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IEAGHG
High Temperature Solid Looping Cycles Network
Combined Meetings Report

IEA GREENHOUSE GAS R&D PROGRAMME

International Energy Agency

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Attendees of the 7th High Temperature Solid Looping Cycles Network Meeting, Luleå, Sweden, September 2017

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Introduction

The IEAGHG High Temperature Solid Looping Cycles Network (HTSLCN) emerged from the preceding International Workshop on In-situ CO_2 Removal (ISCR) and aims at bringing together researchers and developers of CO_2 capture technologies that operate at high temperatures in cyclic processes using either circulating or fixed beds of solids.

The 6th HTSLCN Meeting took place from 1st to 2nd September 2015 at the Department of Energy, Politecnico di Milano, in Italy. It was jointly organised by IEAGHG and Politecnico di Milano. 72 attendees from 19 countries enjoyed a two-day programme with 45 presentations, organised in 8 sessions, and site visits to research facilities at Politecnico di Milano.

The 7th HTSLCN Meeting took place from 4th to 5th September 2017 at Kulturens Hus in Luleå, Sweden, hosted by Swerea MEFOS. 50 attendees enjoyed a two-day programme with 39 presentations and participated in the Grand Opening of the STEPWISE pilot plant.

The 8th HTSLCN Meeting took place from 20th to 21st of January 2020 at Chemelot Industrial Park, in Geleen, The Netherlands, hosted by TNO in collaboration with the CLEANKER and LEILAC projects. 30 attendees enjoyed a two day programme with a total of 16 presentations and a site visit to the LEILAC plant in Lixhe, Belgium.

A potential location for the 9th HTSLCN Meeting in September 2021 is the CLEANKER project in Piacenza/Vernasca.

The following report summarises the main points of discussion and the conclusions from the meetings. The presentations are available for download in the members' area of the HTSLCN on IEAGHG's website.

6th HTSLCN Meeting

1st – 2nd September 2015
Politecnico di Milano, Milan, Italy

Hosted by

POLITECNICO DI MILANO

Summary

The 6th HTSLCN Meeting took place from 1st to 2nd September 2015 at the Department of Energy, Politecnico di Milano, in Italy. 72 attendees from 19 countries enjoyed a two-day programme with 45 presentations, site visits to research facilities at Politecnico di Milano and a stunning dinner at Lake Como.

Two keynotes covered the progress made in calcium and chemical looping technologies respectively in the last decade. The technical sessions provided the latest advances in calcium and chemical looping pilot plant testing, solid carrier fundamentals, system modelling, process and heat integration, and sorption enhanced reforming technologies. Other topics were utilisation of biomass as a fuel, techno-economics of a large-scale packed bed reactor for chemical looping and the application of calcium looping in cement plants. The meeting formally closed with a discussion forum that summarised the main conclusions from the earlier presentations and the most burning issues for the future.

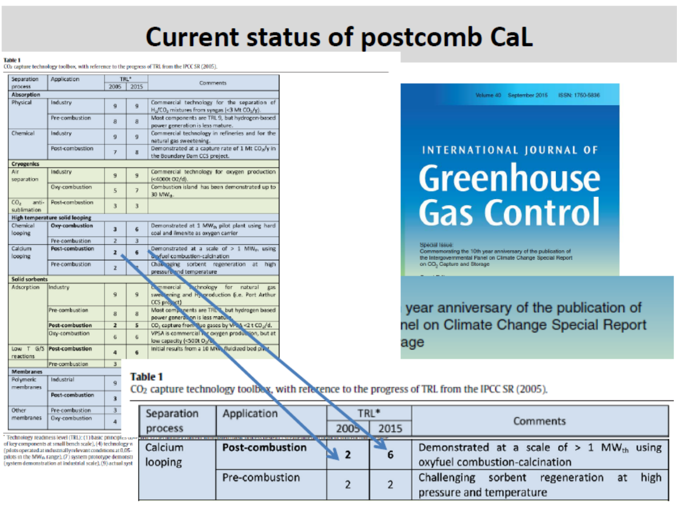
The 7th HTSLCN Meeting will take place from 4th to 5th September 2017 at Swerea MEFOS in Luleå, Sweden.

Welcome and Keynotes

At the beginning, Matteo Romano (Politecnico di Milano) and Jasmin Kemper (IEAGHG) welcomed all participants to the meeting. Then, Giovanni Lozza (Dean of the School of Industrial and Information Engineering at Politecnico di Milano) gave a short welcome speech about the history of the Department of Energy and the importance to move new technologies through to industrial commercialisation, so that they become state-of-the-art. Two keynotes covered the progress made in calcium and chemical looping technologies respectively in the last decade.

Progress on the CaL PCC process, Carlos Abanades (CSIC-INCAR)

The presentation started out with the question “Why post-combustion CO_2 capture by CaL?” and subsequently delivered the answers. Benefits of the CaL process include a relatively cheap sorbent and a lower energy penalty of around 6-8%, as compared to 8-12% for solvent-based PCC processes, and thus a low cost per ton of CO_2 captured. The sorbent, CaO, further offers the potential of integration of the process into a cement plant. Due to the co-capture of SO_2, the flue gas does not require prior desulphurisation and the process in general is very suitable for retrofitting. Thus, interest in this technology is growing, as the ever-increasing number of publications on the topic confirms. Since 2005, CaL has progressed from TRL 2 to 6, with a number of pilot plants now existing that exceed 1 MWth scale and 2000h of operation. Further improvements of the CaL process are possible by improving sorbent activity, reducing heat demand in the calciner and alternative reactor/process designs. Another important takeaway message is that sorbent related issues, such as attrition, are no longer a pitfall for standard CaL processes.



Progress on CLC processes, Tobias Mattisson (Chalmers University)

CLC processes have achieved a similar technology development as CaL, increasing their TRL to 6 since 2005. More than 1000 materials based on Fe, Mn, Ni, Cu and Co have been screened and actual operational experience is now exceeding 7000h and 1 MWth scale. CLC can achieve 100% CO_2 capture and complete gas conversion with gaseous and liquid fuels. However, for solid fuels gas conversion is between 80-95% and CO_2 capture rate below 99%. Several projects, such as $NoCO_2$ and ACCLAIM, investigate CLC with solid fuels and aim to increase the performance of the process. The presentation highlighted many low-cost materials are available for CLC oxygen carriers (OC), e.g. high-concentration Mn oxides, ilmenite and industrial Fe oxide waste materials. Another benefit of CLC is that it relies on state-of-the-art circulating fluidised bed (CFB) design, so common and commercialised technology components. The expected efficiency penalty of CLC is about 4% and the cost of CO2 capture in the range of 16-26 €/tCO_2. Focus should now be on demonstrating cheap materials work in large scale and exploring the potential of chemical looping reforming (CLR) technologies.

CHALMERS

Cost of carbon capture

Type of cost	estimation, €/tonne CO_2	range, €/tonne CO_2	Efficiency penalty, %
CO_2 compression	10	10	3
Oxy-polishing	6.5	4-9	0.5
Boiler cost	1	0.1-2.3	-
Oxygen carrier	2	1.3-4	-
Steam and hot CO_2 fluidization	0.8	0.8	0.8
Coal grinding	0.2	0.2	0.1
Lower air ratio	-0.5	-0.5	-0.5
Total	20	15.9-25.8	3.9

Taken from: Lyngfelt, A.; Leckner, B., "A 1000MWth boiler for chemical-looping combustion of solid fuels-Discussion of design and costs", Applied Energy, 2014, In press.

Session 1: Calcium and chemical looping pilots and tests

Robert Stevens (US DOE NETL) opened this session with presenting work done on coal-based CLC process modelling. For a 550 MWel supercritical pulverised coal (SCPC) power plant with CO_2 capture, using Fe2O3 as an oxygen carrier (OC) resulted in a 13% reduction in cost of electricity (COE), while using CaSO4 could realise a 21% reduction (compared to the reference plant). In addition, $CaSO_4$ offers further cost advantages, as it is a cheap option for an OC.

Alberto Abad (CSIC-ICB) presented results for coal-based CLC in a 50kW unit. Here, two parameters are of great importance: the CO_2 capture efficiency and combustion efficiency. Generally, fuel reactor temperature should be as high as possible. However, there is a trade-off for the solids circulation rate: it should be as low as possible to achieve high capture efficiency but as low as possible to decrease the oxygen demand. The study derived optimal operating conditions and confirmed their feasibility for standard circulating fluidised beds (CFBs).

Jochen Ströhle (TU Darmstadt) showed results from test campaign in a 1 MWth CLC plant that were carried out under the projects ECLAIR and ACCLAIM. During the tests, autothermal CLC operation with ilmenite as OC was achieved. In addition, the experiments showed that using ilmenite as well as co-combustion of torrefied biomass with the coal increased CO_2 capture performance, by 17%-points and 10%-points respectively.

The presentation from Karl Mayer (TU Wien) informed delegates about the results from tests in a 120 kWth CLC pilot plant with different OC materials and over 1000h of run time. The results were used to implement design changes, which led to a slimmer air and fuel reactor, equalised temperatures across both reactors and an improved loop seal. A benchmark campaign with the optimised design confirmed the gas leakage issues of the former design have been resolved and both the CH_4 conversion and CO_2 yield have improved.

Dennis Lu (NRC) presented work done under the PERD programme, which is funded by Natural Resources Canada (NRC). The project investigates the suitability of pressurised CLC (PCLC) using natural gas (NG) as a fuel for steam assisted gravity drainage (SAGD), a process to enhance oil sands and heavy crude oil production. A pinch point analysis successfully identified possibilities for heat transfer, which will be used for process optimisation. The study confirmed that Canadian ilmenite is suitable for PCLC, both in terms of cost and environmental impact. Based on the results of this work, CanmetENERGY will develop a small 200 kWth pilot plant.

Tobias Mattisson (Chalmers University) presented work on the suitability of combined Mn oxides as OC materials for use in CLC and chemical looping with oxygen uncoupling (CLOU). The analysis showed that Mn-Fe-Si carriers likely have a direct reaction as in CLC and that Mn-Mg systems reveal considerable oxygen uncoupling and reactivity, which both increased with the Mg content. As both materials rely on cheap raw materials, they are thus promising for application in CLC and CLOU. The presentation from Matthias Hornberger (IFK) showed results from a 200 kWth pilot plant that aimed to demonstrate CaL for power plant application. The test runs achieved more than 90% CO_2 capture efficiency over a wide range of operating conditions. The next step will be to investigate the feasibility of the process for cement plan integration at pilot scale.

Tadaaki Shimizu (Niigata University) presented insight about the role of nitrogen oxides in coal based CaL processes. Due to the transportation of char from the fuel reactor to the carbonator, formation of NOx and N_2O can occur. However, other reactions might occur simultaneously that could lead to a reduction of these components. Tests in a bench scale dual fluidised bed reactor showed that, overall, presence of char reduced NOx and N_2O in the carbonator. Another finding was that a certain NO concentration in the flue gas exists, below which net NOx formation will occur. Thus, in terms of process design, the SCR/deNOx unit should ideally be located behind the CaL process.

Session 2a Calcium looping fundamentals

Peter Clough (Imperial College London) started this session with a presentation on limestone calcination rates at high partial pressures. The experiments showed that calcination kinetics in the presence of steam are significantly enhanced, as compared to N_2. Reason for the considerably faster calcination in presence of steam is due to the adsorption of H_2O on the active sites, which weakens the bonding between CO_2 and CaO. Modelling of the experimental results showed generally a good match. Prediction of the bed temperature needs to be improved by developing a heat and mass transfer model that accounts for the endothermic reaction.

Peiting Liang (Tsinghua University) presented work on pore size distribution during calcination and the development of a respective rate equation model. The results show that the pore structure of calcined $CaCO_3$ has a bimodal distribution with corresponding average pore sizes of 2.8 nm and 50 nm. The model, which calculates the pore size distribution by using the vacancy rate equation, was generally in good agreement with the experimental results. Future work will use the findings to describe pore size changes during gas-solid reactions.

Stefano Stendardo (ENEA) presented work undertaken in the FP7 project ASCENT on the implementation of advanced solid cycles for H2 production in power generation. Sorption enhanced reforming (SER) experiments were carried out to investigate cycling behaviour and to characterise the cycled specimen. Overall, the experiments showed that fly ash and cement are suitable support materials. In addition, the spent material can be used as a raw material in the cement industry. Future activities will include synthesis and characterisation of the cement-based material, as well as testing at lower temperatures.
The presentation from Zinovia Skoufa (Aristotle University of Thessaloniki) informed delegates about the CO2free.com project. The aim of this project is the development of both natural and synthetic sorbents with high sorption capacity and stability. The materials were tested in a fixed bed reactor to evaluate their capacity and stability under industrially relevant conditions. Ca-Al and Ca-Zr both showed high activity and satisfactory stability after 20 cycles of carbonation/calcination. Analysis of test samples revealed that the better performance of Ca-Al is due to less agglomeration while retaining a porous structure. Compared to the synthetic materials, the natural sorbents showed significantly lower sorption capacities and earlier as well as more intense deactivation.

Session 2b: Chemical looping fundamentals

Maria Angel San Pio Bordeje (TU EIndhoven) opened this session. As there is a lack of models capable of predicting redox kinetics for OCs, it was the aim of this work to develop a model filling this gap and to optimise the OC and systems integration. Experimental studies concluded gas phase diffusion and mass transfer limitations do not play a significant role in kinetics. It was found that solid diffusion and oxygen vacancy models appeared to be a good approach to calculate the redox kinetics.

Ana Isabel Serrano (CSIC-ICB) presented work on the feasibility of ethanol, diesel and engine oils as fuels for a continuous CLC process with Fe20-γAl_2O_3. Experiments were carried out in a 1 kWth CLC unit in order to determine combustion efficiency, CO2 capture efficiency and OC-to-fuel ratio. All fuels showed an improvement in combustion efficiency when increasing temperature from 800°C to 900°C. Engine oil generally performed better than ethanol or diesel at low OC-to-fuel ratios. Long-term tests showed that combustion efficiency was unaffected by either operating time or impurities. Overall, 200h of operation were successfully accomplished with the same batch of Fe20-γAl_2O_3 as OC.

Syed Abbas presented research on a novel sorption enhanced chemical looping steam reforming (SECLSR) process concept, which uses two packed bed reactors with 3 process stages to separate H_2, CO_2 and N_2 from natural gas. A 1D heterogeneous model was developed and validated with experiments in a lab scale reactor. Modelled and experimental values of the conversion rates were generally in good agreement. Another aim of the work is to develop novel oxygen transfer membranes (OTMs) for SECLSR. Ni-Co OTMs supported by polycrystalline alumina fibres were synthesised and assessed. Advantages of the new materials included high porosity, thermal stability and favourable physical properties.

Michela Martini (TU Eindhoven) presented on a Ca-Cu looping process. This is an SER based process where a second chemical loop with Cu/CuO is incorporated to solve the problem of endothermic $CaCO_3$ calcination. This work has developed a model for packed bed reactors with several cycles in order to achieve steady state. Operating conditions have been chosen to avoid hydration of CaO and obtain uniform temperature and composition profiles. The initial conditions led to a relatively high CH_4 conversion and prevented achieving the target CO_2 capture efficiency. Thus, future work will be required to solve these issues.

Petteri Peltola (Lappeenranta University of Technology) presented detailed modelling and power plant simulation of a CLOU reactor system in a 1500 MWth ultra supercritical (USC) power plant. The hydrodynamic operating range was found feasible and within normal commercial CFB conditions. Net plant efficiencies higher than 42%LHV and CO_2 capture efficiencies in excess of 95% were obtained. The efficiency penalty as compared to the baseline power plant without CO_2 capture was 2.5%-points and thus better than an oxy-combustion plant with CO_2 capture at 7.5%-points. However, some assumptions were uncertain at this point and further research into these areas is required.

Session 3a: Calcium-copper based material fundamentals

Changlei Qin (Chongqing University) started the session with a presentation on Ca-Cu looping. The objectives of this work were to develop a suitable composite particle, study the effect of key variables on the calcination process and identify the best operating condition and particle characteristics. A model coupling chemical kinetics and heat and mass transfer was developed and used to simulate calcination behaviour of both uniform and core-in-shell particles. Increasing temperature and porosity as well as decreasing $CaCO_3$ grain size led to higher $CaCO_3$ decomposition. Overall, core-in-shell particles showed a better matching of CuO reduction and $CaCO_3$ decomposition, with only small particle temperature fluctuations.

Juana Maria Alarcon Rodriquez (CSIC-INCAR) presented experimental work demonstrating that the reduction of CuO with a fuel gas can supply the energy required to carry out calcination of $CaCO_3$ in the same fixed bed reactor. A pseudo-homogeneous dynamic model was used to calculate heat and mass transfer between the reduction and calcination reactions and was found to adequately describe the process under the considered operating conditions. Future work will include a detailed evaluation of the key design parameters, other materials and the oxidation step with different N_2 dilutions.

Laura Diez (CSIC-ICB) showed the results of a study about different materials for Ca-Cu CLR processes. Several studies in the past have focussed on Al_2O_3 as support material, due to its good chemical and mechanical behaviour, availability and low cost. The current work evaluated CuO supported on different materials ($MgAl_2O_4$, ZrO_2, TiO_2, SiO_2), synthesised via different methods and with varying Cu contents. The results showed that there seems to be a limit in Cu content for preventing agglomeration, which depends on the support material. The tests further identified suitable powdered materials, supported on Al_2O_3 or $MgAlvO_4$, with Cu contents of ~65% that presented high stability, fast kinetics and no agglomeration.

Session 3b: Chemical looping fundamentals (continued)

Mohammad Ismail (University of Cambridge) opened the session. The main aim of the presented study was to develop stable OCs containing Fe-Ca-Al-O by different synthesis methods and to characterise the fresh and cycled materials. Other objectives were to study the CO_2 capture and H_2 production capacities of the OCs and to undertake a comparison of the different support materials. Conversion experiments were carried out in a bench-scale fluidised bed reactor. The results showed that $CaO+Al_2O_3$ containing Fe_2O_3 had a better performance than pure Fe_2O_3, or individual CaO/Al_2O_3 supported Fe_2O_3 . In all cases, particles containing 60 wt% Fe_2O_3 exhibited higher stability in reactivity over several cycles.

Arnold Lambert (IFPEN) informed delegates about the mechanism of OC degradation during multiple CLC cycles. Although CLC technology is proven at scales up to 1 MWth and many OCs have been tested successfully, the search for OCs with higher reactivity, lower cost and lower attrition rate is still ongoing. The purpose of this presentation was to provide first thoughts on the mechanism of particle ageing and to determine morphology changes during ageing in TGA and batch fluidised bed experiments. The experimental results led to several conclusions and recommendations. For all materials, it will be important to minimise the Kirkendall effect, i.e. avoid active metal ion migration. For natural ores, large porosity increases need to be avoided as well. In case of supported particles, it will be essential to increase the support's inherent mechanical and chemical resistance.

Ewa Marek (University of Cambridge) presented a study on iron ore characterisation for CLC processes. Pyrite, FeS_2, is regarded as a cheap, abundant and promising material for CLC processes. This work aimed at testing roasted pyrite, studying the effect of material cycling on kinetics and evaluating pyrite materials impregnated with 50 mol% Mn. The cycling tests showed that pyrite with added Mn underwent slower conversion during CO/CO_2 reduction than pure pyrite. However, both materials revealed slower reoxidation with increasing number of cycles.

Session 4: Calcium and chemical looping modelling

Yaoyao Zheng (University of Cambridge) started the session with a presentation about the in situ gasification of a Polish char in presence of Fe-based OCs for CLC. The aim of this work was to understand how the presence of OCs affect the char gasification rate. The results show that the presence of Fe_2O_3 does not have a significant effect on the gasification rate; the step is controlled by chemical kinetics. ZrO_2-supported Fe_2O_3 however causes a low apparent gasification rate. ZrO_2 appears to inhibit the gasification step and the degree of this is affected by temperature. Future work will focus on clarifying the exact mechanism of this inhibition effect.

Paul Fennel (Imperial College London) presented work on the interaction between Fe-based CLC OCs and biomass tar. Apart from causing operational issues in the downstream process equipment, the presence of tar can lead to coking of the OC. This can result in temporary deactivation and reduced CO_2 capture efficiency. The aim of this work is to study the interactions, develop a model, check if tar leads to OC deactivation and develop OC with enhanced tar cracking capabilities. Application of CLC in biogas upgrading could benefit from the results of this study. Both investigated materials, 100FeMM and 60Fe40AlMM showed enhanced tar cracking and carbon deposition. No obvious deleterious effects on OC reactivity was observed after exposure to the biomass tar during experiments.

Vincenzo Spallina (TU Eindhoven) presented work on CLR with packed bed reactor (PBR) technology. CLR has only been studies using interconnected CFBs but H_2 production is more economically feasible at high pressure thus a PBR design is favourable. A CLR-PBR is expected to have +1.5%-points gain in reforming efficiency compared to the benchmark FTR-SMR technology, especially when CO_2 capture is required. This study successfully tested a commercial Ni-based OC and provided the proof of principle of the process at lab scale. Carbon deposition and change in reformate composition have been observed and need consideration in further studies.

Luca Mancuso (AmecFW) showed results of a techno-economic assessment (TEA) of large-scale PBR-CLC for coal-based gasification plants (IGCC). The work was done under the project DEMOCLOCK, which aims at demonstrating the technical, economic and environmental feasibility of this technology and prepare it for commercialisation. The results show that the levelised cost of electricity (LCOE) of the IGCC plant with CLC is slightly lower than the benchmark IGCC plant with CCS. However, it is slightly higher than both SCPC and oxy-SCPC with CCS. In terms of CO_2 avoidance cost (CAC), the IGCC plant with CLC has lower CAC than the IGCC with CCS benchmark and the SCPC with CCS plant. The lowest CAC has the oxy-SCPC plant with CCS. The next steps are to develop a full scale design and demonstrate it in an industrial facility.

Andy Antzara (Aristotle University of Thessaloniki) presented on the production of high purity H_2 via sorption enhanced chemical looping steam methane reforming (SE-CL-SMR). SE-CL-SMR has a 55% lower thermal demand than compared to conventional SMR. The study investigated CaO and NiO based materials for a combined CLR with CO_2 capture, using NiO/ZrO_2 as OTM and CaO/ZrO_2 as the CO_2 capture sorbent. Experiments in a bench scale unit show that high purity H_2 (>95%) can be produced and 79% CO_2 capture can be achieved. Both materials exhibited excellent stability after 20 cycles, i.e. 60h of testing.

Fabrizio Scala (Universita Federico II di Napoli) presented on the development of a novel lab scale twin bed CaL reactor for sorbent characterisation. The aim is to get realistic information about the thermal history of the sorbent. Experiment with this new set up showed good solid transfer efficiency and overall stability of the system, in terms of bed masses, for the two connected reactors. The next experiments will be directed at studying this system under realistic high temperature conditions.

David Hanak (Cranfield University) showed delegates the results of evaluating a CaL retrofit to a power plant. The modelling was done with Aspen Plus®, based on a 580 MWel coal fired power plant that was retrofitted with either CaL, amine scrubbing or chilled NH4 scrubbing. In terms of modelling, the CaL retrofit scenario turned out to be less complex than the other two scenarios. The efficiency penalties were found to be 9.5%-points for amine scrubbing, 9.0%-points for the chilled NH_4 process and 7.9%-points for CaL. When switching fuel, this number can be further reduced to 7.7%-points for 20% biomass co-firing and 6.7%-points for NG. The CaL scenarios led to a 50-60% increase in net power output of the plant.

Matteo Romano (Politecnico di Milano) presented on the integration of CaL in cement plant using entrained flow reactors. The distinctive feature of the process is the high integration level of the carbonator in the suspension heater of the cement plant. Simulations show that the integrated plant has a positive net power output and that CO_2 capture efficiencies of up to 95% can be achieved.

Session 5a: Sorption enhanced reforming materials

Julien Meyer (IFE) opened the session with a presentation about the development of an agglomerated CO_2 sorbent with enhanced stability for SER. The aim of the work was to improve the SER process. Develop a high performing sorbent and to minimise sorbent cost. A CaO based sorbent was successfully synthesised and tested in both fixed and fluidised bed reactors. The sorbent has 4x the CO_2 uptake of limestone after 40 cycles and 7x the crushing strength of calcined limestone.

Maria Navarro (CSIC-ICB) presented on catalyst testing for SER. The objective of the work was to obtain stable materials to run the SER Ca-Cu looping cycle. For this, a catalyst with high refining activity and resistance against deactivation is required. In experiments, the commercial catalyst HiFUEL R110 has shown to be stable for up to 100 oxidation/reduction cycles. Preliminary test with a PGM-based catalyst showed high activity and high space velocity for up to 10 cycles.

Gemma Grasa (CSIC-ICB) also presented the evaluation of catalysts for SER. The aim of this work was to obtain mayenite supported Ni catalysts with sufficient activity for the SER process. Experimental results showed high activity for the investigated catalysts, which is dependent on the reforming temperature and the Ni content. Presence of CO_2 allows for a lower Ni content and the materials showed high stability over 15 reforming/regeneration cycles.

Max Schmid (IFK) provided information about biomass gasification with oxy-SER in a 200 kWth pilot plant. In oxy-SER, the regeneration step is operated under oxyfuel conditions and is thus able to achieve high CO_2 outputs. The pilot plant tests showed no difference in syngas between SER and oxy-SER. For the oxy-SER process, the flue gas of the regenerator has a higher CO_2 and H_2O concentration than in the SER process, due to the gas recirculation. During the test runs, >90 vol% CO_2 and >70vol% H_2 were achieved, confirming the suitability of the oxy-SER process for H_2-rich syngas production with pre-combustion CCS.

Session 5b: Calcium looping modelling

Michael Reitz (TU Darmstadt) started the session with presentation about an indirectly heated CaL process. The feasibility of this process was successfully demonstrated in a 300 kWth pilot plant. More than 500h of coupled fluidised bed operation and 300h of CO_2 capture were achieved. Observed CO2 capture efficiency was >90%. The pilot plant was hydrodynamically stable and there was no issue with the performance of the heat pipes.

Tom Hills (Imperial College London) presented on characteristics of Portland cement made from CaL sorbent. Cement samples were made in the lab and then tested in terms of compressive strength. Caveats here were that the number of samples per condition was small, clinker production in the lab differs from realistic production and EU/US standards require larger batch samples for testing. The preliminary results from the test are that clinker made from CaL CaO appears to be suitable for use in commercial cement, as the lab made cement showed a higher compressive strength than the commercial reference.

Yolanda Lara (CIRCE) presented about heat integration configurations for CaL. Three configurations have been modelled and the available heat quantified: reference case, cyclonic preheater and mixing seal valve. Fuel and O_2 consumption are reduced for the cyclonic preheater and mixing seal valve configurations, compared to the reference case. In addition, the dimensions for those two configurations are lower. % and total amount of recovered heat were comparable for both new cases, so an assessment of the economics for the will be necessary.

Letitia Petrescu (Babes Bolyai University) provided results of a life cycle analysis (LCA) for IGCC plant with CaL and CLC. The aim of this study was to evaluate and compare LCA impacts for abated and unabated IGCC plants. A cradle-to-grave approach has been used to investigate three cases: IGCC, IGCC with CaL and IGCC with CLC. 11 environmental impact categories were defined, calculated and compared. IGCC with CaL appears to be more environmentally benign overall than the other two cases. In terms of the key performance indicators (KPIs) capture rate and specific CO_2 emissions, it was found that the IGCC with CLC case performs best.

Plenary discussions

During the plenary discussion, the main conclusions from the meeting and future challenges were summarised. The next steps in CaL and CLC will require large amounts of funding and industrial support/commitment and the only chance to get a higher profile in the political agenda will be to adapt RD&D accordingly. An update of the economics of solid looping processes with data from large-scale pilots will be necessary. 5 years ago, there was much more optimism regarding a CO_2 price. However, this did not materialise. Another challenge will be to take the current systems/pilots from MW scale to 10s of MW scale, as there is currently no incentive for industrial companies to pick up CaL and CLC technologies. But there are also opportunities, most technologies are/were aimed at power generation but can also be applied to other sectors and especially application in the industrial sector appears very promising now. For 'standard' CaL, every part of the system is already well known technically, the main issue is global interest and momentum for CCS and climate change are going down, an exception is North America where CCUS activities are relatively high (Boundary Dam, Cenovus). CCS is not an unproven technology anymore, and interest is also starting to pick up in China. It is good if other CCS systems such as amine based CCS succeed, as CaL and CLC development/deployment will benefit from their success and learnings as well. Current fuel switching attempts to NG will not be a permanent solution, so it is expected that CCS technologies will remain important/become important again.

Conclusions and recommendations

The 6th HTSLCN Meeting covered sessions about CaL and CLC pilot plant testing, CaL/CLC/Ca-Cu cycle fundamentals, process modelling, industrial applications, and SER materials and testing. Delegates were able to join a site visit to research facilities of the Department of Energy at Politecnico di Milano.

The technical programme provided the attendees with two keynotes summarising the progress of Cal and CLC in the last decade. These reiterated that sorbent related issues, such as attrition, are no longer a pitfall for standard CaL cycles. Both technologies had now progressed to TRL6 and had been demonstrated at pilot scales of 1-3 MWth. The costs of CaL were now estimated to be 20-30% lower than a conventional oxyfired CFB process. Costs of a packed bed CLC process were found to be lower than a reference using integrated gasification combined cycle (IGCC) technology. Chemical looping reforming processes were identified as a promising application for H_2 production. In addition, it was shown that co-combustion of torrefied biomass could improve performance of CLC. Finally, it was noted that the net steps in CaL and CLC would require large amounts of money and industrial support.

Recommendations from this meeting included the need for Cal and CLC to get a higher profile on the political agenda. This challenge would need to be addressed against a background of a generally declining interest in CCS technologies globally. A further update of the economics with data from the large scale pilot plants would also be necessary. In addition, further work should be done on the potential abatement of nitrogen oxides through CaL processes compared to other CO_2 capture technologies.

Delegates at the 6th HTSLCN Meeting.

View over Lake Como.

7th HTSLCN Meeting

4th – 5th September 2017
Swerea MEFOS, Luleå, Sweden

Hosted by

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IEAGHG Research Networks
www.ieaghg.org

Summary

The 7th HTSLCN Meeting took place from 4th to 5th September 2017 at Kulturens Hus in Luleå, Sweden, hosted by Swerea MEFOS. 50 attendees enjoyed a two-day programme with a total of 39 presentations, the Grand Opening of the STEPWISE pilot plant and a relaxing dinner with musical entertainment by Prof Anders Lyngfelt.

Concluding from the panel discussions and technical sessions, it was noted that solid looping technologies now urgently need to move forward in term of scale. Especially since the progress appears to have stalled during the last two years with no new large pilot or demonstration plant having been announced. However, this development is not exclusively concerning solid looping technologies but rather all CCS technologies, as requests for technical details and costs have driven some researchers/engineers back to the lab. Negative emissions through solid looping with biomass and flexible operation have been identified as the hot topics of this meeting. It is important that the HTSLCN community has started work on these topics. The forthcoming IPCC Special Report on 1.5°C will hopefully help to regain momentum for CCS technologies. Next to biomass, sorption enhanced reforming technologies appear as a promising near-term option to party replace conventional H2 production. Thus, opportunities for solid looping currently seem to be in the industrial sectors, rather than in the primarily targeted power sector.

The 8th HTSLCN Meeting will take place from 20th to 21st January 2019 at Brightlands Chemelot Campus in Geleen, The Netherlands, and will offer the opportunity to visit the pilot plant of the LEILAC project.

Welcome and Keynotes

Application of HT sorbents in power and industrial plants, Matteo Romano (Politecnico di Milano)

This keynote presented the technical prospects of CaL and SEWGS in power generation, industrial plants and biomass applications. In the power sector, CaL is a mature technology (TRL 6-7, demonstrated at 0.1-2 MW scale) and ready for scale-up in coal fired power plants. The opportunities are strongly linked to the need for flexible power production. For NG fired power plants, CaL won't be competitive as a PCC technology, as the carbonator will be less efficient, fan energy consumption will be high and the overall plant efficiency will be low due to NG conversion in the calciner (60% -> 35%). For the industry sector, there are several opportunities in iron and steel plants, where demonstration activities are already ongoing (e.g. STEPWISE project using SEWGS technology). There is also high potential in H_2 with CCS but significant development of both materials and processes is still needed and competing with conventional reforming will be tough. CaL is a very suitable technology for cement plants. It can be either used in a post-combustion capture configuration or in a configuration that is highly integrated with the cement production process (both approaches are currently pursued in the projects CEMCAP and CLEANKER). With regards to biomass, opportunities exist for bio-CCS/BECCS applications, which can generate negative emissions, and biofuel production.

STEPWISE – Sorption enhanced water-gas-shift (SEWGS) technology platform for cost effective CO2 reduction in the iron and steel industry, Paul Cobden (ECN)

SEWGS technology is advantageous for CO2 reduction in iron and steel plant because it combines a high carbon capture ratio with a uniquely low steam use. The process is able to operate under sour conditions, removing H_2S as well as CO_2. SEWGS technology builds upon the vast industrial experience with PSA systems and at the same time provides a means of process intensification, i.e. combining several process steps into one. For blast furnace gas (BFG), the costs per tonne of CO_2 avoided are expected to be about 25% lower than state of the art CCS technology. The STEPWISE project will demonstrate the SEWGS technology on BFG at TRL 6.

Session 1: Calcium looping modelling

Denggao Chen (Tsinghua University) opened the first sessions with a presentation on CFD modelling for entrained flow Cal in a cement plant. A 3D CFD modelling frame was developed to provide information about the variations in CO_2 concentration and temperature of the entrained carbonator. The effect of carbonation kinetics and sorbent circulation rate on CO_2 capture and temperature distribution was studied. The model can be used to design and optimise the entrained carbonator. Next steps are to include the effect of sorbent degradation on CO_2 capture and certain heat transfer effects.

Maurizio Spinelli (Politecnico di Milano) also presented modelling results for an entrained flow CaL carbonator in cement plants. The results show that a relatively high solid loading is required to obtain high CO_2 capture rates. The sorbent capacity has a significant impact on the carbon capture rate, too. The downdraft carbonator option allows for higher residence time and higher sorbent loadings, thus improving the capture rate. Further research is needed on how different raw meals and calcination conditions affect sorbent performance. This includes experimental validation of the concept under realistic conditions.

Reinhold Spörl (IFK) presented work on CaL for blast furnace top gas treatment and recycling (TGR-BF). Based on previous work by the ULCOS project and IEAGHG, CaL for TGR-BF was assessed with the help of process simulation in Aspen Plus™. The simulations included heat integration and power generation for the CaL system. The results were compared to the alternative CO_2 capture technologies VPSA and amine scrubbing. TGR with CaL has lower overall CO_2 emissions than VPSA or amine scrubbing. In addition, the CaL process can replace the conventional steel mill power plant(s) and fully cover its own electricity demand with low carbon power. CAPEX for CaL is higher than for the other two capture technologies but the CO_2 avoidance costs are in the same range or lower (with the caveat that costs are highly site specific and cannot be easily generalised).

Hui Wang (Tsinghua University) informed delegates about the results of a multi scale modelling exercise for the carbonation process in CaL. The aim was to gain a deeper understanding of the CaO-CO_2 carbonation mechanism. In the model, the assumption of uniform $CaCO_3$ film formation at the grain surface was replaced with product island morphology. The carbonation reaction, i.e. initial fast stage with subsequent product layer diffusion stage, was modelled and found to be in good agreement with experimental data. The controlling step for large grain and pore size is product layer diffusion, while for small grain and pore size it is pore plugging.

Session 2: Economics and environmental impacts

Peter Ohlemüller (TU Darmstadt) started this session with a presentation about the thermodynamic and economic evaluation of a full scale CLC plant. Aspen Plus, Ebsilon Professional and Matlab were used to model a 1000 MWth hard coal fired CLC power plant with ilmenite as the OC. The results show that the energy penalty, in this case 5%-points (of which 4%-points are for compression), is lower than for other CO_2 capture technologies. Fuel costs were identified as the largest contributor to plant lifetime costs. With a range of 13-23 €/tCO_2, CO_2 avoidance cost for CLC was found to be very competitive. The next step will be to build a demonstration plant at 10 MW scale, in order to start closing the gap between current pilots and the modelled full scale case.

Dora Andreea Chisalita (Babes-Bolyai University) presented an environmental assessment of an integrated steel mill with CCS. The aim of this work was to evaluate and compare the life cycle impacts of steel production coupled with different CCS technologies: MEA based amine scrubbing, SEWGS and CaL. LCA methodology was used for this assessment. The results show that applying CCS decreases global warming potential (GWP) by 52-62% compared to the unabated benchmark. However, all other environmental indicators increased. Within the considered boundary conditions of this work, SEWGS was the most environmentally benign option among the investigated CCS technologies.

Tom Hills (Calix Europe) provided information about alkali-activated nano-active MgO as a sorbent for the SEWGS process. The aim of this work was to exploit this MgO based sorbent for CO2 capture. The sorbent has a high sorption capacity and is a WGS catalyst at the same time. In this regards, the fast kinetics can be a challenge for the process. The nano-active MgO was coated with an alkali metal nitrate salt that melt at >300°C and activates the MgO, enabling bulk carbonation. The nano-active precursor was found to be less susceptible to sintering and has a higher CO2 capture capacity than a nano-particle precursor. Next steps are to optimise the sorbent in terms of production and mechanism and to optimise the whole SEWGS process.

Session 3: Calcium looping testing

Jochen Ströhle (TU Darmstadt) opened the session with a presentation about the results from the SCARLET project. This project evaluates an oxy-fired CaL process, including test in a 1 MWth pilot plant. The pilot was operated for more than 1200h in CO_2 capture mode, running continuously in steady state. CO_2 capture rates of at least 95% were achieved during the test runs. For a hard coal fired power plant, the efficiency penalty of the process is 7%-points and the CO_2 avoidance cost is 20 €/tCO_2. CO_2 avoidance costs in industrial plants are higher: 30 €/tCO_2 for cement plants and 40 €/tCO_2 for steel plants. Efficiency penalty and CO_2 avoidance cost of the oxy-fired CaL process are lower across all investigated plant types than those of amine and oxyfuel CCS. The results of the 1 MWth pilot plant are now being used to design and optimise a scale up to a 20 MWth pilot plant.

Carlos Abanades (CSIC-INCAR) presented results from the CaL pilot plant in La Pereda. The aim of this work was to investigate oxygen-rich conditions in the calciner. In general, this mode of operation is beneficial in terms of energy demand and cost. The CO_2 capture performance under oxygen-rich conditions was as expected. A discrepancy between experimental and calculated values has been detected. A possible explanation for the observed lower sorbent performance under high make-up flows is that the particles might advance in cycle number before leaving the calciner.

Matthias Hornberger (IFK) presented an evaluation of CaL looping for emissions-free cement under the project CEMCAP. Both tail-end and integrated CaL scenarios were tested in 200-230 MWth pilot plants. Results for the tail-end option show that this design is easy to integrate into a cement plant. However, the energy efficiency is reduced and there are some minor technical uncertainties. Integration of the integrated CaL concept is more complex but the energy efficiency will be high. This option requires more research on raw meal sorbent performance and the sizing of the entrained flow carbonator. Both options investigated can achieve >90% CO_2 capture rate, which can be adjusted by the looping ratio and the integration level.

Joseba Moreno (IFK) presented an evaluation of flexible CaL operation with a bubbling/turbulent fluidised bed (BFB/TFB) carbonator. Test were done within the framework of the FlexiCaL project in a 230 kWth pilot plant, with the regenerator in CFB mode and the carbonator in BFB/TFB mode. The results show that >92% CO_2 capture efficiency and >90vol% CO_2 concentration can be achieved during full load stable operation. Sorbent degradation was compensated by minimum addition of fresh limestone. Next step in the project will be the investigation of part-load operation.

Session 4: Chemical looping combustion fundamentals

Marc Duchesne (NRC) started the session with a presentation about phase transformations during CLC. Tests carried out in a fixed bed reactor showed that oxidation is required for sintering but bulk FeO/Fe formation was not necessary. The flue gas acted in a similar manner to the reducing gas. High temperature X-ray diffraction (HT-XRD) tests showed that predictions matched the detected phases for all flue gases but one (i.e. 99.9mol% CO_2, 0.1mol% CH_4). In addition, phase separation was observed. Eutectic melts were identified and mainly contained Cl2, K2O and/or Na2O.

Patrick Moldenhauer (Chalmers University) provided the delegated with information about OC development for CLC of CH_4. The development and investigation of Ca-Mn based OCs with perovskite structure took place under the projects INNOCUOUS and SUCCESS. Experiments were carried out in a 300 Wth and 10kWth test unit. For this, a series of Ca-Mn OCs (C14 and C28) was produced up to multi-ton scale with spray drying. The perovskite structure was easy to produce. CLOU ability was observed for all OCs produced. Several OCs could match the performance of reference materials and showed a combination of high reactivity and low attrition. The expected lifetime of the Ca-MnO_3 based materials is 700-12000h.

Airy Tilland (IFPEN) presented a comparison of different devices for the measurement of CLC kinetics. The work is part of the SUCCESS project. As a first step, a comparison between fixed and fluidised bed was carried out. Experiments with both set ups show a fast reaction rate for Cu-based materials as OC. It was found that for reliable kinetic measurements the fuel to OC ratio has to be increased. Further investigations concluded that for the selected Cu-based materials, a small CLC unit or a riser coupled with a regenerator appear to promising devices for kinetic studies. The small CLC unit is more flexible but also more complex to model in terms of hydrodynamics.

Session 5: Sorption enhanced reforming fundamentals and testing

Robert Bloom (University of Leeds) opened the session with an overview of recent SER research activities at the University of Leeds. The work included development of a novel Ni/Co fibrous OC. The materials were synthesised via three different methods: wet impregnation (WI), deposition precipitation (DP) and hydrothermal synthesis (HT). The results show that DP and HT improved the Ni/Co distribution and lowered crystallite size. Co doping increased the reduction capacity of all OCs and a ratio of 30:1 (Ni:Co) proved to be most effective. Other current work includes the development of CaO based sorbents with Saffil fibres as inert support and modelling of a combined SE-CLSR process.

Julien Meyer (IFE) presented work on SER in a fluidised bed using combined sorbent catalyst materials (CSCMs). Advantages of CSCMs include an improvement in mass transfer and reaction kinetics, avoidance of particle segregation, decreased material production and improved techno-economics of the process. Results show that hydrothermal synthesis with high shear granulation allows to produce CSCMs suitable for SER in fluidise beds. Satisfactory mechanical properties for the CSCMs have been observed.

Matt Boot-Handford (Imperial College London) presented about C-SHIFT, a novel process for low carbon H_2 and power production, which is investigated in the ASCENT project. C-SHIFT combines the concepts of SEWGS with ENDEX sorbent regeneration technology. These two processes mostly use CaO based sorbents but alternative sorbents that are capable of operating in more moderate temperature ranges are desirable for the C-SHIFT process. K_2CO_3-promoted hydrotalcites (K-HTCs) were tested and the results show that this sorbent is at the lower end of the target capacity for the C-SHIFT process.

Gemma Grasa (CSIC-ICB) also presented work done under the ASCENT project on c Ca/Cu cycle in a lab scale fixed bed reactor. The aim was to test the viability of a Ni-based commercial catalyst, a CaO-based sorbent and a CuO-based material under relevant process conditions. All three materials showed promising results during the tests. Ageing of the catalyst did not alter the operational limits of the system. The CuO-based material was completely converted at the low pO_2 tested and also showed fast reaction kinetics. A calcination efficiency of 95% was achieved.

Isabel Martinez (CSIC-ICB) provided a progress overview of sorption enhanced H_2 production using Ca-Cu looping. The process has so far been validated up to TRL 4. As a standalone H_2 production process, its H_2 efficiency is 2.6%-point higher than a state-of-the-art SMR process. Promising results were obtained when investigation the Ca-CU process for use in NH_4 plants. The specific primary energy consumption is 14% lower than in a state-of-the-art NH_4 plant. The Ca-Cu is also suitable for integration into steel mills, as a means of reducing emissions from BFG.

Session 6: Chemical looping combustion modelling and testing

Marc Duchesne (NRC) opened the session with a presentation about the design of a 600 kWth PCLC facility. PCLC offers the benefit of higher gas-solid reaction rates, use of low cost non-toxic OCs, increased heat transfer rate and use of latent heat, all while having a compact modular design. Key points are that the fuel reactor needs to be designed for pressurised combustion and refining of gaseous fuels. The air reactor is equipped with in-bed heat exchanger tubes. In addition, the solids separator is required to meet solid circulation specifications for the expansion turbine. Basic and detailed engineering work are currently underway and construction and commissioning are expected to begin in 2018, while full operation is expected for 2020.

Peter Ohlemüller (TU Darmstadt) presented results from the operation of a 1 MWth CLC pilot plant with NG, which was part of the project SUCCESS. Challenges when using NG as fuel stem from the low reactivity of CH_4. A highly reactive OC, high inventory in the fuel reactor and high solids circulation rate are necessary, which will all have cost implications. This work produced OCs (C28 and C28RW) at semi-industrial scale and tested them in the pilot plant. For the first time, autothermal operation with NG at 1MWth scale was achieved. A gas conversion rate of 80%, comparable to other CLC units, was observed. The lifetime of the OC was ~500h, and needs optimisation in the future.

Richard Görke (University of Cambridge) presented about properties of novel materials for chemical looping air separation (CLAS). The traditional approach is usually of a trial and error nature, where properties of known materials are used for modelling. This work used an inverse design approach, sweeping through relevant thermodynamic properties (e.g. ΔHr0), using them for modelling and then afterwards looking up suitable materials in a database. With the conditions of ΔHr0 = 100 – 400 kJ/mol and Tred = 773 – 1173 K, a feasible region for OCs was established and some OCs were mapped against this region (CuO/Cu_2O and Mn_2O_3/Mn_3O_4).

Session 7: Solid looping for biomass applications

Anders Lyngfelt (Chalmers University) started the last technical session of the meeting with a presentation about bio-CLC. Steam exploded ground wood pellets (black pellets) were tested in a 100 kWth pilot plant. During 4h of operations, ~100% CO_2 capture, 70-75% gas conversion and 25-30% O_2 demand were observed. O_2 demand decreased with increasing air flow, i.e. increased circulation rate and increased pressure drop. It also rises with the content of volatiles. There was a significant by-pass of volatiles, despite addition at the bottom of the bed. In Sweden, fossil CO_2emissions are 43 Mt/a and biogenic CO_2 emissions are 31 Mt/a. Thus, bio-CCS/bio-CLC can play an important role for creating negative emissions, especially at anticipated CO_2 capture costs of 16-26 €/t and efficiency penalties of ~4%-points.

Petteri Peltola (Lappeenranta University) presented about a comparison of oxy-CFB, CaL and CLOU for integration into a large-scale, biomass co-fired CHP (50% coal, 50% biomasss based on LHV). The objectives of this work were to study the integration of these processes, their energetic assessment and the calculation and comparison of the plants KPIs. The plant design includes flue gas condensers (FGCs), as the high share of co-red biomass leads to an increase in moisture content and thus an increased amount of heat that can be recovered. No ASU was needed for the CLOU case, resulting in the highest net power production among all three cases (apart from the air-CFB reference case without CO_2 capture). The high flue gas moisture in the oxy-CFB case leads to the highest district heating (DH) production of all cases. All three investigated cases have higher DH production and lower net power production than the reference case.

Joseph Yao (Imperial College London) presented results on pressurised in-situ CO_2 capture from biomass combustion with CaL. For this, experiments were carried out in a spout fluidised bed reactor. The results show that the tar yield is lowered by the presence of CaO, high temperatures and total pressure, while O_2 partial pressure (PO2) has no effect. CaO helps to crack heavier tars into lighter ones. High PO_2 and Cao were found to crack less conjugated tar species while additional simultaneous increase in T was found to crack more conjugated tar species as well. Initial test showed no constraint in terms of biomass species. However, CO_2 capture rate seems to be limited by rapid combustion kinetics at high PO_2.

Reinhold Spörl (IFK) showed results from process modelling exercise of sorption enhanced gasification (SEG) of biomass. A 1D gasifier reactor model, consisting of a 2-phase BFB and a kinetic reaction model, and a 0D regenerator model were used. Heat losses in the model were adjusted to match experimentally measured temperature profiles of the freeboard. Comparison with experimental results from a 200 kWth pilot plant showed a good agreement. Next steps will include the extension of the model for other fuels and impurities.

Peter Clough (Cranfield University) presented about H_2 production from SER of biomass. The aim of this work was to investigate combined Ca and Ni particles, some of them supported on C_2S, in a fluidised bed reactor. The experimental results show that H_2 purity and yield approached equilibrium. The use of supported particles resulted in a significant decrease in CH_4 production. However, some operational issues, such as coking on the particles, coking within the reactor and attrition of the particles, have been observed.

Eva Sundin (CEO of Swerea MEFOS) closed the session with an overview of the Swerea Group and its activities. She also provided an introduction to the Grand Opening ceremony of the STEPWISE pilot plant that participants would attend after the closing panel discussion.

Plenary discussions

Going forward, flexibility of CaL and CLC systems will be needed, especially for electricity production. How HTSLC systems can be adapted to meet this need will be an important research question. This will also be a question for industrial plants, especially whether it will be different from the power sector or whether they will require the same/a similar amount of flexibility. Steel plants might have limitations in terms of flexibility: steel plants usually prefer continuous operation and flexibility is rather needed regarding the integration into the system/plant, so what will the cost implication be in this case? More experiments and modelling studies could help with addressing those issues which should also include start-up and shut-down operations. Another question is as to how flexibility will be different for CaL and CLC systems. CLC by definition is very inflexible, as a certain constant circulation rate is needed. Compartments in the air reactor could be used but this would make the process more complex. Similar approaches could be applied to CaL, bubbling beds for example. At the end of the day, flexible CaL and CLC will need to be compared to other flexible technologies, not to baseload, to have a fair comparison, and both flexible and inflexible systems need to be compared against the price of electricity/energy storage.

In addition, CaL and CLC have to move forward in scale. However, it appears that developments have stalled or are even moving backwards a little bit, this also applies for CCS in general. Pushed by decision makers to go back to the lab to address details and costs, no new and/or larger pilot plants have been announced lately.

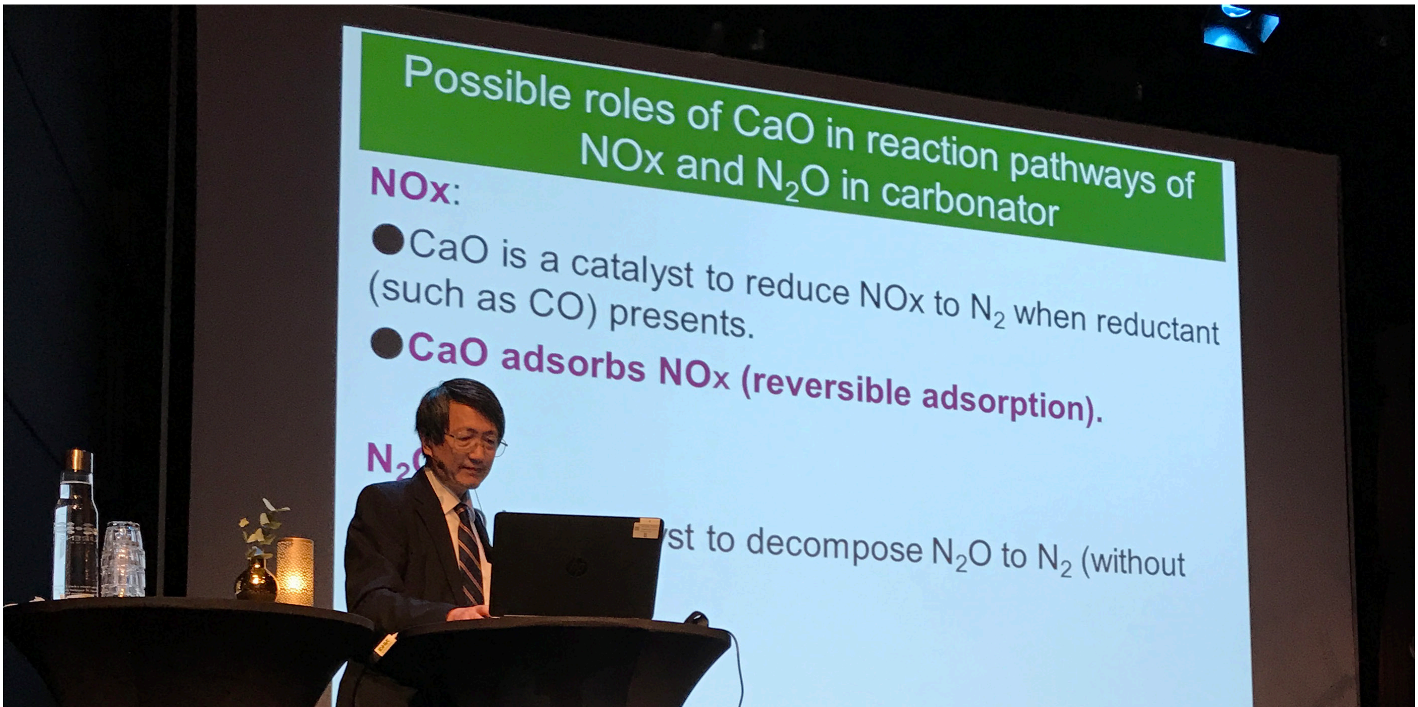
Negative emissions are another hot topic, and it is important that the HTSLC community starts addressing this, especially as there might be competition with other CO_2 capture and mitigation technologies. CaL and CLC with biomass can help with realising negative emissions. The IPCC's SR1.5 will hopefully help with regaining momentum for CCS and to "keep the flame alight".

In conclusion, the near-term opportunities for HTSLC technologies appear to be bio-CLC and SER/SEWGS (especially as replacement of conventional hydrogen production), and are rather in the industrial than in the power sector.

Conclusions and Recommendations

Concluding from the panel discussions and technical sessions, it was noted that solid looping technologies now urgently need to move forward in term of scale. Especially since the progress appears to have stalled during the last two years with no new large pilot or demonstration plant having been announced. However, this development is not exclusively concerning solid looping technologies but rather all CCS technologies, as requests for technical details and costs have driven some researchers/engineers back to the lab. Negative emissions through solid looping with biomass and flexible operation have been identified as the hot topics of this meeting. It is important that the HTSLCN community has started work on these topics. The forthcoming IPCC Special Report on 1.5°C will hopefully help to regain momentum for CCS technologies. Next to biomass, sorption enhanced reforming technologies appear as a promising near-term option to party replace conventional H_2 production. Thus, opportunities for solid looping currently seem to be in the industrial sectors, rather than in the primarily targeted power sector.

Delegates at the 7th HTSLCN Meeting.



Tadaaki Shimizu presenting on environmental impacts of CaL.

8th HTSLCN Meeting

20th – 21st January 2020
Brightlands Chemelot Campus, Geleen, The Netherlands

Hosted by

Summary

The 8th High Temperature Solid Looping Cycles Network (HTSLCN) Meeting took place from 20th to 21st of January 2020 at Chemelot Industrial Park, in Geleen, The Netherlands, hosted by TNO in collaboration with the CLEANKER and LEILAC projects. 30 attendees enjoyed a two day programme with a total of 16 presentations and a site visit to the LEILAC plant in Lixhe, Belgium.

The first day started off with a welcome from the organisers TNO and IEAGHG. The first session was about chemical looping combustion (CLC) and contained presentations on the CLARA project (which investigates chemical looping gasification (CLG) for biofuel production), the assessment of natural ores and industrial wastes for CLG, the integration of pumped thermal energy storage fuelled by CLC with an open cycle gas turbine (OCGT), and a techno-economic assessment of a packed bed reactor for chemical looping reforming (CLR).

The second, and last, session was all about Calcium looping (CaL) processes. The session started with presentations about two projects: BREIN-STORM (which explores high temperature solid looping processes in the steel industry) and HyPER (which investigates bulk hydrogen production by sorption enhanced reforming (SER)). The attendees were also informed about the flexibility of a circulating fluidised carbonator in a 1.7 MWth CaL pilot plant, integration of an indirectly heated CaL process in lime and cement plants, CaL systems with thermochemical energy storage and the application of CaL in waste-to-energy (WTE) plants.

The second day started with a dedicated session on the CLEANKER project (CLEAN clinKER production by CaL process). The first presentation provided an overview of the project, which aims at demonstrating the Calcium Looping (CaL) concept at TRL7 in a configuration highly integrated with the cement production process, making use of entrained flow reactors. The demonstration plant will capture CO_2 from a portion of the flue gas of a cement plant in Vernasca (Italy) operated by Buzzi Unicem.

The rest of the session then dealt with the characterisation of the cement raw meal that is used as CO_2 sorbent, the calcination kinetics and the modelling, engineering and construction of the demonstration plant. In the afternoon, the attendees of the 8th HTSLCN Meeting were then able to visit the LEILAC (low emissions intensity lime and cement) demonstration plant in Lixhe, Belgium. The project's aim is to assess whether direct separation calcining technology can work at the higher temperature required and will capture over 95% of the process CO_2 emissions.

http://www.cleanker.eu/
https://www.project-leilac.eu/

Concluding from the technical sessions and the wrap-up session, it was noted that a lot of the hot topics identified during the panel discussion of the last meeting are being addressed now. Two examples for this are the flexibility of solid looping systems and achieving negative emissions with solid looping systems by using biomass. Questions and uncertainties regarding the use of CaL for coal fired power plants in Europe remain due to the phase-out of these plants. This has caused a shift to industrial applications, which offers a vast RD&D landscape for solid looping systems. There was also agreement that although the meeting was smaller this time, attendees were pleased with the variety and novelty of topics presented.

Presentations will be made available in the HTSLCN section of the IEAGHG website. A potential location for the 9th HTSLCN Meeting in September 2021 is the CLEANKER project in Piacenza/Vernasca (Italy).

Delegates at the 8th HTSLCN Meeting.

Site visit to the LEILAC demonstration plant, Lixhe, Belgium.

Annex

International Steering Committee

Carlos Abanades, CSIC-INCAR, Spain

Ben Anthony, Cranfield University, UK

Ningsheng Cai, Tsinghua University, China

Paul Cobden, ECN, Netherlands

Bernd Epple, TU Darmstadt, Germany

Adolfo Garza, Cemex, USA

Jasmin Kemper, IEAGHG, UK

Dennis Lu, Natural Resources Canada, Canada

Anders Lyngfelt, Chalmers University of Technology, Sweden

Tobias Pröll, University of Natural Resources Vienna, Austria

Matteo Romano, Politecnico Di Milano, Italy

Andrés Sanchez, ENDESA, Spain

Stuart Scott, University of Cambridge, UK

Organising Committee 6th HTSLCN Meeting

Matteo Romano, Politecnico Di Milano

Isabel Martinez, Politecnico Di Milano

Jasmin Kemper, IEAGHG

Organising Committee 7th HTSLCN Meeting

Lawrence Hooey, Swerea MEFOS

Lotti Järlebro, Swerea MEFOS

Jasmin Kemper, IEAGHG

Siân Twinning, IEAGHG

Organising Committee 8th HTSLCN Meeting

Tes Apeldoorn, TNO

Soledad van Eijk, TNO

Ilona Kaandorp, TNO

Jasmin Kemper, IEAGHG

Suzanne Killick, IEAGHG

List of acronyms

Acronym	Explanation
CAL	Calcium looping
CFB	Circulating fluidised bed
CLC	Chemical looping combustion
CLOU	Chemical looping with oxygen uncoupling
CLR	Chemical looping reforming
COE	Cost of electricity
CSCM	Combined sorbent catalytic material
HTSLCN	High Temperature Solid Looping Cycles Network
IEAGHG	IEA Greenhouse Gas R&D Programme
ISCR	International Workshop on In-situ CO2 Removal
LHV	Lower heating value
OC	Oxygen carrier
OTM	Oxygen transfer membrane
PCC	Post-combustion capture
PCLC	Pressurised chemical looping combustion
SADG	Steam assisted gravity drainage
SCPC	Supercritical pulverised coal
SECLSR	Sorption enhanced chemical looping steam reforming
SEM	Scanning electron microscopy
SEM-EDX	Scanning electron microscopy with energy dispersive X-ray spectroscopy
SER	Sorption enhanced reforming
TGA	Thermogravimetric analysis/analyser
TRL	Technology readiness level
USC	Ultra supercritical

Evaluating technology options to mitigate greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

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