KINCAT

NTNU SINTEF

Strong Point Centre Kinetics and Catalysis

Annual Report
2005

KinCat
Strong Point Centre Kinetics and Catalysis

The centre was established July 1, 1998 by NTNU and SINTEF in recognition of the strong scientific level of the members participating. The centre consists of the Group for Catalysis and Petrochemistry, Department of Chemical Engineering, NTNU and the Group for Catalysis and Kinetics, SINTEF Materials and Chemistry.

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This report was edited by:

Silje Fosse Håkonsen
Edvard Bergene
Anders Holmen

Annual Report 2005

KINCAT

Strong Point Centre Kinetics and Catalysis

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KinCat Members Spring 2006

Department of Chemical Engineering
Group for Petrochemistry and Catalysis

Academic staff

Professor Edd A. Blekkan
Professor De Chen
Professor Anders Holmen
Assoc. Professor Magnus Rønning
Assoc. Professor Hilde J. Venvik
Adjunct Professor Kjell Moljord
Adjunct Professor Erling Rytter
Assoc. Prof. Emeritus Egil Haanæs

Doctoral students

Erlend Bjørgum
Øyvind Borg
Svatopluk Chytil
Hilde Dyrbeck
Bjørn Christian Enger
Vidar Frøseth
Nina Hammer
Florian Huber
Silje Fosse Håkonsen
Ingvar Kvande
Astrid Mejdell
Hilde Meland
Esther Ochoa-Fernández
Espen Standal Wangen

Postdoctoral fellows 2005/2006

Matam Santhosh Kumar
Thomas Løften
Jianmin Xiong
Zhixin Yu
Tiejun Zhao

Research assistant

Geir Haugen

Guests

Enrique Garcia Bordeje (Post doc-fellow, Instituto de Carboquimica (CSIC) Spain)
Sara Lögdberg (PhD-student, KTH, Stockholm, Sweden)
Jögen Nietshe (PhD-student, University Freiberg, Germany)
Magnus Rydén (PhD-student, Chalmers, Göteborg, Sweden)
Tang Shuihua (Post doc-fellow, Dalian Institute of Chemical Physics, China)

Dewi Tristantini (PhD-student, Chalmers, Göteborg, Sweden)
Teresa Ubieto (PhD-student, Zaragoza University, Spain)
Quin Xin (Professor, Dalian Institute of Chemical Physics, China)

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

SINTEF Materials and Chemistry, Catalysis and Kinetics

Administration

Research Director Edvard Bergene
Senior-/Project Secretary Berit Broli

Research scientists

Research Scientist Håkon Bergem
Research Scientist Erlend Bjørgum
Research Scientist Torbjørn Gjervan
Research Scientist Odd Asbjørn Lindvåg
Senior Scientist Rune Lødeng
Research Scientist Rune Myrstad
Professor II Emeritus Odd A. Rokstad

Laboratory personnel

Senior Engineer Ingunn Tanem
Engineer Camilla Otterlei

KinCat members spring 2006

First row: E. Bergene, Z. Yu, H. Venvik, A. L. Mejdell, H. Bergem, D. Chen, T. Gjervan, I. Tanem.

Second row: M. S. Kumar , A. Holmen, S. F. Håkonsen, H. Dyrbeck, B. C. Enger, E. Bjørgum, S. Lögdberg, N. Hammer, E. Ochoa-Fernández, Ø. Borg, T. Zhao.

Third row: J. Xiong, V. Frøseth, E. S. Wangen, F. Huber, R. Lødeng. R. Myrstad, E. A. Blekkan, M. Rønning.

Not present: S. Chytil, C. Otterlei, I. Kvande, H. Meland, O. A. Lindvåg, G. Haugen

Research Areas

- Conversion of Natural Gas
  - Synthesis Gas Production
  - Small Scale H_2 Production
  - Fischer-Tropsch Synthesis
  - Dehydrogenation of Ethane and Propane
  - Absorbants for CO_2-capture

- Upgrading of Oil Fractions
  - Hydrotreating
  - Catalytic Reforming/Isomerization
  - Heavy Oil Characterization and Upgrading

- Environmental Catalysis
  - Sulfur Reduction by Hydrotreating

- Free Radical Chain Reactions
  - Partial Oxidation of Methane and NGL compounds

- Fundamental Studies of Heterogeneous Catalysis
  - Surface Science
  - Preparation of Catalytic Materials (supported metals and metal oxides, zeolites, supports)
  - Kinetics (steady-state and transient kinetics, SSITKA)
  - Adsorption and Diffusion in Porous Media
  - Catalyst Deactivation (sintering, coke formation)
  - Characterization of Heterogeneous Catalysts

- Microreactors and Membrane reactors

- Production and Application of Carbon Nanofibers

Main Laboratory Equipment

- Reactor Laboratories

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

- Catalyst Preparation Laboratory

- Catalyst Characterization

    - Surface area (BET), porosity and pore size distributions
    - Chemisorption
    - TP methods (temperature programmed methods such as TPR, TPO, TPD)
    - TGA and DSC
    - Raman and IR spectroscopy (in co-operation with Ugelstad Laboratory)
    - Acidity determination by TPD
    - UV-VIS (Avaspec 7048 UB)

- Microsopic and Spectroscopic Methods

    - 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), NMR and Raman spectroscopy and AFM (atomic force microscopy).
    - EXAFS and other synchrotron-based techniques are available through the Swiss/Norwegian beamline at ESRF in Grenoble.

KinCat
Strong Point Centre Kinetics and Catalysis

The strong point centre in Kinetics and Catalysis was established by NTNU and SINTEF on July 1st 1998, with the purpose of supporting fundamental research within the field of heterogeneous catalysis.

Activities in 2005

- 4 candidates completed their dr. ing. degrees: Zhixin Yu, Kjersti Omdahl Christensen, Ingrid Aartun and Sølvi Storsæter. The titles of the dissertations are enclosed.
- Zhixin Yu was awarded for the best PhD thesis at Faculty of Science and Technology, NTNU in 2005.
- A one day seminar on synthesis and application of carbon nanofibers/nanotubes was arranged with international participation (21/9-2005).
- Investments in new equipment: 3 gas chromatographs (Agilent 6890N), 2 micro gas chromatographs (Agilent 3000A), ordering of a combined Raman and IR instrument (HORIBA Jobin Yvon LabRAM high-resolution combined Raman-FTIR instrument with a microthermometric catalyst cell working from liq. N_2 to 1000 °C). Together with Ugelstad laboratory.
- Established research cooperation with Massachusetts Institute of Technology, USA sponsored by Hydro, Statoil, NFR, NTNU and MIT.
- Ph.D. students Sara Lögdberg (KTH, Stockholm) and Dewi Tristantini (CTH, Göteborg) are investigating a process for converting biomass into transportation fuel (diesel). Part of their experimental work is done in Trondheim.
- Ph.D. student Jörg Nietsche (Universtiy of Freiberg) worked in Kincat laboratories sponsored by ENGAS.
- TEMCAT (Advanced Electronmicroscopy in Catalysis) obtained funding from NANOMAT (NFR) and Statoil.
- Ph.D. student Espen Standal Wangen spent 6 months at the University of Alberta, Canada.
- Participated in the EUROKIN network.
- Coordinated NTNU network on carbon materials.
- Five seminars were arranged with international participants.
- PhD-student Teresa Ubieto from Zaragoza University worked for three months on a kinetic study of CNT.

- Post.doc. Thomas Løften worked three months on hydrogen storage in nanocarbon materials sponsored by NTNU gas research center.
- Post. Doc. Enrique Garcia Bordeje from Instituto de Carboquimica (CSIC) in Spain worked at our group three months on synthesis of CNF coated monoliths, sponsored by NFR.
- Post. Doc. Tang Shuihua from Dalian Institute of Chemical Physics, China worked six months on CNF supported electrocatalysts in fuel cells at Department of Material Science and Technology and Department of Chemical Engineering, sponsored by NT faculty.
- Prof. Qin Xin from Dalian Institute of Chemical Physics, China had one month research stay sponsored by NT faculty.
- Participated in large national research programs such as NANOMAT, Petromax and Renergi.
- Prof. Edd A. Blekkan spent 2 months at the Statoil Research Center and 4 months at Cardiff University as part of his sabbatical in the spring term.

PhD Candidate and Postdoctoral Projects

Kinetics of high temperature catalytic reactions

Dr.ing. candidate: Erlend Bjørgum
Supervisors: Prof. Anders Holmen, Prof. De Chen

Primary processes for conversion of natural gas components are usually carried out at high temperatures. Most of these processes involve reactions on the surface of the solid catalysts or they may involve a combination of surface and gas phase reactions. The project focuses on activation and conversion of methane at high temperatures. The studies are concentrated on the catalytic partial oxidation of methane.

A cyclic gas-solid reaction system can be used to produce syngas from partial oxidation with high selectivity. The main advantage of the process is to eliminate the gas phase oxidation resulting in a high selectivity to syngas. The concept can be applied to separate air *in situ* based on adsorption if a multifunctional catalyst is designed properly.

The objective for the experimental work has been to develop efficient multifunctional materials with high capacity of oxygen storage and high selectivity to hydrogen and syngas. $La_{1-x}Sr_xFe_yCo_{1-y}O_{3-\delta}$ perovskite-type oxides are examples of such multifunctional materials. A Tapered Element Oscillating Microbalance (TEOM) reactor connected to a Mass Spectrometer (MS) has been used to study the oxygen adsorption and desorption in these perovskite oxides. Experiments have also been performed where synthesis gas has been produced with both high selectivity and methane conversion over these perovskite oxides.

Publications and presentations in 2005:

1. E. Bjørgum, D. Chen, M.G. Bakken, K.O. Christensen, A. Holmen, O. Lytken, I. Chorkendorff, *Energetic Mapping of Ni Catalysts by Detailed Kinetic Modeling,* J. of Phys. Chem. B 109 (2005) 2360-2370.
2. E. Bjørgum, K.O. Christensen, R. Lødeng, D. Chen, A. Holmen, *In situ catalyst characterization by the Oscillating Microbalance Catalytic Reactor (TEOM),* Adv. Catal., accepted for publication.
3. E. Bjørgum, H.L. Lein, D. Chen, A. Holmen, *Reduction/oxidation behaviour of* $La_{0.5}Sr_{0.5}Fe_xCo_{1-x}O_{3-\delta}$ *perovskite oxides studied by TEOM-MS*, submitted.
4. E. Bjørgum, H.L. Lein, D. Chen, A. Holmen, *Methane conversion over* $La_{1-x}Sr_xFe_yCo_{1-y}O_{3-\delta}$ *perovskite oxides*.
5. E. Bjørgum, D. Chen, A. Holmen, *Activation and dehydrogenation of methane on nickel catalysts*, manuscript under preparation.

Financial support:
The Norwegian Research Council (NFR)

The role of support for Co-based Fischer-Tropsch catalysts

PhD candidate: Øyvind Borg
Supervisor: Prof. Anders Holmen

The Fischer-Tropsch synthesis is an important part of most natural gas conversion (GTL) process developments in recent years. 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 a comparatively low price.

Mass transfer effects are important in Fischer-Tropsch synthesis. Even though the reactants are in the gas phase, the pores will be filled with liquids, namely wax and water. Since diffusion in the liquid phase is almost three order of magnitude slower than in the gas phase, even slow reactions may become mass transfer limited.

Selectivity is the most important property of the Fischer-Tropsch catalysts. It is a characteristic feature of Co-based Fischer-Tropsch catalysts that the selectivity of higher hydrocarbons (C_{5+}) increases with increasing conversion. Water is a main product during Fischer-Tropsch synthesis and the presence of water adds complexity to the behaviour of supported Co catalysts.

The rate and the selectivity for a Fischer-Tropsch catalyst usually depend on the support. In some cases cobalt reacts with the support and part of the cobalt will therefore not be active in Fischer-Tropsch synthesis. It is usually assumed that, regardless of the promoter and the support, the intrinsic activity of Co will remain constant. However, major variations in selectivity between different supports have been reported in literature. An explanation has so far not been given.

It is the aim of the project to study the behaviour of cobalt catalyst supported on different oxides in order to obtain information about support effects on the performance of Fischer-Tropsch catalysts.

Publications and presentations in 2005:

1. Borg, Ø., Storsæter, S., Frøseth, V., Myrstad, R., Bergene, E., Lindvåg, O. A., Rytter, E., Eri, S., Holmen, A., *Fischer-Tropsch synthesis on different alumina supported Co catalysts*, Oral presentation, The 229th ACS National Meeting, 13-17 March 2005, San Diego, USA.

2. Borg, Ø., Storsæter, S., Blekkan, E. A., Eri, S., Rytter, E., Holmen, A., *The effect of different γ-alumina supports on cobalt Fischer-Tropsch catalysts*, Poster, Europacat-VII, 28 August – 1 September 2005, Sofia, Bulgaria.
3. Storsæter, S., Borg, Ø., Blekkan, E. A., Holmen, A., *Study of the effect of water on Co supported Fischer-Tropsch catalysts*, J. Catal. 231 (2005) 405.
4. Storsæter, S., Borg, Ø., Blekkan, E. A., Tøtdal, B., Holmen, A., *Fischer-Tropsch synthesis over Re-promoted Co supported on* Al_2O_3, SiO_2 *and* TiO_2*: effect of water*, Catal. Today 100 (2005) 343.
5. Frøseth, V., Storsæter, S., Borg, Ø., Blekkan, E. A., Rønning, M., Holmen, A., *Steady-State Isotopic Transient Kinetic Analysis (SSITKA) of CO Hydrogenation on different Co catalysts*, Appl. Catal. A 289 (2005) 10.
6. Lögdberg, S., Borg, Ø., Frøseth, V., Blekkan, E. A., Boutonnet, M., Järås, S., Holmen, A., *Cobalt particle size effects in α- and γ-*Al_2O_3 *supported catalysts for Fischer-Tropsch synthesis*, Oral presentation, Gas-Fuel 05, 14-16 November 2005, Brugge, Belgium.
7. Yu, Z., Borg, Ø., Frøseth, V., Enger, B. C., Chen, D., Holmen, A., Rytter, E., Moljord, K., Wigum, H., *Carbon Nanofiber Supported Cobalt Catalysts For Fischer-Tropsch Synthesis With High Activity And Selectivity*, Oral presentation, 2nd NTNU SEMINAR Synthesis and Applications of Carbon Nanofibers/Nanotubes, 21 September 2005, Trondheim, Norway.
8. Tristantini, D., Lögdberg, S., Gevert, B., Borg, Ø., Holmen, A., *Effect of water addition on hydrocarbon production via Fischer-Tropsch synthesis from different model bio-syngases over un-promoted and rhenium-promoted alumina-supported cobalt catalysts*, Poster, Europacat-VII, 28 August - 1 September 2005, Sofia, Bulgaria.
9. Rønning, M., Borg, Ø., Storsæter, S., van Beek, W., Blekkan, E. A., Holmen, A., *Identification of cobalt species in the temperature programmed reduction of Fischer-Tropsch catalysts using in situ X-ray absorption spectroscopy*, Oral presentation, 3rd Norwegian User Meeting – Application of Synchrotron Radiation, 10-11 March 2005, Orkanger, Norway.
10. Tristantini, D., Lögdberg, S., Gevert, B., Borg, Ø., Holmen, A., *A study of hydrocarbon production via Fischer-Tropsch (FT) synthesis from different model bio-syngases over un-promoted and rhenium-promoted alumina supported cobalt catalyst*, Poster, SYNBIOS: Second-Generation Automotive Biofuels, 18-20 May 2005, Stockholm, Sweden.

Financial support:
The Norwegian Research Council (NFR) and Statoil ASA.

Steam reforming of methane over Ni-catalysts

Dr. ing. candidate: Kjersti Omdahl Christensen
Supervisors: Prof. Anders Holmen, Prof. De Chen, Dr.ing. Rune Lødeng

Methane may be converted to synthesis gas by steam reforming or by reaction with O_2 through secondary reforming and partial oxidation. Steam may also be replaced by CO_2. In petrochemistry synthesis gas is used for the production of methanol, oxo-alcohols and ammonia. Steam reforming reactions are generally catalysed by transition metals, especially nickel supported on alumina, and promoted by other metals such as calcium, magnesium and potassium.

This project deals with steam reforming of methane to synthesis gas. The work concentrates on fundamental deactivation studies on Ni based reforming catalysts on different supports and with different promoted metals. The main reasons for deactivation are sintering, coke formation and oxidation of Ni^0. Experiments have shown large differences in resistance to deactivation between different commercial catalysts. It is therefore of interest to study the mechanism for deactivation including the following problems:

- Metal-support interactions
- Effect of Ni crystallite size
- Determine the surface coverage of O, H and C on the catalysts with transient methods
- Study the dissosiative adsorption of CH_4 and H_2O on active surfaces

Publications and presentations in 2005:

1. E. Bjørgum, D. Chen, M.G. Bakken, K.O. Christensen, A. Holmen: *Energetic mapping of Ni catalysts by detailed kinetic modeling.* J. Phys. Chem. B 109 (2005) 2360.
2. D. Chen, R. Lødeng, K.O. Christensen, A. Anundskås, O. Olsvik, A. Holmen: *Kinetic Modelling of Steam Reforming on Ni Catalysts: Formation of Filamentous Carbon*. Submitted.
3. E. Bjørgum, K.O. Christensen, R. Lødeng, D. Chen, A. Holmen: *In situ characterization by the oscillating microbalance catalytic reactor.* Advances in Catalysis, Submitted.
4. D. Chen, R. Lødeng, K.O. Christensen, A. Anundskås, O. Olsvik, A. Holmen: *Kinetic Modelling of Steam Reforming on Ni Catalysts: Reforming Reactions in Presence of Transport Limitations*. Submitted.
5. R. Lødeng, D. Chen, K. O. Christensen, H. S. Andersen, M. Rønnekleiv, A. Holmen: *A Deactivation Study of Natural Gas Prereforming*. Submitted.
6. D. Chen, E. Bjørgum, R. Lødeng, K.O. Christensen, A. Holmen: *Microkinetic model assisted design for steam methane reforming*. Lecture. 7th Natural Gas Conversion Symposium. Dalian, China, June 6 -10, 2004.

Financial Support:
The Norwegian Research Council (NFR), Norsk Hydro and Statoil.

New preparation methods for supported metal catalysts

Dr. ing. candidate: Svatopluk Chytil
Supervisor: Prof. Edd A. Blekkan

In this project the goal is to improve the methods for the design and preparation of supported catalysts. The mesoporous silica (SBA-15) was choosen as a catalyst support since the mateial provides a well-defined and tunable porous structure. In the first stage of our investigation the catalyst carrier was functionalized with pre-prepared Pt-nanoparticles. The synthesised Pt nanoparticles and the finished catalyst were extensively characterized (UV-Vis, Dynamic light scattering (DLS), Transmission electron microscopy (TEM), N_2 adsorption-desorption, XRD, TEM and H_2 chemisorption), and the impact of the impregnation method explored. The catalytic properties were studied using toluene hydrogenation as a model reaction. The material shows the kinetic features of supported platinum catalysts, but the activity was lower when compared to a material prepared by a conventional wet-impregnation technique. This was most likely caused either by agglomeration of the Pt particles, as indicated by the TEM and DLS results, or that the active platinum sites are covered by residues of the copolymer or by the silica.

A second approach in order to functionalize the SBA-15 with platinum is the deposition precipitation (DP) method. In addition to the methods already mentioned UV-Vis diffusive reflectance, TPR, NIR and ^{29}Si MAS NMR is used to study the materials. The results show that SBA-15 synthesized at 100 °C is a suitable support also for this functionalization route, since it can withstand the hydrothermal treatment related to the DP. UV-Vis diffusive reflectance and TPR turned to be a good tool to characterize the surface species coexisting with the platinum nanoparticles on the impregnated solids after the DP was applied. Using ^{29}Si MAS NMR we were able to monitor the impact of the DP method on the short range ordering of the parent SBA-15 and the NIR provides information about the metal-support interaction. Catalytic activity in toluene hydrogenation was examinated, and the material shows a comparable activity to the catalyst prepapared by a conventional wet-impregnation technique.

Publications and presentations in 2005:

1. S. Chytil, W.R. Glomm, E. Vollebekk, H. Bergem, J. Walmsley, J. Sjoeblom, E.A. Blekkan, *Microporous and Mesoporous Materials* 86 (2005) 198.

2. S. Chytil, W.R. Glomm, E. Vollebekk, H. Bergem, J. Walmsley, J. Sjoeblom, E.A. Blekkan: *Platinum nanoparticles encapsulated in mesoporous silica: Preparation, characterisation and catalytic activity*, (oral presentation) 2nd International School-Conference on Catalysis for Young Scientists, Catalyst Design, Novosibirsk-Altai Mountains, Russia, July 25-29, 2005
3. S. Chytil, W.R. Glomm, E. Vollebekk, H. Bergem, J. Walmsley, J. Sjoeblom, E.A. Blekkan: *Platinum nanoparticles encapsulated in mesoporous silica: Preparation, characterisation and catalytic activity*, (poster presentation), EUROPACAT VII, Sofia, Bulgaria, 28 Aug – 1 Sep 2005.

Financial support
The Norwegian Research Council, through the Strategic University Programme" Scientific Design of new Catalysts and Supports".

Selective catalytic oxidation of hydrogen

Dr.ing candidate: Hilde Dyrbeck
Supervisor: Professor Edd A. Blekkan

The catalytic oxidation of hydrogen played a major part in the development of heterogeneous catalysis in the early 19th century. Industrially today, hydrogen is a very important product and reactant in numerous catalytic reactions, and much hope is pinned on hydrogen as a future energy carrier thus avoiding (or at least aiding in harnessing) CO_2 emissions.

Catalytic combustion of hydrogen might be an important part of this technology, since ordinary (flame) combustion of hydrogen leads to NO_X formation and emission. In this project we aim at improving the mechanistic understanding of the catalytic oxidation of hydrogen. The main idea is to further develop the principle of selective catalytic oxidation of hydrogen (in the presence of hydrocarbons), with the ultimate goal of developing better processes for catalytic dehydrogenation. Here the selective hydrogen removal can provide *in situ* heat generation and at the same time push the equilibrium towards the reaction products. The knowledge developed can also be applied to the energy-applications of hydrogen combustion, particularly linked to NO_X reductions and the removal of hydrogen emissions.

Publications and presentations in 2005:

1. H. Dyrbeck, L. Låte and E.A Blekkan: *Catalytic combustion of hydrogen in the presence of hydrocarbons over noble metal catalysts*. Poster. 6th International Workshop on Catalytic Combustion, Ischia, Italy, September 11-14, 2005.

Financial and other support:

The project is funded by the Norwegian research council (NFR), through the "KOSK" programme.

Production of hydrogen from natural gas by catalytic partial oxidation

PhD-candidate: Bjørn Christian Enger
Supervisor: Prof. Anders Holmen and dr.ing. Rune Lødeng

Hydrogen can be produced from natural gas by a number of different processes. Steam reforming is the current industrial standard, but catalytic partial oxidation (CPO), oxidative steam reforming (OSR) and CO_2 reforming are alternative processes that have received scientific attention the last 20 years.

Syngas (H_2 and CO) can be produced by CPO of methane. At high temperatures close to 100% conversion and selectivity (thermodynamic equilibrium) can be achieved even at higher pressures, but the thermal stability of reactor system and catalyst is a problem and low temperature processes are sought.

CPO is generally considered to follow two different possible mechanisms or routes, the direct route and the indirect route. Autothermal reforming (ATR) represents the extreme version of the indirect route. In an ATR reactor a fraction of the methane feed is first combusted to CO_2 and water, and the remaining methane is subsequently reformed to syngas in a catalyst bed. The direct route involves the direct oxidation of methane with oxygen to syngas without the formation of CO_2 and water.

This project focuses on CPO of methane, but will include studies and aspects from the RENERGI project: H_2 production from natural gas, which is a collaboration between NTNU/SINTEF and Statoil, funded by The Norwegian Research Council and Statoil.

Financial support:

The Norwegian Research Council (NFR), the Department of Chemical Engineering, NTNU and Statoil (RENERGI).

SSITKA and hydrogenation of CO

Dr.ing. candidate: Vidar Frøseth
Supervisor: Prof. Anders Holmen

Steady-State Isotopic Transient Kinetic Analysis (SSITKA) is an experimental method for the determination of *in situ* kinetic information about the reaction mechanism and the catalyst-surface reaction intermediates. Steady-state kinetic information that can be obtained from the SSITKA technique includes concentrations of different types of adsorbed reaction intermediates, coverages, surface lifetimes, site heterogeneity, activity distributions, and identification of possible mechanisms.

SSITKA is based on a switch of isotopic labelled streams. The transient responses of the isotopic labels are monitored at the system outlet by a mass spectrometer to differentiate between the isotopic masses. The SSITKA technique is used to study the hydrogenation of CO on cobalt-based catalysts using a fixed-bed reactor at 210 ^{o}C and 1.85 bar. The study includes different supports as carbon nanofibers, and both low surface area and high surface area oxidic supports.

Publications and Presentations in 2005:

1. V.Frøseth, S. Storsæter, Ø. Borg, M. Rønning, E.A. Blekkan, A. Holmen; *Steady state isotopic transient kinetic analysis (SSITKA) of CO hydrogenation on different Co catalysts*. Appl. Catal. A 289 (2005) 10-15.
2. Z. Yu, Ø. Borg, D. Chen, B.C. Enger, V. Frøseth, E. Rytter, H. Wigum, A. Holmen, *Carbon nanofiber supported Co catalysts for Fischer-Tropsch synthesis with high activity and selectivity*, accepted Catal. Lett.
3. Z. Yu, Ø. Borg, V. Frøseth, B.C. Enger, D. Chen, A. Holmen, E. Rytter, K. Moljord, H. Wigum, *Carbon Nanofiber Supported Cobalt Catalysts For Fischer-Tropsch Synthesis With High Activity And Selectivity*, Oral presentation, 2nd NTNU SEMINAR Synthesis and Applications of Carbon Nanofibers/Nanotubes, 21 September 2005, Trondheim, Norway.
4. Ø. Borg, S. Storsæter, V. Frøseth, R. Myrstad, E. Bergene, O.A. Lindvåg, E. Rytter, S. Eri, A. Holmen; *Fischer-Tropsch synthesis on different alumina supported Co catalysts*, Oral presentation, 229th ACS National Meeting, San Diego, CA, USA, March 13-17, 2005.

Financial support:
The Norwegian Research Council (NFR) and Department of Chemical Engineering, NTNU.

Nanostructured Au catalysts for hydrogen production

PhD-candidate: Nina Hammer
Supervisors: Assoc. Prof. Magnus Rønning and Prof. De Chen

Metal nanoparticles are highly attractive for catalysis because of their size- and shape-dependent properties. This is especially the case for gold which is active only when the particle size is below approximately 10 nm. Highly dispersed gold nanoparticles in conjunction with a partially reducible oxide (ceria, titania) have shown to exhibit high catalytic activity in the water-gas shift (WGS) reaction and in oxidation reactions such as CO oxidation. There is a controversy over the nature of the active sites in supported gold catalysts and in particular the roles played by metallic and non-zero valent gold.

The structure and morphology of the oxide support materials seem to be important for the catalytic activity. The metal – support interaction and the particle size are highly dependent on calcination conditions and preparation method. High catalytic activity is achieved by keeping the particle size of both Au and oxide particles below 10 nm. Such small particles may be a concern in catalytic reactors. This can be avoided by supporting the nanoparticles on carbon nanofibres (CNF). The size and morphology of the CNF provide high surface area while maintaining macroscopic pore sizes and problems associated with mass transfer limitations are significantly reduced. Activity measurements indicate that depositing TiO_2 on CNF lead to more stable catalysts. X-ray absorption spectroscopy (XAS) analysis have demonstrated the presence of both Au(0) and Au(I) in the catalyst during the WGS reaction.

The aim of this project is to prepare Au-based catalysts for the water-gas shift reaction and methanol steam reforming. Different methods such as impregnation, deposition-precipitation, ion exchange, and fixation of colloids will be tested to introduce metal/oxide into the surface of the CNF. The CNF surface properties can be tuned in order to generate sites for adsorption of catalyst precursors. Pre-treatment techniques including plasma/steam treatment, oxidation in HNO_3 or air have been selectively employed to obtain desired zeta potential of the CNF surface. The present work will involve preparation of designed metal/oxide/CNF by depositing the catalyst particles onto the CNF. Characterisation techniques such as XRD, TPO, TPR, XAS, TEM/STEM, Raman and BET will be used to obtain information about the structure and morphology of the catalysts. The catalysts are being tested for activity in methanol reforming and the water-gas shift reaction.

Publications and presentations in 2005:

1. Nina Hammer, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Gold Nanoparticles in Catalysis.* Poster. Nanomat Birkeland Conference, June 2-3, 2005, Trondheim, Norway.
2. Nina Hammer, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Au/oxide catalysts on carbon nanofibres for water-gas shift reaction*. Poster. EuropaCat-VII, August 28- September 1, 2005, Sofia, Bulgaria.
3. Ingvar Kvande, Gisle Øye, Esther Ochoa Fernandez, Nina Hammer, Magnus Rønning, Anders Holmen, Johan Sjöblom and De Chen: *Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres.* Poster. NT05: Sixth International Conference on the Science and Application of Nanotubes, June 26 - July 1, 2005, Gothenburg, Sweden
4. Nina Hammer, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Oxide/CNF and oxide based supports for Au catalysts.* Oral presentation. 2nd NTNU Seminar, Synthesis and applications of Carbon nanofibers/nanotubes, September 21, 2005, Trondheim, Norway.
5. Ingvar Kvande, Gisle Øye, Esther Ochoa Fernandez, Nina Hammer, Magnus Rønning, Anders Holmen, Johan Sjöblom and De Chen*: Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres*. Oral presentation. 2nd NTNU Seminar, Synthesis and applications of Carbon nanofibers/nanotubes, September 21, 2005, Trondheim, Norway.

Financial support:
Strategic funding, NTNU

Nanocrystalline Cu-Ce-Zr mixed oxide catalysts with high surface area for clean fuel applications

PhD candidate: Florian Huber
Supervisors: Ass. Prof. Hilde J. Venvik and Prof. Anders Holmen

Mixed oxide catalysts containing Cu, Ce and Zr are widely used in environmental heterogeneous catalysis. Examples include reactions relevant in hydrogen production (methanol steam reforming, water-gas shift, selective CO oxidation) for fuel cell applications, as well as selective catalytic NO reduction for automotive emission control. In the catalytic processes, copper - in its reduced state - is typically viewed as the active catalyst component in such mixed metal oxide materials. Ceria and zirconia enhance catalytic activity and stability via metal-support interactions and/or improved dispersion of the active metal component. A large and stable catalyst surface as well as a homogeneous metal distribution are prerequisites for a high catalytic activity.

The scope of the project is to study fundamental aspects of the catalyst preparation and catalytic reaction. The catalyst materials are characterised by ICP-AES, XRD, N_2 adsorption-desorption, TPO/TPR, TEM/STEM-EDX and XAS. The water-gas shift reaction is used as test reaction. Thus, the catalyst structure can be correlated to the shift activity and stability under reaction conditions.

This project is a part of the SINTEF/NTNU project "Advanced catalyst/reactor systems for conversion of hydrocarbons to hydrogen for fuel cells".

Publications and presentations in 2005:
M. Rønning, F. Huber, H. Meland, H. Venvik, D. Chen, A. Holmen: *Relating Catalyst Structure and Composition to the Water-Gas Shift Activity of Cu-Zn Based Mixed-Oxide Catalysts.* Catal. Today 100 (2005), 249-254.

Dehydrogenation of NGL components at very short contact times

PhD-candidate: Silje Fosse Håkonsen
Supervisor: Prof. Anders Holmen

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 study the oxidative dehydrogenation of NGL components at very short contact times and high temperatures. The selection of convenient catalytic systems is an important part of the project as well as the development of kinetic models describing the process.

The experiments will be based on monoliths or ceramic foams impregnated with Pt, Pt-Rh, Pt-Sn supported on alumina or hydrotalcite. Different metal oxides will also be included in the study since oxidic catalysts have been extensively studied for the oxidative dehydrogenation of propane. The preparation involves washcoating the monolith/foam using the standard procedure. This standard method could be modified to investigate the effect of the preparation technique on the activity and the properties of the catalytic material. Based on the idea that the reactions take place in two zones, different material may be deposited on the entrance side of the monolith and in the rest of the monolith. The experimental work will be focused on obtaining selectivity-conversion data for different catalytic systems and for different parameters (NGL/O_2 ratio, diluents, flow rates).

Publications and presentations in 2005:

1. S. F. Håkonsen, B. Silberova, S. F. Jensen, A. Holmen: *Oxidative Dehydrogenation of Ethane at Short Contact Times.* Poster. Seventh European Congress on Catalysis, Sofia, Bulgaria, 28 August – 1 September, 2005.
2. S. F. Håkonsen, B. Silberova, A. Holmen: *The Production of Ethene via Oxidative Dehydrogenation of Ethane over Pt-Sn Monoliths.* Poster. 5th World Congress on Oxidation Catalysis, Sapporo, Japan, 25 – 30 September, 2005.
3. S. F. Håkonsen and A. Holmen. *Oxidative dehydrogenation of lower alkanes*. Handbook of Heterogeneous Catalysis (Eds: Ertl, Knötzinger, Schüth, Weitkamp). Accepted.

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

Carbon nanofibers for application in fuel cells

PhD-candidate: Ingvar Kvande
Supervisor: Prof. De Chen

Carbon nanofibers have many unique properties such as high resistance to strong acid and base, high electronic conductivity, high surface area and high mechanical strength. One of the most outstanding features is the presence of a large number of edges, which in turn constitutes sites that are readily available for chemical reaction or physical interactions. These unique properties might provide multifunctional properties for application as electrode materials.

In order to enhance the efficiency of the electrode, the material should have high surface area where noble metal can be finely dispersed, high electric conductivity, high oxidation resistance which enables it to be used at high temperatures and special interaction between substrate and metal nanoparticles stablilizing nanoparticles.

Work done at the Department of Chemical Engineering has made possible the production of different carbon nanofiber (CNF) structures with rather high quality. However, further optimization is needed for application in fuel cells. High crystallinity of CNF with fewer defects ensures high electric conductivity and high oxidation resistance. One of the project objectives is to establish a routine for well controlled synthesis to achieve these properties as well as optimization of CNF nanostructure and diameter. The preparation of nanocatalyst particles will be a key step for synthesis of desired CNF. Reproducibility will be assessed for both this catalyst production and for the synthesis of the CNFs. The scale up of the CNF synthesis is also to be achieved. Functionalization of CNFs is important to make deposition of metal-precursors possible. Both oxidation and nitrogenation to get surface groups for interaction is to be tested to understand the influence on metal deposition.

Some of the work will also be related to the development of catalytic particles of two binary alloys (Pt-Ru, Pt-Cr) with controlled surface composition and particle size deposited on carbon nanofibres for the application in acid fuel cells. The effect of the CNF structure on the nanocomposite material will be studied. Non-noble metal electrocatalysts supported on carbon nanofibres as well as unsupported will be developed and tested in a related project.

Publications and presentations in 2005:

1. I. Kvande, G. Øye, E. Ochoa Fernandez, N. Hammer, M. Rønning, A. Holmen, J. Sjöblom, D. Chen, *Tailoring of Carbon Nanotube/Nanofibresurface properties by Plasma Treatment and the preparation of Gold on CNT, Poster,*6th International conference on the Science and Application of Nanotubes , NT05., Gothenburg, Sweden, June26-July1, 2005
2. I. Kvande, S. T. Briskeby, Z. Yu, M. Tsypkin, D. Chen, M. Rønning, A. Holmen. B. Børresen, R.Tunold, *Carbon nanofibers as support for electrocatalysts*. Poster. NANOMAT-Birkeland conference, Trondheim, 2-3 juni, 2005
3. I. Kvande, S. T. Briskeby, M. Tsypkin, D. Chen, M. Rønning, A. Holmen. B. Børresen, R.Tunold, *Synthesis and Applications of Pt/CNF/CNT in fuel cells,* Oral Presentation*,* 2nd NTNU SEMINAR, Synthesis and Applications of Carbon nanofibres/Nanotubes, Trondheim, September 21, 2005.
4. I. Kvande, G. Øye, E. Ochoa Fernandez, N. Hammer, M. Rønning, A. Holmen, J. Sjöblom, D. Chen, *Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres,* Oral

Presentation, 2^{nd} NTNU SEMINAR, Synthesis and Applications of Carbon nanofibres/Nanotubes, Trondheim, September 21, 2005.

Financial support:
Research Council of Norway, Grant No. 158516/S10 (NANOMAT)

Preparation of catalysts and support materials

PhD candidate: Hilde Meland
Supervisors: Prof. Anders Holmen, Assoc. Prof. Magnus Rønning, Assoc. Prof. Hilde Venvik

Heterogeneous catalysts usually consist of metals or metal oxides placed on appropriate carriers. The final design of the catalysts will highly determine their usefulness and efficiency. Although the preparation is of the outmost importance for the application of the material, this is still an area where fundamental knowledge is lacking.

The purpose of the present project is to obtain fundamental insight into preparation techniques for carriers embracing a wide range of particle sizes and properties and in particular in the functionalisation of these materials will both be established by wet-chemical methods and other methods, such as flame synthesis and spray drying. The support materials and the catalysts are characterized applying all central methods and will be studied in important applications like water-gas shift, alkane dehydrogenation and CO hydrogenation. The application of the catalysts also entails industrial collaboration.

Publications and presentations in 2005:

1. M. Rønning, F. Huber, H. Meland, H. Venvik, D. Chen, A. Holmen: *Relating Catalyst Structure and Composition to the Water-Gas Shift Activity of Cu-Zn Based Mixed-Oxide Catalysts.* Catal. Today, 100(3-4) (2005), 249-254.
2. H. Meland, T. Johannessen, B. Arstad, H.J. Venvik, M. Rønning, A. Holmen: *Preparation of low temperature water-gas shift catalysts by flame spray pyrolysis.* Submitted.

Financial support:
The Norwegian Research Council (NFR) through the Strategic University Programme “Scientific Design of New Catalysts and Supports”

Sorption enhanced reaction process for the production of hydrogen

Dr. ing. Candidate: Esther Ochoa-Fernández
Supervisor: Prof. De Chen

The steam methane reforming (SMR) is currently the major process for large-scale production of hydrogen. This process involves multiple steps and severe operation conditions. The alternative cost-effective process for hydrogen production is then highly desirable. Within the last few years the concept of sorption enhanced reaction process (SERP) has received increased attention. A CO_2 acceptor can be installed together with the catalyst in the reactor and the normal equilibrium limits of reforming are shift, allowing H_2 yields larger than 95 %. Another important advantage is that the steam reforming can be run a much lower temperatures, which will significantly lower the investment and operation cost.

The present work will evaluate different acceptors that can selectively remove CO_2 from the SMR reaction zone at moderately high temperatures in the presence of a large partial pressure of steam. Specially, nanocrystalline lithium zirconate has been found to have excellent properties for CO_2 removal at high temperatures. The material has very good capture rates still keeping high stability. In addition, the regeneration stage is also carried out fast and at relative low temperatures.

The prepared acceptors will be installed into a fix bed reactor together with a Ni based catalyst. Steam methane reforming will be used for catalysts and acceptor screening.

Publications and presentations in 2005:

1. E. Ochoa-Fernández, D. Chen, Z. Yu, B. Tøtdal, M. Rønning and A. Holmen. *Carbon nanofiber supported Ni catalyst: effects of nanostructure of supports and catalysts preparation*. Catalysis Today. 102-103C (2005) 45
2. E. Ochoa-Fernández, H.K. Rusten, H.A. Jakobsen, M. Rønning, A. Homen and D. Chen. *Sorption enhanced hydrogen production by steam methane reforming using* Li_2ZrO_3 *as sorbent: sorption kinetics and reactor simulation.* Catalysis Today. 106 (2005) 41
3. E. Ochoa-Fernández, T. Grande, M. Rønning and D. Chen *Nanocrystalline Lithium Zirconate with Improved Kinetics for High Temperature CO2 Capture*. Chemistry of Materials. (2005) Accepted.
4. E. Ochoa-Fernández, T. Grande, H.K. Rusten, H.A. Jakobsen, A. Holmen, M. Rønning and D. Chen. *Novel solid high temperature* CO_2 *absorbents for the production of* H_2 *by sorption enhanced steam reforming.* Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

5. E. Ochoa-Fernández, T. Zhao, G. Haugen, H.K. Rusten, M. Rønning, H.A. Jakobsen and D. Chen. *Application of CO_2 sorption enhanced hydrogen production with CO_2 removing: precombustion in power generation.* Oral presentation. The Third Trondheim Conference on CO_2 Capture, Transport and Storage, Trondheim, October 10-11, 2005.
6. H.K. Rusten, E. Ochoa-Fernández, D. Chen, Erik Hessen and H.A. Jakobsen. *Modelling and simulation of sorption enhanced hydrogen production.* Oral presentation. The Third Trondheim Conference on CO_2 Capture, Transport and Storage, Trondheim, October 10-11, 2005.
7. E. Ochoa-Fernández, H.K. Rusten, H.A. Jakobsen and D. Chen. *Solid high temperature CO_2 acceptors for the production of H_2 by sorption enhanced steam reforming.* Oral presentation. Gas-Fuel 05, Brugge, November 14-16, 2005.

Financial support:
The Research Council of Norway

Fischer-Tropsch synthesis catalysis

Dr.ing. candidate: Sølvi Storsæter
Supervisor: Prof. Anders Holmen

Fischer-Tropsch synthesis is an important part of most natural gas conversion process developments. A key element in improved Fischer-Tropsch technology is the development of active catalysts with high wax selectivity. The catalysts used for Fischer-Tropsch synthesis are often cobalt-based and promoted by noble metals and/or metal oxides on a suitable support. The synthesis is a very complex reaction involving metal-support interactions and metal-promoter effects and secondary reactions. Mass transfer effects are also important in the FT synthesis. Fundamental studies of model catalysts are important in order to understand the mechanism behind the catalytic performance.

Water is one of the products in the Fischer-Tropsch synthesis. Regarding the effect of water there is very little and apparently contradictive information available on cobalt-based catalysts. The project is focusing on the effect of co-feeding water using cobalt-based catalysts on different supports (Al_2O_3, SiO_2, TiO_2). A fixed-bed apparatus has been used for reaction kinetics studies. CO and H_2 are reacting over a Fischer-Tropsch catalyst in a fixed-bed reactor at 20 bars and 210 °C, the exit gas is analyzed for hydrocarbons, carbon monoxide and carbon dioxide. Different partial pressures of water are added to the feed in order to study the effect of water on the activity and selectivity.

In addition the project is focusing on the use of transmission electron microscopy (TEM) in addition to other characterization techniques to study cobalt surfaces influenced by the supported material as well as by the promoters. The information from the model studies will form a basis for the development of a microkinetic model of the synthesis on supported catalysts at realistic temperatures and pressures.

The reaction kinetics studies have given very important information of the behavior of unpromoted Co catalyst and Re promoted Co catalysts supported on different supports upon co-feeding water during Fischer-Tropsch reaction.

Publications and presentations in 2005:

1. S. Storsæter, Ø. Borg, E.A. Blekkan, A. Holmen: *Study of the effect of water on Fischer-Tropsch synthesis over supported cobalt catalysts*. J. Catal. 231 (2005) 405.
2. S. Storsæter, Ø. Borg, E.A. Blekkan, B. Tøtdal: *Fischer-Tropsch synthesis of Co supported on* Al_2O_3*,* SiO_2 *and* TiO_2. Catal. Today 100 (2005) 343.
3. S. Storsæter, B. Tøtdal, J.C. Walmsley, B.S. Tanem, A. Holmen: *Characterixation of alumina, silica, and titania-supported cobalt Fischer-Tropsch catalysts.* J. Catal. 236 (2005) 139.
4. V. Frøseth, S. Storsæter, Ø. Borg, E.A. Blekkan, M. Rønning and A. Holmen: *Steady-state isotopic transient kinetic analysis (SSITKA) of CO hydrogenation on different Co catalysts.* Appl. Catal. A: General 289_(2005) 10.
5. Ø. Borg, S. Storsæter, S. Eri, H. Wigum, E. Rytter A. Holmen: *The effect of water on the activity and selectivity for γ-alumina supported cobalt Fischer-Tropsch catalysts with different pore sizes.* Catal. Letters Accepted.
6. S. Storsæter, D. Chen, A. Holmen: *Microkinetic modelling of the formation of* C_1 *and* C_2 *products in the Fischer-Tropsch synthesis over cobalt catalysts.* Surf. Sci., accepted
7. Ø. Borg, S. Storsæter, S. Eri, E. Rytter, A. Holmen: *The effect of different gamma-alumina supports on cobalt Fischer-Tropsch catalysts.* Poster. Europacat-VII, Sofia, August 28 - September 1, 2005.

Financial support:
The Norwegian Research Council (NFR).

Upgrading of heavy oils

PhD-candidate: Espen Standal Wangen
Supervisors: Prof. Edd A. Blekkan, dr.ing. Anne Hoff

Heavy oil is a generic term including heavy crudes, residues, synthetic crude oils from coal, products from shale oil and tar sand production, and similar oils. The heavy oils have properties that make them difficult to process, these being high densities, high boiling points, high molecular weights, high viscosities, and a relatively high concentration of heteroatoms.

Future oil discoveries are to a larger degree predicted to be heavy oil finds, but legislation and environmental concerns impose regulations in petroleum product quality. Legislation dictates upper limits of sulphur, nitrogen, and aromatics concentration in transportation fuels.

Upgrading heavy oils means reducing carbon-to-hydrogen ratio, reducing molecular weight, and removing heteroatoms. This can be achieved either by carbon rejection or hydrogen addition. Delayed Coking and Flexicoking are examples of processes in which the carbon-to-hydrogen ratio is lowered by means of carbon rejection. Any process based on hydrotreating and hydrocracking by definition belongs to the second group.

In this project reactions of vacuum residua are studied in different reactor systems. To understand the complex reactions detailed feed and product characterization is necessary. A series of thermal and catalytic reactions in a thin film of bitumen has been investigated in a purpose-built setup using Curie-point alloys to facilitate rapid and repeatable heating. This work was performed at the University of Alberta in Canada. Analytical techniques that are being used include thermogravimetric analysis (TGA), SARA fractionation of the oil (saturates, aromatics, resins, asphaltenes), elemental analysis (carbon, hydrogen, sulphur, metals), determination of molecular weights (VPO or GPC), simulated distillation, and liquid chromatography. ^{1}H-NMR and ^{13}C-NMR may give information about aromaticity and concentration of olefins, and cooperation with The University of Bergen in order to perform NMR as part of the heavy oil characterization will be initiated during the spring of 2006.

Financial support:
Statoil ASA
Additional award granted by The Research Council of Norway

Production, characterization and application of carbon nanofibers

Dr. ing candidate: Zhixin Yu
Supervisors: Prof. De Chen, Prof. Anders Holmen

It has recently been shown that some types of carbon nanofibers (CNFs) are capable of absorbing high quantities of hydrogen. These CNFs consist of very small graphite plates which are stacked in a perfectly arranged conformation. The CNFs hold the promise as a good medium for storage of hydrogen, in particular for storage on-board a vehicle. However, rather broad range of experimental capacity of hydrogen storage in this new type carbon material has been reported. The surface area, nanostructure, and pretreatment of the fibers seem to be crucial.

The decomposition of carbon containing gases on metal catalysts (Ni, Fe, or Co) or bimetal catalysts (Ni-Fe, Fe-Mo) are used for the synthesis of CNFs. The reaction conditions, including temperature, hydrogen partial pressure, gas precursors and space velocity are used for controlling the nanostructure and productivity of the carbon fibers. The catalyst preparation especially the influence of the metal crystallite size, metal loading and support will also be tested to tailor the nanostructure of the carbon fibers. Different techniques including HRTEM, SEM, BET, TPO and XRD will be used for the characterization of CNFs. Other techniques including XPS, EXAFS, chemisorption and TPR are used for characterization of the catalysts. A high-pressure hydrogen storage unit has been built which can stand pressures up to 120 bars. Some initial measurements of hydrogen storage capacities on different carbon nanostructures have been performed.

The work aims at producing CNFs in large quantities with well-controlled nanostructures and high purity for a number of practical applications.

Publications and presentations in 2005:

1. Z. Yu, D. Chen, B. Tøtdal, T. Zhao, Y. Dai, W. Yuan, A. Holmen: *Catalytic engineering of carbon nanotube production*. Appl. Catal. A: General 279 (2005) 223.
2. Z. Yu, D. Chen, B. Tøtdal, A. Holmen: *Effect of catalyst preparation on the carbon nanotube growth rate*. Catal.Today 100 (2005) 261.
3. E. Ochoa-Fernández, D. Chen, Z. Yu, B. Tøtdal, M. Rønning, A. Holmen: *Carbon nanofiber supported Ni catalyst: effects of nanostructure of supports and catalysts preparation*. Catal. Today 102-103 (2005) 45.

4. Z. Yu, D. Chen, B. Tøtdal, A. Holmen: *Parametric Study of Carbon Nanofibre Growth by Catalytic Ethylene Decomposition on Hydrotalcite Catalysts.* Mater. Chem. Phys. 92 (2005) 71.
5. Z.Yu, D. Chen, B. Tøtdal, A. Holmen: *Effect of support and reactant on the yield and structure of Carbon Growth by Chemical Vapor Deposition*. J. Phys. Chem. B 109 (2005) 6096.
6. D. Chen, Z. Yu, I. Kvande, Anders Holmen*: Fundamental Understanding of the Growth of Carbon Nanotubes by Microkinetic Modeling.* Poster. 6th International Conference on the Science and Application of Nanotubes, Gothenburg, Sweden, 12 June-1 July, 2005.
7. S.Y. Larsen, T. Foosnaes, H.A. Oye, Z. Yu: *Carbon nanofibers in large-scale electrode application*. Poster. Carbon'05 Conference, Gyeongju, South Korea, 3-7 July, 2005.

Financial support:
The Norwegian Research Council (NFR) and Statoil.

Microstructured reactors for hydrogen production

Dr.ing. candidate: Ingrid Aartun
Supervisors: Prof. Anders Holmen and Assoc. prof. Hilde J. Venvik

Hydrogen is expected to play an increasingly important role as an energy carrier in the future. Hydrogen for fuel cells can be produced from light alkanes (propane/butane). These are liquid at moderate pressures and the distribution infrastructure is partly existent.

In the project, fundamental aspects of catalytic partial oxidation and oxidative steam reforming of light alkanes in small-scale, microstructured reactor systems are studied. Experimental investigations include temperature effects, ignition and extinction behavior, residence time effects and catalyst stability.

It has been demonstrated that synthesis gas can be produced with high selectivity in microstructured reactors. The chemical reaction takes place in microchannels ($1\mu m = 10^{-6}m$), where high heat and mass transfer rates can be achieved. This facilitates high selectivity and throughput, as well as improved process control and security which is essential when dealing with explosive mixtures of hydrocarbons and oxygen.

Microstructured reactors made of Fecralloy (72.6% Fe, 22% Cr, 4.8% Al) were oxidized to form a porous surface layer of alumina, and subsequently impregnated with either Rh or Ni. The experiments indicate that Rh is an active and relatively stable catalyst for both partial oxidation and oxidative steam reforming of propane, while Ni is less active and prone to deactivation. Rh-impregnated Fecralloy reactors demonstrated higher H_2-selectivity than microstructured reactors made of pure Rh. No coke formation or other deactivation was observed in the Rh/Al_2O_3/Fecralloy system.

Publications and presentations in 2005:

1. I. Aartun, H. J. Venvik, A. Holmen, P. Pfeifer, O. Görke and K. Schubert, *Temperature profiles and residence time effects during catalytic partial oxidation and oxidative steam reforming of propane in metallic microchannel reactors,* Catalysis Today 110 (2005) 98-107; Special Issue: "Catalytic Microchannel Reactors"
2. I. Aartun, B. Silberova, H. Venvik, P. Pfeifer, O. Görke, K. Schubert and A. Holmen, *Hydrogen production from propane in Rh-impregnated metallic microchannel reactors and alumina foams,* Catalysis Today 105 (2005) 469-478. Special issue: "2nd International Conference on Structured Catalysts and Reactors".
3. I. Aartun, B. Silberova; H.J. Venvik, A. Holmen. *Hydrogen production from propane in Rh-impregnated metallic microchanneled reactors and alumina foams,* 2nd International Conference on Structured Catalysts and Reactors; 16.10.2005 - 19.10.2005, Oral presentation
4. I. Aartun, B. Silberova, H.J. Venvik, P. Pfeifer, O. Görke, K. Schubert, A. Holmen, *Temperature profiles and residence time effects in metallic microchannel eactors for hydrogen production*, AIChE Spring National Meeting; 10.04.2005 - 14.04.2005, Oral presentation

Financial support:

The Norwegian Research Council through the joint SINTEF/NTNU project *Advanced catalyst/reactor systems for conversion of hydrocarbons to hydrogen for fuel cells* and the Department of Chemical Engineering, NTNU.

Chemisorption characterization and cobalt nanoparticles synthesis for Fischer-Tropsch reaction

Postdoctoral fellow:	Dr. Jianmin Xiong
Supervisor:	Prof. Anders Holmen, Prof. De Chen and Prof. Edd Blekkan

Chemisorption characterization:
The characterization of catalysts used in Fischer-Tropsch synthesis is important for establishing the relationship between the catalyst properties and the performance in Fischer-Tropsch synthesis. Chemisorption is widely used method to study the dispersion of the catalyst and hence the number of active sites. The project deals with a detailed study of the important parameters for determination of chemisorption properties of Co catalysts including reduction conditions, evacuation conditions and temperature for chemisorption.

Cobalt nanoparticles synthesis for Fischer-Tropsch reaction:
Nanoparticles have obtained a lot of attention because of its interesting characters and many usages in different fields. It is a challenge to synthesize cobalt nanoparticles with controlled size and narrow distribution because of strong magnetic interactions and uncontrolled agglomeration between the cobalt particles. The aim of this project is to synthesize size-controllable cobalt nanoparticles with narrow size distribution and deposit the nanoparticles on the support. The performance of the catalyst are studied at Fischer-Tropsch conditions (170 °C, 20 bar, $H_2/CO = 2$).

Financial support:
The project is funded by the Norwegian research council (NFR), through the “KOSK” programme.

Carbon nanofiber supported catalysts for Fischer-Tropsch synthesis and hydrodesulphurization

Postdoctoral fellow:	Dr. Zhixin Yu
Supervisors:	Prof. De Chen, Prof. Edd A. Blekkan, Prof. Anders Holmen, Prof. II Kjell Moljord, Prof. II Erling Rytter.

Carbon nanofibers (CNFs) are nanostructured materials consisting of interwoven fibers of graphitic carbon, which could provide novel opportunities when used as supports for metal or metal oxide catalysts. In addition to their chemical inertness, CNFs are characterized by high purities, high mechanical strengths, high surface areas, high thermal stability, and tunable bulk density. It has been found that the CNFs are very interesting supports for Fischer-Tropsch (F-T) synthesis and hydrodesulphurization (HDS). This project is aimed at exploring new opportunities for the use of CNFs as catalyst support for F-T synthesis and HDS.

For F-T synthesis, CNFs supported cobalt catalysts will be prepared. The catalysts are to be prepared with different metal loadings, on different CNF structures (fishbone, platelet, and fishbone-tubule), by different methods (incipient wetness, wet impregnation, deposition-precipitation, etc), and with promoters (Re, etc). The main purpose is to tailor the CNF support to achieve maximum cobalt dispersion and optimize the C_{5+} selectivity. The platelet CNFs supported cobalt catalysts have shown promising results for F-T synthesis, both in terms of activity and selectivity. However, the catalysts deactivate at a faster rate than the alumina supported cobalt catalysts.

For HDS, CNFs supported Mo catalysts will be prepared and Co and/or Ni will be used as promoters. The catalysts are to be prepared with different Mo precursors, different loadings, and different Mo/Co, Mo/Ni ratios, etc. The purpose is to prepare approximately monolayer coverage of Mo on CNFs and then to promote the catalysts with an optimum amount of Co or Ni. The catalysts will be tested for thiophene desulphurization at atmospheric pressure and dibenzothiophene or 4,6-dimethyldibenzothiphene desulphurization at high pressures. Hydrodenitrogenation experiments on the prepared catalysts will also be carried out.

It is very important to characterize the F-T and HDS catalysts to correlate the activity/selectivity with the catalyst structure. The characterization will be performed by TEM, EDX, Chemisorption, BET, XRD, TGA, TPR, TPD, EXAFS, etc. The catalysts are to be improved according to the structure-activity/selectivity relationships.

Publications and presentations in 2005:

1. Zhixin Yu, Øyvind Borg, De Chen, Bjørn Christian Enger, Vidar Frøseth, Erling Rytter, Hanne Wigum and Anders Holmen: *Carbon nanofiber supported cobalt catalysts for Fischer-Tropsch synthesis with high activity and selectivity*. Accepted by Catalysis Letters.
2. Øyvind Borg, Zhixin Yu, De Chen, Erling Rytter, Vidar Frøseth, Hanne Wigum and Anders Holmen: *Fischer-Tropsch synthesis over carbon nanofiber supported cobalt catalysts*. In preparation.
3. Vidar Frøseth, Zhixin Yu, De Chen and Anders Holmen: *CO hydrogenation on cobalt on carbon nanofiber supports studied by steady-state isotopic transient kinetic analysis (SSITKA)*. In preparation.

Financial support:
Statoil R&D.

Fabrication and high-temperature CO_2 capture properties of nanocrystalline material

<u>Postdoctoral Fellow:</u> Dr. Tiejun Zhao
<u>Supervisor:</u> Prof. De Chen

High performance and cost efficient CO_2 capture technologies are desired to significantly reduce CO_2 from fuel-fired power stations or hydrogen production processes. Currently available solid adsorbents for high-temperature CO_2 separation including carbon-based absorbents, metal oxides, zeolites, and hydrotalcite compounds do not cover the following points: adequate CO_2 adsorption/desorption kinetics, high selectivity and sorption capacity, good hydrothermal stability. Recently, a series of the alkali zirconate/silicate mixed oxides such as Li_2ZrO_3 (Na_2ZrO_3) and Li_4SiO_4 have been reported as good candidates for the CO_2 removal at high temperatures. However, such materials from conventional solid-state preparation method often limit sorption kinetic behavior or capture capacity due to the limited solid diffusion rate of carbon dioxide and the limited purity. The fine-tuning nanocrystalline material seems to be crucial for developing the optimized high-temperature CO_2 sorbents. In addition, since the CO_2-capture reaction is volume-increased and often exothermic, such materials with the open pore structure and the larger pore volume are expected to intensify the capture/regeneration rate of carbon dioxide and to reduce sintering of the nanoparticles.

We have developed a novel liquid-phase method to prepare nanosized Li_2ZrO_3 and Na_2ZrO_3 after calcination including automatic nanoexplosion and in-situ carbonation. From kinetic study, much improved properties such as the capacity and capture rate can be obtained. Furthermore, the CO_2 uptake and release is fully reversible under mild condition. The materials are characterized by different techniques including HRTEM, SEM, XRD and TEOM.

The further work aims at extending the above novel method to develop other highly efficient CO_2 sorbents and assembling the composite containing supported carbon nanofiber and the nanocrystalline sorbents.

<u>Publication and presentation in 2005:</u>

1. E. O. Fernandez, T. Zhao, G. Huogen, H.K. Rusten, M. Rønning, H.A. Jakobsen and D. Chen, *Application of CO_2 Sorption Enhanced Hydrogen Production: Precombustionin Power Generation*, The Third Trondheim Conference on CO_2 Capture, Transport and Storage, Oct, 2005.
2. Tiejun Zhao, Esther Ochoa-Fernández, Magnus Rønning, De Chen, Jun Zhu and Weikang Yuan, *High-temperature carbon dioxide sorption on novel*

microbeads of nanocrystalline sodium zirconate, submitted to International Symposia on Chemical Reaction Engineering, 19.

3. Tiejun Zhao, Esther Ochoa-Fernández, Magnus Rønning and De Chen, *Fabrication and high-temperature CO_2 capture properties of nanocrystalline Na_2ZrO_3*, to be submitted.

Financial support:
The Norwegian Research Council (NFR).

Sorption enhanced steam methane reforming (SESMR)

Researcher: Geir Haugen
Supervisors: Prof. De Chen and Prof. Magnus Rønning

Hydrogen is an important reactant and energy carrier, and steam methane reforming (SMR) of hydrocarbons is the primary route for large-scale hydrogen production. Climate change and the greenhouse effect have forced the need for a more environmental friendly energy production. The reforming of natural gas is thermodynamic favored by low pressure, high temperature and high Steam-to-carbon ratio. Generally the pressure is relative high (20-40bar) in steam reformers because compression of gas is not economic attractive and because of downstream applications. High steam to carbon ratio increase the conversion, but also leads to larger process equipment since more gas has to be transported. High steam to carbon ratio also results in large air and/or water coolers and a loss of thermal efficiency since the condensation heat of water is generally lost from the process

In the novel sorption enhanced steam methane reforming (SESMR) process, a CO_2 acceptor is installed together with the catalyst to remove CO_2 from the gas phase and hence altering the equilibrium for the reforming and water-gas shift reactions. The SESMR process can run at lower temperatures than conventional steam reforming and may reduce investment and operation costs. By using a suitable CO_2 adsorbent during the reaction, hydrogen with purity higher than 95% can be obtained

Adsorbents allows the reformer to be operated at a much lower temperature than the conventional case, typical around 550C compared to 850-950C. The reformer is an adiabatic reactor where the adsorption heat of CO_2 gives heat to the reforming reactions. The process gas leaving the reactor is hydrogen and some unreacted methane on dry basis. The CO and CO_2 are low because of the adsorbent and WGS.

The project focus on process simulation and evaluation of the concept SESMR compared to the conventional SMR. Thermochemical analysis of different adsorbents has been studied. A model in Hysys has been build. Another important part is reactor design and estimation of reactor sizes. The properties to the adsorbents are important. The kinetics has a large impact on reactor sizes, while thermochemical properties are important for the energy efficiency and the hydrogen yield. An adsorbent, able to keep the partial pressure of CO_2 at a minimum, will give the best hydrogen yield and energy efficiency but is also harder to regenerate.

The adsorbents were not able to shift the reforming reaction against hydrogen production at the same extent as the high temperature in the conventional case. Therefore, the SE-SMR cases had to be operated on a lower pressure and a higher steam-to–carbon ratio to reach competitive conversion.

Financial support:
Statoil Research Center

SINTEF Projects

Hydrogen from natural gas

A competence building project, KMB - 2005-2007

Staff (catalysis): Senior scientist Rune Lødeng (Process technology), Prof. Anders Holmen (NTNU).
Pd.D. candidate: Bjørn Christian Enger (NTNU) (see separate description).

Key functional materials with a potential of enabling more efficient process technology for production of hydrogen from natural gas are addressed in the project, including:

- O_2 adsorbents for air separations ("Process chemistry").
- Membrane materials for selective H_2 removal ("Energy conversion & materials").
- Catalysts for production of H_2 from natural gas ("Process technology").

The major goal of the experimental catalyst study is related to production of H_2 at moderate temperature. Activity, stability and selectivity issues will be addressed.
Catalytic partial oxidation (CPO), dry and in presence of steam (oxidative reforming), has been studied over a number of Co-based catalysts and a few Ni-based catalysts. The kinetic testing was performed in co-feed mode in a quartz reactor at atmospheric pressure. Typical temperatures and gas hourly space velocities were in the range 400-700^{o}C and 7500-15000hr^{-1} (CH_4), respectively. Catalyst particles of 90-177 μm were typically diluted by inert material of a similar size. Low surface area α-Al_2O_3 was applied in most runs.
The results obtained so far with prereduced Co and Ni catalyst show that the composition of the product mixture typically approach equilibrium. Different deactivation mechanisms are important, including oxidation of the active phase as well as carbon formation.

Funding: 50/50 STATOIL/The Norwegian Research Council (The RENERGI program).

Dehydrogenation of propane over chromium oxide based catalysts

Staff: Prof. Chen De, Prof. Anders Holmen, Senior scientist Rune Lødeng

Propane dehydrogenation kinetics has been studied in the tapered element oscillating microbalance. Kinetic data for the main reaction and carbon formation has been obtained and applied for building kinetic models.

Client: Borealis

Compact gas to products technology

Staff: Siv.ing. Rune Myrstad, Dr.ing. Edvard Bergene: SINTEF, Prof. Anders Holmen: NTNU.

The goal of this project is identification and evaluation of concepts for micro structured reactors, enabling compact and efficient offshore gas to products technology with main focus on the methanol synthesis (throughput and selectivity).

The project is a part of the KMB (Competence building with user involvement)-project "Enabling production of remote gas" under Petromaks (Solutions for remote gas) program, the Research Council of Norway.

Through a coordinated effort by industry and research institutions, the KMB-project will address challenges related to critical technology barriers concerning floating production of natural gas from remote fields. Specific challenges are: Safety, reliability, process equipment movement, weight and compactness combined with robust operation.

Client: The Research Council of Norway.

Improved Fischer-Tropsch catalysts

Staff: Siv.ing. Rune Myrstad, Dr.ing. Edvard Bergene and Ing. 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 2005:

1. A.-M. Hilmen, E. Bergene, O.A. Lindvåg, D. Schanke, S. Eri and A. Holmen: *Fischer-Tropsch synthesis on monolithic catalysts with oil circulation.* Catal. Today 105 (2005) 357.
2. Ø. Borg, S. Storsæter, S. Eri, H. Wigum, E. Rytter A. Holmen: *The effect of water on the activity and selectivity for γ-alumina supported cobalt Fischer-Tropsch catalysts with different pore sizes.* Catal. Letters (2006)
3. Ø. Borg, S. Storsæter, V. Frøseth, R. Myrstad, E. Bergene, O.A. Limdvåg, E. Rytter, S. Eri, A. Holmen*: *Fischer-Tropsch Synthesis on Different Alumina Supported Co Catalysts.* Lecture. 229th ACS National Meeting, San Diego, CA., USA. March 13-17. 2005.
4. Ø. Borg, S. Storsæter, S. Eri, E. Rytter, A. Holmen: *The effect of different gamma-alumina supports on cobalt Fischer-Tropsch catalysts.* Poster. Europacat-VII, Sofia, August 28 - September 1, 2005.

Client: Statoil R&D

Hydrotreating

Staff: Dr.ing. Håkon Bergem, Siv.ing. Rune Myrstad, Ing. Camilla Otterlei, Dr. ing. Thor Mejdell 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

Refinery operations / Octane processes

Staff: Dr.ing. Torbjørn Gjervan and Senior ing. Ingunn Tanem.

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

Advanced catalyst/reactor systems for conversion of hydrocarbons to hydrogen for fuel cells

Staff: Hilde Venvik (Project Manager), Rune Bredesen, Hallgeir Klette, Anja Olafsen, Ivar M. Dahl, Unni Olsbye, Friedemann Rohr, Kari Anne Andreassen, Sara Molinas, Rune Lødeng, Bjørnar Arstad, Torbjørn Gjervan, Edvard Bergene, Kim Andre Johnsen.
PhD Candidates Ingrid Aartun and Florian Huber, Postdoctoral fellows Marcus Fathi and Bozena Silberova, Professor Anders Holmen.

The objective of the project was to demonstrate space and energy efficient small-scale reactor systems for production of hydrogen for fuel cells from hydrocarbons. Possible applications range from stationary power systems for distributed energy production to on-board hydrogen production in fuel cell vehicles.

Catalytic partial oxidation (CPO) and oxidative steam reforming (OSR) of propane to a mixture of hydrogen and carbon monoxide (syngas) was performed at high temperature (600-1000ºC) in two types of short contact time structured catalysts; metallic microstuctured reactors and ceramic foams. Rhodium was applied as the active catalytic material. The microstructured reactors consist of 100µm wide channels, and were found promising with respect to reaction control and stability.

A heat exchange type reactor design was developed for catalytic partial oxidation of propane in order to minimize heat loss and balance exothermic and endothermic reaction zones. Kinetic data for the exothermic propane oxidation and the endotermic dry and steam reforming reactions, as well as the reverse water gas shift (RWGS) and methanisation reactions were acquired and applied in a predictive heat exchanger model. An experimental reactor was built and tested with satisfactory agreement to the model.

Upgrading of synthesis gas to pure hydrogen is required after CPO/OSR reactions, the first step being the water-gas shift (WGS) reaction for conversion of carbon monoxide to hydrogen. New and improved WGS catalysts have been targeted through assessing the relation between catalyst activity and composition, synthesis, and nanostructure of the catalyst.

The combination of OSR and WGS in successive steps was performed to obtain a product composition containing more than 35% hydrogen and below 2% carbon monoxide. The tests revealed problems with WGS catalyst stability not present when a model feed to the WGS reactor was applied. The deactivation could not be ascribed to the most common by-products (C_2H_4, C_3H_6, CO_2) or residues (C_3H_8) from the high temperature OSR reaction, and further investigations are required.

To obtain a product composition with satisfactory purity for any hydrogen application, treatment beyond WGS is needed. This is often obtained by one or more well-controlled catalytic reaction steps. An alternative approach is the application of 100% hydrogen selective membranes. The project has contributed to the development and demonstration of palladium-based membranes with extraordinarily low thickness (down to 1 μm) and superior hydrogen flux properties. The patented fabrication technique enables the use of a wide range of supports, shapes and sizes of the membrane modules to be applied.

Finally, including reaction and separation in a single unit, so-called (catalytic) membrane reactors (CMR), facilitates process intensification. In the project it was demonstrated that self-supported, 1.6 μm thin Pd-23%Ag membranes could be studied and applied under WGS conditions with promising stability and performance. Thus, a pure or nitrogen diluted hydrogen gas could be obtained directly from the WGS reactor.

Two PhD scholars have been educated, completing in June 2005 and August 2006, and 2 post-doctoral fellows have worked in the project. In addition 4 Master students have been affiliated with the project. The research on microstructured reactors was conducted in collaboration with Forschungszentrum Karlsruhe, Germany. The project has resulted 9 scientific publications in refereed international journals, 10 oral and 10 poster presentations at international research conferences, 10 presentations at Norwegian conferences and meetings, 6 SINTEF reports and 4 NTNU Master Theses. Before completing the last PhD Thesis in August 2006, 2-4 additional publications and 1 more presentation are expected.

Publications and presentations in 2005 (see also publications under the individual PhD and Post docs.):

1. B. Arstad, H. Venvik, H. Klette, J. Walmsley, W. M. Tucho, R. Holmestad, A. Holmen and R. Bredesen, *Studies of self-supported 1.6 μm Pd/23 wt.% Ag membranes during and after hydrogen production in a catalytic membrane*

reactor, Catalysis Today, accepted; Special issue: 7th International Conference on Catalysis in Membrane Reactors

2. B.Silberova, H.J. Venvik, J. Walmsley and A.Holmen, *Small-scale hydrogen production from propane*, Catalysis Today100 (2005) 457-462; Special issue: “11th Nordic Symposium on Catalysis”
3. B. Silberova, H. J. Venvik and A. Holmen, *Production of hydrogen by short contact time partial oxidation and oxidative steam reforming of propane,* Catalysis Today 99 (2005) 69-76. Special issue: "The Selectivity Issue: Driving the Innovation in Oxidation Catalysis"

Client:
The Research Council of Norway. The project is a Strategic Institute Programme on natural gas utilisation under the programme “Energy for the future” from 1.11.2000 to 31.3.2005.

Catalyst/reactor systems for production of hydrogen from methanol for miniaturised power

Staff: Assoc. prof. Hilde Venvik (Project Manager), NTNU, dr. scient Bjørnar Arstad dr. ing. Edvard Bergene, dr. ing. Dag Wang, PhD Henrik Rogne, SINTEF, Professor Anders Holmen, NTNU.

The main purpose is to develop a microchannel reactor system for production of hydrogen from methanol. A microstructured reaction zone is being designed. The incorporation of suitable catalyst coatings to the microchannel walls is also targeted. A first design of a feed supply and evaporation microsystem has also been fabricated and tested.

This activity is a sub-project under the joint NTNU/SINTEF progamme "Gas Conversion to Fuels and Chemicals". It is the main goal of the programme to study catalytic processes for conversion of natural gas to chemicals and fuels including hydrogen.

Client: The Research Council of Norway, program on Catalysis and Organic Synthetic Chemistry (KOSK). Start-up: 2003, extended for 2006.

Catalytic nanoarchitectures for hydrogen production from methanol

Staff: Dr. ing. Hilde Venvik (Project Manager), Dr. scient Bjørnar Arstad, PhD John Walmsley, PhD Helge Kristiansen, SINTEF, Dr.ing. candidate Hilde Meland, Associate Professor Magnus Rønning, Professor Anders Holmen, NTNU.

The main purpose is to develop active catalytic systems for application in microchannels. Based on recent developments at SINTEF and UiO, the possibility of applying porous silicon as catalyst support within microstructures has been explored. Cu-based catalysts will be studied and applied initially, while other catalysts may be applied later.

The project is a research activity within the FUNMAT research project "Materials for Hydrogen Technology"; sub-project "Nanosized Functional Materials for (Electro)catalytic Hydrogen Processes". FUNMAT is a national consortium for research within functional materials and nanotechnology and has four senior partners: SINTEF, the Norwegian University of Science and Technology (NTNU), the University of Oslo (UiO), and Institute for energy technology (IFE).

Client: The Research Council of Norway, NANOMAT program.
Duration: 2003 – 2006.

Dr.ing Theses in 2005

Zhixin Yu: Synthesis of Carbon Nanofibers and Carbon Nanotubes. Department of Chemical Engineering, NTNU, 2005:18.

Kjersti Omdahl Christensen: Steam Reforming of Methane on Different Nickel Catalysts. Department of Chemical Engineering, NTNU, 2005:46.

Ingrid Aartun: Microstructured Reactors for Hydrogen Production. Department of Chemical Engineering, NTNU, 2005:131.

Sølvi Storsæter: Fischer-Tropsch Synthesis over Cobalt Supported Catalysts. Department of Chemical Engineering, NTNU, 2005:134.

Erlend Bjørgum: Methane Conversion over Mixed Metal Oxides. Department of Chemical Engineering, NTNU, 2005:222.

Diploma Students in 2005

Spring 2005

Trine-Lise Bakksjø	Karakterisering av tunge oljer
Bjørn Christian Enger	Fisher-Tropsch katalysatorer på ulike modifiserte aluminabærere
Siri Line Halsen	Oksidativ dehydrogenering av etan
Ingeborg Haugros	Studier av katalysator for metanolsyntesen
Jeanette Hegdal	Separasjon av oljer i SARA-fraksjoner
Elisabeth Vollebekk	Katalytisk hydrogenbehandling: modellstudier

Presentations at Group Meetings 2005

Torbjørn Gjervan: Cutting edge of bimetallic catalysis.

De Chen: Catalysis in natural gas conversion with CO_2 management.

Nina Hammer: Catalysis by gold.

Rune Myrstad: Compact Fischer-Tropsch reactors.

Anders Holmen: Fischer-Tropsch synthesis on monolithic catalysts with oil circulation.

Esther Ochoa Fernandez: Hydrogen production by CO_2-adsorption enhanced steam reforming of methane.

Courses Given by Group Members

TKP4110 Chemical Reaction Engineering

Coordinator:
Professor Anders Holmen

Lectures:
Professor Anders Holmen, Assoc. Professor Jens-Petter Andreassen,
Professor De Chen (laboratory exercises)

Semester: Fall

Level: 3^{th} 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. 3rd ed., 1999.

Exam:
Written + exercises

TKP4120 Process technology

Responsible:
Professor Edd A. Blekkan

Lecturers:
Professor Edd A. Blekkan and Professor Bjørn Hafskjold.

Semester: Fall

Level: 2nd year

Credits: 7.5 SP

Restricted admission: No

Course plan: 4 lectures, 4 hours exercises and 4 hours self study per week

Goal: The course gives an introduction to the process industry, and provides tools for quantitative calculations and modeling of processes, including mass- and energy balances, equilibrium calculations, basic reaction kinetics and reactor design.

Prerequisites: None

Contents:
Topics from thermodynamics and physical chemistry: State variables, ideal gas, equations of state, work and heat, Laws of thermodynamics, entropy, Gibbs energy, equilibrium. Topics from process engineering: The balance principle. Mass balances. Mass balances with chemical reactions. Energy balances (2nd law of thermodynamics). Heat exchange. Mechanical work (compression and expansion). Work from heat. Mechanical energy balances. Introduction to process dynamics. Introduction to kinetics and chemical reaction engineering.

Teaching form/language: Lectures (in Norwegian), compulsory exercises and project work

Course material:
S. Skogestad, Prosessteknikk, Tapir Akademisk Forlag 2000.
Morten Helbæk, Fysikalsk kjemi, Fagbokforlaget 1999.

Examination form: Written exam (4 hours)

TKP4150 Petrochemistry and oil refining

Responsible:
Professor Edd A. Blekkan

Lecturers:
Professor Edd A. Blekkan and Professor II Kjell Moljord (Statoil)

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 handsouts.

Exam: Written

TKP4155 Reaction Kinetics and Catalysis

Responsible:
Assoc. Professor Magnus Rønning

Lectures:
Assoc. Professor Magnus Rønning. Adj. Professor Erling Rytter

Semester: Fall

Level: 4th year

Credits: 7.5 SP (2.5 Vt)

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. Microkinetic 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. Acid–base catalysis in aqueous and non-aqueous solutions. Multifunctional catalysis. Catalysis by transition metal complexes. Ziegler-Natta and single-site polymerisation catalysts. Solvent effects, phase transfer catalysis, catalysis by enzymes.

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: Written

TKP4700 Catalysis and petrochemistry

Coordinator for specialization in catalysis and petrochemistry:
Professor Anders Holmen

Course description:
The specialization involves the following modules:

Catalysis and petrochemistry laboratory work/project	15 SP
TKP1 Environmental catalysis	3.75 SP
TKP2 Modeling of catalytic reactions	3.75 SP
TKP3 Heterogeneous catalysis. Advanced course	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.

TKP1 Environmental and energy catalysis

Responsible:
Professor Anders Holmen

Credits: 3.75 SP

Prerequisites:
TKP4155 Reaction kinetics and catalysis or equivalent knowledge

Module description:
Catalysis occupies a very important position within areas such as environmental technology and energy production. Within environmental technology catalysis becomes more and more important not only for removing of unwanted components such as NO_X, sulfur etc., but also for the development of selective processes. The course will give the fundamentals for catalytic processes for purification of exhaust gases (NO_X, CO, unburned hydrocarbons etc). Within energy production the focus is on catalytic combustion, production of H_2 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:
Norwegian

TKP2 Modeling of catalytic reactions

Responsible:
Professor De Chen

Credits: 3.75 SP

Prerequisites:
TKP 4110 Reaction kinetics and catalysis or equivalent knowledge

Module description:
Microkinetic modeling, catalyst design, elementary reaction steps, theoretical estimation of rate constants, collision and transition state theory, BOC (bond-order conservation) theory, diffusion and reaction in porous catalyst, kinetics for coke formation and deactivation, percolation theory and Monte Carlo simulation, introduction to MATLAB.

Teaching form:
Seminars, self-study, exercises/project work with presentation.

Course material:
Articles and excerpts from textbooks.

Language:
English

TKP3 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:
Norwegian

TKP4700: Projects 2005

Project	**Diploma student**
Scavengers for treatment of mercaptane-rich oil and condensate	Anne Næss Høie
Membrane reactor for hydrogen production	Brynjar Fausk Aardal
Fischer-Tropsch (FT) catalysts	Helene Wendelbo
Fischer-Tropsch synthesis i micro reactors	Kari Faksvåg

Carbon nanofibres as catalyst support	Lars Erik Fareid
Prparation of catalysts for hydrogen production	Jin Qian
Gold catalyst supported on structured carbon supports	Sarka Zarubova
Catalytic dehydrogenation of propane	Silje Nielsen

KP8111 Catalytic conversion of hydrocarbons

Responsible:
Professor Edd Anders Blekkan

Credits: 6 SP

Prerequisites:
TKP4155 Reaction kinetics and catalysis and TKP4150 Petrochemistry and oil refining.

Course description:
The course is given every second year, next time in spring term 2007.
The emphasis of the course is on reaction mechanisms and kinetics of the catalytic conversion of hydrocarbons. Both homogeneous and heterogeneous reactions are considered, and homogeneous catalytic complexes are discussed as well as surfaces and structures of heterogeneous catalysts. Theories of forming and breaking C-C bonds in hydrocarbons, as well as the influence of simple reagents like hydrogen, oxygen, water, ammonia and carbon monoxide are reviewed. Examples are chosen from oil refining and petrochemical processes.

Teaching methods:
Seminars, self studies.

Course material:
B.C. Gates: Catalytic Chemistry, J. Wiley and sons, New York 1992, and articles and handouts.

KP8112 Applied heterogeneous catalysis

Responsible:
Professor Anders Holmen

Credits: 6 SP

Prerequisites:
TKP4155 Reaction kinetics and catalysis.

Course description:
The course is given every second year, next time in the fall term 2007.
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.

KP8109 Environmental catalysis.

Responsible:
Professor De Chen

Credits: 6 SP

Course description:
The course is given every second year, next time in spring term 2006.
The course gives an overview on processes and developments in environmental catalysis. It covers catalysis for end of pipe treatments as well as the transition to more environmental processes with no or only limited formation of unwanted byproducts. Catalysis in energy technology (hydrogen as an energy carrier, fuel cells) will be discussed. The design of processes, catalysts and reactors for

removal of pollutants is treated. Focus will be on reaction mechanisms and kinetics for the catalytic conversion of pollutants.

Teaching methods:
Seminars.

Course material:
Selected scientific papers.

KP8113 Characterization of heterogeneous catalysts

Responsible:
Assoc. Professor Magnus Rønning

Credits: 6 SP

Course description:
The course is given every second year, next time in fall term 2006.
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 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.

Course material:
Selected scientific papers.

Publications in 2005

Z. Yu, D, Chen, B. Tøtdal, T. Zhao, Y. Dai, W. Yuan, A. Holmen: *Catalytic engineering of carbon nanotube production.* Appl. Catal., A: General, 279 (2005) 223.

E. Bjørgum, D. Chen, M.G. Bakken, K. Omdahl Christensen, A. Holmen, O. Lytken, I. Chorkendorff: *Energetic Mapping of Ni Catalysts by Detailed Kinetic Modelling.* J. Phys. Chem. B 109 (2005) 2360.

T. Sperle, D. Chen and A. Holmen: *Prereforming of natural gas on a Ni catalyst. Criteria for carbon free operation.* App. Catal. A: General 282 (2005) 195

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I. Aartun*, B. Silberova, H.J. Venvik, P. Pfeifer, O. Gørke, K. Schubert and A. Holmen: *Temperature profiles and residence time effects in metallic microchannel reactors for hydrogen production.* Lecture. AIChE Spring National Meeting, Atlanta, USA. April 10-14, 2005.

P. Bichon, G. Haugros, H.J. Venvik, A. Holmen, E.A. Blekkan*: *Steam reforming of ethanol over supported Co and Ni catalysts.* Lecture. 4th International Conference on Environmental Catalysis. Heidelberg, Germany, June 5-8, 2005.

P. Bichon, G. Haugom, H.J. Venvik, A. Holmen, and E.A. Blekkan*: *Steam reforming of ethanol over supported Co and Ni catalysts.* Lecture, 19th North American Catalysis Society Meeting, Philadelphia, Pennsylvania, USA. May 22-27, 2005.

Ø. Borg, S. Storsæter, S. Eri, E. Rytter, A. Holmen: *The effect of different gamma-alumina supports on cobalt Fischer-Tropsch catalysts.* Poster. Europacat-VII, Sofia, August 28 - September 1, 2005.

E. Ochoa-Fernández, T. Grande, H.K. Rusten, H.A. Jakobsen, A. Holmen, M. Rønning, D. Chen: *Novel solid high temperature CO_2 absorbents for the production of H2 by sorption enhanced steam reforming.* Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

S. Chytil, E. Vollebekk, W.R. Glomm, J. Walmsley, J. Sjöblom, E.A. Blekkan: Platinum nanoparticles encapsulated in mesoporous silica: *Preparation, characterisation and catalytic activity.* Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

S. Fosse Håkonsen, B. Silberova, A. Holmen: *The production of ethene via oxidative dehydrogenation of ethane over Pt-Sn monoliths.* Flash Presentation + Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

S. Løgdberg, M. Boutonnet, A. Holmen., S. Jærås: *Co/alumina catalysts prepared by the microemulsion technique for production of Fischer-Tropsch diesel.* Flash Presentation + Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

D. Tristantini, S. Løgdberg, B. Gevert, Ø. Borg, A. Holmen: *Effect of water addition on hydrocarbon production via Fischer-Tropsch synthesis from different model bio-syngases over unpromoted and rhenium-promoted alumina-supported cobalt catalysts.* Poster. EuropaCat-VII, Sofia, August 28-September 1, 2005.

B. Arstad, H. Venvik, H. Klette, J. Walmsley, W.M. Tucho, R. Holmestad, R. Bredesen, A. Holmen: *Studies of self-supported 1.6 μm thin Pd/23% Ag membranes during and after hydrogen production in a catalytic membrane reactor.* Oral presentation. 7Th International Conference on Caalysis in Membrane reactors, 11-14 September 2005, Cetraro, Italy.

A. Holmen*, K. Hauge and R. Lødeng: *Non-conventional routes to petrochemicals from natural gas – the future.* RFP 10007A. Oral Presentation.18 World Petroleum Congress, September 25-29, 2005 Johannesburg, South Africa.

S. Fosse Håkonsen*, B. Silberova and A. Holmen: *The Production of Ethene via Oxidative Dehydrogenation of Ethane over Pt-Sn Monoliths.* Poster. 5th World Congress on Oxidation Catalysis, 25-30 September 2005, Sapporo, Japan.

E. Ochoa-Fernández*, H.K. Rusten, H.A. Jacobsen, M. Rønning, A. Holmen and D. Chen: *Sorption enhanced steam ,ethane reforming using* Li_2ZrO_3 *as sorbent: sorption kinetics and reactor simulation.* Lecture. Gas-Fuel 05, 14-15 November 2005, Brugge, Belgium.

S. Lögdberg*, M. Boutonnet, S. Järås, Ø. Borg, V. Frøseth, E.A. Blekkan, A. Holmen: *Cobalt particle size effects in α- and* γ-Al_2O_3 *supported catalysts for Fischer-Tropsch synthesis.* Lecture. Gas-Fuel 05, 14-15 November 2005, Brugge, Belgium.

S. Chytil*, W. Glomm, J.C. Walmsley, J. Sjöblom, E.A. Blekkan: *Platinum nanoparticles encapsulated in mesoporous silica: Preparation, characterisation and catalytic activity in toluene hydrogenation.* Lecture, 2nd International

School - Conference on Catalysis for Young Scientists; 25-29 July 2005, Novosibirsk-Altai, Russia.

H. Dyrbeck*, L. Låte, E.A Blekkan: *Catalytic combustion of hydrogen in the presence of hydrocarbons over noble metal catalysts.* Poster, 6th International Workshop on Catalytic Combustion, Ischia, Italy, 11-14 September, 2005.
Nina Hammer, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Au/oxide catalysts on carbon nanofibres for water-gas shift reaction*. Poster. EuropaCat-VII, August 28- September 1, 2005, Sofia, Bulgaria.

Nina Hammer, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Gold Nanoparticles in Catalysis.* Poster. Nanomat Birkeland Conference, June 2-3, 2005, Trondheim, Norway.

Ingvar Kvande, Gisle Øye, Esther Ochoa Fernandez, Nina Hammer, Magnus Rønning, Anders Holmen, Johan Sjöblom and De Chen: *Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres.* Poster. NT05: Sixth International Conference on the Science and Application of Nanotubes, June 26 - July 1, 2005, Gothenburg, Sweden

Nina Hammer*, Ingvar Kvande, Vidar Gunnarsson, Bård Tøtdal, Xin Xu, De Chen, Magnus Rønning: *Oxide/CNF and oxide based supports for Au catalysts.* Oral presentation. 2nd NTNU Seminar, Synthesis and applications of Carbon nanofibers/nanotubes, September 21, 2005, Trondheim, Norway.

Ingvar Kvande*, Gisle Øye, Esther Ochoa Fernandez, Nina Hammer, Magnus Rønning, Anders Holmen, Johan Sjöblom and De Chen*: Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres*. Oral presentation. 2nd NTNU Seminar, Synthesis and applications of Carbon nanofibers/nanotubes, September 21, 2005, Trondheim, Norway.

KINCAT SINTEF NTNU
Strong Point Centre Kinetics and Catalysis

Seminar
Heterogen Katalyse

Tirsdag 25/1 2005

Professor János B. Nagy
Facultés Universitaires Notre-Dame de la Paix, Namur, Belgia.

”The synthesis of coiled carbon nanotubes and the preparation and properties of CNTs – polymers nanocomposites”.

Seminaret holdes kl 1015 i rom 323, Kjemiblokk 5, 3 etasje.

19/04/2006

KINCAT SINTEF
Strong Point Centre Kinetics and Catalysis

Seminar
Heterogen Katalyse

Fredag 17/6 2005

Professor Dong Ju Moon
Korea Institute of Science & Technology (KIST), Korea.

”Fuel processor, hydrogen station and internal reforming in SOFC”.

Seminaret holdes <u>kl 1415</u> i rom 323, Kjemiblokk 5, 3 etasje.

23/01/2006

2^{nd} *NTNU SEMINAR*
Synthesis and Applications of Carbon Nanofibers/Nanotubes

Wednesday 21/09 2005 kl 08^{30}, Aud. PFI 510

8:30-8:40 Prof. David G. Nicholson, Dean of Faculty of Natural Science and Technology
Opening Remarks

8:40-9:30 Prof. **Krijn P. de Jong,** Inorganic Chemistry and Catalysis, Debye Institute, Utrecht University
Carbon Nanofibers and Carbon Nanotubes for Catalysis.
Preparation, Characterization and Performance

9:30-10:20 Prof. ***Qin Xin ,*** *Dalian Institute of Chemical Physics, Dalian, China*
Advances in Electrocatalysts for Polymer Exchange Membrane Fuel Cell

10: 20-10:35 Coffee

10:35-11:05, J. ***Enrique Garcia Bordeje****, Instituto de Carboquímica (CSIC),Miguel Luesma Castán 4, 50018 Zaragoza, Spain*
Synthesis and Applications of Carbon Monolith

11:05 – 11:25 ***Magnus Rønnin****g, Department of Chemical Engineering, NTNU*
Nanomaterials for Hydrogen Technology in NANOMAT Program

11:25-12:00 De Chen, Department of Chemical Engineering, NTNU
Synthesis and Applications of Carbon Nanofiber/nanotube, NTNU Network.

Lunch 12:00

13:10-13:35 **Zhixin Yu[1],** Øyvind Borg, De Chen[1], Vidar Frøseth, Bjørn Christian Enger[1], Erling Rytter[2], Kjell Moljord[2] and Anders Holmen[1] *[1]Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), N-7491 Trondheim, Norway [2]Statoil R&D, Postuttak, NO-7005 Trondheim, Norway*
Carbon nanofiber supported Co catalysts for Fischer-Tropsch synthesis with high activity and selectivity

13:35-13:55 Lina Jonasson , Department of Materials Science and Engineering,
Electrochemical Formation of Carbon Nanostructures in Fluoride Melts

13:55-14:15 ***Turid Worren****, Melina Garcia, De Chen, Department of Materials Science and Engineering, NTNU, Eleanor Campbell, Gothenburg University and Charmers University of technology, Sweden*

Growth of Vertically Aligned Carbon Nanofibers and Nanocones

14: 15-14:30 Coffee

14:30-14: 50 ***Nina Hammer,*** *Ingvar Kvande,* Vidar Gunnarsson, Bård Tøtdal, **Xin Xu, De Chen, Magnus Rønning*
Department of Chemical Engineering, Department of Physics, Norwegian University of Science and Technology, NTNU, **Beijing Institute of Petrochemical Technology, Beijing, China*

Oxide/Carbon Nanofiber based Supports for Au Catalysts

14:50-15:10 **Ingvar Kvande**, Nina Hammer, Magnus Rønning, Anders Holmen, and De Chen *Gisle Øye,* and Johan Sjöblom *Department of Chemical Engineering, NTNU*

Electrostatic Deposition of Gold Nanoparticles on Plasmachemically Modified Carbon Nanofibres

15:10-15:40 ***Ingvar Kvande/Stein Trygve Briskeby****, Department of Chemical Engineering/ Department of Materials Technology, NTNU*

Synthesis and Applications of Pt/CNF/CNT in Fuel Cells

15:40-16:00 **Sten Yngve Larsen**[1], Trygve Foosnaes[1] , Harald A. Oye[1] , Zhixin Yu[2]
Department of Materials Science and Technology, Department of Chemical Engineering/ NTNU

Carbon Nanofibres in Large-Scale Electrode Application

16:00 ***Closing Remarks***

Sponsors: Strategic Research Area Materials, NTNU
Faculty of Natural Sciences and Technology, NTNU

SEMINAR

Synthesis and Applications of Carbon Nanofibers/Nanotubes

Monday, 21/11, 2005 kl 13^{30}-14^{30}, KV-323

Prof. Wei-Kang Yuan

State Key Laboratory of Chemical Reaction Engineering
East China University of Science and Technology
Shanghai, China

CNF as Catalyst: Multiscale Structure and Catalytic Performance

KINCAT

Strong Point Centre Kinetics and Catalysis

Seminar
Heterogen Katalyse

Onsdag 7/12 2005

Dr. Matam Santohosh Kumar

Ph.D. from Humboldt Universität zu Berlin, Berlin, GERMANY .

”Nature of Fe-sites in Fe Zeolites and their catalytic role in the abatement of NO_X”.

Seminaret holdes kl 1015 i rom 323, Kjemiblokk 5, 3 etasje.

23/01/2006

KINCAT SINTEF
NTNU
Strong Point Centre Kinetics and Catalysis

Seminar
Heterogen Katalyse

Fredag 16/12 2005

Dr. Jianmin Xiong
Ph.D. from Dalian Institute of Chemical Physics, Dalian, China.

"Study of Co supported on activated carbon for liquid fuel production through FT-synthesis".

Seminaret holdes kl 1315 i rom 323, Kjemiblokk 5, 3 etasje.

23/01/2006

NTNU Network on Carbon Nanomaterials, 2005

Coordinator: Prof. De Chen
Members:
Faculty of NT:

Department of Chemical Engineering (IKP):	Prof. De Chen
	Prof. Anders Holmen
	Assoc. Prof. Mangnus Rønning
	Dr. Gisle Øye
	Prof. Johan Sjøblom
	Prof. Hågg MayBritt
Department of Materials Technology (IMT):	Prof. Trygve Foosnæs
	Prof. Svein Sunde
Department of Biotechnology (IB):	Prof. Bjørn E. Christensen
Department of Physics (IP):	Assoc. Prof. Bård Tøtdal.
	Prof. Anne Borg
	Assoc. Prof. Turid Worren

Faculty of Medicine

Department of Cancer Research and Molecular Medicine (IKM)	Prof. Duan Chen

Faculty of IT

Department of Machine design and materials technology	Prof. Oksman Kristiina

Technology Transfer Office (TTO)	Dr. Inge Hoved Gangås

The overriding objective of the network is to set up a platform that promotes the fundamental investigation related to carbon nanomaterials (CNM), e.g. synthesis, characterization and applications. The sub-goals are as follows:

1) Continuing the NTNU network established in 2004.
2) Enhance the existing CNM projects by multidisciplinary approaches
3) Conduct initial studies to attract funding for development of applications of CNM.
4) Enhance the international cooperation. Prepare joint project applications.

Financial support:
NTNU strategic research area Materials, Dean’s funding form NT faculty, Gas research center, NTNU, NFR