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THE INFLUENCE OF ELECTRIC HEATING CATALYST PLACEMENT ON THE AFTER-TREATMENT PERFORMANCE OF HEAVY-DUTY DIESEL VEHICLES

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Abstract: Based on a real driving emission test conducted on a heavy-duty diesel truck equipped with PEMS equipment under cold start and low-load conditions, this study investigates the influence of the EHC (electric heating catalyst) placement on the exhaust temperature, NO_x conversion efficiency, and EHC power consumption of the heavy-duty diesel vehicle's after-treatment system. The two after-treatment schemes tested are EHC+DOCoF+SCR+ASC (Scheme 1) and DOCoF+EHC+SCR+ASC (Scheme 2). The research findings indicate that, in Scheme 1, the temperatures at T4 (at the front end of the after-treatment system), T5 (after the DOCoF), and T6 (before the SCR) are higher than those in Scheme 2 during both cold start and low-load conditions. During the cold start phase, Scheme 1 excels in terms of urea injection timing, NO_x conversion efficiency, and EHC power consumption compared to Scheme 2. In the low-load phase, Scheme 1 outperforms Scheme 2 in terms of EHC power consumption, while its NO_x conversion efficiency is comparable to that of Scheme 2.
Keywords: Heavy-duty diesel vehicle; Electric heating catalyst; Real driving emission; Layout position; After-treatment

1 INTRODUCTION

With the rapid growth of China's economy and the continuous improvement of people's living standards, the number of cars in our country has been increasing year by year. In 2023, China's auto production and sales reached 30.11 million and 30.09 million units respectively, ranking first in the world for many consecutive years. The rapid growth of car ownership is accompanied by an increase in vehicle pollutant emissions, according to the "Annual Report on Mobile Source Environmental Management in China (2023)"released by the Ministry of Ecology and Environment[1]. In 2022, the national emissions of motor vehicle pollutants, including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM), were 7.43 million tons, 1.912 million tons, 5.267 million tons, and 53,000 tons respectively. Among them, the NO_x emissions from heavy-duty diesel vehicles accounted for 78.3% of the total vehicle emissions. Reducing NO_x emissions from heavy-duty diesel vehicles has become the focus of research. Selective Catalytic reduction (SCR) technology, as an effective means to reduce NO_x emissions [2], has been widely applied in the after-treatment systems of heavy-duty diesel vehicles.

In low temperature environment, the efficiency of SCR system will be significantly affected, resulting in the increase of NO_x emissions. To solve the problem of low SCR conversion efficiency under low temperature and low load，Han Feng using the two-stage urea SCR system[3], the first stage SCR system is tightly coupled after the engine turbocharger. In the engine WHTC cycle, the SCR injection temperature is reached within 80s after cold start, about 450s earlier than that of the single-stage urea SCR system. Zhu Minlin adopting the dual-spray SCR system[4], NO_x emissions were significantly reduced compared to single-spray systems. The NO_x emissions in the cold-state WHTC cycle decreased by 65.4%, and those in the hot-state WHTC cycle decreased by 92.9%. Liu Chenxi studied the scheme of ozone collaborative treatment of NO_x under the cold start condition[5]. The test showed that ozone (O3) collaborative treatment could significantly reduce NO_x emissions at the cold start stage when the exhaust temperature was below 100 ℃, and the maximum conversion efficiency could reach 60.29%. Hasan's research has found that advancing or delaying the closing of the valves can increase the exhaust temperature of diesel engine after-treatment under low-load conditions[6], achieving an exhaust temperature increase of up to 60°C at most. Xie Yuzhuo found that the electric heating system can improve the aftertreatment temperature of diesel engines[7], thereby enhancing the conversion efficiency of SCR under cold start conditions. The higher the power of the electric heating system, the better the NO_x emission reduction effect. Leahey[8], Zamir[9], Manuel[10], Gao studied the NO_x emission reduction effect of electric heating system[11]. The experimental results show that exhaust electric heating is an effective technology that can reduce NO_x emissions during cold start of diesel vehicles.

In summary, both domestic and foreign researchers have carried out a great deal of research work in the field of aftertreatment technology for heavy-duty diesel vehicles, and corresponding research achievements have been obtained. Li Changyu[12], Ramadhas found that the transient emissions and specific emissions of NO_x under cold start conditions of diesel vehicles account for a relatively large proportion of the total emissions[13]. Zhang Dan and Wang have found that both transient and specific emissions of NO_x in low-speed and low-load cycles of diesel vehicles are very high[14,15], which requires special attention. Therefore, how to effectively reduce NO_x emissions from heavy-duty diesel vehicles during cold start and low-load conditions has become a key focus of current research. Among various research solutions, electric heating technology is a scheme that can effectively increase the exhaust temperature during cold start and low-load conditions without significantly affecting fuel consumption. In current studies, the electric heating arrangement is always positioned before the DOC, while there are few studies on placing the electric heating before the SCR system. Therefore, this paper uses a heavy-duty diesel vehicle equipped with an electric heating after-treatment system to carry out vehicle real-road emission tests under cold start and low-load conditions, aiming to investigate the influence of the electric heating arrangement position on the after-treatment performance of heavy-duty diesel vehicles during cold start and low-load conditions.

2 EXPERIMENTAL DESIGN

2.1 Test Vehicle and After-treatment System

The test vehicle is a stake diesel truck meeting the National VI emission standards. The main information of the vehicle is shown in Table 1 below.

Table 1 Vehicle and Engine Parameters

Parameters / Unit	Data
Engine Arrangement Form	In-line, front-engine rear-wheel drive
Intake Method	Turbocharging
Displacement/ L	2.5
Cylinder Number	4
Rated Power of Engine/ kW	100
Maximum Torque of Engine/ N·m	360
Rated Power Speed/ r·min-1	3200
curb Mass/ kg	2565
Maximum Mass/ kg	4495
Vehicle Dimensions/ mm	5990*2180*2391

The after-treatment system of the vehicle adopts a combination of EHC, DOCoF, SCR, and ASC. EHC (Electric Heating Catalyst) converts electrical energy into thermal energy through electric heating elements. When exhaust gas flows through the heating chamber, it is heated to the required temperature by the electric heating catalyst, The electric heating power is 1.5 kW and the power supply voltage is 12V. DOCoF (DOC on DPF) is a novel integrated after-treatment package combining DOC and DPF. Unlike the traditional separate packaging of DOC and DPF, the DOCoF integrates both functions into a shorter structure, enhancing exhaust heat preservation. It oxidizes CO, HC, and NO in the exhaust, raises exhaust temperature, traps particulate matter, and reduces PN and PM emissions. SCR (Selective Catalytic Reduction System) primarily reduces NOx in the exhaust. After the exhaust temperature reaches the urea injection threshold, the urea injection system sprays urea into the exhaust pipe. Under high temperatures, urea decomposes into ammonia (NH_3), which reacts with NO_x on the catalyst surface to convert NO_x into N_2 and H_2O. ASC (Ammonia Slip Catalyst) further oxidizes excessive or unreacted ammonia (NH_3) from the SCR system into harmless N_2 and H_2O, preventing ammonia from being directly released into the atmosphere.

2.2 Test Equipment

The test equipment is the OBS-ONE series portable emission testing system (PEMS) from Japanese brand HORIBA. This equipment can continuously measure the exhaust flow and emission pollutant concentrations of the test vehicle on actual roads, including NO_x, CO, CO_2, PN, etc. Meanwhile, it can real-time monitor the test environment temperature and humidity, GPS data and the vehicle's OBD information. By collecting the emission pollutant concentrations and exhaust flow, the emission mass of each exhaust pollutant can be calculated. Combined with the collected OBD parameters of the test vehicle, the specific emission of the vehicle can be determined.

2.2 Test Scheme

The test prototype shall not carry additional loads except for the testing equipment, equipment tooling, driver, and data collection engineer. The vehicle shall start the test with a cold start, and the water temperature of the prototype shall be less than 30°C before the test begins. The test shall be conducted on paved roads under low-load conditions, with the average vehicle speed ranging from 15 km/h to 20 km/h. The test duration shall be at least sufficient to ensure that the cumulative work of the test vehicle reaches 1 times the engine WHTC cycle work.The electric heating catalyst is based on the T6 temperature sensor: the electric heating system is activated when the T6 temperature is lower than 180°C and turned off when the T6 temperature exceeds 200°C. The test prototype shall carry out real-road emission tests with two after-treatment schemes respectively.
(1) After-treatment Scheme 1: EHC + DOCoF + SCR + ASC, as shown in Figure 1:

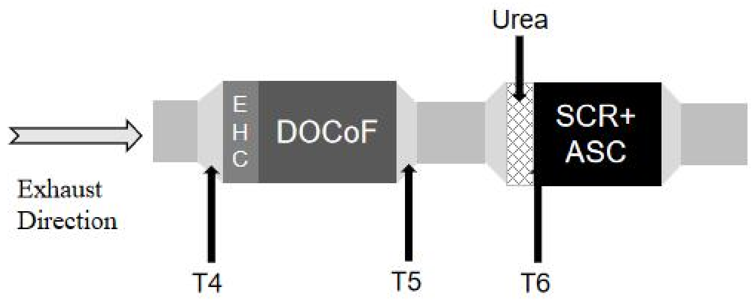

Figure 1 After-treatment Scheme 1

In this scheme, the electric heating catalyst is positioned at the front of the DOC in the after-treatment system. By heating the exhaust gas ahead of the DOC, the DOC can reach its oxidation temperature more rapidly. Once the DOC reaches the oxidation temperature, it releases heat through oxidation reactions. The thermal energy from both the oxidation reactions and electric heating diffuses to the downstream of the after-treatment system, increasing the temperature of the SCR system. NO_x will undergo a reduction reaction on the surface of the SCR catalyst, reducing NO_x emissions.

(2) After-treatment Scheme 2: DOCoF+EHC+SCR+ASC, as shown in Figure 2:

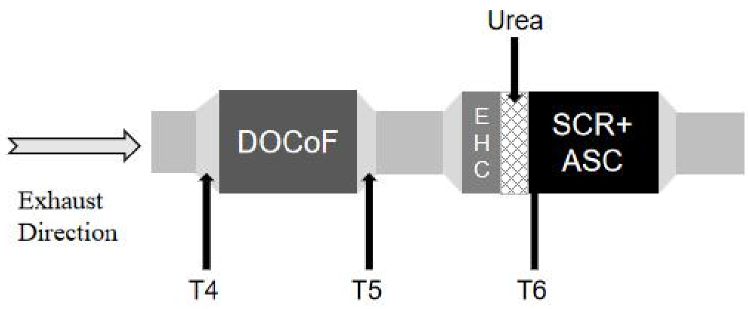

Figure 2 After-treatment Scheme 2

In this scheme, the electric heating catalyst is positioned in front of the SCR, which can directly heat the SCR system to increase its temperature. NO_x will undergo a reduction reaction on the surface of the SCR catalyst, reducing NO_x emissions.

3 RESULT AND DISCUSSION

3.1 Exhaust Temperature Characteristics During Cold Start

At the start of the test, the engine coolant temperature was below 30°C. The period from the start of the test until the engine coolant temperature reached 70°C is defined as the cold start phase. The cold start duration for Scheme 1 was 986 seconds, while that for Scheme 2 was 969 seconds. The exhaust gas temperatures at different positions in the after-treatment system were measured using temperature sensors T4, T5, and T6. Specifically, sensor T4 was located at the foremost end of the after-treatment system, sensor T5 at the rear end of the DOCoF, and sensor T6 at the front end of the SCR.

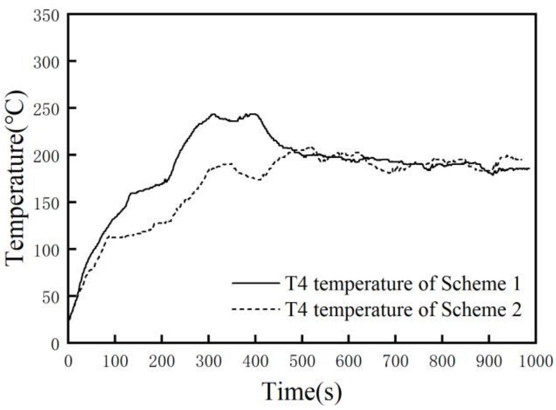

Figure 3 T4 Temperature during Cold Start

The figure 3 shows a comparison of T4 temperatures between the two schemes. The average temperature of Scheme 1 is 186.8°C, while that of Scheme 2 is 168.1°C. Since the EHC of Scheme 1 is located behind the T4 sensor, at the beginning of the test, both the engine exhaust temperature and the thermal radiation from the activated EHC act on T4, so the T4 temperature of Scheme 1 rises faster than that of Scheme 2. The EHC of Scheme 1 is turned off at 402 seconds, and the T4 temperature drops rapidly due to the absence of thermal radiation from the EHC. The EHC of Scheme 2 is turned off at 506 seconds. Since the EHC of this scheme is located in front of the SCR, the switching of the EHC has no effect on the T4 temperature. Subsequently, due to the similar driving conditions, the T4 temperatures of the two schemes gradually stabilize and remain between 180 and 210°C.

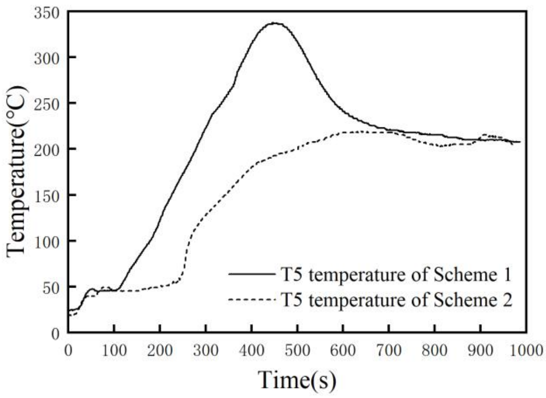

Figure 4 T5 Temperature during Cold Start

The figure 4 shows a comparison of T5 temperatures between the two schemes. The average temperature of Scheme 1 is 203.1°C, while that of Scheme 2 is 155.1°C. The T5 temperature of Scheme 1 began to be significantly higher than that of Scheme 2 at around 107 seconds, with a trend similar to that of T4 temperature. This is because the heat from the EHC diffused to T5 after passing through the DOCoF. The T5 temperature of Scheme 1 reached a maximum of 338°C, while the maximum temperature of Scheme 2 was only 209°C. This is because the T4 temperature sensor of Scheme 1 is located at the front end of the EHC, so the temperature before the DOCoF is higher than the T4 temperature. Moreover, when the exhaust gas temperature reaches the oxidation temperature of the DOC (200°C), and the concentrations of HC and CO in the exhaust are high, according to the Arrhenius equation, the rate of the oxidation reaction increases exponentially with temperature, generating more heat. In contrast, the T4 temperature of Scheme 2 exceeded 200°C for only 99 seconds, and the maximum temperature did not exceed 210°C. The heat generated by the oxidation reaction was limited, mostly from the engine. Therefore, the T5 temperature of Scheme 1 was significantly higher than that of Scheme 2.

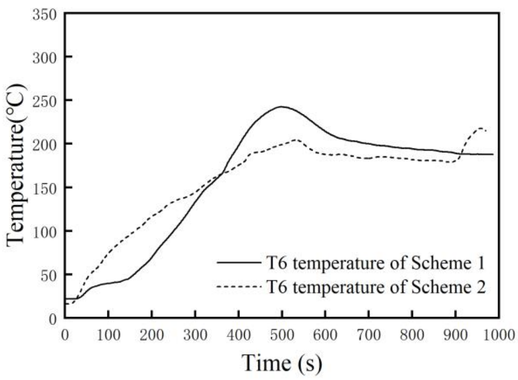

Figure 5 T6 Temperature during Cold Start

The figure 5 shows a comparison of T6 temperatures between the two schemes. The average temperature of Scheme 1 is 158°C, and that of Scheme 2 is 155.9°C. Additionally, the EHC of Scheme 2 was activated again at 873 seconds. Since the EHC of Scheme 2 is directly arranged in front of the T6 sensor, it directly heats T6 after being turned on. Therefore, the T6 temperature of Scheme 2 remained higher than that of Scheme 1 in the early stage of cold start. At 262 seconds, due to the DOC of Scheme 1 reaching the oxidation temperature and the delayed diffusion of heat from the front-end EHC, the temperature of Scheme 1 increased rapidly and exceeded that of Scheme 2 at 361 seconds.

3.2 NO_x Conversion Efficiency during Cold Start

An NO_x sensor is respectively arranged upstream of the DOC and downstream of the ASC in the exhaust after-treatment system. The upstream NO_x sensor is used to measure the original exhaust NO_x concentration (C_u), and the downstream NO_x sensor is used to measure the NO_x concentration in the treated tail exhaust. The sampling port of the PEMS device is located at the tail of the exhaust pipe, which can also measure the nitrogen oxide concentration in the tail exhaust (C_d). For accurate calculation, the value measured by the PEMS device is used here. The calculation method of NO_x conversion efficiency (η) is $\eta = \frac{C_u - C_d}{C_u} \cdot 100\%$.

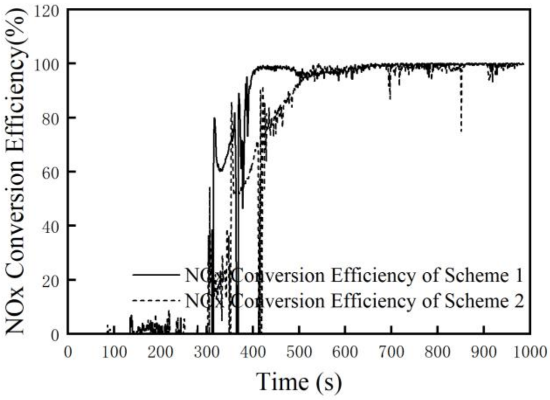

Figure 6 NO_x Conversion Efficiency during Cold Start

The figure 6 shows a comparison of NO_x conversion efficiency between two schemes. The average conversion efficiency of Scheme 1 is 64.82%, while that of Scheme 2 is 59.55%. Before 300 seconds, the after-treatment temperature was too low, and the overall conversion efficiency was close to 0, so this portion of the data is not analyzed in detail. At 317 seconds, the conversion efficiency of Scheme 1 shows a significant improvement, but urea injection does not begin until 377 seconds. During this period, the conversion efficiency ranges between 60% and 80%. This is due to the ammonia storage in the SCR system—when the temperature rises but has not yet reached the urea injection threshold (180°C), the urea in the SCR partially hydrolyzes to produce NH3, enabling partial $DeNO_x$ capability. After urea injection begins, the conversion efficiency increases rapidly and remains above 95%. Similarly, for Scheme 2, urea injection starts at 419 seconds. Between 305 seconds and 419 seconds, the DeNOx capability is attributed to ammonia storage.

3.3 Exhaust Temperature Characteristics During low-load conditions

The engine power in the trip stage is less than 10% of the maximum power, which is defined as the low-load condition. Among them, the low-load condition of Scheme 1 is 4,458 seconds, and that of Scheme 2 is 4,663 seconds.

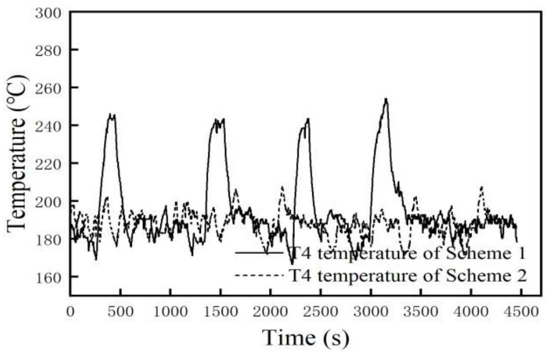

Figure 7 T4 Temperature during low-load Condition

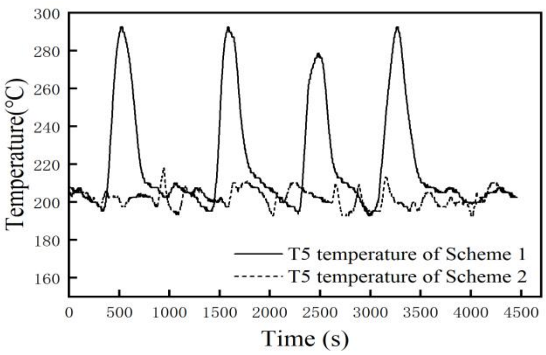

Figure 8 T5 Temperature during Low-load Condition

The figure 7 and 8 shows the temperature comparison of T4 and T5 between the two schemes. The average T4 temperature of Scheme 1 is 195.2°C, and the average T5 temperature is 220.5°C. The average T4 temperature of Scheme 2 is 188.2°C, and the average T5 temperature is 202.3°C. When the EHC of Scheme 1 is turned on, the temperature will rise to about 250°C, and when the EHC is turned off, the temperature will drop rapidly. Since the EHC of Scheme 2 is at the rear end, the T4 and T5 temperatures are not affected by its switching. Due to the oxidation reaction of DOCoF, the T5 temperature is higher than T4. Among them, the T5 temperature of Scheme 1 is 25.3°C higher than the average T4, and the T5 temperature of Scheme 2 is 14.1°C higher than the average T4. The temperature rise effect of Scheme 1 is better, which is because the front-end temperature of DOC in Scheme 1 is higher than that in Scheme 2.

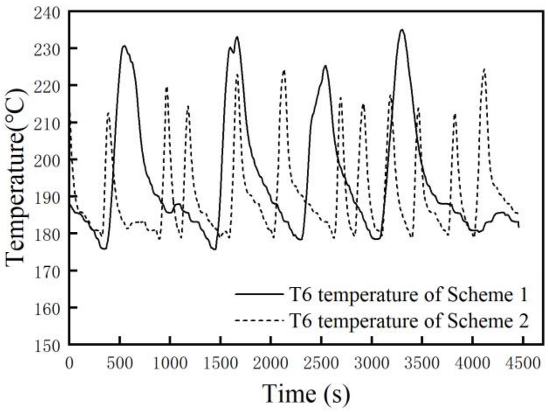

Figure 9 T6 Temperature during Low-load Condition

The figure 9 shows the temperature comparison of T6 between the two schemes. The average temperature of Scheme 1 is 194.8°C, and that of Scheme 2 is 190.4°C. When the EHC is turned on, the T6 temperature of Scheme 1 is higher, and its temperature retention capacity is better. However, when the EHC is turned on, the T6 temperature of Scheme 2 is lower, and its temperature retention capacity is poorer. In the low-load condition, Scheme 1 is turned on 4 times in total, with each activation lasting about 180 seconds, and the total activation time is 740 seconds. While Scheme 2 is turned on 11 times in total, with each activation lasting about 80 seconds, and the total activation time is 901 seconds.

3.4 NOx Conversion Efficiency During low-load conditions

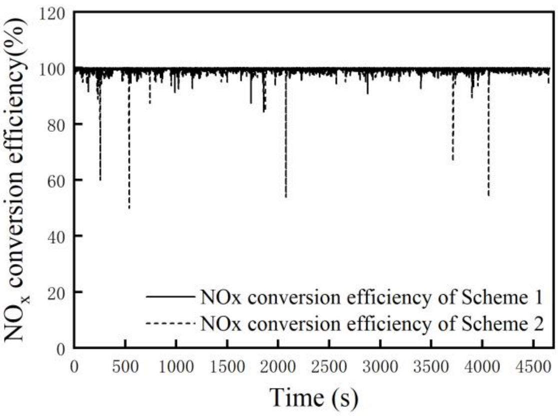

Figure 10 NOx Conversion Efficiency during Low-load Condition

The figure 10 shows the NOx conversion efficiency comparison between the two schemes. Due to the effect of the electric heating EHC, the average NOx conversion efficiency of both schemes under low-load conditions reaches more than 99%. As the EHC of Scheme 2 is frequently turned on and off, the conversion efficiency at some points where the T6 temperature is lower than 180°C is only about 60%. However, these points with low conversion efficiency have little impact on the overall conversion efficiency of the working conditions.

4 CONCLUSION

(1) In the entire test condition, the average T6 temperature of Scheme 1 is 188.1°C, and that of Scheme 2 is 184.4°C. The T6 temperature of Scheme 1 is 3.7°C higher than that of Scheme 2.

(2) In the cold-start condition, the urea injection time of Scheme 1 is 377 seconds, while that of Scheme 2 is 419 seconds. The urea injection time of Scheme 1 is 42 seconds earlier than that of Scheme 2, indicating that Scheme 1 has better NOx emission reduction capability under cold-start conditions. Its NOx conversion efficiency is 5.27%

higher than that of Scheme 2, and the NOx conversion efficiencies of the two schemes are close under low-load conditions.

(3) In the entire test condition, the total activation time of EHC for Scheme 1 is 1,142 seconds, while that for Scheme 2 is 1,407 seconds. The activation pattern of EHC in Scheme 1 features longer single activation duration and fewer activation times, whereas Scheme 2 shows shorter single activation duration and more activation times.

(4) Overall, Scheme 1 outperforms Scheme 2 in terms of temperature raising effect, NOx conversion efficiency, and EHC power consumption.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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