Experimental and kinetic studies of \( \text{H}_2 \) effect on lean exhaust aftertreatment processes: HC-SCR and DOC

MUHAMMAD MUFTI AZIS

Department of Chemistry and Chemical Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015
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Muhammad Mufti Azis
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Cover: The picture illustrates the concept of utilizing H₂ to improve DOC and HC-SCR performances on lean exhaust aftertreatment processes.

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Abstract
With a growing concern to lower greenhouse gas emissions from road transportation, lean burn and diesel engines will keep playing an important role in the future. Development of a highly efficient and durable process to reduce NO\textsubscript{x} to N\textsubscript{2} becomes a challenging issue especially in the presence of ample O\textsubscript{2} concentration as in lean burn exhaust. One way to reduce NO\textsubscript{x} emissions in lean exhaust is by using hydrocarbon-selective catalytic reduction (HC-SCR). HC-SCR over Ag/Al\textsubscript{2}O\textsubscript{3} catalysts appears to be a promising technology to abate NO\textsubscript{x} emission in lean burn exhaust. The function of the Diesel oxidation catalyst (DOC), as a part of a lean exhaust aftertreatment process, is to oxidize CO, HC and NO. Interestingly, addition of H\textsubscript{2} has been shown to promote the HC-SCR activity over Ag/Al\textsubscript{2}O\textsubscript{3} and NO oxidation activity over Pt/Al\textsubscript{2}O\textsubscript{3} catalyst.

The overall focus of this thesis was to increase understanding of the mechanisms of the H\textsubscript{2} effect on the model catalysts of Ag-Al\textsubscript{2}O\textsubscript{3} and Pt/Al\textsubscript{2}O\textsubscript{3}. A combination of experimental and kinetic modeling approaches was utilized as a way to examine mechanistic effects of H\textsubscript{2}.

Temperature-programmed desorption (TPD) technique was used to characterize thermal stabilities of various surface NO\textsubscript{x} species formed during NO oxidation and C\textsubscript{3}H\textsubscript{6}-SCR conditions over Ag/Al\textsubscript{2}O\textsubscript{3} catalyst. In addition, DRIFTS analysis was used to identify different types of nitrate species. These TPD results elucidated the dual roles of H\textsubscript{2} to remove inhibiting nitrate on active sites and facilitate formation of inactive nitrate species mainly on the Al\textsubscript{2}O\textsubscript{3} support.

An initial development of a microkinetic model to describe H\textsubscript{2}-assisted NO oxidation over Ag/Al\textsubscript{2}O\textsubscript{3} was conducted using a set of transient data. The single role of H\textsubscript{2} to remove inhibiting nitrate species on active sites was examined. In the further model development, a global kinetic model of H\textsubscript{2}-assisted C\textsubscript{3}H\textsubscript{6}-SCR, including NO oxidation, C\textsubscript{3}H\textsubscript{6} oxidation and C\textsubscript{3}H\textsubscript{6}-SCR in the presence and absence of H\textsubscript{2}, was proposed. This model was based on dual roles of H\textsubscript{2} to remove inhibiting nitrates from active sites and simultaneously form more active Ag sites. The model could effectively capture a wide range of feed concentrations and temperatures, including temperature-programmed and transient experiments.

The influence of H\textsubscript{2} on NO oxidation over Pt/Al\textsubscript{2}O\textsubscript{3} as a DOC catalyst was evaluated with various feed mixtures. Formation of Pt oxide has been known to lower the NO oxidation activity over Pt/Al\textsubscript{2}O\textsubscript{3}. The role of H\textsubscript{2} to retard the Pt oxide formation was investigated. This resulted in a temporal enhancement in NO\textsubscript{2} yield due to H\textsubscript{2} addition during temperature ramp experiments. In addition, the effect of C\textsubscript{3}H\textsubscript{6} and CO to influence the NO oxidation was also investigated. Addition of H\textsubscript{2} mainly serves to weaken the inhibition effect of C\textsubscript{3}H\textsubscript{6} and to a much lesser degree CO. This is mainly due to an enhancement of lower temperature C\textsubscript{3}H\textsubscript{6} oxidation. The promotional effects of H\textsubscript{2} to increase NO\textsubscript{2} yield was proposed as a result of effects of H\textsubscript{2} on surface chemistry and/or reactions. These effects could be clearly distinguished from exothermal heat effects from mainly H\textsubscript{2} but also C\textsubscript{3}H\textsubscript{6} and CO oxidation.

Keywords: HC-SCR, DOC, Silver Alumina, Platinum Alumina, Hydrogen effect, Kinetic modeling, NO\textsubscript{x} reduction, NO oxidation.
List of Appended Papers

This thesis is based on the work presented in the following papers:

I. **On the role of H\textsubscript{2} to modify surface NO\textsubscript{x} species over Ag-Al\textsubscript{2}O\textsubscript{3} as lean NO\textsubscript{x} reduction catalyst: TPD and DRIFTS studies**
Muhammad Mufti Azis, Hanna Härelind, Derek Creaser
*Catalysis Science & Technology, 5, 2015, 296-309.*

II. **Microkinetic modeling of H\textsubscript{2}-assisted NO oxidation over Ag-Al\textsubscript{2}O\textsubscript{3}**
Muhammad Mufti Azis, Hanna Härelind, Derek Creaser
*Chemical Engineering Journal, 221, 2013, 382-397.*

III. **Kinetic modeling of H\textsubscript{2}-assisted C\textsubscript{3}H\textsubscript{6} selective catalytic reduction of NO over silver alumina catalyst**
Muhammad Mufti Azis, Hanna Härelind, Derek Creaser
*Chemical Engineering Journal, DOI:10.1016/j.cej.2014.10.057*

IV. **Evaluation of H\textsubscript{2} effect on NO oxidation over a Diesel Oxidation Catalyst**
Muhammad Mufti Azis, Xavier Auvray, Louise Olsson, Derek Creaser
*submitted*

Other publications not included in this thesis:

I. **On the evaluation of synthetic and natural ilmenite using syngas as fuel in chemical-looping combustion (CLC)**
Muhammad Mufti Azis, Erik Jerndal, Henrik Leion, Tobias Mattisson, Anders Lyngfelt
*Chemical Engineering Research and Design, 88(11), 2010, 1505-1514.*

II. **The Effect of Bituminous and Lignite Ash on the Performance of Ilmenite as Oxygen Carrier in Chemical-Looping Combustion**
Muhammad Mufti Azis, Henrik Leion, Erik Jerndal, Britt-Marie Steenari, Tobias Mattisson, Anders Lyngfelt
*Chemical Engineering & Technology, 36(9), 2013,1460-1468.*
Contribution report

**Paper I**

I partially prepared the catalyst, performed flow reactor and DRIFTS experiments, interpreted the results together with my coworkers and was responsible for writing the manuscript.

**Paper II**

I prepared the catalyst, performed flow reactor experiments, performed modeling, interpreted the results together with my coworkers and was responsible for writing and submitting the manuscript.

**Paper III**

I prepared the catalyst, performed flow reactor experiments, performed modeling, interpreted the results together with my coworkers and was responsible for writing and submitting the manuscript.

**Paper IV**

I performed flow reactor experiments, interpreted the results together with my coworkers and was responsible for writing the manuscript.
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<th>Description</th>
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<tbody>
<tr>
<td>AIP</td>
<td>Aluminium isopropoxide</td>
</tr>
<tr>
<td>APU</td>
<td>Auxiliary power unit</td>
</tr>
<tr>
<td>ATR</td>
<td>Autothermal reformer</td>
</tr>
<tr>
<td>BET</td>
<td>Brunauer–Emmett–Teller</td>
</tr>
<tr>
<td>BOC</td>
<td>Bond-order conservation</td>
</tr>
<tr>
<td>CPSI</td>
<td>Cells per square inch</td>
</tr>
<tr>
<td>DAE</td>
<td>Differential algebraic equations</td>
</tr>
<tr>
<td>DFT</td>
<td>Density functional theory</td>
</tr>
<tr>
<td>DOC</td>
<td>Diesel oxidation catalyst</td>
</tr>
<tr>
<td>DOE</td>
<td>Design of experiment</td>
</tr>
<tr>
<td>DME</td>
<td>Dimethyl ether</td>
</tr>
<tr>
<td>DPF</td>
<td>Diesel particulate filter</td>
</tr>
<tr>
<td>DRIFTS</td>
<td>Diffuse reflectance infrared Fourier transform spectroscopy</td>
</tr>
<tr>
<td>E85</td>
<td>Ethanol fuel blend of 85% denatured ethanol fuel and 15% gasoline</td>
</tr>
<tr>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
</tr>
<tr>
<td>FTIR</td>
<td>Fourier transform infrared</td>
</tr>
<tr>
<td>FTP</td>
<td>Federal test procedure</td>
</tr>
<tr>
<td>GHSV</td>
<td>Gas hourly space velocity</td>
</tr>
<tr>
<td>HC</td>
<td>Hydrocarbon</td>
</tr>
<tr>
<td>HT</td>
<td>High temperature</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>LNT</td>
<td>Lean NO\textsubscript{x} trap</td>
</tr>
<tr>
<td>LT</td>
<td>Low temperature</td>
</tr>
<tr>
<td>MLR</td>
<td>Multi-linear regression</td>
</tr>
<tr>
<td>MS</td>
<td>Mass spectrometer</td>
</tr>
<tr>
<td>NSR</td>
<td>NO\textsubscript{x} storage and reduction</td>
</tr>
<tr>
<td>PGM</td>
<td>Platinum group metal</td>
</tr>
<tr>
<td>SCR</td>
<td>Selective Catalytic Reduction</td>
</tr>
<tr>
<td>SSE</td>
<td>Sum of squared errors of prediction</td>
</tr>
<tr>
<td>TPD</td>
<td>Temperature-programmed desorption</td>
</tr>
<tr>
<td>TPR</td>
<td>Temperature-programmed reaction</td>
</tr>
<tr>
<td>UBI-QEP</td>
<td>The unity bond index-quadratic exponential potential</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compounds</td>
</tr>
<tr>
<td>WHSV</td>
<td>Weight hourly space velocity</td>
</tr>
</tbody>
</table>
### Nomenclature

#### Roman symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>mass and/or heat transfer area</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_i$</td>
<td>pre-exponential factor</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$C$</td>
<td>concentration</td>
<td>mol.m$^{-3}$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>heat capacity</td>
<td>J.mol$^{-1}$.K$^{-1}$</td>
</tr>
<tr>
<td>$Def_f$</td>
<td>effective diffusivity</td>
<td>m$^2$.s$^{-1}$</td>
</tr>
<tr>
<td>$E_a$</td>
<td>activation energy</td>
<td>kJ.mol$^{-1}$</td>
</tr>
<tr>
<td>$F_{tot}$</td>
<td>molar flow rate</td>
<td>mol.s$^{-1}$</td>
</tr>
<tr>
<td>$h$</td>
<td>convection heat transfer coefficient</td>
<td>J.m$^2$.mol$^{-1}$</td>
</tr>
<tr>
<td>$\Delta H_R$</td>
<td>enthalpy change of overall gas reaction</td>
<td>J.mol$^{-1}$</td>
</tr>
<tr>
<td>$k$</td>
<td>rate constant</td>
<td>s$^{-1}$</td>
</tr>
<tr>
<td>$K_{eq}$</td>
<td>equilibrium constant</td>
<td>-</td>
</tr>
<tr>
<td>$k_c$</td>
<td>mass transport coefficient</td>
<td>m.s$^{-1}$</td>
</tr>
<tr>
<td>ln(k_ref)</td>
<td>natural logarithmic of rate constant at ref. temperature</td>
<td>mol.s$^{-1}$.kg$^{-1}$</td>
</tr>
<tr>
<td>$N_c$</td>
<td>number of sites</td>
<td>mol.kg$^{-1}$</td>
</tr>
<tr>
<td>$r$</td>
<td>reaction rate</td>
<td>mol.s$^{-1}$.kg$^{-1}$</td>
</tr>
<tr>
<td>range</td>
<td>range for parameter scaling</td>
<td>-</td>
</tr>
<tr>
<td>$R$</td>
<td>gas constant</td>
<td>J.mol$^{-1}$.K$^{-1}$</td>
</tr>
<tr>
<td>$\Delta S_R$</td>
<td>entropy change of overall gas reaction</td>
<td>J.mol$^{-1}$.K$^{-1}$</td>
</tr>
<tr>
<td>$t$</td>
<td>time step</td>
<td>s</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$w$</td>
<td>mass of segmental catalyst</td>
<td>kg</td>
</tr>
<tr>
<td>$\Delta X$</td>
<td>thickness of segmental layer</td>
<td>m</td>
</tr>
<tr>
<td>$y$</td>
<td>molar fraction</td>
<td>-</td>
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</tbody>
</table>

#### Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$\beta$</td>
<td>fitted kinetic parameters</td>
<td>-</td>
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<tr>
<td>$\Gamma$</td>
<td>lumped mass transfer coefficient</td>
<td>m$^3$.s$^{-1}$</td>
</tr>
<tr>
<td>$\theta$</td>
<td>fractional surface coverage</td>
<td>-</td>
</tr>
<tr>
<td>$\nu$</td>
<td>stoichiometric coefficient</td>
<td>-</td>
</tr>
<tr>
<td>$\chi$</td>
<td>stoichiometric coefficient of adsorbed species</td>
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#### Subscript

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<thead>
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<th>Subscript</th>
<th>Description</th>
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<tr>
<td>$b$</td>
<td>backward reaction</td>
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<tr>
<td>$f$</td>
<td>forward reaction</td>
</tr>
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<td>$g$</td>
<td>gas</td>
</tr>
<tr>
<td>$i$</td>
<td>gas component index</td>
</tr>
<tr>
<td>$j$</td>
<td>reaction index</td>
</tr>
<tr>
<td>$k$</td>
<td>tank index</td>
</tr>
<tr>
<td>$n$</td>
<td>layer index</td>
</tr>
<tr>
<td>$\text{ref}$</td>
<td>reference condition</td>
</tr>
<tr>
<td>$s$</td>
<td>solid</td>
</tr>
<tr>
<td>$w$</td>
<td>surface component index</td>
</tr>
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Chapter 1

Introduction

1.1 NO\textsubscript{x} emission abatement from lean-burn engine

Improvement of urban air quality is always an important environmental issue particularly with a growing concern to create a sustainable society. Road transportation is a major contributor to urban air pollution and therefore regulations have been made in several countries to reduce emissions from road transportation such as the Clean Air Act in the US and European emission standard EURO. The major air pollutants targeted in the regulations are CO, Nitrogen oxide (NO\textsubscript{x}), Hydrocarbon and particulate matter [1]. Since global warming is also an alarming concern nowadays, very recently greenhouse gases emissions (notably CO\textsubscript{2}) from vehicles have also been regulated for light duty and heavy duty fleets [1, 2].

NO\textsubscript{x} is an interesting and important air pollutant. Its occurrence in the atmosphere is due to exhaust gas produced in combustion engines, which is the most common form of propulsion for vehicles [3]. Emission of NO\textsubscript{x} to the atmosphere has severe consequences. Firstly, NO\textsubscript{x} plays a crucial role in the acid deposition problem [4]. In the atmosphere, NO readily oxidizes to NO\textsubscript{2} (reddish brown gas) and NO\textsubscript{2} reacts further with water vapor to from nitric acid and cause acid deposition (acid rain) that damages trees, soils and lakes. Secondly, NO together with NO\textsubscript{2} are responsible for the formation of photochemical smog. Nitrogen oxides reacts with sunlight and volatile organic compounds (VOC) to form air-borne particles and ground level ozone known as photochemical smog. Smog usually occurs in large cities with sunny and warm climates packed with heavy road traffic. Photochemical smog has also serious health effects as it may cause or exacerbate respiratory related diseases [3, 4].

Most Internal combustion engines (ICE) nowadays use fossil fuel and compressed air. Since air contains 79% N\textsubscript{2}, in a highly oxidative atmosphere N\textsubscript{2} can be converted to NO\textsubscript{x}. The so called thermal NO\textsubscript{x} is produced from equilibrium reactions between N\textsubscript{2} and O\textsubscript{2} at elevated temperatures such as in an ICE. Thermal NO\textsubscript{x} is conceived as the major contributor of NO\textsubscript{x} formation from conventional diesel engines which primarily consists of NO (70-90% of total NO\textsubscript{x}). The mechanism of NO formation is described by the extended Zeldovich mechanism[3, 5]:

\begin{align*}
O + N\textsubscript{2} & \leftrightarrow NO + N \\
N + O\textsubscript{2} & \leftrightarrow NO + O \\
N + OH & \leftrightarrow NO + H
\end{align*}

\begin{align*}
(1.1) & \\
(1.2) & \\
(1.3) &
\end{align*}
There are also minor routes for NO\textsubscript{x} formation originating from prompt NO and fuel nitrogen [5].

In the late 70s, the commercial three way catalyst was introduced in the US and functioned effectively to reduce CO, hydrocarbon and NO\textsubscript{x} emissions in parallel from gasoline engines. In an ordinary gasoline engine, the ratio between the air and fuel is near stoichiometric conditions for complete combustion. In line with the demand to achieve better fuel efficiency, diesel engines or lean-burn engines will increasingly become the major type of combustion engine in the future. In a diesel engine or lean-burn engine, the O\textsubscript{2} supply (as air) is in excess with respect to the amount of fuel and this will result in improved power output with lower CO\textsubscript{2} emissions [1, 6]. However, the conventional three way catalyst does not function effectively to remove emissions from the lean-burn exhaust, particularly NO\textsubscript{x} emissions. Therefore, improved designs of vehicle emission abatement system for lean exhaust are continuously being designed and implemented [6].

There are two broad methods to control NO\textsubscript{x} emissions from ICE: pollution prevention aiming to reduce NO\textsubscript{x} generation (primary technique) and post-combustion treatment aiming to reduce NO\textsubscript{x} emissions (secondary technique) [3]. In a primary technique, NO\textsubscript{x} generation in the ICE is suppressed by decreasing combustion temperature and controlling the oxygen-fuel concentration. An example of a primary technique is Exhaust Gas Recirculation (EGR). Selective catalytic reduction is an example of a secondary NO\textsubscript{x} abatement method.

![Diagram of aftertreatment system](image)

**Figure 1.1** General schematic view of aftertreatment system in a lean-burn or diesel engine vehicle

A catalytic aftertreatment system is a common method to abate vehicle emission from mobile sources. For a modern diesel engine, the catalytic aftertreatment system often consists of three primary parts: diesel oxidation catalyst (DOC), diesel particulate filter (DPF) and NO\textsubscript{x} reduction catalyst as depicted in Figure 1.1. The main function of the DOC is to oxidize carbon containing species and to oxidize NO to NO\textsubscript{2}. In the following part, the DPF traps solid particulate matter and NO\textsubscript{2} produced upstream in the DOC can be used for passive regeneration of the DPF. Eventually, a NO\textsubscript{x} catalyst is installed to convert the NO\textsubscript{x} to N\textsubscript{2} before releasing it to the atmosphere.
For NO\textsubscript{x} reduction in a lean-burn system, Selective Catalytic Reduction (SCR) is a reliable method and has been widely installed in both mobile and stationary systems. With the SCR technique, the NO\textsubscript{x} is converted to \( \text{N}_2 \) with the aid of reductants. One way to do this is by using NH\textsubscript{3} (or urea solution) as the reducing agent, so called NH\textsubscript{3}-SCR. Additional installation of a urea tank is needed onboard and it further requires an injection strategy to achieve better efficiency in NH\textsubscript{3} consumption.

Another technology to catalytically reduce NO\textsubscript{x} is the lean NO\textsubscript{x} trap (LNT) pioneered by Toyota which appeared on the market in 1994 [7]. Here, the NO\textsubscript{x} is stored on a catalyst (typically a Barium based catalyst) under a lean period that is followed by a short period of rich operation to regenerate the catalyst using a reducing agent. One of the challenges in LNT is deactivation by sulphur poisoning, where sulphur is converted to strongly bound sulphates and thus decreases the NO\textsubscript{x} storage capacity (as nitrates). Several attempts to improve the LNT technique have been discussed in literature [8].

The third concept of de-NO\textsubscript{x} technology in a lean-burn engine is hydrocarbon-SCR (HC-SCR). Here, the goal is to use the diesel fuel itself as a reducing agent and therefore installation of an additional tank for a reducing agent is not required. One of the potential catalysts for HC-SCR is silver alumina. Since studies of HC-SCR over silver alumina catalysts will comprise a large part of this thesis, it merits further discussion as presented in the following chapter.

1.2 Objectives and scope of the thesis

The overall goal of the project is to increase understanding of the reaction mechanisms of the \( \text{H}_2 \) effect on HC-SCR and DOC from lab-scale studies. For this purpose, both experimental and modeling approaches were used. Two types of catalyst were used: Ag-Al\textsubscript{2}O\textsubscript{3} and Pt/Al\textsubscript{2}O\textsubscript{3} to represent a HC-SCR catalyst and DOC, respectively. As indicated by the distribution of publications appended to this thesis, a larger portion of the thesis is allocated for HC-SCR than DOC studies.

In this thesis, a large portion of the experimental studies were based on activity measurements using monolithic samples and flow reactor facilities. Temperature-programmed reactions as well as transient tests have been used widely to understand the \( \text{H}_2 \) effect on both HC-SCR and DOC. Some of the data were then used to assemble kinetic models for mechanistic studies. In addition, temperature-programmed desorption (TPD) and DRIFT Spectroscopy were also used to facilitate the development of mechanistic models.

1.3 The outline of the thesis

This thesis is divided into 10 chapters and the highlights of each chapter are presented here. Chapter 1 is intended to present a general overview and the objective of this thesis. Chapter 2 deals with a brief literature review on DOC particularly related to the characteristics of the NO oxidation reaction. Chapter 3 presents a literature review on HC-SCR over silver alumina, reaction mechanisms and \( \text{H}_2 \) promotional roles. Subsequently, experimental methods used in the present work are presented in Chapter 4. Chapter 5 gives an overview of the kinetic
and reactor model used in the present work. Chapter 6 summarizes Paper I by describing the H₂ role to modify surface NOₓ species in the framework of HC-SCR. Chapter 7 summarizes Paper II and Paper III related to the mechanistic modeling studies of the H₂ effect on NO oxidation and C₃H₆-SCR. Chapter 8 contains results from surface species quantification to support C₃H₆-SCR kinetic model. Chapter 9 summarizes an evaluation of the H₂ effect to enhance NO oxidation over Pt/Al₂O₃ (Paper IV). Eventually, Chapter 10 presents concluding remarks of this thesis and an outlook for future work.
Chapter 2
Diesel Oxidation Catalyst

2.1 General
The function of the Diesel Oxidation Catalyst (DOC) is to oxidize CO, HC and soluble organic fractions in particulate matter [9]. In addition, the DOC also facilitates oxidation of NO to NO₂. It has been widely reported in the literature that the presence of NO₂ from the outlet stream of the DOC is not only beneficial to enhance oxidation of trapped particulate matter in the subsequent DPF unit, but also favorable for the fast SCR reaction over the NH₃-SCR unit (the common type of current technology for NOₓ removal). As shown in Figure 1.1, DOC is typically placed as the first catalyst to process the exhaust gases due to its oxidative functionality. For this purpose, noble metal based catalysts containing Pt and Pd are commonly employed as the main components in a DOC. When appreciable amounts of sulphur are present in the fuel, it may invoke deactivation of the DOC and facilitate formation of undesired sulphate PM by the DOC. Undesired oxidation of SO₂ in the DOC may also invoke H₂SO₄ formation. Subsequently, interaction between H₂SO₄ and water vapor leads to crystallization of sulphate components known as sulphate particulates [9, 10]. This process contributes to an increase in the PM emissions from the outlet DOC stream.

2.2 NO oxidation over Pt/Al₂O₃

Considering the beneficial effects of NO₂ formation as addressed earlier, kinetic studies of NO oxidation over the DOC have been widely reported in literature, e.g. a DOC review by Russell et al. [11]. Other than for the DOC application, NO oxidation is also known to be one of the primary steps of the lean NOₓ trap (LNT) application. As a result, considerable attention on NO oxidation studies has also been reported for conventional LNT catalysts, Pt/BaO/Al₂O₃ e.g. in [12, 13]. NO oxidation in the lean exhaust atmosphere over Pt/Al₂O₃ exhibits some interesting features that can be summarized by the following points:

- At high temperature, the activity for NO oxidation is typically limited by thermodynamic equilibrium. It is also worth noting that the reaction is self-inhibited by the produced NO₂.
During temperature-programmed oxidation, hysteresis phenomenon for NO oxidation conversion is commonly observed where the activity during the cooling ramp is usually lower than the preceding heating ramp.

The NO oxidation reaction is also ascribed to be a structure-sensitive reaction.

Related to its interaction with other compounds like CO and HC, it has been found that NO, CO and HC inhibit each other for their oxidations.

Due to the thermodynamic limitation at high temperature, the DOC is expected to have optimal performance in the medium-high temperature range. An example of NO oxidation activity over Pt/Al₂O₃ catalyst during a heating and subsequent cooling ramp is shown in Figure 2.1 where the hysteresis of NO oxidation is clearly shown. The hysteresis phenomenon on the DOC is generally explained by formation of Pt oxide facilitated by O₂ and NO₂ [13-15]. The build-up of Pt oxide with time which deactivates NO oxidation has also been widely studied in literature [12, 13].

![Figure 2.1](image.png)

**Figure 2.1** Hysteresis behavior of NO oxidation activity over 1 wt.% Pt/Al₂O₃ catalyst with ramping rates of ± 5°C/min. Inlet feed: 500 ppm NO, 8% O₂, 5% H₂O and Ar balance.

Since NO oxidation is a structure sensitive reaction, a number of studies have been conducted to relate the effect of Pt particle size/morphology on NO oxidation. Pt dispersion (particle size) has been reported to have a more important role than support materials [16]. Interestingly, it has been shown that larger particle size is beneficial for NO oxidation [16, 17]. This has been attributed to a higher resistance of large particles against Pt oxide formation by weakening the Pt-O bond [18]. Aging treatments have also been reported as a way to modify the Pt particle size [17]. The presence of O₂ in the gas composition during an aging treatment is beneficial as it further increased the NO oxidation conversion. This was proposed to be due to less Pt oxide formation and better ability to dissociate O₂ during adsorption step which is often regarded as the rate limiting step in NO oxidation [17, 19].
The interaction of CO, HC and NO on the oxidation of each component is already presented in literature e.g. in [20]. The presence of HC was found to inhibit NO oxidation and can be ascribed to competitive adsorption on the oxidation sites or reduction of NO$_2$ to NO due to reaction with HC [11]. Similarly, CO was found to inhibit NO oxidation in the same manner as HC i.e. competitive adsorption and NO$_2$ reduction to NO by CO [15, 20]. The inhibition of CO and HC on NO oxidation disappeared as the temperature increased, approaching the light-off temperature for CO or HC oxidations. Hauff et al. [15] reported that in NO/CO mixtures following complete conversion of CO, the NO oxidation conversion is higher than in the absence of CO. This is proposed due to the ability of CO to block the surface at low temperature and thus prevent Pt oxidation to occur. Related to the role of CO to retard Pt oxide formation, increasing CO concentrations has also been reported to improve NO oxidation conversion on a Pt/TiO$_2$ catalyst [21].

2.3 H$_2$ effect on DOC

Addition of H$_2$ in real diesel exhaust gas, as a way to improve oxidation activity over Pt and Pt-Pd DOC catalysts, has been reported by Herreros et al.[22]. As a result, improvements in NO$_2$ yield as well as higher CO and HC conversion were obtained. Only a portion of this promotional effect was found to stem from the temperature rise due to H$_2$ oxidation. Due to the complex gas composition of real diesel exhaust, it is challenging to investigate the intrinsic contribution of H$_2$ to promote the main reactions in DOC. It is already known that cofeeding of H$_2$ into the lean gas mixture may also lead to NO$_x$ reduction to N$_2$O and N$_2$ over Pt catalysts. This process is known as H$_2$-SCR and has been widely investigated in the literature as reviewed by Hamada and Haneda [23].

Addition of H$_2$ to improve low temperature CO oxidation over Pt/Al$_2$O$_3$ catalysts as one of the main reactions in DOC has been widely studied [24-26]. It has been proposed to result from interactions between surface species causing a reduction in CO desorption activation energy [12, 27] or coupling of the CO and H$_2$ oxidation surface chemistries via the hydroxyl intermediate [28-30]. These mechanisms that enhance CO oxidation may also be linked to the improved NO oxidation.

As a residue that originates from unconverted fuel and lubricating oil, the presence of HC in the exhaust is common. For NO oxidation over a DOC, admission of HC such as C$_3$H$_6$ or dodecane (C$_{12}$H$_{26}$) has been found to inhibit NO oxidation and vice versa [20, 31]. Since H$_2$ may enhance the oxidation performance of Pt/Al$_2$O$_3$ [22], it is thus of interest to investigate the interplay between the inhibition effect of HC and promotion effect of H$_2$ on the NO oxidation reaction. Using Pt/Al$_2$O$_3$, addition of HC to a gas containing NO$_x$ may also lead to its conversion to N$_2$O and N$_2$ via the HC-SCR process and addition of H$_2$ has also been reported to boost its low temperature activity [32].
Chapter 3

Hydrocarbon-Selective Catalytic Reduction (HC-SCR) over silver alumina catalyst

3.1 General

Early work on NO\textsubscript{x} removal in lean-burn or diesel engine exhaust conditions with hydrocarbon-SCR (HC-SCR) was pioneered by Iwamoto and Yahiro [33] and separate work by Held et al. [34] in the early 90s. Since then, numerous catalysts have been proposed and tested such as zeolite based catalysts, platinum group metal (PGM) catalysts and several base metal oxides [35]. It appeared eventually that the two most promising candidates for HC-SCR are Cu-ZSM5 (typical maximum activity at high temperature region around 350°C) and Pt/Al\textsubscript{2}O\textsubscript{3} (typical maximum activity at low temperature region around 250°C) [6]. However, challenges still remained since a significant amount of NO\textsubscript{x} is emitted in a temperature window between 250 and 350°C (quite common diesel exhaust temperature) which is not effectively covered by either Pt/Al\textsubscript{2}O\textsubscript{3} or Cu-ZSM5. In addition, one shortcoming with Pt/Al\textsubscript{2}O\textsubscript{3} as a HC-SCR catalyst is its significant selectivity for production of N\textsubscript{2}O which is one of the detrimental greenhouse gases and hence its emission to the atmosphere must be minimized.

Cu-ZSM5 as an alternative candidate for a HC-SCR catalyst unfortunately also has some limitations. It has been reported in literature that Cu-ZSM5 suffers from poor hydrothermal durability, where the activity for NO\textsubscript{x} removal degrades in the presence of water vapor (real exhaust gas typically contains a H\textsubscript{2}O concentration >10%) due to de-alumination of the zeolite framework at high temperature [6, 35]. Several attempts to augment the water resistance of zeolite based materials have been reported [36, 37]. However, the main issue related to poor low temperature activity over Cu-ZSM5 has hindered further development of this catalyst as a HC-SCR catalyst.

3.2 Silver alumina for HC-SCR

There is considerable interest in developing HC-SCR catalysts that are economically competitive, with a high activity over a broad temperature window, good hydrothermal stability, sulphur tolerance, as well as providing potential for a minimal fuel penalty. Silver
alumina appears to be a promising candidate for HC-SCR application and has been widely investigated since the pioneering work by Miyadera in 1993 [38]. However, it is worth mentioning that the poor performance of silver alumina catalysts in the low temperature region should have deterred much continued interest, until it was found that the addition of $H_2$ to the inlet feed gave a substantial increase in the low temperature activity [39, 40]. Since then, numerous studies have been devoted to investigate the role of $H_2$ and the reaction mechanism of $H_2$-assisted HC-SCR.

Silver alumina catalysts have been tested with various types of hydrocarbons (HC) i.e. short chain, long chain, aromatic, alcohol, biodiesel and real diesel fuel [41-47]. Tests with silver alumina have shown that reductants with a high carbon number were more superior than low carbon number reductants in terms of activity and tolerance to water. As the carbon number increases, the “mean bond energy” (the average of all C-H and C-C bond energies in a HC) decreases and therefore HC activation (a step in the HC-SCR process) will be accelerated [43]. However, problems related to fouling due to carbon deposition notably with long HC chains have also been reported, which decreased the HC-SCR performance [44, 48]. The use of more complex HC reductants such as aromatics gave lower activity than straight HC due to less favorable HC activation [44]. Furthermore, it has been suggested that the $NO_x$ removal efficiency is not only influenced by the structure of HC, but also by the silver morphology over the catalyst [44].

As a result of growing interest to use bio-based fuel in the transportation sector, the feasibility to use various bio-based fuels such as alcohols (methanol and ethanol), biodiesel and DME have also been widely investigated in the literature [41, 45, 47, 49]. Since the early work on silver alumina by Miyadera [38], it has been shown that oxygenated HC (such as ethanol) is easier to be partially oxidized than non-oxygenated straight chain HC. Comparing the activity of low molecular weight alcohols, it appears that propanol and ethanol gave remarkably higher $NO_x$ removal activity compared to methanol [43, 50]. As a result, oxygenated HC gives higher $NO_x$ removal activity than non-oxygenated straight chain HC. Formation of gas phase $H_2$ or ad-$H$ atoms from oxygenated HC has also been proposed as a reason of higher $NO_x$ conversion with alcohols [51, 52]. Recently, it is also reported that addition of methanol instead of $H_2$ was found to improve octane-SCR activity over Ag/Al$_2$O$_3$ catalyst, again due to the possible formation of $H_2$ from methanol decomposition [53]. These results therefore show a promising application of Ag/Al$_2$O$_3$ with alcohol fuels. Commercial scale Ag based HC-SCR technology using E85 fuel as reductant has been reported by General Electric, Tenneco and Umicore to achieve as high as 85-95% $NO_x$ conversion over a temperature range of 325-425°C [54].

The use of DME as a reductant for Ag/Al$_2$O$_3$ has also been tested. DME-SCR over Ag/Al$_2$O$_3$ showed relatively low $NO_x$ reduction activity similar to methanol-SCR [49]. Further, Erkfeldt et al.[41] and Arve et al.[45] investigated several biodiesel fuels over silver alumina catalysts and reported considerable $NO_x$ reduction activity at high temperature above ca. 350°C. It has been suggested that high hexadecane concentration (as a biodiesel model compound)
above 200 ppm may inhibit NO\textsubscript{x} reduction notably at 300 and 400°C by hindering NO adsorption on the surface and difficulty to partially oxidize the adsorbed HC. While at high temperature such as 550°C, increasing HC concentration is beneficial for NO\textsubscript{x} reduction as a result of greater oxidation of HC which appeared to facilitate HC-SCR [45]. The knowledge on the role of active sites over Ag/Al\textsubscript{2}O\textsubscript{3} as a NO\textsubscript{x} reduction catalyst is still unclear. Depending on the preparation method, several suggestions have been put forward mentioning the presence of metallic silver, oxidized silver, isolated ionic silver and silver aluminate [55, 56]. Furthermore, it has also been suggested that the role of small silver clusters (Ag\textsubscript{5}\textsuperscript{5+}) is important [57]. Although the exact role of each possible silver site is still being investigated, it is generally accepted that metallic silver has an oxidizing function and is thus responsible for activation of HC and NO\textsubscript{x}. Small silver clusters and oxidized silver have been proposed to activate the NO\textsubscript{x} reduction activity by partially oxidizing the reductant and promoting surface nitrate formation. Shimizu and Satsuma have summarized various silver states as active sites in their review and references therein [43]. The proportion of small silver clusters and metallic silver depends much on the silver loading and preparation technique. With impregnation methods, high silver loading tends to produce more metallic silver while low silver loading gives a higher proportion of small clusters of silver [55]. Sol-gel methods are favorable for producing catalysts containing small silver clusters and oxidized silver which are more finely distributed in the alumina matrix [58].

3.3 Mechanistic studies of HC-SCR

One of the most challenging parts in HC-SCR over Ag/Al\textsubscript{2}O\textsubscript{3} catalysts is to understand the reaction mechanism of NO\textsubscript{x} reduction, which is particularly complicated by the nature of hydrocarbons used that contribute to the formation of a number of intermediates (both spectators and active intermediates) during reaction. Several literature reports have addressed mechanistic aspects of NO\textsubscript{x} reduction over Ag/Al\textsubscript{2}O\textsubscript{3} [35, 43, 47, 57, 60].

A general schematic diagram of the HC-SCR mechanism over Ag/Al\textsubscript{2}O\textsubscript{3} is shown in Figure 3.1. Generally, the first step of HC-SCR is activation of NO and HC by O\textsubscript{2}. NO and O\textsubscript{2} will form NO\textsubscript{x} surface species (nitrates and nitrites). Strongly adsorbed nitrate is known to self-inhibit the NO\textsubscript{x} reduction at low temperature [50, 61]. For activation of HC, the O\textsubscript{2} partially oxidizes the HC to form oxygenated HC surface components. Although the formation of oxygenated HC is generally agreed to occur, however, the structure and role of oxygenated HC surface compounds remains a subject of debate in the literature. Different interpretations of HC intermediates can be due to a variety of experimental conditions [43]. In the subsequent part of the HC-SCR mechanism, the nitrogen containing species are expected to react with oxygenated HC surface species forming several surface intermediates where the major surface species are R-NO (nitroso species), R-ONO (nitrite species), R-NO\textsubscript{2}(nitro species), R-CN (cyanide species), R-CNO(isocyanate species) and R-NH\textsubscript{2} (amine species) [60]. It is believed that cyanide, isocyanate and amines are the dominant routes to eventually form gaseous N\textsubscript{2} during the HC-SCR [62-64].
Figure 3.1 Schematic diagram of the reaction mechanism of H₂-assisted HC-SCR over Ag/Al₂O₃, adapted from [59, 60]

3.4 The effect of H₂ on HC-SCR over Ag/Al₂O₃

Figure 3.2 Promotional effect of H₂ to improve C₃H₆-SCR (500 ppm NO, 1000 ppm C₃H₆, 8% O₂) and NO oxidation (500 ppm NO, 8% O₂) over 2 wt.% Ag-Al₂O₃. Gas hourly space velocity (GHSV) was ca. 29000 h⁻¹.

Perhaps, the most interesting feature of the silver alumina system for HC-SCR is the fact that addition of small amounts of H₂ can strongly promote low temperature NOₓ reduction activity as reported by Satokawa in the early 2000s [39, 65]. As a result, a wider temperature window for HC-SCR process is obtained as illustrated in Figure 3.2a. Another catalyst that is promoted by H₂ for HC-SCR activity is Ag-MFI [66]. Defining the exact role of H₂ in HC-SCR over Ag/Al₂O₃ is far from trivial. From literature, there are several proposed explanations for the “H₂ effect” including:

- the enhancement of the partial oxidation of the reducing agent [60, 67].
- formation of reactive N species (like –NCO species [68] or gas phase radicals [60]) from the reducing agent.
- the accelerated formation of active cationic silver clusters [43, 57].
- the destabilization of surface nitrates blocking active silver sites [40, 51, 67, 69-72]
- generation of Ag-hydride leading to formation of hydroperoxy radicals (HO₂), peroxide (O₂⁻) and superoxide ions (O₂⁻) [57, 73].
It should also be considered that in a HC-SCR, it is possible that \( \text{H}_2 \) can have multiple roles among the effects mentioned above \([40]\). A study by Kim et al.\([74]\) classified the roles of \( \text{H}_2 \) as *fast* and *slow* processes. The kinetic effect of \( \text{H}_2 \) was classified as a *fast process* in the time range of seconds. Here, \( \text{H}_2 \) activates formation of adsorbed surface species and chemical changes in oxidized silver. A morphological change such as the formation of silver clusters is classified as a *slow process* in the time scale of minutes.

It is also obvious that addition of \( \text{H}_2 \) facilitates higher NO oxidation activity over Ag/Al\(_2\)O\(_3\) as illustrated in Figure 3.2b. Satokawa et al.\([39]\) suggested that the increase in NO\(_2\) yield in the presence of \( \text{H}_2 \) is due to the role of \( \text{H}_2 \) to decompose nitrate formed on Ag/Al\(_2\)O\(_3\). Formation of nitrate itself is known to self-inhibit the NO\(_x\) reduction process over Ag/Al\(_2\)O\(_3\) \([61]\). In another study, Sadokhina et al.\([75]\) proposed that the role of \( \text{H}_2 \) in NO oxidation is indirect by promoting formation of nitrate on Ag and Al which subsequently may decompose to NO\(_2\) in the gas phase with the aid of NO.

It is important to mention that with the addition of \( \text{H}_2 \), NH\(_3\)-SCR over Ag/Al\(_2\)O\(_3\) was also considerably promoted \([76]\). For this reason, the study of Ag/Al\(_2\)O\(_3\) for HC-SCR and NH\(_3\)-SCR has gained a lot of interest in the present literature.

### 3.5 Onboard \( \text{H}_2 \) production

Concentrations of \( \text{H}_2 \) in diesel exhaust gas range from very little to almost non-existent. Katare and Liang \([26]\) reported the average molar ratio of CO/\( \text{H}_2 \) from diesel exhaust under a FTP (Federal Test Procedure) test is around 40-70 (mol/mol) with a maximum \( \text{H}_2 \) concentration of 0.07%. For gasoline exhaust, the average molar ratio of CO/\( \text{H}_2 \) is approximately 3 (mol/mol) with a maximum \( \text{H}_2 \) concentration of 2%. Therefore, other techniques, namely onboard diesel reforming, have been applied as a way to produce \( \text{H}_2 \) \([77]\). The produced \( \text{H}_2 \) can also be used to power a fuel cell of an APU (Auxiliary Power Unit) to support comfort systems on larger vehicles such as heavy-duty trucks and busses.

Utilization of a small amount of \( \text{H}_2 \) for the aftertreatment system will cause an increase in the fuel penalty. Kannisto et al.\([78]\) evaluated the fuel penalty in a combined ATR (Auto Thermal Reformer) and Ag/Al\(_2\)O\(_3\) HC-SCR system. Assuming fuel consumption and NO\(_x\) emission of 200 g/kWh and 1 g/kWh respectively, the combined use of fuel as reductant (C/N = 6-8) and for producing ca. 1000 ppm \( \text{H}_2 \) resulted in an approximately 2% fuel penalty. They also estimated that by comparing the economic price of urea, the equivalent fuel penalty for NH\(_3\)-SCR technology is approximately 0.5%. Thus, to be able to compete with existing NH\(_3\)-SCR technology, either a lower amount of \( \text{H}_2 \) for the aftertreatment process should be required and/or the efficiency of the reforming process must be higher.
Chapter 4
Experimental methods

4.1 Catalyst preparation: synthesis and washcoating

Silver alumina powder was prepared by a freeze dried sol-gel method as described by Kannisto et al. [58]. Briefly described here, aluminium isopropoxide (98+%; Aldrich) was used as a precursor of sol gel γ-Al₂O₃. For Ag-Al₂O₃ synthesis, the solution of aluminium isopropoxide (AIP) was mixed with silver nitrate (>99.5%; VWR) in deionized water (milli-Q water). To obtain a pH of around 4.5, 10 vol.% of nitric acid solution was added gently and then the solution was stirred overnight to form a transparent aluminum hydroxide sol. Subsequently, evaporation of isopropanol was performed under reduced pressure and temperature of around 45°C. When the sol became a transparent gel, the gel was freeze-dried. The resulting dry powder was then collected and crushed into a fine powder. The powder was placed in a ceramic crucible in a furnace for calcination.

<table>
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<th>Catalysts</th>
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<td>Pt/Al₂O₃</td>
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<td>Paper IV</td>
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Platinum alumina powder was prepared by a wet impregnation method as described by Auvray [79]. In brief, pre-calcined γ-alumina (Puralox SBa-200, Sasol) was mixed with a certain amount of deionized “MilliQ” water under stirring and controlled pH. Nitric acid was then added drop-wise to reach a stable pH of ca. 4. A solution containing the Pt was prepared by dilution of the appropriate amount of Pt(NO₃)₂ (Heraeus). It was then added drop-wise to the stirred alumina slurry. During this operation, the pH decreased. The resulting solution was frozen by dipping in liquid N₂ and dried overnight under vacuum so as
to sublimate the water. Eventually, the resulting catalyst powder was calcined in a furnace. Table 4-1 presents the summary of catalysts used in this thesis. Characterization of surface area and pores size distribution of powders were performed with a BET instrument (Micromeritics).

Bare cordierite monoliths (400 CPSI, 188 parallel channels with 1.1 mm open channel dimension) with 2 or 4 cm length and 2 cm diameter were used. Prior to coating, the bare monolith was calcined to remove impurities. The catalysts powder was mixed with binder boehmite (Disperal Sol P2; Condea) and then mixed with milli-Q water under vigorous stirring. The monolith was coated by either dropping it into slurry or using non-graduated pipettes to deposit the slurry uniformly onto the channels. The coated monolith was typically dried under a hot air gun at 90°C for about 5 minutes and then briefly calcined at 600°C for 1-2 minutes. The monolith was then cooled down before it was weighed. The coating process was repeated until the targeted weight of washcoat was deposited. Eventually, the coated monolith was calcined in a furnace at 550 or 600°C.

4.2 Flow reactor experiments

Flow reactor experiments were used extensively as the main equipment for activity measurements. A schematic diagram of flow reactor is shown in Figure 4.1. It consists of a horizontal quartz tube (88 cm long and 2 cm diameter) heated by a helical heating coil on the outer surface of the tube. To prevent heat loss, the reactor was covered by quartz wool insulation. The monolith was placed inside the tube near to the outlet end of the tube. To avoid bypass flow around the monolith, it was sealed inside the tube by a thin layer of quartz wool. To measure and regulate temperature, two thermocouples (type K) were placed inside the sample. One was positioned at around 1 cm from the outlet end of the sample and the other one was inserted through the length of monolith until it protruded approximately 5 mm from the inlet end. The inlet temperature signal was controlled by a
Eurotherm temperature controller. The inlet gases were supplied by a number of separate mass flow controllers, whereas water vapor was provided by a controlled evaporation and mixing system (all Bronkhorst Hi-Tech). Argon was used as a carrier gas. The total typical flow of inlet gas was 3000-3500 mLn/min (1 Bar and room temperature), whereas in TPD experiments, a lower total flow was usually used.

The reactor outlet gas composition was analyzed by a MKS 2000 FTIR instrument measuring the concentrations of NO, NO$_2$, H$_2$O, N$_2$O and NH$_3$ when HC was not fed. Additional measurements from aforementioned gases were made: CO, CO$_2$ and C$_3$H$_6$ when C$_3$H$_6$ (propene) was added. In some cases, a small part of the outlet flow from the reactor was sampled to a Hiden HPR 20 quadrupole mass spectrometer (MS) for gas analysis especially for diatomic gas measurements such as H$_2$, N$_2$, and O$_2$.

4.3 In-situ DRIFT spectroscopy

![Figure 4.2 Schematic diagram of DRIFT Spectroscopy](image)

Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) is a useful in-situ technique to identify adsorbed surface species on a catalyst surface by detecting molecular vibration using mid-region infrared energy (wavenumber 200-4000 cm$^{-1}$) [80]. In DRIFT spectroscopy, an infrared (IR) source irradiates an IR beam which is reflected to enter the interior structure of a powder sample. The unabsorbed IR beam is transmitted to other particles or reflected out to a collecting mirror and sent to an IR beam detector for further analysis. A schematic diagram of DRIFT spectroscopy is depicted in Figure 4.2. The energy difference in vibrational states will characterize specific types of surface species. Adsorbed surface species on a catalyst will partially absorb IR photons and cause vibrations. However, only vibrations that trigger dipole moment changes can be detected with this technique [80]. The change of the dipole moment is proportional to the intensity of the IR band.

The DRIFT instrument used in this work was a Bio Rad FTS6000 spectrometer. One of the advantages of using DRIFT is the relatively simple operating procedure, where the analyzed sample can be mounted directly onto a DRIFT instrument for analysis. The powder sample was placed in a sample holder (supported by a metallic grid) of a high temperature Harrick Praying Mantis cell coated with Silcolloy® 1000 and equipped with a KBr window. To
regulate temperature, the DRIFT cell was equipped with a Eurotherm heating system and water cooling system. In addition, a K-type thermocouple was placed near the sample holder to indicate the bed temperature. The gases were supplied by a number of mass flow controllers (Bronkhorst Hi-Tech). A fast switching valve is installed in the feed gas lines to allow a smooth step response during experiments. The outlet gas from the DRIFT instrument is continuously sampled by a mass spectrometer (Balzer Quadstar 420) to facilitate gas analysis.
Chapter 5
Modeling methods

5.1 General

The role of a kinetic model is to consolidate available experimental data with theoretical principles. It is hoped that a realistic kinetic model can capture the physical and chemical phenomena on the catalyst and hence it can give essential insights in the development of a catalyst. In a modern catalysis research cycle, development of a catalyst is not merely attributed to the knowledge of catalyst synthesis and surface science, but also uses kinetic modeling to elucidate the important steps in a reaction network (Figure 5.1). There are three interconnected aspects i.e. synthesis, performance and design that are all important to create a successful catalyst for industrial applications. A better understanding of kinetic information will improve the synthesis and design aspects of the catalyst to obtain the best performance of a catalyst [81].

![Figure 5.1 Schematic diagram of modern catalysis development. Adapted from [81]](image)

5.2 Kinetic modeling: global and microkinetic approaches

In this work, both global and microkinetic modeling approaches were used. A global kinetic model combines adsorption, surface reaction and desorption steps with a global rate expression. Alternatively, one way to resolve the kinetic rate expression is by assuming that one of the steps (can be adsorption, surface reaction or desorption) is the rate determining step and all remaining steps in quasi-equilibrium. Generally, kinetic rate expressions of global kinetic models can then be written as a function of gas phase properties as shown in equation (5.1) [81].
A microkinetic analysis is a tool to investigate the reaction mechanism over heterogeneous catalysis by assembling several elementary steps without pre-assuming that any step is the rate determining step or intermediate surface species most abundant [82]. Microkinetic analysis will typically generate a large number of elementary steps and form a highly correlated and non-linear mathematical system. Since a wide range of kinetic parameter values may fit the experimental data, determination of kinetic parameters should be partially based on theoretical principles (physically and chemically sound) and other correlations to describe the experimental data with the proposed microkinetic model.

A mean-field approximation is often used along with a microkinetic analysis which assumes [83, 84]:

- random distribution of all adsorbed species over the catalyst surface.
- the absence of interactions among the adsorbed species.

With these assumptions, the probability for all active sites (i.e. neglecting differences between step and terrace sites) to adsorb gas phase reactants is considered equal. Microkinetic and global kinetic modeling along with mean-field approximation has been used in paper II and III. A more detailed work accounting for interaction of surface species on steps and terraces of active sites is typically conducted by using kinetic Monte Carlo simulations. An example of comprehensive overview of this technique has been presented by Reuter [85].

In a microkinetic model, all elementary steps are described as reversible reactions and the rate of an elementary step as either a forward or backward reaction can be expressed as:

$$r_j = k_j \cdot \prod_{i=1}^{i=l} y_{i}^{\nu_{i}} \cdot \prod_{w=1}^{w=W} \theta_{w}^{\nu_{w}}$$  \hspace{1cm} (5.2)

$$k_j = A_{ij} \cdot \exp \left( -\frac{E_{a_{ij}}}{R \cdot T} \right)$$  \hspace{1cm} (5.3)

From equation (5.2), it can be noted that the order of the reaction with respect to gas phase or surface species concentration ($v$) corresponds to the stoichiometric coefficient of the reactant. Preexponential factors and activation energies are the common kinetic parameters to estimate as described in the famous Arrhenius equation (5.3). In order to obtain reasonable kinetic parameter values, there are several strategies to determine kinetic parameters [8]:

- investigating a sub-system from a larger system and determine the kinetic parameters independently
- information from literature
- thermodynamic restrictions
collision theory and transition state theory
statistical thermodynamics
regression analysis with experimental data.

A combination of these methods can be used to obtain kinetic information from parameter estimation.

Estimation of preexponential factors for adsorption steps is generally taken from collision theory or transition state theory. The sticking coefficient at zero coverage for collision theory is then fixed or estimated from literature values. For desorption and surface reaction steps, a reasonable limit for preexponential factors can be obtained from transition state theory [82].

Estimation of activation energies can be approximated from DFT calculations, bond-order conservation theory (BOC) or via the related but more advanced UBI-QEP (Unity Bond Index-Quadratic Exponential Potential) calculations and literature values [82]. To illustrate, literature values of UBI-QEP estimates have been used in paper II to estimate activation energies of desorption steps [86].

Thermodynamic restrictions based on overall gas phase reactions can also be applied in microkinetic modeling. Thermodynamic restrictions for all elementary steps can be shown as:

$$\prod_i \left( \frac{A_{i_f}}{A_{i_b}} \right)^{v_i} = \exp \left( \frac{\Delta S_R}{R} \right)$$

$$\Delta H_R = \sum_i v_i \cdot E_{a_f} - \sum_i v_i \cdot E_{a_b}$$

5.3 Reactor model

Monolith-supported catalysts are the standard form of catalysts used in this thesis. For modeling purposes, the monolith catalyst or monolith reactor was simulated with a single channel reactor model as depicted in Figure 5.2. Here, the reactor model only briefly presented. A more detailed description of reactor model including mass and heat transport equations used in the model can be found in paper II page 385 to 386.

As seen in Figure 5.2a, the monolith reactor was modeled as tanks-in-series where the channel was segmented both in the axial and radial directions. By dividing the washcoat into several layers (Figure 5.2b), the reactor model is able to account for internal mass transfer resistance which is commonly excluded in a conventional kinetic model. In each tank and layer, mass and heat balance equations were solved for all gas and adsorbed surface species. The theoretical number of tanks required in the axial direction can be estimated using the dispersion model for laminar flow in an open-open system as described in [87].
The theoretical number of tanks-in-series ($n_t$) typically gives a large number of tanks and hence requires extensive computational time. Therefore, an alternative approach to estimate the number of tanks-in-series was employed by investigating the effect of varying the number of tanks and layers on the calculated sum of the squares of error (SSE). It is also important to mention that the size of each tank (in axial direction) and layer (in radial direction) was gradually varied as illustrated in Figure 5.2 to obtain a finer discretization where the concentration gradients were steeper.

### 5.4 Modeling of mass balance

The gas phase mass balance in each tank was modeled as a steady state mass balance between axial convective flow and radial mass transfer as shown in equation 5.6.

$$F_{tot} \cdot (y_{i,k-1,0} - y_{i,k,0}) - \Gamma_{i,k,0} \cdot (c_{i,k,0} - c_{i,k,1}) = 0$$  (5.6)

A film model was applied to describe the mass and heat transport from the bulk gas to the washcoat. The values of transport coefficients varied along the axial direction of the channel according to the empirical correlation given by Hawthorne [88].

The mass balance inside the washcoat is developed for each layer and characterized by radial diffusion (perpendicular to the bulk flow) and reactions. Equation 5.7 shows the mass balance in each layer (for layers $n \geq 1$).

$$\Gamma_{i,k,n-1} \cdot (c_{i,k,n-1} - c_{i,k,n}) - \Gamma_{i,k,n} \cdot (c_{i,k,n} - c_{i,k,n+1}) + \sum_j v_{i,j} \cdot \Gamma_{j,k,n} \cdot w_{s,k,n} = 0$$  (5.7)

While the the overall mass transport coefficient ($\Gamma$) between gas phase-washcoat and between each layer in washcoat can be written as:

$$\Gamma_{i,k,0} = \frac{A_k}{k_c, k} + \frac{0.5 \cdot \Delta X_i}{D_{eff,i,k}} \quad \text{and} \quad \Gamma_{i,k,n} = \frac{A_k}{D_{eff,i,k}} + \frac{0.5 \cdot \Delta X_{n+1}}{D_{eff,i,k}}$$  (5.8)
However for the bottom layer (n= N), $I_{i,k,N} = 0$, inferring no transport to the monolith substrate.

The effective washcoat diffusivity was calculated from the Bosanquet [89] correlation by including gas diffusivity, Knudsen diffusivity and a factor accounting for the porosity and tortuosity of the washcoat. Gas diffusivity was calculated from the Fuller-Schettlet-Gidding relationship [90] and corrected for the current segmental washcoat temperature while Knudsen diffusivity was approximated by using the semi-empirical Knudsen correlation [91].

A microkinetic model in this work was used to describe the transient simulations and therefore should be able to explain the dynamic change of surface species coverages. The dynamic mass balance of surface species is dictated by their involvement in reactions and expressed as:

$$N_c \cdot \frac{d\theta_{w,k,n}}{dt} = \sum_j r_{j,k,n} \cdot X_{w,j} \quad (5.9)$$

### 5.5 Modeling of heat balance

The reactor model used here also facilitates heat balance calculations. The gas phase heat balance in each tank is assumed to be steady-state and adiabatic:

$$F_{tot} \cdot c_{pg} \cdot (T_{g,k-1} - T_{g,k}) - h_k \cdot A_k \cdot (T_{g,k} - T_{s,k}) = 0 \quad (5.10)$$

Accumulation terms in the gas phase mass balances (equations 5.6) and the gas phase heat balance (equation 5.10) were neglected because the characteristic time constants for these transport processes is considerably smaller compared to accumulation of surface species (equation 5.9) and heat in the solids (catalyst and washcoat).

For the heat balance in the washcoat, heat transfer in the radial direction within the washcoat was neglected. However, heat accumulation and transport between solid (washcoat and substrate) and gas in each tank was included. Also, axial heat conduction between solid segments and heat contribution from reactions in each tank were included.

### 5.6 Matlab implementation: simulation and parameter estimation

The mass and energy balances were expanded for each gas phase component, surface component, tank and layer. The solution of these equations gives the concentrations of gas and surface components, gas and catalyst temperature in each layer and tank for each measurement time. The resulting differential and algebraic (DAE) equations were solved using the ODE15s function in Matlab R2008a® and the results were stored in a large multi-dimensional matrix.

Parameter fitting was performed using the lsqnonlin function in Matlab R2008a®. This function uses a gradient search method to perform non-linear regression. For modeling purposes, the rate constant which follows the Arrhenius expression (equation 5.3) needed to be modified to decouple the high correlation between preexponential factors and activation energies. As a result, the fitted parameters were logarithmic values of the rate
constant \((\ln(k_{\text{ref}}))\) at the average experimental temperature \((T_{\text{ref}})\) and the activation energy \((Ea)\) as shown as:

\[
k_j = \exp \left( \ln(k_{\text{ref}})_j - \frac{Ea_j}{R} \left( \frac{1}{T_{s,k}} - \frac{1}{T_{\text{ref}}} \right) \right)
\]  \hspace{1cm} (5.11)

Prior to the fitting, each parameter was scaled according to:

\[
\beta_{\text{scaled}} = \frac{\beta_{\text{unscaled}} - \beta_{\text{initial value}}}{\text{range}}
\]  \hspace{1cm} (5.12)

The scaling factor called \textit{range} was set so that a scaled parameter value of +1 approximately doubled the reaction rate from the initial parameter value and a scaled value of -1 corresponded to approximately half the reaction rate. Subsequently, the upper and lower bounds were determined in accordance with the scaled values. The objective of non-linear regression was to minimize the sum of the square of error (SSE) where the residuals were typically calculated from outlet gas measured and calculated mole fractions.
6.1 Roles of surface NO\textsubscript{x} species

As seen from the proposed HC-SCR mechanism in Figure 3.1, activation of NO\textsubscript{x} is characterized by formation of surface NO\textsubscript{x} species mainly as nitrate and/or nitrite species. Subsequently, surface NO\textsubscript{x} species play a role by reacting with oxygenated HC (a result of HC activation) to form a number of intermediates which eventually lead to the formation of N\textsubscript{2}. For this reason, surface NO\textsubscript{x} species have been suggested to be important intermediates and therefore it is important to understand their formation, stability and reactivity to elucidate the mechanism of HC-SCR.

It is interesting to note that H\textsubscript{2} may play a dual role in its interaction with nitrate species. On one hand, H\textsubscript{2} has been proposed to promote elimination of nitrates during H\textsubscript{2}-assisted HC-SCR [59, 67, 70, 92]. On the other hand, it has also been shown from FTIR studies that H\textsubscript{2} activates accumulation of nitrates on the surface during NO oxidation [56, 67, 73, 93]. Thus, an additional objective for studying surface NO\textsubscript{x} species was to examine whether these seemingly contradictory roles for H\textsubscript{2} could be compatible.

In order to investigate and clarify the characteristics and stability of nitrate species on Ag-Al\textsubscript{2}O\textsubscript{3}, a series of in-situ DRIFTS and TPD studies have been conducted. Here, the focus has been placed on understanding the role of H\textsubscript{2} to modify the surface NO\textsubscript{x} species in relation to the promotional effect of H\textsubscript{2} for NO oxidation and C\textsubscript{3}H\textsubscript{6}-SCR. A more detail description of these studies can be found in Paper I.

6.2 TPD studies of NO\textsubscript{x}

Temperature-programmed desorption (TPD) is a useful technique to investigate the thermal stability of adsorbed species. TPD studies to investigate the stability of surface NO\textsubscript{x} species over Ag/Al\textsubscript{2}O\textsubscript{3} have been reported in the literature [50, 75, 94, 95]. Figure 6.1 shows desorption profiles from TPD of NO\textsubscript{x}. 

Chapter 6

Stability of surface NO\textsubscript{x} species: TPD and DRIFTS studies
As seen from the upper panel of Figure 6.1 for TPD following an NO oxidation pretreatment, two desorption peaks were observed: a low temperature (LT) peak at 277-340°C and a high temperature (HT) peak at ca. 440°C. It is noteworthy that the LT peaks were skewed to higher temperatures with increasing adsorption temperature. The major NO\textsubscript{x} components desorbed were NO at both LT and HT peaks whereas NO\textsubscript{2} was only observed at the LT peak following adsorption at 200 and 250°C.

![Figure 6.1](Image)

**Figure 6.1** Desorption profiles of TPD NO\textsubscript{x} in Ar flow over 2 wt.% Ag-Al\textsubscript{2}O\textsubscript{3} catalyst following adsorption treatments at 200 (red), 250 (green) and 300°C (blue). Preceding adsorption condition from upper panel to lower panel respectively: 500 ppm NO + 4% O\textsubscript{2} (total flow of 1500 ml/min.), 500 ppm NO + 4% O\textsubscript{2} + 0.1% H\textsubscript{2} (total flow of 1500 ml/min.) and 150 ppm NO\textsubscript{2} + 4% O\textsubscript{2} (total flow of 3500 ml/min.)

Interestingly, desorption of the LT peak was not accompanied by O\textsubscript{2} desorption. DRIFT analysis (discussed below in section 6.3 as well as in Paper I) indicated that nitrates were a key surface species that is also related to the LT peak. Hence, this indicates that adsorption of NO and NO\textsubscript{2} over oxidized silver yielded formation of nitrate species by borrowing O atoms from oxidized Ag \cite{96} or Al\textsubscript{2}O\textsubscript{3} \cite{97}. Decomposition of the LT surface NO\textsubscript{x} species apparently left borrowed O atoms on Ag and Al\textsubscript{2}O\textsubscript{3}.
As illustrated previously in Figure 3.2b, addition of H₂ clearly promoted NO oxidation reaction over Ag/Al₂O₃. From TPD results following pretreatment in H₂-assisted NO oxidation (middle panel of Figure 6.1), it can be noted that along with higher activity for NO oxidation in the presence of H₂, the LT peak observed from NO-O₂ TPD was significantly suppressed and shifted towards the HT peak. The shift was also accompanied by higher total quantities of NOₓ adsorbed and desorbed. H₂ induced NOₓ adsorption over Ag-Al₂O₃ can then be related to the increase of the HT surface NOₓ species. Due to the fact that the LT peak decomposed thermally at higher adsorption temperatures and was suppressed significantly in presence of H₂ which both gave higher NO oxidation conversion, it is therefore reasonable to assign the LT peak as the result of the decomposition of nitrates on the active sites.

The lower panel of Figure 6.1 shows the desorption profile following pretreatment with NO₂-O₂ adsorption. As displayed here, a substantial release of NO₂ was also observed that peaked at 440-460°C similar to the desorption profile following H₂-assisted NO oxidation (middle panel of Figure 6.1). Further, additional experiments for NO₂-O₂ TPD on Al₂O₃ (not shown here) gave a similar TPD profile as in Ag-Al₂O₃. Therefore, it was evident that the HT nitrate results from NO₂ adsorption and primarily located on the Al₂O₃ support. It is also then likely that the HT nitrates formed on the Al₂O₃ support are spectator surface species. From literature, a reaction path of NOₓ storage by a spillover mechanism has been proposed [70, 75, 98]. An alternative mechanism of NOₓ storage by NO₂ readsorption on the Al₂O₃ support has also been proposed [51]. Based on the results of these TPD studies, it is indicative that the NO₂ readsorption mechanism is most probable for NOₓ storage on Al₂O₃ as it is related to gas phase NO₂. However, this does not negate the possibility that a spillover mechanism also contributes to NOₓ storage on Ag-Al₂O₃.

Quantitative analysis was performed by integrating the amount of LT NOₓ species from Ag-Al₂O₃ and Al₂O₃ to identify the amount of surface NOₓ species possibly on active sites (Figure 6.2a). At 300°C, it could be observed that the amount of surface NOₓ species on Ag-Al₂O₃ was more or less equal to Al₂O₃, thereby indicating that Ag sites were largely free from LT surface NOₓ species by this temperature. Figure 6.2b compares the calculated reaction rates for NO oxidation and H₂-assisted NO oxidation during adsorption steps. As seen here, the rate of NO₂ formation was always higher in the presence of H₂ at all temperatures, even at 300°C where Ag was largely free from the presumably inhibiting LT NOₓ species. If removal of inhibiting nitrate species was the only promoting role of H₂ for NO oxidation, one would expect the NO oxidation reaction rates with and without H₂ feed to be nearly equal at 300°C. If all inhibiting surface NOₓ species were thermally removed at 300°C, comparison of reaction rates at this temperature indicates that as much as 60% of total rate with H₂ feed could not be due to removal of inhibiting surface NOₓ. Therefore, these findings indicate that H₂ should have additional promoting roles.
Figure 6.2 The amount of surface NO\textsubscript{x} species from integration of LT desorption peak after NO-O\textsubscript{2} adsorption over Ag-Al\textsubscript{2}O\textsubscript{3} and Al\textsubscript{2}O\textsubscript{3} (upper panel, a) and reaction rate for NO oxidation and H\textsubscript{2}-assisted NO oxidation over Ag-Al\textsubscript{2}O\textsubscript{3} (lower panel, b).

6.3 Stability of surface NO\textsubscript{x} species from in-situ DRIFT Spectroscopy

Figure 6.3 shows the ensuing evolution of IR spectra as a result of an increase in cell temperature after adsorption of NO\textsubscript{x}. Peak assignments were mainly taken from [98, 99] where the presence of monodentate, bidentate and bridging nitrates is observable. From DRIFT results, the thermal stability of nitrate species were found to be in the order of bridging < bidentate < monodentate nitrate and therefore it is reasonable to regard the LT desorption peak to primarily originate from the decomposition of bidentate and bridging nitrate species as in agreement with [50].

In the presence of H\textsubscript{2} in the feed, it is apparent that the formation of the bidentate nitrate at 1248 cm\textsuperscript{-1} was less pronounced. It is therefore suggested that the vibration of bidentate nitrate at 1248 cm\textsuperscript{-1} can also be associated with the LT desorption peak. By associating TPD and DRIFT, it is suggested that H\textsubscript{2} eliminated surface nitrate species on active sites (LT peak) which is predominantly as bidentate nitrate (1248 cm\textsuperscript{-1}).
Figure 6.3 DRIFT Spectra of adsorbed species during temperature ramp following adsorption of NO oxidation (top), H₂-assisted NO oxidation (centre) and NO₂-O₂ adsorption (bottom) over 2 wt.% Ag-Al₂O₃ at 200°C. Adsorption conditions from upper to lower panel, respectively: 1000 ppm NO + 8% O₂, 1000 ppm NO + 8% O₂ + 0.1% H₂ and 300 ppm NO₂ + 8% O₂.

6.4 Mechanistic insight regarding C₃H₆-SCR and H₂-assisted C₃H₆-SCR

A series of TPD studies were also conducted to investigate the quantities and nature of adsorbed NOₓ and COₓ species during C₃H₆-SCR and H₂-assisted C₃H₆-SCR over the Ag-Al₂O₃ catalyst. Figure 6.4 presents the NOₓ and COₓ desorption profiles following adsorption conditions of C₃H₆-SCR and H₂-assisted C₃H₆-SCR.
Figure 6.4 Desorption profiles following C₃H₆-SCR and H₂-assisted C₃H₆-SCR in Ar flow over 2 wt. % Ag-Al₂O₃ at 200 (red), 250 (green) and 300°C (blue). Preceding adsorption conditions: 500 ppm NO + 4% O₂ + 0.1% C₃H₆ with 0 or 0.1% H₂ (total flow of 1500 ml/min).

As seen in Figure 6.4, two remarkable NOₓ peaks attributable to LT and HT peak were observed following C₃H₆-SCR. By comparing the NOₓ desorption profile for C₃H₆-SCR (Figure 6.4) and NO oxidation (Figure 6.1), both of them have a similar profile with LT and HT NOₓ desorption peaks. This presence of both LT and HT nitrates in approximately the same temperature range indicates that NO oxidation and C₃H₆-SCR share some mechanistic features.

The improvement in NOₓ reduction activity for H₂-assisted C₃H₆-SCR (Figure 6.4) was accompanied by a significant decrease in the LT NOₓ desorption peak. At the same time, the HT NOₓ desorption peak increased remarkably. Therefore, again removal of the inhibiting LT nitrate, in this case aided by reaction with H₂, improved the NOₓ reduction activity. The HT peak mostly consists of NO probably because the catalyst also contained adsorbed HC which was oxidized by the adsorbed NOₓ species during their decomposition and desorption. It can also be seen that the HT nitrate peak had a broad shoulder towards lower temperatures. This shoulder probably results from the presence of the adsorbed HC species acting as reductants and destabilizing the nitrate species to cause some lower temperature NOₓ decomposition.

From the desorption profiles of CO and CO₂ for H₂-assisted C₃H₆-SCR, one can observe that a CO peak was obtained at lower temperature compared to the one in the absence of H₂. Furthermore, the concentration of COₓ released was much higher than in the absence of H₂, consistent with the higher conversion of C₃H₆ obtained with addition of H₂. Higher concentrations of desorbed CO and CO₂ infer that H₂ has a promotional effect on low temperature C₃H₆ activation. HC activation to form oxidized HC species, itself is often
suggested as a key step in HC-SCR over Ag-Al₂O₃ [40, 67, 92]. This greater formation of surface HC and oxidized HC in the presence of H₂ is likely linked to the removal of inhibiting nitrate species as suggested by the suppression of the LT nitrates also with H₂. There was also a broadening and shift to lower temperature of the COₓ desorption peaks with the addition of H₂ which suggests that a greater quantity of possibly more reactive adsorbed HC species with lower thermal stabilities were formed. This perhaps points to the fact that H₂ may have other effects to promote the NOₓ reduction activity in addition to removal of inhibiting nitrate species.

Greater accumulation of adsorbed COₓ due to both C₃H₆-SCR and H₂-assisted C₃H₆-SCR pretreatments at elevated temperatures indicates that the reactions to activate the HC and form oxygenated HC on the surface have relatively high activation energies. In other words, the activation energy to partially oxidize HC to form oxygenated HC species is higher than the activation energy of subsequent reactions between surface NOₓ species with oxygenated HC species that lead to formation of N₂. Greater accumulation of oxygenated HC surface species may also be due to less inhibiting nitrates covering the active sites where oxygenated HC are formed.

In this series of studies, it seems that the promoting role of H₂ appears to be only partially due to the removal of inhibiting surface NOₓ species. As a result the findings here support the possibility of other H₂ promoting roles as already described in the literature [39, 40, 59, 67, 92]. It has however been observed here that the formation of surface nitrate species in the absence of H₂ depends on the donation of oxygen from surface oxides. As a result the removal or prevented formation of these nitrate species caused by H₂ may be linked to some partial reduction of Ag species and thus formation of sites with enhanced activity.
Chapter 7

Kinetic studies of the H$_2$ effect on NO oxidation and C$_3$H$_6$-SCR over Ag-Al$_2$O$_3$

7.1 General

One approach to investigate a large and complex reaction mechanism as exemplified by HC-SCR over Ag/Al$_2$O$_3$ catalyst is to divide it into simpler subsystems. As a part of the HC-SCR reaction mechanism, NO oxidation to NO$_2$ has been investigated as an important sub-reaction within HC-SCR [56, 93, 100]. As shown in Figure 3.2b, Ag-Al$_2$O$_3$ is considered as a poor catalyst for NO oxidation [56, 101], however the addition of H$_2$ dramatically improves its low temperature activity even with the presence or absence of H$_2$O in the feed [39, 56, 73, 92, 102]. TPD results shown previously in Chapter 6 show that there are common features of adsorbed NO$_x$ species between NO oxidation and C$_3$H$_6$-SCR. Therefore, it is also probable that the mechanism by which H$_2$ promotes low temperature NO oxidation shares some common features with how H$_2$ promotes low temperature HC-SCR over Ag-Al$_2$O$_3$.

For mechanistic studies, kinetic models of H$_2$ effect have been constructed with the following featured highlights:

- In paper II, a microkinetic model for H$_2$-assisted NO oxidation was examined. Here, the single role of H$_2$ to remove self-inhibiting nitrate was proposed.
- In paper III, a global kinetic model to describe the promoting effect of H$_2$ on NO oxidation and C$_3$H$_6$-SCR was proposed. A wide range of feed and reaction conditions were examined. Here, the proposed role of H$_2$ was expanded not only to remove inhibiting nitrate but also to form new active sites.

7.2 Microkinetic modeling of H$_2$-assisted NO oxidation (Paper II)

The kinetic behavior of NO oxidation over silver alumina was investigated using transient data generated by a reduced factorial Design of Experiments (DOE). DOE has been found to be a useful method to investigate the influence of several controllable factors on some measurable effects. Here, the feed concentrations and feed temperature were varied systematically between low and high levels around a centre point condition. The experiments were performed in three batches with constant temperatures and transient
switches in the feed concentrations of reactants. Table 7-1 shows the levels of concentrations and temperature used to study the kinetic behavior of NO oxidation.

**Table 7-1** The concentration and temperature levels in DOE of NO oxidation

<table>
<thead>
<tr>
<th></th>
<th>NO (ppm)</th>
<th>O₂ (%)</th>
<th>NO₂ (ppm)</th>
<th>H₂ (%)</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>low (-1)</td>
<td>400</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>250</td>
</tr>
<tr>
<td>centre (0)</td>
<td>600</td>
<td>7</td>
<td>50</td>
<td>0.1</td>
<td>325</td>
</tr>
<tr>
<td>high (+1)</td>
<td>800</td>
<td>8</td>
<td>100</td>
<td>0.2</td>
<td>400</td>
</tr>
</tbody>
</table>

**The effect of varied factors**

The steady-state results from the reduced factorial design of experiments were analyzed by multi-linear regression (MLR) analysis. The MLR model gave a coefficient of determination of 0.994 and the normalized coefficient plot including their 95% confidence intervals are shown in Figure 7.1.

![Normalized coefficient plots from MLR with 95% confidence interval bars](image)

The magnitude and trend of the coefficients were proportional to their effect on NO oxidation conversion. The results from MLR analysis was used to support the development of the reaction mechanism in the microkinetic model. Some important aspects from MLR analysis can briefly be summarized as follow:

- H₂ clearly promoted the NO oxidation conversion as illustrated by its positive coefficient.
- The individual effects of NO and NO₂ were both negative on NO oxidation conversion. This can be rationalized by formation of self-inhibiting surface nitrates from NO and NO₂, since both are precursors to surface nitrates in the absence of HC.
**Kinetic analysis**

A Langmuir–Hinshelwood based reaction mechanism was used to model the oxidation of NO and H₂ involving 5 gas phase species: NO, O₂, NO₂, H₂ and H₂O. In addition, 6 surface components (NO*, O*, NO₂*, NO₃*, H* and OH*) were considered as well as vacant sites (*). Molecular adsorption was used to characterize the adsorption of NO and NO₂, whereas dissociative adsorption was used for O₂, H₂ and H₂O [103, 104]. There were 4 reversible surface reactions in the reaction network which explained the formation or consumption of NO₂*, the inhibition effect by NO₃* and the effect of H*. In total there were 18 elementary steps used in the microkinetic model. It is important to mention that the reaction mechanism was also developed based on multi-linear regression analysis using the steady state results from DOE experiments. Figure 7.2 shows all elementary steps used in the model as well as highlighting the role of H₂.

![Diagram](image.png)

**Figure 7.2** Schematic role of H₂ to promote NO oxidation and all elementary steps used in the model

An example of kinetic modeling results taken from a transient series at 400°C is shown in Figure 7.3. As seen here, the kinetic model used captured well the transient data of gas concentrations with correct trends and time-scale of responses. The activating role of H₂ by decreasing the surface nitrate coverage can be seen even at 400°C although this effect is not as high as at 250°C.
Besides NO oxidation, H$_2$ oxidation to H$_2$O is an additional reaction that occurs when H$_2$ was fed. The nature of this reaction is fast and complete conversion of H$_2$ to H$_2$O was always observed already at 250°C which is also confirmed by the model. According to the model prediction of the H$_2$ concentration profile, the H$_2$ concentration decreased rapidly at the front part of monolith to form water due to its fast reaction. In addition, the model predictions as well as calculation of a Weisz modulus indicated the importance of internal transport limitations for diffusion of H$_2$ into the washcoat.
Instead of considering only the average surface coverage throughout the monolith, the current reactor model also allowed an analysis of the local surface coverage axially along the monolith as well as through the washcoat depth for each measurement time. In addition, the distribution profile of gaseous components both throughout the washcoat and axially through the gas phase could be analyzed.

According to the modeling results, the enhancing effect of H$_2$ to reduce surface nitrate was isolated to a relatively small portion of the catalyst due to the fast reaction rate of H$_2$ oxidation (nearly 100% conversion for all experiments in this study) suggesting that internal transport resistance may play a role even for H$_2$-assisted HC-SCR with Ag-Al$_2$O$_3$. At high temperature, the effect of transport resistance was more prevalent causing the portion of the catalyst affected by H$_2$ to be even smaller. In the absence of H$_2$ in the feed, the gradient of nitrate coverage in the front part of monolith disappeared and the nitrate coverage became equal throughout the catalyst.

7.3 Kinetic modeling of H$_2$-assisted C$_3$H$_6$-SCR (Paper III)

**Paper III** presented a global kinetic model to describe the role of H$_2$ to enhance NO oxidation and C$_3$H$_6$-SCR. The overall objective here was to propose an effective global kinetic model for C$_3$H$_6$-SCR based on a mechanistic representation of the promotional effect of H$_2$. A global kinetic model was developed successively based on experiments consisting of temperature-programmed reaction (TPR) and transient series experiments, covering a comprehensive set of inlet conditions. Reaction conditions used for model development included: NO oxidation, C$_3$H$_6$ oxidation and C$_3$H$_6$-SCR with and without H$_2$. In addition, the proposed model not only simulates the reaction kinetics but also all relevant mass transport resistances in the monolith reactor.

As mentioned earlier (Chapter 3), multiple roles for the promotional effect of H$_2$ on HC-SCR have been described. Considering the many possible roles of H$_2$ suggested in the literature, it is difficult to develop a kinetic model containing a comprehensive representation of the promoting role(s) of H$_2$. However, one could broadly summarize the literature by saying that H$_2$ has been suggested to have at least two overall roles: influencing surface coverages of most notably nitrates and oxygenated hydrocarbon intermediates and modifying/forming new more active sites. Thus, the global kinetic model presented here was intended to at least contain a representation of these dual general roles of H$_2$. It has also been widely reported that the role of H$_2$ involves the formation of reactive species or intermediates. However, these may simply be a consequence of the H$_2$ effect and linked to higher SCR activity.

In the previous section (7.2), a microkinetic model for H$_2$-assisted NO oxidation was described. It was based on the single role of H$_2$ to decompose nitrates over one type of site, however for a limited range of temperature. Initial kinetic model screening during model development indicated that a model based on a single role of H$_2$ to remove inhibiting
nitrates was insufficient to well reproduce all experimental data studied here, for two reasons:

- From the NO oxidation and C<sub>3</sub>H<sub>6</sub>-SCR experimental data, NO<sub>2</sub> yield and NO<sub>x</sub> conversion are higher in the presence of H<sub>2</sub> over the entire temperature range, even at the highest temperature of 500°C (NO<sub>2</sub> yield and NO<sub>x</sub> conversion were ca. 132% and 108% higher respectively). Nitrate poisoning should play a diminishing role at higher temperature where activities with and without H<sub>2</sub> eventually become equal.

- For the current data in addition to NO oxidation, there is C<sub>3</sub>H<sub>6</sub> oxidation and C<sub>3</sub>H<sub>6</sub>-SCR reactions which are also affected to different degrees by the presence of H<sub>2</sub> as illustrated for NO oxidation and C<sub>3</sub>H<sub>6</sub>-SCR in the point above.

\[ \text{Figure 7.4 Schematic representation of reaction mechanism used in the present model} \]

Figure 7.4 presents a schematic diagram of the reaction mechanism used in the final model. For site designation, S<sub>1</sub> can be regarded as oxidized Ag sites while S<sub>2</sub> represents reduced Ag sites. The dual roles of H<sub>2</sub> were to remove inhibiting nitrates from S<sub>1</sub> and in parallel to form a new site, S<sub>2</sub>. Formation of S<sub>2</sub> is promoted by H<sub>2</sub> and is thus more active than S<sub>1</sub> for NO and H<sub>2</sub> oxidation as well as C<sub>3</sub>H<sub>6</sub>-SCR reactions. In the model, addition of NO<sub>x</sub> initiates formation of poisoning nitrates over S<sub>1</sub> denoted as S<sub>1</sub>-NO<sub>3</sub>. The proposed reaction mechanism shown by Figure 7.4 is intended to be able to replicate the following features of the experimental results:

- NO oxidation and C<sub>3</sub>H<sub>6</sub>-SCR would be promoted by H<sub>2</sub> due to removal of poisoning nitrates from S<sub>1</sub> and the simultaneous generation of S<sub>2</sub>.

- C<sub>3</sub>H<sub>6</sub> oxidation will be inhibited for experiments with NO feed by nitrates on S<sub>1</sub>. However, in the presence of NO and H<sub>2</sub> feed, C<sub>3</sub>H<sub>6</sub> consumption will increase due to removal of nitrates from S<sub>1</sub> that gives higher C<sub>3</sub>H<sub>6</sub> oxidation and generation of S<sub>2</sub> that is more active for C<sub>3</sub>H<sub>6</sub>-SCR.

- For experiments with NO feed, H<sub>2</sub> consumption will be greater because it removes nitrates from S<sub>1</sub> and generates S<sub>2</sub>. 

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At higher temperatures, $C_3H_6$ and $H_2$ oxidation by NO$_2$ will occur over $S_1$.

Table 7-2 presents the reactions used in the final model including two types of active sites, $S_1$ and $S_2$. To keep the model as simple as possible, first order reactions with respect to each reactant, surface species or site vacancy were assumed for reaction rates. For all reactions that were intended to occur on a site, their rates were set proportional to the quantity of that site (e.g. $S_2$) or the quantity of the vacant site ($S_1$ free of nitrate). Sites were conserved by the following balance, fulfilled by the model:

$$\theta_{S_1} + \theta_{S_1-NO_3} + \theta_{S_2} = 1$$  \hspace{1cm} (7.1)

Further, for all reactions involving O$_2$ the reaction orders with respect to O$_2$ were lumped with the kinetic parameters. In addition, the reversible surface reactions of oxidized $S_1$ site to reduced $S_2$ site and vice versa (reactions 7 and 8 in Table 7-2) should also involve formation and consumption of oxygen. However, since the stoichiometries of these reactions are not exactly known, they are neglected. Since all experiments were always performed under conditions with a large excess of O$_2$, the changes in O$_2$ concentration due to reactions were small. As a result, neglecting oxygen formation/consumption has a negligible impact on the modeling results.
Table 7-2 Reaction mechanism and reaction rate used in the kinetic model

<table>
<thead>
<tr>
<th>No.</th>
<th>Reaction</th>
<th>Reaction rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NO oxidation over S₁ and S₂</td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>NO (g) + 0.5 O₂(g) ( \overset{s_1}{\leftrightarrow} ) NO₂ (g)</td>
<td>( r_{1a} = k_{1a} \cdot \left( y_{NO} - \frac{1}{K_{eq_{1,T}}} \cdot y_{NO2} \right) \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td>1b</td>
<td>NO (g) + 0.5 O₂(g) ( \overset{s_2}{\leftrightarrow} ) NO₂ (g)</td>
<td>( r_{1b} = k_{1b} \cdot \left( y_{NO} - \frac{1}{K_{eq_{1,T}}} \cdot y_{NO2} \right) \cdot \theta_{S_2} )</td>
</tr>
<tr>
<td></td>
<td>H₂ oxidation over S₁ and S₂</td>
<td></td>
</tr>
<tr>
<td>2a</td>
<td>H₂ (g) + 0.5 O₂(g) ( \overset{s_1}{\rightarrow} ) H₂O (g)</td>
<td>( r_{2a} = k_{2a} \cdot y_{H_2} \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td>2b</td>
<td>H₂ (g) + 0.5 O₂(g) ( \overset{s_2}{\rightarrow} ) H₂O (g)</td>
<td>( r_{2b} = k_{2b} \cdot y_{H_2} \cdot \theta_{S_2} )</td>
</tr>
<tr>
<td></td>
<td>C₃H₆ oxidation over S₁</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>C₃H₆ (g) + 4.5 O₂(g) ( \overset{s_1}{\rightarrow} ) 3CO₂ (g) + 3H₂O (g)</td>
<td>( r_3 = k_3 \cdot y_{C_3H_6} \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td></td>
<td>C₃H₆ and H₂ oxidation with NO₂ over S₁</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>NO₂ (g) + H₂ (g) ( \overset{s_1}{\rightarrow} ) NO (g) + H₂O (g)</td>
<td>( r_4 = k_4 \cdot y_{NO2} \cdot y_{H_2} \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td>5</td>
<td>9NO₂ (g) + C₃H₆(g) ( \overset{s_1}{\rightarrow} ) 3CO₂ (g) + 9NO(g) + 3H₂O (g)</td>
<td>( r_5 = k_5 \cdot y_{NO2} \cdot y_{C_3H_6} \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td></td>
<td>Surface reaction: nitrate formation and removal</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>NO (g) + O₂(g) + S₁ ( \leftrightarrow ) S₁ - NO₃</td>
<td>( r_6 = k_6 \cdot \left( y_{NO} \theta_{S_1} - \frac{1}{K_{eq_{2,T}}} \cdot \theta_{S_1-NO3} \right) )</td>
</tr>
<tr>
<td></td>
<td>*( \approx 0 )†</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( K_{eq_{2,T}} = \frac{\theta_{S_1-NO3}}{y_{NO} \cdot \theta_{S_1}} )</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>2 H₂(g) + S₁ - NO₃ ( \rightarrow ) NO(g) + 2H₂O(g) + S₂</td>
<td>( r_7 = k_7 \cdot y_{H_2} \cdot \theta_{S_1-NO3} )</td>
</tr>
<tr>
<td>8</td>
<td>S₂ ( \rightarrow ) S₁</td>
<td>( r_8 = k_8 \cdot \theta_{S_2} )</td>
</tr>
<tr>
<td></td>
<td>C₃H₆ SCR over S₁ and S₂</td>
<td></td>
</tr>
<tr>
<td>9a</td>
<td>C₃H₆ (g) + NO (g) + 4 O₂(g) ( \overset{s_1}{\rightarrow} ) 0.5N₂ + 3CO₂ + 3H₂O (g)</td>
<td>( r_{9a} = k_{9a} \cdot y_{C_3H_6} \cdot y_{NO} \cdot \theta_{S_1} )</td>
</tr>
<tr>
<td>9b</td>
<td>C₃H₆ (g) + NO (g) + 4 O₂(g) ( \overset{s_2}{\rightarrow} ) 0.5N₂ + 3CO₂ + 3H₂O (g)</td>
<td>( r_{9b} = k_{9b} \cdot y_{C_3H_6} \cdot y_{NO} \cdot \theta_{S_2} )</td>
</tr>
</tbody>
</table>

†) quasi-equilibrium imposed

The kinetic parameter fitting was carried out in stages, where parameters for reactions that were exclusive to experimental sets were fitted first. Then for experimental sets involving additional reactions, the additional parameters were successively fitted. A complete list of kinetic parameters can be found in Paper III. From statistical analyses, all kinetic parameters were found to be significant within 95% confidence intervals. An example of the results
from the proposed model for temperature-programmed reaction of H$_2$-assisted C$_3$H$_6$-SCR is shown in Figure 7.5

![Figure 7.5](image)

**Figure 7.5** Comparison between simulation and experimental data for H$_2$-assisted C$_3$H$_6$-SCR. Inlet feed: 500 ppm NO, 1000 ppm C$_3$H$_6$, 8% O$_2$, 1000 ppm H$_2$, 5% H$_2$O.

**The effect of varying C$_3$H$_6$ and H$_2$ concentrations**

Transient experiments involving stepwise increasing C$_3$H$_6$ and H$_2$ concentrations were also conducted at 375°C. In the absence of H$_2$, the catalyst was inactive for SCR at this temperature and increasing C$_3$H$_6$ concentration did not promote SCR activity since NO$_x$ conversion was always below 2%, as also predicted well by the model. C$_3$H$_6$ consumption and NO oxidation at this temperature were also negligible which is in agreement with the previous TPR data.

Figure 7.6a shows the effect of C$_3$H$_6$ on H$_2$-assisted C$_3$H$_6$-SCR. By increasing stepwise the C$_3$H$_6$ feed concentration, the resulting increase of NO$_x$ conversion was captured well by the model. From the dynamics of the surface species, it was found that the changes in all surface species were negligible. These modeling results indicate that a first order dependence on C$_3$H$_6$ concentration for SCR as shown by reaction 9a and 9b in Table 7-2 appears satisfactory. Further, the model prediction for the activation energy of reaction 9b (ca. 64 kJ/mol) is lower than the SCR reaction on reaction 9a (ca.186 kJ/mol). From the dynamic changes in NO$_x$ conversion and gas concentrations, it was apparent that the effect of increasing C$_3$H$_6$ concentration was immediate and the model reproduced this behavior well.
Figure 7.6 Comparison between simulation and experimental data to investigate the effect of varying C₃H₆ concentration for H₂-assisted C₃H₆-SCR (a, top panel) and varying H₂ concentration for H₂-assisted C₃H₆-SCR (b, bottom panel). Inlet feed: (a) 500 ppm NO, 500–2500 ppm C₃H₆, 8% O₂, 1000 ppm H₂, 5% H₂O, (b) 500 ppm NO, 1000 ppm C₃H₆, 8% O₂, 0–2000 ppm H₂, 5% H₂O.

Finally, the promotional effect of H₂ was examined by varying the H₂ feed concentration from 0 to 2000 ppm (Figure 7.6b). The increase in NOₓ conversion is immediate along with higher H₂ concentration. They also resulted in higher S₂ coverages and lower nitrate coverage on S₁ (S₁-NO₃). However, the fractional vacancy of the site S₁ is nearly stable. As a result, the model predicts a higher reaction rate for H₂-assisted C₃H₆-SCR by reaction 9b due to higher availability of S₂. Related to C₃H₆ consumption, a nearly constant S₁ and higher S₂ means that higher C₃H₆ consumption is almost exclusively due to higher SCR activity.
**Evaluation of mass transport resistances**

Discretization in both axial and radial direction facilitates an investigation of possible mass transfer effects for each measurement time. This is illustrated by Figure 7.7 showing a surface plot of NO concentration during H$_2$-assisted C$_3$H$_6$-SCR experimental conditions at 450°C.

![Figure 7.7](image)

Figure 7.7 Bulk gas and washcoat NO concentration predicted by model at 450°C during H$_2$-assisted C$_3$H$_6$-SCR. (a) top view over monolith washcoat (unscaled dimensions) (b) bulk gas and surface plot over washcoat.

As shown here, NO concentration drops steadily in the axial direction as it is consumed via NO oxidation and SCR reactions. An NO concentration gradient through the depth of the washcoat of as much as 80 ppm is observable at the monolith inlet (Figure 7.7b). This indicates some influence of internal pore mass transfer resistance for NO at 450°C. For the same results at 200°C, an NO concentration gradient of only 8 ppm was observed which indicates that mass transfer resistance is stronger, as expected, at high temperatures.

To further evaluate internal mass transfer resistance as a function of temperature, the Weisz moduli were calculated for NO, C$_3$H$_6$ and H$_2$ during H$_2$-assisted C$_3$H$_6$-SCR as well as C$_3$H$_6$-SCR. The results of calculation for H$_2$-assisted C$_3$H$_6$-SCR were plotted in Figure 9 of [Paper III](#). Under H$_2$-assisted C$_3$H$_6$-SCR conditions, NO was found to be mildly influenced by internal mass transfer between 250-500°C. While calculations for C$_3$H$_6$ and H$_2$ under the same conditions showed that only a small portion of the data (notably above 400°C) were influenced by mass transport resistance. Similar analyses for NO and C$_3$H$_6$ under C$_3$H$_6$-SCR condition indicated that the influence of internal mass transfer only played role at high temperature above 436°C. Since mass transport resistance was found to be important at higher temperature and under specific reaction conditions, it can be concluded that a larger fraction of experimental data gathered in the present study was nevertheless free from the influence of mass transport resistances.
Chapter 8

Surface species quantification as a support for SCR modeling

Kinetic models to describe the effects of $H_2$ to promote NO oxidation and $C_3H_6$-SCR over $Ag/Al_2O_3$ catalysts have been constructed in Chapter 7. In the kinetic model of Paper III, dual roles of $H_2$ were proposed to facilitate removal of nitrate as well as formation of more active Ag sites. These two key factors enabled simulation of NO oxidation and $C_3H_6$-SCR cases for a wide variety of feed mixtures and temperatures.

In addition, temperature-programmed desorption (TPD) studies of NO$_x$ over $Ag/Al_2O_3$ and $Al_2O_3$ as a way to probe nitrate species formed on the catalyst have been presented in Chapter 6 / Paper I. There, the dual roles of $H_2$ to influence nitrate species were verified. It was shown that $H_2$ played a role in removing inhibiting nitrate on active sites as well as to facilitate storage of inactive nitrate species mainly on the catalyst support. Hence, it is of interest to envisage the applicability of TPD experiments to provide an estimate of surface NO$_x$ quantity, which thus may improve the existing $C_3H_6$-SCR kinetic model in Paper III.

8.1 Experimental estimation of surface NO$_x$ species using TPD technique

A series of TPD experiments have been conducted as a way to estimate the amount of various nitrate species over Ag-$Al_2O_3$ catalyst based on similar TPD protocols conducted previously in Paper I. Figure 8.1 shows the NO$_x$ desorption peaks during temperature ramps (desorption step) that were preceded by adsorption treatments with NO oxidation and $H_2$-assisted NO oxidation. The previous TPD studies in Paper I showed that there were 2 easily discernible types of NO$_x$ desorption peaks, identified as low temperature and high temperature peaks. As seen in Figure 8.1 for NO oxidation pretreatments, the NO$_x$ desorption peaks assignable to low temperature and high temperature peaks were not clearly distinguishable. Therefore, a fitting procedure to separate NO$_x$ desorption peaks was carried out using an open access peakfit function in Matlab [105]. The results from the peak-fitting procedure using Gaussian functions are also presented in Figure 8.1.
Deconvolution of NO\textsubscript{x} desorption peaks over 2 wt.% Ag-\textsubscript{2}Al\textsubscript{2}O\textsubscript{3} during temperature ramp in Ar flow. The plots show the raw data (blue), fitted functions (red) and deconvoluted peaks (green). Preceding adsorption conditions are: 500 ppm NO+8%O\textsubscript{2} (left panels) or 500 ppm NO+8%O\textsubscript{2}+0.1%H\textsubscript{2} (right panels).

The results from peak fitting of NO\textsubscript{x} desorption peaks (Figure 8.1) identified the presence of 3 types of surface NO\textsubscript{x} species denoted as peak I, peak II and peak III, respectively. Integration of each peak yielded the amount of NO\textsubscript{x} species (in \(\mu\text{mol}\cdot\text{g}^{-1}\)) and is displayed in Table 8-1. For comparison, the concentration of atomic Ag in 2 wt.% Ag-\textsubscript{2}Al\textsubscript{2}O\textsubscript{3} catalyst is 185 \(\mu\text{mol}\cdot\text{g}^{-1}\).

Figure 8.1 and Table 8-1 show that peak I and peak II are the dominant desorption peaks following NO oxidation pretreatment. Whereas, peak II and peak III are the only desorption peaks observed following H\textsubscript{2}-assisted NO oxidation. As shown in Table 8-1, the quantity of NO\textsubscript{x} desorbed in all peaks generally decreased with higher adsorption temperatures.
Table 8-1 Approximation of NO\(_x\) quantities during desorption step shown in Figure 8.1

<table>
<thead>
<tr>
<th>Adsorption temperatures with NO+O(_2) pretreatment</th>
<th>Peak I (μmol.g(^{-1}))</th>
<th>Peak II (μmol.g(^{-1}))</th>
<th>Peak III (μmol.g(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>44.4</td>
<td>15.2</td>
<td>-</td>
</tr>
<tr>
<td>250°C</td>
<td>31.9</td>
<td>11.3</td>
<td>-</td>
</tr>
<tr>
<td>300°C</td>
<td>9.6</td>
<td>11.5</td>
<td>-</td>
</tr>
<tr>
<td>350°C</td>
<td>-</td>
<td>1.3</td>
<td>4.3</td>
</tr>
<tr>
<td>400°C</td>
<td>-</td>
<td>-</td>
<td>1.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Adsorption temperatures with NO+O(_2)+H(_2) pretreatment</th>
<th>Peak I (μmol.g(^{-1}))</th>
<th>Peak II (μmol.g(^{-1}))</th>
<th>Peak III (μmol.g(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>200°C</td>
<td>-</td>
<td>25.7</td>
<td>41.9</td>
</tr>
<tr>
<td>250°C</td>
<td>-</td>
<td>20.1</td>
<td>32.1</td>
</tr>
<tr>
<td>300°C</td>
<td>-</td>
<td>10.9</td>
<td>20.6</td>
</tr>
<tr>
<td>350°C</td>
<td>-</td>
<td>5.0</td>
<td>11.5</td>
</tr>
<tr>
<td>400°C</td>
<td>-</td>
<td>1.4</td>
<td>4.9</td>
</tr>
</tbody>
</table>

8.2 Interpretation of surface NO\(_x\) species to give insights for mechanistic study

With the addition of H\(_2\), the NO oxidation activity over the Ag/Al\(_2\)O\(_3\) catalyst is largely promoted nearly at all temperatures as shown in Figure 3.2b. It is thus of interest to relate the results from the TPD in Figure 8.1 with the mechanistic study of H\(_2\)-assisted NO oxidation or H\(_2\)-assisted C\(_3\)H\(_6\)-SCR. As suggested in Figure 8.1, there are 3 types of surface NO\(_x\) species that can be related to nitrate species (see DRIFTS results on Figure 6.3). Peak I observed in Figure 8.1 could be associated to the low temperature peak as observed in Figure 6.1, which implies that this peak can then be attributed to the nitrate species located on the active part of the catalyst.

Addition of H\(_2\) caused a notable increase in the quantities of peak II and peak III (Table 8-1). As a result, peak II and peak III can then be related to the high temperature peak previously observed in Figure 6.1. These peaks are likely to originate from the decomposition of inert nitrate species mainly on the Al\(_2\)O\(_3\) support.

As addressed in the beginning of this chapter, it is of interest to demonstrate the applicability of NO\(_x\) TPD in Figure 8.1 as a way to improve the kinetic model of C\(_3\)H\(_6\)-SCR. Experimental estimation of surface species would help the model to better predict the quantity of surface species. To implement this, a residual calculation for the quantity of surface species can be included in addition to the residual calculation for gas composition in the objective function of the parameter estimation for the kinetic model.

Paper II and III addressed that one crucial role of H\(_2\) in improving low temperature activities of SCR and NO oxidation is to eliminate inhibiting nitrate species viz. peak I. With the aid of the current model in Paper III, kinetic parameters describing elimination of peak I by H\(_2\) can be re-tuned to follow the same trend as in Table 8-1. Similarly, the increase in NO oxidation
conversion with the increase in temperature can also be explained by the decrease of peak I.

In addition, the quantification of NO\textsubscript{x} storage based on peaks II and III in Figure 8.1 may also serve as a basis to reveal the mechanism of H\textsubscript{2}-induced NO\textsubscript{x} storage on Ag/Al\textsubscript{2}O\textsubscript{3} catalyst. As addressed earlier, these peaks are attributable to the nitrate species probably on the Al\textsubscript{2}O\textsubscript{3} support. A mechanistic study of the storage process for instance through a readsorption or spill-over mechanism can be envisaged from a modeling point of view. From literature, the concept of NO\textsubscript{x} storage and reduction (NSR) over Ag/Al\textsubscript{2}O\textsubscript{3} catalysts with the aid of H\textsubscript{2} to abate low temperature NO\textsubscript{x} emission has been recently reported by Tamm et al [106, 107] as well as by a group at General Motors [108]. Therefore, a mechanistic study of the H\textsubscript{2} effect on the NO\textsubscript{x} storage mechanism will also be advantageous for development of possible NSR processes involving a Ag/Al\textsubscript{2}O\textsubscript{3} catalyst.
Chapter 9

Evaluation of the H\textsubscript{2} effect on DOC

Addition of H\textsubscript{2} as a way to improve the NO oxidation activity over DOC has been presented by Herreros et al. [22] in an engine bench study. In order to gain a deepened insight into H\textsubscript{2} effects on DOC, a systematic investigation on a lab-sized monolith supported Pt/Al\textsubscript{2}O\textsubscript{3} catalyst was performed as presented in Paper IV. The effect of CO and C\textsubscript{3}H\textsubscript{6} in the inlet feed, combined with different concentrations of H\textsubscript{2}, was investigated. In addition, transient experiments with H\textsubscript{2} switched in and out of the feed were also conducted to identify the time scale of the H\textsubscript{2} effect with various gas mixtures. Eventually, the surface chemistry and exothermal heat effect due to H\textsubscript{2} addition could also be discriminated.

9.1 The effect of H\textsubscript{2} with various gas mixtures

In order to investigate the effect of H\textsubscript{2} on Pt/Al\textsubscript{2}O\textsubscript{3}, activity measurements using temperature-programmed reaction (TPR) experiments were conducted. Table 9-1 displays the synthetic exhaust gas inlet compositions used in the TPR experiments.

<table>
<thead>
<tr>
<th>Gas mixture notation</th>
<th>Inlet composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO/O\textsubscript{2}</td>
<td>500 ppm NO, 8% O\textsubscript{2}, 5% H\textsubscript{2}O</td>
</tr>
<tr>
<td>NO/O\textsubscript{2}/CO</td>
<td>500 ppm NO, 8% O\textsubscript{2}, 200 ppm CO, 5% H\textsubscript{2}O</td>
</tr>
<tr>
<td>NO/O\textsubscript{2}/C\textsubscript{3}H\textsubscript{6}</td>
<td>500 ppm NO, 8% O\textsubscript{2}, 200 ppm C\textsubscript{3}H\textsubscript{6}, 5% H\textsubscript{2}O</td>
</tr>
<tr>
<td>NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6}</td>
<td>500 ppm NO, 8% O\textsubscript{2}, 200 ppm C\textsubscript{3}H\textsubscript{6}, 200 ppm CO, 5% H\textsubscript{2}O</td>
</tr>
</tbody>
</table>

Prior to each experiment, a pretreatment was conducted to obtain a Pt oxide free surface over the catalyst. For this purpose, the catalyst was exposed consecutively to the following oxidative and reductive dry atmospheres at 450°C:

- 10% O\textsubscript{2} in Ar (balance in all experiments) with duration of 20 min.
- 2% H\textsubscript{2} in Ar with duration of 30 min.

Figure 9.1 shows the results of the H\textsubscript{2} effect on NO oxidation as a function of catalyst temperature with various gas mixtures, during TPR heating ramps that were preceded by
catalyst pretreatment and inert cooling steps. The “catalyst temperature” here is a measure of the temperature near the outlet end of the monolith. Despite the presence of oxidation reactions that caused increased axial temperature gradients, the use of catalyst temperature should in fact provide a very modest estimate of any promotional effects of H₂ minus exothermal heat effects.

Figure 9.1 The effect of H₂ concentration on NO oxidation over Pt/Al₂O₃ with various gas mixtures during heating ramp following pretreatment of the catalyst. Total flow of 3000 ml/min was used with Ar balance equivalent to GHSV of ca. 29000 h⁻¹ or WHSV of 562 h⁻¹. See table 9.1 for inlet feed condition.

Generally, the effect of H₂ on the NO₂ yield varied, depending upon the temperature region and feed H₂ concentration. Measurement of the H₂ signal (not shown) indicated that H₂ was generally already fully converted by 200°C in all cases, even with the highest H₂ concentration. It is also noteworthy that above 300°C, the NO₂ yield should be limited by thermodynamic equilibrium as reported in [19]. The onset of equilibrium is evident in Figure 9.1 for all gas mixtures by the leveling off and even eventual decrease in NO₂ yields at temperatures above 300°C.

Figure 9.1a shows the result for the NO/O₂ mixture where addition of H₂ had both negative and positive effects on the NO₂ yield. At low temperature (below 200°C), addition of H₂ lowered the NO₂ yield. However, between 200-300°C, H₂ was found to enhance the NO₂ yield in this mixture. Additionally, it was also found that addition of H₂ up to 750 ppm improved the NO₂ yield, however with 1000 ppm H₂ the NO₂ yield started to decrease.

Figure 9.1b shows the result for the NO/O₂/CO gas mixture. It was observed that H₂ had little effect on the NO₂ yield, although a marginal increase in the NO₂ yield could still be
seen between 180-300°C with higher H\textsubscript{2} concentration. Addition of H\textsubscript{2} also lowered the temperature to attain complete CO conversion from ca. 135°C in the absence of H\textsubscript{2} to ca. 126°C in the presence of 1000 ppm of H\textsubscript{2}.

As shown in Figure 9.1c for the NO/O\textsubscript{2}/C\textsubscript{3}H\textsubscript{6} mixture, a strong inhibition effect of C\textsubscript{3}H\textsubscript{6} on the NO oxidation was observed by the delayed light-off for NO oxidation to at least 220°C. Addition of H\textsubscript{2} was however found to decrease the light-off temperature as well as to increase the NO\textsubscript{2} yield within a temperature range of 220-325°C. As the onset for C\textsubscript{3}H\textsubscript{6} conversion started, there was also detectable formation of CO which was probably due to partial oxidation of C\textsubscript{3}H\textsubscript{6}.

Eventually, the effect of H\textsubscript{2} was also investigated on a complete mixture of NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6} (Figure 9.1d). An increase of the H\textsubscript{2} concentration was found to decrease the light-off temperature for NO, C\textsubscript{3}H\textsubscript{6} and CO oxidation. Further, addition of low amounts of H\textsubscript{2} such as 250 ppm H\textsubscript{2} was found to be beneficial for the NO\textsubscript{2} yield in the temperature range above 220°C. Addition of higher H\textsubscript{2} concentrations, however, gave a lower NO\textsubscript{2} yield above 240°C. The detrimental effect of H\textsubscript{2} was most prominent with H\textsubscript{2} concentrations of 750 and 1000 ppm.

9.2 The effect of H\textsubscript{2} to influence hysteresis

![Figure 9.2 The effect of H\textsubscript{2} to influence the hysteresis of NO oxidation over 1 wt.% Pt/Al\textsubscript{2}O\textsubscript{3} catalyst.](image)

As addressed in Chapter 3, the hysteresis phenomenon during NO oxidation over Pt/Al\textsubscript{2}O\textsubscript{3} is commonly reported in literature. In connection with hysteresis, PtO formation is often proposed as the reason behind different activities during heating and cooling ramps [15]. Figure 9.2 demonstrates the results of TPR from heating and cooling ramps during NO oxidation reaction over Pt/Al\textsubscript{2}O\textsubscript{3} with and without H\textsubscript{2}. As seen here, addition of 1000 ppm of H\textsubscript{2} altered the heating and cooling curves (Figure 9.2b), which resulted in a broadened hysteresis loop compared to that in the absence of H\textsubscript{2} (Figure 9.2a).
9.3 Transient NO\(_2\) yields at constant temperature

It has been shown in literature that the NO oxidation conversion decreases as a function of time due to the gradual build-up of Pt oxide [13]. In connection to the H\(_2\) promotional effect, it was therefore of interest to investigate if H\(_2\) may influence the decay in the NO oxidation activity as well as the dynamic effect of H\(_2\) to influence NO oxidation in various mixtures.

![Figure 9.3](image)

**Figure 9.3** The evolution of the normalized NO\(_2\) signal for various gas mixtures as a function of time. The reactor was heated from 120 to 230°C and held constant at 230°C for 1h.

Figure 9.3 presents the evolution of the normalized NO\(_2\) signal for various gas mixtures as a function of time. The NO\(_2\) signal was rescaled to the values within a range of 0 to 1 by normalization based on the maximum and minimum NO\(_2\) outlet signals over the time range. As seen here, when the temperature was held constant, there was a substantial decrease in the NO\(_2\) signal as it dropped by as much as 30% from its maximum value. A comparison of the NO/O\(_2\) mixture with the other H\(_2\)-containing gas mixtures, shows that the rate of decay of the NO\(_2\) yields were similar. In fact, there was a slightly faster rate of decrease in NO\(_2\) observed for NO/O\(_2\) with H\(_2\) compared to without H\(_2\).

9.4 Transient experiments with in/out H\(_2\) switching

To determine the dynamic effect of H\(_2\) with various gas mixtures, transient experiments involving switching in/out H\(_2\) were conducted and the results are presented in Figure 9.4. Similar to Figure 9.3, generally one can still observe a decline in the NO\(_2\) signal as a function of time for all gas mixtures, despite the periodic switching of H\(_2\). MS measurements indicated that H\(_2\) was always fully converted in all cases.
Figure 9.4 The dynamic effects of switching in and out 750 ppm of H₂ with different gas mixtures (see Table 9-1). The catalyst was previously exposed to TPR by cofeeding 750 ppm of H₂ with corresponding gas mixture from 120 to 230°C and held constant at 230°C.

Introduction of 750 ppm of H₂, clearly caused the catalyst temperature (T_cat) to increase for all gas mixtures (Table 9-2). The temperature rise was naturally due to the exothermal H₂ combustion and was most prominently observed for the C₃H₆ containing mixtures. Therefore, the response of the NO₂ signal due to switching H₂ feed on and off, is due not only to possible effects of H₂ on surface chemistry and reactions but also to the temperature variations.

Table 9-2 Catalyst temperatures during exposure of catalyst intermittently with 750 ppm H₂ with set point inlet gas temperature of 230°C

<table>
<thead>
<tr>
<th>Gas mixtures</th>
<th>Approximate catalyst temperature (°C) without H₂</th>
<th>with 750 ppm H₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO/O₂</td>
<td>227-228</td>
<td>232-233</td>
</tr>
<tr>
<td>NO/O₂/CO</td>
<td>228-230</td>
<td>234-235</td>
</tr>
<tr>
<td>NO/O₂/C₃H₆</td>
<td>235-237</td>
<td>245-246</td>
</tr>
<tr>
<td>NO/O₂/CO/C₃H₆</td>
<td>233</td>
<td>247-248</td>
</tr>
</tbody>
</table>

For the NO/O₂ mixture (Figure 9.4a), feeding in H₂ generally caused a lower NO₂ yield, which is contrary to the corresponding TPR results (Figure 9.1a). In contrast to the effect of H₂ on the NO/O₂ mixture, the effect of H₂ on the NO/O₂/CO mixture was found to be positive by giving higher NO₂ yields in the presence of H₂ (Figure 9.4b). In addition, complete conversion of CO was always observed under these conditions as indicated by the CO₂ signal.
The dynamic effect of H\textsubscript{2} on C\textsubscript{3}H\textsubscript{6} containing gas mixtures is shown in Figure 9.4c and d. Addition of H\textsubscript{2} in these cases caused a notable increase not only in the NO\textsubscript{2} yield but also a slight increase in N\textsubscript{2}O formation. It could also be seen that the effect of H\textsubscript{2} was almost instantaneous on the NO\textsubscript{2} yield when switched in, however, when switched out it declined more slowly over about 5 min, nearly following the decline in the catalyst temperature. For the NO/O\textsubscript{2}/C\textsubscript{3}H\textsubscript{6} mixture (Figure 9.4c), a remarkable increase in the NO\textsubscript{2} yield from 60 ppm to ca. 150 ppm could be observed in the second H\textsubscript{2} switch cycle (at ca. 1200 s). Observation at the same transient time for the NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6} mixture indicates that addition of H\textsubscript{2} increased the NO\textsubscript{2} yield from 15 ppm to ca. 150 ppm (Figure 9.4d). From Figure 9.4c and d, complete conversion of C\textsubscript{3}H\textsubscript{6} was always observed in the presence of H\textsubscript{2}, whereas in the absence of H\textsubscript{2}, C\textsubscript{3}H\textsubscript{6} was detected in the outlet stream. The same also applies for CO in the NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6} mixture as depicted in Figure 9.4d.

9.5 Discrimination of heat and chemical effects due to addition of H\textsubscript{2}

The transient results presented in Figure 9.4 can also be used to probe the characteristics of the H\textsubscript{2} effect by comparing the response times for the NO\textsubscript{2} yield and catalyst temperature. Figure 9.5 shows the response of normalized NO\textsubscript{2} yields, H\textsubscript{2} feed and catalyst temperature upon introduction of H\textsubscript{2}. Each of the values was rescaled in the range of 0 to 1 by normalization based on their maximum and minimum values within the time range. Additionally, a minor time lag between FTIR and temperature measurements was neglected.

![Figure 9.5](image)

*Figure 9.5* The normalized NO\textsubscript{2}, H\textsubscript{2} feed and catalyst temperature signals from the second cycles (ca. 1200 s) in Figure 9.4 with corresponding gas mixtures.

As presented in Table 9-2, the increase in the catalyst temperature was due to the exothermal heat from H\textsubscript{2} combustion, but also in some cases the increased oxidation of CO and C\textsubscript{3}H\textsubscript{6} caused by the H\textsubscript{2} feed. However it started to increase only about 15 s after the start of H\textsubscript{2} feed, due to the thermal inertia of the catalyst, monolith and glass tube encasing the monolith.

For both NO/O\textsubscript{2} (Figure 9.5 left panel) as well as NO/O\textsubscript{2}/CO mixtures (see Figure 9 in Paper IV), the NO\textsubscript{2} signal first decreased when H\textsubscript{2} feed started and then it increased at about the same rate as temperature began to increase. The negative effect on the NO\textsubscript{2} yield
immediately following H\textsubscript{2} feed, indicated the presence of a rapid chemical effect which lowered the NO\textsubscript{2} yield. Subsequently, the gradual increase in NO\textsubscript{2} in parallel with the temperature increase indicated that this NO\textsubscript{2} increase was most likely merely resulting from heat effects.

However, for both NO/O\textsubscript{2}/C\textsubscript{3}H\textsubscript{6} (Figure 9.5, right panel) and NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6} (see Figure 9 in Paper IV) mixtures, the NO\textsubscript{2} signal immediately increased when the H\textsubscript{2} feed was switched in. Afterwards, the NO\textsubscript{2} continued to increase along with the catalyst temperature. Again, the immediate increase of NO\textsubscript{2} along with H\textsubscript{2} feed shows the presence of H\textsubscript{2} chemical effects that beneficially alter surface species or reactions to increase the NO\textsubscript{2} yield.

### 9.6 Influence of H\textsubscript{2} on Pt oxide formation

It is generally accepted that Pt oxide formation is the phenomenon causing hysteresis behavior of NO oxidation over Pt/Al\textsubscript{2}O\textsubscript{3} during TPR experiments \cite{15}. With the aid of Figure 9.2, one can observe that addition of H\textsubscript{2} modified the hysteresis behavior. This implies that H\textsubscript{2} likely plays a role to influence Pt oxide formation. The extent of Pt oxide formation and the resulting hysteresis is reported to be related to the amount of NO\textsubscript{2} at medium and high temperatures near the thermodynamic equilibrium \cite{15, 109}. This is due to the strong oxidative power of NO\textsubscript{2} to promote Pt oxide formation \cite{13}.

As seen from Figure 9.1a for the NO/O\textsubscript{2} mixture, addition of H\textsubscript{2} improved the NO\textsubscript{2} yield in the temperature range of 200-300°C. Improvement of the NO\textsubscript{2} yield can be associated with H\textsubscript{2} preventing the formation of inactive Pt oxide over the catalyst. Deactivation due to Pt oxide formation is obviously a slow process, occurring on the scale of several minutes as illustrated by Figure 9.3. Also, at least at 230°C, it occurs for all of the gas mixtures with or without H\textsubscript{2}. It is likely then that H\textsubscript{2} hinders Pt oxide formation during the TPR, only at low temperatures, mostly below 200°C, when H\textsubscript{2} conversion was less than complete. However, at temperatures above 200°C, Pt oxide starts to form towards the rear part of the monolith which is no longer exposed to H\textsubscript{2}, but is required for NO oxidation. The result is that the promotion of NO\textsubscript{2} formation with H\textsubscript{2} during the TPR with the NO/O\textsubscript{2} mixture was a temporary effect. It results from H\textsubscript{2} retarding Pt oxide formation at low temperature and the rate of Pt oxide formation lagging behind that of the temperature increase. As illustrated by Figure 9.3 and Figure 9.4a, when the temperature ramp was stopped at 230°C, the Pt oxide formation was able to catch up and overtake the effect of the temperature increase. For operation at 230°C (Figure 9.4a), there was no longer any benefit remaining from any earlier retardation of Pt oxide formation. In addition, the transient experiment with NO/O\textsubscript{2} (Figure 9.5) also demonstrated that switching in H\textsubscript{2} gave an immediate decrease in the NO\textsubscript{2} yield, which was probably due to H\textsubscript{2} reacting with NO\textsubscript{2} facilitated by the catalyst.

The results from Figure 9.1 also indicate that the presence of CO in the absence of H\textsubscript{2} generally gave higher NO\textsubscript{2} yield for NO/O\textsubscript{2} as in agreement with \cite{15}. Similar to H\textsubscript{2}, this enhancement effect of CO on NO oxidation is presumably due to the role of CO to retard Pt...
oxidation at low temperature below 135°C when CO was still detectable in the outlet stream [15, 21]. With the relatively low CO concentration used here (200 ppm), it appears from comparison of Figure 9.1a and Figure 9.1b that CO has only a weak inhibition effect on NO oxidation. When H₂ and CO coexist, it is apparent that both species share the same function to retard Pt oxide formation. As a result, addition of H₂ to the NO/O₂/CO mixture resulted in only a marginal increase in the NO₂ yield. The addition of H₂ at 230°C to NO/O₂/CO (Figure 9.4b) had only a minor influence on the NO₂ yield. An immediate negative effect of H₂ on NO₂ yield can be due to surface reaction between H₂ and NO₂.

9.7 H₂ influence on C₃H₆ and CO oxidation and interactions with NO oxidation

In C₃H₆ containing mixtures, it is evident that C₃H₆ has a strong inhibition effect on NO oxidation at low temperature, before the onset of C₃H₆ oxidation (Figure 9.1c and d). Addition of H₂ was found to weaken the inhibition effect of C₃H₆ by lowering the light-off temperature for C₃H₆ oxidation which in turn promoted NO oxidation. It is also notable that C₃H₆ caused the light-off temperature for CO oxidation to increase approximately 25°C. In contrast, the first detection of NO₂ formation was delayed by about 100°C or until almost complete conversion of C₃H₆ was obtained. This demonstrates how C₃H₆ has a considerably larger inhibiting effect on NO oxidation than CO oxidation. In contrast, the effect of CO to inhibit C₃H₆ conversion through competitive adsorption was also small probably due to the low concentration of CO used here.

It has been suggested that C₃H₆ inhibits NO oxidation by reaction of C₃H₆ with NO₂ to form NO particularly at low temperatures [20, 110] as illustrated in the reaction below:

\[ C_3H_6(g) + 9NO_2(g) \rightarrow 3CO_2(g) + 3H_2O(g) + 9NO(g) \]  \hspace{1cm} (9.1)

There is also the possibility that C₃H₆ preferentially adsorbs on sites and thus blocks both NO and CO oxidation. Undoubtedly both of these inhibition mechanisms play a role. However, considering that C₃H₆ has a much stronger inhibition effect on NO oxidation rather than on CO oxidation, the reaction of C₃H₆ with NO₂ into NO would probably appear to be the more prominent cause of C₃H₆ inhibition on NO oxidation.

From the transient experimental results with NO/O₂/C₃H₆ and NO/O₂/CO/C₃H₆ mixtures in Figure 9.4 and Figure 9.5, it appeared that the H₂ effect to improve NO₂ yield was instantaneous. The transient data also confirms that H₂ activates C₃H₆ oxidation and thereby promotes the NO oxidation reaction. Interestingly, the increase in NO₂ signals were found to be faster than that of temperature, suggesting that H₂ affected adsorbed species and surface reactions in addition to the exothermal effect due to its combustion (Figure 9.5). As addressed earlier, the effects of H₂ here can then be related to a decreased blocking effect of adsorbed C₃H₆ species and prevention of the reaction of C₃H₆ with NO₂ forming NO.

The inhibition effect of CO on NO oxidation, as shown in [15], cannot be fully demonstrated in Figure 9.1b probably due to the relatively low amount of CO used here (200 ppm of CO).
As shown in Figure 9.1b, addition of H\textsubscript{2} promotes CO oxidation by lowering the temperature for complete conversion of CO. Therefore, H\textsubscript{2} should also be able to promote NO oxidation for a NO/O\textsubscript{2}/CO mixture by eliminating inhibition effects of CO. Although H\textsubscript{2} lowers the light-off temperature for CO oxidation, the activity for NO oxidation below 130°C is negligible (Figure 9.1a) which makes the effect of H\textsubscript{2} to enhance NO\textsubscript{2} yield in a NO/O\textsubscript{2}/CO mixture become less prominent.

The TPR results with NO/O\textsubscript{2}/CO/C\textsubscript{3}H\textsubscript{6} (Figure 9.1d) showed that the addition of a low concentration of H\textsubscript{2} such as 250 ppm appeared to be beneficial for NO oxidation with respect to the light-off temperature as well as the NO\textsubscript{2} yield over the entire temperature range. Therefore, it can be suggested that the addition of about 250 ppm of H\textsubscript{2} is optimal to enhance the NO\textsubscript{2} yield for this complete DOC gas mixture. Higher H\textsubscript{2} concentrations were however found to lower the NO\textsubscript{2} yield for the temperature range of 250-400°C. The detrimental effect of increasing H\textsubscript{2} concentration at these higher temperatures was probably due to NO\textsubscript{2} consumption by H\textsubscript{2}.
Chapter 10

Conclusions and outlook

The overall focus of this work is to increase understanding of the mechanisms of the H₂ effect on HC-SCR and DOC from lab-scale studies. Two types of catalyst namely Ag-Al₂O₃ and Pt/Al₂O₃ were used as model catalysts for HC-SCR and DOC, respectively. A combination of experimental measurements and kinetic modeling approaches were utilized as a way to examine mechanistic effects of H₂ for both catalysts.

NO oxidation to NO₂ has been suggested as a subsystem within the HC-SCR reaction network over Ag/Al₂O₃. Paper I demonstrated the role of H₂ to modify surface NOₓ species during NO oxidation and C₃H₆-SCR over Ag-Al₂O₃ catalyst. TPD results suggested formations of two general groups of surface NOₓ species: a less thermally stable group of so called “LT nitrates” and a more thermally stable group of “HT nitrates”. LT nitrate species were more likely related to the formation of inhibiting nitrate species on active sites. Feeding of H₂ was found to eliminate the LT nitrate and subsequently promoted the NO oxidation and C₃H₆-SCR. In addition, the presence of H₂ also promoted the formation of a greater variety of adsorbed hydrocarbons. As a result, it suggested that H₂ caused other effects to promote C₃H₆-SCR over Ag-Al₂O₃. It was also found that H₂ facilitated the formation of nitrate species mainly on the Al₂O₃ support. It was also indicative that the mechanism of NOₓ storage on the Al₂O₃ support was mainly via NO₂ readsorption.

Paper II is focused on describing the promotional effect of H₂ on NO oxidation by a single role of H₂ to remove strongly adsorbed nitrate species on the active sites. A microkinetic model to describe a set of transient data based on a factorial design was constructed. A single type of active site was used to simplify the microkinetic model. A reaction network based on the Langmuir-Hinshelwood mechanism was proposed and it showed that the modeling results could capture well the experimental results.

A kinetic model for H₂-assisted C₃H₆-SCR over Ag-Al₂O₃ catalyst was developed in Paper III. The model was based on dual roles of H₂ to remove strongly adsorbed nitrates and simultaneous formation of more active Ag sites. The SCR reaction on the newly formed sites i.e. reduced Ag sites, was more rapid as reflected by significantly lower activation energy.
From experimental observations, a substantial amount of \( \text{NO}_2 \) formation was observed under both \( \text{H}_2 \)-assisted \( \text{NO} \) oxidation and \( \text{H}_2 \)-assisted \( \text{C}_3\text{H}_6 \)-SCR. However, in the absence of \( \text{NO}_x \), addition of \( \text{H}_2 \) did not promote the \( \text{C}_3\text{H}_6 \) oxidation reaction. For the SCR feed mixture, \( \text{H}_2 \) was found to promote \( \text{C}_3\text{H}_6 \) oxidation. Whereas in the absence of \( \text{H}_2 \), it appeared that the presence of \( \text{NO}_x \) inhibited \( \text{C}_3\text{H}_6 \) oxidation. The model could effectively capture a wide range of feed concentrations and temperatures, including temperature programmed experiments and transient experiments. From statistical analyses, all fitted kinetic parameters were found to be significant within 95% confidence intervals. Evaluation of mass transfer resistance in the washcoat indicated that during \( \text{H}_2 \)-assisted \( \text{C}_3\text{H}_6 \)-SCR, a mild influence from internal mass transfer for \( \text{NO} \) could be considered important already at 250°C. However, a larger fraction of experimental data was free from the influence of mass transport resistances.

As a continuation of studies, the use of TPD for surface species quantification to support a kinetic model, as presented in Chapter 8, will be of interest. This concept will test the applicability of TPD as a way to probe nitrate species on the catalyst. In addition, modeling of \( \text{H}_2 \) effects to induce \( \text{NO}_x \) storage over \( \text{Ag/Al}_2\text{O}_3 \) support will be advantageous to investigate the possibility to use \( \text{Ag/Al}_2\text{O}_3 \) catalysts in \( \text{NO}_x \) storage and reduction (NSR) processes.

A follow up study involving the DRIFT-MS technique to relate the changes in surface species with gas phase can be a potential route to enhance understanding of the HC-SCR mechanism. Chansai et al.[68] have highlighted the importance of short time contact to be able to identify reactive surface species and minimize their interference from spectator surface species. Repeated fast cycling with \( \text{H}_2 \) pulsing has been carried out recently by Kim et al. [74] showing effects on the \( \text{NO}_x \) conversion over two different time scales as a function of cycle time owing possibly to slow morphological changes in silver sites and other faster kinetic effects. Further clarification and verification by which \( \text{H}_2 \) modifies surface species formation, combined with morphological changes over \( \text{Ag-Al}_2\text{O}_3 \), can be an interesting direction for further studies to improve our understanding of HC-SCR over \( \text{Ag-Al}_2\text{O}_3 \) catalyst.

**Paper IV** focuses on the evaluation of \( \text{H}_2 \) effects on \( \text{NO} \) oxidation over \( \text{Pt/Al}_2\text{O}_3 \) using 4 gas mixtures: \( \text{NO/O}_2 \), \( \text{NO/O}_2/\text{CO} \), \( \text{NO/O}_2/\text{C}_3\text{H}_6 \) and \( \text{NO/O}_2/\text{CO/\text{C}_3\text{H}_6} \). Formation of Pt oxide is known to deactivate \( \text{NO} \) oxidation which is a slow process occurring over the scale of several minutes. The results from TPR with \( \text{NO/O}_2 \) and \( \text{NO/O}_2/\text{CO} \) mixtures showed that \( \text{H}_2 \) promoted the \( \text{NO}_2 \) yield in the temperature range of 200-300°C. \( \text{H}_2 \) was proposed to retard Pt oxide formation mainly at low temperatures (below ca. 200°C) which gave a temporal increase in \( \text{NO}_2 \) yield. For steady operation at higher temperatures with complete conversion of \( \text{H}_2 \), Pt oxide formation was unaffected by \( \text{H}_2 \). Additionally, it also appeared that \( \text{CO} \) played a role to retard low temperature Pt oxide formation which gave higher \( \text{NO}_2 \) yield in the absence of \( \text{H}_2 \).
The interaction of H$_2$ to influence C$_3$H$_6$ and CO inhibition effects on the NO oxidation reaction was also investigated. For NO oxidation in C$_3$H$_6$ containing mixtures, it was evident that the promotional role of H$_2$ was to weaken the inhibition effect of C$_3$H$_6$ by lowering the light-off temperature for C$_3$H$_6$ oxidation. In addition, it has been widely reported in literature that H$_2$ promotes the oxidation of CO which thus may also promote NO oxidation. However, with low CO feed concentration such as 200 ppm used in Paper IV, CO was found to have only a weak inhibition effect on NO oxidation. From the interaction between CO and C$_3$H$_6$, it was found that CO has only a weak inhibition effect on C$_3$H$_6$ oxidation.

Transient experiments involving in/out switching of H$_2$ were conducted with all gas mixtures at 230°C. Upon introduction of H$_2$, the time response of H$_2$ and NO$_2$ signals as well as the catalyst temperature was used to discriminate between the heat and chemical effects. For C$_3$H$_6$ containing mixtures, it was found that the time response of the increase in the NO$_2$ signal was faster than the increase in catalyst temperature which indicated that H$_2$ had an effect on the catalytic surface chemistry to promote NO oxidation. The effects of H$_2$ can be related to a decreased blocking effect of adsorbed C$_3$H$_6$ species and prevention of the reaction of C$_3$H$_6$ with NO$_2$ to form NO.

For future studies, it is of interest to develop a kinetic model to gain a deeper understanding of the mechanism of the H$_2$ effects on Pt/Al$_2$O$_3$. For model construction, the model could start from simulating the H$_2$ effects on DOC mixtures with and without C$_3$H$_6$, from the results presented in Paper IV. A model for Pt catalysts can be a useful reference especially if there is an interest to extend the investigation of H$_2$ effects to bimetallic Pt-Pd DOC catalysts.
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References


[79] X. Auvray, Fundamental studies of catalytic systems for diesel emission control, Department of Chemical and Biological Engineering, Chalmers University of Technology, Göteborg, 2013.