

Physico-Chemical Modeling of an Integrated SCR on DPF (SCR/DPF) System

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ABSTRACT

A physico-chemical model of a Cu-zeolite SCR/DPF-system involving NH_3 storage and SCR reactions as well as soot oxidation reactions with NO_2 has been developed and validated based on fundamental experimental investigations on synthetic gas test bench. The goal of the work was the quantitative modeling of NO_x and NH_3 tailpipe emissions in transient test cycles in order to use the model for concept design analysis and the development of control strategies. Another focus was put on the impact of soot on SCR/DPF systems. In temperature programmed desorption experiments, soot-loaded SCR/DPF filters showed a higher NH_3 storage capacity compared to soot-free samples. The measured effect was small, but could affect the NH_3 slip in vehicle applications. A bimodal desorption characteristic was measured for different adsorption temperatures and heating rates. Therefore, a multiple-site NH_3 adsorption and desorption model was implemented which proved to be in good agreement with the experimental findings. In steady-state NO_x conversion experiments for NO_2/NO_x ratios up to 50%, the SCR reactivity was unaffected by the soot loading under the applied test conditions reaching full conversion for a large temperature range. For even higher NO_2/NO_x ratios, an increase in NO_x conversion efficiency was detected for temperatures up to 250 °C for soot-loaded filters. An extended SCR reaction mechanism involving reactions on two active sites, NH_4NO_3 formation and the inhibition by surface nitrate species was calibrated. The model was validated with NEDC data showing high model quality for both, NO_x and NH_3 slip prediction. The same parameter set, derived from synthetic gas experiments, was used and an additional water adsorption model was calibrated. The transferability of the kinetics to real exhaust conditions was confirmed by supplementary simulations of FTP75 and US06 data. The promoting soot effect on NO_x conversion was further investigated by modeling, resolving the local reaction of NO_2 in the soot layer and the change in the SCR stoichiometry.

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INTRODUCTION

The high demand for emissions reduction resulting from ever tightening emission legislation on the one hand, and the increasing competition between different powertrain concepts for high fuel efficiency on the other, call for the application of active exhaust after-treatment measures in future Diesel passenger car concepts. The specific layout of the most suitable aftertreatment system is time-consuming due to the huge variety of vehicle concepts, the increasing complexity of powertrain architectures and the strong need for cost-reduction. The two established technologies for the reduction of nitrogen oxides (NO_x), selective catalytic reduction (SCR) and the lean NO_x trap (LNT), have both proven their applicability in standard production to meet NO_x emission

requirements. Furthermore, in combination with low NO_x engine measures such as multiple path exhaust gas recirculation (MP-EGR), the additional NO_x reduction potential in the exhaust system could be used to recalibrate the engine towards lower CO_2 emissions or to downsize the exhaust aftertreatment system [9, 28]. For the multi-dimensional trade-off between catalyst performance, efficiency and system costs, the integration of different exhaust aftertreatment components such as the integration of the SCR washcoat into the particle filter (SCR/DPF), can be seen as one possible solution. To systematically assess and compare different exhaust aftertreatment systems in terms of performance, interactions, critical states and calibration effects, exhaust aftertreatment simulation is a powerful tool that is used throughout the whole development process.



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Starting from experimental characterization, a physico-chemical model is developed and validated. This model can then be efficiently applied in the concept phase either for design and layout comparisons or for detailed investigations of 3D effects, e.g. non-uniform flow distribution. By deriving physical real-time models, operation and control strategies are evaluated and the functional development process is supported early on in the design process, reducing calibration efforts and hardware tests [29].

The focus of this work is the development and validation of a physico-chemical model for an SCR/DPF system based on global kinetic modeling. Fundamental kinetic investigations on a synthetic gas bench (SGB) are presented which are used for the derivation of reaction mechanisms and parameters. The impact of soot on NH_3 storage and NO_x conversion is analyzed extensively discussing the role of NO_2 in the SCR/DPF operation. In a validation step, the model is tested under transient conditions on an engine test bench (ETB).

FUNDAMENTALS

PHENOMENOLOGICAL ASPECTS OF SCR/DPF SYSTEMS

The SCR/DPF is a combined, cost-efficient NO_x /soot reduction technology, addressing the need for high catalytic activity at low exhaust temperatures alongside high fuel and DPF regeneration efficiency. It is based on the SCR technology with Ammonia (NH_3) as reductant which has been studied extensively for passenger car applications regarding, for example, reaction kinetics and NH_3 storage [12, 16]. In order to apply a SCR functionality onto a DPF substrate, washcoat loadings need to be reduced to avoid excessive exhaust back pressure [7]. Hence, the risk of reductant slip or the impact of filtered material such as soot or ash on the NO_x conversion efficiency is increasing compared to flow-through SCR applications [1, 2]. In addition, particle numbers are introduced into legislation as a further requirement. Due to its low NO_2 sensitivity, the Cu-zeolite technology provides a high potential for SCR/DPF applications [8]. Experimental studies have been dedicated to the assessment of NO_x conversion efficiency of SCR/DPF systems in comparison to flow-through SCR substrates. It is reported for laboratory and engine testing on Cu-zeolites that, depending on the washcoat loading, similar NO_x conversion efficiencies can be reached with soot-free SCR/DPF systems [2, 7]. For back pressure optimization, highly porous substrate materials have been tested, but the optimum trade-off between NO_x conversion efficiency and back pressure penalty has to be defined for any specific exhaust system [2, 5]. For highly soot-loaded filters (> 8 g/l), a negative impact on NO_x conversion efficiency is reported from laboratory light-off testing for different zeolite-based technologies and different NO_2/NO_x ratios [6]. This is mainly explained by

soot inhibition blocking the active sites since the maximum NO_x conversion efficiency is reestablished after thermal regeneration. Light-off experiments for a Cu-based technology with 5 g/l soot loading have also been conducted in preliminary work [28]. The results highlight the role of nitrogen dioxide (NO_2) in soot-loaded SCR/DPF applications and the impact of passive soot regeneration by NO_2 on the local NO_2/NO_x ratio, as shown in Figure 1.

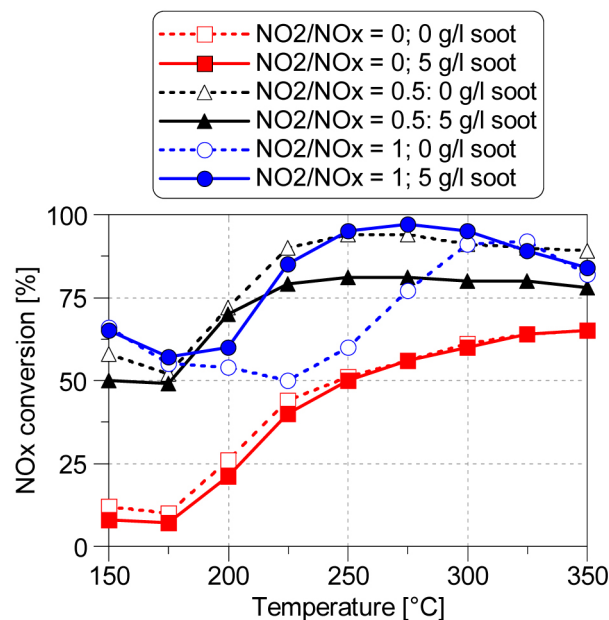


Figure 1. Light-off experiments with a Cu-zeolite SCR/DPF technology; Comparison of soot-free and soot-loaded filter for different NO_2/NO_x ratios in temperature programmed reaction experiments

For low NO_2/NO_x ratios, no inhibition effect on NO_x conversion efficiency has been found, whereas for $\text{NO}_2/\text{NO}_x = 0.5$ the soot-loaded filter shows reduced activity. This has also been reported by other authors, who have seen a minor impact on NO_x conversion efficiency for soot loadings up to 5 g/l in engine testing [2]. For high NO_2/NO_x ratios, an increase in NO_x conversion efficiency has been observed in presence of soot loading. This was related to the passive regeneration activity in the soot layer, reducing the NO_2/NO_x ratio in the filter and changing the SCR reaction pathways.

The different regeneration behavior of SCR/DPF systems and its control is also discussed in literature as an important aspect. In different ageing experiments, the thermal durability of a Cu-zeolite has been tested [11]. For this purpose, a “never to exceed” temperature has been introduced, at which the catalyst activity strongly decreases. This activity loss has also been correlated to the reduced BET surface of the washcoat. For passive regeneration experiments, an increased rate of soot oxidation has been found compared to uncoated filters, suggesting a reoxidation of NO to NO_2 by the washcoat [10]. During soot oxidation experiments with O_2 ,

due to the lack of platinum group metals (PGM) in the washcoat, higher CO emissions have been measured [6].

SCR ON ZEOLITE-BASED CATALYSTS

There are a few publications about SCR/DPF modeling. Koltsakis and his coworkers presented a simulation based conceptual study, comparing SCR/DPF systems with flow-through SCR catalysts by virtually transferring existing SCR kinetic models into the wall of a DPF [3]. The same group also virtually combined existing submodels for NO_x conversion and passive soot oxidation to setup an SCR/DPF model without further experimental investigations [4]. The effect of soot on NO_x conversion and the impact of the SCR/DPF washcoat on the CRT[®] effect were investigated discussing the role of the local NO₂/NO_x ratio for the deNO_x performance. However, there is little to be found about validated models based on synthetic gas and engine test bench data with SCR/DPF samples that can be applied both for deNO_x performance with and without soot loading and soot regeneration behavior in transient operation.

There are a large number of articles discussing reaction mechanisms and modeling approaches for SCR catalysts, both on a micro and macro kinetic scale. The selective reduction of NO and NO₂ with NH₃ to N₂ and H₂O on vanadium-based catalysts has been studied extensively by Koebel and coworkers, revealing the role of NO₂/NO_x ratio for the SCR reaction rate [12,15]. The formation of ammonium nitrate (NH₄NO₃) at low temperatures and the role of ammonium nitrite (NH₄NO₂) as an important reaction intermediate is also discussed here. The group proposed that after the dimerization of NO₂ to N₂O₄, a disproportion reaction with H₂O to form nitrous (HNO₂) and nitric (HNO₃) acid occurs. This reaction is then followed by the reaction with NH₃ yielding NH₄NO₃ and NH₄NO₂ [12,15]. Since an increasing number of SCR catalysts in automotive applications are ion-exchanged zeolite-based catalysts, the established reaction mechanisms have been transferred by the same group for Fe-ZSM5 zeolites and the contribution of specific reaction pathways have been analyzed [13,14]. In the absence of NO₂, the NO oxidation activity of the metal sites is commonly accepted as the rate determining step in the SCR reaction, forming NO₂ on the catalyst surface. A major step is then seen in the reaction of adsorbed NO₂ with adsorbed NH₃ forming NH₄NO₃- and NH₄NO₂-species, where the latter decompose to the main products of the SCR reaction N₂ and H₂O [18,20]. The highest SCR reaction rate for a NO₂/NO_x ratio of 0.5 is explained by the reduction of the surface nitrate species by NO forming NH₄NO₂, which decomposes in the described manner [12]. There are several side reactions and by-products reported for zeolite catalysts, such as the formation of N₂O resulting from NH₄NO₃ decomposition, or the NH₃ oxidation with O₂ or NO₂ [15]. The selectivity of the

SCR catalyst depends on its oxidation activity, temperature and feed gas composition.

Global kinetic models of zeolite-based SCR catalysts have been proposed by numerous authors, e.g. Schuler and Chatterjee taking into account NH₃ storage and NO_x conversion for different NO₂/NO_x ratios in steady state and transient operating conditions [19,22]. Furthermore, the modeling of NH₃ inhibition in Standard SCR reaction and the development of reaction rate expressions for SCR side reactions are presented. The global SCR reaction with NO₂ is used widely, although its stoichiometry is not experimentally confirmed for a large temperature range [13]. More detailed models taking into account the nitrite and nitrate formation on the catalyst surface have been presented, e.g. that by Sjövall et al. whose goal was to cover the full temperature and space velocity (SV) range of an Fe-zeolite in a Diesel application [21].

PASSIVE REGENERATION ON DPF

For the soot impact on NO_x conversion, a DPF model simulating soot filtration and soot oxidation by O₂ and NO₂, referred to as passive regeneration, is needed. There is a whole range of models for soot deposition and soot oxidation in monolithic substrates, as in [23,25]. Koltsakis and his coworkers have developed a detailed model calculating pressure drop and soot accumulation in DPF systems, taking into account deep pore filtration and cake formation in the inlet channels. Also, the regeneration behavior with O₂ for catalyzed DPF systems has been analyzed extensively according to temperature distributions, carbonaceous emissions and material strain, with the onset of soot oxidation by O₂ reported at T = 550 °C [5,25]. The passive regeneration regime which becomes important for filter operation at exhaust temperatures of T > 200 °C has been studied, for example, by Jacquot and coworkers [26]. The group developed a phenomenological model for soot oxidation by NO₂, based upon fixed-bed reactor experiments with carbon black, in which the impact of H₂O and O₂ on soot burning rates was investigated. They found an increase of soot reactivity with O₂, which they attributed to the direct reaction of O₂ with soot-NO₂ intermediates. They also noted a catalytic effect of H₂O. Wenninger et al. experimentally validated the model for wall-flow filters [27].

METHODOLOGY

SYNTHETIC GAS EXPERIMENTS

Two filter types have been tested on a synthetic gas test bench: A bare Silicon Carbide (SiC) filter without washcoat (Filter A) and a Cu-zeolite technology coated on the same filter material (Filter B). The specifications for the bare filter are listed in [Table 1](#).

Table 1. Filter specifications

Specifications	Filter A / B
Filter material	SiC
Length [mm]	152
Width / Height [mm]	17 / 17
Cell density [cpsi]	300
Wall thickness [mIn]	12
Material porosity [%]	58
Mean pore size [μm]	22
Catalytic coating [-]	uncoated / Cu-zeolite
Degreening	2hrs@600 °C

By the use of mass flow controllers, various synthetic gas mixes are produced out of separate stores. Liquid components, such as water, are added by evaporators to the feed gas, creating total flow volume rates from 5 to 30 l/min. The gas mixtures are fed into a quartz glass tube inside the reactor in which the monolithic samples are placed on a carrier. Both the inlet and outlet temperatures of the samples are controlled for the minimization of temperature gradients inside the test samples. All gas containing lines are heated and the feed gas composition is measured via a bypass of the reactor. For the detection of the outlet gas concentrations, different analyzers are used: A Fourier Transform Infrared Spectrometer (FTIR) for CO, NO, NO₂ and NH₃ emissions; a Non Dispersive Infrared Detector (NDIR) for CO and CO₂ emissions; a Flame Ionization Detector (FID) for total hydrocarbon emissions; a Paramagnetic Analyzer (PMA) for O₂ emissions. The different test conditions are summarized in [Table 2](#) and a short description of the experimental procedures is given below:

Temperature Programmed Desorption (TPD)

After stabilizing the temperature with feed gas containing H₂O and N₂, the filter is exposed to 250 ppm NH₃ until the inlet concentration equals the outlet concentration (equilibrium). Then NH₃ dosing is switched-off and the temperature is increased until no more NH₃ is detected. The integrated NH₃ desorption signal is used to estimate NH₃ storage capacity.

Steady-State NO_x Conversion

After stabilizing the temperature with feed gas containing H₂O, O₂ and N₂, the sample is conditioned with feed gas containing 200 ppm NO_x until equilibrium is reached. Then NH₃ is added with NH₃/NO_x = 1.25 until NH₃ slip and NO_x conversion are stabilized. Finally, NH₃ dosing is switched-off and the reaction of the stored NH₃ with 200 ppm NO_x feed is detected. The experiments are conducted at different temperatures, NO₂/NO_x ratios and space velocities (SV). In a

different experimental routine, the stabilized sample is first saturated with NH₃ and then NO_x is dosed with varying NO₂/NO_x ratios for a fixed time duration.

NH₃ and NO Oxidation / TPR

After stabilizing the temperature with feed gas containing H₂O and N₂, the filter is exposed to 250 ppm NH₃ until the inlet concentration equals the outlet concentration. Then NH₃ dosing is switched-off and a temperature programmed reaction (TPR) is realized by increasing the temperature until 650 °C. For NO oxidation experiments, a TPR is realized with NO, O₂, H₂O and N₂ in the feed gas.

Soot Reactivity

After stabilizing the temperature with feed gas containing N₂, 500 ppm NO₂ with different O₂ and H₂O concentrations is added and the soot burning rate is measured for a duration of one hour by the detection of CO and CO₂. Then, NO₂ dosing is switched-off and a TPR is realized until 750 °C with O₂ in the feed gas. The experiment is stopped when no more CO and CO₂ are detected at the outlet. This is defined as complete regeneration of the filter. The total amount of burnt soot is calculated by an integral carbon species balance. The samples are also weighed and the result is compared to the burnt soot estimate. The soot loading procedure on ETB is further explained in the next section.

ENGINE TESTING

On engine test bench full size SCR/DPF test samples of 5.66 × 6 inch have been tested for NO_x conversion in different emission cycles: NEDC for cold start analysis, FTP75 and US06 for highly transient operating conditions. The test engine is a 4-cylinder DI- engine of the 2 l-class. It is equipped with a single-stage turbo charger of Variable Turbine Geometry (VTG), a common rail injection system and an EGR system. The exhaust line configuration consists of a closed coupled DOC and cDPF in a combined canning upstream of the NH₃ injection port. The SCR/DPF is placed downstream of a connecting pipe of 80 cm length. By this setup, a high uniformity of the NH₃ distribution and no impact of the engine-out soot emissions on the SCR/DPF soot loading is realized during the cycle testing. For the controlled soot-loading of the SCR/DPF sample, the cDPF is dismantled and the SCR/DPF is loaded with soot at a constant operation point. Prior to each validation test, a DPF regeneration is run. After system cool-down, the SCR/DPF is preconditioned with NH₃. During the test, NH₃ dosing is started at T_{inlet} = 180 °C with NH₃/NO_x = 1. The emissions are measured upstream and downstream of the SCR/DPF with an FTIR analyzer.

The engine was also used for the controlled soot loading of lab-scale test samples. A low-load engine operation point with high EGR rates was chosen for the loading experiments. Dry soot was extracted of the exhaust line downstream DOC

Table 2. Overview of experiments on synthetic gas test bench for SCR/DPF characterization

Experiment	Feed gas composition	Tested samples	Temperature	Soot load	SV
NH ₃ adsorption / TPD	250 ppm NH ₃ , 5% H ₂ O	Filter A Filter B	150 / 200 / 250 °C heat-up to 600 °C	0 / 2.5 / 9 g/l	20k h ⁻¹
Steady-state NO _x conversion	250 ppm NH ₃ , 200 ppm NO _x , 8% O ₂ , 5% H ₂ O with NO ₂ /NO _x = 0 / 0.25 / 0.5 / 0.75 / 1	Filter B	150 / 175 / 200 / 225 / 250 / 300 °C	0 / 2.5 / 5 g/l	20k / 40k h ⁻¹
NH ₃ oxidation / TPR	250 ppm NH ₃ , 8% O ₂ , 5% H ₂ O	Filter B	150 to 600 °C	0 g/l	20k h ⁻¹
NO oxidation / TPR	200 ppm NO, 8% O ₂ , 5% H ₂ O	Filter B	150 to 600 °C	0 g/l	20k h ⁻¹
Passive regeneration with NO ₂ at constant temperature	250 / 500 ppm NO ₂ , 0 / 2 / 8% O ₂ , 0 / 2 / 8% H ₂ O	Filter A Filter B	250 / 350 / 400 °C	0 / 2.5 / 8 g/l	20k h ⁻¹
Active soot regeneration with O ₂ in temperature programmed reaction	250 / 500 ppm NO ₂ , 0 / 2 / 8% O ₂ , 0 / 2 / 8% H ₂ O	Filter A Filter B	250 / 350 / 400 °C to 750 °C	0 / 2.5 / 8 g/l	20k h ⁻¹

by the use of a pumping unit. With this methodology the impact of soot on NO_x conversion or NH₃ storage as well as engine specific soot oxidation kinetics were analyzed.

MODELING APPROACH

For the simulation of the physical and chemical behavior of a SCR/DPF system, the commercial software *AxiSuite*® from *Exothermia S.A.* is used. The numeric calculation of the balance equations for mass, momentum and energy for a catalytic converter and a catalyzed wall-flow DPF has been presented in [23,25]. The module *AxiTrap*® for plugged filters consists of different modeling levels taking into account the 3D heat and mass transfer into the filter, the physical transport phenomena from the gas phase to the gas-solid interfaces and the coupled intralayer reaction-diffusion phenomena in the washcoat and soot layer. For the calculation of the diffusion fluxes and the resulting rates of species formation, a “quasi-steady” approach represented by Equation 1 is used.

$$\dot{n}_j(k_{m,j}, c_{g,j}, c_{s,j}) = \sum_i s_{i,j} r_i(\bar{c}_{s,i,j}, T) \quad (1)$$

The diffusion flux of species *j* is driven by the concentration gradient between the bulk gas phase and the solid phase. The corresponding mass transfer coefficients are derived from film theory for laminar flow based on Sherwood correlations. Since the rates of the surface reactions involving species *j* are equal to the diffusive mass transfer to the surface, there is no accumulation of species *j* on the surface. The reaction rates, *r_i*, in Equation 1 are generally modeled as non-linear functions of species concentrations, specific reaction orders, a kinetic rate constant, *k_i*, and inhibition terms, *G_i*, accounting for the species interactions. In Equation 2, the general rate expression is given for a reaction involving both, adsorbed and gas phase species.

$$r_i = \frac{k_i \prod_k \psi_k^{a_k} \prod_l P_l^{b_l}}{G_i} \quad (2)$$

The rate constant, *k_i*, is modeled as an Arrhenius type expression, describing the temperature sensitivity of the reaction (Equation 3).

$$k_i = A_i \exp(-E_{A,i} / RT) \quad (3)$$

For the SCR/DPF model different global-kinetic reaction rates are used, as listed in the Appendix. Both, Eley-Rideal type reactions with one adsorbed species and Langmuir-Hinshelwood type reactions with two gas phase components are applied. Furthermore, a multiple site NH₃ adsorption model, based on kinetic expressions, and a Dubinin-Radushkevich model for water adsorption on zeolites, as presented in [24], is calibrated.

EXPERIMENTAL RESULTS

NH₃ STORAGE

The results for the TPD experiments with filter B are shown in Figure 2 for different adsorption temperatures (150 °C, 175 °C, 200 °C) and heating rates (dT/dt = 15 °C/min, dT/dt = 5 °C/min). After the start of NH₃ dosing, NH₃ is first adsorbed completely on the washcoat for all adsorption temperatures. Also, the NH₃ slip characteristics are similar for all tests showing a steep NH₃ gradient. The gradient diminishes when NH₃ concentration reaches ~75% of the dosed NH₃ value. The following, slower dynamics of NH₃ saturation shows an asymptotic characteristic. It can be seen in Figure 2b, that the adsorption and desorption kinetics of the saturated filter are highly temperature sensitive since the NH₃ signal oscillates. This is caused by only minor variations of the inlet temperature of ~ 2 °C.

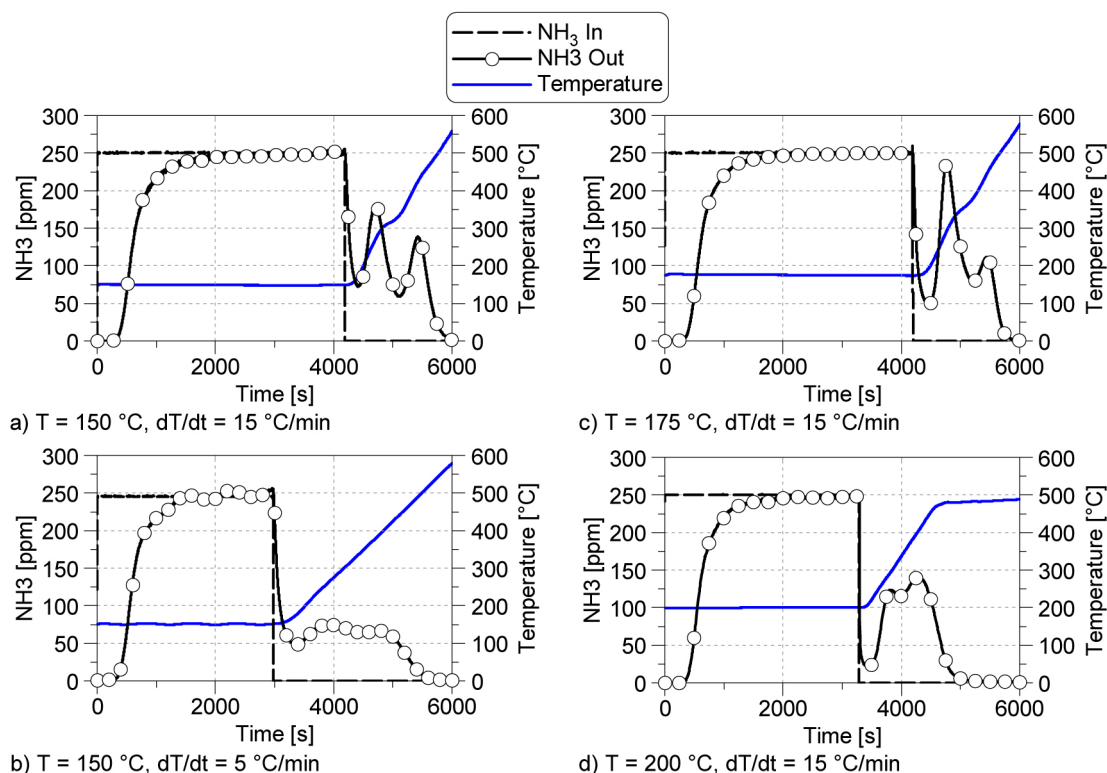


Figure 2. NH_3 adsorption and desorption experiments for soot-free filter B with 250 ppm NH_3 with a) $T = 150\text{ }^\circ\text{C}$; $dT/dt = 15\text{ }^\circ\text{C/min}$, b) $T = 150\text{ }^\circ\text{C}$; $dT/dt = 5\text{ }^\circ\text{C/min}$, c) $T = 175\text{ }^\circ\text{C}$; $dT/dt = 15\text{ }^\circ\text{C/min}$ and d) $T = 200\text{ }^\circ\text{C}$; $dT/dt = 15\text{ }^\circ\text{C/min}$

The desorption signals of all tests show two distinct peaks located at about 250 - 300 °C and 400 - 450 °C, suggesting multiple storage sites with different energy levels for the NH_3 storage. The slow heating rate of 5 °C/min also results in two different peaks, albeit with lower amplitudes. Due to the temperature control of the reactor, there is a temporary decrease of the heating rate observed for experiments 2a and 2c. This could also effect the time characteristic of the desorption signal by reducing the amplitude of the first peak. Therefore, a correlation between the adsorption temperature and hence the adsorbed amount of NH_3 and the amplitude of the NH_3 desorption signals can not be established.

Kröcher has reported similar bimodal characteristics for Fe-zeolites in TPD experiments, assuming weakly bond ammonia on acid Lewis sites and strongly chemisorbed ammonia on Brønsted sites. The desorption temperatures were located at 220 °C and 450 °C [13], which is in the observed temperature range. There has been a third desorption temperature described by the same group at $T = 140\text{ }^\circ\text{C}$ for weakly bond NH_3 on Lewis sites or in the zeolite structure of the washcoat. Since SCR activity is considered low in this temperature range this was not further assessed here.

The impact of soot on NH_3 storage was investigated using the same protocol. This was done as soot might be expected to increase the NH_3 storage capacity due to its high geometric surface area. For this purpose the total amount of stored ammonia of TPD experiments is calculated by the time integral of the NH_3 signal after dosing has been switched-off, as stated in Equation 4.

$$m_{\text{NH}_3} = \int_{t_{\text{NH}_3, \text{off}}}^{t_{\text{end}}} \left(c_{\text{NH}_3} \frac{M_{\text{NH}_3}}{M_{\text{Feed}}} \dot{m}_{\text{Feed}} \right) dt \quad (4)$$

In Figure 3, the results for NH_3 storage capacity are depicted as a function of temperature for filter A and B, with and without soot. Filter A shows very little NH_3 storage for the soot-free sample. The stored NH_3 slightly decreases with increasing adsorption temperature. With a soot loading of 2.5 g/l, a minor increase in NH_3 storage capacity for filter A at $T = 150\text{ }^\circ\text{C}$ can be observed. For higher temperatures, the effect cannot be resolved with the applied method. The results suggest that NH_3 does hardly adsorb on Diesel engine soot on bare filters. The soot-free filter B shows the typical monotonic temperature dependence for zeolite based SCR catalysts. The maximum NH_3 storage capacity of 0.75 g/l at $T = 150\text{ }^\circ\text{C}$ is lower compared to flow through substrates described in literature [17]. This might be related to reduced washcoat loading in the filter with. Furthermore, the