2019 was a year of refreshing the iCSI Centre, with new people joining while others were leaving. First of all, we are proud of the first two iCSI PhDs, Dr. Ata ul Rauf Salman and Dr. Dimitrios Pappas, who both finalized their degrees in December. They are now in new positions in Norwegian industry, and we wish them success there. We have also welcomed two new PhD candidates to the University of Oslo, Karoline Kvande and Julie Hessevik, and a new Postdoctoral fellow to NTNU, Yalan Wang. All three are well qualified and motivated for their research tasks, and we look forward to following their work in the coming years.

Educating master’s students is important to the Centre. In 2019, 13 master’s students were associated with iCSI, of which five delivered directly into the ongoing projects. The gender balance within iCSI also improved this year, with all personnel categories now balancing – either way – within a 40/60 distribution. In 2019 our young scientists and senior researchers continued to show their innovation potential by disseminating high quality research from the Centre. iCSI researchers gave 27 presentations at national and international conferences. The number of publications increased from the year before, and 18 reviewed papers were published. At the end of the year, even more were submitted for review. The publication and presentations lists can be found on p. 58-60.

As announced in 2018, it was an absolute highlight when the Award for Excellence in Natural Gas Conversion 2019 was presented to iCSI professor Unni Olsbye at the 12th Natural Gas Conversion Symposium in San Antonio, Texas in June. She is the first woman to be admitted to this hall of fame in natural gas conversion.

Three iCSI PhD candidates did industrial exchanges in 2019, at Inovyn, Dynea/KA Rasmussen, and Haldor Topsoe. They returned enthusiastic about their new experiences, while also having contributed with new perspectives and skills at the industrial sites.

Due to the Midway evaluation workload and the desire to change the season for holding the scientific seminar, iCSI rescheduled the seminar for early summer 2020. This delay was partially compensated by SAC member Enrique Iglesia visiting both NTNU and UiO for full-day meetings with the candidates and other project staff. iCSI appreciated this opportunity to be challenged in inspiring discussions with a man with broad practical experience and a tremendous knowledge within kinetics and catalysis.

Once more the representation on the iCSI Board has changed. Torgeir Lunde, the representative from Yara, replaced Odd-Arne Lorentsen. UiO representative Einar Uggerud (Head of Department of Chemistry) replaced Kristin Vinje, and Marco Piccinini, the representative from Inovyn, replaced Terje Fuglerud. When Odd-Arne left, the Board decided to appoint Pablo Beato from Haldor Topsoe as the new Chair. He has been a Board member from the start-up of iCSI and knows the Centre well. iCSI thanks everyone for their efforts during their period on the Board.

Finally, as the Midway evaluation expert panel concluded very favorably for iCSI, and the RCN Board decided that the Centre may continue its efforts, we have started to look forward. We want to learn from our scientific and personal experiences and listen to the advice given to us in the Midway evaluation and by our scientific advisory committee (SAC). We continuously work to ensure that we are focusing on the right problems and making optimal use of the unique possibility that we have been given to create innovation through iCSI.
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Time to refresh!

In many senses, the past year has been a time for refreshing the iCSI Centre! It is now 4½ years since the iCSI board was established and the last contract details of the iCSI consortium were finalized. Several personnel changes have occurred since then and in 2019, the composition of the Board was refreshed again. Torger Lunde, the representative from Yara, replaced Board chair Odd-Arne Lorentsen. UiO representative Einar Uggerud (Head of Chemical department) replaced Kristin Vinje, and Marco Piccinini, the representative from Inovyn, replaced Terje Fuglerud. I have been a member of the Board since its founding and when Odd-Arne left, the Board decided to appoint me as the new Chair. I am grateful for their confidence and it is a real pleasure to work with so many passionate and engaged people. In particular, I appreciate the collaboration with Hilde and Anne, who are not only the leaders but also the souls of the management group. They have navigated us effectively and successfully through the midway evaluation process, which is enabling us to continue the Centre’s work for the next five years.

However, the workhorses of the Centre are of course the PhD students and postdoctoral fellows. In the beginning of 2016, we started to hire PhD students, and the scientific work at iCSI was launched. Now in 2019, we are proud to have witnessed the first iCSI students obtaining their PhD degree. Aataul Rauf Salman defended his thesis, entitled Catalytic oxidation of NO to NO2 for nitric acid production on December 6, 2019. A week later, on December 13, 2019, Dimitrios Papas defended his thesis, entitled Direct methane to methanol conversion over Cu-exchanged zeolites: Building structure – activity relationships. As a co-supervisor of Dimitrios, it has been an amazing journey to follow his growth, both scientifically and personally. It is even more satisfying to know that both newly minted doctors have obtained positions in industry and are now part of the Norwegian labour market. Three PhD defences will follow in 2020 and, as is typical for mature scientific work, this correlates well with the steep increase in the number of scientific publications coming from the iCSI Centre during 2019. I am sure that this trend will continue through 2020 and beyond.

However, 2020 will also be a time to refresh the scene with the new PhD candidates and postdocs who started at the iCSI Centre during 2019: Karoline Kvande (PhD) at UiO/Topsøe, Julie Hessevik (PhD) at UiO/Yara Rasmussen/Yara and Yalan Wang (postdoc) at NTNU/Inovyn. Another five new young researchers will be hired this year, and it is comforting to know that they will find a well-functioning infrastructure, which further guarantees the progress in their respective innovation areas.

In my view, the start of the next cycle of students will also be a good opportunity for all of us to refresh our ideas. We have to sit down and try to learn from our scientific and personal experiences and listen to the advice given to us by the midway evaluation and our internal scientific advisory committee (SAC). In November 2019, we actually organized a leader meeting to do so – what better place could we have chosen than Farris Bad at a hotel under the motto “Relax, Rejuvenate, Refresh!”. In this sense, I hope that we constantly rethink or adjust our research goals and try to think “out of the box”, thereby ensuring that we are still focusing on the right problems and making use of the unique possibility we have been given to create innovation within the iCSI Centre.

Vision, objectives and strategy

iCSI focuses on Catalysis Science and Innovation related to a range of industrial processes that are key to Norwegian land-based industry, industrial competitiveness, as well as future chemical processing and energy conversion with a minimum environmental footprint. The industrial partners involved supply key sectors of the global market (catalysts, chemicals, fertilizer, plastics, fuels, etc.), which are the very products that impact our food supply and standard of living the most. The iCSI consortium represents leading competence and technology, for which the core business relies largely or completely on catalytic processes. iCSI represents significant industrial operations in Norway as well as worldwide.

iCSI’s main basic vision has been to establish an integrated competence and technology platform that promotes world class energy and raw material efficiency and allows spin-off activities in the different directions of prime interest for the industrial partners. Furthermore, iCSI is developing a strong competence base for the Norwegian chemical industry in the long term and to the benefit of society in terms of securing jobs, reducing energy consumption and abating harmful emissions to the environment. State-of-the-art methodology in synthesis, characterization and technology development is applied in order to obtain a detailed understanding of complex catalysts under industrially relevant conditions, thereby identifying factors critical to their performance. iCSI researchers also develop predictive tools for optimization of materials, chemistries and processes.

iCSI’s main objective is to boost industrial innovation and competitiveness and provide efficient, low-emission processes.

This can be achieved through:

• Improved understanding of the kinetics and chemistry of the catalytic processes as a basis for performance enhancement and process optimization.

• Synergy between applied and basic research, competence-building and education through interaction between industry, research institutes and universities

• Development of new materials and experimental and theoretical methods
iCSI organization

The Norwegian University of Science and Technology (NTNU) is serving as Host institution for the iCSI Centre. The iCSI research partners - NTNU, SINTEF Industry and the University of Oslo (UiO) - represent the main research groups involved in heterogeneous catalysis research in Norway, located in Trondheim (NTNU and SINTEF) and Oslo (UiO and SINTEF). The industrial partners - Yara, KA Rasmussen AS, Dynea, INOVYN and Haldor Topsøe A/S - also conduct their own significant R&D. The collaboration enables the optimized use of complementary competence and a shared, highly advanced, experimental infrastructure that is being utilized, expanded and developed within iCSI.

The research is organized into 6 Industrial Innovation Areas (IIA1-6), each with 1-6 work packages. Cutting-edge research topics addressing the key challenges are identified for each of the iCSI industrial innovation areas (IIA1-5) and defined as Work Packages. IIA6 is focusing on the development of methodology in line with the international forefront, and these methods are gradually being integrated into the activities of IIA1-5. Each IIA has 2-3 research partners and 1-2 industrial partners, while IIA6 is generic and involves all partners.

Industrial Partners

An overall objective for iCSI is to strengthen the competitive position of the industrial partners by securing their technological lead with respect to selected catalysts and process operations and enabling them to further reduce their environmental footprint. In addition, certain Norwegian industrial operations and industrial core competences can be secured and developed.

Yara International ASA is a Norwegian-based chemical company with fertilizer as its largest business area. Yara also works with industrial gases, catalyst production and NOx abatement solutions for industrial plants, vehicles and vessels in its product portfolio. In addition to being present in more than 51 countries, Yara operates 2 industrial production sites in Norway, Porsgrunn and Glomfjord, with approx. 700 employees. In iCSI, Yara aims to further strengthen its global competitiveness through innovation.

KA Rasmussen AS is a refiner of precious metals and supplier of catalysts and products based on precious metals located in Hamar, Norway among other places in Europe. KA Rasmussen has specialized in technology for producing structured catalysts for the Ostwald process, and silver particles for the oxidation of methanol. In iCSI, KA Rasmussen wants to expand its catalyst market base, contribute to meeting emissions targets and reduce the net consumption of noble and scarce metals in their product range.

Dynea AS is a Norwegian-owned company for wood adhesives production, industrial coatings and licensing of Silver Formaldehyde plants with productions sites in Norway, Denmark and Hungary. Dynea holds several unique technologies for licensing, and its further technology R&D is based in Norway. In iCSI, Dynea aims to continue its technological leadership in formalin production for improved plant operations and reduced cost, as well as increase its licensing.

INOVYN Ltd. is a leading producer of chlorovinyls and associated products, wholly owned by INEOS. INOVYN has 8 European production sites and 4300 employees, of which INOVYN Norway AS constitutes about 300 employees in two sites: The chlorine/VCM production at Rafnes and the PVC plant at Herøya. Through iCSI, INOVYN wants to further improve the VCM technology to achieve world class energy and raw material efficiency.

Haldor Topsøe A/S is a catalyst producer and process plant technology developer based in Denmark. Topsøe is known for its emphasis on research and scientific excellence as a basis for its business. In iCSI, Topsøe aims to explore new, direct routes from lower alkanes to bulk chemicals, thereby expanding their technology range and potentially reducing the energy consumption and emissions associated with such production.
Centre Board

The Board is the decision-making body for the execution of ICSI’s vision and objectives. Its functions and mandate are described in the ICSI Consortium Agreement: “The Centre Board shall ensure that the intentions and plans underlying the Contract for the Project are fulfilled, and that the activities discussed in the Project description and the Work Plan are completed within the approved time frame. The Centre Board will further ensure that the interaction between the Centre, the Host institution and the other Consortium participants functions smoothly”. Each partner is represented (permanent + deputy) and has one vote. The Research Council of Norway is represented by an observer.

The board members since August 2019 are:

Johan Skjelstad
Project Manager at K A Rasmussen.

Lars Axelsen
General Manager of Technology Sales & Licensing at Dynea.

Dr. Marco Piccinici
Vinyl Chloride Monomer and Organic Chlorine Derivatives Research Manager at INOVYN

Torgeir Lunde
Head of Ammonia/Nitric Acid Technology Centre at Yara International

Professor Einar Uggerud
Head of Department of Chemistry at University of Oslo

Professor Karina Mathisen
Vice Dean for Education and Dissemination at the Faculty of Natural Sciences, NTNU

Dr. Duncan Akporiaye
Research Director at SINTEF Industry.

Dr. Aase Marie Hundere
Special advisor RCN, with Responsibility for Nanotechnology and Advanced Materials

Scientific Advisory Committee

Prof. Alessandra Beretta
Politecnico di Milano, Italy

Prof. Enrique Iglesia
University of California, Berkeley, USA

Prof. Graham Hutchings
Cardiff University, United Kingdom

Three renowned scientists from prominent institutions who have excelled within ICSI-relevant areas of heterogeneous catalysis have committed to contribute to ICSI and act as inspiration for the ICSI researchers. Their main tasks are to advise the ICSI Board on the ongoing work in the Centre, to participate and interact with the young researchers at the ICSI Annual Seminar, and to promote ICSI’s internationalization and recognition.

Management and Administration

The Centre is hosted by the Department of Chemical Engineering at NTNU. The administration team consists of a Centre Director, a Coordinator/Vice Director and an Economy Adviser. In 2019, the increased administrative responsibilities that followed the Midway Evaluation of the Centre’s for Research-based Innovation generation III (SFI-III) led to a temporary extension of the coordinator team to three part-time members from August 2018 to May 2019. All coordinators have experience from academic and/or industrial research.

Hilde Johnsen Venvik
Professor
ICSI Centre Director
Scientific Highlight 2019

The first iCSI publication from iCSI Industrial Innovation Area 3 (IIA3) came out in 2019! IIA3 is called Frontier formalin technology development, and formalin (formaldehyde in aqueous solution) is a widely used base chemical, for example in adhesives and resins in the wood industry. Under industrial reaction conditions, some of the feedstock (methanol) and/or product (formaldehyde) is lost to CO and CO2, and the iCSI team of industrial and academic researchers are exploring the possibilities for suppressing this formation. The main target in IIA3 is to improve the selectivity to formaldehyde of the process that uses silver (Ag) as a catalyst for the oxidation of methanol to formaldehyde through a fundamental understanding of the reaction and the silver catalyst surface.

The publication came out in Volume 62 of the journal Topics in Catalysis, containing selected papers from the 18th Nordic Symposium on Catalysis, Copenhagen, 26-28 August 2018. PhD student Stine Lervold received a special invitation to publish after winning the prize for best poster at the conference. The work is a joint effort between the industrial researchers at Dyneia and KA Rasmussen, and NTNU and SINTEF. Two NTNU Master students also contributed.

In the study, we compare experiments under industrially relevant conditions with high formaldehyde selectivity (>90%) to model exposures, for example methanol and steam alone. From this it was found that the massive morphological changes of the electrolytic silver catalyst particles under methanol-to-formaldehyde reaction conditions at 650 °C are mainly an effect of oxygen (O2) in the gas phase (fresh catalyst in left picture, after reaction in right picture). Hence, while the results confirm the role of dissolved O to the restructuring phenomena discussed by many authors, dissolved H appears not to be prerequisite, which contrasts with several claims. The interested reader will find additional details and conclusions on page 34!


Conversion of methanol and product selectivity. Fresh catalyst in left picture, post-reaction in right picture.

iCSI Moments 2019

Awards

Conferences
Midway Evaluation

On April 1, 2019, iCSI had a site visit from the international expert panel engaged by the Research Council of Norway (RCN). The panelists included generalists Professor Alison McKay from the University of Leeds and Mattias Lundberg from the Swedish Foundation for Strategic Research (SSF), and scientific experts Associate Professor Ilenia Rossetti from the University of Milan and Professor Lars Pettersson from the KTH Royal Institute of Technology, Sweden. The panel’s findings and views of the Centre were reported to RCN, whose Board confirmed on September 9, 2019:

RCN’s recommendation to the Board included the following:

...The panel appreciates the Centre's balance between basic research and topics of a more applied nature. Choosing applied issues directly contributes to deeper insight and opportunities for improvement of established industrial processes. The panel concludes that this is an excellent centre that conducts research that is internationally competitive and addresses relevant issues identified by the Centre's industrial partners. Scientific production is high and at a good and sometimes excellent level.... The Centre has engaged internationally profiled professionals in a Scientific Advisory Committee (SAC) that provides constructive input to the Centre and individual feedback to PhD fellows. The fellows at the Centre are motivated and value collaboration and dialogue across work packages. The panel recommends that the Centre continue to facilitate various measures for mobility – both internationally and to/from business.....The Centre’s recent initiative towards Process 21 and positioning in relation to the EU are important measures in this direction. The Centre has good management and good support in the host institution and with partners.....All industry partners are active on the Board and have clear objectives for participation in the Centre..... In the past three years, the Centre has been encouraged to allocate more resources to research projects that have industrial interest.

The Centre will be continued for a new three-year period without the implementation of specific measures as a result of the evaluation.

Visit from SAC member Enrique Iglesia

Enrique Iglesia, a member of the iCSI Scientific Advisory Committee, was the recipient of the 2019 Michel Boudart Award for the Advancement of Catalysis. The Michel Boudart Award recognizes and encourages individual contributions to the elucidation of the mechanism and active sites involved in catalytic phenomena and to the development of new methods or concepts that advance the understanding and/or practice of heterogeneous catalysis.

The Award is sponsored by the Haldor Topsøe Company, and is administered jointly by the North American Catalysis Society and the European Federation of Catalysis Societies.

Professor Iglesia and his research group have advanced the design, synthesis, and structural and mechanistic characterization of solid catalysts for chemical reactions involved in the production, conversion, and use of energy carriers, in sustainable syntheses of chemicals and intermediates, and in the protection of the environment.

In August 2019, Professor Enrique Iglesia contributed to iCSI with full-day visits first at NTNU and then at UiO. At both sites he gave an inspiring guest lecture, entitled C-C Coupling and O-atom Removal in Oxygenate Reactions at Lewis Acid-Base Pairs on Oxide Surfaces. The rest of the day was spent on individual meetings with PhD candidates and Postdocs (NTNU) and meetings with the various iCSI project teams (UiO). The candidates were grateful to have this opportunity for inspiring discussions and were very impressed both with Professor Iglesia's broad practical experience and his overview of various topics and issues.

iCSI is proud and pleased to have a professional capacity like this in the Scientific Advisory Committee. We admire his endurance through the two days of program from early morning to late evening.
What really mattered on his academic path was the influence of Professor Paul Emmett at NTNU in the late 1960s. But he also found inspiration in the lectures of visiting professor Åge Solbakken was an important mentor for Anders, and he was also close friends in Trondheim and his family in Østerdalen. His first job was close to good friends in Trondheim and his family in Østerdalen.

After graduating from Department of Chemical Engineering at NTH in 1966, he started to work for SINTEF Applied Chemistry. This was not (according to him) due to a wish for a research career, but because the job was close to good friends in Trondheim and his family in Østerdalen.

Åge Solbakken was an important mentor for Anders, and he also found inspiration in the lectures of visiting Professor Paul Emmett at NTNU in the late 1960s. But what really mattered on his academic path was the year he spent in the laboratory of Professor Michel Boudart at Stanford University from 1978 to 1979. Upon returning to Norway, a position in the Department of Industrial Chemistry was waiting for him, and in 1984 he was appointed as a professor.

In 1969 oil and gas were discovered in the North Sea. And in 1970 the foundation of Statoil. A proud moment 2010: On the podium with former recipients of the NGCB award, from left: David Trimm, Enrique Iglesia, Lanny Schmidt, Jens Rostrup-Nielsen and Anders Holmen. Later, this recognition was confirmed when he received NGCB’s Award for Excellence in Natural Gas Conversion in 2010 for his achievements in advancing concepts and practical applications of direct and indirect routes for the efficient utilization of natural gas. Throughout his career, Holmen has contributed to the understanding and practice of Fischer-Tropsch synthesis, specifically by unravelling the complex effects of water on reaction rate and selectivity and the utilization of these feedstocks become an important subject. The work in the catalysis group was founded by the Research Council (NTNF) and Norsk Hydro, and later, also by Statoil. The more fundamental PhD work was also supported by Norwegian Industry, due to a great demand for well-educated people.

One key factor in the success of the catalysis group is a large park of pilot plants – some optimized to simulate industrial processes, others achieving high quality kinetic data. The pilot plants, along with access to a number of advanced, state-of-the-art catalyst characterization methods, such as Auger spectroscopy, Scanning Tunneling Microscopy (STM), Electron Microscopy (SEM/TEM) and X-ray Photoelectron Spectroscopy (XPS) have been crucial for the results. Modern techniques such as TEOm (microrabalance) and SSITKA (transient kinetics) were introduced and TAP (temporal analysis of products) were used in co-operation with laboratories outside Norway. The use of X-ray absorption spectroscopy and other synchrotron techniques is also important for the work in the group. The use of TEOm was pioneered by the catalysis group in studying coke formation and diffusion in microporous catalysts.

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When Anders Holmen received the Statoil (now Equinor) Researcher Award in 1994, it was reasoned that ‘he has the primary responsibility for building up a recognized international research environment in the field of industrial reaction catalysis at both NTH and SINTEF. He has initiated research on chemical processes of vital interest to Statoil in petrochemicals, refining and gas conversion. Particularly groundbreaking is his work on coking and deactivating catalysts. Within octane processes, a test and development laboratory has been set up and the laboratory is still operating. He has also initiated the construction of an advanced surface laboratory for atomic level analysis, as well as educated most of the chemical engineers working at Statoil.’

As a SINTEF research scientist in the group led by docent Solbakken in front of the acetylene rig, Anders says. It gives him the opportunity to follow the work closely. He is also very pleased about the social life in the group and to see that the group follows the tradition of celebrating the PhD candidates. Education of the candidates is of course a very important part of the University work – maybe the most important! I feel very privileged to spend my Emeritus time in the Catalysis Group’, Anders says. It gives him the possibility to follow the trends in modern catalysis and to write up unpublished work. Together with his wife Bjørg, he also appreciates spending time with his three grandchildren who live close by. ‘Life is good for this old man!’ he says.

Development of the laboratories has been possible through the tight collaboration with Norwegian industry and now iCSI, have been invaluable in the long-term development of the group’s high professional level.

Professor Emeritus Anders Holmen

Reaction mechanisms come and go, but the results from proper experimental studies remain unchanged. Optimization of concepts and practical applications of direct and indirect routes for the efficient utilization of natural gas….Throughout his career, Holmen has contributed to the understanding and practice of Fischer-Tropsch synthesis, specifically by unravelling the complex effects of water on reaction rate and selectivity and the utilization of these feedstocks become an important subject. The work in the catalysis group was founded by the Research Council (NTNF) and Norsk Hydro, and later, also by Statoil. The more fundamental PhD work was also supported by Norwegian Industry, due to a great demand for well-educated people.

One key factor in the success of the catalysis group is a large park of pilot plants – some optimized to simulate industrial processes, others achieving high quality kinetic data. The pilot plants, along with access to a number of advanced, state-of-the-art catalyst characterization methods, such as Auger spectroscopy, Scanning Tunneling Microscopy (STM), Electron Microscopy (SEM/TEM) and X-ray Photoelectron Spectroscopy (XPS) have been crucial for the results. Modern techniques such as TEOm (microrabalance) and SSITKA (transient kinetics) were introduced and TAP (temporal analysis of products) were used in co-operation with laboratories outside Norway. The use of X-ray absorption spectroscopy and other synchrotron techniques is also important for the work in the group. The use of TEOm was pioneered by the catalysis group in studying coke formation and diffusion in microporous catalysts.

Be sure that you measure what you want to measure and not something else, such as rates influenced by diffusion. Later, this recognition was confirmed when he received NGCB’s Award for Excellence in Natural Gas Conversion in 2010 for his achievements in advancing concepts and practical applications of direct and indirect routes for the efficient utilization of natural gas. Throughout his career, Holmen has contributed to the understanding and practice of Fischer-Tropsch synthesis, specifically by unravelling the complex effects of water on reaction rate and selectivity and the role of Co crystallite size and of supports on catalyst reactivity and stability.

So, how did Anders Holmen accomplish this? After graduating from Department of Chemical Engineering at NTH in 1966, he started to work for SINTEF Applied Chemistry. This was not (according to him) due to a wish for a research career, but because the job was close to good friends in Trondheim and his family in Østerdalen.

Anders Holmen has contributed to the understanding and practice of Fischer-Tropsch synthesis, specifically by unravelling the complex effects of water on reaction rate and selectivity and the role of Co crystallite size and of supports on catalyst reactivity and stability. A proud moment 2010: On the podium with former recipients of the NGCB award, from left: David Trimm, Enrique Iglesia, Lanny Schmidt, Jens Rostrup-Nielsen and Anders Holmen.

The professor explains that heterogeneous catalysis takes place on the surfaces of solid materials. Therefore, thorough knowledge of the surface is important. New or improved techniques for surface studies are continuously being developed. In recent years we have also seen tremendous development in theoretical methods for describing surface reactions. Catalysis researchers must have an open mind for all these new methods. However, we will not succeed without hard-working people who have an eye for quality and an understanding of all the traps you can walk into. The catalysis group is doing very well and maintains a high standard of teaching and research, which makes it a pleasure for Anders to follow the work closely. He is also very pleased about the social life in the group and to see that the group follows the tradition of celebrating the PhD candidates. Education of the candidates is of course a very important part of the University work – maybe the most important! If you do not apply for a grant or a research project - you can be sure that you won’t get anything.
iCSI Moments 2019

Fun at the lab

Celebration - Midway evaluation passed!

Diligent master students

New PhDs
Two new PhD candidates, Karoline Kvande and Julie Hessevik, joined ICSI in 2019.

**Karoline** started in April 2019 in the Catalysis Section at UiO with Stian Svelle as her main supervisor. The overall objective of her PhD project is to measure the activity of transition metal containing porous catalysts in the continuous catalytic process for the direct activation of lower alkanes.

Karoline likes being busy. She took both her Bachelor's and Master's degrees in chemistry at the University of Oslo and at the same time, she worked as a kayak trainer and was very active in Realistforeningen. Now, she says, ‘the best thing about being a kayak trainer and was very active in Realistforeningen is the opportunity to dig into details on interesting topics. As a relatively recent PhD candidate, Julie’s biggest challenges so far have been coordinating the various activities at the start of a PhD – teaching, taking classes, seminars and working on her project.

Like Karoline, Julie is also very happy to be part of a centre for research-based innovation (SFI). ‘It’s nice to see that industry is interested in the research, and that’s an additional motivating factor for me. We often have meetings with our industry partners, which gives us the chance to work on and discuss complex issues with more people, who have other kinds of experience’, she says.

For the future, she doesn’t want to limit herself to a specific career path yet. ‘I like challenges and enjoy research, technology development and project work. What I envision that would be fun is being able to do project-based work in a company or research institution, but I’m open to various opportunities that may arise along the way’.

And when not at work, Julie loves to be physically active, especially through climbing and other outdoor activities.

**Julie** joined the NAFUMA group in December. Together with Helmer Fjellvåg and Anja Olafsen Sjåstad as supervisors, she will study catchment of platinum group metals. The objective is to investigate how such metals are transported in the gas phase under process conditions and how these can be recovered/captured by metals and by metal oxide catchment gauzes.

Julie had experience from a variety of areas and institutions before she joined ICSI. She obtained her Bachelor’s degree in nanotechnology and her Master’s degree in nanoscience from the University of Bergen. For her Master’s thesis she worked on the synthesis, characterization and testing of catalysts (homogeneous and heterogeneous) for copolymerization of CO₂ and epoxides. At university, she also found time to serve as a board member of the student council for Nanotechnology/Nanoscience students at the University of Bergen. Following her studies, she worked as an engineer in NTNU’s Department of Materials Science and Engineering for one year and later in the start-up company CrayoNano for two years.

Now, back at university, she appreciates the opportunity to dig into details on interesting topics. As a relatively recent PhD candidate, Julie’s biggest challenges include stemming from project-based work in a company or research institution, but I’m open to various opportunities that may arise along the way’.

About life outside the university, she says, ‘I’m generally happy to learn new things and often have many small projects going on, also outside of job. But my regular activities in everyday life are experimenting in the kitchen with new and exciting foods, as well as keeping myself active through paddling, strength training and good walks. Otherwise, I love being social, so I try to find time for friends and family as often as I can.’ We wish Karoline all the best for her research and the other parts of her life.

**The best part of life as a PhD candidate is that you have the opportunity to go into depth on a topic you are interested in, as well as the flexibility you have.”**

- PhD candidate Julie Hessevik
iCSI’s industry partners are actively involved in the research programmes and offer a two-month industry exchange programme to the PhD candidates. This is a unique opportunity for the candidates to gain experience with industrial challenges and thinking. In 2019, the three candidates Stine Lervold, Samuel Regli and Endre Fenes from iCSI took advantage of this opportunity and visited Dynea and KA Rasmussen, Haldor Topsøe and Inovyn, respectively.

Stine is a PhD candidate focusing on improving the performance of the existing formalin production process technology (WP 3.1). During 2018/2019 she completed a two-month internship at Dynea AS and KA Rasmussen AS through the iCSI industrial exchange programme.

“I did my exchange at both of my industrial partners, KA Rasmussen and Dynea. During this period, I got to experience the industrial aspect of formaldehyde production, but also the origin of the silver catalyst. Having the opportunity to experience the process first-hand broadened my perspective beyond the lab and gave me a better understanding of the importance of my PhD work. While experiencing parts of the industry relevant for the MTF process, I was also challenged with other tasks industry encounters.

This has been a unique chance to meet others, and interact and exchange ideas in a new and inspiring environment. Not only has this benefited my development as a scientist, but it also gave me a glimpse of what the future could look like after finishing my degree. I highly encourage other iCSI researchers to use this opportunity to get to know our industrial partners.”

Not only PhD candidates benefit from the exchange. Stine’s host at KA Rasmussen and iCSI board member, Johan Skjelstad, has this comment on the value created for KA Rasmussen:

“The PhD student exchange yielded a great benefit in the form of a study on new production methods. This would not have been possible without NTNU’s research training and methodology in attacking new problems.”

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**Scientific Activities**

**iCSI main Industrial Innovation Areas (IIAs) and Work Packages (WP):**

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<td>Sintef</td>
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<tr>
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</table>
Scientific Activities
IIA1: 21st Century Ammonia Oxidation and Nitric Acid Technology Development

The Team in 2019

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<tr>
<th>Name</th>
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<th>Role</th>
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</thead>
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<tr>
<td>Anja Olafsen Sjåstad</td>
<td>UiO</td>
<td>IIA leader, PhD supervisor and WP responsible (WP1.1), advisor (WP1.2)</td>
</tr>
<tr>
<td>David Waller</td>
<td>YARA</td>
<td>Industrial senior (Yara), PhD supervisor (WP1.1), industry researcher (WP1.2-1.3)</td>
</tr>
<tr>
<td>Helmer Fjellvåg</td>
<td>UiO</td>
<td>Advisor (WP1.1-1.2)</td>
</tr>
<tr>
<td>Asbjørn Slagtern Fjellvåg</td>
<td>UiO</td>
<td>PhD candidate (WP1.1)</td>
</tr>
<tr>
<td>Julie Hessevik</td>
<td>UiO</td>
<td>PhD candidate (WP1.1)</td>
</tr>
<tr>
<td>Susmit Kumar</td>
<td>UiO</td>
<td>Researcher (WP1.1)</td>
</tr>
<tr>
<td>Oskar Iveland</td>
<td>UiO</td>
<td>Master student (WP1.1)</td>
</tr>
<tr>
<td>Oleksii Ivashenko</td>
<td>UiO</td>
<td>Postdoctoral fellow (WP 1.1 )</td>
</tr>
<tr>
<td>Sang Baek Shin</td>
<td>YARA</td>
<td>Industry researcher (WP 1.3)</td>
</tr>
<tr>
<td>Ketil Evjedal</td>
<td>YARA</td>
<td>Industry researcher (WP 1.1)</td>
</tr>
<tr>
<td>Malin Bjørneboe</td>
<td>YARA</td>
<td>Industry researcher (WP 1.1)</td>
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<tr>
<td>Van Giau Nguyen</td>
<td>YARA</td>
<td>Industry researcher (WP 1.1)</td>
</tr>
<tr>
<td>Ant Clausen</td>
<td>YARA</td>
<td>Industry researcher (WP 1.1)</td>
</tr>
<tr>
<td>Torgeri Lunde</td>
<td>YARA</td>
<td>Industry researcher (WP 1.1-1.2)</td>
</tr>
<tr>
<td>Johan Skjelstad</td>
<td>KA Rasmussen</td>
<td>Industry Researcher (WP1.1-1.2)</td>
</tr>
<tr>
<td>Thomas By</td>
<td>KA Rasmussen</td>
<td>Industry Researcher (WP1.1-1.2)</td>
</tr>
<tr>
<td>Silje Fosse Håkonsen</td>
<td>SINTEF</td>
<td>Researcher WP responsible (WP1.2)</td>
</tr>
<tr>
<td>Børge Holme</td>
<td>SINTEF</td>
<td>Researcher (WP1.2)</td>
</tr>
<tr>
<td>Magnus Ranning</td>
<td>NTNU</td>
<td>PhD supervisor, WP responsible (WP1.3)</td>
</tr>
<tr>
<td>Rune Lødeng</td>
<td>SINTEF</td>
<td>PhD supervisor, researcher (WP1.3)</td>
</tr>
<tr>
<td>Ata Al Rauf Salman</td>
<td>NTNU</td>
<td>PhD candidate (WP1.3)</td>
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<tr>
<td>Minadir Saracevic</td>
<td>NTNU</td>
<td>Master student (WP1.3)</td>
</tr>
<tr>
<td>Bjørn Christian Enger</td>
<td>SINTEF</td>
<td>Researcher (WP1.3)</td>
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Motivation
Nitric acid is a valuable commodity chemical with an annual global production of about 65 million tonnes. The production is a three-step process where NH₃ is first oxidized to NO over a Pt-Rh gauze catalyst at high temperature, and this is followed by a homogeneous gas phase oxidation of NO to NO₂ at moderate temperatures. Finally, the nitric acid is obtained by absorption of NO₂ in water. A major technological challenge is loss of Pt and Rh in the highly exothermic first step. To avoid permanent loss and costly noble metal recovery, an optimized catchment (recovery) system is required.

This is targeted in WP1.1 and WP1.2 through investigating fundamental aspects of PGM species volatilization and transport, as well as surface reaction and reconstruction, gas absorption and diffusion into the solid phase catchment system. WP1.3 concerns the development of new catalyst technology for oxidation of NO to NO₂, which would reduce future capital investments and increase the energy recovery if the bulky homogeneous oxidation system could be replaced by a compact, heterogeneously catalyzed process.

Publication
Publications and conference contributions from IIA1 are listed in page 58

Reconstruction of Pd-Ni catchment gauzes during high temperature ammonia oxidation

The financial cost of Pt-loss during ammonia oxidation is one of the largest single expenses in nitric acid production. The current commercial Pd/Ni catchment unit can capture the lost Pt with high efficiency with simple handling in the reactor. Unfortunately, the Pd/Ni alloy is victim to severe grain reconstruction during the Pt-catchment process (picture at top). This causes problems with pressure drop in the ammonia oxidation reactor, and it can therefore not be used to its full potential. Via in-situ tomography experiments at ESRF we have mapped the development of the morphology of pure Pd and Pd/Ni wires during this Pt-catchment process. Combined with home lab experiments, we have seen the impact of the grain boundary structure on the grain reconstruction phenomena, and how different diffusion rates come into play. When Pt is captured on the surface of the Pd (or Pd/Ni) wire, a flux of rapidly diffusing Pd atoms move in the grain boundaries and towards the surface, meeting the Pt incoming from the gas phase. In the end, this causes the grain boundaries to crack open and grain reconstruction to occur (figure at right). This strongly resembles corrosion on base metal alloys and their oxidation behaviour. In other words, we do not see corrosion by oxidation, but by platination.

Visual schematic of the development of pure Pd-gauzes during Pt-catchment. To the left, experimental results showing the difference between poly- and mono-crystalline wires. Especially visible are the diffusion in grain boundaries in the polycrystalline wire, and the diffusion limitation in the monocrystalline wire. At right is how we interpret this in our model for corrosion by platination.
Experimental investigations of Pt/PtRh volatilization and catchment

A dedicated six-zone reactor system is used to generate PtO\(_2\) vapor in dry air/inert gas mixture and subsequent catchment on pure Pd and Pd-Pt binary alloys. The furnace is optimized to provide temperature gradients in the range 800–1200°C, representative of those used between the location for the Pt volatilization in the ammonia oxidation step and the catchment material in the industrial process.

A set of polished Pd and Pd-Pt discs with diameters of 5-6 mm and different Pd-Pt compositions have been exposed to a flow of PtO\(_2\) vapor for four hours at 900°C. The diffusion profile has subsequently been analysed using Sputtered Neutral particle Mass Spectrometry (SNMS).

Our results show that for the low Pt-containing samples, Pt is picked up from the gas stream and a clear diffusion profile is observed. However, for samples that initially contained high amounts of Pt we measure the opposite effect where Pt is actually lost from the catchment sample under these conditions. This behaviour is more pronounced in the catchment samples containing the most Pt. An interesting observation is that with higher PtO\(_2\) partial pressure, more Pt is caught by the discs (figure below). The turning point (with net zero uptake of Pt) also seems to shift to higher Pt containing alloys when increasing the PtO\(_2\) partial pressure in the gas phase. An unexpected large Pt loss is observed from the Pd45Pt55 sample exposed under zero PtO\(_2\) partial pressure. This point (and others) will be run again to check if this diffusion profile is really valid, and to assess the reproducibility in the data.

Catalytic oxidation of NO to NO\(_2\) for nitric acid production

Replacing the homogenous gas phase oxidation of NO to NO\(_2\) step in nitric acid production with a more compact heterogeneous catalytic process offers several advantages: a) a significant increase in recovery of high-quality heat, b) acceleration of the oxidation reaction and c) potential for a substantial decrease in capital expenditure (CAPEX) for new plants. Some efforts have been made to find a catalyst that is effective under industrial conditions, but to this date, the process is still carried out as a homogeneous reaction in modern nitric acid plants.

The current work aims to find efficient catalysts for oxidation of NO to NO\(_2\) under conditions relevant to nitric acid plants, enabling significant process intensification. This also involves gaining a fundamental understanding of reaction kinetics and the mechanism of oxidation of NO over promising catalysts. The industrial process dictates the conditions of catalytic investigations: feed composition of 10% NO, 6% O\(_2\), 15% H\(_2\)O, pressure 1–10 bar and temperatures in the range 150–450 °C.

Mimicking industrial conditions in a laboratory is challenging. A dedicated setup was built that was capable of investigating the activity of powdered catalysts using realistic feed concentrations at atmospheric pressure partially simulating nitric acid plant conditions. The activity of the catalysts was studied as a function of temperature to provide information about the onset temperature of catalytic conversion. The stability of the catalysts was probed by studying catalytic activity as a function of time. Although water is an integral part of the reaction mixture in the nitric acid plant, catalytic experiments were performed in the absence and presence of water to elucidate the effect of water on catalyst activity and structure. The NO conversion levels at 350°C for the various catalysts are presented in the figure below.

Platinum catalysts supported on Al\(_2\)O\(_3\) and ZrO\(_2\) are active for the oxidation of NO. But we also seek to identify potential replacements of platinum group metal (PGM) catalysts, exhibiting superior or comparable catalytic activity. Transition metal oxide (manganese) on different support materials (Al\(_2\)O\(_3\), SiO\(_2\), ZrO\(_2\)) and perovskites (LaCo\(_{1−X}\)B\(_X\)O\(_3\), B = Mn, Ni) were investigated in this respect. The experiments revealed that zirconia-supported catalysts with low manganese loading are promising cost-efficient catalysts for the conversion of NO in nitric acid production.

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[Net Pt uptake in Pd and Pd-Pt binary alloys after 4 hours exposure to different PtO\(_2\) partial pressures.]

[NO Conversion over various catalysts at 350 °C during temperature scan from 150 °C to 450 °C. Feed 10% NO, 6% O\(_2\) (15 % H\(_2\)O when present) in balance Ar.]

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IIA2: Abatement of Nitrogen-containing Pollutants. State-of-the-art SCR Catalysis

The Team in 2019

Jasmina Hafizovic Cavka  SINTEF  IIA leader
David Waller  YARA  Industrial senior Yara, industry researcher (WP2.1)
Silje Fosse Håkonsen  SINTEF  Researcher and WP responsible (WP2.1)
Karl Isak Skau  YARA  Industry researcher (WP2.1)
Martin F. Sunding  SINTEF  Researcher (WP2.1)

Motivation

Selective Catalytic Reduction (SCR) is a core technology in the treatment of exhaust gases (NOX) from various sources, and the applications are emerging due to stricter emission regulations and circular economy. The most common SCR catalyst technology for power and marine applications is based on vanadium oxides combined with other oxides; typically supported on monolithic structures to allow high throughput and minimum pressure drop for the reduction of NOX with ammonia (NH3). Catalyst lifetimes may be as long as 5 years but vary due to differences in their exposure to poisons, dust and soot. It is therefore desirable to rejuvenate or regenerate the SCR catalysts. The former typically involves dust removal and washing to remove surface particulates and soluble deposits but implies difficulties with respect to obtaining full recovery of the activity. Regeneration, on the other hand, may involve the addition of an active phase to recover the original activity. Recovering the catalyst activity in a simpler way would be highly beneficial. This objective is targeted in WP2.1 through first gaining a deeper understanding of the mechanisms causing the catalyst deactivation through thorough characterization of the catalyst at different stages of its lifetime, and then translating this knowledge into new measures.

Commercial catalysts are mainly based on vanadium oxide (V2O5) supported on an anatase (TiO2) carrier. The total load of V2O5 is around 1–5 wt% depending on the specific application. To improve chemical and physical properties of the catalyst WO3 and MoO3 are also added. The SCR catalysts lifetime is dependent on the application, and the catalyst normally deactivates due to fouling, sintering, poisoning, or a combination of these.

Research project

Commercial vanadia-based SCR monoliths were installed on ships running on low sulphur (S) fuels. Experience from the industry indicates that lowering the S-content in the fuel can cause unexpected problems for the SCR catalyst, such as higher Si deposits on the catalyst wall. To understand the cause of deactivation, the characterization toolbox developed in the project was applied to both the fresh catalyst and one catalyst that has been aboard a ship running on mostly ultra-low sulphur fuel. Powder XRD of fresh and spent catalyst did not show significant changes; the support TiO2 phased remained in its anatase form after exposure to flue gases. Other compounds were detected by the XRD. The BET analysis confirmed a decrease of the available surface area by 22%.

Cross sections of both the fresh and used catalyst were studied by SEM-EDS to look for Si distributions. It was known from before that Si is present in the fresh catalyst in the form of glass fibres used to increase the mechanical strength of the monolith structure. This Si is associated with some other elements. A SEM image and EDS map of the Si layer on the fresh catalyst is shown in part A of the figure below. In addition to these fibres, our results show the presence of a uniform Si-rich layer on both the fresh and used catalysts. In both catalysts a dense film of Si rich (50-100 nm) was observed on the outer surface of the catalyst wall. On the used catalyst a thicker (about 1µm), more porous layer was also detected underneath the dense surface Si rich layer (part B of the figure below).

The source of the thicker Si-rich layer in the used catalyst is not yet clear, but it is believed to originate from the exhaust stream. The Si could potentially diffuse from the fibres to the surface and thereby create Si-rich layers. However, this is not believed to be the primary source of Si, as thicker Si-rich layers have not been observed in used catalysts from other applications. The nature of the Si was further studied byToF-SIMS to try to shed some light on the origin of the Si. Results revealed the presence of SiOx near the surface in both the fresh and used samples. No Si(CH3) groups, commonly found in e.g. silicon oil, were detected.

A diluted HF wash has been utilized to see if it is possible to wash off the Si from the outer surface of the catalyst. Results show that Si is successfully removed, but the wash also has a negative effect on the catalyst itself. However, it may be possible to tune the HF concentration and wash time so as to remove the Si without affecting the catalyst.
IIA3: Frontier Formalin Technology Development

The Team in 2019

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<td>Jasmina Hafizovic Cavka</td>
<td>SINTEF</td>
<td>IIA leader</td>
</tr>
<tr>
<td>Kristin Bingen</td>
<td>DYNEA</td>
<td>Industrial senior, industry researcher (WP3.1-3.2-3.3), WP responsible (3.2)</td>
</tr>
<tr>
<td>Mads Lid</td>
<td>DYNEA</td>
<td>Industry researcher (WP3.2-3.3)</td>
</tr>
<tr>
<td>Johan Skjelstad</td>
<td>KA Rasmussen</td>
<td>Industrial senior, industry researcher (WP 3.1)</td>
</tr>
<tr>
<td>Thomas By</td>
<td>KA Rasmussen</td>
<td>Industry researcher (WP 3.1)</td>
</tr>
<tr>
<td>Hilde Venvik</td>
<td>NTNU</td>
<td>PhD supervisor, WP responsible (WP3.1), advisor (WP3.3)</td>
</tr>
<tr>
<td>Stine Lervold</td>
<td>NTNU</td>
<td>PhD student (WP3.1)</td>
</tr>
<tr>
<td>Rune Ladeng</td>
<td>SINTEF</td>
<td>PhD supervisor (WP3.1), researcher (WP3.2-3.3)</td>
</tr>
<tr>
<td>Roman Tschentscher</td>
<td>SINTEF</td>
<td>Researcher (WP3.2-3.3)</td>
</tr>
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Motivation

Formalin is a base chemical that is widely used in adhesives and resins applied in the wood industry. The production proceeds by catalytic oxidation of methanol to formaldehyde, in excess air over a mixed metal oxide catalyst or excess methanol over a silver-based catalyst. Dynea owns both process technologies, and KA Rasmussen is a manufacturer of silver catalysts. The silver process is assumed to have the highest economic improvement potential, due to lower energy consumption and the possibility of increasing the formaldehyde yield beyond 90-92%.

The main objective of IIA3 is improving the formaldehyde yield of the silver-based process. The fast and exothermic nature of the reactions involved requires control of the heat and mass transfer phenomena as well as the surface chemistry proceeding on the silver surface.

Gas phase chemistry may play an additional role at typical reaction temperatures exceeding 600 °C, at which temperature structural changes in the Ag catalyst also occur that are known to affect both the reaction chemistry and the catalyst stability. The lifetime of the catalyst in industrial operation is in the order of months, depending on parameters such as particle morphology, size distribution and the structure of the catalyst bed in addition to the reaction conditions. Further developments are achievable by a more detailed understanding of the reaction conditions and tuning of the silver particle/bed morphology, thus controlling both selectivity and stability.

Activity and post-reaction surface morphologies of the Ag methanol oxidation to formaldehyde catalyst for CO and H₂ oxidation reaction sub-systems.

Gas phase reactions in the product mixture are suppressed by minimizing void volume and residence time at high temperature. Finally, heat tracing of tubes leading to the analysis is important to avoid polymerization of the formaldehyde product.

The oxidation of H₂ and CO represents reaction sub-systems important for optimizing the formaldehyde production process and can provide information on relevant reaction pathways associated with restructuring. Catalysts exposed to oxygen alone, or CO or H₂ oxidation, at temperatures in the range 600-670 °C undergo severe restructuring of the surface on the mesoscopic scale. A smoothened surface with refacteted areas and pinholes is visible, similar to what is observed after methanol oxidation, industrially as well as in the laboratory experiments (see High-light on page 12).

The Ag catalyst displays similar, high initial activity for both CO and H₂ oxidation (bottom figure below). However, while the H₂ conversion seems to be facilitated by the restructuring during time on stream, the opposite occurs for CO conversion. This suggests that the CO to CO₂ route is inhibited by the dynamics occurring between Ag and oxygen at high temperature, and that restructured Ag and dissolved O does not promote the CO to CO₂ route at high temperature. Reaction mechanisms that explain CO₂ formation mainly by CO oxidation may need to be reconsidered.
The CuCl₂ oxidation of ethylene to EDC, i.e. 1,2 dichloroethane, in a continuous process is still required to remain competitive and ensure high plant reliability and energy efficiency. The introduction of ethylene was pioneered in the 1950s and has been a major driver of the production of polyvinylchloride (PVC), which finds widespread application in numerous sectors such as building, flooring, piping, profiles, cables, etc. VCM production is the most widely produced plastic and finds application in the production of chlorine and caustic soda.

**Motivation**

Polyvinylchloride (PVC) produced by polymerization of the monomer vinyl chloride (VCM), is the third most widely produced plastic and finds application in numerous sectors such as building, flooring, piping, profiles, cables, etc. VCM production is the most widely produced plastic and finds application in the production of chlorine and caustic soda. The oxidation state of the Cu and vacancy concentration on the surface of the catalyst during the reaction, thereby causing the aggregation and loss of active Cu. Coatings of alkali and/or rare earth metals are often used as promoters to increase the activity, selectivity and stability. In the project, the promoter effects on reduction, oxidation, and steady-state reaction rates are studied experimentally and theoretically. Another main challenge of this process is that the Cu(I) forms on the surface of the catalyst during the reaction, which can cause the aggregation and loss of active Cu. Coatings of alkali and/or rare earth metals are often used as promoters to increase the activity, selectivity and stability. In the project, the promoter effects on reduction, oxidation, and steady-state reaction rates are studied experimentally and theoretically.

The kinetic model developed was also based on the CuCl₂/Al₂O₃ and K-doped CuCl₂/Al₂O₃ catalysts. The proposed model fits well with the experimental results and can be used to describe the reaction rate and Cu²⁺ (the active Cu species) concentration during the steady state. It was reported that the CuCl₂ is dispersed as a monolayer on the Al₂O₃ surface. Therefore, the influence of Cu by support facet can be significant on ethylene oxychlorination. We prepared two types of supports with different morphologies – one platelet, one tubular, and specific facets exposed. They are used as the supports of CuCl₂ and evaluated in ethylene oxychlorination. It was demonstrated that the CuCl₂/Al₂O₃-P, with platelet structure and (110) termination, had a higher ethylene conversion and stability than that of 5Cu/Al₂O₃-T, with tubular structure and (111) termination. Kinetic analysis proved that the oxidation rate can be greatly enhanced by the Cu/P, and this is important also for the regeneration of the active Cu²⁺.

**Promoter effects on ethylene oxychlorination**

CuCl₂/Al₂O₃-based catalyst is commonly used as a commercial catalyst in the industry, while dopants like alkali metals are used as the promoters. The main objective of the project is to gain a better understanding of the promoter effect on ethylene oxychlorination from the kinetic perspective.

A multiwavelength analysis method using chemometrics has been developed in the project to analyse the UV-VIS-NIR spectra. Multivariate Curve Resolution with Alternating Least Squares (MCR-ALS) was used to analyse and interpret these spectra. A program algorithm for deep data analysis (DDA) has been established, where the key compounds and their standard spectra, as well as the changes of these components over time, are obtained.

The effects of promoters such as metal (K, Li, Na, Rb, Cs, La, Mg, Ca, etc) chlorides on the catalytic performance at steady-state conditions were analysed in terms of the relative rates of the reduction, oxidation, and hydrochlorination steps. New intermediates species were detected, such as CuCl₂, with chloride vacancy, the complexes of MCl₅-CuCl₂. This provides a significantly better understanding of the dynamic evolution of the active sites during the course of the reaction.
IIA 5: The Next Step in Direct Activation of Lower Alkanes

The Team in 2019

Stian Svelle  
UIO  
IIA Leader, PhD supervisor, WP responsible (WP5.1-5.2-5.3)

Pablo Beato  
Haldor Topsøe A/S  
Industrial senior, Industry researcher (WP5.1-5.2-5.3)

Unni Olsbye  
UIO  
PhD supervisor (WP5.1-5.2)

Dimitrios Pappas  
UIO  
PhD student (WP5.1-5.2)

Karoline Kvande  
UIO  
Master student (WP5.1-5.2), PhD candidate (WP5.2)

Lars Fahl Lundegaard  
Haldor Topsøe A/S  
Industry researcher (WP5.1)  

Aino Nielsen  
Haldor Topsøe A/S  
Industry researcher (WP5.1)

Martin R. N. Grøndahl  
Haldor Topsøe A/S  
Industry researcher (WP5.2)

Mia Bodenhoff  
HTAS/DTU  
Master student (WP5.2)

Bjørnar Arstad  
SINTEF  
Researcher (WP5.3)

Motivation

Researchers at SINTEF, UiO and Haldor Topsøe AS join forces for developing new nanostructured catalyst materials. To this end, they try to reveal the mechanism of the direct conversion of lower alkanes to chemicals or liquid fuels over copper-doped zeolite catalysts. To this end, they try to reveal the mechanism of the direct conversion of lower alkanes to chemicals or liquid fuels over copper-doped zeolite catalysts.

Publication

Publications and conference contributions from IIA5 are listed in page 60.

A Generation Change

The year 2019 marked a milestone for the activities within IIA5. Dimitrios Pappas defended his PhD, a new PhD candidate, Karoline Kvande, has started her work, and a new postdoc will start in early 2020. Looking back, the activities within IIA during the first half of the Centre’s existence have been tremendously successful. Starting from scratch, we have now moved to the research front within our topic, evidenced by the large number of publications and in particular the two papers in the high impact Journal of the American Chemical Society and a review article on the chemistry of Cu-zeolites in general published in Chemical Society Reviews. Apart from the great contributions of the candidates working on the project, a major contributing success factor has been the collaboration with the University of Turin. Through this collaboration, the IIA activities have gained access to extensive competence in characterization accumulated over decades. In supporting projects, we have carried out extensive quantum chemical calculations (yet to be published) and an effort has been made to evaluate process feasibility (Mia Bodenhoff, Master’s thesis, DTU, Denmark). Looking ahead, we have identified several ambitious new objectives, and we are confident of making the second Centre period equally successful for IIA5!

2019 Research Highlight

As the 2019 research highlight, we would like to emphasize the publication Zeolite surface methoxy groups as key intermediates in the stepwise conversion of methane to methanol in 2019, and a new postdoc will start in early 2020. They are listed in page 60.

The low temperature activation and transformation of methane as well as other lower alkanes directly into valuable chemicals, such as methanol, is commonly considered “a dream reaction” due to its enormous industrial potential. Haldor Topsøe AS supplies essential technology for most existing routes but is monitoring potential extensions for the current portfolio and the application of zeotype materials.

We are particularly pleased by this work, as it is a product of the collaboration among the entire IIA team, unlocking the full synergy of the team. Solid state NMR and sample activation and pretreatment was carried out at SINTEF. This was a milestone experiment for us, which required extensive method development. Thanks to iCSI-IIA5 activities, significant new competence has been built. Furthermore, measurements of methanol productivities have been done at UiO, Haldor Topsøe has prepared materials, and through the collaboration with the University of Turin, characterization has been carried out.

In this collaboration, we show that surface methoxy groups (SMGs) located at zeolite Bransted sites are the stable key species to trap and store the methane oxidation products. We followed the reaction steps in situ via infrared spectroscopy and applied solid state NMR spectroscopy on copper mordenites after methanol loading. The SMGs are identical to those formed on a copper-free reference zeolite after reaction with methanol. These SMGs react with water, methanol, or carbon monoxide to yield methanol, dimethyl ether and acetate. We find no evidence for stable SMGs directly at copper sites.

To conclude, we have identified two potential bottlenecks in the methane to methanol reaction, namely (1) the absolute amount of active copper species, tunable by a properly adjusted stoichiometry, and (2) the amount of Bransted acid sites able to stabilize the SMG intermediate without overoxidation. Our finding explains why H-form mordenites outperform their Na-form analogues. This observation has general impact on any future process that tries to trap the intermediate methane oxidation product towards methanol.

The pathway of the stepwise MTM conversion. CuII is present after oxidation (Step 1) but gets reduced to CuI by methane (Step 2). The reaction leads to the formation of stable surface methoxy groups (SMGs) and side products like water, COx and DME.

References

(1) the absolute amount of active copper species, tunable by a properly adjusted stoichiometry, and (2) the amount of Bransted acid sites able to stabilize the SMG intermediate without overoxidation. Our finding explains why H-form mordenites outperform their Na-form analogues. This observation has general impact on any future process that tries to trap the intermediate methane oxidation product towards methanol.
IIA 6: Generic Projects for Additional Industrial Synergies

The Team in 2019

- Magnus Rønning (NTNU), IIA leader, PhD supervisor and WP responsible (WP6.1)
- Anja Olafsen Sjåstad (UiO), WP responsible (WP6.2)
- De Chen (NTNU), WP responsible (WP6.3)
- Ragnar Fagerberg (SINTEF), WP responsible, researcher (WP6.4)
- Torbjørn Gjervan (SINTEF), WP responsible, researcher (WP6.4)
- Samuel K. Regli (NTNU), PhD candidate (WP6.1)
- Hilde Johnsen Venvik (NTNU), PhD supervisor (WP6.1)
- Martin Meuche (NTNU), Master student (WP6.1)
- Edd A. Blekkan (NTNU), WP responsible and PhD supervisor (WP6.5)
- Jia Yang (NTNU), Researcher and PhD supervisor (WP6.5)
- Moses Mawanga (NTNU), Postdoctoral fellow (WP6.5)
- Oleksii Ivashenko (UiO), Postdoctoral fellow (WP 6.2)
- Pablo Beato (Haldor Topsøe), Industrial senior researcher (WP6.1)
- David Waller (YARA), Industrial senior researcher (WP6.2)
- Helmer Fjellvåg (UiO), Researcher (WP6.2)
- Christine Pettersen (UiO), Master student (WP6.2)
- Martin Jensen (UiO), PhD candidate, not ICSI (WP6.5)
- Yanying Qi (NTNU), Postdoctoral fellow (WP6.3)
- Terje Fuglerud (INOVYN), Industry senior researcher (WP6.1-WP6.3)
- Kristin Bingen (Dynea), Industry senior researcher (WP6.3)
- Kumar R. Rout (SINTEF), Researcher (WP6.3)
- Rune Ledeng (SINTEF), Researcher (WP6.4)
- Ingeborg Helene Svenum (SINTEF), Researcher (WP6.4)
- Øystein Dahl (SINTEF), Researcher (WP6.4)
- Anna Lind (SINTEF), Researcher (WP6.4)
- Carlos Grande (SINTEF), Researcher (WP6.4)
- Martin Fleissner Sunding (SINTEF), Researcher (WP6.4)
- Mathieu Grandcolas (SINTEF), Researcher (WP6.4)
- Otto Lunder (SINTEF), Researcher (WP6.4)
- John Lein (SINTEF), Researcher (WP6.4)
- Athanasios Chatzitakis (UiO), Researcher (WP6.4)

Motivation

Some ICSI work packages are allocated to research with the intention of moving the research to the forefront and providing methodological tools that can be applied in the industrial innovation areas IIA1-5. In particular, advanced spectroscopic and microscop- ic investigations under conditions highly relevant to industrial operation are targeted. Another effort is directed towards advancing atomistic and kinetic modelling of metals and oxides, as well as reactor modelling, to eventually enable an integrated, multi-scale modelling approach.

Publication

Publications and conference contributions from IIA6 are listed on page 60.

Advanced Operando Characterization of Heterogeneous Catalysts for Sustainable Process Industries

PhD Project, WP6.1

This work package is investigating heterogeneous catalysts during operation at industrially relevant conditions and developing the necessary data analysis tools as needed. In order to link structural properties of the material with catalytic activity during reaction, we apply spectroscopy (infrared, X-ray, UV-Vis) in-house and at synchrotrons. We have synergies with four out of the five other industrial innovation areas within ICSI and collaborations within KinCat (Fe-based Fischer-Tropsch synthesis to olefins from renewable feedstocks and selective catalytic reduction of NO by ammonia over Cu-based catalysts) and with SUNCAT at Stanford University.

With our setup we can combine several techniques for simultaneous characterization of the bulk and the surface of catalysts during reaction at industrially relevant concentrations, temperatures (473-723 K) and pressures (up to 20 bar). Key characterization techniques in this project are X-ray absorption spectroscopy with synchrotron radiation, X-ray diffraction, UV-VIS spectroscopy, Fourier-transform infrared spectroscopy and Raman spectroscopy. New insight on the active sites of the catalysts and the respective kinetics of the chemical reactions can guide towards favourable compositions and conditions, thereby enabling processes with higher efficiency, lower cost, reduced emissions or by-products and improved lifetimes.

The activity this year has focused particularly on multivariate statistical analysis of in situ and operando X-ray Absorption Spectroscopy data. The increasingly larger datasets associated with studies of catalysts at work, often combining several characterization techniques, call for automated procedures for analysing a large number of spectra simultaneously. The work has made strides in finding previously unknown inter-
Advanced Synthesis and Characterization – Novel Thin Film Preparation and Reactor STM

Postdoctoral Fellowship, WP6.2

In this work package we are developing nanostructured surfaces, which act as model catalysts relevant for industrial processes. The obtained model catalysts are utilized in surface sensitive operando studies by means of Reactor STM-MS and Near Ambient-Pressure (NAP) XPS-MS. We are currently focusing on catalytic ammonia oxidation at intermediate temperatures (200-400 °C) for environmental applications. Since Pt-Rh gauzes are used as catalysts for ammonia oxidation for nitric acid production, this bimetallic alloy is also considered for the ammonia slip process.

Three activities are ongoing in parallel to reveal the role of Rh in the PtRh alloy at ammonia slip conditions:

1. Understanding of alloying of PtRh surfaces based on Pt(111) and Rh(111) single crystals
2. Observing oxidation of alloyed surfaces using in situ STM and NAP XPS
3. Capturing ammonia oxidation live with high pressure Reactor STM and NAP XPS

With the aim of understanding the structure and morphology of PtRh alloys, we previously constructed a roadmap for alloy preparation on the Pt(111) surface. In 2019 a complementary work on Rh(111) was initiated together with Christine Pettersen. From the comparison of PtRh/Pt(111) and PtRh/Rh(111), it follows that they exhibit distinct surface morphology, which in future can be used to improve catalytic performance.

To explain the behaviour of PtRh alloys in ammonia oxidation conditions, the obtained surfaces were oxidized in various conditions to identify surface structures possible in the presence of O₂. The lower part of the figure above highlights the differences in surface structures of oxidized PtRh prepared on Pt(111) and Rh(111) crystals.

Finally, the NAP XPS data obtained at MAXIV in collaboration with international partners at Lund University have been analysed and provide the first operando insights on how the surface species present on PtRh/Pt(111) are driving product distribution during ammonia oxidation. This activity has synergies with IIA1 (21st Century Ammonia Oxidation and Nitric Acid Technology Development).

All the experimental results collected to date form a solid basis for further operando studies of PtRh/Rh(111) at the MAXIV and PtRhAl₂O₃/NiAl(110) at the SOLEIL synchrotrons scheduled in 2020.

Reaction Mechanism Investigation by Combined DFT Calculations and Microkinetic Modelling

Postdoctoral Fellowship WP6.3

Developing new catalysts or improving existing catalysts depends on a better understanding of the reaction mechanism on the catalyst surface and the relationship between the catalyst properties and performance. The Density Functional Theory (DFT) calculation has been carried out to describe surface reactions and provide so-called descriptors of catalytic activity and selectivity to be able to tailor catalysts atom by atom. Microkinetic modelling is utilized to investigate the reaction mechanism and predict information about surface coverages and relative rates of various elementary steps under reaction conditions. By developing this methodology, the project has enabled us to bridge the gap from the atomic level to kinetic analysis at the macro-scale.

The approach is currently being employed in reaction systems of ethylene oxychlorination and methanol oxidation to formaldehyde. An understanding of mechanisms and processes on many levels has been gained, including the atomic insights of the active sites and elementary steps of the reactions, understanding the details of the atomic structure of the active sites of CuCl₂, the interaction between the CuCl₂ and the alumina surfaces, as well as the effects of alkali and/ or rare earth promoters on the CuCl₂ reduction and CuCl oxidation in ethylene oxychlorination.

UHV STM of oxidized PtRh alloy prepared on Rh(111) and Pt(111) surfaces. Low energy electron diffraction images in the insets show long and short range ordered structures observed in each case. Activity 2.

Cluster-Size-dependent Eads,C₂H₄ and inserted adsorption configurations at CuCl₂ and (CuCl₂)₃/γ-Al₂O₃ (110).

Adsortion energy of ethylene as a function of formation energy of Cl vacancy on (CuCl₂)₄/γ-Al₂O₃ (110) and the mapping of the ΔeV of all the Cl atoms on (CuCl₂)₄/γ-Al₂O₃ (inserted figure).
Anodization of 3D Printed Titanium for Photocatalysis (PHOTO-3D)

SINTEF Work, WP 6.4:
Titanium dioxide (TiO₂) is a common material for photocatalysis due to its high efficiency, low cost, chemical inertness and high photostability. Highly ordered, vertically oriented arrays of TiO₂ nanotubes can be prepared on a Ti substrate by electrochemical anodization. The use of TiO₂ nanotubes generally offers a larger surface area compared to nanoparticles, as well as channels for enhanced electron transfer. The TiO₂ nanotubes also have high adsorption capacity and efficient charge separation can be achieved, which reduces the efficiency loss due to recombination of photogenerated electrons and holes.

The main idea of this project is to produce an advanced photocatalyst by combining the concept of 3D printing and anodization of titanium (Ti), and to prove its activity towards water cleaning and water splitting under solar illumination (figure below).

Many literature reports are based on anodization of Ti foils, whereas here we use 3D printed Ti structures as substrates for the anodization. The benefit of using 3D printing in the design of a photocatalytic reactor or electrode is that the structure can be computer-designed to satisfy multiple criteria. We can optimize the 3D structures of the photocatalytic reactors to substantially increase the surface area/volume accessible to the light, compared to what is possible with conventional photocatalytic reactors and yielding a crucial improvement in the efficiency of the photocatalysts.

The figure below illustrates some selected electrode designs that have been successfully 3D printed and anodized. When working with 3D printed materials, factors such as material roughness and alloying elements, as well as the lower accessibility of the surface to be anodized, affect the anodization process. This requires the development of new photocatalyst preparation methodologies. The next step in this project is to test these photocatalysts in wastewater treatment and water splitting.
Two new PhDs

Candidate: Ata ul Rauf Salman  
Date of defense: December 6, 2019  
Title of thesis: Catalytic oxidation of NO to NO2 for nitric acid production  
Public trial lecture: Nitrogen fixation beyond Haber-Bosch – recent developments in heterogeneous catalysis and electrocatalysis  
The Committee:  
First opponent: Professor Lars J. Pettersson, KTH, Sweden  
Second opponent: Dr. Sang Baek Shin, Yara Technology Centre, Porsgrunn  
Administrator: Professor Hilde J Venvik, NTNU  
Supervisor: Professor Magnus Rønning, NTNU  
Co-supervisors: Rune Lødeng, SINTEF, Bjørn C. Enger, SINTEF  
ICSI project: 21st century Ammonia Oxidation and Nitric Acid technology development.  
Industry partner: YARA  
Current Position: Equinor, Herøya

Candidate: Dimitrios Papas  
Date of defense: December 13, 2019  
Title of thesis: Direct methane to methanol conversion over Cu-exchanged zeolites: Building structure - activity relationships  
Public trial lecture: Overview of catalysts for methanol synthesis from carbon dioxide – structure to property relations  
The Committee:  
First opponent: Professor Jeroen A. van Bokhoven, ETH Zürich, Switzerland  
Second opponent: Assistant Professor Chris Paolucci, University of Virginia  
Administrator: Professor Ola Nilsen, UiO  
Supervisor: Professor Stian Svelle, UiO  
Co-supervisors: Pablo Beato, Haldor Topsøe, Professor Unni Olsbye, UiO  
ICSI project: The next step in direct activation of lower alkanes  
Industry partner: Haldor Topsoe AS  
Current Position: CorrTek Membrane Science, Oslo

The current work aims to replace the homogenous reaction in the Ostwald process from 1902 with a more compact heterogeneous catalytic process for producing nitric acid. This is done by finding efficient catalysts for oxidation of NO to NO$\textsubscript{2}$ at conditions relevant to nitric acid plants, enabling significant process intensification of the production plant. Additionally, the aim was to gain fundamental understanding of reaction kinetics and the mechanism of oxidation of NO over promising catalysts. Further details in the current work and results are described on page 31 under the Scientific Activities in IIA1.

The direct conversion of methane to added value chemicals, in particular methanol, is a topic intensively researched by the academia and the industry due to large environmental and economic benefits. Such a process could provide an alternative to the capital- and energy-intensive syngas route for methanol synthesis as well as contribute in reducing methane flaring. To this end, different catalytic processes have been investigated over the past decades.

In this thesis, copper-loaded zeolites are investigated for the direct conversion of methane to methanol. Zeolites, which have numerous applications in catalysis, are microporous aluminosilicates with defined structures able to host active metal centres. The conversion of methane to methanol over copper-exchanged zeolites is a stepwise process. Initially the material is pre-treated in oxygen at high temperature, then methane activation takes place at a lower temperature, and finally methanol is extracted by hydrolysis of the stabilized intermediate. Different copper-exchanged zeolites have been investigated, including chabazite, ferrierite and mordenite, aiming to understand the mechanism of the conversion as well as the fundamental properties of the materials. These are achieved by combining activity measurements with in-situ and operando characterization techniques and establishing structure activity relationships.
iCSI is an attractive project for international researchers. The 89 master students, PhD candidates, post-docs and guest researchers within or affiliated with iCSI represent 22 countries. Non-Norwegians make up 64% of this group of employees.

In July 2019, SINTEF researcher Ingeborg-Helene Svennum returned after one year as a guest researcher in the group of Professor Manos Mavrikakis at the University of Wisconsin-Madison College of Engineering.

Overview of international collaborations:

Universities and Institutes

- Aalto University, Finland
- Anna University, Department of Chemistry, Chennai, India
- Bulgarian academy of Science, Bulgaria
- Cardiff University, United Kingdom
- Chalmers University of Technology, Sweden
- CNR, Italy
- Dalian Institute of Chemical Physics, Chinese Academy of Sciences, China
- Delft University of Technology, Netherlands
- Durham University, United Kingdom
- East China University of Science and Technology, China
- ECN, Netherlands
- European Research Institute of Catalysis A.I.S.B.L., Belgium
- Ghent University, Belgium
- Institut de Recherches sur la Catalyse et l'Environnement de Lyon, CNRS, France
- Instituto Nacional del Carbon, INCAR-CSIC, IMDEA Energy Institute, Spain.
- Karlsruhe Institute of Technology – KIT, Germany
- KAUST, Saudi Arabia
- Kemijski Institut (NIK), Slovenia
- Leiden University, Netherlands
- Linné University, Sweden
- Lund University, Sweden
- MAX IV Laboratory, Lund, Sweden
- National University of Science and Technology, Pakistan
- Paul Sherrer Institut, Schweiz
- Politecnico di Milano, Italy
- Politecnico di Milano, Italy
- Royal Institute of Technology (KTH), Sweden
- School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, China
- Shanghai Institute of Applied Physics, China
- Shanxi Institute of Coal Chemistry, Chinese Academy of Sciences, (ICC), China
- Sarbonne University, France
- Stanford University, California, USA
- Swiss-Norwegian Beamlines at ESRF, France
- Technical University of Denmark, Denmark
- Technische Universiteit Eindhoven, Netherlands
- Tianjin University, China
- University of California, Berkeley, USA
- University of Cape Town, South Africa
- University of Duisburg-Essen, Germany
- University of Porto, Portugal
- University of Sheffield, United Kingdom
- University of Wisconsin-Madison, USA
- University of Torino, Italy
- Utrecht University, Netherlands

Companies

- Arkema France SA, France
- Asociacion Espanol de Normalizacion, Spain
- B.T.G. BV, Netherlands
- Borealis, Austria
- BTG-BTL, Belgium
- C2P2, Lyon (CNRS)
- Compania Espanola de Petroleos, Spain
- DOW chemicals
- ENI S.p.a., Italy
- Fundacio EURECAT, Spain
- GE Healthcare, Norway
- Holol Topsoe AS, Denmark
- Johnson Matthey, UK
- Linde, Germany
- Perstorp AB, Sweden
- Processi Innovativi SRL, Italy
- ProfMOF AS, Norway
- Repsol SA, Spain
- SABIC, Saudi Arabia
- SICAT Sarl, France
- STI, Finland
- Steeper, Denmark
- Strane Innovations SAS, France
- Tata Steel UK Limited
- Turkiye Petrol Rafinerileri Anonim Sirketi (Tüpras),
- UOP LLC
- Velocys, USA
- VTT, Finland
European research projects


Research Council of Norway (RCN) projects with international collaborations


MBCL - Moving Bed Carbonate Looping. CLIMIT-supportedd (Gassnova). Owned by FTG (fjell Technology Group), iCSI Partners involved: NTNU, SINTEF, International partner: Southeast University, China. Duration 2017-202x


NanoCat4Fuels - Production of JP-8 Range Fuels and Chemicals from Pyrolysis Bio-Oil using Nanostructured Catalyst. Indo-Norwegian initiative on renewable fuels and chemicals within the Bioinar and EnergiX work program. iCSI Partners involved: SINTEF, International partner: Anna University, Department of Chemistry, Chennai, India. Duration 2018 – 2021

Accounts 2019

Table 1 summarizes the costs in 2019 and the total budget for the period of the Centre after revision in January 2020. The different cost codes concern respectively:

- NTNU costs in Payroll and indirect expenses
- Other research partners (SINTEF and UiO) in Procurement of R&D services
- Equipment code includes rent of research equipment acquired to serve needs for the SFI
- Other operating expenses regroups mainly research at industrial partners

<table>
<thead>
<tr>
<th>Cost code</th>
<th>Costs 2019, kNOK</th>
<th>2015-2023 Total budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payroll and indirect expenses</td>
<td>7 792</td>
<td>59 413</td>
</tr>
<tr>
<td>Procurement of R&amp;D services</td>
<td>11 169</td>
<td>92 378</td>
</tr>
<tr>
<td>Equipment</td>
<td>902</td>
<td>7 305</td>
</tr>
<tr>
<td>Other operating expenses</td>
<td>4 917</td>
<td>34 078</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>24 780</strong></td>
<td><strong>193 174</strong></td>
</tr>
</tbody>
</table>

Table 2 presents the cost and financing per partner. The industrial partners are Yara ASA, Dynea AS, INOVYN AS, KA. Rasmussen AS and Haldor Topsoe AS.

<table>
<thead>
<tr>
<th>Cost and Financing per partner</th>
<th>2019 Accounts</th>
<th>2015-2023 Total budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>NTNU</td>
<td>10 137</td>
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<tr>
<td>University of Oslo</td>
<td>6 378</td>
<td>49 543</td>
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<tr>
<td>SINTEF</td>
<td>4 792</td>
<td>7 858</td>
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<tr>
<td>Industrial partners</td>
<td>3 475</td>
<td>49 543</td>
</tr>
<tr>
<td>Research Council of Norway</td>
<td>-</td>
<td>96 000</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>24 780</strong></td>
<td><strong>193 174</strong></td>
</tr>
</tbody>
</table>

Table 3 presents the costs per Industrial Innovation Area (IIA). The iCSI Management and administration include the overall administration of the Centre (Director, Coordinator and Economy advisor, meetings, seminars, SAC compensation and expenses, international exchange funding).

<table>
<thead>
<tr>
<th>Industrial Innovation Area (IIA)</th>
<th>Costs 2019</th>
<th>2015-2023 Total budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIA1 21st century Nitric Acid technology development</td>
<td>3 783</td>
<td>36 648</td>
</tr>
<tr>
<td>IIA2 New NOx abatement technologies</td>
<td>621</td>
<td>7 574</td>
</tr>
<tr>
<td>IIA3 Frontier formalin technology development</td>
<td>2 800</td>
<td>22 907</td>
</tr>
<tr>
<td>IIA4 PVC Value Chain</td>
<td>4 692</td>
<td>31 027</td>
</tr>
<tr>
<td>IIA5 The next step in direct activation of methane</td>
<td>4 067</td>
<td>34 492</td>
</tr>
<tr>
<td>IIA6 Generic projects</td>
<td>6 980</td>
<td>36 323</td>
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<tr>
<td>IIA7 2020 Catalysis</td>
<td>-</td>
<td>7 495</td>
</tr>
<tr>
<td>ICSI Management and administration</td>
<td>1 838</td>
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</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>24 780</strong></td>
<td><strong>193 174</strong></td>
</tr>
</tbody>
</table>

*In all tables above values appear in 1000 NOK (as per January 2020 10 NOK are equivalent to 1€)
# Education

## Postdoctoral fellows with financial support from iCSI in 2019

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>Years</th>
<th>Gender</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yanying Qi</td>
<td>NTNU</td>
<td>China</td>
<td>2016-2020</td>
<td>F</td>
<td>IIA6</td>
</tr>
<tr>
<td>Oleksii Ivashenko</td>
<td>UiO</td>
<td>Ukraine</td>
<td>2016-2020</td>
<td>M</td>
<td>IIA1/IIA6</td>
</tr>
<tr>
<td>Yalan Wang</td>
<td>NTNU</td>
<td>China</td>
<td>2019-2021</td>
<td>F</td>
<td>IIA4</td>
</tr>
</tbody>
</table>

### Yalan Wang

One new postdoctoral fellow was welcomed in 2019, Yalan Wang joined ICSI in May. She finalized her PhD in the Catalysis group at Department of Chemical Engineering, NTNU, in March 2019.

## 2019 PhD candidates with financial support from iCSI

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>Years</th>
<th>Gender</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ata ul Rauf Salman</td>
<td>NTNU</td>
<td>Pakistan</td>
<td>2015-2019</td>
<td>M</td>
<td>IIA1</td>
</tr>
<tr>
<td>Dimitrios Pappas</td>
<td>UIO</td>
<td>Greece</td>
<td>2016-2019</td>
<td>M</td>
<td>IIA5</td>
</tr>
<tr>
<td>Endre Fenes(^1)</td>
<td>NTNU</td>
<td>Norway</td>
<td>2015-2020</td>
<td>M</td>
<td>IIA4</td>
</tr>
<tr>
<td>Samuel Regli</td>
<td>NTNU</td>
<td>Switzerland</td>
<td>2016-2020</td>
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<td>IIA6</td>
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<td>Stine Lervold</td>
<td>NTNU</td>
<td>Norway</td>
<td>2016-2020</td>
<td>F</td>
<td>IIA3</td>
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<tr>
<td>Asbjørn Slagtern Fjellvåg</td>
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<td>Norway</td>
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<tr>
<td>Hongfei Ma</td>
<td>NTNU</td>
<td>China</td>
<td>2017-2020</td>
<td>M</td>
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<tr>
<td>Moses Mawanga</td>
<td>NTNU</td>
<td>Uganda</td>
<td>2018-2021</td>
<td>M</td>
<td>IIA6</td>
</tr>
<tr>
<td>Karoline Kvande</td>
<td>UIO</td>
<td>Norway</td>
<td>2019-2021</td>
<td>F</td>
<td>IIA5</td>
</tr>
<tr>
<td>Julie Hessevik</td>
<td>UIO</td>
<td>Norway</td>
<td>2019-2023</td>
<td>F</td>
<td>IIA1</td>
</tr>
</tbody>
</table>

\(^1\) Endre Fenes left ICSI in 2019 for a job in the industry, and his defense is delayed.

## 2019 PhD candidates in ICSI with financial support from other sources,

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>Years</th>
<th>Gender</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bjørkedal, Ole H.</td>
<td>NTNU</td>
<td>Norway</td>
<td>2016-2020</td>
<td>M</td>
<td>Selective catalytic reduction (SCR) of NO(_x) emissions in maritime transport.</td>
</tr>
<tr>
<td>Muhammad Zubair</td>
<td>NTNU</td>
<td>Pakistan</td>
<td>2017-2020</td>
<td>M</td>
<td>Enhanced visible light adsorption TiO(_2) based catalysts for photocatalytic H(_2) production</td>
</tr>
<tr>
<td>Martina Cazzolano</td>
<td>NTNU</td>
<td>Italy</td>
<td>2017-2020</td>
<td>F</td>
<td>Cu/CNF for selective hydrogenation of hydroxyacetone to 1,2-propanediol</td>
</tr>
<tr>
<td>Joakim Tafjord</td>
<td>NTNU</td>
<td>Norway</td>
<td>2017-2020</td>
<td>M</td>
<td>Iron-based Fischer Tropsch synthesis based on renewable feedstocks</td>
</tr>
<tr>
<td>Jianyu Ma</td>
<td>NTNU</td>
<td>China</td>
<td>2017-2020</td>
<td>M</td>
<td>Chemical looping desulphurization</td>
</tr>
<tr>
<td>Mario Ernesto Casa-legno</td>
<td>NTNU</td>
<td>Spain</td>
<td>2018-2022</td>
<td>M</td>
<td>Catalyst for onboard hydrogen generation from bioethanol</td>
</tr>
<tr>
<td>Jibin Antony</td>
<td>NTNU</td>
<td>India</td>
<td>2018-2021</td>
<td>M</td>
<td>Nanostructured hybrid catalysts for photocatalytic applications</td>
</tr>
<tr>
<td>Ask Lysne</td>
<td>NTNU</td>
<td>Norway</td>
<td>2019-2022</td>
<td>M</td>
<td>Staging and Multiple Hydrogen Feed of Biomass to Fischer-Tropsch Fuel Synthesis</td>
</tr>
<tr>
<td>Dumitrita Spinu</td>
<td>NTNU</td>
<td>Romania</td>
<td>2019-2022</td>
<td>F</td>
<td>Low temperature CO(_2) capture</td>
</tr>
<tr>
<td>Junbo Yu</td>
<td>NTNU</td>
<td>China</td>
<td>2019-2022</td>
<td>M</td>
<td>Hydrogen membrane separation technology</td>
</tr>
<tr>
<td>Magnus Mortén</td>
<td>UiO</td>
<td>Norway</td>
<td>2015-2019</td>
<td>M</td>
<td>Acid strength of metal substituted aluminium phosphates</td>
</tr>
<tr>
<td>Emil S. Gutterød</td>
<td>UiO</td>
<td>Norway</td>
<td>2016-2019</td>
<td>M</td>
<td>On the kinetics and confinement effects of partial methane oxidation over Cu-MOFs</td>
</tr>
<tr>
<td>Volodymyr Levchenko</td>
<td>UiO</td>
<td>Ukraine</td>
<td>2016-2020</td>
<td>M</td>
<td>Au-based catalysts for C-C and C-X couplings</td>
</tr>
<tr>
<td>Giuseppe Rotunno</td>
<td>UiO</td>
<td>Italy</td>
<td>2016-2019</td>
<td>M</td>
<td>Autocatalysis and chiral amplification in metal organic frameworks</td>
</tr>
<tr>
<td>Mustafa Kemurcu</td>
<td>UiO</td>
<td>Norway</td>
<td>2017-2020</td>
<td>M</td>
<td>Ethene oligomerization</td>
</tr>
<tr>
<td>Martin Jensen</td>
<td>UiO</td>
<td>Norway</td>
<td>2018-2022</td>
<td>M</td>
<td>Materials for catalytic oxidation of ammonia</td>
</tr>
</tbody>
</table>
### 2019 International exchange PhD candidates and visiting researchers, NTNU and UiO

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Gender</th>
<th>Duration</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weixin Qian</td>
<td>East China University of Science and Technology</td>
<td>M</td>
<td>8 mths</td>
<td>The mechanistic and kinetic study of CO and CO2 hydrogenation to chemicals and fuel</td>
</tr>
<tr>
<td>Xiaoli Yang</td>
<td>Dalian Institute of Chemical Physics</td>
<td>F</td>
<td>8 mths</td>
<td>The conversion of syngas to liquid hydrocarbons with OX-ZEO process</td>
</tr>
<tr>
<td>Nianju Hou</td>
<td>Tianjin University</td>
<td>F</td>
<td>12 mths</td>
<td>Ethanol fuel cells and also the ORR catalysts for fuel cells</td>
</tr>
<tr>
<td>Gang Wang</td>
<td>East China University of Science and Technology</td>
<td>M</td>
<td>3 mths</td>
<td>Oxidation of propene to propene oxide with gold catalyst</td>
</tr>
<tr>
<td>Wenzhao Fu</td>
<td>East China University of Science and Technology</td>
<td>M</td>
<td>2 mths</td>
<td>Redox catalytic cycle of VOC oxidation and ethylene epoxidation</td>
</tr>
<tr>
<td>Hao Zhang</td>
<td>Shanghai Institute of Applied Physics</td>
<td>M</td>
<td>2 mths</td>
<td>XAS study of nanoclusters in electrochemical reaction</td>
</tr>
<tr>
<td>Silvia Bordiga</td>
<td>University of Turin</td>
<td>F</td>
<td>1 mth</td>
<td>Spectroscopic investigations of porous materials</td>
</tr>
<tr>
<td>Tommaso Selleri</td>
<td>Department of Energy, Politecnico di Milano</td>
<td>M</td>
<td>1 mth</td>
<td>Operando UV-vis measurement on Cu-CHA catalysts</td>
</tr>
<tr>
<td>Lukasz Kuterasinski</td>
<td>Jerzy Haber Inst.of Cat. and Surf. Chemistry, Polish Ac.of Sciences</td>
<td>M</td>
<td>2 weeks</td>
<td>Conversion of methanol to hydrocarbons over hierarchical zeolite catalysts</td>
</tr>
</tbody>
</table>

### 2019 Postdoctoral researchers working on projects in iCSI with financial support from other sources, NTNU and UiO

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Country</th>
<th>Duration</th>
<th>Project Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen, Qingjun</td>
<td>NTNU</td>
<td>China</td>
<td>2015-2019</td>
<td>First principles modeling of Co based FTS catalysts</td>
</tr>
<tr>
<td>Jørgen Svendby</td>
<td>NTNU</td>
<td>Norway</td>
<td>2017-2019</td>
<td>Designing new renewable nanostructured electrode and membrane materials for direct alkaline ethanol fuel cell</td>
</tr>
<tr>
<td>Xiang Feng</td>
<td>NTNU</td>
<td>China</td>
<td>2017-2019</td>
<td>Catalytic pyrolysis of biomass towards olefin production</td>
</tr>
<tr>
<td>Strømsheim, Marie Davre</td>
<td>NTNU</td>
<td>Norway</td>
<td>2018-2020</td>
<td>Surface chemistry and segregation phenomena of PdAlloy membranes</td>
</tr>
<tr>
<td>Gavrilovic Ljubisa</td>
<td>NTNU</td>
<td>Serbia</td>
<td>2018-2020</td>
<td>Bio Fischer-Tropsch (BioFT) Staging and Multiple Hydrogen. Feed of Biomass to Fischer-Tropsch Fuel Synthesis</td>
</tr>
<tr>
<td>Zhenping Cai</td>
<td>NTNU</td>
<td>China</td>
<td>2018-2020</td>
<td>Conversion of lignocellulosic wastes into biofuels and bioplastics</td>
</tr>
<tr>
<td>Ainara Moral</td>
<td>NTNU</td>
<td>Spain</td>
<td>2018-2020</td>
<td>MBCL project</td>
</tr>
<tr>
<td>Yuanwei Zhang</td>
<td>NTNU</td>
<td>China</td>
<td>2018-2019</td>
<td>MBCL project – simulation work</td>
</tr>
<tr>
<td>Suresh Balasingam</td>
<td>NTNU</td>
<td>India</td>
<td>2018-2020</td>
<td>Energy storage by high energy supercapacitors</td>
</tr>
<tr>
<td>Irene Panela Herrero</td>
<td>UIO-Katalyse</td>
<td>Spain</td>
<td>2017-2020</td>
<td>Production of aromatics from methanol via metal-exchanged zeolites</td>
</tr>
<tr>
<td>Andrea Lazzarini</td>
<td>UIO-Katalyse</td>
<td>Italy</td>
<td>2017-2019</td>
<td>Detailed characterization of complexes and nanostructured materials</td>
</tr>
</tbody>
</table>
**Autumn 2019 Specialization projects students**

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Gender</th>
<th>Project Description</th>
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</thead>
<tbody>
<tr>
<td>Ingvill Andrea Ræd</td>
<td>Norway</td>
<td>F</td>
<td>Low temperature selective hydrogenation using noble metal catalysts</td>
</tr>
<tr>
<td>Petter Tingelstad</td>
<td>Norway</td>
<td>M</td>
<td>Biomass conversion to fuels / Oxidation, autoclave, catalyst</td>
</tr>
<tr>
<td>Kishore Rajendran</td>
<td>India</td>
<td>M</td>
<td>Biomass conversion to chemical / Fixed bed reactor, ethanol</td>
</tr>
<tr>
<td>Oscar I. Encinas</td>
<td>Spain</td>
<td>M</td>
<td>High temperature CO₂ capture / combustion - fixed bed</td>
</tr>
<tr>
<td>Maren W. Kveinå</td>
<td>Norway</td>
<td>F</td>
<td>CO₂ emission reduction by CO to carbon / CNF - Fixed bed</td>
</tr>
<tr>
<td>Yun Liu</td>
<td>South Korea</td>
<td>F</td>
<td>Low temperature CO₂ capture / TGA</td>
</tr>
<tr>
<td>Jithin Gopakumar</td>
<td>India</td>
<td>M</td>
<td>Ethylene oxychlorination on Cu based catalysts</td>
</tr>
<tr>
<td>Hammad Farooq</td>
<td>Pakistan</td>
<td>M</td>
<td>Carbon formation and catalysis in the conversion of methyl chloride and silicon into dimethylchlorosilane</td>
</tr>
<tr>
<td>Jørgen L. Grinna</td>
<td>Norway</td>
<td>M</td>
<td>Low temperature CO₂ capture by solid sorbents</td>
</tr>
<tr>
<td>Vilde Vennes Jacobsen</td>
<td>Norway</td>
<td>F</td>
<td>Production of olefins from waste plastics</td>
</tr>
<tr>
<td>Susanne K. Stokkevåg</td>
<td>Norway</td>
<td>F</td>
<td>Oxidation of methanol to formaldehyde (MTF) over Ag catalysts</td>
</tr>
<tr>
<td>Anne Charlotte G. Wold</td>
<td>Norway</td>
<td>F</td>
<td>Kinetic study of processes for high temperature CO₂ capture by solid sorbents</td>
</tr>
<tr>
<td>Jon Arve Selnes</td>
<td>Norway</td>
<td>M</td>
<td>Catalytic methane abatement for natural gas engines</td>
</tr>
<tr>
<td>Eirik Søreide Hansen</td>
<td>Norway</td>
<td>M</td>
<td>Hydrogen production from biomass derived compounds by sorption enhanced reforming</td>
</tr>
<tr>
<td>Julie Christine Claussen</td>
<td>Norway</td>
<td>F</td>
<td>Polymers Assisted Preparation of Iron based Fischer-Tropsch Catalysts for biomass to fuel</td>
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**Spring 2019 Master thesis in Chemical engineering (NTNU) or Chemistry (UiO) associated with ICSI**

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Gender</th>
<th>Project Description</th>
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</thead>
<tbody>
<tr>
<td>Galina T. Yavasheva</td>
<td>Bulgaria</td>
<td>F</td>
<td>Synthesis and characterization of bimetallic nanoparticles for selective catalytic conversion of ammonia</td>
</tr>
<tr>
<td>Mia Bodenhoff1)</td>
<td>Denmark</td>
<td>F</td>
<td>Combined experimental, spectroscopic, and theoretical mechanistic investigations</td>
</tr>
<tr>
<td>Dumitrut Spinu</td>
<td>Moldavia</td>
<td>F</td>
<td>Production of Fuels from Lignin by Fast Hydropyrolysis with Coupled Catalytic Upgrading</td>
</tr>
<tr>
<td>Minadir Saracevic</td>
<td>Norway</td>
<td>M</td>
<td>Efficient catalysts for achieving NO /NO₂ equilibrium</td>
</tr>
<tr>
<td>Martin Meuche</td>
<td>Norway</td>
<td>M</td>
<td>Perovskite catalysts study by MS and FTIR</td>
</tr>
<tr>
<td>Lisa L. Landfall</td>
<td>Norway</td>
<td>F</td>
<td>New catalysts for low-temperature selective catalytic reduction (SCR)</td>
</tr>
<tr>
<td>Kristiane S. Oftebro</td>
<td>Norway</td>
<td>F</td>
<td>Photocatalytic Ammonia Synthesis</td>
</tr>
<tr>
<td>Erik A. Jørgensen</td>
<td>Norway</td>
<td>M</td>
<td>Fischer-Tropsch Synthesis: Conversion of Bio-Syngas to Hydrocarbons</td>
</tr>
<tr>
<td>Abdul R. Toutounji</td>
<td>Lebanon</td>
<td>M</td>
<td>Carbon formation and catalysis in the conversion of methyl chloride and silicon into dimethylchlorosilane</td>
</tr>
<tr>
<td>Fatemeh Khodadady</td>
<td>Qatar</td>
<td>F</td>
<td>Process design and evaluation of CO₂ capture on solid sorbents</td>
</tr>
<tr>
<td>Siyu Wang</td>
<td>China</td>
<td>F</td>
<td>Synthesis of low temperature sorbents for CO₂ capture</td>
</tr>
<tr>
<td>Tho Ba Tran</td>
<td>Norway</td>
<td>M</td>
<td>Kinetic study of ethylene oxychlorination on promoted CuCl₂/Al₂O₃ catalysts</td>
</tr>
</tbody>
</table>

1) Mia Bodenhoff was a student at DTU, performing her master in collaboration with Haldor Topsøe and IIA5

**2019 International exchange bachelor or master students, NTNU and UiO**

<table>
<thead>
<tr>
<th>Name</th>
<th>Country</th>
<th>Gender</th>
<th>Project Description</th>
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<tbody>
<tr>
<td>Angelo Bella</td>
<td>Italy</td>
<td>M</td>
<td>Synthesis of titanium free mordenite zeolites for the direct conversion of methane to methanol</td>
</tr>
<tr>
<td>Alizée Bataille</td>
<td>France</td>
<td>F</td>
<td>Production of H₂ using red mud</td>
</tr>
<tr>
<td>Christian Maier</td>
<td>Germany</td>
<td>M</td>
<td>Catalytic methane abatement for natural gas engines</td>
</tr>
<tr>
<td>Asma Hayoune</td>
<td>Algeria</td>
<td>F</td>
<td>Photocatalytic H₂ production</td>
</tr>
<tr>
<td>Henrik Schuster</td>
<td>Germany</td>
<td>M</td>
<td>Catalytic Methane Abatement for Natural Gas Engines</td>
</tr>
<tr>
<td>Constance Debionne</td>
<td>France</td>
<td>F</td>
<td>Polymers Assisted Preparation of Iron based Fischer-Tropsch Catalysts for biomass to fuel</td>
</tr>
<tr>
<td>Philip Walter Putze</td>
<td>Germany</td>
<td>M</td>
<td>Methodology Development for the Characterization of Contact Mass in the Direct Process</td>
</tr>
</tbody>
</table>

1) Mia Bodenhoff was a student at DTU, performing her master in collaboration with Haldor Topsøe and IIA5
iCSI Publications and conference contributions 2019

IIA1: 21st Century Ammonia Oxidation and Nitric Acid Technology Development
Journal Publications
Bundu, Silje; Hok, Prasanta; Jensen, Martin; Gunnars, Anette Eleonor; Nguyen, Phuong Dan; Fjellvåg, Helmer; Sjåstad, Anja Olsøsen: Controlled alloying of Pt-Rh nanoparticles by the polyol approach. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

Fjellvåg, Asbjørn Slagtern; Waller, David; Skjelstad, Johan; Sjåstad, Anja Olsøsen: Ni- and Pd-Grain Reconstruction of PdNi alloys. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

Kumar, Susmit; Waller, David; Fjellvåg, Helmer; Sjåstad, Anja Olsøsen: Development of custom-made bimetallic alloy model systems based on platinum-rhodium for heterogeneous catalysis. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

Fjellvåg, Asbjørn Slagtern; Waller, David; Skjelstad, Johan; Sjåstad, Anja Olsøsen: Ni- and Pd-Grain Reconstruction of PdNi alloys. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

Fjellvåg, Asbjørn Slagtern; Waller, David; Skjelstad, Johan; Sjåstad, Anja Olsøsen: Ni- and Pd-Grain Reconstruction of PdNi alloys. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

IIA3: Frontier Formalin Technology Development
Journal Publications
Lervold, Stine; Arnesen, Kamilla; Beck, Nikolas; Ladeng, Rune; Yang, Jia; Birger, Kristin; Skjelstad, Johan; Venvik, Hilde Johnson: Morphology and Activity of Electrocatalytic Silver Catalyst for Partial Oxidation of Methanol to Formaldehyde Under Different Exposures and Oxidation Reactions. Topics in catalysis 2019; Volume 62.(7-11) s. 699-711

IIA4: PVC Value Chain: World Class Energy and Raw Material Efficiency for the Production of Chlorine and Vinyl Chloride Monomer (VCM)
Journal Publications
Wang, Yang; Wang, Hongjin; Dam, Anh Hoang; Xiao, Ling; Qi, Yangyang; Liu, Ji; Yang, Jia; Zhi, Yi-An; Holmen, Anders; Chen, De: Understanding effects of Ni particle size on steam methane reforming activity by combined experimental and theoretical analysis. Catalysis Today 2019 s. 1-9

IIA4: PVC Value Chain: World Class Energy and Raw Material Efficiency for the Production of Chlorine and Vinyl Chloride Monomer (VCM)
Journal Publications
Wang, Yang; Wang, Hongjin; Dam, Anh Hoang; Xiao, Ling; Qi, Yangyang; Liu, Ji; Yang, Jia; Zhi, Yi-An; Holmen, Anders; Chen, De: Understanding effects of Ni particle size on steam methane reforming activity by combined experimental and theoretical analysis. Catalysis Today 2019 s. 1-9

Oral Presentations
Kumar Rout, Terje Fuglerud, Marco Piccinini, Endre Fenes, Hongfei Ma, De Chen: Alkali Metal Doping of Ethylene Oxidation Catalysts: Kinetics and Descriptors. Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

Kumar, Rout; Ver, Rune; Ladeng, Nikolas; Skjelstad, Johan; Yang, Jia; Birger, Kristin; Skjelstad, Johan; Venvik, Hilde Johnson: Morphology and Activity of Electrocatalytic Silver Catalyst for Partial Oxidation of Methanol to Formaldehyde Under Different Exposures and Oxidation Reactions. Topics in catalysis 2019; Volume 62.(7-11) s. 699-711


Oral Presentations
Kumar Rout, Terje Fuglerud, Marco Piccinini, Endre Fenes, Hongfei Ma, De Chen: Insights into potassium promoter effects on Cu/Co Catalysts for reactions relevant to thermal cycling of methanol to formaldehyde (MTR). Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

Oral Presentations
Kumar Rout, Terje Fuglerud, Marco Piccinini, Endre Fenes, Hongfei Ma, De Chen: Insights into potassium promoter effects on Cu/Co Catalysts for reactions relevant to thermal cycling of methanol to formaldehyde (MTR). Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

Formaldehyde Under Different Exposures and Oxidation Reactions. Topics in catalysis 2019; Volume 62.(7-11) s. 19269-19280

Ma, Hongfei; Fenes, Endre; Qi, Yangyang; Rout, Kumar Ranjan; Fuglerud, Terje; Chen, De: Kinetic Analysis and Design of Catalytic Redox Cycles in Ethylene Oxidation. Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

IIA3: Frontier Formalin Technology Development
Journal Publications
Lervold, Stine; Arnesen, Kamilla; Beck, Nikolas; Ladeng, Rune; Yang, Jia; Birger, Kristin; Skjelstad, Johan; Venvik, Hilde Johnson: Morphology and Activity of Electrocatalytic Silver Catalyst for Partial Oxidation of Methanol to Formaldehyde Under Different Exposures and Oxidation Reactions. Topics in catalysis 2019; Volume 62.(7-11) s. 699-711

Oral Presentations
Kumar Rout, Terje Fuglerud, Marco Piccinini, Endre Fenes, Hongfei Ma, De Chen: Alkali Metal Doping of Ethylene Oxidation Catalysts: Kinetics and Descriptors. Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

Ma, Hongfei; Fenes, Endre; Qi, Yangyang; Rout, Kumar Ranjan; Fuglerud, Terje; Chen, De: Kinetic Analysis and Design of Catalytic Redox Cycles in Ethylene Oxidation. Eurocat 2019 14th European Congress on Catalysis; 2019-08-18 - 2019-08-23, Aachen, Germany

IIA: 21st Century Ammonia Oxidation and Nitric Acid Technology Development
Journal Publications
Bundu, Silje; Hok, Prasanta; Jensen, Martin; Gunnars, Anette Eleonor; Nguyen, Phuong Dan; Fjellvåg, Helmer; Sjåstad, Anja Olsøsen: Controlled alloying of Pt-Rh nanoparticles by the polyol approach. Journal of Alloys and Compounds 2019; Volume 779. s. 879-885

Fjellvåg, Asbjørn Slagtern; Waller, David; Skjelstad, Johan; Sjåstad, Anja Olsøsen: Grain Reconstruction of Pt and PdNi Alloys for Platinum Capture. Johnson Matthey Technology Review 2019; Volume 63.(4) s. 236-246

Kumar, Susmit; Waller, David; Fjellvåg, Helmer; Sjåstad, Anja Olsøsen: Development of custom-made bimetallic
The effect of aerosol-deposited ash components on a gas phase reaction on Ni catalyst: Experimental and DFT study. Applied Catalysis B: Environmental 2019; Volume 249. s. 306-315

Ranga, Chanaky, Alexandria Vaios I; Lauwert, Jeroen; Lammertsma, Rune; Thibaut, Joris W: Effect of Co incorporation and support selection on deoxygenation selectivity and stability of (Co)Mo catalysts in anode HDO. Applied Catalysis A: General 2019; Volume 571. s. 61-75

Ruut, Kumar Ranjan; Galietta, Maria Victoria; Chen, De: Highly selective CO removal by sorption enhanced Boudouard reaction for hydrogen production. Catalysis science & technology 2019; Volume 9(15). s. 4100-4107


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THE PEOPLE AT ICSI
Acknowledgements

The authors acknowledge all the contributors to the Annual Report 2019:

Pablo Beato, Haldor Topsøe; Anders Holmen, NTNU; Karoline Kvande and Julie Hessevik, UiO; Stine Lervold, NTNU; IIA leaders: Anja O. Sjåstad, and Stian Svelle, UiO; Jasmina Hafizovic Cavka and Sille Fosse Håkonsen, SINTEF; De Chen and Magnus Renning, NTNU; The authors thanks Ingrid Nuse Translating for proofreading and Benjamin A. Ward for photos at UiO and also other contributors from iCSI to iCSI Moments 2019, as well as Asbjørn Slagtern Fjellvåg for the cover photo. Last, but not least, thanks to Maiken Skogstad and Espen Weemundstad, NTNU Grafisk Senter, for their efforts in making the report presentable.

Authors

Dr. Anne Hoff and Prof. Hilde Johnsen Venvik, NTNU

Design and print

NTNU Grafisk senter att: Maiken Skogstad