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ARTICLE

Experimental Analysis of the Influence of Exhaust Thermal Management on Engine NO_x Emission

Jinliang Zhu[1], Xiulei Wang[1], Guihua Wang[1], Xianglin Zhong[2], Zhenguo Li[3], Zhiming Wang[1], Ke Sun[1,*] and Shuzhan Bai[1,*]

[1]School of Energy and Power Engineering, Shandong University, Jinan, 250061, China

[2]China Automotive Technology & Research Center Co., Ltd., Tianjin, 300300, China

[3]National Engineering Laboratory of Mobile Source Emission Control Technology, Tianjin, 300300, China

[*]Corresponding Authors: Ke Sun. Email: sunkeke@sdu.edu.cn; Shuzhan Bai. Email: baishuzhan@sdu.edu.cn

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ABSTRACT

Exhaust thermal management is essential to allow engines to meet the Euro VI emissions standards and reducing nitrogen oxide emissions is one of the most important targets being pursued nowadays. Along these lines, in the present study, engine's thermal performances have been evaluated on the basis of a WHTC test, namely a transient engine dynamometer schedule defined by the global technical regulation (GTR) developed by the UN ECE GRPE group (the GTR is covering a world-wide harmonized heavy-duty certification (WHDC) procedure for engine exhaust emissions). The influence of thermal management on fuel consumption, intake, and tailpipe NO_x have been quantitatively analyzed for the overrun state. The results have shown that there can be a strong influence on the after-treatment temperatures and tailpipe NO_x. In particular, the average temperature upstream of the diesel oxidation catalyst (DOC) has been found to increase from 245°C to 254°C, the average temperature of the selective catalytic reduction (SCR) to increase from 248°C to 253°C, the SCR's minimum temperature to increase from 196°C to 204°C, and the peak value of the NO_x emissions in the low-temperature region to decrease from 73 to 51 mg/s. However, the influence of the overrun state's thermal management strategy on the fuel consumption, the air intake, the ammonia storage, the NO_2/NO_x ratio, and the urea consumption has been observed to be relatively limited.

KEYWORDS

Intake throttling valve; NO_x emissions; overrun; diesel

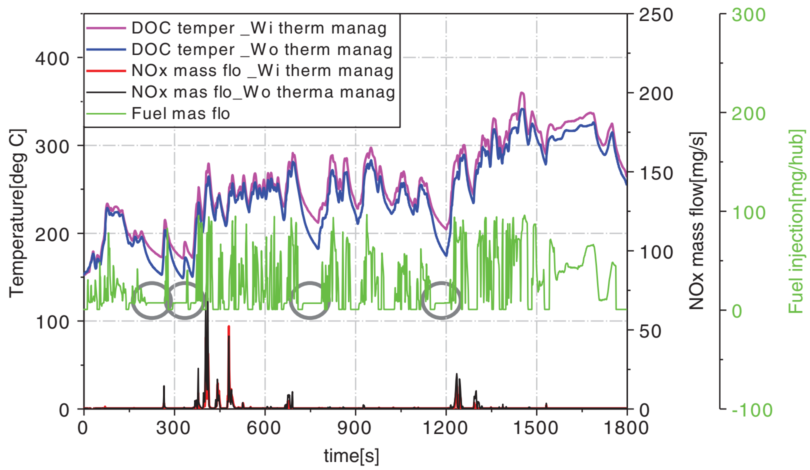
Nomenclature

CW_{Engine}	engine cycle work
dm_{air}	air mass flow
dm_{NO_x}	NO_x mass flow
K	impulse coefficient
n	engine speed
P	gas inlet pressure
R	gas constant
SE_{NO_x}	specific emission

T_{air}	gas inlet temperature
u	molar mass of the mixed gas
V_{eng}	theoretical total cylinder volume
cpsi	cells per square inch

Graphical Abstract

The figure shows the intake throttling valve's influence on the engine's exhaust temperature under the world harmonized transient cycle (WHTC). The exhaust temperature upstream of the diesel oxidation catalyst (DOC) increased by 22°C, 24°C, 29°C, and 30°C during the four long idle regions. This shortened the low-temperature region sensitive to the selective catalytic reduction's (SCR's) efficiency and reduced the NO_x tail emissions from 0.21 to 0.16 g/kW·h, a decrease of 24%.



1 Introduction

Strict nitrogen oxide (NO_x) emissions from heavy-duty diesel engines require clean combustion in the cylinder and an efficient after-treatment system [1]. Copper (Cu)-based selective catalytic reduction (SCR) have good nitrogen oxide conversion efficiency and hydrothermal stability at low temperatures [2–4]. Cu-based SCR with urea as the ammonia source is considered a primary technology that meets the Euro VI NO_x emissions standards for heavy-duty diesel engines [5–8]. The world harmonized transient cycle (WHTC) is a transient test cycle with 1,800 operating points. It includes a cold-start WHTC and a hot-start WHTC, and a test cycle runs for a total of 1,800 s. The first 600 s simulate urban working conditions, the middle 600 s simulate suburban working conditions, and the final 600 s simulate high-speed working conditions. Euro VI emissions regulations require the WHTC tail exhaust NO_x, including the after-treatment aging coefficient (with a value of 1.15), to be less than 0.46 g/kW·h. Engineering margin coefficients, such as the product consistency, are generally set to 1.1; therefore, the NO_x emissions should not exceed 0.36 g/kW·h. The cold-start WHTC, which accounts for nearly 15% of the total emissions weight, cannot inject urea when the SCR's temperature is low, which results in high NO_x tail emissions. Therefore, the hot-start WHTC attempts to control the NO_x emissions so they are as low as possible.

Many factors, such as the space velocity, the temperature, and the ammonia–nitrogen ratio, affect an SCR's conversion efficiency. Among these, the temperature has the largest effect on the nitrogen oxides [9,10]. Research regarding an SCR's catalyst activity at low temperatures has garnered much attention, and many studies have been performed in this field [11–15]. Research concerning diesel engines' thermal management has primarily focused on medium and low engine loads [16–19]. Zhang et al. [20] studied the method of injecting a small amount of diesel upstream of the diesel oxidation catalyst (DOC) and then changing the engine's operating point to increase the after-treatment temperature. Guan et al. [21] studied the effects of intake throttling, the intake valve's closing timing, a lower injection pressure, late injection timing, and exhaust gas recirculation on the exhaust temperature under low loads. However, few studies exist for no-load thermal management of the exhaust temperature. In this study, the WHTC was used to evaluate the exhaust thermal management's effects when there was no load on the engine. The results can provide a reference for diesel engine temperature management.

2 Experimental Setup and Methods

2.1 Experimental Setup

The test engine was an electronically controlled high-pressure common rail Euro VI engine. The air intake system was a supercharged waste gate turbocharger (WGT) intercooler with exhaust gas recirculation (EGR) and a throttling valve (TV). The post-processing configuration consisted of a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), a selective catalytic reduction (SCR), an ammonia slip catalyst (ASC). The pipe used during the tests was a standard truck exhaust pipe wrapped with insulating layer, and the temperature dropped by 11°C–12°C from a point downstream of the turbine to a point upstream of the DOC. The length of the exhaust pipe used on the test bench, 2.4 m, was the same as that required for a vehicle's pipeline layout. The urea injection system used a Bosch DeNO$_x$2.2 system. A Continental Automotive Electronics Co., Ltd. (China) 2.8 generation onboard NO$_x$ sensor was installed downstream of the turbine and the SCR. Bosch temperature sensors were installed upstream of the DOC, the DPF, and the SCR, as well as downstream of the SCR, as shown in Fig. 1. Tables 1 and 2 present the specifications for the test engine and catalyst, respectively.

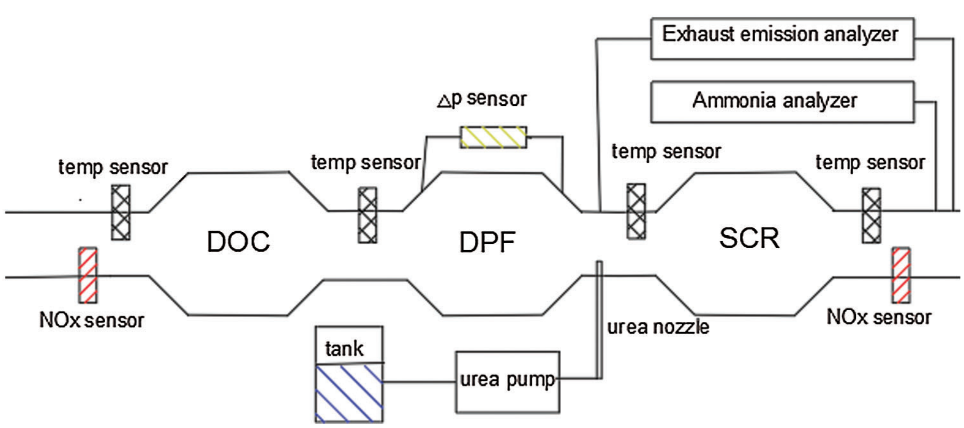


Figure 1: Schematic of the after-treatment layout

Table 1: Test engine specifications

Project	Specification
Engine type	6-cylinder in-line/inter-cooling
Bore × stroke, mm × mm	108 × 130
Swept volume, L	7.14
Compression ratio	18
Maximum torque, N/m	1100
Rated speed, r/min	2100
EGR type	Electronically-controlled EGR
Turbocharger	WGT

Table 2: Catalyst specifications

	DOC	DPF	SCR
Volume, L	6.6	13.0	15.1
Diameter, mm	284	284	266.7
Length, mm	105	205	270
Density * cpsi	400	300	600

2.2 Experimental Methods

The WHTC is composed of 1,800 transient operating conditions and runs for a total of 1,800 s. The total WHTC consists of both cold- and hot-start WHTCs. The test cycle in this study was a hot-start WHTC. Four intervals are long idle speed, which are 190–255 s, 275–325 s, 705–770 s, and 1145–1200 s, respectively.

An engine is in the overrun state when it has little or no fuel injection. For an engine in this state, the uncontrolled and controlled inlet throttling valves were compared. Then factors influencing the nitrogen and oxygen emissions, including the air intake, the after-treatment temperature, the NO_2/NO_x ratio, the ammonia storage setting, and the urea injection, were studied.

3 Results and Discussion

3.1 Intake Throttling Valve's Influence on the Air Intake

The intake throttling valve affected the combustion temperature by affecting the combustion in the cylinder. Fig. 2 shows that when the engine was in the overrun state, the intake throttling valve's opening degree was different and the intake air's mass flow without thermal management measures was not actively controlled (the intake throttling valve's opening degree was 0%), as shown by the red line. The throttle valve with thermal management measures throttled the intake air (the intake throttle valve opening is 90%), as shown by the blue line. At other loads, the blue and red lines coincided, indicating that the engine's air intake mass flow were the same.

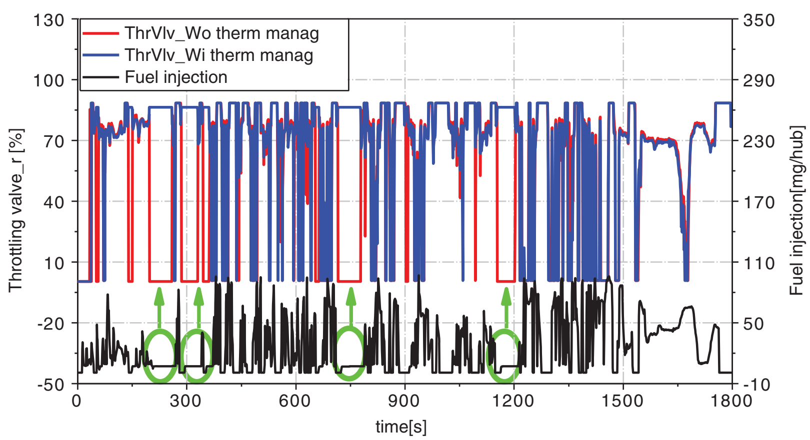


Figure 2: Intake throttling valve's opening degree

The air intake throttling valve's different opening degrees affected the engine's air intake. As shown in Fig. 3, when the engine was in the overrun state, the intake air mass flow, with and without thermal management measures, were 70 and 130 kg/h, respectively, and were nearly the same for the other working conditions. The total intake air was composed of fresh air and exhaust gas recirculation. When thermal management measures were applied, the WHTC's total intake air changed from 455,326 to 440,845 kg, a decrease of 3.2%. Eq. (1) presents the formula used to calculate the total intake air mass flow [22].

$$dm_{air} = \frac{n * K * P * V_{eng} * u}{R * T_{\rm air} * 2} \tag{1}$$

In Eq. (1), dm_{air} is the total intake air mass flow, n is the engine speed, K is the impulse coefficient, P is the gas inlet pressure, V_{eng} is the theoretical total volume of the cylinder, u is the molar mass of the mixed gas, R is the gas constant, and T_{air} is the gas inlet temperature.

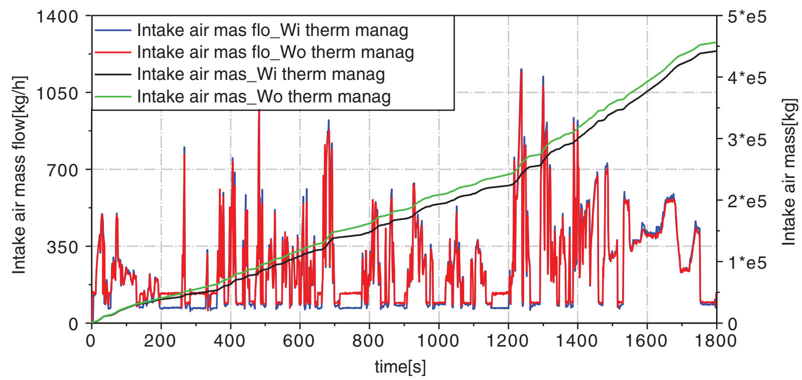


Figure 3: Engine intake air mass flow

3.2 Intake Throttling Valve's Influence on the Exhaust Temperature

The SCR's reaction and the DPF's active regeneration were closely related to the after-treatment temperature. The after-treatment temperature is one of the key aspects of the Euro VI engines. Fig. 4 shows the thermal management strategy's influence on the temperature upstream of the DOC and SCR under WHTC. The thermal management strategy effectively increased the test cycle's exhaust temperature. The minimum temperature upstream of the DOC increased from 153°C to 175°C during the engine's first overrun period when the thermal management strategy was incorporated. During the second, third, and fourth overrun periods, the minimum temperature upstream of the DOC increased from 150°C to 174°C, from 183°C to 212°C, and from 173°C to 203°C, respectively. The average temperature upstream of the DOC increased from 245°C to 254°C.

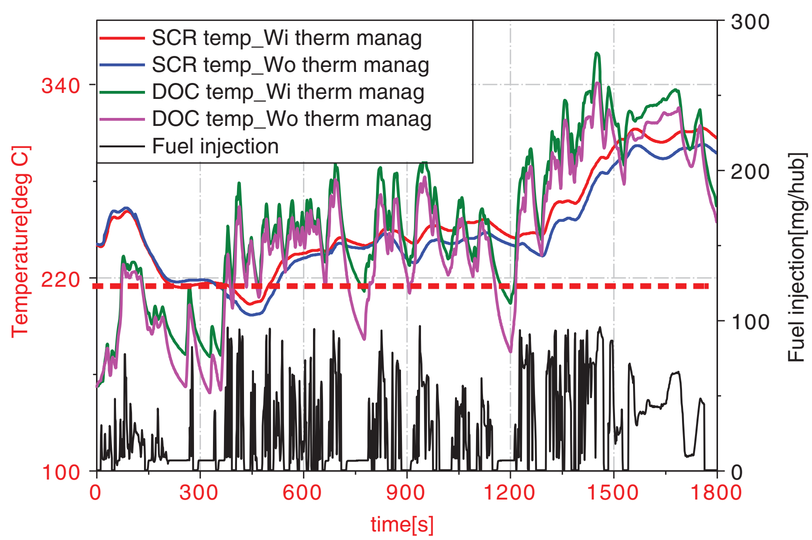


Figure 4: Engine exhaust temperature

The DOC's temperature change affected the SCR's temperature. The lowest temperature upstream of the SCR increased from 196°C to 204°C when thermal management was utilized. Under the WHTC, the average temperature upstream of the SCR increased from 248°C to 253°C. Temperature was the most important factor that affected the SCR's conversion efficiency, and it was especially critical in the low-temperature area. The SCR, coupled with thermal management strategies, could improve the conversion efficiency of nitrogen oxides.

3.3 Intake Throttling Valve's Influence on the NO_2/NO_x Ratio

The oxidation of NO to NO_2 in the DOC was primarily affected by the temperature and the space velocity. The composition of the NO_2/NO_x mixture affected not only the NH_3 and NO_x reaction rate, but also the urea consumption. Under the WHTC, the upstream NO_x changed sharply; the peak value reached 830 ppm and the average value was 295 ppm. Fig. 5 shows that the NO_2/NO_x ratio had many burrs, which were primarily affected by the space velocity. During the first 1,300 s of the WHTC, the DOC's temperature was lower than 310°C, and the NO_2/NO_x ratio was positively correlated with the after-treatment temperature. After 1,300 s, the DOC's maximum temperature reached 360°C, and the NO_2/NO_x ratio was negatively correlated with the after-treatment temperature. During the first half of the WHTC, the NO_2/NO_x ratio was less than 50%, and the fast and standard NH_3 and NO_x reactions occurred in the SCR. During the WHTC's second half, the NO_2/NO_x ratio was more than 50% at some operating points and a slow reaction of NH_3 with NO_x occurred. Under the WHTC, the mean value of the NO_2/NO_x ratio changed from 33.7% to 34.6% with the thermal management strategy, an increase of 0.9%.

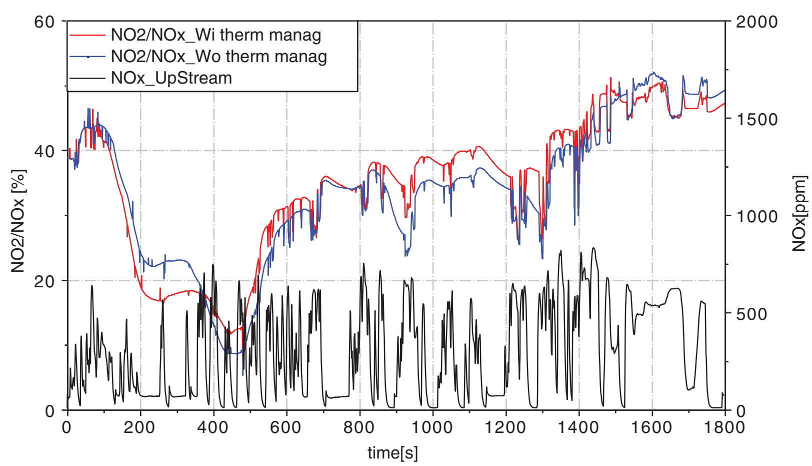


Figure 5: NO_2/NO_x ratio upstream of the SCR

3.4 Intake Throttling Valve's Influence on the Emissions Performance

The primary factors affecting the NO_x conversion efficiency were the temperature, the space velocity, and the ammonia storage. Figs. 6 and 7 show the effects of the temperature and the space velocity, respectively, on the NO_x emissions under the WHTC. There were two primary parts of NO_x escape in the hot-start WHTC. A large amount of NO_x escaped from between 400 and 500 s; this was caused by a low SCR temperature. A small amount of NO_x also escaped between 1200 and 1400 s because of the large space velocity. The mass flow of the NO_x was determined by the engine exhaust, the volume concentration of the NO_x, and the moles of gas [23], and its formula is shown in Eq. (2).

$$dm_{NO_x} = NO_{x\_ppm} * dm_{EG} * \frac{NO_{x\_mol}}{EG_{mol}} \tag{2}$$

In Eq. (2), dm_{NOx} represents the mass flow of the NO_x, NO_{x_ppm} is the volume concentration of the NO_x, dm_{EG} is the mass flow of the exhaust gas, NO_{x_mol} is the molecular weight of the NO_x, and EG_{mol} is the molecular weight of the tail gas.

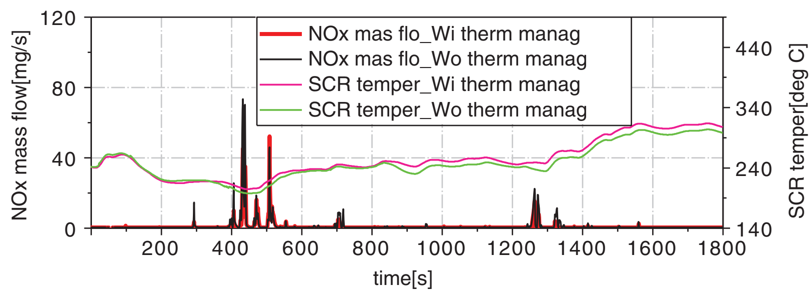


Figure 6: Influence of the temperature on the NO_x emissions

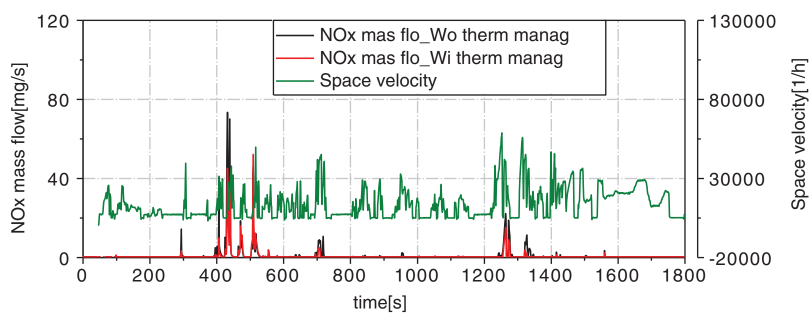


Figure 7: Influence of the space velocity on the NO_x emissions

After the addition of the thermal management measures, during the first instance of escaping NO_x (400–500 s), the maximum tail NO_x mass flow decreased from 73 to 51 mg/s. During the second instance (1200–1400 s), the maximum tail NO_x mass flow decreased from 22 to 15 mg/s when the airspeed exceeded 4,000 h^{-1}. Under the hot-start WHTC, the NO_x emissions decreased from 0.21 to 0.16 g/kWh, reducing the nitrogen oxide emissions by 24%. The formula for calculating the specific NO_x emissions is shown in Eq. (3) [24]:

$$SE_{NO_x} = \frac{\int dm_{NO_x}}{CW_{Engine}}, \tag{3}$$

where SE_{NOx} is the specific emission, dm_{NOx} is the NO_x mass flow, and CW_{Engine} is the engine cycle work.

3.5 Intake Throttling Valve's Influence on the Ammonia Storage

Proper ammonia storage can increase the NO_x conversion efficiency under very low ammonia leakage conditions. The ammonia storage was primarily affected by the temperature and the space velocity. Fig. 8 shows that lower SCR temperatures corresponded to larger ammonia storage setting values. At the lowest and highest SCR temperatures, the ammonia storage setting reached its maximum and minimum values of 0.7 and 0.4 g/L, respectively. Under the WHTC, the ammonia storage setting's mean value changed from 0.6 to 0.59 g/L when thermal management measures were utilized, a change of 1.7%.

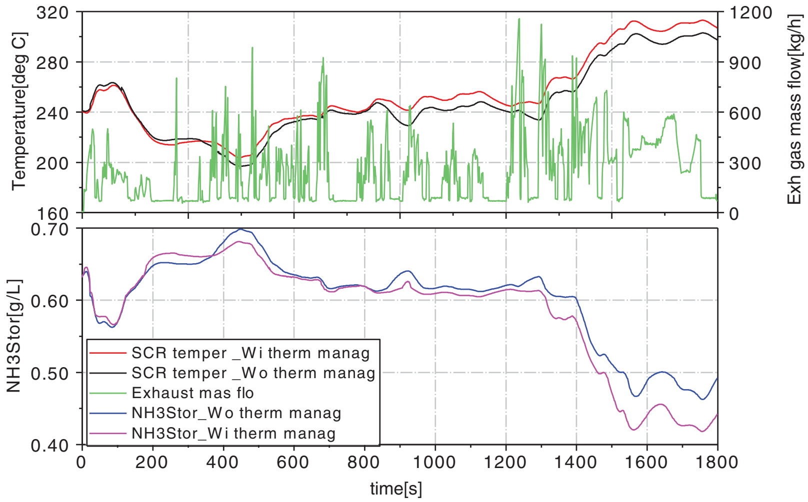


Figure 8: Ammonia storage setting

3.6 Intake Throttling Valve's Influence on the Urea Consumption

The urea injection was affected by factors such as the amounts of NO_x emitted by the engine, the ammonia storage, and the NO_x conversion efficiency. Fig. 9 shows that that the urea injection flow mass was larger between 400 and 500 s when there was no thermal management (the SCR's temperature was lower). There was little difference between the urea injection flow mass with and without thermal management in the other sections. The total urea injected increased from 171 to 174 g under the influence of thermal management measures, a change of 1.7%.

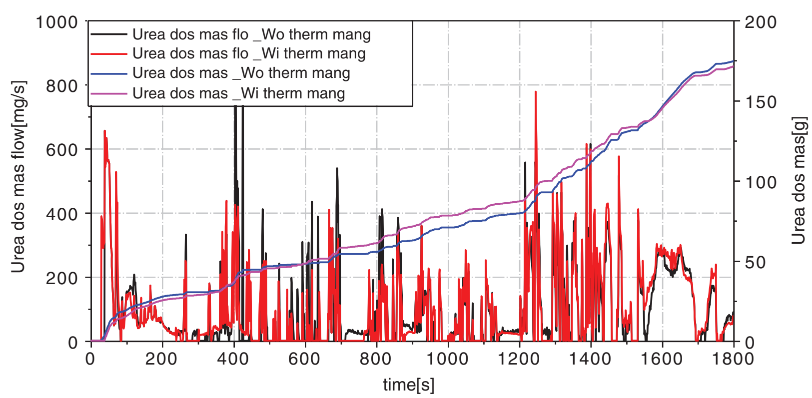


Figure 9: Urea injection

3.7 Intake Throttling Valve's Influence on the Fuel Consumption

The fuel consumption was primarily related to the engine's working points, and the air intake also had an effect. When the air intake was insufficient and the combustion was poor, the engine consumed more diesel to produce the same amount of torque. Fig. 10 shows that the fuel injection mass flow was different when the engine was in the overrun state. The fuel injection mass flow were 7.5 and 6.4 mg/hub with and without thermal management measures, respectively. When there was a load on the engine, the black and red lines coincided, indicating that the fuel injection mass flow were nearly equal. Under the WHTC, the total amount of fuel injected increased from 45.40 to 45.95 g/hub when thermal management measures were adopted, an increase of 1.2%.

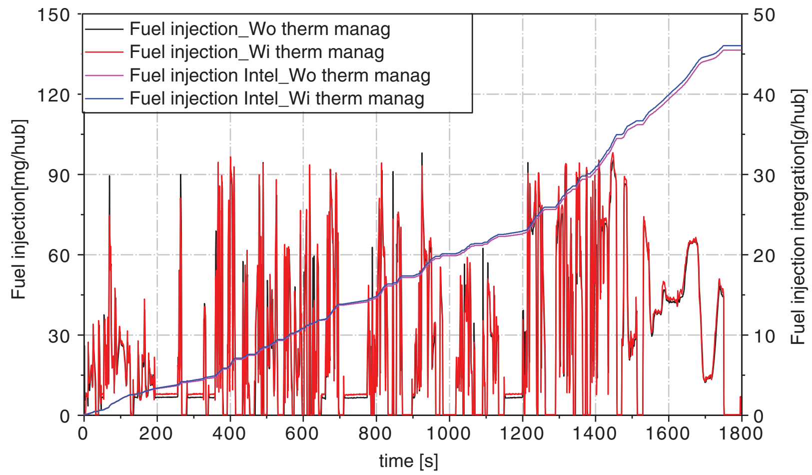


Figure 10: Fuel injection quantity

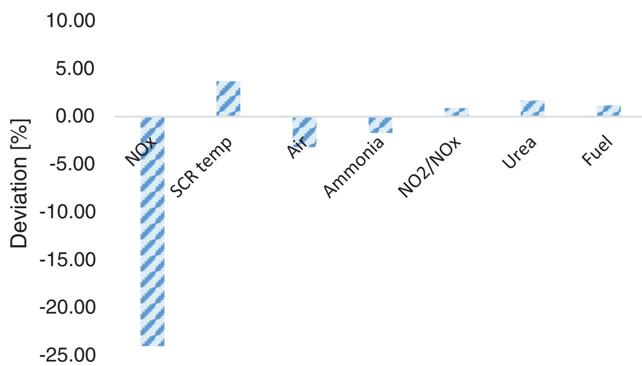


Figure 11: Thermal management results

4 Conclusions

This article proposes a new method of thermal management for an engine in the overrun state. The thermal management strategy significantly affected the DOC's temperature, the SCR's temperature, and the exhaust NO_x. The DOC's average temperature increased from 245°C to 254°C, the SCR's average temperature increased from 248°C to 253°C, and the nitrogen oxide emissions were reduced by 24% when thermal management strategies were adopted. In the zone where the SCR's temperature was lower than 210°C without thermal management, the average temperature was 201.4°C. The corresponding average temperature with thermal management was 208.8°C, an increase of 3.7%. The thermal management strategy had little influence on the intake air, the ammonia storage, the NO_2/NO_x ratio, the urea consumption, and the fuel consumption. The total amount of air intake decreased by 3.2%. The average value of the ammonia storage decreased by 1.7%. The average value of the NO_2/NO_x ratio increased by 0.9%. The total urea consumption increased by 1.7%. The total fuel consumption increased by 1.2%. The thermal management results are shown in Fig. 11. While the fuel and urea consumptions were nearly unchanged, this method significantly improved the after-treatment temperature and reduced the nitrogen oxides emissions. These results have a certain reference significance for the Euro VI standards as well as for stricter emissions requirements.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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