

Implications of Engine Start-Stop on After-Treatment Operation

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ABSTRACT

It is commonly accepted that future powertrains will be based to a large extent on hybrid architectures, in order to optimize fuel efficiency and reduce CO₂ emissions. Hybrid operation is typically achieved with frequent engine start-and-stops during real-world as well as during the legislated driving cycles. The cooling of the exhaust system during engine stop may pose problems if the substrate temperature drops below the light-off temperature. Therefore, the design and thermal management of after-treatment systems for hybrid applications should consider the 3-dimensional heat transfer problem carefully. On the other hand, the after-treatment system calculation in the concept design phase is closely linked with engine calibration, taking into account the hybridization strategy. Therefore, there is a strong need to couple engine simulation with 3d aftertreatment predictions.

In this paper, we perform measurements in flow-through catalytic substrates and wall-flow DPF systems to monitor the thermal losses after engine shut-off. In parallel, we use an existing 3-dimensional modeling platform (axisuite®/Exothermia SA), which is enhanced with a heat transfer submodel to account for free convection and radiation from the front and rear substrate faces. The model predictions are compared with experimental data under various operating conditions.

The validated model is used to predict the performance of a diesel after-treatment system of a hybrid vehicle application. The performance of the after-treatment system in terms of DOC conversion efficiency is studied in detail with the help of 3-dimensional modeling during engine start-stop operation. The importance of heat losses is illustrated and the potential

implications for exhaust system thermal management are discussed.

INTRODUCTION

The pressure to reduce CO₂ emissions by increased powertrain efficiency in diesel applications results in generally lower exhaust gas temperatures. In addition, a hybrid operating system is characterized by frequent engine start-and-stops, thus several cooling-downs of the exhaust system. These cooling periods may result in catalyst temperature decrease below the light-off temperature, which will temporarily deactivate the aftertreatment device. Therefore, it is very crucial to study and optimize the thermal behavior of the exhaust system, so that this drawback is avoided by proper design of aftertreatment device geometry and general thermal management (e.g. potential need of external heating).

The numerical investigation of the heat transfer under near-zero mass flow is a new technological challenge and only few research works have been published on this subject. Chung et al. [1] performed a numerical simulation of the catalytic converter cool-down process using Computational Fluid Dynamics (CFD) software and validated it with experimental results. Chen et al. [2] provided a 3-dimensional model to simulate the thermal and conversion characteristics of monoliths operating under flow maldistribution conditions. Klein and Cheng [3] studied the catalyst temperature behavior in regular engine shut-down and restarting. Braun et al. [4] simulated the cold start-up of an automotive three-way catalytic converter using a CFD-code application. Shu et al. [5] investigated the temperature as a function of time for both steady-state and transient driving operations. Adamczyk et al. [6] studied the device cool-down characteristics for the

cold-start converter modeling. Katare et al. [7] made a hybrid approach for the exhaust aftertreatment modeling and, more specifically, for a DOC.

In the present work, the commercial axisuite® modeling platform is used to simulate the three-dimensional flow and heat transfer inside the aftertreatment system comprising a DOC and DPF in-series under transient operating conditions. The model has been recently extended to account for the free convection and radiation heat losses during engine shut-off. The target is to predict the DOC/DPF temperature both while the engine is on and during the shut-off, when the mass flow is equal to zero. The numerical method is validated with experimental measurement results from cool-down/light-off experiments, performed on the engine test bench.

In the following section, the modeling approach is briefly described and followed by the experimental set-up description section. The experimental investigation of the after-treatment system thermal behavior is studied under highly transient driving cycle conditions, performed with a diesel engine on a transient engine dyno. The Torque-Speed profile is derived by the commercial CRUISE software for the legislated NEDC cycles for both conventional and hybrid operation modes. The experimental and modeling results are discussed, and the conclusions are outlined.

MODELING APPROACH

MAIN BALANCE EQUATIONS

The modeling tool used for the simulation of the flow-through catalytic converter is “axicat” [8]. The model has been extensively used in the past to simulate 3-way catalysts (3WCC) [9, 10], diesel oxidation catalysts (DOC) [11, 12], DeNO_x catalysts [13], selective catalytic reduction (SCR) catalysts [14] and lean NO_x traps [15]. The main differential and algebraic equations for the heat and mass transfer in the converter are given in Figure 1 below.

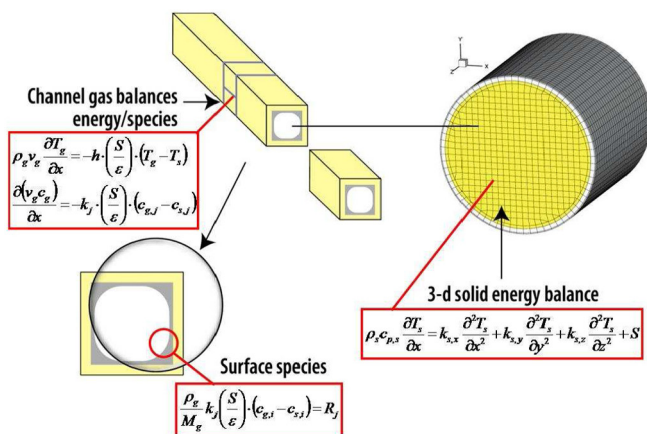


Figure 1. Flow-through catalytic converter schematic and basic model equations.

The model is equipped with intra-layer discretization to account for the coupling between reaction and diffusion phenomena. In case of multi-layer washcoats or extruded catalysts, these phenomena play an important role. The basic intra-layer equations for flow through catalyst modeling are presented in Figure 2 below.

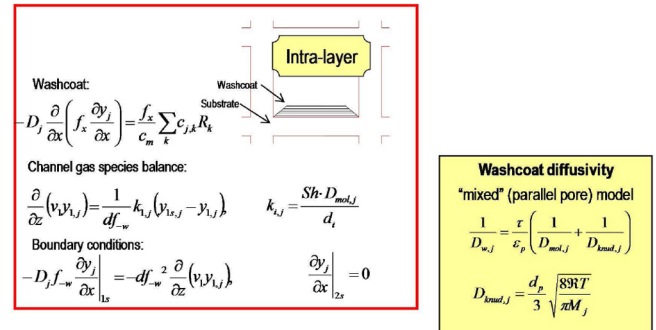


Figure 2. Intra-layer modeling equations.

HEAT TRANSFER BOUNDARY CONDITIONS

For the investigation of the thermal behavior of the emission control device, the heat losses from the monolith periphery and faces are taken into account, the latter being critical at near-zero flow conditions.

The boundary conditions are taken into account for the heat losses from the monolith periphery to the ambient by free convection and radiation for the heat conduction equation:

$$\lambda_{s,r} \frac{\partial T_s}{\partial r} = C_{amb} \cdot h_{amb} (T_s - T_{amb}) + \epsilon_{rad} \cdot \sigma \cdot (T_s^4 - T_{amb}^4) \quad (1)$$

at $r = 0.5D_f$

Heat losses by free convection and radiation from the front and rear faces of the device are taken into account as boundary conditions for the heat conduction equation as shown below:

$$\lambda_{s,z} \frac{\partial T_s}{\partial z} = C_{amb,f} \cdot h_{amb,f} \cdot (T_s - T_{\infty,in}) + C_{rad,f} \cdot (1 - \epsilon) \epsilon_{rad} \cdot \sigma \cdot (T_s^4 - T_{\infty,in}^4) \quad (2)$$

at $z = 0$ and

$$\lambda_{s,z} \frac{\partial T_s}{\partial z} = C_{amb,r} \cdot h_{amb,r} \cdot (T_s - T_{\infty,out}) + C_{rad,r} \cdot (1 - \epsilon) \epsilon_{rad} \cdot \sigma \cdot (T_s^4 - T_{\infty,out}^4) \quad (3)$$

at $z = L$.

The terms for natural convection and radiation, which are included in the above expressions, are explained in detail below:

Natural (Free) Convection

In case of near-zero flow conditions, natural convection from the monolith faces becomes important. The convection coefficient from the monolith faces $h_{amb,F}$ is computed using the equations for natural convection for a vertical plate. For the 3D simulation, the following equations are used:

The local Nusselt number is computed based on the following equation:

$$Nu_x = \left(\frac{Gr_x}{d} \right)^{\frac{1}{4}} g(Pr) \quad (4),$$

$$\text{with } g(Pr) = \frac{0.75\sqrt{Pr}}{(0.609 + 1.221\sqrt{Pr} + 1.238Pr)^{\frac{1}{4}}} \quad (5)$$

$$\text{and } Gr_x = \frac{g \beta (T_s - T_\infty) x^3}{\nu^2} \quad (6)$$

Radiation

The emissivity ε_{rad} refers to the substrate material. The term $1 - \varepsilon$ refers to the fraction of the face area of a monolith occupied by solid material.

STUDY OF COOL-DOWN BEHAVIOR

EXPERIMENTAL SET-UP

For the current study, the experiments were performed on an engine test bench, using a PSA DW12 2.2ℓ displacement engine. The variables which were recorded throughout the experiments were:

- temperatures in the monolith
- gas temperature upstream and downstream of the catalyst

The catalyst used for the first series of experiments is a Diesel Oxidation Catalyst, with cordierite monolith of dimensions 76×144mm (length × diameter), cell density equal to 400cps and wall thickness equal to 0.15mm.

Twelve K-type thermocouples of 0.5mm diameter are placed inside the catalyst, as shown in [Figure 3](#), at 3 points along the axis (0, 38 and 76mm) and 4 different radii for each axial position (0, 23, 45 and 66mm).

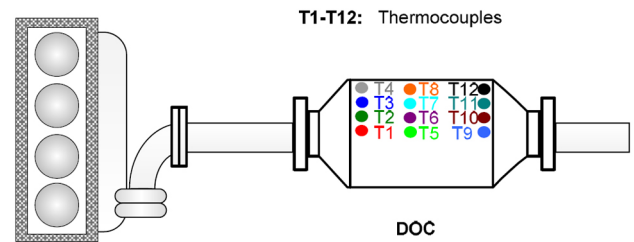


Figure 3. Experimental system set-up for DOC and thermocouple locations.

RESULTS AND MODEL VALIDATION

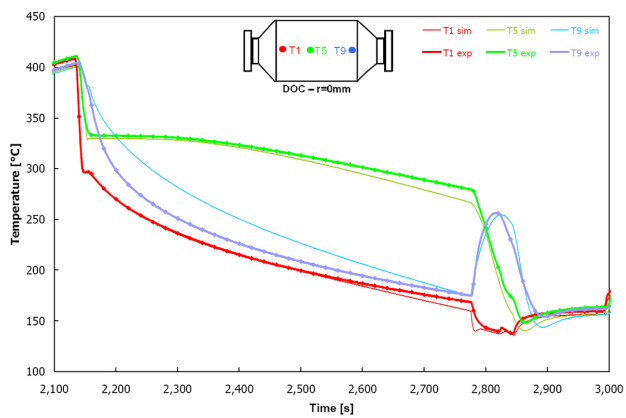
The following pictures ([Figure 4](#) and [Figure 5](#)) show the comparison graphs between the numerical and experimental data for along both the axis and the radius of the monolith. [Figure 4](#) captures the gas temperature along the axis for four different radial positions, (a) center of the DOC - (d) periphery, during a ten minutes shut-off of the engine. At the moment t=2135s the engine shuts off and the monolith cools down under zero flow mode for ten minutes. At the moment t=2778s the engine restarts, having a short period of idle for some seconds, before it operates under load again.

In [Figure 5](#) the measured and calculated temperature fields of the DOC are presented at the X-Y plane in the middle of the monolith. The three first pairs of pictures are taken for the moments 2150s (immediately after the engine shut-off), 2400s and 2700s, when the engine is off and the DOC is cooling down under zero-flow mode. The fourth pair of pictures shows the moment 2820s when the engine restarts after the cooling-down period.

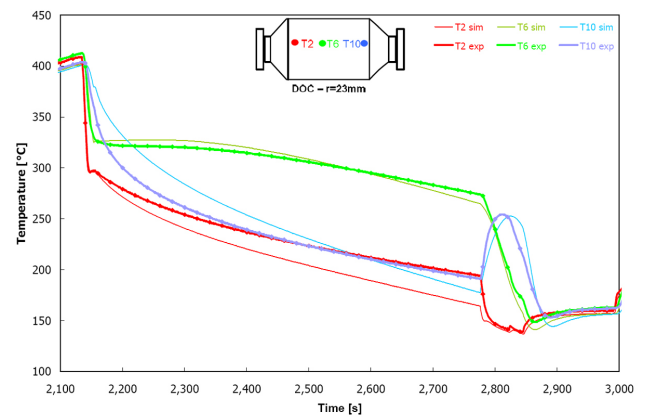
In order to highlight the importance of the heat losses calculation under zero flow, the respective results about the temperature prediction for the case of a simulation with adiabatic front and rear catalyst faces are shown in the right column of [Figure 5](#). It is obvious that the cooling of the monolith when the engine is shut-off is underestimated, since the heat losses are not taken into account in the adiabatic model.

The agreement between the numerical simulation and the experimental results is very good for all the axial and radial positions, both while the engine is on and during the near-zero mass flow condition of the shut-off engine.

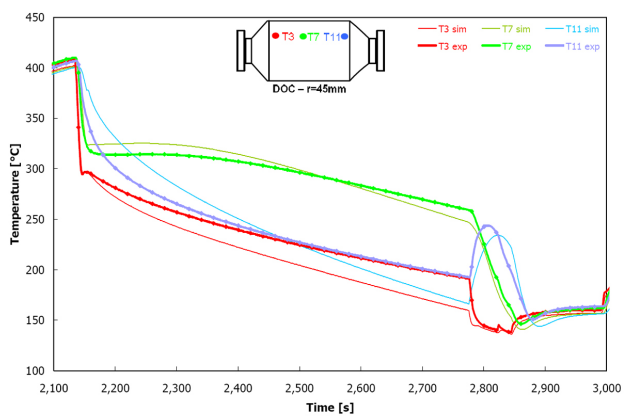
From the above results it can be concluded that the calculation of the natural convection when the engine is shut-off substantially affects the accuracy of the temperature prediction. The experimental results of this work as well as the corresponding developed submodel are expected to allow more precise prediction of emissions from the engines of hybrid vehicles in the future.



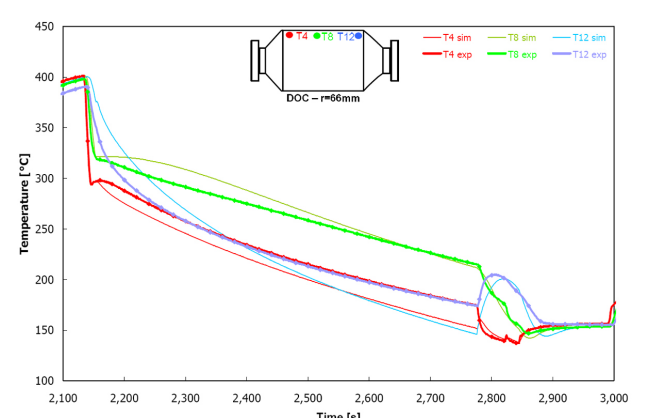
(a)



(b)



(c)



(d)

Figure 4. Catalytic converter temperature along axis vs. time for four different radial positions (shut-off of 10 minutes).

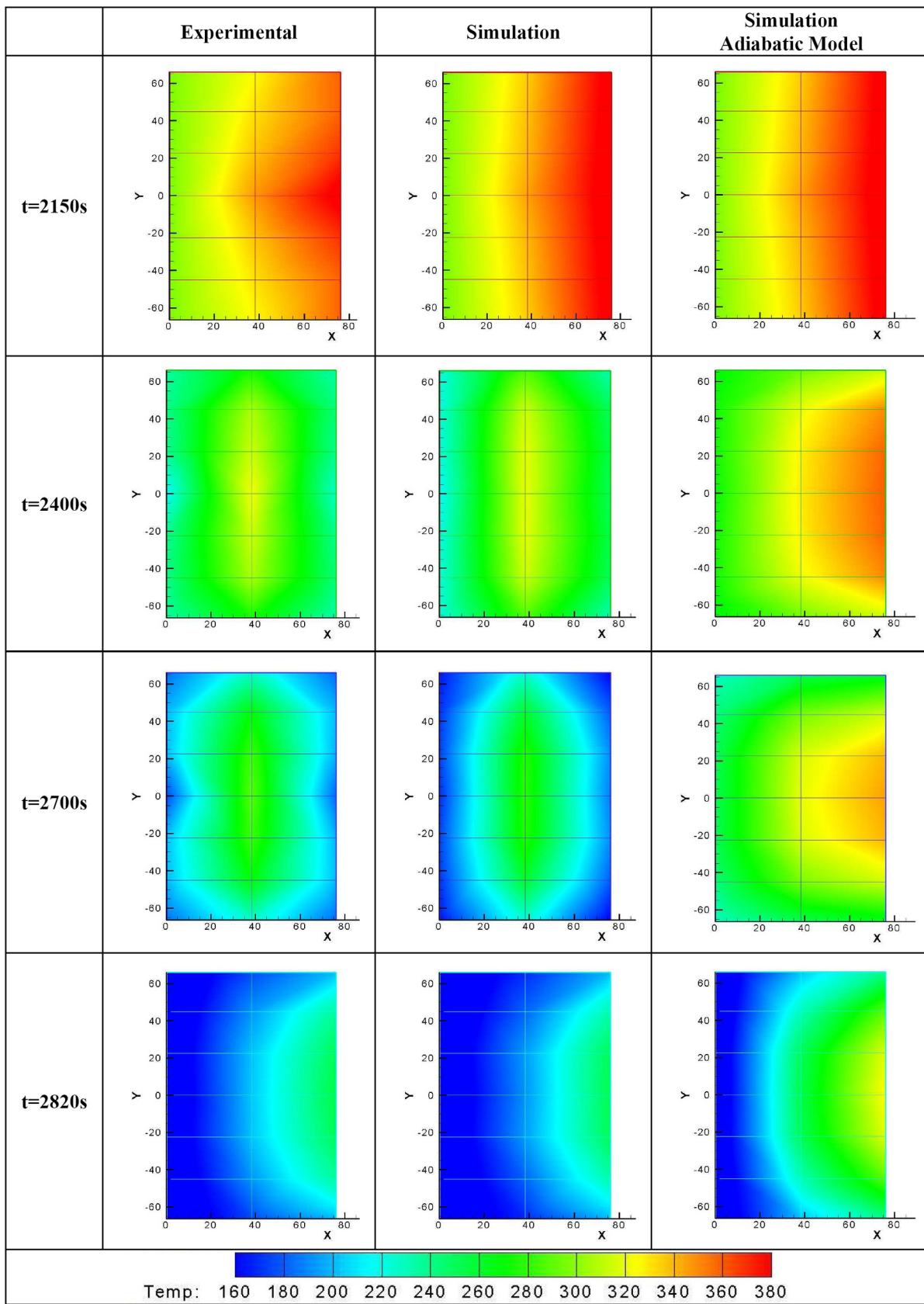


Figure 5. Catalytic converter temperature field [°C] for four different moments.