Annual Report

2010

KinCat

Catalysis Group – SINTEF – NTNU

KinCat
Catalysis Group

The centre was established July 1, 1998 by NTNU and SINTEF in recognition of the strong scientific level of members participating. The centre consists of the catalysis group, Department of Chemical Engineering, NTNU and the catalysis research team, SINTEF Materials and Chemistry. As of January 2008 the centre has been established as a Gemini centre by NTNU and SINTEF.

Program leader:

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Karin Wiggen Dragsten
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Annual Report 2010

KINCAT

Catalysis Group

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KinCat Members Spring 2011
Department of Chemical Engineering

Catalysis Group

Academic staff:

Professor Edd A. Blekkan
Professor De Chen
Professor Anders Holmen
Professor Magnus Rønning
Professor Hilde Venvik
Adjunct Professor Erling Rytter
Adjunct Professor Kjell Moljord

Laboratory personnel:

Engineer Karin Wiggen Dragsten

Doctoral students 2010/2011:

Hoang Ahn Dam
Hassan Jamil Dar
Asmira Delic
Ilya Gorelkin
Daham Gunawardana
Fatemeh Hayer
Fan Huang
Saima Sultana Kazi
Andreas Helland Lillebø
Fengliu Lou
Oana Mihai
Navaneethan Muthuswamy
Tayyaba Noor
Eleni Patanou
Xuyen Kim Phan
Paul Radstake
Shreyas Pandurang Rane
Miroslav Surma
Ingvild Tronstad
Nikolaos Tsakoumis
Charita Udani
Nicla Vicinanza
Andrey S. Volynkin
Alexey Voronov
Georg Voß
Jia Yang
Hi Le
Sara Boullosa-Eiras

Postdoctoral fellows 2010/2011:

Javier Fermoso Dominguez
Bjørn Christian Enger
Nina Hammer
Ingeborg-Helene Svenum
Estelle Vanhaecke
Espen Wangen
Tiejun Zhao
Jun Zhu

Visitors:

Juan Maria Gonzalez Carballo

Technical and administrative staff shared with other groups at the Department of Chemical Engineering:

Harry T. Brun
Arne Fossum
Jan Morten Roel
Lisbeth H.B.Roel
Frode Sundseth

SINTEF Materials and Chemistry, Catalysis and Kinetics

Administration:

Research Manager Torbjørn Gjervan
Senior-/Project Secretary Berit Broli

Reseach scientists:

Research Scientist Håkon Bergem
Research Scientist Svatopluk Chytil
Research Scientist Ingvar Kvande
Research Scientist Anna Lind
Research Scientist Odd Asbjørn Lindvåg
Research Scientist Hilde Meland
Research Scientist Rune Myrstad
Senior Scientist Rune Lødeng
Professor II Emeritus Odd A. Rokstad

Laboratory personnel:

Senior Engineer Ingunn Tanem
Engineer Camilla Otterlei
Engineer Merete Wiig

KinCat members spring 2011: (from left to right)

1 st row: Daham Gunawardana, Jun Zhu, Saima Kazi, Hilde Venvik, De Chen, Xuyen Phan, Nicla Vicanaza, Nikolaos Tsakoumis.

2nd row: Fengliu Lou, Hassan Dar, Fan Huang, Shreyas Rane, Tiejun Zhao, Fatemeh Hayer, Jia Yang, Rune Lødeng, Håkon Bergem, Karin Dragsten, Asbjørn Lindvåg.

3rd row: Edd Blekkan, Hilde Meland, Merete Wiig, Espen Wangen, Tayaaba Noor, Estelle Vanhaecke, Oana Mihai, Sara Bollousa, Eleni Patanoui, Asmira Delic, Rune Myrstad, Navaneethan Muthuswamy.

4th row: Magnus Rønning Andrey Volynkin, Camilla Otterlei, Anders Holmen, Andreas Lillebø, Nina Hammer, Torbjørn Gjervan, Ingeborg-Helene Svenum, Georg Voß, Miroslav Surma, Paul Radstake, Anna Lind, Alexey Voronov, Javier Dominguez, Svatopluk Chytil, Ilya Gorelkin,

Not present: Hoang Dam, Bjørn Christian Enger, Ingunn Tanem, Li He, Charita Udani, Ingvild Tronstad, Kjell Moljord, Erling Rytter, Ingvar Kvande.

Research Areas

- **Conversion of Natural Gas**
  - Synthesis gas and hydrogen production
  - Fischer-Tropsch synthesis
  - Dehydrogenation of ethane and propane
  - Solid acceptors for CO_2-capture
  - Production of methanol and dimethyl ether (DME)

- **Upgrading of Oil Fractions**
  - Hydrotreating
  - Catalytic reforming/isomerization
  - Heavy oil characterization and upgrading

- **High Temperature Chemistry**
  - Free radical chain reactions
  - Partial oxidation of methane and NGL compounds

- **Environmental Catalysis**
  - Sulfur reduction by hydrotreating
  - Preferential oxidation of CO
  - Wastewater treatment

- **Fundamental Studies of Heterogeneous Catalysis**
  - Surface science
  - Preparation of catalytic materials (supported metals and metal oxides, zeolites, supports, nanoparticles)
  - Kinetics (steady-state and transient kinetics, SSITKA)
  - Adsorption and diffusion in porous media
  - Catalyst deactivation (sintering, coke formation)
  - Characterization of heterogeneous catalysts
  - Reactor, kinetic and first principles (DFT) modeling

- **Microstructured Reactors and Membrane Reactors**

- **Production and Application of Carbon Nanofibers**

- **Photocatalysis**
  - Water splitting.
  - Photoreforming

- **Biofuels**
  - Biomass gasification reforming and water-gas shift
  - Bioethanol steam reforming
  - Hydrogenation of bio-oils to biofuel diesel

Main Laboratory Equipment

Reaction Laboratories

- Small pilot plants for catalytic reforming/isomerization and hydrotreating/ hydrocracking
- Several set-ups for high pressure reactions as well as for reactions at atmospheric pressure
- Conventional microbalance reactors
- Oscillating microbalance reactors (TEOM)
- Dedicated laboratory for studying microreactor technology
- Membrane reactor laboratory
- CSTR reactors
- Transient kinetics (Steady-State Isotopic Transient Kinetic Analysis)
- Multireactor system for CNF synthesis

Catalyst Preparation Laboratory

- Spray drier

Catalyst Characterization

- Surface area (BET), porosity and pore size distributions
- Chemisorption
- Temperature programmed methods such as TPR, TPO and TPD
- TGA and DSC
- Raman and IR spectroscopy
- Acidity determination by TPD
- UV-VIS
- Scanning tunneling microscopy (STM) – in co-operation with Dept. of Physics.
- The following methods are available at NTNU:
  EM (electron microscopy), XPS (X-ray photoelectron spectroscopy), AES (auger electron spectroscopy), NMR, AFM (atomic force microscopy) and XRD (X-ray diffraction).
- Synchrotron radiation EXAFS and XRD are frequently used through ESRF and other facilities.
- Microcalorimetry

Highlights from the Activities in 2010

- Three candidates completed their PhD degrees: Li He, Sara Boullosa Eiras and Hamidreza Bakhtiary Davijany. The titles of dissertations are enclosed.
- Anders Holmen received the Award for Excellence in Natural Gas Conversion in Lyon, June 2010.
- De Chen was spending a sabbatical leave during 2009/2010 at the University of California at Berkeley, USA.
- Edd A. Blekkan was spending a sabbatical leave during the fall semester 2010 at Cambridge University, UK.
- Hilde Venvik is appointed as the director for the Gas Technology Centre NTNU-SINTEF.
- Hilde Venvik is appointed as full professor.
- The main research laboratories of the Catalysis Group have been completely renovated during 2010/2011. The laboratories will be in operation during Spring 2011.
- The Group participates in inGAP (Innovative Natural Gas Processes and Products) – a Centre for Research–based Innovation (SFI) with participation from the University of Oslo, SINTEF, NTNU, Statoil, INEOS, Borealis and Halldor Topsøe AS. The centre was evaluated with good results and extended for 3 years.
- The Group is re-established as a Gemini centre (twin research centre).
- Several seminars were arranged with international participants. The programs are enclosed.
- Strategic support from NTNU (from the main administration as well as from the faculty) consisting of PhD scholarships and financial support.
- The Group participates in two European projects, one devoted to advanced cleaning for production of synthesis gas and the other to waste water cleaning.
- Members of the Group participate in the Eurokin network and in large national research programs such as GASSMAKS, NANOMAT, PETROMAKS, RENERGI, KOSK II.

Ph. D Candidates and Postdoctoral Projects

Reactor Design and Simulation for Oxidative Dehydrogenation of Ethane to Ethylene

PhD Student: Hassan Jamil Dar
Supervisor: Professor De Chen
Co-supervisor: Professor Hugo A. Jakobsen

Ethylene is produced in the petrochemical industry by steam cracking. In this process, gaseous or light liquid hydrocarbons are heated to 750–950 °C, inducing numerous free radical reactions followed by immediate quench to freeze the reactions.

By introducing oxygen to an ethane feed, ethylene can be produced via oxidative dehydrogenation of ethane (ODE). Oxidative dehydrogenation of ethane holds the promise of being an interesting alternative to steam cracking for ethylene production. Oxidative dehydrogenation of ethane converts ethane directly into ethylene and removes the thermodynamic limitations seen in steam cracking. It will also reduce the reactor volume.

The goal of the project is to optimize the reactor design for the maximum yield of ethylene.

The following objectives will be helpful in achieving the goal:

- A reliable kinetic model to describe the chemistry of oxidative dehydrogenation of ethane in the gas phase
- A proper model to describe the tubular reactor
- Analysis of different parameters (like temperature, C_2H_6/O_2 ratio) to get better yield is performed.

The reaction routine analysis will also be carried out for better understanding of the ODE in gas phase.

Financial support:
The project is funded by inGAP, Centre for Research-based Innovation.

Solar hydrogen production by photocatalytic water splitting

Ph.D. candidate: Asmira Delic
Supervisor: Prof. Magnus Rønning

Photocatalytic water splitting using sunlight is an environmentally clean alternative to hydrogen production from fossil fuels. In photocatalysis photochemical reactions take place at a solid surface, usually a semiconductor. Upon illumination the semiconductor becomes catalytically active when photoelectrons and photo-holes are generated. In overall water splitting the holes oxidize water to O_2 and protons. The electrons reduce protons to H_2. The most appropriate semiconductor for photocatalytic reactions is considered to be TiO_2.

Currently there are two major challenges regarding the use of TiO_2 for photocatalytic water splitting. The first problem is deactivation through recombination of the photogenerated electron-hole pairs. The second problem is that the material is active upon UV radiation and not visible light, which is the main part of the solar spectrum. The goal of this project is to address these problems though modifying the TiO_2 catalyst.

A promising approach for suppressing the recombination of electron-hole pairs is to couple TiO_2 with carbon-based materials. The synergetic effects depend on the type of carbon material as well as the synthesis route of the TiO_2–carbon composites. Photo-response in the visible light region can be achieved through grafting of transition metals on TiO_2 surface.

This project explores the structure and function of composites with different transition metals grafted, different TiO_2:CNT ratios, different types of carbon nanotubes (CNT) and with TiO_2 located inside and outside the carbon nanotubes. The CNT are prepared by CVD on porous carbon support, with subsequent decoration of the tubes by TiO_2. The structure and morphology of the catalysts are investigated by characterization techniques such as XPS, UV-vis, SEM, XRD, BET, TGA and Raman spectroscopy. Assemblies of TiO2-CNT/Nafion/Pt are used to test the photocatalytic activity. In a photoelectrochemical (PEC) reactor H_2 and O_2 are produced in separate chambers, resembling a reversed fuel cell. The catalytic activity is evaluated by measuring the rate of H_2 and O_2 evolution.

Presentation in 2010:
A. Delic, E. Vanhaecke, M. Rønning, *TiO2 on Aligned CNT Substrate for Photocatalytic Water Splitting,* First International Conference on Materials for Energy 2010 July 4-8, Karlsruhe, Germany

Financial support:
Strategic funding, NTNU.

Comparative study of selected catalysts for methane partial oxidation.

PhD candidate:	Sara Boullosa Eiras
Supervisors:	Prof. Anders Holmen, Prof. De Chen

Catalytic partial oxidation of methane (CPO) is an interesting alternative to the conventional steam methane reforming (SMR) for synthesis gas production. The obtained syngas has the proper H_2/CO ratio for methanol or Fischer-Tropsch synthesis. The conversion of methane and the selectivity to CO and H_2 in the CPO process is favored at high temperatures. However, the exothermicity of the reaction, particularly, the combustion of methane, might provoke high local temperatures leading to deactivation of the catalyst. Rh based materials are considered as the most promising catalysts for CPO. However, the high cost makes it necessary to use the Rh efficiently by achieving a good dispersion and stability. However, the extreme reaction conditions working with in CPO makes it very challenging. Therefore, the main objective of the project has aimed to develop a thermal stable catalytic system for the CPO process.

Initially we have focused on developing thermal stable Al_2O_3-based nanocomposites (Zr_xCe_1-xO_2-Al_2O_3) by a modified Pechini route. Especially, the thermal stability of the formed composite supports calcined between 1173 and 1473K has been systemically studied employing various characterization techniques. The formation of a protective layer of oxides on the Al_2O_3 surface can substantially improve the thermal stability of the nanocomposites. Then, 5 wt % Zr_xCe_1-xO_2-Al_2O_3 composites with high thermal stability are used as a candidate material for the CPO process. Afterwards, Rh has been introduced in the alumina based nanocomposites by incipient wetness impregnation.

Typically, loadings of 0.1 and 0.5 wt.% have been employed. CPO has been investigated over these Rh-based catalysts by running experiments in a fixed-bed reactor operating at 1 atm.

The project is part of a large research effort in the catalysis group dealing with the conversion of methane.

Publications and presentations:

1. T. Zhao, S. Boullosa-Eiras, Y. Yu, D. Chen, A. Holmen, M. Rønning. *Synthesis of nanocomposites and structured catalysts by impregnation and calcination of room-temperature polymerizable metal-complexes*, submitted to Topics in Catalysis.
2. S. Boullosa-Eiras, E. Vanhaecke, T. Zhao, D. Chen, A. Holmen. *Raman spectroscopy and X-ray diffraction study on the phase transformation* of ZrO_2-Al_2O_3 and CeO_2-Al_2O_3 nanocomposites, Catalysis Today, in press.

3. S. Boullosa-Eiras, T. Zhao, E. Vanhaecke, D. Chen, A. Holmen. *Partial oxidation of methane to synthesis gas on* $Rh/Zr_xCe_1\text{-}xO_2\text{-}Al_2O_3$, in preparation.
4. S. Boullosa-Eiras, T. Zhao, D. Chen, A. Holmen. *Effect of the preparation methods and alumina nanoparticles on the catalytic performance of* $Rh/Zr_xCe_1\text{-}xO_2\text{-}Al_2O_3$ *in methane partial oxidation,* submitted to Catalysis Today.
5. S. Boullosa-Eiras, T. Zhao, E. Vanhaecke, D. Chen, A. Holmen. $CeO_2\text{-}ZrO_2\text{-}Al_2O_3$ *mixed oxide nanocomposites supported Rh: a promising catalyst for partial oxidation of methane to syngas.* Oral presentation. 9th Novel Gas Conversion Symposium. Lyon, France. 30.05-3.06 2010.
6. T. Zhao, S. Boullosa-Eiras, Y. Yu, D. Chen, A. Holmen, M. Rønning. *Synthesis of supported catalysts by impregnation and calcination of a room-temperature polymerizable metal-complex solution.* Poster presentation. 14th Nordic Symposium on Catalysis, Marienlyst, Denmark, 29.08-31.08 2010.

Financial Support:
The project is funded by The Research Council of Norway (NFR), and Statoil.

Conversion of synthesis gas from biomass to liquid fuels by the Fischer-Tropsch synthesis

PhD candidate:	Andreas Helland Lillebø
Post.doc:	Bjørn Christian Enger
Project director/Supervisor:	Prof. Edd A. Blekkan , Prof. Anders Holmen,

The main objective is to study CO hydrogenation (Fischer-Tropsch synthesis) on modified Fischer-Tropsch catalysts using synthesis gas ($CO + H_2$) derived from biomass. The technology for conversion of biomass to liquid fuels (BTL) is similar to the technology for gas to liquids (GTL) and the objective is to focus on the differences and challenges specific to biomass derived synthesis gas. In particular, biomass derived synthesis gas contains large amounts of contaminants like alkali, H_2S, COS, NH_3, HCN, dust and tars. Cobalt based Fischer-Tropsch catalysts are very sensitive to contaminants and ppm levels of contamination are known to modify the hydrocarbon selectivity and cause catalyst deactivation. It is possible with state-of-art technology to remove the contaminants down to acceptable levels. However, the economic risk related to a trip or failure, where a breakthrough of contaminants reaches the catalyst, is very high because of the high replacement cost for the catalyst. Thus, knowing the severity of and managing this risk as well as designing catalysts which are more tolerant to contaminants will help to reduce the commerical risk for BTL.

Publications and presentations in 2010:

1. Christine M. Balonek, Andreas H. Lillebø, Shreyas Rane, Erling Rytter, Lanny D. Schmidt, Anders Holmen, *Effect of Alkali Metal Impurities on Co-Re Catalysts forFischer-Tropsch Synthesis from Biomass-Derived Syngas.* Catal. Lett., 138 (2010) 8-13
2. Bjørn Christian Enger, Åse-Lill Fossan, Øyvind Borg, Erling Rytter, Anders Holmen, *Cobalt catalysts on modified aluminas in the Fischer Tropsch synthesis.* J. Catal. accepted.
3. Bjørn Christian Enger, Rune Lødeng, Anders Holmen, *UBI-QEP evaluation of Ni(100) and Ni(111) sites for syngas formation*, poster at Novel Gas Conversion Symposium (NGCS) 9, Lyon, France, 1-4 June 2010
4. Bjørn Christian Enger, Rune Lødeng, Anders Holmen*, Reaction pathways from* CH_4 *to* H_2 *over transition metals*, poster at American Chemical Society (ACS) meeting 240, Boston, USA, 22-26 August 2010
5. Bjørn Christian Enger, Rune Lødeng, Anders Holmen*, Reaction pathways from* CH_4 *to* H_2*. UBI-QEP evaluation of transition metals*, oral presentation at American Chemical Society (ACS) meeting 240, Boston, USA, 22-26 August 2010
6. Bjørn Christian Enger, Åse-Lill Fossan, Jia Yang, Vidar Frøseth, Anders Holmen, *What can we learn from Fischer-Tropsch synthesis over Zn modified catalyts?*, oral presenation at Rotvoll, 7 September 2010
7. Bjørn Christian Enger, Anders Holmen, *Challenges for Fischer-Tropsch catalysis in biomass to liquids (BTL) conversion*, oral presentation at Rotvoll, VISTA-dagen, 16 September 2010

Financial support:

The Norwegian Academy of Science and Letters (VISTA), Statoil, SINTEF, NTNU and Norwegian Research Council through NRC project 190763 Biomass to liquid fuels.

Hydrogen production by Sorption Enhanced Steam Reforming (SESR) process from biomass derived compounds

Postdoctoral Fellow: Dr. Javier Fermoso
Supervisor: Prof. De Chen

Special attention has been paid to hydrogen production technology due to its increasing demand, not only in conventional industrial use (oil refining and synthesis of chemicals), but also the clean and efficient energy generation by means of fuel cells. It requires H_2 production on a massive scale for transportation fuel production and stationary power generation. So, there is an imperative interest in developing new technologies to produce hydrogen from renewable sources, such as biomass, at a high energy efficiency, cost attractive and in an environmental friendly manner. Recently, there has been increasing interest in the socalled Sorption Enhanced Steam Reforming (SESR) process for hydrogen production. The idea behind this new reforming process is that steam reforming (SR), water gas shift (WGS) and CO_2 removal reactions occurs concurrently in one reactor with a mixture of reforming catalyst and CO_2 acceptor. One important advantage of this process is that many types of biomass feedstock; from gas phase (biogas and syngas from biomass gasification), liquid phase (bioethanol, glycerol, etc.) to solid phase (raw lignocellulosic biomass) materials can be directly converted to high purity H_2 (> 97 vol.%) without CO_2 emissions in a single reactor. In addition, new sorbents based on Ca are being developed which has shown improved CO_2 capture capacity, stability with respect to those obtained with naturally found materials, like artic dolomite, during the SESR process.

Publications in 2010:

1. L. He, J.M.S. Parra, E.A. Blekkan, D. Chen. *Towards efficient hydrogen production from glycerol by sorption enhanced steam reforming*. Energy Environ. Sci. 3, 1046-1056 (2010).
2. L. He, H. Berntsen, D. Chen. *Approaching sustainable H2 production: Sorption enhanced steam reforming of ethanol.* J. Phys. Chem. A 114, 3834-3844 (2010).
3. L. He, D. Chen. *Single-stage production of highly concentrated hydrogen from biomass-derived syngas*. ChemSusChem 3, 1169-1171 (2010).

New concepts in the catalytic dehydrogenation of propane

PhD student: Ilya V. Gorelkin
Project leader: Professor Edd A. Blekkan

The production of light alkenes (C_2-C_4) is a central part of the petrochemical industry. Due to a higher growth in the demand for propene compared to other alkenes, the selective production of propene via catalytic dehydrogenation of propane is interesting. In this project we study fundamental and applied issues in propane dehydrogenation, mainly the development of a new concept in process heating. The concept is based on the *in situ* catalytic combustion of hydrogen, at conventional processing conditions for propane dehydrogenation, i.e. around 600 °C. The subject of study are reactions between hydrogen and oxygen on supported noble metal catalysts (platinum, iridium, and bimetallic systems involving these and other metals) in the presence of hydrocarbons (propane, propene) and microkinetic modelling of such reactions.

Presentations 2010:
Gorelkin, Ilya; Blekkan, Edd Anders. *Concepts and models of the catalytic dehydrogenation of propane*. 12th Norwegian Catalysis Symposium; 2010-11-29 - 2010-11-30 NTNU

Financial support:
The Gassmaks program from The Research Council of Norway.

Multi-technique probing of catalytic reactions at real working conditions

Postdoctoral Fellow: Dr. Nina Hammer
Supervisor: Prof. Magnus Rønning

Heterogeneous catalysts are typically multiphase systems and the structure of the catalyst, i.e. their surface properties, defects, particle shapes and other structural properties, are most decisive for their performance. The structural and chemical state of the active species in the catalysts will depend on the process conditions. To understand how these properties can affect the catalytic performance, is a major goal in catalysis research and hence the importance of in situ investigations of catalysts under real working conditions.

Synchrotron radiation techniques offer many of the necessary capabilities for probing the composition and structure of catalyst materials on the nanometer scale of the active particles. The techniques also allow for a study of the influence of the reaction conditions. These studies are essential in order to establish a basic understanding of catalytic reactions, the mechanisms of selectivity, activity and stability. A number of spectroscopic characterisation techniques have been adapted in recent years to study catalysts under working conditions. It is clear that, depending on its detection principle, each of these methods has its strength and limitations and will only give specific information. However, combining techniques such as XAS, XRD and Raman in situ provides a tool for studying a wide range of scientific problems which is much more powerful than the separate techniques.

The aim of this project is to use various in situ characterisation techniques to study the structure of catalytic systems under working conditions. The main focus will be on the XAS, XRD and Raman techniques and the experiments will be performed at the Swiss-Norwegian beamline. The experimental work will be in collaboration with other existing projects in our group, where it is essential for further developments of the systems to gain a better understanding of the structural properties during the reaction.

Publications and presentations in 2010:

1. N. Hammer, T. Zscherpe, D. Chen and M. Rønning, *Selective oxidation of CO on Au-*TiO_2 *catalysts on a structured carbon support,* oral presentation, 239th National Meeting of the American Chemical Society, Division Fuel Chem, San Francisco, USA, Mars 2010.
2. N. Hammer, T. Zscherpe, D. Chen, M. Rønning, *Selective oxidation of CO on Au-*TiO_2 *catalysts on a structured carbon support*, American Chemical Society Symposium Series (ACS) 2010, Vol. 55 (1).
3. I. Kvande, S.T. Briskeby, N. Hammer, M. Rønning, J.C. Walmsley, S. Sunde, D. Chen, *Direct evidence of strong interaction between PtO nanoparticles and carbon nanofibres*, oral presentation,14th Nordic Symposium on catalysis; 2010-08-29-2010-08-31
4. I. Kvande, J. Zhu, T. Zhao N. Hammer, M. Rønning, S. Raaen, J.C. Walmsley, D. Chen, *Importance of oxygen-free edge and defecte sites for the immobilization of colloidal Pt oxides particles with implications for the preparation of CNF-supported catalysts*, J. Phys. Chem. C, 144 (4), 2010, 1752.

Financial support:
The project is funded by The Research Council of Norway (NFR), through the SYNKROTRON programme.

Direct Synthesis of Dimethyl Ether in Microstructured Reactors

PhD candidate: Fatemeh Hayer
Supervisors: Prof. Hilde J. Venvik, Prof. Anders Holmen

Dimethyl ether (DME) has promising potential as an alternative fuel and can be produced from wide range of resources such as natural gas, coal and biomass. The direct synthesis of DME from synthesis gas is highly exothermic and proper temperature control to avoid run-away is important. The performance assessment of microstructured reactors could provide the key to intensify compact production of DME fuel, and the project focused on so-called integrated micro packed bed reactor-heat exchangers (IMPBRHE) for this reason. The specific features of three IMPBRHEs for direct DME synthesis over physical mixtures of CuO-ZnO-Al_2O_3 and γ-Al_2O_3 catalysts were investigated experimentally as well as by mathematical modelling and simulation. The reactors had different number of reaction slits or different slit dimensions, either contained equally spaced pillars over the complete slit or at the inlet and outlet only. The measured (at 20 °C) pressure drop was always small (<0.12 bar) relative to the total pressure (50 bar) and showed linear dependence with GHSV to confirm the predicted laminar flow for Re=0.1-2. A narrow residence time distribution (RTD) was estimated by dispersion analysis, i.e. investigations of the Peclet and Bodenstein numbers. Careful temperature measurements inside the slits, along the reactor housing and at oil inlet and outlet, confirmed that the reaction slit temperature is mainly controlled by the oil heat exchange to give a practically uniform temperature profile over reactors for set inlet oil temperatures of 220-320 °C. The micro packed beds were found free of the internal as well as external mass transfer limitations, as confirmed by no significant change in the CO conversion and DME yield for different catalyst particle sizes, no effect of varying the linear gas velocity, and no effect of manipulating reactant diffusion coefficient.The performance of a single slit micropacked bed reactor in direct DME synthesis was represented by a 3D pseudo homogeneous reactor model, incorporating kinetic expressions for the methanol synthesis and methanol dehydration reaction from literature. The concentration and temperature distribution in the reaction slit was estimated by assuming a uniform wall temperature. The model was adopted at low Reynolds numbers, i.e. small catalyst particles and long residence times. The reactor simulation showed good agreement with experimental results and could be further developed to assess the potential of microstructured packed bed reactors for intensification of conventional large-scale processes.

Publications

1. F. Hayer, H. Bakhtiary-Davijany, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen, "*Synthesis of Dimethyl Ether from Syngas in a microchannel*

reactor - simulation and experimental study", Chemical Engineering Journal, 167 (2011) 610–615.
2. F. Hayer, H. Bakhtiary-Davijany, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen," *Characteristics of integrated micro packed bed reactor-heat exchanger configurations in the direct synthesis of dimethyl ether*", Submitted to Chemical Engineering and Processing: Process Intensification Journal
3. F. Hayer, H. Bakhtiary-Davijany, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen," "*Modeling and simulation of an integrated micro packed bed reactor-heat exchanger configuration for direct dimethyl ether synthesis*", Submitted to Catalysis Letters, Special issue honoring Prof. Anders Holmen's 70th birthday.

Presentation and poster

1. F. Hayer, H. Bakhtiary-Davijany, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen, "*Synthesis of Dimethyl Ether from Syngas in a Microchannel Reactor - Simulation and Experimental Study*", Oral presentation at International Conference on Microreaction Technology, IMRET11, March 8-11, 2010, Kyoto, Japan.
2. F. Hayer, H. Bakhtiary-Davijany, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen, "*Direct Synthesis of Dimethyl Ether from Syngas in a Fixed Bed Reactor - Simulation and Experimental Study*", poster presentation at Novel Gas Conversion Symposium, NGSC9, May 30 - June 3, 2010, Lyon, France.

Financial support

The project is funded by the Research Council of Norway under GASSMAKS research program and Statoil ASA through the Gas Technology Centre (NTNU-SINTEF).

In-situ Polymerization of Conducting Polymers on CNT/CNF

PhD candidate: Fan Huang
Supervisor: Prof. De Chen

Continuing the studies from previous year, this year the focus has been on the manufacturing and examination of the batteries and supercapacitors using the composite materials developed earlier. All-solid-state supercapacitors were made from the PANI/ACNTs as the anode and ACNTs as the cathode, PVA-H_2SO_4 as both the separator and the solid electrolyte. Charge-discharge, cyclic voltammetry, impedance were carried out to examine the performance. The resultant supercapacitor was also used with a motor to work as a demonstration. In addition batteries were assembled, using a glove-box. The PANI/ACNTs composite was chosen as the anode in the Li-ion batteries. The cathode is lithium metal and different types of ionic liquids were used as the electrolyte. Charge-discharge and impedance measurements were done. Furthermore, the metal oxides, for example TiO_2 has been synthesized on the ACNTs as well. Photo-electrochemical properties were examined. Some good results were obtained, indicating the promising future for this type of composite as the candidate for photo-luminance applications such as solar cell.

Presentations in 2010:

1. Fan Huang, Estelle Vanhaecke, De Chen*, Composites of Conducting Polymers and Carbon Nanostructures for Energy Storage,* , Oral Presentation. 1st international conference on materials for energy 2010, Karlsruhe, Germany
2. Fan Huang, Estelle Vanhaecke, De Chen, *Composites of Conducting Polymers (Metal Oxides) and Carbon Nanostructures for Energy Storage,* Oral presentation 5th Nanolab user meeting, 2010.

Financial support:
The Norwegian Research Council (NFR)

Synthesis of Carbon Nanotube/graphene Hybrids for Thermocells

Ph. D. candidate: Fengliu Lou
Supervisor: De Chen

Low-grade heat, from such sources as industrial waste streams, geothermal activity, and solar heating, is projected to be a major sustainable energy source. Thermocells that utilize the temperature dependence of electrochemical redox potentials to produce electrical power may become an attractive alternative for harvesting low-grade heat, given their simple design, direct thermal-to-electric energy conversion, continuous operation, low expected maintenance, and zero carbon emission. However, the wide application of thermocells is limited by the high price of electrode materials and lower energy conversion efficiency. Carbon nanotube/graphene hybrids were selected as electrode materials in our investigations due to their high surface area and electrical conductivity. Expanded graphite and graphene oxide were selected as catalyst supports for the growth of carbon nanotubes by chemical vapor deposition of ethane.

The objectives of this project:

1. Synthesize carbon nanotube/graphene hybrids with high surface area, proper surface properties and large pore size.
2. Design a good method for the preparation of electrodes by using carbon nanotube/graphene hybrids.
3. Prepare a kind of thermocell with high output power and energy conversion efficiency.

Financial support:
This project is funded by VISTA

Partial oxidation of methane.
Studies on mechanism and kinetics

PhD candidate: Oana Mihai
Supervisors: Profs Anders Holmen and De Chen

The mechanism and kinetics understanding of methane partial oxidation by chemical looping pathway is the purpose of this research project. The reaction is based on methane feeding by using lattice oxygen of perovskites oxides type $LaFeO_3$ as oxygen source. The work involves the studies regarding the reaction mechanism and the optimization of catalyst composition in order to obtain maximum yield of synthesis gas. The iron-based perovskites are suitable catalysts for partial oxidation process due to their ability to utilize a large part of its lattice oxygen during reaction, a good thermal stability. Different preparation methods of catalyst were used in order to get various averages of crystal sizes of $LaFeO_3$ perovskites. The work have been studied the effect of various crystal sizes on catalytic performances during the methane partial oxidation reaction.

The experiments were carried out using a fixed bed quartz microreactor with the catalyst sample fixed on a sinter and performed at high temperatures in the temperature range of 1053 – 1173K, atmospheric pressure and various flow rates. The process is simulated by a redox cycle, switching between oxygen and methane flows both being diluted in argon. In order to avoid the mixing of methane and oxygen in gas phase, the reactor system was flushed with argon between the oxidation and reduction steps. The product analysis is carried out by a quadrupole mass spectrometer system (Balzers Quadstar 422).

The properties of surface and bulk oxygen are also important. Reactive surface oxygen will give total CH_4 combustion to CO_2 and H_2O while the bulk oxygen can react with CH_4 to give selective oxidation products as CO and H_2. An important part of this work will be to determine the surface reaction mechanisms.

Publications and presentations in 2010:

1. O. Mihai, D. Chen, A. Holmen, *"The effect of crystal size of perovskites on methane partial oxidation",* Poster presentation at 9th Novel Gas Conversion Symposium, 30.05- 3.06.2010, Lyon, France.
2. O. Mihai, D. Chen, A. Holmen, "*Catalytic consequence of lattice oxygen of lanthanum ferrite perovskite in chemical looping reforming of methane",* Oral presentation at International Mexican Congress on Chemical Reaction Engineering (IMCCRE 2010), 6-10.06.2010, Ixtapa-Zihuatanejo, Guerrero, Mexico.
3. O. Mihai, D. Chen, A. Holmen, "*Methane partial oxidation by oxygen lattice of* $LaFeO_3$ *perovskite catalysts"*, Poster presentation at Gordon Research Conferences-Catalysis, 27.06-2.07.2010, New London, New Hamphire, USA.
4. O. Mihai, D. Chen, A. Holmen, "*Experimental investigation of lanthanum ferrite perovskite in methane partial oxidation to syngas*", Oral presentation at Norwegian Catalysis Symposium, 29-30.11.2010, Bergen, Norway.
5. O. Mihai, D. Chen, A. Holmen, "*Catalytic consequence of oxygen of lanthanum ferrite perovskite in chemical looping reforming of methane*", Industrial and Engineering Chemistry Research, special issue of International Mexican Congress on Chemical Reaction Engineering (IMCCRE 2010), http://pubs.acs.org/doi/abs/10.1021/ie100651d

Financial support:

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Carbon nanofibers supported core-shell nanoparticles for fuel cell applications

Ph.D. cadidate: Navaneethan Muthuswamy
Supervisor: Prof. De. Chen

The investigations have been focused on developing highly efficient fuel cells in order to overcome the fast depletion of fossil fuels and to meet the challenge of global warming. Low-temperature fuel cells, such as, polymer electrolyte membrane fuel cells (PEMFC) and direct-methanol fuel cells (DMFC) are believed to be the most promising alternatives to combustion engines.

Pt supported on high-surface area carbon black is regarded as the best catalyst for electrochemical reactions (both anode and cathode) such as hydrogen oxidation reaction (HOR), methanol oxidation reaction (MOR) and oxygen reduction reaction (ORR). Low stability of the catalyst is one of the major problems in commercialization of fuel cells. The two major causes for the catalyst stability issues are poisoning and aggregation of Pt nanoparticles (NPs). Poisoning can be defined as deactivation of active sites due to blocking by irreversibly adsorbed species from either fuel impurities or from reaction intermediates, e.g. carbon monoxide. Aggregation is mainly due to the electrochemical carbon corrosion. Generally, commercially available carbon black undergoes electrochemical corrosion during fuel starvation and start-up/shutdown processes. As a result, the fuel cell performance will be reduced. By preparing Pt enriched core-shell system on carbon nanofiber (CNF) the catalyst stability can be improved.

Pt enriched core-shell system can enhance the stability of the catalyst via the so-called ligand effect, where the core metal modifies the electronic structure of the Pt by donating electron density. Thus, the Pt-CO bond strength weakens and thereby allowing CO to be more easily oxidized by OH molecules adsorbed at the neighboring Pt surface. But still the mechanism is under debate. And, by supporting the core-shell system on carbon nanofibers the aggregation process can be reduced as carbon nanofibers has high carbon corrosion resistance. Moreover, it has been lately demonstrated that the CNF supported metal particles have less susceptible to CO poisoning.

The purpose of this project is preparing Pt enriched core-shell nanoparticles on carbon nanofibers and testing the catalyst stability with MOR. The project is conducted in collaboration with electrochemical energy group at The Materials Science Department, NTNU.

Presentation in 2010:

Navaneethan Muthuswamy, Jose L. Gomez de la Fuente, Tiejun Zhao, Mikhail Tsypkin, Magnus Rønning, Frode Seland, Svein Sunde, De Chen. *Platelet carbon nanofibers supported Pt nanoparticles for fuel cell application*. Poster presentation. 4th International symposium on carbon for Catalysis, Dalian, China, November 7-10, 2010.

Financial support:

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Integrated process for hydrogen production with CO_2 capture using Sorption enhanced reactions

PhD candidate: Tayyaba Noor
Supervisor: Prof. De Chen

Steam reforming is currently the major process for large-scale production of hydrogen. Hydrogen production from steam reforming is a process that involves multiple steps and severe operating conditions. A pre-reforming step is normally necessary to convert heavy hydrocarbons to methane and synthesis gas, in order to lower the coking potential. The methane reformer is normally operated at 800-950 °C and 20-35 bar and need large amounts of energy to maintain the reaction temperature. The reformer is followed by high and low temperature water-gas shift reactors, and then carbon dioxide removal. In some cases, methanation is necessary to reduce the carbon monoxide concentration. All these steps make hydrogen production very costly. An alternative, cost-effective process for hydrogen production is therefore highly desirable.

Objectives:

1. Develop highly active and stable catalysts with high coking resistance, enabling the use of Norwegian natural gas as a feed stock for one-step, large-scale hydrogen production.
2. Explore solid CO_2 sorbents in sorption enhanced reactions for hydrogen production.
3. Test experimentally hydrogen production using sorption enhanced steam reforming of natural gas and Kinetic study of water-gas shift reaction

Series of hydrotalcite based Nickel-Cobalt catalysts have been developed using spraying drying technique. These catalyst have been prepared with different Ni and Co loadings and characterized by techniques like XRD, SEM, Chemisorption and BET. A calcium, cerium, zirconium based mix oxide sorbent has also been developed. The kinetic study of water gas shift reaction is under progress. The reaction conditions such as catalyst amount, temperature, pressure and steam to carbon ratio will be optimized in terms of kinetics. The sorption enhanced steam reforming of natural gas and water gas shift reaction will be studied later. Stability of the materials will be tested in multi-cycle runs.

Poster Presentations:

1. Tayyaba Noor, Saima Kazi, De Chen, "*Development and testing of mixed oxides nanoparticles for CO2 capture in sorption enhanced reactions*" InGAP-Nanocat summer School, 21-26 June, 2009, Trondheim, Norway.

2. Tayyaba Noor, Anna Lind, Andres Holmen, De Chen, "*Synthesis and Characterization of Ni Hydrotalcite Catalyst for Hydrogen Production Using Co Precipitation, Spray Drying, Microemulsion Method*" Norwegian symposium on catalysis, 30 Nov-01 Dec, 2009, Trondheim, Norway.
3. Tayyaba Noor, De Chen, Anna Lind, Andres Holmen "*Synthesis and Characterization of Ni Hydrotalcite Catalyst and Calcium based sorbent for Hydrogen Production*", 9th Novel Gas Conversion Symposium (NGCS 9), May 2010, Lyon, France.

Financial Support:
The project is funded by Norwegian Research Council through the KOSK Programme.

Microcalorimetry and microkinetics of heterogeneous catalysts.

PhD candidate: Eleni Patanou
Supervisor: Prof. Edd A. Blekkan
Co-supervisor: Prof. De Chen

Microkinetic modeling is very useful in the modern approach of improving and developing heterogeneous catalysts. In this project the microkinetic modelling constitutes a key tool in order to link information from theory, experimental surface science, mechanistic studies and kinetic and finally deactivation studies. The BOC theory is used as a framework where the main model input is the binding energies of the adsorbed species on the catalyst surfaces. As the amount of heat involved during the adsorption process is closely related to the adsorbate - substrate bond strength, the values of the heat of adsorption will be theoretically estimated and experimentally confirmed.

Adsorption microcalorimetry is recognized to be the most reliable method to determine the energy of the bonds between the adsorbed species and the adsorbents. Using a high sensitive Tian Calvet type calorimeter coupled to a volumetric chemisorption apparatus, the amount of heat transferred per unit time is detected as a function of the amount of the probe molecule adsorbed on the catalyst. In order to preserve the surface clean from any contamination of undesirable adsorbed species the catalyst is treated in a unique cell and transferred directly from the reduction into the calorimeter in order to start the adsorption process with the chosen probe gas.

In the present work microcalorimetric results will be used to eliminate errors and to assure better fitting of the computational techniques with the experimental data for heterogeneous catalysts widely used from the group i.e. Fischer-Tropsh catalysts.

Financial support:
The Research Council of Norway (NFR) and industrial partners through the inGAP programme.

Catalyst formulations for use in microstructured reactors for conversion of synthesis gas to liquids

Ph.D-Candidate: Xuyen Kim Phan
Supervisors: Profs Anders Holmen and Hilde J. Venvik

Potential natural gas reserves in the world are more than 6000 trillion cubic feet. However, approximately 25% of these gas reserves are located offshore with no economic feasibility to be produced, transported and sold. This calls for finding solution for utilization of the resources. Exploiting offshore natural gas presents challenges that possibly could be overcome by offshore conversion of gas to liquids (e.g. methanol, synthetic gasoline/diesel (Fischer-Tropsch technology) or dimethyl ether (DME)). For offshore gas-to-liquids (GTL), the production unit would require compact, efficient, robust, lightweight, reliable and safe technologies. Microstructured reactors may present an interesting potential for offshore GTL technology. Development of catalysts for use in microstructured reactors is an important part to get a more viable technology. The purpose of the present work is preparation, characterization and performance of different catalyst formulations for use in microstructured reactors for conversion of synthesis gas to liquids.

The Cu-based coatings were prepared using different techniques: slurry coating of $CuO/ZnO/Al_2O_3$ obtained via 2-stage co-precipitation, sol-gel coating of Al_2O_3 followed by Cu-Zn impregnation, colloid coating of Al_2O_3 followed by Cu-Zn impregnation, and colloid coating of Al_2O_3 followed by deposition-precipitation of Cu-Zn. The coated monoliths were characterized (XRD, BET, N2O titration) and studied in the methanol synthesis reaction at 80 bar.
The stacked foil microstructured reactor (SFMR) for producing methanol from synthesis gas could be demonstrated at high pressure, proved up to 80 bar. It is furthermore shown that two different active catalyst foil coatings could be prepared and tested, Pd/CeO_2 and $CuO/ZnO/Al_2O_3$. The performance of the catalyst-reactor systems could also be compared to that of a laboratory scale fixed-bed reactor (FBR) containing catalyst particles of similar composition. The differences between two reactor types – SFMR and FBR – are found using the 2-stage co-precipitated $CuO/ZnO/Al_2O_3$ catalyst. Only minor differences in

performance exist between the two reactors that can be related to different temperature properties of the two systems. The Pd/CeO_2 catalysts show high initial activity in both SFMR and FBR, but deactivate significantly to reach steady-state after about 60-120 hours. The maximum methanol productivity obtained in the SFMR is higher for the Pd than the Cu system on a mole of active metal basis (Pd/Cu), although at higher temperature and significantly higher methane by-product formation.

MPS-Al_2O_3 support was successfully synthesized from Al_2O_3 nanoparticles and sacrificed PS beads. The structure obtained contained uniformly spherical pores which were interconnected throughout the whole sample. The support was confirmed having α-phase alumina, but had relatively higher water adsorption capacity than that of a conventional α-Al2O3, giving a higher Co dispersion of Co/MPS-Al_2O_3 than that of Co/α-Al_2O_3. The SSITKA studies showed that this higher dispersion helped improving rate of reaction, comparable with the Co/γ-Al_2O_3 catalyst, but without sacrificing the selectivity as compared with α-Al_2O_3. The MPS-Al_2O_3 supported cobalt catalyst hence seems to combine the advantages of both Co/α-Al_2O_3 and Co/γ-Al_2O_3 catalysts.

Publication and presentation in 2010

1. Xuyen K. Phan, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Janina Thormann, Peter Pfeifer, Hilde J. Venvik, and Anders Holmen. "*Preparation and performance of Cu-based monoliths for methanol synthesis*". Submitted to Applied Catalysis A: Gerneral.
2. Xuyen K. Phan, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Janina Thormann, Peter Pfeifer, Hilde J. Venvik, and Anders Holmen. "*Preparation and Performance of a Catalyst-Coated Stacked Foil Microreactor for the Methanol Synthesis*". Ind. Eng. Chem. Res., 2010, 49, 10934-10941.
3. Xuyen K. Phan, John Walmsley, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Peter Pfeifer, Hilde J. Venvik, Anders Holmen. "*Characterization and performance of Pd/CeO_2 Catalysts as a Powder in Fixed-bed Reactor and as a Coating in Stacked Foil Microreactor for the Methanol Synthesis*". In preparation.
4. Xuyen K. Phan, Jia Yang, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Hilde J. Venvik, Anders Holmen. "*Studies of Macroporous structured Alumina based Cobalt Catalysts for Fischer-Tropsch Synthesis*". Submitted to Catalysis Letters.
5. Xuyen K. Phan, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Janina Thormann, Peter Pfeifer, Hilde Venvik, Anders Holmen. *Preparation and performance of Cu-based monoliths for methanol synthesis.* Poster Presentation at Novel Gas Conversion Symposium, Lyon, France, 30th May- 3rd June 2010.

6. Xuyen K. Phan, Hamidreza Bakhtiary-Davijany, Rune Myrstad, Janina Thormann, Peter Pfeifer, Hilde J. Venvik, Anders Holmen. *Preparation and Performance of a Catalyst coated Stacked Foil Microreactor for the Methanol Synthesis.* Oral Presentation at ICSRE 21, Philadelphia, USA, 13-16th June 2010.

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Dehydrogenation of NGL components at very short contact times

Ph.D. candidate: Paul B. Radstake
Supervisors: Profs. Anders Holmen and Magnus Rønning

Lower olefins such as ethene and propene are important intermediates for a large number of industrial processes. NGL (C_2-C_4 components in natural gas) is an excellent feedstock for production of lower olefins and Norway has access to large quantities of NGL. Oxidative dehydrogenation at very short contact times represents a new, exciting and promising way of converting NGL components to the corresponding olefins. It holds the promise of greatly reducing the reactor volume, as well as of autothermal operation. Another advantage is that it overcomes the thermodynamic limitations and avoids the necessity of continuous catalyst regeneration.

The purpose of the project is to characterize the oxidative dehydrogenation of NGL components at very short contact times and high temperatures. The focus of the project will be mainly on the selection of both convenient catalytic systems and suitable characterization techniques in order to further understand the fundamentals of this type of reactions. The experimental work will be based on powdered Pt-Sn catalysts. Parameters to be investigated are mainly catalyst loading, atomic ratios of the different elements, type of support, synthesis procedures and catalyst precursors. The characterization will be based on both physicochemical and spectroscopic techniques as well as the catalytic performance. Parameters within the catalytic testing experiments will be investigated as well. These parameters include reaction temperature, gas flow rates and gas ratios.

Presentations in 2010:
P. B. Radstake, M. Rønning, A. Holmen, *Oxidative dehydrogenation of ethane at short contact times,* Poster presentation, Nordic Symposium on Catalysis, Helsingør, Denmark, August 29th-31st, 2010

Financial support:
The project is funded by the Norwegian research council (NFR), through the GASSMAKS program.

Studies on relation between catalyst properties and selectivity in Fischer-Tropsch Synthesis

PhD Candidate: Shreyas Rane
Supervisors: Prof. Anders Holmen and dr. Øyvind Borg, Statoil.

The Fischer-Tropsch synthesis is rapidly becoming the most important technology for conversion of natural gas to liquid fuels (GTL). A key element in improved Fischer-Tropsch technology is the development of active catalysts with high wax selectivity. Supported cobalt is the preferred catalysts for the Fischer-Tropsch synthesis of long chain paraffins from natural gas due to their high activity and selectivity, low water-gas shift activity and relatively slow deactivation.

The present project deals with the study of the relation between catalyst properties and their effects on the Fischer-Tropsch synthesis. As a part of experimental work, the supported cobalt catalysts are prepared by incipient wetness impregnation without adding any promoter. The studies involve the effect of different alumina supported catalysts with constant metal particle size of cobalt on the C5+ selectivity. All catalysts are characterised by standard techniques such as H_2- chemisorption, Oxygen titration and TPR (Temperature Programmed Oxidation and Reduction), XRD (X-ray Diffraction), BET-surface area measurements, SEM (Scanning Electron Microscopy) and SSITKA (Steady-State Isotopic Transient Kinetic Analysis. The catalysts are tested in a fixed bed reactor at industrially relevant conditions (H_2: CO = 2, 20 bar, and 483 K). Based on experimental results, it is concluded that the C5+ selectivity is dependent on the alumina phase and its pore size distribution. In order to gain theoretical understanding about variations in hydrocarbon selectivity, the Raman spectroscopy will be used. Apart from this work, the synthesis reaction was studied for carbon nanofiber/felt supported cobalt catalysts, having platelet and fishbone structure, to examine long-run stability as compared to alumina support.

Publication and presentations:

1. Shreyas Rane, Øyvind Borg, Jia Yang, Erling Rytter, Anders Holmen. *Effect of alumina phases on hydrocarbon selectivity in Fischer-Tropsch synthesis.* Applied Catalysis A: General, 388 (2010) 160-167.
2. Shreyas Rane, Øyvind Borg, Erling Rytter, Anders Holmen. *Relation between hydrocarbon selectivities, activity and particle size for alumina supported cobalt based catalysts in Fischer-Tropsch synthesis.*, In preparation
3. Shreyas Rane, Øyvind Borg, Erling Rytter, Anders Holmen. Fischer-Tropsch Synthesis: *Comparative study on alumina and carbon nanofiber supported cobalt catalysts.*, In preparation
4. Saka Zarubova, Shreyas Rane, Jia Yang, Yingda Yu, Ye Zhu, De Chen, Anders Holmen *Fischer-Tropsch synthesis on Hierarchically Structured Co-Nanoparticles/Carbon Nanofibers/Carbon-felt Composites,* Accepted for ChemSusChem
5. Christine M. Balonek, Andreas H. Lilleø, Shreyas Rane, Erling Rytter, Lanny D. Schmidt and Anders Holmen. *Effect of alkali metal impurities on Co-Re catalysts forFischer-Tropsch synthesis from biomass-derived syngas.* Catalysis Letters 138 (2010) 8-13.
6. Shreyas Rane, Erik. Z. Tveten, Øyvind Borg, Erling Rytter, Anders Holmen. *Performance of supported Co Catalysts for Fischer-Tropsch synthesis*. 21st NAM 2009, oral presentation
7. Shreyas Rane, Øyvind Borg, Erling Rytter, Anders Holmen. *Effect of cobalt particle size, alumina and its porosity on hydrocarbon selectivity in Fischer-Tropsch synthesis.* Norwegian Catalysis Symposium, 2009, poster presentation
8. A. Holmen, J. Yang, S. Rane, Ø. Borg, E. Rytter. *Selectivity and activity for Fischer-Tropsch synthesis catalysts.* Lecture 239th American Chemical Society National Meeting, March 21-25. 2010, San Francisco, USA.
9. Shreyas Rane, Øyvind Borg, Erling Rytter, Anders Holmen. *Effect of cobalt particle size on Fischer-Tropsch hydrocarbon selectivities for θ-alumina as support*. Nordic Catalysis Symposium, 2010, poster presentation.
10. Shreyas Rane, Jia Yang, Bjørn Christian Enger, Øyvind Borg, Erling Rytter, Anders Holmen. *Alumina Supported Co Catalysts for Fischer-Tropsch Synthesis:Effect of Particle Size and Alumina Modifications on Activity and Selectivity*. 22nd NAM 2011,

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Hydrogen Production by Sorbent Enhanced Reforming (SER)

PhD- candidate: Kazi Saima Sultana
Supervisor: Prof. De Chen

An approach to improve the coventional SMR process is sorption -enhanced reaction process (SERP) for hydrogen production, which combines the reforming and shift reactions with in situ removal of the produced CO_2 by means of adsorption. Such a configuration has a number of technologically beneficial consequences: it affects a favorable shift in thermodynamic equilibrium towards hydrogen production, decreases the reaction temperature, removes carbon dioxide from the hydrogen product stream, thus decreasing the requirements for hydrogen purification. All these steps lower investment and operation cost of sorption enhanced steam methane reforming. However, the challenge of SESMR depends on the selection of appropriate CO_2 acceptor.

The project focused on developing of new calcium based CO_2 acceptors. The new sorbents are prepared at different compositions by spray drying method. The prepared sorbents are studied by different techniques including scanning electron microscope (SEM), transmission electron microscope (TEM), X-ray diffraction (XRD), XPS, TGA to find information about the morphology, stability and capacity of the sorbents. Among the prepared sorbents CaCe (10:1), CaCeZr (10:1:1) and CaZr (8:1) mixed oxides have shown a very promising property for CO_2 capture. These oxides have stable capacity 0.53, 0.45 and 0.46 (g of CO_2/ g of sorbent) respectively for 20 cycles. Sorption capacity of CaAl (8:1) and CaAlMg (10:1:1) mixed oxide sorbents are lower 0.25 and 0.30 (g of CO_2/gof sorbent) compared to other mixed oxides after 20cycles. All the prepared synthetic sorbents show better capature capacity compared to natural dolomite (Arctic). The CO_2 capture property of one of the prepared sorbent ($CaCeZrO_x$) is studied at different CO_2 partial pressures but the constant temperature of 843 K. The obtained capacities both from the fixed bed reactor and TGA are compared. The fixed bed and TGA show very similar capture capacity at each CO_2 pressure, but provided different kinetic behaviour. The CO_2 capture kinetics is also studied as a function of temperature and different compositions of CO_2 and steam respectively. Steam shows significant effect on the stability of the acceptors, but not very much on the kinetics and capacity of CO_2 capture.The CO_2 capture properties of Ca-based mixed oxide ($CaCeZrO_x$) in sorption enhanced steam methane reforming have been studied by a fixed-bed reactor in the presence of 40wt% nickel hydrotalcite catalyst prepared by co-precipitation method. Our new $CaCeZrO_x$ mixed oxide acceptor produces 96% high purity of hydrogen at the low temperature of 843K.

Multicycle tests in situ capture in steam reforming of methane show a moderate decrease in the sorption capacity of $CaCeZrO_x$, providing an incentive for further improvement and evaluation under steam reforming conditions.We report a synergetic effect between the catalysts and acceptors on CO_2 capture by a comparative study between SESMR and CO_2 capture kinetics, which has not been reported previously. The capacity of the CO_2 capture on the acceptors in the SESMR can not be simply predicted by independent CO_2 capture kinetic study. In addition, the residence time has a significant influence on the CO_2 capture. These two factors should be addressed in the future study in order to get a better understanding of the SESMR process.

Financial support:
The Norwegian research Council (NFR)

Microkinetic modeling of ethylene oxychlorination

Ph.D. candidate: Miroslav Surma
Supervisor: Prof. De Chen

The oxychlorination of ethylene is an industrially important reaction catalysed by $CuCl_2/Al_2O_3$ and promoted with KCl. Although many kinetic models have been proposed, none of them is able to describe the reaction over a wide temperature interval. This is caused by rather complex reaction mechanisms in which many different intermediates could occur. Deactivation of the catalyst in industrial processes is another issue. Microkinetic modeling elucidates the reactions taking place on the catalyst surface. Many compounds being involved in the microkinetic model exist for only short period of time and/or are hardly visible by common characterization techniques. Thus, clever combination of different techniques has to be used to get comprehensive data for further analysis. In situ IR, in situ Raman spectroscopy, TEOM, TPD, TPSR, SSITKA and many others are popular methods for microkinetic data extracting.

The purpose of the project is to obtain a reliable microkinetic model to describe the oxychlorination of ethylene and link this model to reactor simulation. MATLAB is used as the computational enviroment for all simulations. The setup capable recording both the mass spectra and UV/VIS reflectance in situ data has been constructed and very good correlation between both results was found.

Presentations in 2010:
M. Surma., D. A. Hoang, D. Chen. *Different approaches for the evaluation of reaction mechanisms in microkinetic modeling of methane partial oxidation.* Poster presentation. 14th Nordic Symposium on Catalysis, 29-31 August 2010, Marienlyst, Denmark

Financial support.:
The project is funded by NTNU and the Norwegian research council through the InGAP centre.

Understanding catalytic effects in Pd alloy model systems and membranes through advanced characterization and modelling.

Postdoctoral Fellow:	Ingeborg-Helene Svenum
Supervisors:	Professor Hilde J. Venvik, Professor Manos Mavrikakis, Univ. of Wisconsin-Madison, USA, Professor Anne Borg, Dept. of Physics, NTNU

The manipulation of adsorption properties of catalysts and membranes in H_2/CO mixtures has been targeted many researchers, and has relevance to natural gas conversion in general and hydrogen technology in particular. We recently discovered that CO inhibition of hydrogen transport through PdAg membranes was significantly reduced by membrane heat treatment in air. Analysis indicated changes in CO an H_2 heats of adsorption to play a role and surface spectroscopy indicated segregation phenomena to be involved. The overall objective of the project is therefore to understand the response of Pd alloy surfaces to carbon monoxide and carbon dioxide the in presence of hydrogen by advanced characterization techniques in conjunction with detailed calculations, and to apply this knowledge to improved membranes, membrane reactors and catalysts.

The project partners are the NTNU Departments of Chemical Engineering and Physics and SINTEF Materials and Chemistry, with the University of Wisconsin-Madison as an international partner. The research is conducted through the postdoctoral fellowship and one PhD project at Dept. of Physics. Experimental investigations of binding energies, adsorption sites and surface species are targeted through modelling and experiments. The density functional theory calculations are performed using the DACAPO code, which is a state-of-the-art plane wave-pseudopotential implementation of DFT. Characterization is performed through high resolution, surface sensitive photoelectron spectroscopy and diffraction using high intensity, X-ray range, tuneable synchrotron radiation. Both model systems (single crystals) and membrane samples surfaces (sputtered Pd alloy thin films) are being studied.

Financial support:
The project is funded by the Research Council of Norway (KOSK II programme, Contract No. 197709/V30) and Statoil ASA through the NTNU-SINTEF Gas Technology Centre.

Insulating liquids

Ph.D. candidate: Ingvild Tronstad
Supervisors: Prof. Edd A. Blekkan,
Dr. Marit-Helen G. Ese, SINTEF Energiforskning AS

High voltage transformers are insulated with mineral oil and solid cellulose (paper wrapped around the copper windings). Failures (short-circuits), caused by deposits on the windings in these transformers have dramatic consequences for everyday life and industry. To prevent failures it is important to understand how the insulating materials work in the transformer. By the use of traditional analytical methods such as titration, as well as introducing new techniques such as QCM (Quartz Crystal Microbalance) and microcalorimetry, we try to understand the reactions and effects of the chemicals in the insulating materials. Corrosion and formation of copper sulphide in transformer insulations and oxidation of insulating liquids (including alternative, environmentally friendly liquids), are the main areas of study. The project is a part of the KMB project "Thermal and electromagnetic performance of transformers", which is a joint effort between NTNU, SINTEF Energiforskning AS, Statnett, Hafslund, Statkraft, EDF, ABB, Nynäs, Siemens, NVE and The Research Council of Norway.

Financial support:
Statnett, Hafslund, Statkraft, EDF, ABB, Nynäs, Siemens, NVE and The Research Council of Norway.

Deactivation of Cobalt based Fischer – Tropsch synthesis catalysts

PhD candidate: Nikolaos Tsakoumis
Supervisor: Prof. Anders Holmen
Co-supervisors: Prof. II Erling Rytter and dr.ing Øyvind Borg, Statoil.

The Fischer-Tropsch synthesis (FTS) is an important part of most natural gas conversion (GTL) process developments in recent years. Modern Fischer-Tropsch synthesis aims at converting synthesis gas into high quality diesel. A key element in improved Fischer-Tropsch technology is the development of active and stable catalysts with high wax selectivity. Cobalt is considered the most favourable metal for the synthesis of long-chain hydrocarbons. Deactivation is an inevitable phenomenon in FTS. Different mechanisms for catalyst deactivation have been proposed including re-oxidation of active sites, carbidization, polymeric surface carbon formation, sintering, metal support compound formation and surface reconstruction. Catalyst poisoning from impurities in the catalyst as well as from the feed may also result in catalyst deactivation.

The project aims at studying catalyst deactivation by different techniques. The main challenge for studying deactivation of FTS is the fact that the catalyst is embedded in wax after use. The wax, which is a main product, is limiting the range of techniques that can be used and the high sensitivity of the active phase against oxygen hampers the handling procedure. This leads to low reliability of the results that are obtained through a procedure involving sampling, dewaxing and characterizing at inert conditions. Thus, recent catalyst deactivation research has turned into advanced in-situ/operando characterization studies. Proper selection of techniques will allow monitoring of the changes occurring inside the reactor during FTS and provide information that will assist in improved understanding of deactivation phenomena. Achieving realistic FT conditions (200-400^{o}C, 20 bar, $H_2/CO=2$) with simultaneous monitoring of the active sites is very challenging. We have optimized a quartz capillary in-situ cell in order to combine photon based techniques at realistic FT conditions. The cell has been successfully tested at the Swiss-Norwegian beam lines (SNBL - ESRF, Grenoble). The XAS and XRPD techniques were combined for the in situ characterization of the catalyst with simultaneous product analysis. Several parameters have a pronounced influence on the FT catalyst deactivation, it is therefore important to involve several characterization techniques in order to distinguish the influence of external conditions and to identify the separate deactivation routes.

Publications and presentations in 2010:

1. Rønning, M., Tsakoumis, N., Voronov, A.S., Johnsen, R., Norby, P., van Beek, W., Borg, Ø., Rytter, E., Holmen, A., *Combined XRD and XANES studies of a Re-promoted Co/γ-Al_2O_3 catalyst at Fischer–Tropsch synthesis conditions,* Catalysis Today, 155 (2010) 289-295.
2. Tsakoumis, N., Rønnning, M., Borg, Ø., Rytter, E., Holmen, A., *Deactivation of cobalt based Fischer-Tropsch catalysts:* A review, Catalysis Today, 154 (2010) 162–182.
3. Rønning, M., Tsakoumis, N., Voronov, A.S., Borg, Ø., Rytter, E., Holmen, A., *Combined XRD and XANES studies of Co-Re/γ-Al_2O_3 catalyst at Fischer – Tropsch synthesis conditions.* Oral presentation, 21-25 March, San Francisco, California, USA, Preprints - American Chemical Society, Division of Petroleum Chemistry, 2010, 55 (1), 75-76.

4. Tsakoumis, N., Voronov, A.S., Rønning, M., Borg, Ø., Rytter, E., Holmen, A., *Co-based Fischer-Tropsch Synthesis: an Operando study from catalyst activation to deactivation,* poster presentation, 14th Nordic Symposium on Catalysis, August 29 – 31, Helsingør, Denmark.

Financial support:
The Norwegian Research Council through inGAP project (Innovative Natural Gas Processes and Products) and the Department of Chemical Engineering, NTNU.

Photocatalytic fuel production by reforming of hydrocarbons and CO_2

Ph.D. candidate: Punchi Patabandige Charitha Udani
Supervisor: Professor Magnus Rønning

The photocatalytic fuel production using solar energy is a challenging research topic which has received much attention in recent years for its potential to provide H_2 as a clean and renewable energy carrier even on a large scale. This can be done with the use of several methods including water photosplitting and even more efficiently, by photoreforming of organic compounds, including methane, alcohols, aldehydes and organic acids.The increasing levels of CO_2 in the atmosphere have now become a global environmental issue because of the green house effect. There have been various approaches not only for recycling of this green house gas but also for an efficient production of fuel alternatives. It is reported that CO_2 can be re-introduced in the energy cycle by photoreforming into fuels such as CO, CH_4, CH_3OH, and H_2 .

The project is mainly focused on producing fuel alternatives with the use of an artificial solar light source and various photocatalysts. Various hydrocarbons, catalyst synthesis methods and catalysts formulation will be used, comparing noble metals with transition metals and combinations of these with the aim to prepare cost-effective catalyst systems. To investigate the crystal phase changes and morphology changes, the photocatalysts will be subjected to characterization also after exposure to the reaction conditions and as far as possible, in situ characterization when the catalysts are working.

Financial support:
The project is funded by strategic funding, NTNU.

Development of carbon nanostructured supports

Postdoctoral Fellowship: Dr. Estelle Vanhaecke
Supervisor: Prof. De Chen, Prof. Magnus Rønning

The study is aiming at gaining a better understanding of the effects of the surface properties of the foils on the alignment, diameter distribution, structure and the yield of nanocarbons.

The results suggest that the foils with low surface tension energy such as Al, Ti, and stainless steel should be selected for the growth of well vertically aligned CNTs arrays with relatively small diameter. The surface tension energy of the Cu foil is too high for growth of aligned CNTs. Surface modification is required, for example by introducing a buffer layer in order to lower the surface tension energy. The catalytic performance of the Fe particles on the graphite foil is different from the metallic foils. Although the contact angle or surface tension energy on the graphite foil and the Ti foils are similar, the catalyst particles are much larger on the graphite foil than on the Ti foil. Dissolution of carbon from graphite foil into the Fe particles is believed to cause the lower stability of Fe particles.

Presentations in 2010:

1. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils,* poster presentation, Renewable Energy Research Conference, Trondheim, June 6-8 2010
2. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Catalytic consequence of the interface between catalysts and foils in synthesis of aligned nanocarbons on foils*, oral presentation, 1st International Conference on Materials for Energy, Karlsruhe, Germany, July 4-8 2010
3. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils,* oral presentation, Carbon from Nano to Macro, Clemson University, USA, July 11-16 2010
4. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils,* poster presentation, 14th Nordic Symposion, Marienlyst, Denmark, August 29-31 2010
5. 5) Estelle Vanhaecke, Fan Huang, De Chen, *Catalytic consequence of the interface between catalysts and foils in synthesis of aligned nanocarbons on foils*, poster presentation, Carbocat IV, Dalian, China, November 7-10 2010

Financial support:
Monacat Project, EU Commission Grant Agreement no 226347
www.monacat.eu

Elaboration of carbon nanostructured reactors for catalytic water purification: Catalytic ozonation and nitrates reduction

Postdoctoral Fellowship:	Dr. Estelle Vanhaecke
Supervisor:	Prof. Magnus Rønning

Catalytic ozonation is an innovative technology for the elimination of organic pollutants in water and wastewater. Carbon nanofibers are potential catalysts for ozonation due to the extended mesoporosity, which may have a very positive impact by decreasing the mass transfer resistance usually present in the microporous activated carbon. A continuous flow reactor for the structured catalysed consists of two columns connected to allow the water solution to circulate between the two. The first column is used to transfer the ozone from the gas phase into the liquid phase. The second column holds the structured catalyst and is used to contact the ozonated solution with the solid phase. Thus, there are two biphasic contact columns instead of a triphasic sole system.

The results obtained show that the adsorption and the ozonation by itself are not effective to remove the oxalic acid. The best performance was observed for the untreated sample. The presence of oxygen-containing surface groups (present in high amount on the sample oxidized ACF/CF) has a detrimental effect. Therefore, the basic surface groups (mainly the electron-rich oxygen-free Lewis basic sites on the carbon basal planes) are the active sites for this reaction. The catalytic reduction of nitrates from ground water is becoming an environmental problem, especially for the drinking water. A promising catalyst system is the bemetallic Pd-Cu catalysts. A continuous flow reactor for the structured catalysts has been set up. In this experiment bimetallic catalysts supported on carbon nanofibers/graphite felt (CNFs/GF) are tested with continuous flow of H_2 and CO_2 within 3 hours of reaction and the reactant/products concentrations are measured by UV/Vis spectrophotometer. Different parameters will be studied: the nanostructures of the CNFs such as platelet CNFs/GF vs fishbone CNFs/GF; the deposition technique for the catalysts; the reduction treatments of the bimetallic catalysts.

Partners:
Faculdade de Engenharia da Universade do Porto – PT

Presentations in 2010:
Fernando Pereira, Estelle Vanhaecke, Magnus Rønning, De Chen, *CNFs on Graphite felt, a potential support for ozonation,* poster presentation, Carbocat IV, Dalian, China, November 7-10 2010

Financial support:
Monacat Project EUCommission Grant Agreement no 226347
www.monacat.eu

Palladium based membranes in catalytic reactions

PhD candidate: Nicla Vicinanza
Supervisors: Professor Hilde Johnsen Venvik, Dr. Scient. Rune Bredesen and Dr. Thijs Peters, SINTEF

Palladium-based membranes have been for decades the focus of many studies due to their high hydrogen permeability and selectivity and because they are potential candidates for use in membrane reactors. As palladium is expensive, the main disadvantage that these membranes have is high cost of the material, and the material costs are proportional to the thickness. SINTEF has developed a technology to produce palladium alloy membranes with thickness down to 1-2 µm that significantly improves flux and reduces material costs .

The main aim of this project is to develop a unique thin Pd-alloy membranes with improved thermal stability, sulphur resistance and resistance to flux inhibition by CO, and their integration in reactors and process for water-gas shift and steam reforming. Attention will be devoted to choose the best pretreatment procedure to improve hydrogen permeation through Pd-based membranes. To determine the most promising pretreatment procedure, permeation measurements will be performed and changes in the topography and chemical composition of the membrane surface will be analyzed using AFM and XPS, respectively. The oxidation of the Pd-alloy surface will be investigated using thermal gravimetric analysis (TGA).

Financial support:
Research Council of Norway, RENERGI Programme, Contract no 190779/S60

New approach to metal dusting corrosion

Ph.D. candidate: Daham Sanjaya Gunawardana Panditha-Vidana
Supervisors: Prof. Hilde Venvik and Prof. De Chen

Metal dusting is a corrosive degradation phenomenon on metals and alloys that proceeds by a gradual breakdown of materials into fine, dust-like particles. It constitutes a problem in the chemical and petrochemical industries, where alloys are exposed to carbon-supersaturated gaseous environments with low oxygen and/or steam partial pressures in the temperature range of 300–900 ^{o}C. Metal dusting carries significant cost associated with precautionary measures, monitoring, and, ultimately, replacement of process equipment. This study focuses on understanding the metal dusting mechanism and identifying controlling variables in the point of view of methanol synthesis technology. A long-term objective is development of predictive tools for the metal dusting induction. The project has a multidisciplinary approach that includes experimental and theoretical studies of metal dusting combined with novel surface and bulk characterization.

Both industrial alloy (Inconel 601) and Cr-Ni model alloy samples are tested in laboratory setup under controlled conditions. Each sample first undergoes a controlled oxidation before it is subjected to CO exposure. Sample surfaces after oxidation and CO exposure are investigated in SEM. Results shows formation of a thick, porous oxide layer on Inconel 601 under harsh oxidation conditions. Large amount of filamentous carbon is formed on oxidized Inconel 601 surface under CO exposure at high carbon activity $a_c<1$. Inconel 601 is more susceptible to metal dusting corrosion than Cr-Ni model alloy. The assessment of mass change under relevant reaction conditions will be applied to obtain the rate of metal dusting. Except SEM, available techniques such as TEM, AFM, STM, XRD, EDXS, AES, XPS, and IR and Raman spectroscopic techniques will be applied to investigate the surface and bulk morphologies and compositions. Modelling will be applied to understand better the initial steps leading to the formation of elemental carbon.

Presentations in 2010:

1. P.V.D.S. Gunawardana, Hilde Venvik: *New approach to metal dusting corrosion,* InGAP seminar: Oslo, 15–16 June 2010.
2. P.V.D.S. Gunawardana, Hilde Venvik: *Experimental study of Ni-based alloys in high carburizing environmen*t, Norwegian Catalysis Symposium: Bergen, 29–30 November 2010.

Financial support:

The project is funded by the research council of Norway through Innovative Natural Gas Processes and Products (inGAP).

The role of carbon in catalytic dehydrogenation of hydrocarbons.

PhD candidate: Andrey S. Volynkin
Supervisors: Prof. Edd A. Blekkan, Prof. Magnus Rønning

Carbon can play different roles in catalytic dehydrogenation (DH) of light hydrocarbons. While coke deposition deactivates dehydrogenation catalysts, carbon (with oxygen containing functional groups) can also be catalyst on its own for other dehydrogenation reactions. Another aspect of carbon in dehydrogenation is studies of carbon as support for the active metal. Oxygen containing sites can anchor metal nanoparticles and therefore assist the deposition of metal on carbon. Subsequent reduction in H_2 atmosphere removes the oxygen containing sites and reduces the active metal, making the catalyst able to dehydrogenate hydrocarbons. Metal-support interaction is an important parameter in catalysis and the way Pt and Pt-Sn will interact with carbon support (graphite, active carbon, carbon nanofibres and carbon nanotubes) and the implication of this interaction on the selectivity for DH can be difficult to predict. Carbon nanofibres and carbon nanotubes are not practical catalysts for dehydrogenation-reactions, but provide interesting properties as model systems.

The aim of this project is to improve understanding of effects of carbon on catalytic dehydrogenation of light alkanes, especially:
Synthesis of carbon materials and study of their catalytic properties.
Study of catalytic properties (dehydrogenation) of Pt and Pt-Sn metal catalysts deposited on synthesized carbon materials (graphite, carbon nanofibres and carbon nanotubes). Investigation of metal-support interaction.
Study of coke formation on carbon supported Pt and Pt-Sn catalysts. Application of different spectroscopic techniques to discriminate carbon from support and carbon from coke formed during catalytic tests. Those techniques include Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy and Terahertz time-domain spectroscopy (THz-TDS).

Financial support:
Strategic funding, NTNU.

Study of the deactivation mechanisms on Co-based Fischer-Tropsch catalysts under realistic working conditions

Ph.D. candidate: Alexey Voronov
Supervisor: Prof. Magnus Rønning

The Fisher-Tropsch (FT) synthesis is the central step in gas-to-liquid (GTL) technology where H_2 and CO is converted into synthetic crude oil. The hydrocarbons produced in this step are paraffins and olefins with different carbon chain lengths. Due to low water-gas-shift activity, supported cobalt catalysts are often selected as functional materials for the FT synthesis from natural gas. Nevertheless these catalysts are exposed to several deactivation mechanisms such as active phase transformation, carbon species deposition, surface reconstruction, sintering and cobalt reoxidation. An important challenge is to characterize and describe the individual steps and processes which take place on the catalyst surface during reaction. Since there is no direct method to monitor the behaviour of the Co particles on the support surface, it is essential to apply several characterization techniques in order to distinguish the influence of the various external conditions and define the individual deactivation mechanisms. Investigation at realistic working conditions is necessary to obtain reliable data about the processes which occur on the catalyst during FT reaction. Many parameters have a serious influence to the FT catalyst deactivation, so it is essential to involve several characterization technoques in order to distinguish ifluence of the various external conditions and define the separate deactivation routes.

The purpose of the project is to obtain detailed information about deactivation mechanisms and the effect of reaction conditions which may lead to new insight in catalyst formulation for FT synthesis in commercial GTL technology.

Publications and presentations in 2010:

1. A. Voronov, N. E. Tsakoumis, M. Rønning, Ø. Borg, E. Rytter, A. Holmen, *"In situ deactivation study of the rhenium behaviour in Co-Re Fischer-Tropsch catalysts",* Poster presentation, 14th Nordic Symposium on Catalysis, Marienlyst, Denmark, 29-31 August 2010.
2. N. E. Tsakoumis, A. Voronov, M. Rønning, Ø. Borg, E. Rytter, A. Holmen, "*Co-based Fischer-Tropsch Synthesis: an Operando study from catalyst activation to deactivation*", Poster presentation, 14th Nordic Symposium on Catalysis, Marienlyst, Denmark, 29-31 August 2010.
3. M. Rønning, N. E. Tsakoumis, A. Voronov, R. E. Johnsen, P. Norby, W. van Beek, Ø. Borg, E. Rytter, A. Holmen, Catal. Today 155 (2010) 289.
4. M. Rønning, N. E. Tsakoumis, A. Voronov, Ø. Borg, E. Rytter, A. Holmen, "*Combined XRD and XANES studies of Co-Re/γ-Al_2O_3 catalyst*

at Fischer-Tropsch synthesis conditions", Oral presentation, 239th ACS National Meeting, San Francisco, USA, 21-25 March 2010.

Financial support:
The project is funded by NTNU and the Norwegian research council (NFR) through the InGAP centre.

The State of Promotors in Fischer-Tropsch Catalysts

PhD candidate: Georg Voß
Supervisor: Prof. Magnus Rønning

Supported cobalt catalysts are widely studied and applied for conversion of synthesis gas in low temperature Fischer-Tropsch synthesis. These catalysts provide high activity, high selectivity to long chain paraffins and low water-gas shift activity. It is common practice to add a noble metal promoter to optimize the performance of the catalysts. Recently, more attention has been directed towards an understanding of the promotion

It was found that alloy formation between catalyst-metal and promoter-metal changes adsorption properties due to interaction in the outer shell orbitals. The detailed nanostructure, however, is unknown and further investigations are necessary. Attempts have been made to elucidate the position of the promoter metal on the catalyst and at least some of the promoter is locate in a subsurface layer. Admittedly, it is more probable that the promoter metal is in a solid solution in the bulk metal of the catalyst. Again, there is a need for further studies to be conclusive about the exact location of the promoter in the catalyst. Possible mixed phases between support, catalyst metal, and promoter metal may mask the promoter effect. No effort has been taken so far to try to detect such mixed phases and further investigations are required to collect information about the occupancy of the promoter metal in catalyst phases.

Therefore, this study focuses on the state of promotors in Fischer-Tropsch catalysts. Especially at reaction conditions, the nature and location of the promoter itself is unclear which leads to the utilization of in situ techniques. Vibrational spectroscopies (Raman, FT-IR) and X-ray absorption spectroscopy give information about the electronic state of the promoter. For a precise determination of location and dispersion of the promoter X-ray diffraction measurements may be useful. Surface sensitive techniques such as ion spectroscopies (SIMS, LEIS) and also TEM should give information of the promoter and its direct environment. Further techniques like resonant inelastic X-ray scattering give a more detailed picture of the electronic structure of the promoter, which will be the key element in understanding the promotion effect.

Publications and presentations in 2010:
Norwegian Catalysis Symposium 2010, Bergen, Norway. Poster Contribution.
The State of Promotors in Fischer-Tropsch Catalysts.

Financial support:
The Research Council of Norway, KOSK-II programme

Advanced Cleaning Devices for Production of Green Syngas

Postdoctoral Fellow: Dr. Espen S. Wangen
Supervisor: Professor Edd A. Blekkan

The production of fuels from biomass may become important in the effort of reducing greenhouse gas emissions to the atmosphere. Biofuels may be synthesised through a thermochemical process route, involving biomass gasification to produce synthesis gas (syngas) as the intermediate product. The conditioning of such a gas will be challenging, as it contains large amounts of contaminants. The gas cleaning will involve several steps, e.g. removal of alkali metals and particulates, sulphur (COS, H_2S), and ammonia. Higher hydrocarbons, tars, may cause problems due to condensation and plugging of pipes and processing units, and need to be removed.

The Catalysis group participates in the project "Advanced Cleaning Devices for Production of Green Syngas" (GreenSyngas), funded by the European Commission under its 7th Framework Program. The consortium consists of 10 partners from both industry and academia. The aim of the project is to develop a novel gas conditioning process to clean the raw product gas from a wood gasification plant. The plant is located in Güssing, Austria. The quality of the conditioned syngas should meet the requirements for a feedstock used in the production of vehicle fuels. The task of the Catalysis group is the reforming of unconverted hydrocarbons in the raw product gas from gasification. In addition, studies on the water gas shift reaction will be carried out. The focus of the studies will be reaction kinetics, catalyst stability and deactivation.
Project webpage: http://www.eat.lth.se/greensyngas/

Publications and presentations in 2010:

1. Espen Wangen, Amin Osatiashtiani, Edd A. Blekkan: *Production of biomass derived synthesis gas by catalytic steam reforming.* Poster presentation. Nordic Symposium on Catalysis. Marienborg (Denmark), 29-31 August 2010.
2. Espen Wangen, Amin Osatiashtiani, Edd A. Blekkan: *Catalytic steam reforming for the production of biomass derived synthesis gas*. Poster

presentation. Renewable Energy Research Conference. Trondheim (Norway), 7-8 June 2010.

3. Espen Wangen, Edd A. Blekkan, Azhar Malik, Mehri Sanati, *The Effect of Soot Deposition on Catalytic Activities in the Steam Reforming of a Simulated Producer Gas.* Poster presentation. Novel Gas Conversion Symposium. Lyon (France), 30 May – 3 June 2010.

Financial support:
The project is funded by the European Commission under its 7th Framework Program, and co-financed by the Swedish Energy Agency.

Steady-State Isotopic Transient Kinetic Analysis (SSITKA) of Catalytic Reactions

Ph.D. candidate: Jia Yang
Supervisors: Prof. Anders Holmen, Prof. De Chen

Steady-state isotopic transient kinetic analysis (SSITKA) has proved to be a powerful technique for studying heterogeneous catalyzed reactions. By normal steady-state experiments only the overall reaction rate, i.e. the product of the rate constant and the site coverage, is determined. SSITKA combines both the steady-state and the transient technique and makes it possible to study the intrinsic reaction rate at the active catalytic site decoupled from the site coverage. The method can also be used to study details of the surface reactions such as single or multiple pools of reaction intermediates on the catalytic surface and the reactivity distribution within the pools. A SSITKA experiment consists of making a switch between different isotopic labeled reactant species, such as 12CO and 13CO. The feed for example 12CO-H_2 or 13CO-H_2, is converted at steady-state over the catalyst provided that no isotopic effect occurs, and the transient response after the switch is monitored by a mass spectrometer. The focus so far has been on the production of fuels from natural gas by the Fischer-Tropsch synthesis on Cobalt catalysts. The activity and selectivity depend on the crystal size for small Cobalt particles, and SSITKA has contributed to the detailed understanding of the mechanism. The experiments have recently been expanded to include $C_{16}O$ and $C_{18}O$ as well as $16O_2$ and $18O_2$. The oxygen switches are particularly interesting for oxidation reactions on solid surfaces.

Publication and presentations in 2010:

1. Yang, J., E. Z. Tveten, et al. (2010). "*Understanding the Effect of Cobalt Particle Size on Fischer−Tropsch Synthesis: Surface Species and Mechanistic Studies by SSITKA and Kinetic Isotope Effect*." Langmuir: doi: 10.1021/la101555u

2. Shreyas Rane, Øyvind Borg, Jia Yang, Erling Rytter, Anders Holmen *Effect of alumina phases on hydrocarbon selectivity in Fischer-Tropsch synthesis.* Applied Catalysis A: General 388(1-2): 160-167.
3. J. Yang; A. Helland Lillebø; De Chen; A. Holmen. *Effect of ppm level alkali metal on CoRe/Al2O3 catalyst for the Fischer-Tropsch reaction studied by SSITKA.* 9th Novel Gas Conversion Symposium, Lyon, France. May 30th - June 3rd, 2010.
4. J. Yang, T.J. Zhao, E.Z. Tveten, De Chen, A. Holmen. *Types and reactivity of surface species on Co/Al2O3 catalyst for Fischer-Tropsch Synthesis*. Poster. 14th Nordic Symposium on Catalysis, Marienlyst, Denmark. 29-31 August, 2010.
5. J. Yang, Ø. Borg, De Chen, A. Holmen. *Re Promotion Effect of Carbon Nanotube supported Cobalt Catalyst for Fischer-Tropsch Synthesis Studied by SSITKA.* Poster. Dalian, China, November 7-10, 2010.

Financial support:
The project is funded by the Norwegian research council (NFR), through the "KOSK" program.

Novel structured reactors for selective oxidation of CO

Postdoctoral Fellow: Dr. Tiejun Zhao
Supervisor: Prof. Magnus Rønning

In this project, we focus on the fabrication of novel structured reactors for CO removal in H_2 rich feed, aiming at obtaining fuel cell quality H_2. Cu-CeO_2 nanocomposite and Cu-CeO_2 supported on structured carbon nanofibers (sCNFs) are prepared and tested. Preferential oxidation (PrO_x) has been recognized as one of the most straightforward and cost-efficient methods to achieve acceptable CO concentrations (mostly below 10 ppm) during H2 production in low-temperature proton-exchanged membrane fuel cell applications. During the last decade, the ability of supported noble metal catalysts, in particular containing platinum and gold have been demonstrated for the PrO_x reaction. Special attention has been devoted to the catalysts based on Cu-CeO_2, which exhibit higher selectivity than supported Pt metal catalyst at similar CO conversion levels and considerably higher stability than the Au-containing catalysts.

In this project, a structured carbon nanofiber supported Cu-CeO_2 catalyst has been developed by impregnation of the Cu-Ce-citrate complex solution onto the oxidized structured carbon nanofiber/carbon felt composite support, before calcination at 673 K. For comparison, the powder Cu-CeO_2 nanocomposites are prepared by a similar method. The structured catalyst formed is characterized by TGA, BET, XRD, TPR, SEM, HRTEM, showing that the Cu-CeO_2 nanoparticles are highly dispersed on the surface of structured carbon nanofibers. Both the nanocomposite and the structured catalysts are tested in the preferential oxidation of CO in hydrogen rich gases. A higher activity and selectivity to CO oxidation is achieved on the Cu-CeO_2/sCNF compared to the powdered nanocomposites. This is due to the smaller particle size of Cu-CeO_2 and the high thermal conductivity of the carbon nanofibers.

Publications and presentations in 2010:

1. Zhao, Tiejun; Eiras, Sara Boullosa; Yu, Yingda; Chen, De; Holmen, Anders; Rønning, Magnus. *'Pechini route in pore': Synthesis of supported catalysts by impregnation and calcination of room-temperature polymerizable metal-complexes.* 14th Nordic Symposium on Catalysis; 2010-08-29 - 2010-08-31
2. Yang, Jia; Zhao, Tiejun; Tveten, Erik Zakarias; Chen, De; Holmen, Anders. *Origin of in-situ reduction and oxidation of Co/Al_2O_3 in the Fischer-Tropsch Synthesis*. 14th Nordic Symposium on Catalysis; 2010-08-29 - 2010-08-31
3. Kvande, Ingvar; Zhu, Jun; Zhao, Tiejun; Hammer, Nina; Rønning, Magnus; Raaen, Steinar; Walmsley, John C; Chen, De. *Importance of Oxygen-Free Edge and Defect Sites for the Immobilization of Colloidal Pt Oxide Particles with Implications for the Preparation of CNF-Supported Catalysts*. The Journal of Physical Chemistry C 2010 ;Volum 114.(4) s. 1752-1762
4. Eiras, Sara Boullosa; Zhao, Tiejun; Vanhaecke, Estelle Marie M.; Chen, De; Holmen, Anders. *CeO_2-ZrO_2-mixed oxidenanocommposites supported Rh: a promising catalyst for partial oxidation of methane to syngas.* 9th Novel Gas Conversion Symposium (NGCS 9); 2010-05-30 - 2010-06-03
5. Zhao T., Kvande Ingvar, Magnus Ronning, Anders Holmen, De Chen, *Synthesis of platelet carbon nanofiber/carbon felt composites on in-situ generated Ni-Cu nanoparticles,* Journal of Physic Chemistry C.
6. Sara Boullosa-Eiras, Estelle Vanhaecke, Tiejun Zhao, De Chen, *Anders Holmen,Raman spectroscopy and X-ray diffraction study of the phase transformation of ZrO_2-Al_2O_3 and CeO_2-Al_2O_3 nanocomposites*, Catalyst Today,.
7. Tiejun Zhao, Yingda Yu[2], De Chen[1], Magnus Ronning, *Structured carbon nanofiber supported Cu-CeO_2 catalyst: Catalytic behavior in the preferential oxidation of CO in H_2-rich gases,* 9th Novel Gas Conversion Symposium, Lyon, France,May 30th - June 3rd, 2010, Oral
8. Tiejun Zhao, Yingda Yu, De Chen, Magnus Ronning, *Preferential oxidation of CO in H_2-rich feed over unsupported nanocomposite and*

structured carbon nanofiber supported Cu-CeO$_2$ catalysts, ACS Spring conference, Mar. 21-25, 2010, San Francisco, CA, USA, Oral

9. Tiejun Zhao, Sara Boullosa-Eiras, Yingda Yu, De Chen, Anders Holmen, Magnus Ronning, *Synthesis of supported catalysts by impregnation and calcination of roomtemperature polymerizable metal-complexes,* Norwegian Symposium on Catalysis, Nov 29-30, 2010, Bergen, Norway, Oral

Financial support:
The Research Council of Norway (NFR), KOSK programme

Engineering of Pt nanoparticles in Propane Dehydrogenation

Postdoctoral Fellow: Dr. Jun Zhu
Supervisor: Prof. De Chen

Catalytic dehydrogenation of NGL compounds (ethane, propane, butane) is an important industrial process. Although they have been extensively studied, a complete understanding of reactions on the catalyst surface including selectivity, coke formation and deactivation is still missing. Nanocrystals of different size of noble metals are attractive for use as catalysts because of their different surface-to-volume ratios and high surface area, which in turn cause their surface atoms to be highly active. Meanwhile, nanocrystals of shape control could enable the properties of a nanocrystal to be tuned with a greater versatility than can be achieved otherwise. In this sense, it is of great interest to investigate the effects of different Pt surface atoms on the dehydrogenation reactions.

The project is aimed in that it:

1. explores the novel Pt based nanoparticles with well controlled shapes and sizes towards catalysts with better activity and good stability in propane dehydrogenation (DHP),
2. focuses on the fundamental study of the catalyst structure-properties-performance relationship
3. improves the ability in rational design of catalysts in heterogeneous catalysis.

Up to now, different size and shape of Pt nanoparticles, which have different ratio of surface sites on the surface and varied in the orientations of the surface such as {111}, {100}, have prepared and characterized by XRD, SEM and HRTEM. The effects of surface atoms and facets of Pt nanoparticles on the activity, selectivity and coking in DHP have been investigated for the first time.

According to the experimental results, the catalytic performance indicates a strong structure-sensitive character. The hydrogen reaction order changes from 0 to -0.5 as the Pt particle size increase from 1 to 9 nm, while on cubic and octahedral particles, hydrogen reaction order is -0.2 and -0.5, respectively. The propane reaction order keeps constant on all Pt catalysts. The apparent activation energies of dehydrogenation and cracking on different Pt catalyats also vary a lot, which due to the different ratio of Pt facets, {111} and {100}, edges and corners exposed on the catalyst surface. DFT simulation data are used to interpret the exprimental data and build up dehydrogenation kinetic model.

Publications and presentations in 2010:

1. Kvande, J. Zhu, T. Zhao, N. Hammer, M. Ronning, S. Raaen, J. Walmsley, D. Chen*: Importance of Oxygen-Free Edge and Defect Sites for the Immobilization of Colloidal Pt Oxide Particles with Implications for the Preparation of CNF-Supported Catalysts*, Journal of Physical Chemistry C, 114(4): 1752-1762.
2. J. Zhu, D. Chen, Y. Yu, M. Rønning, A. Holmen: *Effects of Platinum nanoparticle size and shape on Propane Dehydrogenation,* Oral presentation in Norwegian Symposium on Catalysis, Nov. 30th – Dec. 1st, 2010, Bergen, Norway.
3. J. Zhu, D. Chen, Y. Yu, M. Rønning, A. Holmen: *The nature of active sites in Pt nanoparticles for Propane Dehydrogenation,* Poster presentation in 9th Novel Gas Conversion Symposium, C1-C4 Chemistry: From Fossil to Bio Resources, May 30th - June 3rd, 2010, Lyon, France.

Financial support:
The Norwegian Research Council (NFR).

SINTEF projects

Refinery operations / Octane processes

Staff: Senior scientist Torbjørn Gjervan, Research scientists Ingvar Kvande and Hilde Meland and Engineer Merete Wiig

The project aims to improve the performance of the client's commercial catalytic reforming and isomerisation units. This includes catalyst evaluations, process optimization, general trouble-shooting and education of refinery personnel. The heart of the project is a small-scale pilot unit, but additional chemical or physical characterization tools are used as well.

Client: Statoil R&D

Biorefinery; Processes and catalysis

Project category: Strategic own financed project ("Top-down SEP")
Staff at SINTEF Materials and Chemistry, Dept. Hydrocarbon Process Chemistry: Senior scientist Rune Lødeng, Research Scientist Svatopluk Chytil, Research Scientist Håkon Bergem, Chief Research Scientist Michael W. Stöcker, Research Scientist Lenka Hannevold

Main goals
Build general competence on the biorefinery field (major areas are indicated below)
Establish internal cooperation
Establish customer and cooperating partner relations
Establish new research activities

Activities
Lignin pyrolysis; An experimental set-up was built. Lignin samples are supplied by Borregaard.
Hydrotreating of bio oils; Mini pilot test rig; Preparing for smaller scale test facilities for hydrodeoxygenation (HDO) in 2011.
Hot gas conditioning; Build competence on removal of S, NH3, metals, tars, adjustment of syngas composition by reforming, WGS, etc.

Funding: SINTEF MK

Dehydrogenation of propane over chromium oxide based catalysts

Staff: Prof. Chen De, Prof. Anders Holmen (Dept. Chem. Eng. – NTNU), Senior scientist Rune Lødeng (Dept. Hydrocarbon Process Chemistry, SINTEF) and Senior scientist Magne Lysberg (Dept. Process Technology, SINTEF).

Kinetic data for the main PDH reaction and the carbon formation has been obtained in the tapered element oscillating microbalance reactor and applied for building kinetic models. A number of candidate commercial catalysts have been investigated and benchmarked. Predictive modeling of an industrial plant performance was part of the project work earlier. Development of reactor models is part of ongoing work.

Client: Borealis Polyolefine, Linz - Austria

Fischer-Tropsch catalysts

Staff: Research Scientist Rune Myrstad and Research Scientist Odd Asbjørn Lindvåg: SINTEF, Prof. Anders Holmen and Prof. Edd Anders Blekkan: NTNU

The goal of this project is to support the clients' development of catalysts for the Fischer-Tropsch synthesis by testing and characterization of catalysts.

Publications and presentations in 2010:

1. E. Rytter, T. H. Skagseth, S. Eri, A. O. Sjåstad, *Cobalt Fischer−Tropsch Catalysts Using Nickel Promoter as a Rhenium Substitute to Suppress Deactivation*, Ind. Eng. Chem. Res., 49 (2010)
2. A. M. Lind, R. Myrstad, S. Eri, T. H. Skagseth, E. Rytter, A. Holmen, *Spray drying of porous alumina support for Fischer- Tropsch catalysis,* Studies in Surface Science and Catalysis, 175, 685 (2010)

Client: Statoil R&D and The Research Council of Norway through the InGAP program

Preparation of alumina support for Fischer-Tropsch catalysis by spray-drying

Staff: Research Scientist Anna Lind, Research Scientist Rune Myrstad

Porous alumina particles, that are to be used as support in Fischer-Tropsch catalysis, have been produced by spray drying of alumina primary particles. The alumina material is formed by agglomeration of the primary particles during the spray drying process. We have investigated the influence of both instrumental parameters, as well as the condition of the suspension of primary particles on the porosity, as well as the particle size and morphology of the materials. Some of the materials have also been impregnated with cobalt and rhenium by the incipient wetness method and tested in a fixed bed reactor.

Publications and presentations:

1. A. Lind, R. Myrstad, S. Eri, T. Hulsund Skagseth, E. Rytter, A. Holmen, Studies in Surface Science and Catalysis, 175 (2010) 685-688.
2. A. Lind, R. Myrstad, S. Eri, T. Hulsund Skagseth, E. Rytter, A. Holmen: *Spray Drying of Porous Alumina Support for Fischer-Tropsch Catalysis*. Poster presentation. The 10th International Symposium on the Scientific Bases for the Preparation of Heterogeneous Catalysts, Louvain-la-Neuve, Belgium, July 11-15, 2010.

Client: The Research Council of Norway through the inGAP program.

Next-Generation PEM Electrolyser for Sustainable Hydrogen Production

Staff: Research Scientist Anna Lind

In this work a noble iridium catalyst for the oxygen evolution reaction in proton exchange membrane (PEM) water electrolysers has been synthesized and deposited on an antimony-doped thin oxide (ATO) support by a modified polyol method. The method has been optimized for the support and catalyst studied to give a highly controllable catalyst particle size, size distribution, and loading. The products have been characterized using cyclic voltammetry, polarization, scanning electron microscopy, transmission electron microscopy, X-ray diffraction, energy-dispersive X-ray spectroscopy, and thermogravimetric analysis. In order to evaluate the activity and stability of the synthesized electrocatalysts, they have also been tested in situ in a PEM cell under real operating conditions (elevated temperature, specific relative humidity, etc).

Publications and presentations:
E. Sheridan, M. Thomassen, T. Mokkelbost, A. Lind: *The development of a supported iridium catalyst for oxygen evolution in PEM electrolysers*. Oral presentation. The 61st Annual Meeting of the International Society of Electrochemistry, Nice, France, September 26–October 1, 2010.

Client: EU through the seventh framework program for the fuel cells and hydrogen joint technology initiative.

Oxidative coupling of methane followed by oligomerization to liquids

Staff: Research Scientist Anna Lind, Research Scientist Ørnulv Vistad, Dr. Duncan Akporiaye

In this project micro- and mesoporous materials are investigated as sorbents for the purification of ethylene from multi-component effluent streams from the OCM process.

Client: EU through the seventh framework program for research and technological development.

Hydrotreating

Staff: Research ScientistHåkon Bergem, Engineer Camilla Otterlei, SINTEF. Prof. Edd A. Blekkan, NTNU

The project aims to improve the performance of the client's commercial hydrotreating units. New fuel specifications and changing crude oil qualities call for continuous development of existing and new refinery processes. We are involved in research aiming at developing new and better catalysts but also process optimization and modeling based on insight into the detailed mechanisms of the actual reactions. The processes are studied in bench- and pilot scale reactors.

Client: Statoil R&D

Philosophiae Doctor (PhD) theses in 2010

Li He: *Sorption Enhanced Steam Reforming of Biomass-Derived Compounds: Process and Material.* Doctoral theses at NTNU. 2010:2

Sara Boullosa Eiras: *Comparative study of selected catalysts for methane partial oxidation.* Doctoral theses at NTNU. 2010:186

Hamidreza Bakhtiary Davijany: *Performance assessment of a packed bed microstructured reactor- heat exchanger for methanol synthesis from syngas.* Doctoral theses at NTNU. 2010:205

Master (Diploma) Students in 2010

Aderonke Badina: *Characterization of products from the slurry hydrocracking of heavy oil.*

Carlos Besteiro Aparicio: *Direct synthesis of dimethyl ether from syngas on bifunctional catalysts.*

Andreas H. Lillebø: *Characterization and catalytic testing of cobalt/rhenium/γ-*Al_2O_3 *catalyst. Effect of Na, K, Li and Ca promotion.*

Amin Osatiashtiani: *Catalytic conversion of producer gas.*

Juan Bautista Freire: *Catalytic partial oxidation of methane at moderate temperature.*

Project presentations TKP4510 Catalysis/Petrochemistry

Loc Huu Ngyen: *Synthesis and application of nanomaterials in clean energy.*

Damien Vannier: *High temperature water gas shift reaction over nickel catalysts.*

Ayob Esmaelpour: *Bifunctional catalyst for the direct DME synthesis*.

Mahmud Alam: *Kinetics and Deactivation in the Methanol Synthesis Reaction.*

Kimete Osmani: *Water purification by using structured catalysts for hydrogenation of nitrates.*

Vegar Evenrud: Nickel *promotion of cobalt Fischer-Tropsch catalysts.*

Ida Lien Bjørnstad: *Photocatalytic fuel production through photoreforming of hydrocarbons.*

Katrine S.B. Plünnecke: *Catalytic Conversion of Syngas.*

Claire Barilleau: *Fischer-Tropsch synthesis over iron supported catalysts: Conversion of synthesis gas from biomass to liquid fuels.*

Aina Elin Karlsen: *Chemical attrition - method development and investigation of cobalt Fischer-Tropsch catalysts and supports.*

Mario Jimenez Ortega: *Kinetic study of the oxychlorination process.*

Group meetings with seminars 2010

Spring semester 2010

Date	Presenter	Topic
29.01.2010	Andreas Helland Lillebø	Effect of Na, K, Li and Ca on Co/Re/Al2O3 Fischer- Tropsch catalysts.
12.02.2010	Nikolaos Tsakoumis	Deactivation of Co Fischer-Tropsch Catalysts - a review.
26.02.2010	Fatemeh Hayer	Synthesis of DME from syngas in a microchannel reactor – Simulation and experimental study.
12.03.2010	Tiejun Zhao	Preferential oxidation of CO in H2-rich feed over unsupported nanocomposite and structured carbon nanofiber supported Cu-CeO2 catalysts.
09.04.2010	John Walmsley	An overview of TEM imaging and analysis with examples of catalytic studies.
23.04.2010	Hongmin Wang	Optimum design and operation of hydrogen production by a methane autothermal reforming system.
07.05.2010	Sara Boullosa-Eiras	CeO2-ZrO2-Al2O3 mixed oxide nanocomposites supported Rh: a promising catalyst for partial oxidation of methane to syngas
20.05.2010	Professor Sir John Meurig Thomas, Cambridge University, UK	Exploring the interface between heterogeneous and homogeneous catalysis.
21.05.2010	Oana Mihai	Catalytic consequence of lattice oxygen of lanthanum ferrite perovskite in chemical looping reforming of methan
	Jia Yang	Effect of ppm level sodium on CoRe/Al2O3 catalyst for the Fischer-Tropsch reaction studied by SSITKA.
11.06.2010	Xuyen Kim Phan	Methanol production in microreactors.

Autumn semester 2010

Date	Presenter	Topic
27.08.2010	Jun Zhu	Catalytic oxygen remove and C-C bond formation on Au based catalysts
10.09.2010	Espen Wangen	Synthesis Gas From Biomass Gasification. The Güssing Case by
24.09.2010	Javier Fermoso Dominguez	HIGH-PRESSURE CO-GASIFICATION OF COAL AND BIOMASS BLENDS FOR SYNGAS PRODUCTION
15.10.2010	Rune Lodeng	Energy mix and technology today and ahead. Raw materials, Energy, Fuels and Chemicals.
26.10.2010	Louise Olsson, Chalmers University of Technology, Gøteborg, Sweden	Catalysis for cleaning emissions from vehicles
19.11.2010	Dr. Claude Descorme, IRCELYON/Université Claude Bernard Lyon, France	Catalytic wastewater treatment: a focus on the catalytic wet air oxidation and the development of materials
03.10.2010	Odd Ivar Levik,Scandpower	Petroleum processing and technical safety systems'

Courses given by Group Members

TKP4110 Chemical Reaction Engineering

Coordinator: Professor Anders Holmen

Lecturers: Professor Anders Holmen,
Assoc. Professor Jens-Petter Andreassen,
Professor Heinz Preizig (laboratory exercises)

Semester: Fall
Level: 3th year
Credits: 7.5 SP
Course Plan: Lectures (4 h/week), exercises (6 h/week), self study (2 h/week)

Objectives:

The course deals with the design of chemical reactors based on the reaction kinetics and the physical conditions in the reactor

Prerequisites:

The course is based on the compulsory courses at the Faculty of Chemistry and Biology, but students from other faculties may take the course as well, possibly after an introductory self-study.

Contents:

The course is divided in a theoretical part and a laboratory part. The theoretical part contains an overview of homogeneous and heterogeneous reaction mechanisms with particular emphasis on the relation between diffusion, heat transfer and reaction rate. Heterogeneous catalysis including reactions between gases, liquids and solid materials is also dealt with. Calculation of conversion and yields in batch reactors and in flow systems i.e. plug flow reactors and continuous-stirred tank reactors. Reactor stability and optimization of the reaction path. The laboratory work includes one exercise related to a topic from the theoretical part.

Teaching form:

The course is given as a combination of lectures, exercises, self-study and laboratory work. Admission to the exam requires that ½ of the exercises are approved. The theoretical part counts for 75% and the laboratory part for 25% of the final mark. Both parts must be passed in order to pass the course.

Course material:
H. Scott Vogler: Elements of Chemical Reaction Engineering. Prentice-Hall, Inc. 4rd ed., 2006.

Exam: Written + exercises

TKP4150 Petrochemistry and oil refining

Responsible: Professor Edd A. Blekkan
Lecturers: Prof. Edd A. Blekkan, Adjunct Prof. Kjell Moljord (Statoil), Prof. Hilde Venvik, Prof. Anders Holmen

Semester: Spring
Level: 4th year.
Credits: 7.5 SP
Restricted Admission: No
Course Plan: 3 Lectures, 2 hours exercises and 7 hours self study and projects per week.

Objective:
To provide an overview of the central processes for the conversion and upgrading of oil and natural gas.

Prerequisites:
Basis chemistry and mathematics and course TKP4155 Reaction Kinetics and Catalysis or similar knowledge.

Contents:
Feedstocks, Norwegian oil and gas production, energy from fossil fuels. Oil refining, oil products, refinery design and selected processes, catalytic reforming and isomerization, hydrotreating and hydrocracking, catalytic cracking, treatment of heavy oils, hydrogen balance, environmental concerns, new fuels. Examples of basic, intermediate and end products from petrochemistry. Natural gas and LPG as feedstock, synthesis gas production, preparation and use of hydrogen, methanol synthesis, Fischer–Tropsch, ammonia synthesis. Production of light olefins by steam cracking, dehydrogenation and other routes, use of light olefins.

Teaching:
The course is given as a combination of lectures, exercises, self-study and project work including student presentations.

Course material:
J. Moulijn, M. Makkee and A. van Diepen: Chemical Process Technology Wiley & Sons, 2001 and articles and handouts.

Exam: Written

TKP4155 Reaction Kinetics and Catalysis

Responsible: Professor Magnus Rønning
Lecturers: Professor Magnus Rønning and Adj. Professor Erling Rytter.

Semester: Fall
Level: 4th year
Credits: 7.5 SP
Restricted Admission: No
Course Plan: Lectures (4 h/week), exercises (2 h/week), self study (6 h/week)

Objectives:
Introduction to important principles and methods of heterogeneous and homogeneous catalysis.

Prerequisites:
Course TKP4110 Chemical Reaction Engineering or similar knowledge.

Contents:
The importance of catalysis as a key technology in chemical and petrochemical industry, in energy production and for the protection of the environment. Definition of catalysis, elementary reactions, chain reactions and catalytic sequences. Kinetic modeling. Catalyst preparation and characterization. Adsorption, desorption, surface area and porosity. Modern theories for surfaces and surface reactions. Internal and external mass and heat transfer in catalyst particles. The effect of diffusion on reaction kinetics. Multifunctional catalysis. Catalysis by transition metal complexes. Ziegler-Natta and single-site polymerisation catalysts.

Teaching form:
The course is given as a combination of lectures, exercises and self-study.

Course material:
Compendium and articles. Information given at semester start.

Exam: Writte

Catalysis and petrochemistry MSc specialization

Coordinator: Professor Anders Holmen

Course description:
The specialization involves the following modules:

TKP4510 - Catalysis and Petrochemistry, Specialization Project	15 SP
TKP4515 - Catalysis and Petrochemistry, Specialization Course	7.5 SP
Module 1 (KAT) Heterogeneous catalysis. Advanced course	3.75 SP
Module 2 (KEM) Energy and environmental catalysis	3.75 SP

2 modules must be chosen, other modules are also electable. The modules give an overall description of the field catalysis and petrochemistry. However, the modules may also be combined with modules from other specializations such as polymer chemistry and reactor technology. Catalysis and petrochemistry laboratory work/project is compulsory for this specialization.

TKP4515-1 Heterogeneous catalysis, advanced course

Responsible: Professor Edd Anders Blekkan

Credits: 3.75 SP
Prerequisites:
TKP4155 Reaction kinetics and catalysis or similar knowledge.

Module description:
The module covers selected topics in heterogeneous catalysis: Characterization and surface area measurements of porous materials and heterogeneous catalysts, deactivation, activity measurements, kinetics and transient kinetic methods, catalytic materials such as metals, supported metals, oxides, zeolites and solid acids.

Teaching methods:
Seminars, self study, exercises/project work with presentations.

Course material:
Articles and excerpts from textbooks.

Language:
English

KP4515-2 Environmental and energy catalysis

Responsible: Professor Hilde J. Venvik

Credits: 3.75 SP
Prerequisites:
TKP4155 Reaction kinetics and catalysis or equivalent knowledge

Module description:
Catalysis occupies an important position within areas such as environmental technology and energy production. Within environmental technology catalysis has become crucial not only for removing of unwanted components such as NOX, sulfur etc., but also for the development of selective processes. The course will give the fundamentals for catalytic processes for purification of exhaust gases (NOX, CO, unburned hydrocarbons etc). Within energy production the focus is on biofuel production, catalytic combustion, production of H2 and catalysis/reactor technology related to fuel cells. Catalysis for clean production will also be an important part of the course

Teaching methods:
Seminars, self study, exercises/project work with presentations.

Course material:
Articles and excerpts from textbooks.

Language:
English

KP8132 Applied heterogeneous catalysis

Responsible: Professor De Chen
Lecturers: Prof. Hilde J. Venvik and Prof. Anders Holmen

Credits: 7.5 SP
Prerequisites: TKP4155 Reaction kinetics and catalysis.

Course description:
The course is given every second year, next time in the fall term 2011.
The course gives an introduction to modern theories for the most important groups of heterogeneous catalysts: Metals, metal oxides and zeolites. Examples of industrial applications are included. An overview of the principles for design and preparation of heterogeneous catalysis will be given. The course includes a

kinetic description of the different processes involved in a catalytic cycle: Adsorption, surface reaction and desorption in addition to mass and heat transfer. An introduction to different experimental methods for studying catalytic reactions will also be given.

Teaching methods:
Seminars.

Course material:
Selected articles and handouts.

KP8133 Characterization of heterogeneous catalysts

Responsible: Professor Magnus Rønning

Credits: 7.5 SP

Course description:
The course is given every second year, next time in fall term 2012.
In heterogeneous catalysis the reactions take place on the surface of solid materials such as metals, metal oxides and zeolites. It is the conditions on the surface that determines the activity, selectivity and lifetime. Methods for characterization of solid surfaces and of adsorbed components are therefore very important for the understanding of catalytic reactions. The course will give an overview of different methods and a detailed introduction to the use of these methods on catalytic systems. The course covers chemical as well as spectroscopic methods with emphasize on in situ methods.

Course material:
Selected scientific papers.

KP8136 - Modelling of Catalytic Reactions

Responsible: Professor De Chen

Credits: 7.5 SP
Prerequisites: TKP4155 Reaction kinetics and catalysis.

Course description:
The course is given every second year, next time in spring 2013.

The course gives an overview on the methods for building microkinetic model, collecting or theoretically estimating rate constant, and microkinetic simulation. Focus will also on the microkinetic analysis of reaction systems at the atomic level. A project work of microkinetic modeling of a selected reaction system will be included in the course.

Learning methods and activities:
Seminars + project

Course materials:
James A. Dumesic, Dale F. Rudd, Luis M. Aparicio, James E. Rekoske, Andres A. Trenino, The microkinetics of heterogeneous catalysis. ACS professional Reference Book, Washington, DC 1993.
Selected papers

KP8137 - Design and Preparation of Catalytic Materials

Responsible:
Lecturer: Professor Edd Blekkan

Credits: 7.5 SP

Course description:
The course is given every second year, next time spring 2013.
The course gives an overview of principles for design and preparation of catalytic materials. Synthesis methods for support materials as well as catalytically active phases will be described, e.g. (co-)precipitation, impregnation incl. incipient wetness and ion exchange, deposition-precipitation, sol-gel methods, different methods based on pyrolysis and chemical vapour deposition (CVD). The different steps in the preparation, including drying, calcination and reduction, and parameters that influence/control the final catalyst properties are assessed. Important classes of materials such as alumina, silica and zeolites, as well as structured mesoporous materials (MCM-41, SBA-15) are discussed. Carbon nanofiber (CNF) production by catalytic methods is also included, and an introduction to combinatorial methods for parallel synthesis and/or screening of new catalyst systems will be given. Methods for and challenges connected to synthesis scale-up and industrial processing of heterogeneous catalysts are specifically treated.

Learning objective:
The students should be able to make qualified choices and adjustments regarding catalyst preparation methods and synthesis parameters. To some extent they should be able to assess scale-up and industrial production.

Learning methods and activities:
Seminars

Recommended previous knowledge:
Basic knowledge in solid state chemistry and heterogeneous catalysis is required.

Course materials:
Selected handouts and scientific papers

Course on HMS (Health, Environment and Safety) and Laboratory work

Responsible: Professor Hilde J. Venvik

Credits: The course is obligatory and a part of the TKP specialization in catalysis.
Prerequisites: None

Course description:
The goal is to develop a course in HMS (health, environment and safety) covering the activities of the catalysis group. The course is for 5th year students and new Ph.D. students, and is to be held for one week in the beginning of the autumn semester. The goal of the course is

- to give the same qualitative information to everybody working in our laboratories, and thereby improve the safety in the laboratories.
- to improve the attitude to and knowledge in HMS in working life by more teaching and higher demands for this also durting the studies.
- to improve the students’ compentense in using the equipment at hand, and thereby improve the efficiency and the quality of the experimental work.
- to introduce the students to the working environment, and to improve the reliance between all the employees.

Teaching methods: Seminars
Course material: Handouts

Publications in 2010

1. B. C. Enger, R. Lødeng, A. Holmen: *Effects of Noble Metal Promoters on In Situ Reduced Low Loading Ni Catalysts for Methane Activation.* Catal. Lett. **134** (2010) 13-23
2. S.F. Håkonsen, J.C. Walmsley, A. Holmen: *Ethene production by oxidative dehydrogenation of ethane at short contact times over Pt-Sn coated monoliths.* Appl. Catal. A: General **378** (2010) 1-10
3. C.M. Balonek, A.H. Lillebø, S. Rane, E. Rytter, L.D. Schmidt, A. Holmen: *Effect of alkali metal impurities on Co-Re catalysts for Fischer-Tropsch synthesis from biomass-derived syngas.* Catal. Lett. **138** (2010) 8-13
4. B. C. Enger, R. Lødeng, J. Walmsley, A. Holmen: *Inactive aluminate spinels as precursors for design of CPO and reforming catalysts.* Appl. Catal. A: General **383** (2010) 119-27.
5. Lind, R. Myrstad, S. Eri, T. Hulsund Skagseth, E. Rytter, A. Holmen: *Spray drying of porous alumina support for Fischer-Tropsch catalysts.* Stud. Surf. Sci. Catal. **175** (2010) 685-688.
6. N.E. Tsakoumis, M. Rønning, Ø. Borg, E. Rytter, A. Holmen: *Deactivation of cobalt based Fischer-Tropsch catalysts: A review.* Catal. Today **154** (2010) 162-182.
7. S. Løgdberg, M. Lualdi. S. Jærås, J.W. Walmsley, E.A. Blekkan, E. Rytter, A. Holmen: *On the selectivity of cobalt-based Fischer-Tropsch catalysts: Evidence for a common precursor for methane and long chain hydrocarbons.* J. Catal. **274** (2010) 84-98.
8. M. Rønning, N.E. Tsakoumis, A. Voronov, R.E. Johnsen, P. Norby, W. van Beek, Ø. Borg, E. Rytter, A. Holmen, *Combined XRD and XANES studies of a Re-promoted Co/γ-Al2O3 catalyst at Fischer - Tropsch synthesis conditions*. Catal. Today, **155** (2010) 289-295.
9. S.P. Rane, Ø. Borg, J. Yang, E. Rytter, A. Holmen*: Effect of alumina phases on hydrocarbon selectivity in Fischer-Tropsch synthesis.* Appl Catal. A: General **388** (2010) 160-167.
10. J. Yang, E.Z. Tveten, D. Chen, A. Holmen: *Understanding the effect of cobalt particle size on Fischer-Tropsch synthesis: Surface species and mechanistic studies by SSITKA and kinetic isotope effect.* Langmuir **26** (21) (2010) 129-144.
11. X.K. Phan, H.D. Bakhtiary, R. Myrstad, J. Thormann, P. Pfeifer, H.J. Venvik, A. Holmen: *Preparation and performance of a catalyst-coated stacked foil microreactor for methanol synthesis.* Ind. Eng. Chem. Res. **49** (2010) 10934-10941.

12. N. Hammer, T. Zscherpe, D. Chen, M. Rønning, *Selective oxidation of CO on Au-TiO_2 catalysts on a structured carbon support.* Prep. Am. Chem. Soc. Div. Fuel Chem, (2010) 55(1), 102-103
13. Tiejun Zhao, Yingda Yu, De Chen, Magnus Rønning, *Preferential oxidation of CO in H_2-rich feed over unsupported nanocomposite and structured carbon nanofiber supported Cu-CeO_2 catalysts*. Prep. Am. Chem. Soc. Div. Fuel Chem, (2010) 55(1), 187-188
14. C.F. Sanz-Navarro, P.-O. Åstrand, D. Chen, M. Rønning, A.C.T. van Duin, W.A. Goddard III, *Molecular Dynamics Simulations of Metal Clusters Supported on Fishbone Carbon Nanofibers*. J. Phys. Chem. C, 114 (2010) 3522
15. He, Li; Parra, J.M.S.; Blekkan, E.A.; Chen, De, *Towards efficient hydrogen production from glycerol by sorption enhanced steam reforming*, Energy & Environmental Science (2010), 3(8), 1046-1056.
16. Ramachandran, W. M. Tucho, A. L. Mejdell, M. Stange, H. Venvik, J. Walmsley, R. Holmestad, R. Bredesen, A. Borg. *Surface characterization of Pd/Ag23wt% membranes after different thermal treatments.* Applied Surface Science 256 (2010) 6121.
17. A. L. Mejdell, D. Chen, T. A. Peters, R. Bredesen, H. J. Venvik. *The effect of heat treatment in air on CO inhibition of a ~3 μm Pd/Ag 23wt.% membrane.* Journal of Membrane Science 350 (2010) 371–377.
18. Duan, X.; Qian, G.; Zhou, X.; Sui, Z.; Chen, D.; Yuan, W., *Tuning the size and shape of Fe nanoparticles on carbon nanofibers for catalytic ammonia decomposition. Applied Catalysis B: Environmental* 2011, 101, (3-4), 189-196.
19. Zhu, Y.-A.; Chen, D.; Zhou, X.-G.; Astrand, P.-O.; Yuan, W.-K., *First-principles calculations of C diffusion through the surface and subsurface of Ag/Ni(1 0 0) and reconstructed Ag/Ni(1 0 0). Surface Science* 2010, 604, (2), 186-195.
20. Yang, M.-L.; Zhu, Y.-A.; Fan, C.; Sui, Z.-J.; Chen, D.; Zhou, X.-G., *Density functional study of the chemisorption of C1, C2 and C3 intermediates in propane dissociation on Pt(1 1 1). Journal of Molecular Catalysis A: Chemical* 2010, 321, (1-2), 42-49.
21. Mihai, O.; Chen, D.; Holmen, A., *Catalytic Consequence of Oxygen of Lanthanum Ferrite Perovskite in Chemical Looping Reforming of Methane.* Industrial & Engineering Chemistry Research 2010.
22. Lu, W.-X.; Sui, Z.-J.; Zhou, J.-H.; Li, P.; Chen, D.; Zhou, X.-G., *Kinetically controlled synthesis of carbon nanofibers with different morphologies by catalytic CO disproportionation over iron catalyst.* Chemical Engineering Science 2010, 65, (1), 193-200.
23. Lou, F.-L.; Sui, Z.-J.; Sun, J.-T.; Li, P.; Chen, D.; Zhou, X.-G., *Synthesis of carbon nanofibers/mica hybrids for antistatic coatings.* Materials Letters 2010, 64, (6), 711-714.

24. Kvande, I.; Zhu, J.; Zhao, T. J.; Hammer, N.; Ronning, M.; Raaen, S.; Walmsley, J. C.; Chen, D., *Importance of Oxygen-Free Edge and Defect Sites for the Immobilization of Colloidal Pt Oxide Particles with Implications for the Preparation of CNF-Supported Catalysts.* Journal of Physical Chemistry C 2010, 114, (4), 1752-1762.
25. Huang, F.; Vanhaecke, E.; Chen, D., *In situ polymerization and characterizations of polyaniline on MWCNT powders and aligned MWCNT films.* Catalysis Today 2010, 150, (1-2), 71-76.
26. He, L.; Chen, D., *Single-Stage Production of Highly Concentrated Hydrogen from Biomass-Derived Syngas.* ChemSusChem 2010, 3, (10), 1169-1171.
27. He, L.; Berntsen, H.; Chen, D., *Approaching Sustainable H-2 Production: Sorption Enhanced Steam Reforming of Ethanol.* Journal of Physical Chemistry A 2010, 114, (11), 3834-3844.
28. Duan, X.; Zhou, J.; Qian, G.; Li, P.; Zhou, X.; Chen, D., *Carbon Nanofiber-Supported Ru Catalysts for Hydrogen Evolution by Ammonia Decomposition.* Chinese Journal of Catalysis 2010, 31, (8), 979-986.

Presentations at International and National Meetings 2010

1. J.C. Walmsley, R. Dehgham, P.-E. Vullum, R. Holmestad, M. Rønning, A. Holmen, B. Hauback: *TEM analysis of catalyst and energy storage materials. Int. Symp. on Advanced Electron Microscopy for Catalysis and Energy Storage Materials*, January 17-20, 2010, Berlin, Germany.
2. F. Hayer, H. Bakhtiary D., R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen: *Synthesis of Dimetyl Ether from Syngas in a Microchannel Reactor – Simulation and Experimental Study*. Lecture. 11th Int. Conf. Microreaction Technology (IMRET11), March 8-10, 2010, Kyoto, Japan.
3. H. Bakhtiary D., F. Hayer, X.K. Phan, R. Myrstad, H.J. Venvik, P. Pfeifer, A. Holmen: *Reactor Characteristics of an Integrated Micro Packed Bed Reactor-Heat Exchanger for Methanol Synthesis.* Poster. 11th Int. Conf. Microreaction Technology (IMRET11), March 8-10, 2010, Kyoto, Japan.
4. Holmen, J. Yang, S. Rane, Ø. Borg, E. Rytter.: *Selectivity and activity for Fischer-Tropsch synthesis catalysts.* Lecture. 239th American Chemical Society National Meeting, March 21-25. 2010, San Francisco, USA.
5. Holmen: *Supported Cobalt Catalysts for Fischer-Tropsch Synthesis*. Award Lecture. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
6. S. Boullosa Eiras, T. Zhao, E. Vanhaecke, D. Chen, A. Holmen: *CeO_2-ZrO_2-mixed oxidesnanocomposites supported Rh: a promising catalyst for partial oxidation of methane to syngas.* Lecture. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
7. J. Yang, A. Helland Lillebø, D. Chen, A. Holmen: *Effect of ppm level sodium on $CoRe/Al_2O_3$ catalystfor the Fischer-Tropsch reaction studied with SSITKA.* Lecture. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
8. H. Wang, A.H. Dam, D.W. Blaylock, T. Ogura, Y. Zhu, A. Holmen, W.H. Green, D Chen: *Kinetic study of methane steam reforming over core-shell structured bimetal Ni based catalyst.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
9. O. Mihai, D. Chen, A. Holmen: *The effect of crystal size of perovskites on methane partial oxidation.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
10. F. Hayer, H. Baktiary, R. Myrstad, P. Pfeifer, A. Holmen, H.J. Venvik: *Synthesis of Dimethyl Ether from Syngas in a Fixed Bed Reactor – Simulation and Experimental study.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.

11. J. Zhu, D. Chen, M. Rønning, Y. Yu, A. Holmen: *The nature of active sites in Pt nanoparticles for ptopane dehydrogenation.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
12. B.C. Enger, R. Lødeng, A. Holmen: *UBI-QEP evaluation of Ni(100) and Ni(111) sites for sygas formation.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
13. H. Baktiary, F. Hayer, X.K. Phan, R. Myrstad, P. Pfeifer, H.J. Venvik, A. Holmen: *Performance of a microstructured packed bed reactor in the synthesis of methanol.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
14. X.K. Phan, H. Baktiary, R. Myrstad, H.J. Venvik, J. Thormann, P. Pfeifer, A. Holmen: *Preparation and performance of Cu-based monoliths for methanol synthesis.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
15. T. Noor, A. Lindh, A. Holmen, D. Chen: Synthesis and Characterization of Ni *Hydrotalcite Catalyst for Hydrogen Production from Steam Methane Reforming*. Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
16. A.H. Dam, H.M. Wang, A. Holmen, D. Chen: *Steam methane reforming and carbon formation on Ni surface alloying catalyst prepared by surface redox reaction.* Poster. 9th Novel Gas Conversion Symposium. May 30th – June 3rd 2010, Lyon, France.
17. O. Mihai, D. Chen, A. Holmen: *Experimental investigation of lanthanum ferrite perovskite catalyst using tartaric acid as complexing agent on the methane partial oxidation to syngas.* Lecture. International-Mexican Congress on Chemical Reaction Engineering (IMCCRE 2010), June 6-10 2010, Ixtapa-Zihuatanejo, Guerrero, Mexico.
18. D. Chen. R. Lødeng, H. Svendsen, A. Holmen: *Hierarchical multiscale modelling of methane steam reforming reactions.* Lecture. International-Mexican Congress on Chemical Reaction Engineering (IMCCRE 2010), June 6-10 2010, Ixtapa-Zihuatanejo, Guerrero, Mexico.
19. Holmen: *Fischer-Tropsch syntese*. Plenarforedrag. Teknisk kemi och reaktionsteknik vid Åbo Akademi 90 år. June 18, 2010, Åbo, Finland.
20. O. Mihai, D. Chen, A. Holmen: *Methane partial oxidation by oxygen lattice of LaFeO3 perovskite catalysts.* Poster. Gordon Research Conference (Catalysis) June 27-July 2, 2010, Colby-Sawyer, New London, NH, USA.
21. J.H. Bitter, J.P. den Breejin, G.L. Bezemer, A.L. Macedo, L.V. Mattos, F.B. Noronha, P.B. Radstake, V. Frøseth, A. Holmen, K.P. de Jong: *Reaction dependence particle size effects in carbon supported cobalt catalysts.* Lecture. Carbon 2010 - From Nano to Macro. July 11-16. 2010, Clemson, SC, USA.

22. A.Lind, R. Myrstad, S. Eri, T. Hulsund Skagseth, E. Rytter, A. Holmen: *Spray drying of porous alumina support for Fischer-Tropsch catalysts.* Poster. 10th Int. Symp. Scientific Bases for the Preparation of Heterogeneous Catalysts. July 11-15, 2010, Louvain-la-Neuve, Belgium.
23. R. Dehghan-Niri, T.W. Hansen, J.B. Wagner, A. Holmen, E. Rytter, Ø. Borg, J.W. Walmsley: *In-situ reduction of cobalt oxide supported on alumina in an environmental transmission electron microscope.* Lecture. TOCAT6 / APCAT5. July 18-23, 2010, Sapporo, Japan.
24. B.C. Enger, R. Lødeng, A. Holmen: *Reaction Pathways from CH4 to H2 – UBI-QEP Evaluation of Transition Metals.* Lecture. ACS National Meeting, August 23-26 2010, Boston, USA.
25. S. Rane, Ø. Borg, E. Rytter, A. Holmen: *Effect of cobalt particle size on Fischeer-Tropsch hydrocarbon selectivities for θ-alumina support.* Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
26. T. Zhao, S. Boullosa-Eiras, Y. Li, D. Chen, A. Holmen, M. Rønning: *Pechini route in pore: Synthesis of supported catalysts by impregnation and calcination of room-temperature polymerizable metal-complexes.* Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
27. N.T. Tsakoumis, A. Voronov, M. Rønning, Ø. Borg, E. Rytter, A.. Holmen: *Co-based Fischer-Tropsch synthesis: An Operando study from catalyst activation to deactivation.* Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
28. P.B. Radstake, S.F. Håkonsen, M. Rønning, A. Holmen: *Oxidative dehydrogenation of ethanr at short contact times.* Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
29. Voronov, N.T. Tsakoumis, M. Rønning, Ø. Borg, E. Rytter, A. Holmen: *In situ deactivation study of the rhenium behaviour in Co_Re Fischer-Tropsch catalysts*. Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
30. J. Yang, T. Zhao, E. Tveten, D. Chen, A. Holmen: *Origin of in-situ reduction and oxidation of* Co/Al_2O_3 *in the Fischer-Tropsch synthesis.* Poster. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
31. H. Venvik, P. Pfeifer, R. Myrstad, I Aartun, H. Bakhtiary, F. Hayer, X.K. Phan, B.C. Enger, R. Lødeng, O. Görke, K. Schubert, A. Holmen: *Microstructured reactors in compact conversion of natural gas and biomass to liquid fuels and hydrogen.* Lecture. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.
32. S. Løgdberg, M. Lualdi, G. Di Carlo, S. Järås, M. Boutonnet, J.C. Walmsley, E. A. Blekkan, E. Rytter, A. Holmen: *On the selectivity of*

cobalt-based Fischer-Tropsch catalysts. Lecture. 14th Nordic Symposium on Catalysis, August 29-31, 2010, Helsingør, Denmark.

33. B.C. Enger, R. Lødeng, A. Holmen: *Reaction Pathways from CH4 to H2 – UBI-QEP Evaluation of Transition Metals.* Lecture. ACS National Meeting, August 23-26 2010, Boston, USA.
34. R. Dehghan Niri, T.W. Hansen, J.B. Wagner, A. Holmen, E. Rytter, Ø. Borg, J.C. Walmsley: *Using environmental transmission electron microscopy to study the in-situ reduction of* Co_3O_4 *supported on* α-Al_2O_3*.* Poster. International Microscopy Congress (IMC 17) September 19-24 2010, Rio, Brazil.
35. Ø. Borg, Z. Yu, S. Rane, D. Chen, E. Rytter, A. Holmen: *Fischer-Tropsch Synthesis on Co Catalysts Supported on Carbon Nanotubes.* Lecture. CarboCat IV, November 7-10, 2010, Dalian, China.
36. J. Yang, Ø. Borg, D. Chen, A. Holmen: *Re Promotion Effect of Carbon Nanotube Supported Cobalt Catalyst for Fischer-Tropsch Synthesis Studied by SSITKA*. Poster. CarboCat IV, November 7-10, 2010, Dalian, China.
37. Hammer, Nina; Zscherpe, Tina; Chen, De; Rønning, Magnus. *Selective oxidation of CO on Au-*TiO_2 *catalysts on a structured carbon support.* 239th National Meeting of the American Chemical Society. Division Fuel Chem; 2010-03-21 - 2010-03-25
38. He, Li; Zhao, Tiejun; Kazi, Saima Sultana; Rønning, Magnus; Chen, De. *Progresses in carbonate looping process.* 239th National Meeting of the American Chemical Society; 2010-03-21 - 2010-03-25
39. Kazi, Saima Sultana; He, Li; Zhao, Tiejun; Fagerbekk, Siri Albertsen; Lind, Anna Maria; Rønning, Magnus; Chen, De. *New Calcium-based mixed oxide sorbents for* CO^2 *capture in sorption enhanced steam methane reforming.* 9th Novel Gas Conversion Symposium; 2010-05-30 - 2010-06-03
40. Kvande, Ingvar; Briskeby, S. T.; Hammer, Nina; Rønning, Magnus; Walmsley, John; Sunde, Svein; Chen, De. *Direct evidence of strong interaction between PTO nanoparticles and carbon nanofibres.* 14th Nordic Symposium on catalysis; 2010-08-29 - 2010-08-31
41. Muthuswamy, Navaneethan; Gomez de la Fuente, Jose L.; Tsypkin, Mikhail; Zhao, Tiejun; Rønning, Magnus; Seland, Frode; Sunde, Svein; Chen, De. *Platelet carbon nanofibers supported Pt nanoparticles for fuel cell application.* 4th International symposium on carbon for catalysis; 2010-11-07 - 2010-11-10
42. Vanhaecke, Estelle Marie M.; Huang, Fan; Chen, De; Rønning, Magnus. *Development of nanostructured electrodes on foils.* 1st International Conference on Materials for Energy; 2010-07-04 - 2010-07-08

43. Voss, Georg Johannes Bernhard; Rønning, Magnus. *The State of Promotors in Fischer-Tropsch Catalysts.* Norwegian Catalysis Symposium 2010; 2010-11-29 - 2010-11-30
44. Zhao, Tiejun; Yu, Yingda; Chen, De; Rønning, Magnus. *Preferential oxidaton of CO in H_2-rich feed over unsupported nanobomposite and structured carbon nanofiber cupported Cu-CeO_2 catalysts.* ACS Spring conference; 2010-03-21 - 2010-03-25
45. Zhao, Tiejun; Yu, Yingda; Chen, De; Rønning, Magnus. *Structured carbon nanofiber supported Cu-CeO_2 catalyst: Catalytic behavior in the preferential oxidation of CO in H_2-rich gases.* 9th Novel Gas Conversion symposium; 2010-05-30 - 2010-06-03
46. Edd A. Blekkan: *Recent developments in the Fischer-Tropsch synthesis over supported cobalt catalysts.* Keynote (invited) lecture, 9^th Novel Gas Conversion Symposium, Lyon, France May 30 – June 4, 2010.
47. Ilya V. Gorelkin, Edd A. Blekkan: *Concepts and models of the catalytic dehydrogenation of propane.* 12^th Norwegian Catalysis Symposium, Bergen, Nov. 29-30, 2010.
48. Wangen, Espen Standal; Blekkan, Edd Anders: *The Effect of Soot Deposition on Catalytic Activities in the Steam Reforming of a Simulated Producer Gas.* 9th Novel Gas Conversion Symposium, Lyon, France May 30 – June 4, 2010.
49. Wangen, Espen Standal; Osatiashtiani, Amin; Blekkan, Edd Anders: *Catalytic steam reforming for the production of biomass derived synthesis gas.* Renewable Energy Research Conference; Trondheim June 7-8, 2010
50. Wangen, Espen Standal; Osatiashtiani, Amin; Blekkan, Edd Anders: *Production of biomass derived synthesis gas by catalytic steam reforming.* Nordic Symposium on Catalysis; Marienlyst, Denmark Aug. 29-31, 2010.
51. Panditha Vidana, Daham S G; Venvik, Hilde Johnsen. *New approach to metal dusting corroston.* inGAP seminar; 2010-06-15 - 2010-06-16 (oral)
52. Panditha Vidana, Daham S G; Walsmley, John; Venvik, Hilde Johnsen. *Experimental study of Ni based alloys in high carburising environment.* Norwegian Catalysis Symposium 2010 and Annual Meeting for the KOSKII program of the Norwegian Research Council; 2010-11-29 - 2010-11-30 (oral)
53. Li He, De Chen, Submitted abstract, *Coupling CO_2 Capture in Catalytic reactions for the Conversion of Biomass to H_2.* The ninth edition of the Novel Gas Conversion Symposium (NGCS 9), May 30th – June 3rd, 2010, Lyon, France.
54. Li He, Morten Beinset, Helene Berntsen, De Chen, Oral, *Mulifuctional Composites for H_2 production via Sorption Enhanced Steam Reforming*, 2009 – EuropaCat IX Congress, August 30 – September 4,2009, Spain.
55. Kazi Saima Sultana, Tiejun Zhao, Siri Albertsen Fagerbekk, Li He and De Chen: *Calcium based sorbents for CO_2 capture in sorption enhanced*

steam methane reforming. Lecture: 10th International Conference on CO_2 Utilization (ICCDU-X), Tianjin, May 17-21, 2009.

56. De Chen, *Hydrogen production with CO2 capture.* 10th International Conference on CO_2 Utilization (ICCDU-X), Tianjin, May 17-21, 2009.
57. Maria Eugenia Sad, De Chen, Enrique Iglesia. *Catalytic pathways for deoxygenation and carbon-carbon formation on supported metal clusters.* 239th National Meeting of the American Chemical Society, March 21-25, 2010, San Francisco, California, USA.
58. Li He, De Chen, *Highly efficient hydrogen production from biomass*. 239th National Meeting of the American Chemical Society, March 21-25, 2010, San Francisco, California, USA.
59. De Chen. *Properties and catalytic consequences of surface edge-mediated nanoparticals supported on carbon nanofibers.* March 1-3 2010. XIth Netherlands Catalysis and Chemistry Conference. The Netherlands.
60. De Chen, *Catalysis on surface edge-mediated nanoparticals supported on carbon nanofibers*. Keynote lecture. The 3rd International Symposium on New Catalytic Materials. Aug. 13-15, 2010 Mexico.
61. Fan Huang, Estelle Vanhaecke, Magnus Rønning, Edel Sheridan and De Chen, *Composite of Conducting Polymers and Carbon Nanostructures for Energy Storage*. Oral presentation, 1st International Conference on Materials for Energy, Karlsruhe, Germany, July 4-8 2010.
62. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils*. Oral presentation, Carbon conference, Clemson University, USA, July 11-16 2010.
63. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils*. Oral presentation, 1st International Conference on Materials for Energy, Karlsruhe, Germany, July 4-8 2010
64. Fan Huang, Estelle Vanhaecke, De Chen *Composite of Conducting Polymers and Aligned CNT for Energy Storage.* Oral presentation, 1st International Conference on Materials for Energy, Karlsruhe, Germany, July 4-8 2010
65. Estelle Vanhaecke, Fan Huang, De Chen, Magnus Rønning, *Development of nanostructured electrodes on foils*. Poster presentation, 14th Nordic Symposion, Marienlyst, Denmark, August 29-31 2010
66. Fan Huang, Estelle Vanhaecke, De Chen, *Composite of Conducting Polymers, semiconducting oxides and Aligned CNT for Energy Storage*. Poster presentation, 14th Nordic Symposion, Marienlyst, Denmark, August 29-31 2010
67. Estelle Vanhaecke, Fan Huang, De Chen, *Catalytic consequence of the interface between catalysts and foils in synthesis of aligned nanocarbons on foils*. Poster presenation, Carbocat IV, Dalian, China, November 7-10 2010

68. M. Rønning, *Cobalt catalysts in Fischer-Tropsch synthesis*, Invited lecture, Metal Kokkola 2010, November 16-17, 2010, Finland
69. M. Rønning, *Studies of Fischer-Tropsch catalysts at real working conditions*, Invited Keynote lecture, 14th Nordic Symposium on Catalysis, August 29-31. 2010, Helsingør, Denmark.
70. Edd A. Blekkan: *Recent developments in the Fischer-Tropsch synthesis over supported cobalt catalysts*. Seminar, Cambridge University, UK, Oct. 27, 2010
71. Edd A. Blekkan: *Biodrivstoff. Løsning eller problem?* Foredrag Heimdal Rotary, 15. februar 2010.

Alumni
PhD students Catalysis group:

Per Åge Sørum

Hydrogenolysis of esters. Conversion of metylformiat to methanol.

Defense of thesis: 1982

Current position: Statoil Mongstad

Edd Anders Blekkan

Characterization and pyrolysis of heavy oils.

Defense of thesis: November 1985

Current position: Professor NTNU.

Dag Schanke

Hydrogenation of CO over supported iron catalysts.

Defense of thesis: October 1986

Current position: Chief researcher, Statoil

Kjell Moljord

Diffusion og reaksjon i sure organiske ionebyttere: Væskefase dehydratisering av metanol og t-butanol katalysert av sulfonert poly(styrene-divinylbenzen).

Defense of thesis: 1986

Current position: Statoil, Adjunct professor, NTNU

Edvard Bergene

Surface characterization of Pt and Pt/Rh gauze catalysts.

Defense of thesis: March 1990

Current position: Statoil

Rune Lødeng

A kinetic model for methane directly to methanol.

Defense of thesis: 1991

Current position: Senior researcher,SINTEF Trondheim

Trude Dypvik

Oligomerization of ethene on zeolite ZSM-5 type catalysts.

Defense of thesis: January 1992

Current position: Senior advisor, The Research Council of Norway

Ola Olsvik

Thermal coupling of methane.

Defense of thesis: 1993

Current position: Statoil

Anne Hoff

CO hydrogenation over cobalt Fischer-Tropsch catalysts.

Defense of thesis: October 1993

Current position: Statoil

Stein Harald Skaare.

Reaction and heat transfer in wall-cooled fixed bed reactor.

Defense of thesis: December 1993

Current position: Aibel, Oslo

Odd Arne Bariås

Transient kinetic investigation of the catalytic dehydrogenation of propane.

Defense of thesis: December 1993

Current position: Elkem Solar AS

Geir Remo Fredriksen

Hydrogenation of CO on supported cobalt catalysts studied by in situ FTIR spectroscopy.

Defense of thesis: December 1993

Current position: Statoil

Arne Grønvold

Conversion of methanol to lower alkenes over molecular sieve-type catalysts.

Defense of thesis: September 1994

Current position: Ineos

Sturla Vada

Isotopic transient kinetic investigations of catalytic reactions.

Defense of thesis: October 1994

Current position: Statoil

Rune Prestvik

Characterization of the metal function of a Pt-Re/Al2O3 reforming catalyst.

Defense of thesis: October 1995

Current position: Statoil

Anne-Mette Hilmen

Reduction and reoxidation of cobalt Fischer-Tropsch catalysts.

Defense of thesis: October 1996

Current position: Shell, Norway

Karina Heitnes Hofstad

Catatlytic oxidation of methane to synthesis gas.

Defense of thesis: 1996

Current position: Statoil

Håkon Bergem

Sulfur tolerant zeolite supported platinum catalysts for aromatics hydrogenation.

Defense of thesis: April 1997

Current position: Senior researcher, SINTEF, Trondheim

Staale Førre Jenssen

Catalytic decomposition of NO over metal exchanged zeolites.

Defense of thesis: January 1998

Current position: Statoil

Mimmi Kjetså

Etherification of methanol and iso/n-propanol with C4–C6 olefins on a macroporous acid ion exchange resin catalyst.

Defense of thesis: May 1998

Current position: Statoil

De Chen

Methanol conversion to light olefins over SAPO-34: Diffusion, coke depositions and shape selective reactions.

Defense of thesis: 1998

Current position: Professor, NTNU

Hans Petter Rebo

Application of the TEOM reactor for adsorption, diffusion and kinetic studies.

Defense of thesis: March 1999

Current position: Statoil

Marit Senum Brownrigg

Deactivation and regeneration of bifunctional zeolites.

Defense of thesis: August 1999

Current position: Jotun, Dubai.

Ketil Firing Hanssen

Cobalt Fischer-Tropsch catalysts studied by steady-state and transient kinetic methods.

Defense of thesis: 1999

Current position: Senior engineer, Det norske veritas (DNV)

Magnus Rønning

Bimetallic catalysts and platinum surfaces studied by X-ray absorption spectroscopy and scanning tunnelling microscopy.

Defense of thesis: February 2000

Current position: Professor, NTNU

Marcus Fathi

Catalytic partial oxidation of methane to synthesis gas.

Defense of thesis: September 2000

Current position: Statoil

Torbjørn Gjervan

Studies of bimetallic particle formation in reforming catalysts.

Defense of thesis: November 2000

Current position: Research director, SINTEF

Thomas Sperle

Steam reforming of hydrocarbons to synthesis gas.

Defense of thesis: October 2001.

Current position: Statoil

Lucie Bednarova

Study of supported Pt-Sn catalysts for propane dehydrogenation.

Defense of thesis: May 2002

Current position: General Motors, Detroit, USA

Sten Viggo Lundbo

Hydrogenation of carbon monoxide over zirconia and modified zirconia catalysts.

Defense of thesis: June 2002.

Current position: Statoil

Leiv Låte

Oxygen-assisted conversion of propane over metal and metal oxide catalysts.

Defense of thesis: 2002

Current position: Managing Director, Fedem Technology, Trondheim

Petr Steiner

Kinetic and deactivation studies of hydrodesulfurization catalysts.

Defense of thesis: December 2002

Current position: Manager, Hart Energy Consulting.

Bozena Silberova

Oxidative dehydrogenation of ethane and propane at short contact time.

Defense of thesis: January 2003

Current position: Avantium, The Netherlands

Christian Aaserud

Model studies of secondary hydrogenation in Fischer-Tropsch synthesis studied by cobalt catalysts.

Defense of thesis: May 2003.

Current position: Gassco

Kjetil Hauge

Oligomerization of isobutene over solid acid catalysts for production of high octane gasoline.

Defense of thesis: September 2004.

Current position: Statoil

Thomas Løften

Catalytic isomerisation of light alkanes.

Defense of thesis: December 2004

Current position: Statoil Mongstad

Zhixin Yu

Synthesis of carbon nanofibers and carbon nanotubes.

Defense of thesis: January 2005

Current position: Statoil

Kjersti O. Christensen

Steam reforming of methane on different nickel catalysts.

Defense of thesis: March 2005

Current position: Statoil research centre. Trondheim.

Ingrid Aartun

Microstructured reactors for hydrogen production.

Defense of thesis: June 2005

Current position: Statoil, Mongstad

Sølvi Storsæter

Fischer-Tropsch synthesis over cobalt supported cobalt catalysts.

Defense of thesis: June 2005

Current position: Statoil, Mongstad

Erlend Bjørgum

Methane conversion over mixed metal oxides.

Defense of thesis: January 2006

Current position: Statoil, Mongstad

Vidar Frøseth

A steady-state isoptopic transient kinetic study of Co catalysts on different supports.

Defense of thesis: May 2006

Current position: Statoil, Mongstad

Florian Huber

Nanocrystalline copper-based mixed oxide catalysts for water-gas shift.

Defense of thesis: August 2006

Current position: Haldor Topsøe, Danmark

Esther Ochoa Fernandez

CO2 acceptors for sorption enhanced steam methane reforming.

Defense of thesis: June 2007

Current position: Statoil research centre, Trondheim

Øyvind Borg

Role of alumina support in cobalt Fischer-Tropsch synthesis.

Defense of thesis: April 2007

Current position: Statoil research centre, Trondheim.

Espen Standal Wangen

Characterisation and pyrolysis of heavy oils.

Defense of thesis: May 2007

Current position: Postdoc, NTNU

Hilde Dyrbeck

Selective catalytic oxidation of hydrogen and oxygen-assisted conversion of propane.

Defence of thesis: September 2007

Current position: Statoil research centre, Trondehim

Svatopluk Chytil

Platinum supported on mesoporous silica SBA-15:preparation, characterization and catalytic properties.

Defense of thesis: September 2007

Current position: Researcher, SINTEF Trondheim

Ingvar Kvande

Carbon nanofiber supported platinum catalysts

Defense of thesis: December 2007

Current position: Researcher, SINTEF Trondheim.

Hilde Meland

Preparation and characterization of Cu- and Pt-based water-gas shift catalysts.

Defense of thesis: May 2008

Current position: Researcher, SINTEF Trondheim.

Silje Fosse Håkonsen

Role of alumina support in cobalt Fischer-Tropsch synthesis.

Defense of thesis: June 2008

Current position: Researcher, SINTEF Oslo

Bjørn Christian Enger

Hydrogen production by catalytic partial oxidation of methane.

Defense of thesis: December 2008

Current position: Postdoc, NTNU

Nina Hammer

Au-TiO2 catalysts supported on carbon nanostructures for CO removal reactions

Defense of thesis: November 2008

Current position: Postdoc, NTNU

Astrid Lervik Mejdell

Properties and application of 1-5 µm Pd/Ag23wt.% membranes for hydrogen separation.

Defence of thesis: May 2009

Current position: Researcher, Statoil

Li He

Sorption enhanced steam reforming of Biomass Derived Compounds.

Defence of thesis: January 2010

Current position: Postdoc, NTNU

Sara Boullosa Eiras

Comparative study of selected catalysts for methane partial oxidation.

Defense of thesis: October 2010

Current position: Postdoc, NTNU

Hamidreza Baktiary

Preformance assessment of a packed bed microstructured reactor – heat exchanger for methanol synthesis from syngas.

Defense of thesis: November 2010

Current position: Senior researcher, Det norske veritas (DNV)

Xuyen Kim Phan

Catalysts formulations for use in microstructured reactors for conversion of synthesis gas to liquids.

Defense of thesis: January 2011

Current position: Postdoc, NTNU

Fatemeh Hayer

Direct Synthesis of Dimethyl Ether in Microstructured reactors.

Defense of thesis: March 2011

Current position: Postdoc, NTNU