

Calibration and Validation of a Diesel Oxidation Catalyst Model: from Synthetic Gas Testing to Driving Cycle Applications

2011-01-1244

Published
04/12/2011

Francois Lafossas, Yoshifumi Matsuda and Ali Mohammadi
Toyota Motor Europe NV/SA

Akinori Morishima and Mikio Inoue
Toyota Motor Corporation

Maria Kalogirou
Exothermia S.A.

Grigorios Koltsakis and Zissis Samaras
Aristotle Univ. Thessaloniki

doi:[10.4271/2011-01-1244](https://doi.org/10.4271/2011-01-1244)

ABSTRACT

To meet future stringent emission regulations such as Euro6, the design and control of Diesel exhaust after-treatment systems will become more complex in order to ensure their optimum operation over time. Moreover, because of the strong pressure for CO₂ emissions reduction, the average exhaust temperature is expected to decrease, posing significant challenges on exhaust after-treatment. Diesel Oxidation Catalysts (DOCs) are already widely used to reduce CO and hydrocarbons (HC) from Diesel engine emissions. In addition, DOC is also used to control the NO₂ / NO_x ratio and to generate the exothermic reactions necessary for the thermal regeneration of Diesel Particulate Filter (DPF) and NO_x Storage and Reduction catalysts (NSR). The expected temperature decrease of diesel exhaust will adversely affect the CO and unburned hydrocarbons (UHC) conversion efficiency of the catalysts. Therefore, the development cost for the design and control of new DOCs is increasing. To select the best quality product at affordable price, the authors have evaluated exhaust simulation as an additional development tool.

In this study, a multidimensional exhaust modeling tool based on physical background was used. The model is able to solve heat and mass transfer equations under transient conditions.

“Apparent” reaction rates and Langmuir-Hinshelwood rate expressions are used for the description of the chemical reactions. The model includes appropriate HC storage models applicable to DOC with storage capacity.

In principle, exhaust model calibration can be performed using engine bench experimental data under steady state and transient conditions with full scale catalysts. However, with this approach it is indeed difficult to identify chemical mechanisms and to develop a standard calibration procedure. This paper proposes a new DOC model calibration methodology based primarily on synthetic gas tests with small scale catalysts. The main target of this methodology is to define a process to transfer the information obtained from synthetic gas tests to full-scale tests with real exhaust gas, which is not straightforward due to the complex hydrocarbon speciation. In the present work, the hydrocarbon speciation and the chemical reaction parameters of the heavy diesel exhaust hydrocarbons are investigated using well-controlled experiments with small-scale samples fed by real exhaust gas. The main target of this approach is to be able to use this calibration under real exhaust gases under driving cycle application without any modification. This methodology is expected to be also applicable to a wide range of DOC technologies.

In this paper, the calibration methodology is presented step by step. First, the adsorption mechanisms of heavy hydrocarbons (HHC) were calibrated using storage and release curves at constant flow and at different temperatures. Then, standard light-off tests were performed using different gas compositions in order to obtain the CO and HC oxidation rates. Finally, the small-scale catalyst tests with real diesel exhaust were performed. The resulting model calibration was then validated via full scale engine tests under steady state and under New European Driving Cycle (NEDC) conditions. In this study, experimental CO, HC and NO conversion efficiencies were well predicted. Finally this methodology was successfully applied to a new DOC formulation to monitor the impact of the exhaust temperature reduction on the CO and HC conversion efficiency.

INTRODUCTION

Diesel oxidation catalysts (DOCs) are used widely for the abatement of gaseous emissions of diesel engines [1]. Their main function is the oxidation of carbon monoxide (CO) and unburned hydrocarbons (UHC). Additionally they are also used to control the NO_2/NO_x ratio and to generate the necessary temperature increase for the thermal regeneration of diesel particulate filters (DPF) and NO_x storage/reduction (NSR) catalysts.

The upcoming stringent emission regulations (e.g. Euro6) and the strong pressure for CO_2 emissions reduction (targeting at 95g/km in 2020) are posing significant challenges in exhaust aftertreatment in general. The design and control of all after-treatment systems will become more complex in order to ensure optimum operation over time. Additionally, the CO_2 emissions reduction is expected to lead to a decrease of the average exhaust temperature. This temperature reduction, which is linked to the improved fuel efficiency, will adversely affect the CO and UHC conversion efficiency of the DOCs. These new challenges constantly increase the development cost of new DOCs. One of the way to reduce the development cost is to use the exhaust system modeling [2,3,4].

Generally, exhaust simulation models are complex because they have to describe multiple physical phenomena (mass, heat transfer etc) and chemical reactions which take place simultaneously in the DOC [5,6,7]. There are generally well established equations describing the transfer phenomena in the literature. Therefore, the main “bottleneck” for achieving accurate and reliable modeling results remains the determination of the governing chemical reactions scheme and the respective reaction rate coefficients. The use of global Langmuir-Hinshelwood type kinetic equations such as those described in [8] is very common in exhaust after-treatment modeling. The activation energies and pre-exponential factors

included in these reactions have typically to be adapted to the investigated catalyst formulation.

In order to determine these catalyst specific kinetic parameters, the model has to be calibrated with the help of experimental data. Two alternative experimental approaches can be used: (a) Engine bench experiments or (b) Synthetic gas experiments. In the first case, engine bench tests are performed with a full-scale catalyst. The advantages of this method include the realistic gas composition and the possibility to use steady state, transient and driving cycle tests. However, the exhaust gas parameters (flow rate, temperature, gas composition etc) can not be independently controlled. This complicates the identification of chemical mechanisms and the model calibration. In the case of synthetic gas bench (SGB) experiments, small-scale samples are used. These kind of tests can be performed with lower cost but their best asset is the easier and independent control of all experimental conditions. Therefore, it is possible to design experiments which target at the investigation of a single phenomenon such as HC adsorption [9] or specific reactions [10]. In this way, it is possible to calibrate specific parameters based on each performed experiment, significantly facilitating the calibration procedure. However, their main drawback is the fact that real-world transient conditions and the complicated HC mixture of diesel exhaust can not be accurately simulated in SGB [6, 9, 11]. The transferability of the SGB determined kinetics to real world conditions is one of the questions addressed in the present work.

Both engine and SGB calibration approaches have been used in the literature. For example, Premchand et al. [12] exclusively used engine test bench experiments almost covering the whole engine load range (from 5-100%) at two different engine speeds to calibrate their DOC model. They were able to determine one set of kinetics for both engine speeds but their calibration accuracy levels were in the range of -10 to 40% for CO and HCs respectively. Chatterjee et al. [7], on the other hand, used a “mixed” calibration technique. They relied mainly on SGB tests with variable lean mixtures to calibrate the DOC kinetics but they also showed that steady-state engine bench data can be used to calibrate the reversible NO oxidation reaction. Kryl et al. [13] used SGB experiments to calibrate their model. They used simple mixtures containing only the species of interest to examine and calibrate individual oxidation and adsorption reactions. After that, they ran experiments with complex mixtures to calibrate the inhibition terms. They tested their model and calibration results on the Standard European Cycle for light-duty vehicles, type MVEG-B, which were simulated in the laboratory using only C_3H_6 and with real cycles of the same type simulated on an engine test bench. Also Sampara et al. [6] used a dedicated SGB calibration procedure. They relied on approximately 25 tests with variable compositions to

determine the oxidation kinetics for C_3H_6 , CO and NO and to investigate the potential effect of H_2 on the reaction rates. However, it was not possible to successfully use these kinetics to simulate full-scale experiments with the same catalyst. They proposed various reasons for this discrepancy. Among them was their assumption of a single HC (i.e. C_3H_6) in the exhaust gas. Millet et al. [11] faced the same problem with the HC speciation of the exhaust gas during the simulation of a three Way Catalyst. To overcome this problem they included a second calibration step which involved the adaptation of the SGB kinetic constants to engine test bench results with the inclusion of a second hydrocarbon. Pontikakis et al. [9] also investigated the problem of HC speciation and showed that it is necessary to include more than two HC species to describe the exhaust gas. They conducted both SGB and driving cycle tests, but no information was provided regarding the compatibility of the reaction kinetics data between synthetic gas and real exhaust. As they worked with a Euro 3 engine technology, the effect of NO_2 reactions with CO and HC was not critical and was not considered in their study. However, in current and future engines, the lower temperature combustion concepts are associated with lower NO_x levels and higher NO_2/NO_x ratios. Combined with higher CO/HC emissions, it is necessary to consider the low temperature catalytic reactions of CO/HC with NO_2 as will be discussed in the present paper.

In this context, a new DOC model calibration methodology based primarily on synthetic gas tests with small scale catalysts is proposed in this study. The main target of the proposed approach is to be able to use, without any modification, the calibrated parameters under driving cycle conditions with real exhaust. Additionally, this methodology should be applicable to a wide range of DOC technologies. In this direction, the adsorption mechanisms of heavy hydrocarbons were calibrated using storage and release data at constant flow and at different temperatures. Then, light-off tests were performed using different gas compositions in order to obtain CO and HC oxidation rates with respect to temperature. The main target of the presented methodology is to define a process to transfer the information obtained from synthetic gas tests to full-scale tests with real exhaust gas. As it will be shown, this transfer is not straightforward in the case of diesel exhaust gas mainly due to the complex hydrocarbon speciation. To bridge the gap between the SGB and engine tests, well-controlled small-scale tests with real diesel exhaust were performed. These tests provided insight regarding the role of HC speciation and the inhibiting effect of heavy HC on the oxidation reactions. The resulting model calibration was then validated via full scale engine tests under steady state and under New European Driving Cycle (NEDC) conditions. Experimental CO, HC and NO conversion efficiencies were well predicted. Finally, this methodology was successfully applied to a new DOC formulation to monitor the impact of the exhaust temperature reduction on

the CO and HC conversion efficiency and to validate the applicability of the methodology independently of the DOC formulation.

DOC MODEL APPROACH

In this study, a DOC modeling was performed using “axicat”, a module of the commercial *axisuite*® platform [14]. Axicat is a general tool for modeling flow-through catalysts, including three-way catalysts [5, 15], diesel oxidation catalysts [9, 16], DeNOx catalysts [17], selective catalytic reduction (SCR) catalysts [18] and lean NOx traps [19]. The underlying simulation model offers the possibility of calculating the combined transport and reaction phenomena in flow-through catalysts. Intra-layer discretization in the catalyst washcoat allows for detailed simulation of the complex interactions between the chemical reactions and species diffusion.

The main differential and algebraic equations for the heat and mass transfer calculation in the catalytic converter are given in Figure 1. More details on the derivation of the model equations, the boundary conditions and the solution procedure can be found in the above referenced publications.

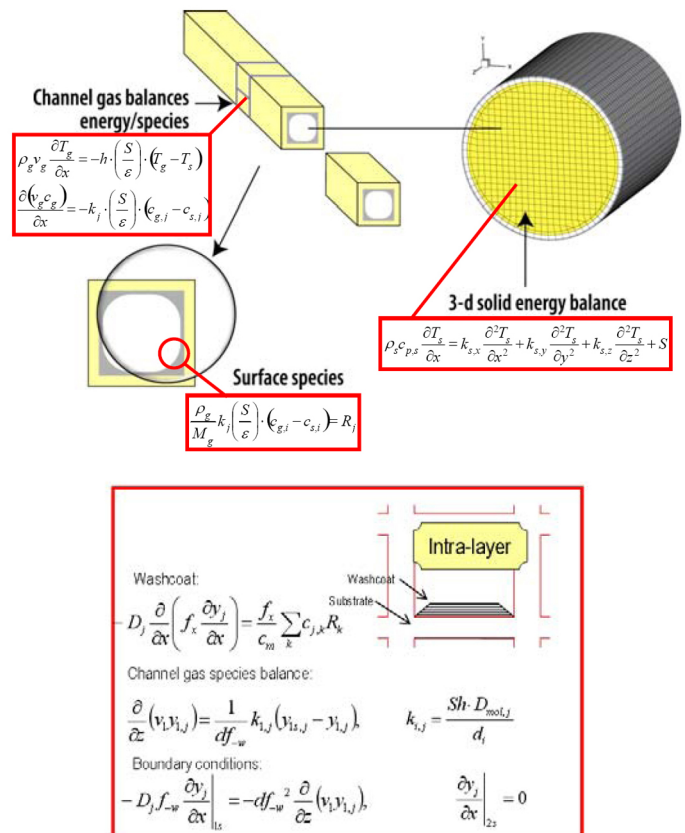


Figure 1. Flow-through catalyst schematic and basic model equations.

In the current modeling approach, the monolith geometry can be discretized in all 3D. For the purposes of the present work, only round-shaped substrates and symmetrical flow were used and therefore a 2D (axisymmetric) discretization was sufficient. The washcoat discretization for the solution of the diffusion-reaction problem in the washcoat is important in the case of substantial diffusion resistance or in the case of multi-layered systems. In this work, the authors have experimentally verified that the washcoat diffusion effects were negligible and, therefore, washcoat internal discretization could be avoided.

The reaction scheme used to calculate the rates of the catalytic heterogeneous reactions depends on the catalytic formulation and the ageing status. *axisuite*® offers a selection of more than 70 built-in reactions plus the possibility to apply user-defined reactions. The reaction rates on Platinum Group Metals (PGM) sites are calculated using “global” reaction rate expressions, based on the Langmuir-Hinshelwood theory [20]. The adsorption reactions are calculated based on the Dubinin-Radushkevich equilibrium isotherm and appropriate linear kinetic rates [21].

The chemical reactions used in the present study are listed in Table 1. These include oxidation reactions for CO (Reaction 2 and 3), oxidation reactions for hydrocarbons (HC) (Reactions 4-10) and reversible oxidation of NO (Reaction 1), taking into account the chemical equilibrium limitation. CO and HC oxidation was assumed to proceed with both O₂ and NO₂.

As it can be seen in Table 1, inhibition terms are used for all reactions. The analytical relationships for these terms are presented in Table 3. As it can be seen the same inhibition terms are assumed for the oxidation of CO by NO₂ and of HC by O₂. Lacking further experimental or literature evidence, the common inhibition term may be justified by the fact that all reactions take place on the same active sites.

In real diesel exhaust gas, a large number of different hydrocarbon species exists. These hydrocarbons present different chemical activity [22]. To deal with this issue, hydrocarbons are grouped in 4 groups to account for the individual oxidation and adsorption properties of the different HC species in the exhaust gas. The properties of the 4 groups of HCs are shown in Table 2. The specific HC that is assumed to simulate the behavior of each group more accurately and was therefore used in the SGB experiments is also given in Table 2.

Together with the oxidation reactions, adsorption phenomena may also play an important role during the warm-up phase of the catalyst. These phenomena may affect both the species availability, and the temperature response of the monolith. Therefore, competitive species adsorption was modeled using

the validated Dubinin and Radushkevich adsorption isotherm and appropriate adsorption/desorption rates (Reactions 11-13).

“axical” employs a quasi-steady-state assumption, according to which the rate of diffusion of the species to the active catalytic sites is equal to the rate of chemical reaction. The coupling between reaction and diffusion rates consists in calculating the molar fractions at the catalytic sites for which the reaction rates become equal with the diffusion rates. The necessary mass transfer coefficients for these calculations are computed using spatially dependent relations for Sherwood numbers.

Typically, the flow in the catalyst channels is laminar. It starts, however, from “plug flow” (piston flow) and the development of the fully developed boundary layer is completed in approximately a ten diameter distance from entrance. In addition, exhaust flow entering the channel is turbulent and it takes some distance for the turbulent flow to become laminar. Mass and heat transfer models for laminar flow are not directly applicable at this region and may need correction. After this entry length, the laminar flow Nusselt number takes an asymptotic constant value. For heat transfer this entrance effect is known as the Graetz-Nusselt problem. Hawthorn [23] proposed a correction of the Nusselt number according to:

$$Nu = Nu_L \left(1 + \frac{a_H}{Gz_D} \right)^{b_H} \quad (1)$$

The correlation of Hawthorn, although commonly used in mathematical models to compute the Nusselt number in channels, in fact calculates the average Nusselt number from the entrance of the channel until a given axial location z . Based on this correlation, we may derive a correlation for the local Nusselt number in any axial location z which is given by:

$$Nu = Nu_L \left[\left(1 + \frac{a_H}{Gz_D} \right)^{b_H} - b_H \frac{a_H}{Gz_D} \left(1 + \frac{a_H}{Gz_D} \right)^{b_H-1} \right] \quad (2)$$

From “mass-heat transfer analogy”, same correction applies to Sherwood number:

$$Sh = Sh_L \left[\left(1 + \frac{a_H}{Gz_D} \right)^{b_H} - b_H \frac{a_H}{Gz_D} \left(1 + \frac{a_H}{Gz_D} \right)^{b_H-1} \right] \quad (3)$$

Table 1. Reaction scheme and calibration targets

Reaction type	Reaction	Reaction rate ¹	Calibration targets ²	
NO reversible oxidation ³	NO +1/2 O ₂ ↔NO ₂	$R=k\frac{[NO][O_2]^{\frac{1}{2}}-[NO_2]\frac{1}{K_p}}{G_5}$	E _i ,A _i ,G ₅	(1)
CO oxidation with O2 and NO ₂	CO +1/2 O ₂ →CO ₂	$R=\frac{k[CO][O_2]}{G_2}$	E _i ,A _i ,G ₂	(2)
	CO +NO ₂ →CO ₂ + NO	$R=\frac{k[CO][NO_2]}{G_1}$	E _i ,A _i ,G ₁	(3)
HC ⁴ oxidation with O2 and NO ₂	C _{x1} H _{y1} + (x ₁ +y ₁ /4) O ₂ → x ₁ CO ₂ + y ₁ /2 H ₂ O	$R=\frac{k[C_{x1}H_{y1}][O_2]}{G_1G_3}$	E _i ,A _i ,G ₁ ,G ₃	(4)
	C _{x2} H _{y2} + (x ₂ +y ₂ /4) O ₂ → x ₂ CO ₂ + y ₂ /2 H ₂ O	$R=\frac{k[C_{x2}H_{y2}][O_2]}{G_1}$	E _i ,A _i ,G ₁	(5)
	C _{x3} H _{y3} + (x ₃ +y ₃ /4) O ₂ → x ₃ CO ₂ + y ₃ /2 H ₂ O	$R=\frac{k[C_{x3}H_{y3}][O_2]}{G_1}$	E _i ,A _i ,G ₁	(6)
	C _{x4} H _{y4} + (x ₄ +y ₄ /4) O ₂ → x ₄ CO ₂ + y ₄ /2 H ₂ O	$R=\frac{k[C_{x4}H_{y4}][O_2]}{G_1}$	E _i ,A _i ,G ₁	(7)
	C _{x2} H _{y2} + (2x ₂ +y ₂ /2) NO ₂ → x ₂ CO ₂ + y ₂ /2 H ₂ O + (2x ₂ +y ₂ /2) NO	$R=\frac{k[C_{x2}H_{y2}][NO_2]}{G_{11}}$	E _i ,A _i ,G ₁₁	(8)
	C _{x3} H _{y3} + (2x ₂ +y ₂ /2) NO ₂ → x ₃ CO ₂ + y ₃ /2 H ₂ O + (2x ₂ +y ₂ /2) NO	$R=\frac{k[C_{x3}H_{y3}][NO_2]}{G_{11}}$	E _i ,A _i ,G ₁₁	(9)
	C _{x4} H _{y4} + (2x ₄ +y ₄ /2) NO ₂ → x ₄ CO ₂ + y ₄ /2 H ₂ O + (2x ₄ +y ₄ /2) NO	$R=\frac{k[C_{x4}H_{y4}][NO_2]}{G_{11}}$	E _i ,A _i ,G ₁₁	(10)
Adsorption – desorption reactions	H ₂ O ↔ H ₂ O (l)	$R_f=kW_o\phi_{eq,j}\phi_{free}$ (Adsorption) $R_b=kW_o\phi_j(1-\phi_{eq,j})$ (Desorption)	E _i ,A _i ,β _j ,W _o	(11)
	C _{x3} H _{y3} ↔ C _{x3} H _{y3} (l)	$\phi_{eq,j}=\frac{1}{\exp\left[A_{ze}\left(\frac{\Re T}{\beta_j}\right)^2\left(\ln\frac{p_{sat,j}}{p_j}\right)^2\right]}$		(12)
	C _{x4} H _{y4} ↔ C _{x4} H _{y4} (l)			(13)

$$k = A \exp \left(-\frac{E}{\Re T} \right)$$

² E_i and A_i are the activation energy and pre-exponential factor included in the term k of each reaction rate. Details about the expressions for the inhibition terms are given in Table 3. Here β_j is the affinity coefficient which is species defined and W_o is the total storage volume per reactor volume.

³ $K_p = e^{-\frac{\Delta G}{\Re T}}$, where ΔG is the change of Gibbs energy of the bidirectional reaction and varies with temperature, R is the universal gas constant and T is the temperature.

⁴HC species are defined in Table 2.

Table 2. HC speciation

Representative hydrocarbon designation	Oxidation rate	Adsorption rate	Representative HC used in SGB tests
C _{x1} H _{y1}	Slow	No	Not tested
C _{x2} H _{y2}	Fast	No	C ₃ H ₆
C _{x3} H _{y3}	Fast	Moderate	C ₁₀ H ₂₂
C _{x4} H _{y4}	Fast	High	Not tested

Table 3. Inhibition terms

Inhibition term	Expression ^{1,2}	Calibration targets ¹
G1	$G_1 = T \cdot (1 + k_{13}[CO] + k_{14}[HC_1])^2 \cdot (1 + k_{15}[CO]^2[HC_1]^2) \cdot (1 + k_{16}[NO]^{0.7})$	k ₁₃ ,k ₁₄ ,k ₁₅ ,k ₁₆
G2	$G_2 = T \cdot (1 + k_1[CO] + k_2[HC_2])^2 \cdot (1 + k_3[CO]^2[HC_2]^2) \cdot (1 + k_4[NO]^{0.7})$	k ₁ ,k ₂ ,k ₃ ,k ₄
G3	$G_3 = (1 + k_6[O_2])^{1.5}$	k ₆
G5	$G_5 = T \cdot (1 + k_{21}[CO] + k_{22}[HC_2])^2 \cdot (1 + k_3[CO]^2[HC_2]^2) \cdot (1 + k_8[NO]^{0.7})$	k ₃ ,k ₈ ,k ₂₁ ,k ₂₂
G11	$G_{11} = T \cdot (1 + k_{27}[CO] + k_{28}[HC_1])^2 \cdot (1 + k_{29}[CO]^2[HC_1]^2) \cdot (1 + k_{30}[NO]^{0.7})$	k ₂₇ , k ₂₈ , k ₂₉ ,k ₃₀

$$k_i = A_i \exp\left(-\frac{E_i}{RT}\right) \quad \begin{cases} [HC_1] = \frac{1}{4} [C_{x1}H_{y1}] + [C_{x2}H_{y2}] + [C_{x3}H_{y3}] + [C_{x4}H_{y4}] \\ [HC_2] = [C_{x1}H_{y1}] + [C_{x2}H_{y2}] + [C_{x3}H_{y3}] + [C_{x4}H_{y4}] \end{cases}$$

EXPERIMENTAL SETUP

SAMPLE PREPARATION

Two 400cpsi/4.5mil DOC samples were used in the experimental part of this study: (1) a full-scale 0.4L catalyst with a diameter of 128.65mm and a length of 30.8mm and (2) a small-scale sample with a diameter of 30mm and a length of 50mm. The small-scale samples were extracted from a catalyst identical to the full-scale one. Both test pieces were aged at 700°C for 55 h in air. The samples had a washcoat loading of 150 g/l and a Pt:Pd ratio equal to 2:1.

SMALL-SCALE SETUP

The small-scale experimental setup is presented schematically in Figure 2. The samples were placed in an electrically heated high temperature tube furnace which can be fed either with synthetic gas (Figure 2a) or real diesel exhaust gas (Figure 2b).

As it can be seen in Figure 2a, a gas mixer (Enviroics S-2000) which can mix up to six different gases was used for the preparation of the inlet gas mixture. In selected experiments, controlled amounts of heavy liquid HCs were introduced by a syringe pump (Cole-Parmer 74900 dual syringe pump). A “saturator” was used to humidify the reaction gas. It consists of a glass flask filled with distilled water. The flask is placed on a magnetic heated stirrer which keeps the water temperature constant with the help of a control thermocouple. As it passes through the flask, the gas stream gets saturated with the amount of water which corresponds to the selected water temperature. For tests with liquid HCs and without water the “saturator” is by-passed.

In the case of the real diesel exhaust (Figure 2b) the gas was produced by a diesel engine mounted on an engine dynamometer. Details about the engine and the dynamometer are given in the next section. The exhaust gas passed through a diesel particulate filter (DPF) prior to entering the furnace in order to avoid any contamination of the small-scale tubes

and test piece with diesel soot emitted from the engine. A controlled fraction of the total exhaust gas flow was then led to the furnace with the help of a vacuum pump via a heated line.

The composition of the incoming gas was kept constant over time for each test by control of the gas mixer and the engine operating point. The stability of the mixture was cross-checked by exhaust gas analysis through a by-pass line (Figure 2) at the beginning and at the end of each test. The inlet and outlet concentrations of the different species (CO, CO₂, HC, NO/NO_x) were measured using a multi-gas analyzer (AMA i60). AMA is a fast analyzer with a response time in terms of T90 better than 2s. Specifically for the HC adsorption tests, an ultra-fast HC analyzer (MEXA-1210FRF, T90 less than 2ms) with two sampling channels was used to continuously monitor the inlet and outlet concentrations.

Temperature inside the test piece was continuously monitored using four K-type thermocouples of 0.5mm diameter (Points T1, T3, T4, T5 in Figure 3). The exact positions of the thermocouples are given in Table 4.

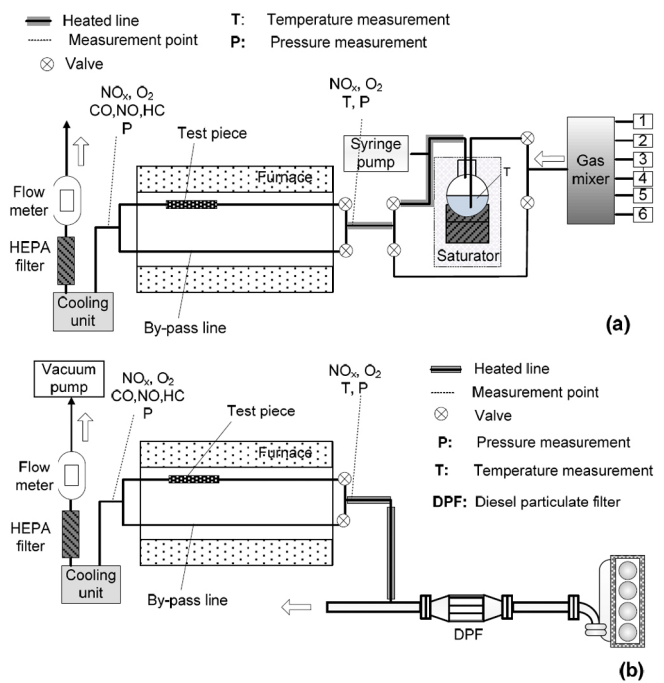


Figure 2. Small-scale experimental setup: (a) synthetic gas bench (b) with real diesel exhaust

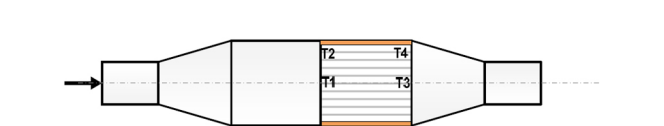


Figure 3. Thermocouple positions inside the small-scale test piece

Table 4. Thermocouple positions (Small-scale)

Temperature label (see Figure 3)	Radial [mm]	Axial [mm]
T1	0	0
T2	12.7	0
T3	0	50
T4	12.7	50

ENGINE TEST BENCH

..... Measurement point T1-T5 Thermocouples
T: Temperature measurement

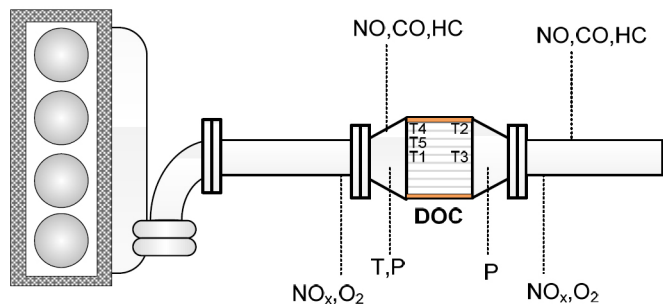


Figure 4. Engine test bench

Table 5. Thermocouple positions (Full-scale)

Temperature label (see Figure 4)	Radial [mm]	Axial [mm]
T1	0	0
T2	64	31
T3	0	31
T4	64	0
T5	54	0

The engine tests were performed on a direct injection common rail 2.2 l diesel engine which complies to Euro 4 emission standards. The engine is turbo-charged, intercooled and uses exhaust gas recirculation. The engine was coupled on a transient eddy-current dynamometer (AVL 350kW) with