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Study on the Emission Characteristics of Urban Buses at Different Emission Standards Fueled with Biodiesel Blends

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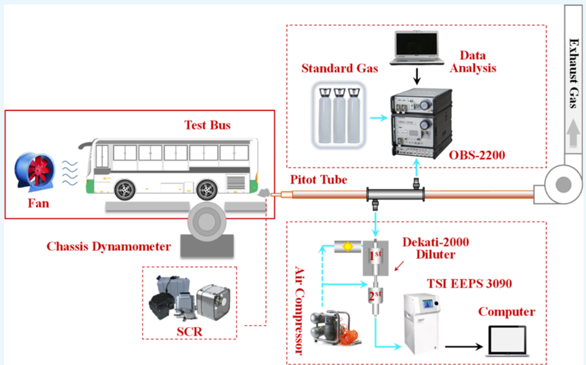
ABSTRACT: Biodiesel is a promising clean and alternative fuel that can meet the demand of energy saving and environmental protection. In this study, the effects of biodiesel blends on the gaseous and particulate emission characteristics of China-III, IV, and V urban buses were investigated based on a heavy chassis dynamometer. The results showed that the biodiesel blend resulted in a reduction in CO, THC, PN, and PM emission but an increase in the NOx and CO_2 emission, and the effects were enhanced with the biodiesel ratio, which also depended on the bus speed. Simultaneously, the emission standards of buses had an obvious effect on the emissions and changed the effect of biodiesel on the emissions. A higher emission standard of the bus highlighted the effect of biodiesel on the emission. From China-III to China-IV to China-V buses, the comprehensive changes produced by B5 in the emissions increased from 5.57 to 6.78 to 6.83%, while for B10, a significant increase in the changes was obtained, reaching 12.98, 14.68, and 15.02%, respectively, for the three emission stage buses.



INTRODUCTION

The diesel engines characterized by larger power, higher thermal efficiency, better fuel economy, and reliability are playing an important role in urban buses.[1] However, the diesel engines consume a large amount of fossil fuel; thus, there are such problems as depletion of fossil energy and serious environmental pollution caused by lavish consumption of fossil fuels in the world nowadays.[2] In this regard, it is necessary to develop renewable and cleaner fuels. The biodiesel, which can be made from fatty acid methyl or ethyl esters, generally exhibits higher oxygen content and cetane number than petroleum diesel.[3] There are many raw materials for producing biodiesel including rapeseed oil, soybean oil, sunflower seed oil, palm oil, waste cooking oil, and so forth.[4] Among them, the waste cooking oil is a very excellent biodiesel raw material because on the one hand, the waste cooking oil comes from a wide range of sources with a large quantity and low price, on the other hand, using waste cooking oil to produce biodiesel can not only solve the food safety problems by avoiding the waste cooking oil return to dining table but also ease the energy safety problem by increasing energy diversity, which will promote the development of circular economy.[5] Even more remarkably, the biodiesel can be blended with petroleum diesel at any ratio; thus, it has the potential to partially, or even totally, replace diesel fuel in diesel engines.[6]

Although the China-VI emission standard will be implemented, the current in-use diesel vehicles are dominated by China-IV and III vehicles. According to the statistics, China-III, IV, and V diesel vehicles account for 51.7, 41.0, and 5.4%, respectively,[7] in the whole diesel vehicles. The vehicles with different emission standards will adopt different inside purification and after-treatment technologies. China-III diesel vehicles mostly adopt only electronic control single pump technology and are not usually installed with additional after-treatment devices. For China-IV and China-V diesel vehicles, they adopt not only the electronic high-pressure common rail technology but also the selective catalytic reduction (SCR) technology or the EGR + DPF technology.[8] Exhaust gas recirculation (EGR) can recirculate part of the exhaust gas discharged by the diesel engine back into the cylinder, reducing NOx. The diesel particulate filter (DPF) can remove more than 90% of particle emissions from diesel engines. Therefore, the application of biodiesel to vehicles with different emission standards may produce different results for gaseous and particulate emissions.

Although biodiesel slightly reduces the engine power and increases the fuel consumption, it possesses good emission performance for some substances.[9] Many researchers reported

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that the use of biodiesel will lead to a reduction in the CO and HC emission. However, the containing oxygen in the biodiesel may result in an increase in oxide including CO_2 and NOx emissions. In addition, it is widely reported that the biodiesel is conductive to reducing PM of diesel engines, but it may produce a negative or positive effect on the PN. Tan et al. reported that the biodiesel can reduce 23.1% of the CO, 46.7% of the HC, and 76.9% of the smoke from a Euro-3 diesel engine at a high load.[10] Macor et al. investigated the effects of B30 on regulated and unregulated pollutant emissions from a Euro-3 diesel engine and got similar results.[11] Karavalakis studied the effect of biodiesel B20 on the pollution for a Euro-4 passenger and found that B20 reduces 11.10% of the CO, 9.6% of the HC, and 7.8% of the PM but increases the NOx by 3.9%.[12] Similar results were also observed by Kousoulidou et al. and Bakeas et al.[13,14] Kaya investigated the effect of biodiesel on the emissions using a Euro 5 passenger car and found that B30 reduces 34% of the CO, 33% of the HC, and 22% of the PN. Kaya et al. also evaluated the effect of biodiesel on the emissions from a Euro-5 diesel vehicle and also found that B30 leads to lower CO, HC, and PN emissions.[15] Shen et al. studied the effects of biodiesel blends at different ratios on the emission of China-IV heavy-duty trucks and found that the CO, HC, and $PM_{2.5}$ emissions decrease with increasing biodiesel content in the blend.[16] However, they did not focus on the engine technology coupling performance with biodiesel. Kousoulidou et al. reported that influence of biodiesel on pollutant emissions primarily depends on the blending ratio and, second, on the engine technology.[14] Cahill and Okamoto demonstrated that the engine technology has a greater influence on the emission rates than biodiesel fuels.[17] Williams et al. compared the effects of specific diesel fuel used in vehicles with different European emission standards on regulated/unregulated emissions and fuel consumption and confirmed the contribution of regulatory upgrades to emissions.[18−20] However, the above studies were confined largely to the application of biodiesel to diesel vehicles under a single emission standard or emission of diesel vehicles under different European standards, but they did not compare the emission characteristics of diesel vehicles under different emission standards with biodiesel blends at different ratios.

Consequently, in this study, the emission characteristics of urban buses of different vehicle emission standards fueled with biodiesel blends from waste cooking oil were investigated, in order to analyze the effect of the vehicle technology, biodiesel blends, and their coupling on the emissions of buses.

■ RESULTS AND DISCUSSION

Emission Rates with Biodiesel Blends of Buses at Different Emission Standards. The significant effects of the binding regulations on the emissions can be seen. The CO emission rate for China III bus was higher than that of China-IV bus, and the CO emission rate of China-V bus was the minimum and is shown in Figure 1. Obviously, the CO emission rate increased with the speeds, the CO emission rate at a middle speed was more than twice as high as that at a low speed, and the CO emission rate at a high speed was more than twice as high as that at a middle speed. As CO is the product of incomplete combustion of fuels and engines are subjected to a low load and small injection at a low speed, the CO emission rate is relatively low. The higher speed usually causes more frequent accelerating and enriching condition of the injection, so the increase in the working cycle per unit time

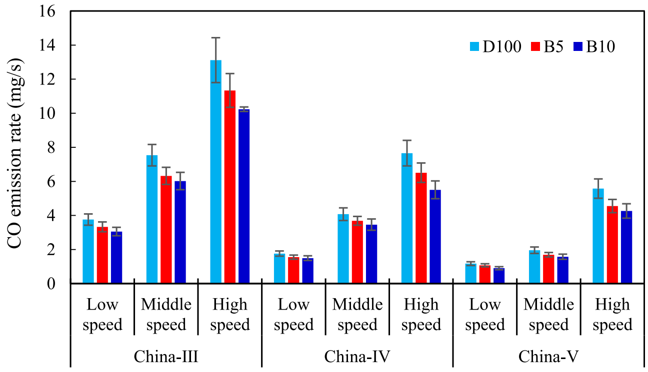

Figure 1. CO emission.

leads to the rise of the CO emission rate.[21] After the bus was fueled with biodiesel blends, as biodiesel contains high cetane number and abundant oxygen molecules which promote the stable operation and full combustion of engines, the CO emission presented a declining trend, and the more biodiesel in the blends, the lower emission of the CO. It should be noted that when combustion temperature of the gas mixture in the engine cylinder is low, high viscosity of biodiesel influences the atmospheric effects of fuel, which easily result in the uneven combustible gas mixture.[22] Therefore, when vehicles are at a low speed, the CO emission rate drops slightly than that of diesel. When vehicles are at a middle and high speed, the CO emission rate significantly drops compared with that of diesel as the combustion temperature in the engine cylinder rises, and atmospheric effects of biodiesel get improved. In addition, the reduction in the CO emission rate enlarged with the increase in the speed.

Figure 2 presents the THC emission rate of buses at different emission stages with biodiesel blends at low, middle,

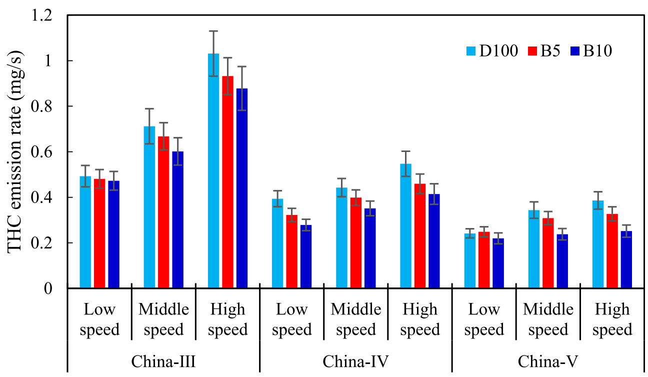

Figure 2. THC emission.

and high speeds. Similar to the emission rules of CO, it can be seen that China-V bus has the lowest THC emission, and the THC emission rate was slightly higher than that of China-IV bus. Moreover, the THC emission rate of China-III bus was much higher than that of China-IV and China-V buses. For every bus, the THC emission rate increases with the speed, and the use of biodiesel results in a reduction in the THC emission rate. THC emission in diesel engines is originated from the zones with too thick or too thin diesel where fuel spray cannot be completely combusted or the chill zone where fuel spray impingement occurs. As the vehicle speed increases, rotational speed and fuel-injection quantity of diesel engines increase,

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and the zones with too thick or too thin diesel in the engine cylinder increase simultaneously. Besides, a single cyclic gas mixture has been formed, and combustion time is shortened, causing the increase in hydrocarbon emission. Biodiesel contains oxygen in its molecules, so oxygen deficit in the high-load cylinder during the combustion can be offset by low air fuel in the high-load cylinder of vehicles, thus improving THC emission.[23,24] Biodiesel with a higher blend ratio contains more oxygen in its molecules, so it shows better emission performance of the gaseous substance THC in various working conditions. In addition, the reduction effect is improved with the increase in the speed.

Figure 3 presents the CO_2 emission rates of buses at different emission stages with biodiesel blends at low-, middle-,

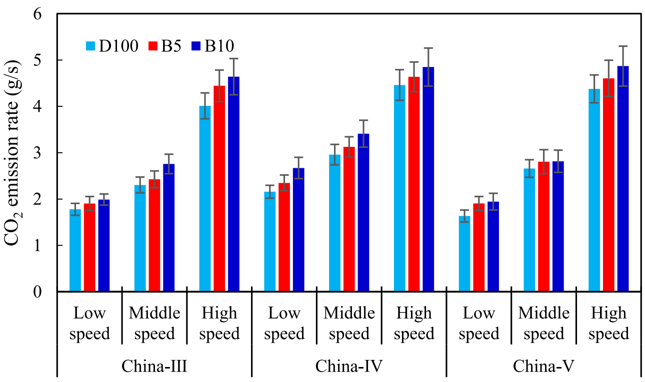

Figure 3. CO_2 emission.

and high-speed conditions. It can be seen that the CO_2 emission rates of China-III and China-IV buses were nearly the same, but the CO_2 emission rate of China-V bus was a little lower, especially at low and middle speeds. It is because that the upgraded China-V test diesel vehicles exhibited higher engine thermal efficiency than China-III and China-IV test diesel vehicles, thus indirectly reducing the CO_2 emission. The speed had a great effect on the CO_2 emission rate of the bus, the CO_2 emission rate increased with the speeds, and it increased significantly at middle and high speeds. CO_2 is a gas substance, dominating the largest emission load of the traditional diesel locomotives. The combustion of engines is a chemical reaction, during which considerable heat is generated, and CO_2 is released from the combination of fuel oil and oxygen. Generally speaking, the area with thin blends of fuel and air in engines at a low load may lead to unstable combustion reactions, thus generating the product of incomplete combustion CO instead of constantly generating CO_2, while in engines at a middle and high load, high temperature contributes to the complete combustion, thus emitting more CO_2.[25,26] The usage of biodiesel led to an increase in the CO_2 emission rate, and the CO_2 emission rate increased with the increased ratio of biodiesel in the blends. The reason is that the calorific value of biodiesel is low, and more fuel needs to be consumed in order to reach the same energy output with diesel combustion under the same working condition, thus generating more carbon emission.[27] Meanwhile, oxygen molecules in biodiesel cause more CO to be oxidized into CO_2.

Figure 4 presents the NOx emission rates of buses at different emission stages with biodiesel blends at low, middle, and high speeds. Because of the upgrade of regulations, China-

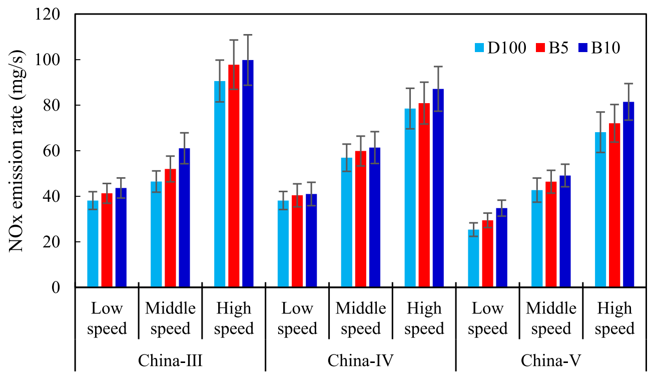

Figure 4. NOx emission.

IV and China-V test diesel vehicles were equipped with more clean and efficient engines, which could effectively reduce the original emission of NOx. It can be seen that the NOx emission rate of China-III bus was the maximum, and the emission rates of China-VI and China-V buses were nearly the same, but both were a little lower than that of China-III bus. The NOx emission rate increased with the speed, and it increased greatly, especially at middle and higher speeds. The NOx emission rate increased with the increase in load of engines because NOx is generated in the conditions of high temperature, high pressure, and rich oxygen. When the vehicle speed increases, the load of engines increases, suggesting that the temperature in the cylinder will increase and single cylinder pressure in the working cycle of engines will also increase, thus causing the increase in NOx emission. It is easier for fueling biodiesel to cause the NOx emission because of its shorter ignition delay and rich oxygen content.[28−30] The use of B5 and B10 fuel caused higher NOx emission, and the NOx emission rate increased with the ratio of biodiesel blending.

Figure 5 gives the PN emission rate of buses at different emission stages with biodiesel blends at low, middle, and high

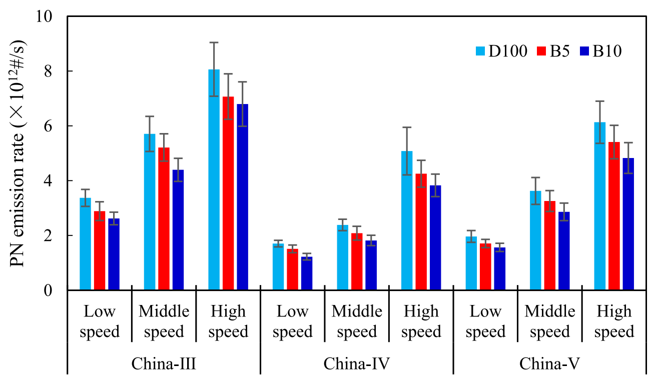

Figure 5. PN emission.

speeds. Obviously, the PN emission rates of China-IV and China-V buses were lower than that of China-III bus, which was also attributed to the improvement of combustion performance of engines under the upgraded regulations. The PN emission rate increased with the speed, and a reduction in the PN emission rate was observed after the bus was fueled with biodiesel blends, and the more the biodiesel in the blends, the lower the emission rate of PN. The increase in working cycle and injection quantity of engines per unit time is the main reason of the increase in the PN emission rate. With the

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increase in vehicle speed and load of engines, injection quantity in the cylinder increases, and the PN emission rate rises. As biodiesel contains oxygen in its molecules, however, carbon molecules in biodiesel combust completely, producing lesser particle matters than pure diesel under the same working condition.[31,32]

Figure 6 presents the PM emission rates of China-III, IV, and V buses at low, middle, and high speeds. Like the PN

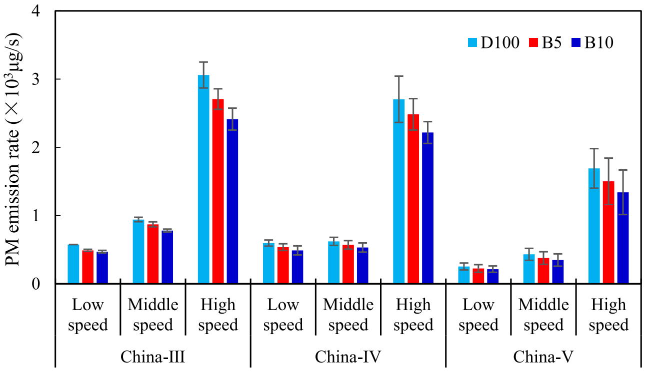

Figure 6. PM emission.

emission characteristic, the PM emission rate of China-III bus was the maximum, and the emission rates of China-IV and China-V buses were lower than China-III bus. The PM emission rates just increased slightly from low to middle speeds, but it increased remarkably from middle to high speeds. It is because that the low speed and engine load cause the small injection quantity. At middle and high speeds, the injection quantity in the cylinder rises with the gradual increase in the engine load, causing the rise of the PM emission rate. Meanwhile, as the PM emission rate is most affected by concentrated accumulated particles (particle size of 50−500 nm) whose explosive growth usually occurs in the worsening combustion condition of oxygen deficit in engines with a high load, the emission rate under the working condition of high speed is high.[33,34] The usage of biodiesel resulted in an obvious reduction in the PM emission, and the reduction effect of B10 on the PM emission rate was better than that of B5. Biodiesel contains oxygen in its molecules, so oxygen deficit in the cylinder can be offset, leading to more significant drop in the PM emission rate.

Emission Factors with Biodiesel Blends of Buses at Different Emission Standards. Figure 7 presents the CO

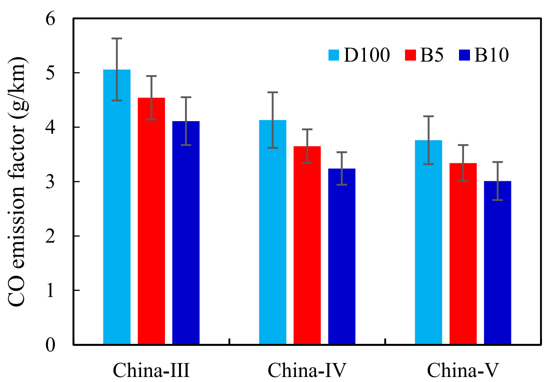

Figure 7. CO emission factor.

emission factors of buses at different stages with biodiesel blends. On the whole, the CO emission factors decreased with the increase in the bus emission standard. For China-III bus, the CO emission factor was 5.06 g/km, and it decreased by 10.3 and 18.8%, respectively, after the bus was fueled with B5 and B10. For China-IV bus, the emission factors decreased by 11.6 and 21.6%, respectively, after it was fueled with B5 and B10. For China-V bus, the application of B5 and B10 resulted in a reduction of 11.2 and 20.0% in the CO emission factors. The conclusions in studies of influence of biodiesel on the emission performance of CO tend to be uniform. Due to the increase in the oxygen content, the product of incomplete combustion CO decreases as the blend ratio increases. In addition, the contribution of fueling biodiesel in the test vehicles under three regulations to CO emission reduction was nearly same as that of pure diesel, and China-IV and China-V diesel vehicles performed better than China-III diesel vehicles in data to a small degree.

Figure 8 gives the THC emission factors of buses at different stages with biodiesel blends. It can be seen that the THC

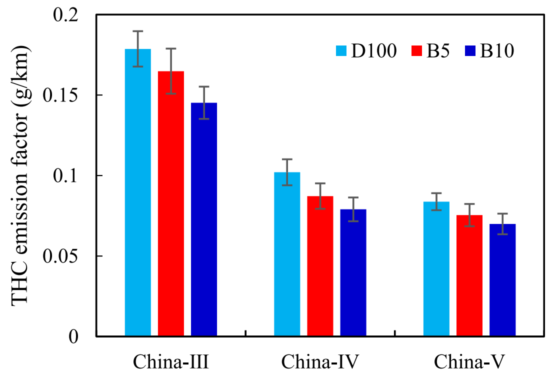

Figure 8. THC emission factor.

emission factors of China-III buses were the highest, followed by China-IV and China-V buses. For China-III bus, the usage of B5 and B10 led to a reduction of 7.7 and 18.7%, respectively. For China-IV bus, the reductions were 14.5 and 22.6%, respectively, after using B5 and B10. For China-V bus, the usage of B5 and B10 reduced the THC emission factors by 10.0 and 16.5%, respectively. It is easily found that emission law of the gaseous substance THC is basically consistent with that of CO in fueling biodiesel.

Figure 9 presents the CO_2 emission factors of buses at different emission stages with biodiesel blends. It can be seen

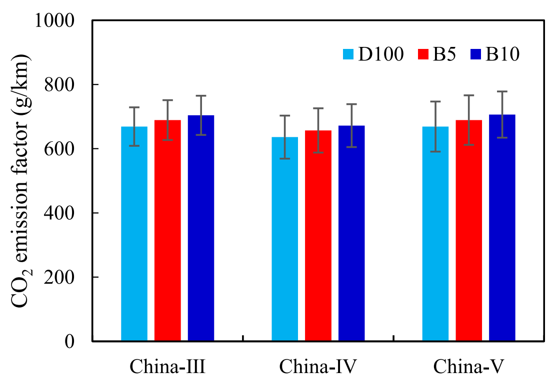

Figure 9. CO_2 emission factor.

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that the CO_2 emission factors of the three buses were nearly the same. When the bus was fueled with biodiesel blends, the CO_2 emission factors increased slightly, and the more the biodiesel in the blends, the higher the CO_2 emission factor. For China-III bus, the application of B5 and B10 resulted in an increase of 3.3 and 5.3% of the CO_2 emission factors. For China-IV bus, the increases were 3.3 and 5.6%, respectively, for B5 and B10. For China-V bus, the usage of B5 and B10 led to an increase of 3.0 and 5.5% in the CO_2 emission factors. It should be noted that different from other gaseous substances in emissions, there has been a few studies on CO_2 in the past long period. In recent years, with the intensifying environmental problems caused by the global carbon emissions, people attach greater importance to the carbon emissions. Most scholars in various countries have made the same conclusion in studies of CO_2 emission in biodiesel: restricted by the oxygen-containing characteristics of biodiesel, more CO is oxidized into CO_2 in combustion. However, some scholars studied other kinds of biodiesel and found that with different raw materials, the prepared biodiesel shows different physical and chemical properties. For instance, the biodiesel produced from soybean contains a high content of unsaturated fatty acid, few C−C bonds, and a low content of oxygen, so the total emission rate of CO_2 is lower than that of pure diesel.[35,36] However, although different kinds of biodiesel show a small increase or decrease in CO_2 emission, a study revealed that the CO_2 emissions from diesel vehicles do not clearly change with increasing biodiesel contents in blends, but the life cycle of CO_2 emissions of biofuels are generally lower than that of petroleum-derived fuels.[37,38]

Figure 10 gives the NOx emission factors of buses at different emission stages with biodiesel blends. It can be seen

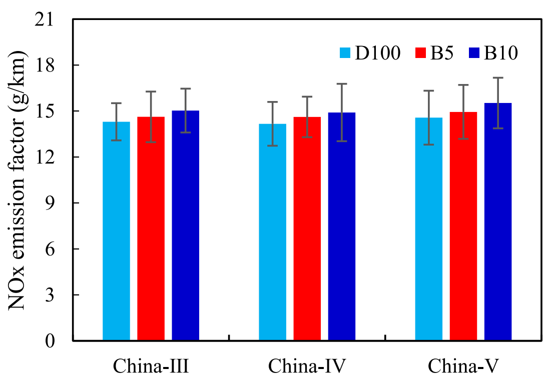

Figure 10. NOx emission factor.

that the NOx emission factors of the three buses were nearly the same. After the bus was fueled with biodiesel blends, the NOx emission factor increased slightly. The higher blend ratio led to the higher emission rate of NOx. For China-III bus, the usage of B5 and B10 increased the NOx emission factors by 2.2 and 5.1%, respectively. For China-IV bus, the application of B5 and B10 led to an increase of 3.3 and 5.6% in the NOx emission factors. For China-V bus, the usage of B5 and B10 increased the NOx emission factors by 2.6 and 6.6%, respectively, and fueling biodiesel performed better in China-IV and China-V test diesel vehicles. The original emission rate of NOx from biodiesel produced from waste cooking oil is universally higher than that from pure diesel. However, a study also showed that the NOx emission rate can be reduced by increasing the proportion of methanol in biodiesel.[39] It could be found that although China-IV and China-V test diesel vehicles were equipped with the SCR after-treatment system, the three test vehicles showed the basically same NOx emission rate, according to the collected data. The reason is that Chinese city bus cycle (CCBC) is a typical transient cycle condition at an average speed of 16.2 km/h, and the unloaded test vehicles have a low load and exhaust temperature. However, the SCR system requires a self-working condition, where urea injection cannot start in too low temperature, so it exerts no effect on the emission reduction of NOx.[40]

Figure 11 presents the PN emission factors of the buses at different emission stages with biodiesel blends. Obviously, the

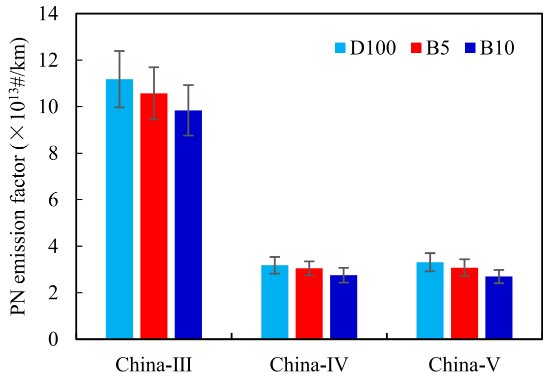

Figure 11. PN emission factor.

PN emission factor of China-III bus was the highest, and the PN emission factors of China-IV and China-V buses were nearly the same, which decreased by more than 70% in comparison with that of China-III bus. It showed that remarkable results have been achieved in emission reduction of PN from vehicles regulated by China-IV vehicle emission standards. The particulates reduce with the increase in the proportion of biodiesel in fuel, mainly because the higher oxygen content and cetane number in fuel at a higher blend ratio cause the stable and full combustion to restrain the generation of particle matters. For China-III bus, the use of B5 and B10 resulted in a reduction of 5.4 and 12.0% in the PN emission factor, while for China-IV bus, the reductions were 4.3 and 13.4%, respectively. For China-V bus, a reduction of 7.0 and 18.5% in the PN emission factors was observed after using B5 and B10, respectively. China-V test diesel vehicles fueled with different ratios of biodiesel exerted the most positive effects on the relative emission reduction rate of the PN, besides the optimization of structure and control strategy of engines, mainly benefiting from the different fuel injection systems in engines. China-V test diesel vehicles were equipped with high-pressure common rail system in diesel engines, showing higher injection pressure than the electronic control injection pump of China-III and IV test diesel vehicles, so injection and atmospheric effects are greatly improved, leading to the more complete combustion and benefitting the emission reduction of particle matters.[41]

Figure 12 gives the PM emission factors of the buses at different emission stages with biodiesel blends. Under the upgraded regulations, the emission rate of PM decreased with the reduction of PN. It can be seen that the higher the emission stage of the bus, the lower the PM emission factors. After the bus was fueled with biodiesel blends, the PM emission factors exhibited a decreasing trend. For China-III

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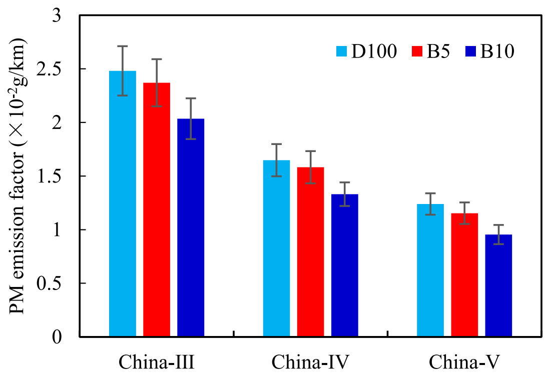

Figure 12. PM emission factor.

bus, the use of B5 and B10 resulted in a reduction of 4.5 and 18.0% in the PM emission factors. For China-IV bus, the use of B5 and B10 led to a reduction of 4.0 and 19.3% in the PM emission factor. For China-V bus, the use of B5 and B10 reduced the PM emission factors by 6.9 and 23.0%, respectively. It can be found that, after the combustion of biodiesel prepared from waste cooking oil, the emissions of PM and PN exhibit good following performance. With the upgrading regulations on the test vehicles, the biodiesel at two different blend ratios exhibits more significant emission reduction of PM, of which B10 plays the greatest role. However, foreign scholars studied the biodiesel produced from hemp and made different conclusions that with the increase in different blend ratios of biodiesel, the emission of PN decreases, but PM increases on the contrary. It is because that the biodiesel produced from this raw material contains a large quantity of molecules and high contents of carbon, and the products are mainly concentrated accumulated particles with large PN and small PM.[42−44] Therefore, the emission performance of biodiesel produced from different raw materials should be discussed in different situations.

Emission Rate of Change with Biodiesel Blends of Buses at Different Emission Standards. On the basis of the above study, the change rate of emission factors of each component of the urban buses at China-III, IV, and V fueled by biodiesel B5 and B10 relative to pure diesel was subjected to the weighted average calculation: the absolute value of arithmetic mean of the sum of the emission rate of change singly. The weighted average of the change rate of CO, THC, CO_2, NOx, PN, and PM emissions from buses fueled by biodiesel B5 and B10 relative to pure diesel D100 under the three regulations is shown in Figure 13. The average change

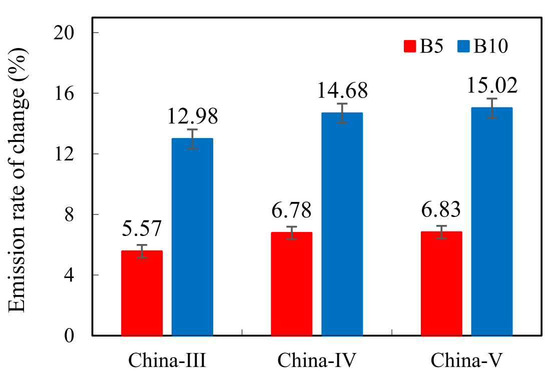

Figure 13. Emission rate of change.

rates of emissions from China-III buses fueled by biodiesel B5 and B10 relative to D100 were 5.5 and 12.9%; the average change rates of emissions from China-IV buses fueled by biodiesel B5 and B10 relative to D100 were 6.7 and 14.6%, which had a slight increase compared with China-III buses; China-V buses also displayed the same trend, that is, the average change rates of emissions from China-V buses fueled by biodiesel B5 and B10 relative to D100 were 6.8 and 15.0%, respectively, which increased compared with China-III and China-IV buses. It can be seen that with the upgrade of emission regulations, the emission performances of diesel vehicles have had a more significant direct feedback of the physicochemical properties of biodiesel. In other words, the unique performance of biodiesel fuel will exert a greater effect with the upgrade of emission regulations.

■ CONCLUSIONS AND RECOMMENDATIONS

In this paper, the emissions of gaseous substances and particle matters on three urban buses fueled with petroleum diesel fuel (D100) and biodiesel produced from waste cooking oil at two blend ratios (B5 and B10) regulated by three emission standards were analyzed and compared in the hub experiment. The conclusions were made as follows:

(1) In different speed ranges of the CCBC driving cycle, the emission rates of gaseous substances and particle matters continuously increased on the whole as the vehicle speed increased.

(2) The emission rates of both the gaseous substances, CO and THC, and the particle matters, PM and PN, decreased as the blend ratio of biodiesel increased.

(3) Due to the oxygen-bearing characteristics of biodiesel, the emission rates of CO_2 and NOx slightly increased as the blend ratio of biodiesel increased.

(4) For three escalating emission stage buses, the comprehensive changes produced by B5 in the emissions increased from 5.57 to 6.78 to 6.83%, while for B10, a significant increase in the changes was obtained, reaching 12.98, 14.68, and 15.02%, respectively.

From an environmental protection point of view, we recommend promoting the appropriate proportion of the blended biodiesel in specific vehicles as long as it does not affect the demand for transportation and establishing dedicated bus lanes to limit the driving speeds of vehicles within an acceptable range, avoiding high-speed or intermittent start−stop working conditions. In the meantime, the in-service diesel vehicles within China III should be upgraded by scrapping or retrofitting after-treatment devices aimed at reducing emissions.

■ EXPERIMENT AND METHOD

Test Fuels. The biodiesel is prepared during the process of refining and processing waste cooking oil through the transesterification of the acid−base catalytic system, whose preparation process is shown in Figure 14. It is similar to petroleum diesel fuel in the physical property but a little different in chemical constituents. It contains high cetane number and abundant oxygen molecules, which promote the stable operation and full combustion of engines. However, it exhibits high viscosity, probably causing the problems of carbon deposit, filter clogging, poor fuel atomization, and coking injector in engines and worn-out engines.[45−47] Therefore, the biodiesel discussed in this study was blends of

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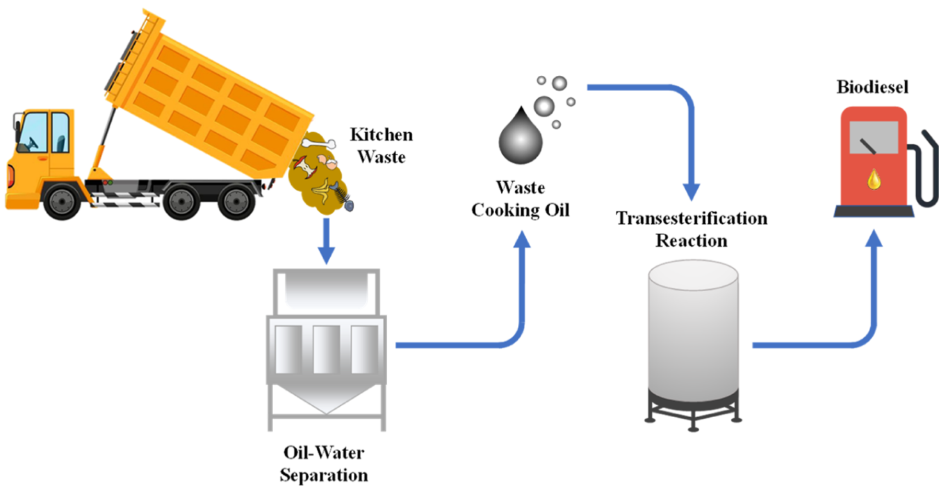

Figure 14. Preparation process of biodiesel.

waste cooking oil and pure diesel at a low ratio, and the low blend ratio also ensures the power performance of engines.

The test fuels used in this study included B5 and B10, and the petroleum diesel D100 was used as a baseline. The biodiesel was produced from waste cooking oil. The physical and chemical properties of the test fuels are shown in Table 1.

Table 1. Physical and Chemical Properties of Test Fuels

fuel property	D100	B5	B10
cetane number	50.8	53.2	54.3
density@20 °C (kg/m^3)	811.8	821.9	823.5
viscosity@20 °C (mm^2/s)	4.09	4.39	5.24
sulfur content (mg/kg)	3.3	4.8	8.0
low heating value (MJ/kg)	43.90	43.75	43.30
distillation at 90% volume (°C)	338.0	339.3	340.4
carbon [% (m/m)]	86.12	85.02	83.64
hydrogen [% (m/m)]	13.84	13.77	12.65
oxygen [% (m/m)]		2.42	4.1
aromatics [% (m/m)]	7.2	7.0	6.9

Test Equipment. The experimental system is shown in Figure 15. It is composed of a chassis dynamometer (MAHA-AIP Ltd.) and three test buses: one China-III bus without any after-treatment devices and China-IV and China-V buses both were installed in an SCR after-treatment system, an OBS-2200, an EEPSTM Engine Exhaust Particle Sizer (TSI Ltd.), and a DI-2000 two-stage diluter (Dekati Ltd.). A Pitot tube flowmeter (HORIBA) was used to measure and sample the exhaust from the test vehicle. The engine powertrains of three test vehicles were not modified in any structure or strategy.

The OBS-2200 vehicle gas emission detection equipment of HORIBA, Japan, was selected as the test device, consisting of shockproof emission measurement unit, master laptop and relative software, sensor, and sampling joint with the Pitot flowmeter. Non-dispersive infrared analysis was employed to measure gas measurement units, CO and CO_2, a hydrogen flame ionization detector was adopted to measure THC, and a chemiluminescence detector was used to measure NOx. The test frequency of the gas measurement units was 10 Hz, meeting the requirements of hub bench real vehicle emissions in tests. Mass emission rates per unit time of gaseous

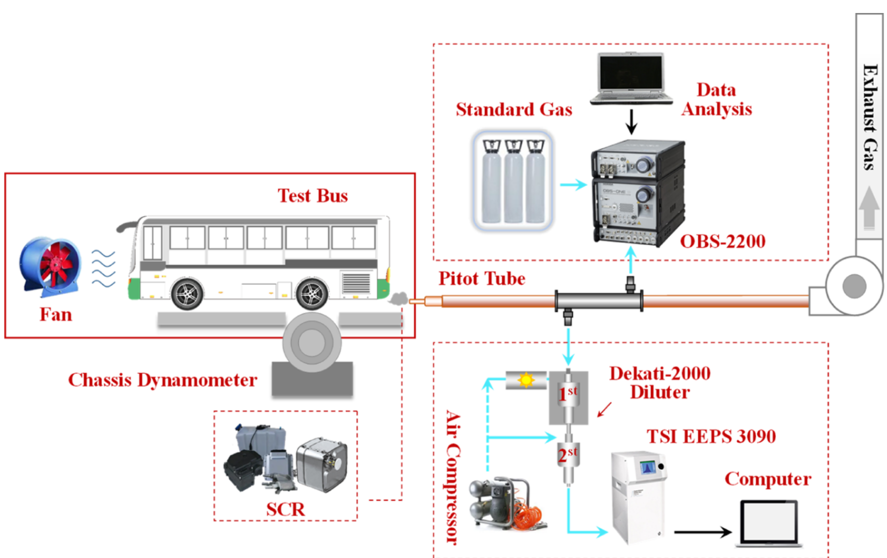

Figure 15. Schematic diagram of the experimental system.

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Table 2. Main Specifications of the Test Bus

parameter	bus 1	bus 2	bus 3
curb weight (kg)	10 100	11 000	11 900
vehicle size (mm)	10 499 × 2500 × 3150	11 880 × 2500 × 3230	11 995 × 2530 × 3150
engine type	Deutz D7E240-EC01	Deutz D7E290-EC01	SDEC SC9DF260Q5
capacity (L)	7.146	7.146	8.820
rated power (kW/rpm)	177/2300	213/2300	192/2300
maximum torque (N m/rpm)	920/1700	1200/1700	1100/1400
fuel system	electronic unit pump	electronic unit pump	high-pressure common rail
after-treatment	none	SCR	SCR
vehicle emission standard	China-III	China-IV	China-V

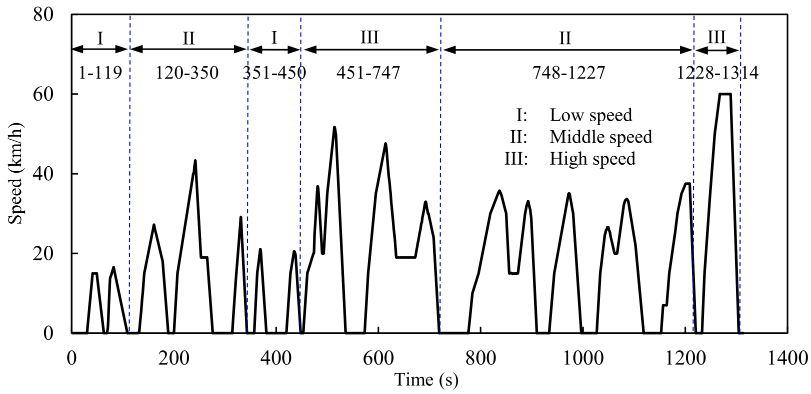

Figure 16. Chinese city bus cycle.

substances were measured by supporting software of the device, according to the volume concentration of gaseous substances and flow measured by the Pitot flowmeter.

The PN and particle size distribution were measured by the TSI EEPS 3090 with good transient response. The measurable range of the particle size is 5.6−560 nm. The EEPS spectrometer can export a complete particle size distribution spectrum in 0.1 s and synchronously output the PN concentration in 32 channels. To simulate the actual dilution process of the engine exhaust in a real-world situation, a two-stage dilution DI-2000 was used to dilute the exhaust gas. The first and second dilution ratio were both set to 8:1. Therefore, the total dilution ratio was 64:1. The temperature of the dilution system must be set to 120 °C to evaporate volatile particles and reduce the partial pressures of the gas phase, thus preventing recondensation at the diluter exit.

Test Vehicle. The detailed information, including three urban buses, respectively, regulated by China-III, China-IV, and China-V emission standards, is shown in Table 2. All the test vehicles, as popular urban buses in Shanghai, China, were rented from a bus company, of which no after-treatment device was installed in China-III bus, and SCR was installed in China-IV and China-V buses. There was no system fault in engines or after-treatment devices and no maintenance record for vehicles.

Test Cycle. The driving cycle used in this study is the CCBC, which can reflect the typical running characteristics of buses in China. The whole CCBC duration was 1314 s (21.9 min), as shown in Figure 16, and its mileage was about 5.897 km. The minimum and maximum speed was 0 and 60 km/h, respectively, and the average speed was 16.2 km/h. The cycle included idling, acceleration, constant speed, and deceleration conditions, which was modeled on the Chinese city bus running conditions. The entire cycle had 14 short sections, and they were divided into three types of working conditions including low-speed condition (1−119 s and 351−450 s) of four short sections, middle-speed condition (120−350 s and 748−1227 s) of seven sections, and high-speed condition (451−747 s and 1228−1314 s) of three sections. In addition, the running conditions were also divided based on acceleration including the idle, acceleration, and deceleration condition.

As the test driving cycle was set on the hub experiment control platform, the test vehicles were fueled with diesel (D100) and biodiesel blends B5 and B10 successively. After three times of operation for each group, the test data were collected, and the average value was calculated.

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Notes

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