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Original Research

Spatiotemporal Distribution of $PM_{2.5}$ and Its Correlation with Other Air Pollutants in Winter During 2016~2018 in Xi'an, China

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Abstract

High concentration of $PM_{2.5}$ has seriously affected people's daily lives in recent years. It is necessary to analyze $PM_{2.5}$ and the correlations with other pollutants in winter. Data presented in this paper were obtained from monitoring stations from 2016 to 2018. Attention was fixed on $PM_{2.5}$ and its monthly and daily variations in winter. Furthermore, the correlations between $PM_{2.5}$ and CO, SO_2, NO_2, O_3 and PM_{10} were studied. The results showed concentrating $PM_{2.5}$ was roughly consistent with the monthly and daily trends. It was January>December>February>November>March. The mass concentration ranges of $PM_{2.5}$ before and after the adjustment of heating energy structures were 64.5-184.1 μg/m^3, and 86.4-140.1 μg/m^3, respectively. The average concentrations of $PM_{2.5}$ were 135.5 μg/m^3, and 109.1 μg/m^3, decreased by 26.4 μg/m^3. $PM_{2.5}/PM_{10}$ was changed from 64.6% to 62.6%, reduced by 2%. The linear correlation analysis revealed a strong correlation between $PM_{2.5}$ and CO, SO_2, NO_2, and PM_{10}, but a negative correlation between $PM_{2.5}$ and O_3. Two multiple linear regression models on the pollutants were established, respectively. This study helps understand the concentrating distribution of $PM_{2.5}$ and other pollutants in winter. It will provide some useful references to control air pollution for some cities, which have a similar type of heating energy structure.

Keywords: adjustment of heating energy structures, correlation, gaseous pollutants, particulate matters, winter

Introduction

With the rapid development of China's economy, air pollution has become an increasingly prominent problem. People pay more attention to a series of problems caused by air pollution [1]. High concentration of particulate matters was still the primary pollutants in heating season [2]. Pollutants would lead to a serious decline in atmospheric visibility, and they could bring many inconveniences to people's normal travel and transport. They also caused different degrees of harm to human bodies [3, 4]. $PM_{2.5}$ was considered as the major pollutant in the atmosphere. It referred to particulate with an average aerodynamic diameter of less than 2.5 μm

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[5]. $PM_{2.5}$ had a small particle size and large specific surface area. $PM_{2.5}$ was the most possible to carry more viruses or bacteria [6]. Relate literature showed that people would be dead if they lived-in this environment for a long-term [7].

All countries adopted a series of related policies and standards to limit the emission concentration of atmospheric particulate matters in the world [8-12]. Specifications for $PM_{2.5}$ concentrations of each standard were shown in Fig. 1. The average daily concentration of 75μg/m^3 was the World Health Organization's Air Quality Guidelines Transition Period Objective-1 (IT-1), which was given as a recommended signal, and it was not a must [13]. The average daily concentrations of Chinese standard were 35 and 75μg/m^3 for $PM_{2.5}$, 50 and 150 μg/m^3 for PM_{10}, 50 and 150μg/m^3 for SO_2, 80 μg/m^3 for NO_2, 4 mg/m^3 for CO, and 1-hour O_3 values, 160 and 200 μg/m^3, respectively [12].

Scholars from different countries carried out some types of corresponding measures and research to solve the existing environmental pollution problems at the same time, and to create a good indoor and outdoor environment [14-25]. For example, plants reduced many pollutants such as volatile organic compounds, carbon monoxide, nitrogen and sulfur oxides, particles, formaldehyde, and heavy metals [14, 15]. Plants also lead to climate change in the environment as well as urban area [16-18]. Furthermore, indoor plants psychologically reduced their stress and other negative feelings, and improve their productivity [19-21]. In addition, people might spend as much as 80~90% of their time indoors [22]. It was more important to breathe safe and clean fresh air in the building environment. More scholars were focusing on the research and development of new filter materials and the performances of air filters to jointly provide measures for a good living environment [23-25].

The effective treatment of the sources of pollution could fundamentally solve the current status of pollution. As a result, study of pollution characteristics

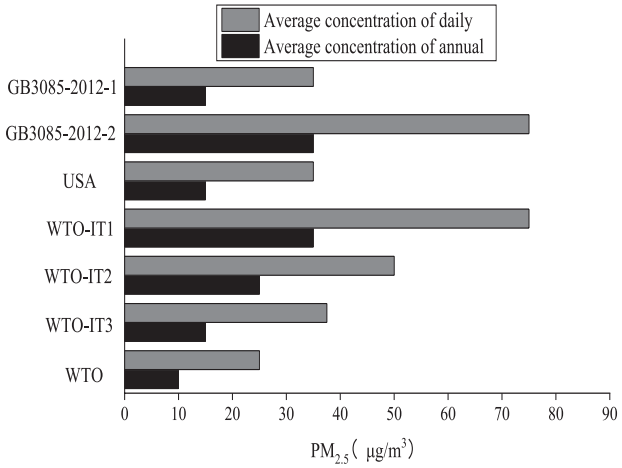

Fig. 1. Rules for $PM_{2.5}$ concentration by different air quality standards.

for $PM_{2.5}$ in winter had been becoming the primary focus of different countries. Like particulate matters [26, 27], types of adjusting energy structure [28], adjusting heating measures in different cities [29, 30], and the correlation between particulate matters and other gassy pollutants [31, 32]. However, there were few studies focused on concentrating $PM_{2.5}$ in atmosphere and the correlation between other pollutants under adjusting heating energy structures in winter. At present, the research on China was limited to some areas, such as Changchun [33], Xi'an [34], Beijing [35] and so on. In addition, there were great distinctions in different regions of China due to the influence of geography and economic factors [36]. The adjustment of heating energy structure also changed the concentration distribution of pollutants, resulting in more complex distribution and source of $PM_{2.5}$ [31]. Therefore, there is a lack of research on the typical areas in central and western regions of China where the heating energy structure was changed from coal to gas or electricity.

Xi'an was taken into an example of this paper. All the data was received from monitoring stations for the whole year from 2016 to 2018. This study would provide the concentration distribution characteristics of $PM_{2.5}$ under adjusting heating energy, which will provide a reference to popularize of heating energy structures adjustment and the control of $PM_{2.5}$ pollution.

Methods

The data used in this paper was from January 31, 2016 to December 31, 2018, which was gathered from the national urban air quality real-time publishing platform. For example, the average concentration values of SO_2, NO_2, PM_{10}, $PM_{2.5}$, O_3 and CO were collected from the weather forecast network (http://www.tianqihoubao.com/aqi/xian) every day. The hourly concentration values of six pollutants from monitoring stations in Xi'an published by the weather network (http://www.tianqi.com/air/xian.html). Some of these Chinese standards were taken into providing references to ensure the validity of data statistics [37, 38]. They would make the data more efficiently. The period of heating season was from November 15 to March 15th in Xi'an [39]. The stage from 2016 to 2017 was before adjusting heating energy structure, and the stage from 2017 to 2018 was after the adjustment of heating energy structure.

Results and Discussion

Xi'an is located at east longitude 107.40°-109.49° and north latitude 33.42°-34.45°. It has a long-established old civilization city with more than 5,000 years of civilization history, and it also has a large population [26]. Pollution of atmospheric in Xi'an had become increasingly serious in recent years. To solve this

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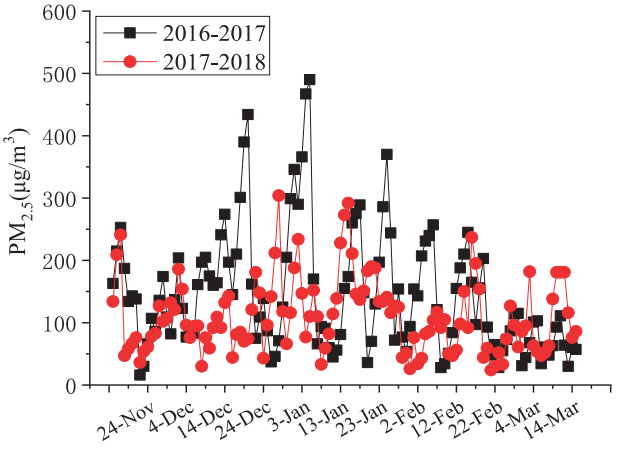

Fig. 2. Monthly characteristics of $PM_{2.5}$ pollution.

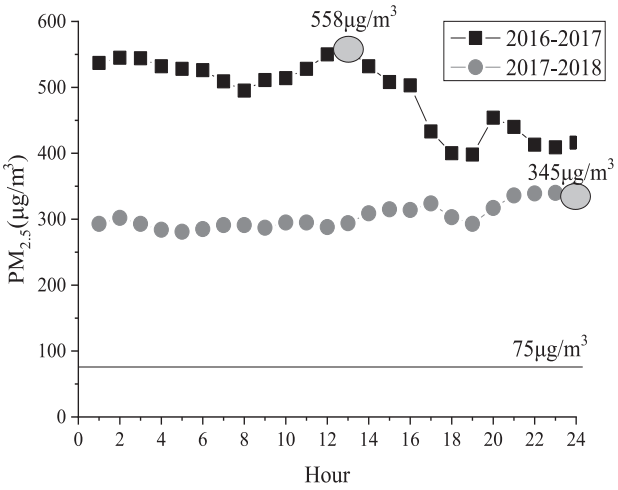

Fig. 3. Daily characteristics of $PM_{2.5}$ pollution.

problem effectively, a series of measures were taken into protecting the blue sky in 2017, making urban residents live without coal was implemented, coal-to-electricity and coal-to-gas were carried out [40, 41]. It would provide the targeted approach to the controlling of fog and haze before and after the adjustment of heating energy strictures in winter.

Monthly Characteristics of $PM_{2.5}$ Pollution under Adjusting Heating Energy

There was the same trend of distribution of $PM_{2.5}$ under the heating period in two winters in Fig. 2. The average monthly concentration of $PM_{2.5}$ was the highest in January, and the lowest in March. It showed January>December>February>November>March. Days of 121 were taken as sample. There were 88 days exceeded the national secondary day standard of 75 μg/m³ before adjusting the heating energy. The ratio of days exceeding standards was 72.7%. There was 86 days exceeded the national secondary day standard of 75 μg/m³ after adjusting the heating energy. The ratio of days exceeding standards was 71.1%. Concentrating $PM_{2.5}$ in the atmosphere was still exceeding the standard [12]. The main reasons were concentrating particulate matters were increased because of the demand for heating in winter. It was not conducive to diffuse pollutants under the low temperature in winter [42]. Particulate matters were still the primary pollutants of the heating season in winter. The ratio of days exceeding standards was decreased by 1.6% after adjusting the heating energy in winter.

Daily Characteristics of $PM_{2.5}$ Pollution under Adjusting Heating Energy

The maximum 2 days of $PM_{2.5}$ concentration were January 5, 2017, and December 28, 2017, respectively. The daily time was taken from 0:00 to 23:00 in Fig. 3. The variation range of $PM_{2.5}$ was from 398 to 558 μg/m³ before adjusting heating energy structure. The average concentration was 491 μg/m³. The variation range of $PM_{2.5}$ was from 281 to 345 μg/m³ after the adjustment. The average concentration was 305 μg/m³. Both of the concentrating $PM_{2.5}$ was far exceeding the limit of the national secondary concentration standard [12]. The average concentration value was decreased by 186 μg/m³. It showed relatively stable after adjusting heating energy structure. The concentrating $PM_{2.5}$ was very low at night, because some of the activities of human were less, and outdoor environment was better at that time. The concentrating $PM_{2.5}$ gradually increased from around 8:00 in the morning, and it had a small change between 11 and 19 o'clock. The gradual rise appeared at 19 o'clock when the heating demand was increasing at night. The activities of humans began to decline after 23 o'clock. The conclusions that were given by Zhu et al. [42] were confirmed the correctness of this paper.

Characteristics of $PM_{2.5}$ and PM_{10} Pollution under Adjusting Heating Energy

As can be seen from Fig. 4, the mass concentration ranges of $PM_{2.5}$ before and after adjusting heating energy structures were 64.5-184.1 μg/m³ and 86.4-140.1 μg/m³. The difference between the maximum values was 44 μg/m³. The average concentrations of $PM_{2.5}$ before and after adjusting heating energy structure were 135.5 μg/m³ and 109.1 μg/m³, which exceeds the national secondary standard (75 μg/m³) 1.81 times, 1.45 times [12]. The mass concentration ranges of PM_{10} before and after adjusting heating energy structures were 116.5-261.2 μg/m³, and 144.9-197.1 μg/m³, respectively. The difference between the maximum values was 64.1 μg/m³. The average concentrations of PM_{10} before and after adjusting heating energy structure were 205.6 μg/m³ and 173.8 μg/m³, which exceeding the national secondary standard (150 μg/m³) 1.37 times, 1.16 times [12]. The mass concentration ranges of $PM_{2.5}/PM_{10}$

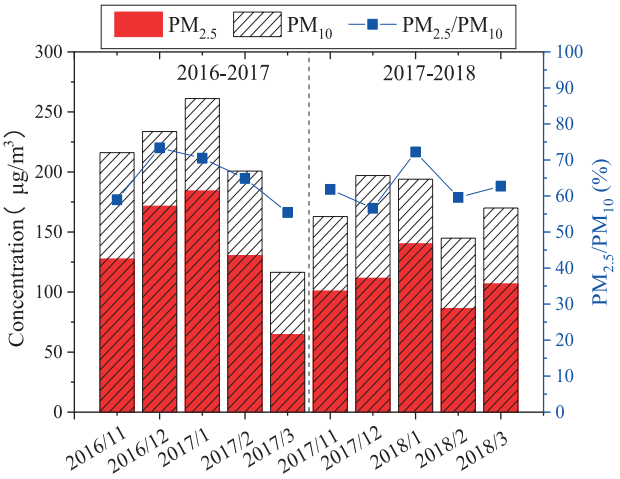

Fig. 4. Concentrating PM changed under adjusting heating energy.

before and after adjusting heating energy structures were 55.4-73.4%, and 56.6-72.2%, respectively. The average concentrations of $PM_{2.5}/PM_{10}$ before and after adjusting heating energy structures were 64.6%, 62.6%, respectively. The ratio of $PM_{2.5}/PM_{10}$ was decreased by 2%. On the whole, the total particulate matters were decreased after adjusting heating energy structure. Especially the large particulate matters were decreased more deeply, which was consistent with the existing literature [26].

Correlativity between $PM_{2.5}$ and Other Major Pollutants

The average concentrations of PM_{10} and $PM_{2.5}$ were all decreased in Fig. 5. There was a good consistency between the two, and a strong correlation. The average concentrations of $PM_{2.5}$ were decreased from 146 μg/m³ to 111 μg/m³, with a decrease of 35.1 μg/m³. The average concentrations of PM_{10} were decreased from 216 μg/m³ to 176μg/m³, with a decrease of 39.9 μg/m³. The decrease ratio of PM_{10} was greater than $PM_{2.5}$. The average concentrations of CO were decreased from 2.26 mg/m³ to 1.79 mg/m³, with a decrease of 0.47 mg/m³. It was useful to reduce the emissions of $PM_{2.5}$ and CO by adjusting the heating energy structure [43]. The average concentrations of SO_2 were decreased from 32.5 μg/m³ to 25.3 μg/m³, with a decrease of 7.2 μg/m³. They were mainly released by coal burning [44]. The average concentrations of NO_2 were increased slightly from 70.5 μg/m³ to 70.8 μg/m³, with an increase of 0.3 μg/m³. The average concentration of NO_2 was increased from carrying out the relevant policies of coal to electricity and coal to gas [45, 46]. NO_2 would generate secondary particles by chemical reactions, which would realize the transformation from gas to particle matters [44]. The average concentrations of O_3 were increased slightly from 26.1 μg/m³ to 29.8 μg/m³, with an increase of 3.7 μg/m³. The decreased temperature and increased particulate matters would all have a great effect on the process of photochemical reaction [44]. It was still necessary to further study the average concentration of O_3.

Analysis of the Correlation between $PM_{2.5}$ and Other Pollutants

Correlation coefficient between the daily average concentration of $PM_{2.5}$ and that of other pollutants was showed in Table 1.

The correlation coefficients of before and after heating energy structures adjustment were as follows: 0.953>0.946>0.688>0.643, 0.916>0.800 >0.681≥0.679. The corresponding pollutants affecting the magnitude of $PM_{2.5}$ were: PM_{10}>CO>NO_2>SO_2, CO>PM_{10}>NO_2>SO_2. It can be found that PM_{10} had the greatest correlation with $PM_{2.5}$ before heating energy structure adjustment, and CO was the most relevant to $PM_{2.5}$ after heating energy structure adjustment. Specifically, correlation coefficient between $PM_{2.5}$ and O_3 was negative relevant. It might be related to spreading regional pollutants, and the way for reducing carbon emissions [45]. Therefore, it was necessary to conduct some deeper research on the selecting of energy structure types.

A multiple linear regression model was established by the software Eviews as follows (1).

$$Y = \beta_0 + \beta_1 X_{CO} + \beta_2 X_{NO_2} + \beta_3 X_{SO_2} + \beta_4 X_{PM_{10}} \quad (1)$$

...where: Y, X_{CO}, X_{NO_2}, X_{SO_2}, and $X_{PM_{10}}$ are the average daily concentration values of $PM_{2.5}$, CO, NO_2, SO_2, and

Table 1. Correlation coefficient between PM2.5 and other pollutants.

Pollutants / Time	2016-2017		2017-2018	
	Fitting formula	R^2	Fitting formula	R^2
PM_{10}	y = -31.9+0.8x	0.953	y = 7.9+0.6x	0.800
SO_2	y = -54.4+6.2x	0.643	y = -6.0+4.6x	0.679
NO_2	y = -81.0+3.2x	0.688	y = -22.4+1.9x	0.681
CO	y = -120.6+118.1x	0.946	y = -71.9+102.1x	0.916
O_3	y = 244.7-3.8x	-0.492	y = 144.1-1.1x	-0.309

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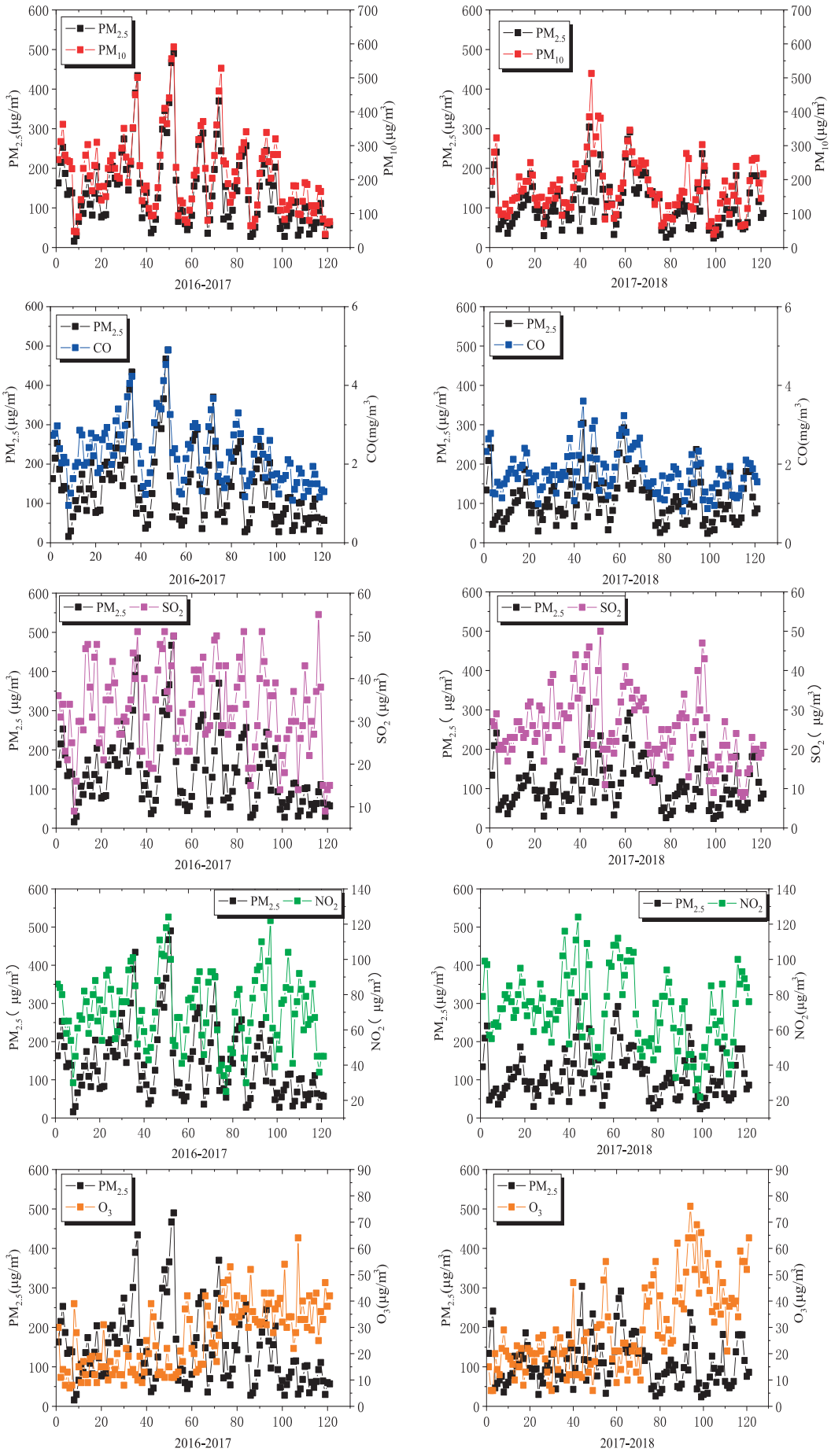

Fig. 5. Correlativity between $PM_{2.5}$ and other pollutants.

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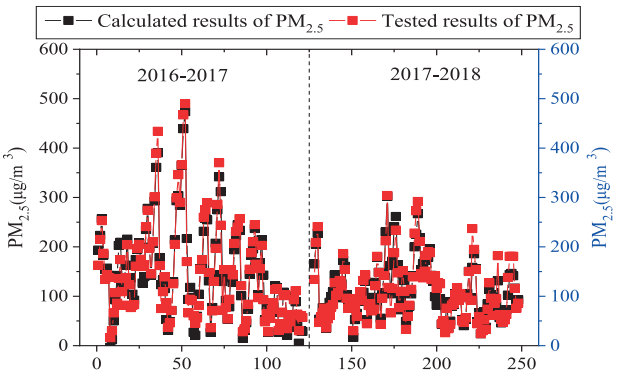

Fig. 6. Comparison of calculated and tested results of $PM_{2.5}$.

PM_{10}, respectively.

The formulas before and after heating energy structures adjustment were as follows:

$$Y_1 = 59.9X_{CO} + 0.051X_{NO_2} - 0.400X_{SO_2} + 0.467X_{PM_{10}} - 80.9 \quad (2)$$

$$Y_2 = 107X_{CO} - 0.591X_{NO_2} - 0.561X_{SO_2} + 0.197X_{PM_{10}} - 58.3 \quad (3)$$

The results showed that the correlation coefficient R was 0.95 and the decision coefficient R^2 was 0.95 before adjustment. While the correlation coefficient R was 0.89 and the decision coefficient R^2 was 0.89 after adjustment. From the point of decision coefficient, the regression equations were obvious.

The concentration of $PM_{2.5}$ before and after heating energy adjustment could be calculated by substituting the corresponding. The average daily concentration values of CO, SO_2, NO_2, and PM_{10} into the formula (1), respectively. Results from the actual test and the calculation of the $PM_{2.5}$ were compared as shown in Fig. 6. It could be seen that the predicted values were consistent with the tested results. It signified that the average daily concentration of $PM_{2.5}$ can be effectively predicted by the multiple linear regression equation (2), and (3).

Conclusions

In this paper, based on the data obtained from monitoring stations in Xi'an for the whole three years from 2016 to 2018, concentration distribution characteristics of $PM_{2.5}$ and its correlation with other air pollutants were analyzed before and after the adjustment of heating energy structures in winter. The conclusions were as follows:

1. The average concentration values of $PM_{2.5}$ were roughly consistent with the monthly and daily trends before and after adjusting heating energy structures in two winters. It was January>December>February>November>March. The ratio of days exceeding standards before and after adjusting heating energy structure was 72.7%, and 71.1% of the national secondary standards in China, respectively.

2. Before and after the adjustment of heating energy structures, the mass concentration ranges of $PM_{2.5}$ in winter were 64.5-184.1 μg/m³, and 86.4-140.1 μg/m³, the corresponding average concentrations of $PM_{2.5}$ were 135.5 μg/m³, and 109.1μg/m³, decreased by 26.4 μg/m³. The mass concentration ranges of PM_{10} were 116.5-261.2 μg/m³, and 144.9-197.1 μg/m³, the corresponding average concentrations of PM_{10} were 205.6 μg/m³, and 173.8 μg/m³, decreased by 31.8 μg/m³. The average concentrations of $PM_{2.5}/PM_{10}$ before and after adjusting were 64.6%, and 62.6%, decreased by 2%.

3. The concentration value of $PM_{2.5}$ showed a strong correlation with CO, SO_2, NO_2, and PM_{10} but a negative correlation with O_3 ($PM_{2.5}/CO$ r_1 = 0.946, r_2 = 0.916; $PM_{2.5}/SO_2$ r_1 = 0.643, r_2 = 0.679; $PM_{2.5}/NO_2$ r_1 = 0.688, r_2 = 0.681; $PM_{2.5}/PM_{10}$ r_1 = 0.953, r_2 = 0.800, $PM_{2.5}/O_3$ r_1 = -0.492, r_2= -0.309).

4. Two multiple linear regression models of $PM_{2.5}$ with the pollutant concentration of CO, SO_2, NO_2 and PM_{10} as independent variables were established before and after energy structure adjustment. This study will be conducive to understanding the concentration distribution of $PM_{2.5}$ and the relationships with other pollutants in Xi'an before and after adjusting heating energy structures in winter. It will provide a reference for Xi'an and some other city to promote the heating energy structures adjustment and the control of $PM_{2.5}$ pollution.

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Conflict of Interest

The authors declare no conflict of interest

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