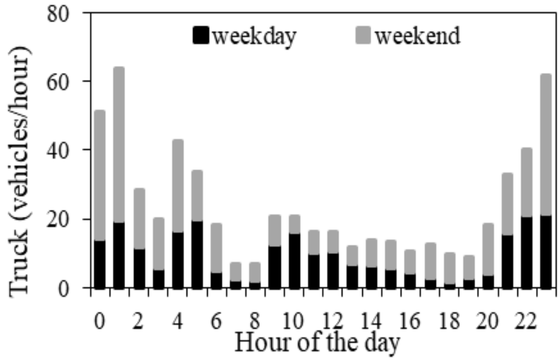

Fig. 5 The diurnal pattern of truck density

Trucks transportation within Bangkok area were regulated and allowed only between 10:00 – 15:00 and after 21:00, resulting in similarity of diurnal pattern of truck and BC concentrations. Figure 5 showed high densities of truck during 4:00 – 5:00 and drastically decreased afterward, as well as, another high truck densities during the night similar to diurnal pattern of BC concentrations (Fig. 3). In addition, more truck densities on weekends than weekdays were consistent with the higher averages BC concentrations on weekends. The possible explanation for this correlation between BC concentrations and truck densities might be due to diesel was their majority fuel. Particularly during nighttime, heavy-duty diesel vehicles should be an important source of black carbon emission.

3.6 Effects of meteorological parameters on BC concentrations

Wind speeds during the sampling period were monitored and found in the range of 0.5 – 2.5 m/s with their average of 1.3 m/s. Wind speed is an important factor related to accumulating BC concentration. Higher wind speed could contribute more emission dispersion, lowering pollutant concentrations in the ambient. Wind speed higher than 0.5 m/s illustrated a significant inverse relation with BC concentrations ($r = -0.377$, $p<0.01$).

Predominant wind directions were observed from east-southeast (ESE), east (E), southwest (SW) and south-southwest (SSW), the frequency percentages of which were 16.4, 10.1, 13.7, and 10.6%, respectively. The contribution of hourly BC concentrations from different wind directions was shown in Fig. 6. During sampling period, BC concentrations larger than 5 $\mu g/m^3$ occurred when the wind blowing from the directions of ENE/E/ESE (28%) and SE/SSE/S/SSW directions

(27%). As the monitoring station is located on the west–northwest curbside of the road. The results indicated that BC mass should be influenced by traffic emissions, which was consistent to the relation between BC concentrations and heavy-duty diesel vehicles on weekends.

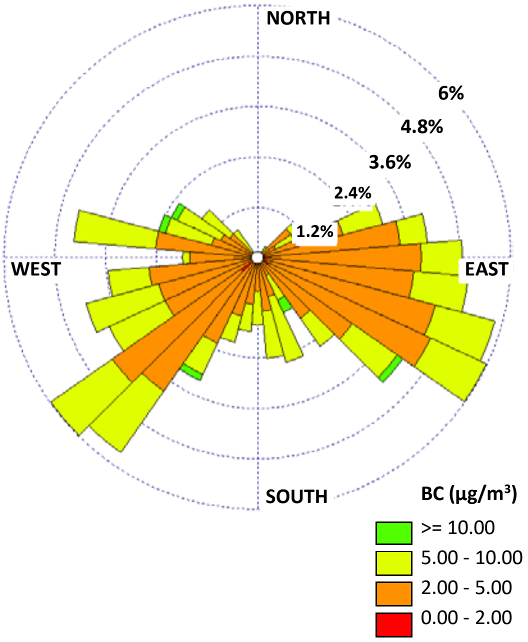

Fig. 6 Pollution rose of hourly BC concentrations

4. CONCLUSION

Hourly BC concentrations in this study were measured at roadside station in the center of Bangkok during dry season in year 2017. The averages of hourly BC concentration and BC/PM2.5 ratio were observed as 4.5±1.9 µg/m^3 and 18%, respectively. The results were lower than a previous study in Bangkok [10]. Diurnal pattern showed two peaks of BC concentrations during the periods of 5:00–7:00 and 21:00–23:00. Two peaks of BC concentrations in this study were more likely due to rush hour traffic concurrently with meteorological condidition. When the prevail wind direction blowed from traffic congestion on the road to the monitoring station, high BC concentrations were sometimes observed. Heavy-duty diesel vehicles should be an important fleet affecting BC concentrations, especially during nighttime and weekends.

5. ACKNOWLEDGMENTS

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