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IFAC-PapersOnLine 48-15 (2015) 427–433

Control Oriented Model for Diesel Oxidation Catalyst Diagnosis

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Abstract:
On-board diagnosis of the after-treatment system is forced by regulation; with diagnosis limits approaching certification values, a tight surveillance of the after-treatment performance is to be done. This paper presents a simple model for a diesel oxidation catalyst, representing both the thermal and chemical behaviour of the system. In addition to the model description, the paper provides hints on the model fitting process and illustrates its performance in several driving conditions. Despite its simplicity, the model allows a proper description of the exhaust temperature variation, allowing the implementation of several model based diagnostic techniques.

Keywords: Diesel oxidation catalyst, DOC, control oriented model, model identification

1. INTRODUCTION

Legislation trend over the last years is to reduce emission limits. Even if current emission limits are kept, the increase in power demands in the future World Harmonised Light-duty Test Procedure (WLTP) driving cycle (eur, 2012; WLT, 2014) will force automotive manufacturers to upgrade the after-treatment systems of current vehicles. In addition, increased On-Board Diagnostics (OBD) requirements, with detection thresholds approaching emission certification values, and the possibility of including Real Driving Emission (RDE) in the certification procedure by the application of Portable Emissions Measurement Systems (PEMS) (Daham et al., 2009), will stress the requirements on the aftertreatment system control and diagnosis. So after-treatment is expected to continue playing a key role for the fulfilment of the legislation in the near future.

Diesel Oxidation Catalysts (DOC) have been used in more diesel vehicles than any other emission control device, being common in both light-duty and heavy duty engines (Johnson, 2010). DOCs can be formulated to perform several key roles (Johnson, 2008): in addition to its main objective (HC and CO oxidation), it is critical to the proper operation of Diesel Particulate Filters (DPF) and deNO$_x$ systems, namely the Lean NO$_x$ Trap (LNT) and the Selective Catalytic Reduction (SCR) (Chen and Wang, 2014). Besides, a DOC also plays a key role during active regeneration of DPFs (Chen and Wang, 2014), which is based on the temperature increment associated to HC and CO burning. Exothermic oxidation of NO to NO$_2$ in a DOC also contributes to enhance the passive regeneration of a DPF (Walker, 2004).

The kinetics of the chemical reactions that take place in a DOC strongly depend on temperatures. In addition, DOCs have an upper limit of temperature, which is usually defined by the mechanical resistance of the employed materials (Johnson, 2008). A lower boundary limit of temperature for DOC oxidation is established by the sudden reduction in its efficiency when temperatures fall below a certain limit (hereinafter light-off temperature). The DOC light-off temperature is generally stated between 200 and 250°C (Johnson, 2006) despite the fact that Sumiya et al. (2009) showed it increases with decreasing oxygen and increasing HC and CO. Ash contamination and thermal aging can also cause light-off temperature variation on aged DOCs.

Several DOC models have already been developed, considering both 1D and control oriented modelling approaches. These models are mainly based on the oxidation of HC, CO and even NO (Zheng and Banerjee, 2009; Young-Deuk and Woo-Seung, 2009). DOCs storage capabilities have been modelled in different studies (Sutjiono et al., 2013; Sampara et al., 2008), as well as the outlet mass flow temperature and the light-off temperature.

This paper proposes a control oriented DOC model for estimating the gas temperature at the DOC outlet. The model is to be used in real time operation in the Electronic Control Unit (ECU) of a series diesel engine for providing a model based estimation of the temperature, which is compared with a measurement for diagnosis purposes. With that aim, the model should be provided with the DOC inlet conditions.

2. EXPERIMENTAL SETUP

The engine used in this study is a light-duty engine equipped with a high pressure common-rail fuel injection system, a variable geometry turbine and a high pressure exhaust gas recirculation system. Despite the original

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10.1016/j.ifacol.2015.10.061

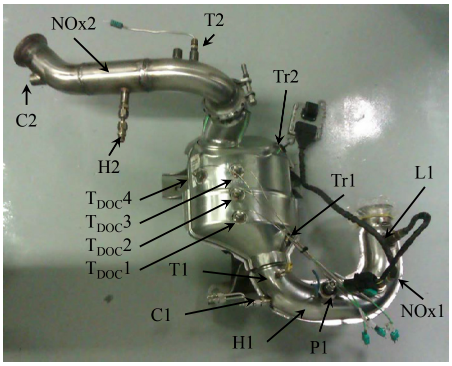

Fig. 1. Detail on DOC instrumentation

engine included a DPF, it was removed and substituted by a back pressure valve for simulating its pressure drop. Hence DOC was the only aftertreatment device in the exhaust line.

Figure 1 shows a detailed view of the DOC instrumentation. The DOC is instrumented with 4 thermocouples along the monolith ($T_{DOC}1$ to $T_{DOC}4$, the first three in the central line) and two at the flow line, one at the inlet (T1) and one at the outlet (T2). The fast response of the thermocouples permits analyzing the thermal transfer between the different parts, e.g. convection to external air and conduction along the DOC. Two commercial NTC sensors (Tr1 and Tr2) are installed next to the thermocouples to take into account the series sensor behavior. A Horiba MEXA 7100 is employed to obtain a complete analysis of the gases. Finally a Cambustion NDIR 500 is employed to determine the instantaneous response of the DOC (C1 and C2), with a time response of around 7 ms.

Two different DOCs were tested: a nominal (new) DOC, and a passive DOC. The passive DOC consisted of a monolith without the precious metal impregnation; it was built on purposes for simulating the behaviour of a faulty unit. In addition, it provided a perfect situation for fitting the thermal transfer model of the DOC, since it presents no HC nor CO combustion.

3. MODELLING APPROACH

The objective of the dynamic DOC model is to capture the DOC outlet temperature. To that aim, the model requires the temperature, mass flow, HC and CO concentrations at the DOC inlet. The model will consider the heat produced through HC and CO oxidation; however, modelling the DOC outlet concentration of these two species is out of the scope of the present paper.

Thermal modelling. The DOC model proposed is mainly based on energy and mass balances, taking the DOC temperatures and the amount of HC stored in the DOC as states. Regarding the thermal modelling of the DOC, an approach based on two lumped thermal energy reservoirs has been used. The two reservoirs represent the DOC core and its housing respectively. It is supposed that the exhaust gas $\dot{m}_{exh}$ entering the DOC leaves it at the DOC inner part temperature. In this sense, the equations governing the DOC temperature variations are:

$$m_{DOC} c_{vDOC} \frac{dT_{DOC}}{dt} = \dot{m}_{exh} c_p [T_{in} - T_{DOC}] + kA[T_{DOC2} - T_{DOC}] + \dot{m}^{oxi}_{HC} LHV_{HC} + \dot{m}^{oxi}_{CO} LHV_{CO} \quad (1)$$

$$m_{DOC2} c_{vDOC2} \frac{dT_{DOC2}}{dt} = -k'A[T_{DOC2} - T_{DOC}] - hA'[T_{DOC2} - T_{env}] \quad (2)$$

where, m_{DOC} is the mass of the inner part of the DOC, c_{vDOC} is the heat capacity, and T_{DOC} is the DOC bulk temperature; kA represents the heat transfer coefficient between the outer part of the DOC and DOC bulk, $\dot{m}^{oxi}_{HC}$ are the oxidized hydrocarbons mass flow and LHV is the lower heating value of the hydrocarbons. The external covering to the DOC bulk is considered in (2) in order to be able to represent more faithfully the DOC temperature dynamics. In this equation, the DOC outer temperature T_{DOC2} is evaluated through the influence of the DOC bulk temperature T_{DOC} with its heat transfer coefficient, $k'A$, and the heat transfer with ambient temperature (T_{env}) through the heat transfer coefficient hA'. Note that radiation has been neglected and that convective coefficients are considered constant for the sake of simplicity.

Finally, the gas temperature at the DOC outlet (T_{out}) can be considered to be equal to the DOC bulk temperature (T_{DOC}). Such simplified DOC models have shown good performance for control tasks (Chen and Wang, 2012). However, in the present paper the temperature sensor dynamics have been taken into account with the following expression:

$$T_{out}(k) = \beta T_{out}(k-1) + [1-\beta] T^{\tau}_{DOC}(k-1) - \alpha[T_{out}(k-1) - [\gamma T_{DOC2}(k-1) + [1-\gamma] T_{env}]] \quad (3)$$

An analogy with equations 1 and 2 can be noticed since (3) represents the energy balance in a control volume around the temperature sensor measuring the DOC outlet temperature. The parameter γ allows considering an average external temperature for heat transfer that depends on the environment and DOC cover temperatures. The parameter α represents the heat transfer coefficient between the sensor and its surroundings. The parameter β allows to model the sensor dynamics, filtering the value of T_{out} with a weighted average of previous values of T_{out} and T_{DOC}. The parameter β is modelled as a function of the exhaust mass flow ($\beta = \beta(\dot{m}_{exh})$). Particularly, the value of β ranges from 0 when there is not exhaust flow to 1 where the exhaust mass flow reaches its maximum.

Such definition for β was decided in order to be able to reproduce the sensor output during start&stop operation: when the engine is stopped the flow is zero and the sensor temperature goes down because the exhaust line cools; however the DOC monolith keeps at a higher temperature. When the engine is started again, this generates a fast increase in the outlet sensor temperature as a consequence of the heat released from the monolith to the exhaust gas flow. Figure 2 illustrates such behaviour during an start event. The proposed model is able to simulate such phenomenon; note that when the engine is stopped, $\beta = 0$ and the DOC outlet temperature (T_{out}) is progressively being