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**3RD HIGH
TEMPERATURE
SOLID LOOPING
NETWORK MEETING**

Report: 2011/15

November 2011

INTERNATIONAL ENERGY AGENCY

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DISCLAIMER AND ACKNOWLEDGEMENTS

IEAGHG supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by IEAGHG as a record of the events of that workshop.

The 3rd international research network on High Temperature Solid Looping processes was organised by IEAGHG in co-operation with the Technical University of Vienna. The organisers acknowledge the financial support provided by VoestAlpine, City of Vienna, Energie AG Oberösterreich and Austrian Fenco Initiative for this meeting and the hospitality provided by the hosts at the Technical University of Vienna.

A steering committee has been formed to guide the direction of this network. The steering committee members for this network are:

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3rd High Temperature Solid Looping network meeting
Technical University of Vienna
Austria
29th August – 2nd September 2011

Executive summary

The third meeting of the IEAGHG high temperature solid looping network was held from 29th August to 1st September at the Technical University of Vienna. It was held in parallel with a meeting of the IEA Fluidised Bed Combustion implementing agreement and the International Conference on Polygeneration. This gave the 108 delegates who attended the network meeting the opportunity to meet with those engaged in these other related areas. For this meeting a considerable effort was made to attract members of the Chemical Looping Combustion (CLC) research community which has been less represented at past meetings where calcium oxide looping (CaL) cycles for CO₂ capture have tended to dominate. This should be a useful change as both processes use similar dual fluidised bed hardware and there is also emergence of hybrid schemes employing both types of reaction. Also several of the larger test facilities are now set up to test both CLC and CaL processes using the same equipment.

This year the meeting was extended to 3 days with inclusion of a site visit to two fluidised bed biomass gasification facilities at Oberwart and Güssing, south of Vienna. One facility also had extensive experimental facilities testing Fischer Tropsch synthesis and mixed alcohol synthesis from the gas leaving the biomass gasifier.

This year saw the first results presented from larger MW scale demonstration plants. Further units will start up shortly and thus more results are expected in the coming year. At the present time the operating campaigns are quite short and all recognised the need to build up experience with longer periods of stable operation

Development of both sorbents and oxygen carriers is ongoing. For sorbents the emphasis has now shifted from proving that activity can be maintained for sufficient cycles to be economic to optimising the preparation and re-activation processes to extend sorbent life. It was also encouraging to see work presented on using the technology in the iron and steel industry.

Designs for CaL systems are entering the third generation of process refinements now that the basic system is better understood. Also more new schemes with combinations of CLC, CaL and sorbent enhanced reforming in both fluidised and fixed bed arrangements are being developed.

CLC is also entering a new phase of larger scale extended testing now that around 16 demonstrations of various sizes have been built accumulating some 5000 hours of collective operation. Most notably this has been done with no failures. A number of presentations in the field of CLC discussed the use of so called CLOU materials for combustion of solid materials such as coal. Chemical Looping with Oxygen Uncoupling (CLOU) implies that at the temperature conditions of the fuel reactor the

oxygen carrier exerts a significant partial pressure of oxygen so that combustion does not have to rely solely on gas/solid and solid/solid reactions between the gases/char and the carrier. Copper oxides are the best example of this type of carrier.

The meeting identified a number of important emerging areas for research and development. High on the list is measurement of emissions. There is some concern particularly with CLC that trace metals may be emitted. A key to progress remain enhancing the performance of naturally occurring materials, mainly the limestone but also engineered sorbents and oxygen carriers. In order to support industrial application there is a need for reliable testing and characterisation methods for these materials. Work is already ongoing on this issue at a few institutions. More work needs to be done on the retrofit and integration of the process into power plant and also cement and steel plants. To date much of what has been done has been optimisation of the basic circulating loop. In particular a large amount of heat contained in the hot CO₂ and depleted flue gas stream has to raise steam or be otherwise used in the power plant. Whilst the general principle of how to do this is established the detailed layout of heat recovery coils and steam and water flows needs further work.

CO₂ quality is an issue which needs further study. The extent to which further clean up can be avoided is uncertain. The quality of raw CO₂ may be improved by process improvements in the main circulating loop. Alternatively processes to further concentrate CO₂ could be employed. The trade off between enhancing the capture process and applying further clean up needs to be better understood.

The time has also come for a better understanding of the economics and cost of the process as well as checking and fully understanding the waste disposal and life cycle impacts. The costs are needed to assess viability of commercial scale units. Confidence that costs are competitive with other capture technologies is essential in the process of getting funding committed to larger scale significantly more expensive demonstrations.

For the first time the meeting covered issues of funding and commercialisation for larger scale demonstration. The EU commission outlined future funding arrangements which were in the pipeline applicable to the technology. Researchers from New Zealand showed how they had concluded work on a hydration process for reactivation of deactivated sorbent and were offering this for commercial development. An opportunity first identified last year in the Alberta oilsands for using CLC to generate steam from gas for Steam Assisted Gravity Drainage SAGD was confirmed as having considerable potential at a number of sites and has a real competitive advantage over other processes. Significant research funding may become available to develop this application.

This year saw a further increase in numbers of submitted presentations and posters as well as delegates. For this reason two of the sessions were held in parallel. The need for a format change was discussed but consensus was that a two day meeting should remain the format and that limited parallel sessions could be used. It was agreed that next year abstracts would be requested from potential presenters and these would be used to decide upon the allocation of the scarce number of talks. As the number of posters rises so more time should be made available for the poster session. The site

visit proved very popular and in principle will be retained if a suitable relevant facility worth visiting can be identified. This year the organisers were again able to attract some sponsorship which has enabled the basic fee for the event to be kept low. Tsinghua University confirmed their earlier offer to host the 2012 meeting at about the same time of year. The following year a tentative proposal to hold the meeting in Alberta was tabled.

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Summary of Presentations

1. Calcium Looping I

1.1. Evaluation of Carbonate looping for post combustion CO₂ capture from a Utilities perspective (Sven Unterberger, EnBW Kraftwerke AG)

EnWB is Germany's 3rd largest energy company generating about ½ its electricity from fossil fuel, ¼ from Nuclear and ¼ from Renewables. The company is interested in learning more about Carbonate looping as a technology to reduce its emissions of green house gases. Key factors for the company are efficiency, ease of integration particularly for retrofits, flexibility of operation, HSE and the by-product and waste products. A new power plant designated RDK-8 is planned with a capacity of 900MW, 600/620 C steam conditions giving an efficiency of 46%. The plant will be capture ready. The company is involved in a 300kg/hr CO₂ capture test in a slip stream of flue gas at Helbronn and is also involved in the CaO looping test plant at Stuttgart.

The company is interested in the CaO looping process because it promises high efficiency but the major drawback is still seen as the deactivation of the sorbent which is not yet fully understood. Another issue is the quality of CO₂ produced by the process which may need to be improved. An overview of work being done at lab, bench and test plant scale was given. Key information needed from test plants is for scale up and Capex/Opex estimation. More testing of sorbents is needed to resolve the issues of lifetime and performance. Detailed design for the water/steam/heat integration has to be tackled and the use of alternative fuels such as gas or biomass for calcination needs to be investigated. Another important issue is utilisation of the sorbent purge in the cement industry. The next major step towards commercialisation is considered to be a 20MW scale demonstration plant. Performance benchmarking and validation of the process performance are also essential.

1.2. Status of the La Perida 1.7MW pilot test facility for post combustion CO₂ capture by CaO looping. (Andres Sanchez, ENDESA)

The new pilot plant is now very close to first operation. The unit is in the final stages of commissioning. An overview of the work programme was given. The unit has two reactors 15 m high made of carbon steel with refractory lining. It is equipped with 12 pressure and 10 temperature points and also 3 viewports are available to check the circulation pattern. The unit is fed from a slip stream of flue gas taken from the 50MW CFB boiler at La Pereda. They are circulated by a fan and rejoin the CFB plant upstream of the ESP. Hot gases from the reactors are cooled with bayonet tubes inserted in the flow. The unit is designed to operate over a wide flow range of 700 to 2250kg/hr CO₂. The reactors are constructed in flanged sections with special expansion joints between them. 2 long duration campaigns are planned in the coming year using two different limestones. A 1 day workshop is planned in Oviedo in February 2012 to discuss progress.

1.3. First results of a 1MWth plant for carbonate and chemical looping. (Jochen Ströhle TU Darmstadt)

The test unit has run in both CLC and CaO looping modes. Carbonate looping mode was commissioned in Jun 2011. Initially a series of single bed carbonation tests were performed on 220Kg of CaO of 300-600 μ m at 700-800C. The bed was first warmed with propane burning and then CO₂ is introduced and take up observed.

Thereafter a continuous test was performed with a synthetic flue gas and using propane as fuel in the calciner. Approximately 3 days of continuous operation was observed. CO₂ capture ranged from 60-80%. Initially capture dropped towards 60% but then rose as fresh make up CaO was introduced. CO₂ in the outlet gases was 2.5% compared to the theoretical equilibrium concentration of 1%. So far only a very short period of really steady operation has been possible during which capture was around 73% with the carbonator in autothermal operation at 650C. The power input to the calciner is currently limiting the capture efficiency.

Current plans are to run test campaigns on a) CLC, b) CaO looping but with real coal derived flue gas, 3) CaO with oxyfuel calcining (as distinct from air fired), 4) CaO with external heating to the calciner.

It was noted that the second international conference on CLC will be held at Darmstadt from 26-28 September 2012.

1.4. Attrition of CaO particles under CaO looping conditions (Tadaaki Shimuzu, Niigata University)

A test method was described in which particles of CaO are fluidised in a reactor which is cycled between high and low temperatures whilst undergoing carbonation/calcination. The CaO is diluted with varying amounts of Quartz. (3-5 times dilution). Attrition is measured by filtering out the fine material, reacting it with HCl and measuring Ca⁺⁺ concentration. Attrition rates decrease as activity decreases becoming lowest when activity drops below 0.4. The addition of the quartz increases attrition rate thus allowing testing to be speeded up.

1.5. New methods of improving the performance of Ca looping cycles (Vasilije Manovic, CANMET)

Whilst steam can be used successfully to reactivate CaO particles it does tend to make them more fragile. Work was described in which CaO had been prepared in pelletized form using calcium Aluminate as a binder. This was found to improve both strength and absorption capacity. Catalysts and oxygen carriers can be incorporated in the pellets. Also spent pellet material can be remade into pellets. A further refinement is to use a core/shell construction of the pellets which reduces attrition.

Test were performed on a 3 reactor looping system consisting of an air reactor, a carbonation reactor and a calciner. CuO was used as the oxygen carrier. It was found that excess air in the flue gas could be used to supplant the air reactor. The system was run for 10 complete cycles during which oxygen activity was found to be stable but CaO activity was reducing.

1.6. Attrition of limestone during calcium looping cycles for CO₂ capture in fluidised beds (Fabrizio Scala, CNR Naples)

The results of measurements of particle size distribution changes and fines elutriation rates were presented. Tests were done in a 40mm diameter tube and materials were recycled batchwise 5 times. Samples of 20g lime were mixed with 150gm silica sand. Tests were done with 3 conditions of calcination/carbonation and also with high and low sulphur gases. Results showed that most fines are produced early in the calcination and most are produced in the first cycle. Higher calcination temperatures produce more fines. Also higher sulphur experiments showed increased fines production. Calcination in the presence of CO₂ was found to enhance sintering but reduce fines production.

It was announced that the 21st FBC conference will be held in Naples from 3-6th June 2012

1.7. Aspects of CaO hydration (Paul Cobden, ECN)

The effect of using steam to restore capacity of CaO has been extensively researched. Hydration using steam is only effective at temperatures below 400C and 300C was found to be a good regeneration temperature. Above 400C there is no regeneration effect. Partial pressure of steam needs to be 0.3 bara. Between 1 and 2 moles of steam per mole CaO are needed. Best results are obtained when the cool down (post calcination) and heat up (pre carbonation) are done under dry conditions. I.e steam only introduced once hydration temperature is reached.

The maximum jump in capacity is obtained with a steam/CaO mole ratio of 1 and the maximum capacity is obtained with a ratio of 2.

ECN noted that they had recently moved to a new lab and could not initially reproduce the results. However this was found to be due to contamination by Silica in the silicone oil present in the new apparatus.

Introducing a hydration step in a continuous process would require a 3rd bed. Despite the effectiveness of hydration in restoring capacity the addition of a third bed needs to be justified. Also, it is important to determine whether hydration is necessary every cycle.

2. Calcium Looping II

2.1. Steam improved Carbonation of CaO and its effect on the sorption enhanced watergas shift reaction. (Zenshan Li, Tsinghua University)

Experiments were conducted in the range 400-620C in a 30mm diameter reactor. At 400 °C without steam addition there was only 5% conversion. At 500C steam addition greatly enhances conversion approximately doubling it but by 620C there is very little additional effect. In cyclic experiments (10 cycles) reaction increased from 30% to

45% when 10% steam was added. The steam appears to enhance the surface diffusion of CO₂ which forms on the particle surface through the WGS reaction. Catalyst has to be present on the surface otherwise the WGS does not proceed.

2.2. Pilot plant results for calcium looping processes: Hydrogen production from biomass and CO₂ capture from fossil fuelled power stations. (Heiko Dieter, Stuttgart University)

For H₂ production the gasifier is a bubbling fluidised bed with a low velocity and the calciner is a circulating fluidised bed with high velocity. The optimum gasification conditions were found to lie between 600 and 700C. 650C was the optimum to maximise hydrogen concentration in the product gas.

For CO₂ capture the carbonator has a higher velocity to give a turbulent flow fluidised bed regime. Calcination was effected using 3 stage oxycombustion which proves to give a very high fuel burnout. So far about 600 hours of stable operation has been accumulated. One good example is a 6 hour run with Calciner at 930C, carbonator at 615C with 15% CO₂ in inlet gas an outlet of <2% CO₂ was achieved. Tests have been performed with both dry and wet flue gas. It has been found that below 640C the presence of extra steam enhances capture enabling capture rates as high as 94%. Sorbent losses were found to be about 5% per hour as a result of attrition of the bed inventory.

2.3. Dual fluidised bed steam gasification of solid biomass coupled with in-situ CO₂ capture. (Cristoph Pfeifer, TU Vienna)

The object of the scheme was to migrate from operation as a conventional biomass gasifier with Olivine circulation. In the 8MW pilot plant gas containing 36-42% H₂ is produced. This is accompanied by 4-8gm/NM³ of tars. In the SEWGS scheme with a CaO sorbent hydrogen levels of 55-70% have been reached and tar, due to the catalytic effects of CaO dropped to 0.3-0.9 gm/NM³. If temperature could be lowered to 600C then as much as 85% hydrogen should be possible.

The tests are ongoing and future plans include reduction of the attrition which is occurring in the cyclones, increasing the residence time in the gasification zone and widening the flexibility to handle other feedstocks. Consideration is being given to moving to a circulating fluidised bed configuration with internal restrictors. Moving to smaller particles should also allow lower velocities and hence less attrition. Currently attrition rates far exceed degradation of sorption capacity.

2.4. Measurements of the quality of cement produced from looped limestone. (Charles Dean, IC London)

Cement contains 670Kg of CaO per ton and thus requires 1200kg as CaCO₃. Per ton of cement production approximately 528kg of CO₂ are released in the calciner, 126kg in pre-calcining and a further 168kg from fuel consumed in the process. Utilising spent sorbent in cement would thus greatly impact emissions. The cement process consists of a number of reactions the main ones being production of Belite

(2CaOSiO_2) at 900-1200C and the onwards conversion to Alite (Ca_3SiO_5) at 1200-1400C. Alite imparts early strength and Belite later strength to Portland cement. Other elements can either enhance or reduce cement quality. Experiments were performed in a 3KW smelted bed reactor in which cement was produced from sorbents. Presence of MgO and ZnO was found to reduce cement quality. The formation of sufficient Alite is a key to cement quality. In experiments so far conducted one case in which Ba and Cr compounds were present, these were found to enhance Alite formation. In general elements present in fuel tend to enhance Alite formation. It can be concluded that spent sorbent can be incorporated into cement possibly in considerable proportions, but careful analysis and control of the blending and clinker production processes will be essential.

2.5. Novel synthetic Ca-based sorbents for CO₂ capture. (Christoph Müller, ETH)

The routes to an ideal synthetic sorbent were discussed. Sol-gel processes combined with a supercritical drying step can produce excellent synthetic sorbents. CaO/Al₂O₃ precursors are used and synthetic materials with better capacity and slower degradation were found. The key to performance is the correct Ca/Al ratio and choice of the precursing compounds.

3. Calcium looping III

3.1. Conditions of CFB Ca looping Coal gasification. (Shying Lin, Japan Coal Energy Centre)

Work on this process under the HyPr Ring project involved operation of a high pressure gasifier and a low pressure regenerator. Solids transfer was through a lock hopper system. The next generation moving towards a practical process is to develop a lower temperature gasification and to perform the calcination at 3Mpa requiring a temperature of 1000-1100C. An arrangement in which a pyrolyser running at 800-900C is placed above a char gasifier operating at 650-750 is proposed.

Recent work has been undertaken to characterise the decomposition of 5 different limestones. Two, Chichibu and Kusu are from Japan and a further three, Dawa, Yangguan and Deying Dolomite all for China. Purity of CaCO₃ varies progressively from 98% CaO down to 52% for the dolomite.

Decomposition was measured using thermogravimetric analysis. Findings are that decomposition temperatures are less than theoretical by about 100C and even more when impurities are present. It is thought that eutectic formation may be responsible for this observation. An AspenPlus analysis of the process has been performed and showed a CaO Coal ratio of 5.071 and an O₂ to coal requirement of 0.857 t/t coal.

3.2. Internal strain on stability of hydrated CaO for high temperature CO₂ capture. (Roger Molinder, Leeds University)

The exact role of water in the effects of CaO hydration is unknown. It does however reduce the strength of the particles. TGA can be used to follow calcination but it

cannot distinguish between loss of water or CO₂. In this research XRD experiments were run in parallel so that the possible role of water could be seen. An XRD analyser was fitted with a special heated sample zone and results of heating compared to those obtained for similar temperature trajectories with TGA. Suitable non overlapping peaks for CaO and CaCO₃ were chosen to determine the amount of decomposition and compared with the TGA results. 12 XRD scans were made at each temperature during the decomposition process. XRD clearly showed higher levels of conversion to CaO than TGA suggesting that water in the form of hydroxide would be responsible for the difference. However there were other possible causes for the difference each of which was systematically investigated and eliminated. The width of the XRD peaks gives an indication of the presence of lattice strain, wider peaks – more strain. It is possible that formation of a hydroxide “shell” is the cause of anisotropic strain in the samples investigated.

3.3. Characterisation of CO₂ sorbents for application of DFB processes. (Jochen Brellocks, ZSW)

ZSW are using a DFB test rig with 100 and 50mm diameter reactors. They also use a pressurized TGA which can be operated up to 1200C and 40bar. Other characterisation tests are for attrition using a small ball mill, XRF and XPD analysis. Microscopy is also used to ascertain the nature of the natural sorbent materials which may display different facies, coral, oolitic, micritic etc. Finally Polarising microscopy can be used and is able to follow calcination. A programme to correlate technical and geological properties of limestone materials has been started using this range of test equipment.

3.4. Process Integration of Ca-looping process with cement manufacturing. (Hyungwoong Ahn, University of Edinburgh)

Production of cement releases 0.72 to 0.98 t/t of CO₂ and this represents around 5% of global emissions. About 60% of the emission is from the dissociation of limestone and the rest from fuel. The theoretical heat of formation of clinker is 1757Kj/Kg compared to about 3306 Kj/Kg actually needed in practical processes. The cement process releases CO₂ and then causes reactions between CaO, Silica and other materials present to occur at high temperature to produce the finished clinker. An integrated capture process was evaluated in which flue gases from the 3rd pre-heater in the cement process are routed to a carbonator. Flue gas from the carbonator is returned to the 2nd preheater. The simulation shows that for this retrofit energy consumption is doubled as it increases by about 3570KJ/kg. The purge of sorbent can however be added to the clinker increasing production by about 10%. It was noted however in questions that this calculation took no account of the electrical energy which could be produced from the hot flue gas and CO₂ leaving the integrated process.

3.5. Thermodynamic analysis of different SE-SMR combined cycle based plants. (Matteo Romano, Politecnico di Milano)

A system comprising a SOFC with SOFC heat routed to a calciner was investigated. Hydrogen is produced in a reformer at 25bar, 700°C with an S/C ratio of 4.5. The calciner in the process runs with steam dilution at 1050°C and is under pressure. The calciner off-gas is routed first through an expander exhausting at 0.3bara as this was found to maximise efficiency. A variant in which oxygen for the calciner is produced using an O₂ membrane was also evaluated. Advanced simulation software for turbine efficiency calculations was used. Overall power generation efficiency was calculated at about 50% similar to other gas fired processes with capture.

3.6. A novel pressure swing adsorption process for low cost CO₂ capture at high temperature. (Junjun Yin, University of Queensland)

Development of a hot PSA process running at about 700°C with a target switching time of 1 minute for the beds was presented. Although thermodynamically feasible the process may lack real applications as pressurised flue gas at 700°C is not a stream which is found in current power production practice.

4. Chemical Looping I

4.1. Degradation of NiO/NiAl₂O₄ carriers in both fluidized beds and fixed bed chemical looping combustion. (Erin Kimball, TNO)

A programme of work to characterise oxygen carriers done jointly by TNO, IFPEN and SINTEF was described. Two reference materials have been chosen, NiO/NiAl₂O₄ a good reference for natural gas combustion and Illmenite (FeTiO₃) which is cheap and good as a reference for syngas or coal combustion. Two synthetic materials developed one by SINTEF (CMT Calcium, manganese, titanium) and the other by IFPEN (CFA Copper, iron, aluminium) have also been chosen for investigation. Results of work on the nickel based material were presented. Material is subjected to attrition testing typically for 3 hours in a jet cup device and results reported as percent particle below 20 and 44 microns. The material showed slightly worse attrition than typical FCC catalyst. Material is then tested in both a fixed bed and fluidised bed set up. The advantage of the fixed bed set up is that impact effects causing attrition are eliminated. Also by taking samples along the bed length the effect of the passing reaction fronts can be explored. Test are performed with different degrees of conversion. In the fixed bed situation oxidation and reduction activity steadily declines when there is incomplete conversion whereas it rises somewhat erratically with increasing number of cycles. Test in the fluidised bed showed much higher loss of surface area when higher conversions (65% v 32.7%) were adopted. Tests will be soon be done on the other three materials.

4.2. Chemical looping combustion of syngas in packed beds. (Paul Hamers, TU Eindhoven)

Simulation of a pair of fixed bed reactors consuming syngas in a chemical looping combustion system was described. Fixed beds were chosen as these are easier to operate under pressure and this enables higher power conversion efficiencies to be reached. The oxidation reactor in the simulation is fed with air preheated by the fuel reactor with conditions set to give an outlet of 1200°C at 20bar from the air reactor. Analysis of the reaction in 1D shows that the temperature rise across the reaction front is steady and is determined by the Heat of reaction and the fraction of active material in the bed. To give a 600°C rise it was shown that Ni based carriers needed to be less than 0.2, Cu about 0.22 and Mn around .45 of the bed fraction respectively. The temperature change across the reaction front in the fuel reactor is much smaller and increases with increasing hydrogen fraction in the syngas. With Ni carriers it is typically in the range 80-110°C. Simulations show that flow rate has to be kept within limits to avoid fuel slip. The conclusions so far are that the system is theoretically possible but further work needs to be done to develop suitable carriers, to study possible side reactions such as coking or water gas shift and to ensure that development of hotspots can be controlled. Initial tests on a MnMgAl₂O₃ carrier at 800°C have shown stable weight gain and loss through 50 cycles. .

4.3. A coupled fluidized bed system for chemical looping combustion – cold model investigation of the operational behaviour (Andreas Thon, TI Hamburg-Harburg)

A plexiglass cold flow model consisting of an air reactor in the form of an 8 meter riser with cyclone and a fuel reactor consisting of two bubbling bed reactors in series was described. Silica sand of 165µm is used as the circulating solid. The reason for modelling 2 fuel reactors in series is that this is expected to be required to get full combustion of CO and H₂ formed by gasification of the intended coal fuel. The model was used to explore the control of the circulation and the crossover of gas flows between the reactors which need to be kept to a minimum. The pressure drops across the air reactor and fuel reactors have to balance to minimise crossover flows. Various alternatives were tried including changing the riser velocity and pressurising either the fuel reactor or the air reactor. CO₂ was injected as a tracer gas to enable the extent of crossover to be measured. About 3% leakage back to the fuel reactor was measured. Elevating fuel reactor pressure reduces this slightly but the main cause is thought to be entrainment of gas with the particles falling down the standpipe leading back to the fuel reactor below the cyclone at the exit of the air reactor. A modification is being considered to reduce this. The model confirms that adequate stable solids circulation can be achieved with minimal cross leakage.

4.4. Experience with high temperature operation of a rotating bed reactor for chemical looping combustion of Methane. (Richard Blom, SINTEF)

This CLC concept makes use of the alternative of moving the entire reactor bed rather than moving the carrier material as in double fluidised bed systems or cycling the feed

as in fixed bed systems. An early Japanese patent envisaged a circular moving bed in for example the capture and release of CO₂ from flue gas at high temperature using a rotating wheel coated with reactive lithium zirconates.

A radial flow system was chosen as this best suits the expansion in volume of the air and fuel flows across the bed. Fuel and air are introduced through two opposing radial segments to flow radially across the bed. Between these inlet ports two smaller segments are placed through which a sweep flow of for example steam can be applied to reduce mixing through leakage across the segment seals. A small reactor using these principles was constructed and tested for the combustion of Methane. The reactor bed was a cylinder of nickel based oxygen carrier of 20cm internal diameter and 30cm external diameter and 40cm high.

Experiments were carried out at temperatures between 650°C and 800°C. Methane conversions of over 80% were achieved with CO₂ capture rates of up to 80%. CO₂ purity varied from as low as 20% to a maximum of 65%. Because of the very small size of the reactor there was significant leakage which accounts for these comparatively low figures. Scale up is likely to have very favourable effects on reducing these inherent leakages.

Scale up to 400MW was investigated and concluded that for pressurised operation at 30Bar a bed of 2.8 M radius but only .32m thick and 2m high weighing 24ton would be required. The concept seem thus to be mechanically feasible at large scale. However this compares with a massive bed of 730tons for atmospheric operation.

Test will continue to include temperatures up to 900°C and further variations in other conditions and funding for larger scale demonstration is being sought..

4.5. Technical approach for chemical looping combustion of solid fuels – first results of batch experiments using wood and bituminous coal. (George Schwebel, University of Siegen)

The development and results from a small scale fixed bed batch reactor designed to investigate the behaviour of solid fuel particles within a bed of oxygen carrier material was described. A few tenths of a gram of fuel particles are introduced through a tube between 25mm high layers of oxygen carrier. The gasification and combustion process in the presence of air with 20% steam addition is then followed. The results show enhancement of the reaction by the oxygen carrier and for wood pellets show complete conversion of carbon prior to the air oxidation cycle. For coal a small amount of residual carbon is left and converts to CO₂ during the oxidation cycle.

4.6. Off design performance of a double loop CFB chemical looping cold flow model with focus on divided loop seal (Aldo Bischi, NTNU)

A full scale cold flow model of a 150Kw double circulating fluid bed reactor system was operated to explore the control and stability in off design conditions. The division of flows was possible in both loop seals and was investigated as a means of control. The system uses FeSi powder of 7000kg/m³ density and starting average size of 34µm. However after circulation this increased to about 50 µm due to loss of fines.

As a result of the programme some improvements were made to the loop seals for example increases in height of return legs and loop seal overflow heights. Tests were

performed at 70% and 50% throughputs. A good correlation was found between solids flux and cyclone pressure drop which should be useful for easy estimation of solids flow.

5. Chemical Looping II

5.1. The European Commission's perspective on Emerging CCS technologies (Peter Petrov, European Commission)

The current and future strategy and funding were outlined. The aim for Europe is to invest 3% of GDP in research, a target which is not yet met. Overall strategy to 2020 is encapsulated in the 3x20% objectives of reducing CO₂ emissions by 20%, improving energy efficiency by 20% and raising renewables share of energy to 20%.

The overall strategy is in the strategic energy technology plan published in 2005. EU initiatives on CCS include a programme of CCS demonstrations and funding of R&D to improve and extend application of CCS. FP7 allocated 140MEuros and 100MEuros is still left for CCS in the FP7 programme. Two calls are of relevance for high temperature looping:-

Energy-2012-2 area 5&6 to submit by 22 March 2012 (22MEuro)

Energy-2013-1 Pilot demo of new capture technology and Next generation sorbents.

After FP7 Horizon 2020 is in development and will cover societal challenges, competitiveness, research excellence with a large research budget 50-100% greater than current.

5.2. Operational experience with Chemical Looping Combustion of gaseous and solid fuels (Anders Lyngfelt, Chalmers University)

To date 16 chemical looping plants of varying size have been placed in operation and about 4500 hours of operating experience has been accumulated. The capacities range from 300watts to 140Kw. Of particular significance is the development of CLOU (Chemical looping oxygen uncoupling) carriers. The key principle is that at temperature in the fuel reactor these carriers decompose to provide a source of gaseous oxygen which enables much better combustion of solid fuels. Typically a partial pressure of oxygen between 1 and 5% at equilibrium would be maintained. Copper oxides are particularly suited as CLOU materials and show rapid oxygen release typically <30 seconds. This allows burning of char and complete burn out of gaseous components which is important because full contact between solids and gas is difficult in fluidised bed systems. With non CLOU materials fuel conversion even of gas is so far limited to 90-95% and CO₂ capture is limited to 96%.

The alternative to employing CLOU materials is to use oxygen polishing whereby the final burnout is accomplished by injecting supplementary oxygen.

5.3. Recent research on Chemical looping at Cambridge (John Dennis, Cambridge University)

Experimental work with iron oxides was described. Materials were prepared by mechanical mixing, co-precipitation and sol-gel methods. Three stages of reaction occur during a CLC cycle with separate fronts moving through a fixed bed system. Gas is converted to Hydrogen and CO, this is further oxidised to CO₂ and steam and finally the essential regeneration step is air re-oxidation of the bed. Fe₃O₄ is first reduced to FeO and then on to metallic iron. The first reduction was found to start with a CO₂/CO ratio of 2.47 or less and reduction on to iron begins only when this ratio falls below 0.5. The supporting material was found to affect the reduction reactions. With Aluminium oxide support experiments could reach no more than 50% conversion to hydrogen but with a zirconium oxide the system could move to 90% conversion in this step. Some coking occurs and is made worse by use of aluminium oxide supports.

5.4. Chemical looping combustion of sour gas (Allan Chambers, Alberta Innovates)

This presentation was a follow up from last year when the significant advantage of CLC for producing steam for Steam Assisted Gravity Drainage (SAGD) recovery from oil sands was described. Currently 0.5 million bbl/day of oil are produced using SAGD but a further 1million bbl/day of production spread over at 26 sites is projected. Approx 2.5bbl of water are used b per bbl oil and the currently installed 6GW of steam raising is projected to increase by a further 12GW to service this expansion. Natural gas is the preferred fuel as it currently is available for 2-6\$/Gj and alternatives only become affordable if this goes above \$10-12 per Gj. Projected costs of steam raising with CO₂ capture are \$92/ton with 89.7% capture versus \$175/ton with only 70% capture using the next most affordable process.

Because the available natural gas is sour the impact of up to 2000ppm H₂S on CLC is being investigated. Tests are done in a fluidised bed on 5.5cm diameter 111cm high using nickel oxide as the carrier. H₂S causes a large spike methane breakthrough. It reacts with the NiO during the reduction phase and appears to uniformly distributed across the reactor. Interestingly the sulphur is released as SO₂ at two points during the cycle, there is a release at the start of the reduction step but also during the middle part of the oxidation step. Presumably some sulphur reacts with the nickel and is subsequently removed during the oxidation. Whilst a niche application the potential is very large in this particular SAGD oilsands application. Supporting funds are available for further research.

5.5. Evaluation of direct Coal CLC processes. (Alberto Abad, CSIC)

Experiments with CLC of coal using two oxygen carriers were described. Ilmenite and a CLOU material 60% Cu on an MgAl oxide support prepared using a spray drying process. CLOU (Chemical Looping with Oxygen Uncoupling) materials exhibit a partial pressure of free oxygen at reactor conditions enabling gas phase oxidation reactions to occur). For the CLOU reactions residence times of 2-7 minutes were used. The non CLOU material Ilmenite showed incomplete combustion of

gases. Fuel reaction temperatures were max 960°C whereas more than 1000°C is needed. Long residence times of up to 30 minutes are also needed. In contrast the CLOU materials achieved 100% combustion and some oxygen is present in the exit of the fuel reactor. Char conversion was 99% and as a result the production of CO₂ in the air reactor was very low. The char burn rate is estimated to be about 60X higher using CLOU materials. No oxygen polishing would appear to be needed to achieve full combustion with CLOU oxygen carrier.

5.6. Novel concepts of looping combustion of solid fuels (Piero Salatino, University of Naples)

In fuel reactors with conventional oxygen carriers the solid - solid reaction is a limitation. Oxidation tends to occur through a process of gasification followed by oxidation. Experiments were performed with CLOU materials in order to measure the limiting step which is the release of oxygen. This was done by adding a large excess of fuel, about 200%. Release rates of the order of 0.1min⁻¹ were measured indicating that residence times of several minutes would be required for complete conversion of the oxygen carrier.

Work had also been done on a novel concept which was to use Carbon as an oxygen carrier. Proposed as the “Carboloop process” Oxygen adsorbs strongly on finely divided carbon and this uptake occurs quickly at temperatures in the range 300-400°C. Approximately 5-10% of the oxygen required for combustion can be taken up at each cycle. A cycle working at 300/600°C was proposed. (Note: For use with coal as the prime source of the carbon some means to deal with the volatiles would be needed)

6. Public Workshop of the EU Project INNOCUOUS on Innovative Oxygen Carrier Materials

6.1. Introduction to INNOCUOUS (Anders Lyngfelt, Chalmers University)

Anders Lyngfelt from Chalmers University of Technology gave a brief overview about the major tasks within the INNOCUOUS-project. INNOCUOUS stands for Innovative Oxygen Carriers Uplifting Chemical Looping Combustion. Oxygen carriers represent the fundamentally new aspect of chemical looping technologies, and they are responsible for the overall process performance in terms of capital and operation costs as well as for health, safety and environmental issues. Thus, INNOCUOUS was started to reach the following key objectives concerning oxygen carrier and chemical looping process development:

- development of new reactive oxygen carriers based on metals other than nickel
- highly reactive materials with reduced nickel content and mixed oxide materials
- optimization of scale-up ready particle manufacture
- testing of new particles under relevant conditions
- overall process integration and next scale design of CLC

6.2. New combined oxide materials (Peter Hallberg, Chalmers University)

Oxygen carrier particles based on MnMg, CaMn and Cu have been investigated in batch experiments within a lab-scale fluidized bed apparatus. The test results include particle reactivity towards syngas and methane, the influence of particle sintering temperature on their crushing strength (attrition characteristic), the influence of operating temperature and the oxygen release ability within an inert or reducing atmosphere. Furthermore, the particle performance after a number of several redox cycles has been investigated. The conclusion of this work is that some of the tested materials showed very good results with even full conversion of methane and successful performance without any attrition in continuous operation.

6.3. Chemical-looping combustion of gaseous fuels with synthetic Fe and Cu based oxygen carriers (Juan Adánez, CSIC – ICB Zaragoza)

The objectives of the work presented were to investigate and to improve the performance of Fe- and Cu-based oxygen carriers with no or little Ni content. The test campaigns with Fe-based materials have been carried out inside a 500 W continuous working pilot rig and with methane as fuel. Fe₂O₃-Al₂O₃ impregnated particles converted methane completely at high temperatures (880°C) and no improvement was achieved by running experiments with Fe-Ni-OC under the same conditions. Experiments also showed that impregnation of Fe and Ni on the same particle leads to worse performance compared to an operation with a mixture of Fe- and Ni-OC. The Al₂O₃- impregnation also increased the oxygen capacity of the particles and no problems with agglomeration have been seen (FeO avoided, reduction to FeAl₂O₄). Beyond the INNOCUOUS project framework, the testing of CuO₁₄- γ Al impregnated particles, optimized for high operating temperatures (no agglomeration), within a 500 W and a 10 kW continuous unit has been presented. Results show successful conversion of fuel at T= 800°C where no agglomeration problems occurred. The influence of sulphur has been investigated and no decay of reactivity has been detected. Even though attrition resistance was improved through impregnation, the particle lifetime needs to be improved further to reduce the costs of Cu-based oxygen carriers for CLC applications.

6.4. Preparation of oxygen carriers for chemical looping combustion by industrial spray drying (Jasper VanNoyen, VITO)

VITO's role within the project is to deliver oxygen-carrier batches produced by spray drying. The spray drying process has a high potential for scale-up with expected capacities up to 100 tons/h. Therefore oxygen carriers produced via spray drying are currently under investigation at partner institutions. Experimental results will be used to find whether spray drying could deliver oxygen carrier materials with flexible characteristics (composition, size range, mechanical strength, ...) in large amounts and if it is superior to other technologies such as freeze granulation or particle impregnation.

6.5. Effect of sulfur and higher hydrocarbons on chemical looping combustion in a 120 kW pilot plant (Karl Mayer, Vienna University of Technology)

A test campaign within a 120 kW CLC pilot plant was conducted to investigate the influence of fuel-related sulphur contaminations and contents of higher hydrocarbons on the process performance. Oxygen carrier particles produced by VITO as well as fuel consisting of hydrocarbons up to pentane have been tested and compared with results from a reference experiment performed with natural gas. The results clearly confirmed that methane is the most critical hydrocarbon in terms of complete conversion. The influence of sulphur was investigated by adding 48 ppmv of H₂S into the fuel reactor, leading to an expected decline of performance due to deactivation of oxygen carriers. However, stable operating conditions during sulphur treatment as well as regeneration of particles back to their initial performance prior to sulphur treatment have been achieved.

6.6. Overall process integration and CLC next scale design (Otmar Bertsch, Bertsch Energy)

As an experienced boiler manufacturer, BERTSCHenergy is responsible for the evaluation of the CLC process integration for large scale power production. Based on the 140kW CLC pilot rig from Vienna University of Technology, an adapted and up-scaled 10 MW fuel power design for a demonstration plant was proposed. For steam generation the air reactor was equipped with membrane walls and a bed material cooler was placed adjacent to the upper loop seal. In addition to this, economiser, super-heater and air-preheater heat exchangers were added to the exhaust gas streams of both reactors. Simulation in IPSEpro have been performed and results show that with this CLC process configuration, generation of 11.6 tons/h steam (65 bar, 450°C) with 92 % efficiency is possible.

7. Calcium looping IV

7.1. Calcium Looping development studies at Cranfield University (Alison Cotton, Cranfield University)

Cranfield has a test facility comprising a Perspex cold model and a 25kw thermal reactor system. The cold model uses copper particles which are selected to satisfy dimensionless scalability criteria. The hot reaction system has an entrained flow carbonator and a bubbling bed calciner. It can work at up to 1000°C and 15bar pressure.

Some analysis of emissions from the hot system has been performed and trace elements Mg and Ni were detected. It is possible that the nickel originates from the stainless steel reactor as the content in lime is very low but does contain Mg.

7.2. The kinetics of CO₂ absorption through pressure swing cycling of CaO. (James Butler UBC)

A pressure swing system has the potential to reduce the amount of heat required for capture using CaO. The main effect is through reduction of the temperature swing and hence the amount of sensible heat required for heating solids for calcination. Cycles operating between 0 and 5, 0 and 10 and 0 and 20 barg were investigated. For the lowest pressure cycle (5barg) a capacity of 0.15 was approached asymptotically over time and number of cycles. However calcining at 10 bar gave a residual capacity of 0.2 which was tending to rise rather than fall after 20 cycles. At 20 bar the same effect was seen and the capacity was up to 0.35. Experiments were done to determine the kinetic rate and used to infer the surface area. At a temperature of 975°C and a pressure of 1 bar an increase in surface area was noted after 20 cycles but not at higher temperatures. The theory put forward to explain this is that sintering is reducing area but also as grain boundaries are eliminated new area is being created. Small nodules are forming, thought to be at nucleation points where carbonation is starting. Elevating the pressure is enhancing the formation of new surface through this process.

7.3. Developments in Ca(OH)₂ superheating.(Vlatko Materic IRL New Zealand)

Two routes in which a hydration step is included have been tested. A standard method is to hydrate the calcined material at 300°C and then heat to 450°C for the reactivation. Whilst this works it does induce some breakage and hence loss as fines. An alternative method is to hydrate as normal at 300°C and then to expose to CO₂ at a higher temperature of 540°C. This produces less fines 0.9% v 1.44% in tests. A mechanism whereby Ca(OH)₂ becomes superheated above its equilibrium decomposition temperature is behind the effect of reactivation by hydration. The design of a suitable hydration step could either be integrated into the main circulating cycle or be a stand alone cycle perhaps less frequent than the main cycle. Steam used in the hydration step is recycled.

Economics have been run and increasing activity from 7.5% to 30% by applying hydration is estimated to give a cost advantage of \$11.4 per ton. The cost of the reactivator for a 100MW unit is estimated to be \$5.3M. Now that the fundamental work on this process has been progressed to this stage IRL would like to transfer this superheating technology.

7.4. Effect of calcination temperature on cyclic CO₂ looping using pretreated dispersed CaO regenerable sorbent. (Stefano Standardo, ENEA)

Sorbents consisting of 75% and 85% CaO on Mayenite (Ca₁₂Al₁₄O₃₃) have been prepared using the following sequence. Dry at 120°C, grind, part calcine at 500°C under 3 atm of CO₂, grind again add water and calcine at 800°C upon which binder forms. Give a final grind to complete preparation. In tests this material was found to improve its capacity over time after about 6 cycles. The addition of water during grinding in the preparation sequence seems to increase the pore area.

7.5. Recent developments in Endex calcium looping. (Rowena Ball, Australian national University)

The Endex concept was briefly explained, the key feature being coupling of the endothermic and exothermic reaction zones by heat transfer through the reactor walls. An exergy analysis of the system is being done and expected to demonstrate the high energy efficiency of this approach. Although advantageous in theory the hardware necessary for the heat transfer and also for transfer of the solids in the CaO looping process between the high and low pressure reactors is yet to be developed.

8. Posters

A total of 22 posters were displayed, some summarising work related to that covered in presentations.

Key conclusions are as follows:-

8.1. Application of the Ca looping coal gasification residue to iron making Industry (Shiyang Lin, Japan coal centre)

Spent material can be used to replace lime in the iron ore sintering process without loss of quality. Considerable cost savings and CO₂ emission savings are possible

8.2. H₂ production and CO₂ capture from biomass using a double Ca-Cu chemical loop (Nuria Rodriguez, Dennis et al - Cambridge University and Abanades et al - CSIC)

From simulation work of a 100MW unit a process seems feasible for production of Hydrogen from biomass without emission of CO₂ using a three fluidised bed reactor system with a Ca-Cu carrier. Ratios of Ca-Cu need to be 1.75 for adiabatic reduction using natural gas and 0.96 if the synthesised gas is used.

8.3. Experimental development of a Ca/Cu for energy/hydrogen generation (Ramon Murillo-Villuendas et al CSIC)

A carrier for use in the proposed fixed bed cyclic process was formulated and tested. A Cu/Ca ratio between 1.3 and 3 is needed depending on choice of fuel. A 60% Cu material was formulated and tested for reforming and oxidative performance. Although the oxidation/reduction tests were successful it was noted that the catalytic activity of the material for reforming would need enhancement by addition of other catalytic components.

8.4. A synthetic stabiliser for calcium based sorbents for use in CO₂ looping (Sultan et al, Cambridge University)

A carrier of Mayenite and MgO was found to slow the rate of deactivation of Piaseck limestone when a hydrolysis method was included in the preparation of the material.

8.5. Enhancing the rate of gasification of solid fuels and their use in chemical looping combustion (Saucedo et al, Cambridge University)

Fundamental measurements of gasification rate have been made finding wide variations according to type of fuel. Gasification of bituminous coals is particularly slow. Finding ways to complete gasification of char or to remove and process char from the oxygen carrier before return to the air reactor are essential for an efficient chemical looping process.

8.6. Preparation of oxygen carriers for chemical looping combustion by industrial spray drying method. (Van Noyen et al, VITO and Lyngfelt et al Chalmers University)

Material produced using an industrial scale spray drying process were compared with those from a freeze granulation method. Properties of the materials proved to be very similar. No particular barriers to production on a large scale using the spray drying method are foreseen.

8.7. Next scale chemical looping combustion – design evaluation(Marx et al, Vienna University of Technology)

Design considerations for scale up to 10MW are presented. A system in which water wall cooling of the reactors and a fluidised bed cooler for solids returning to the air reactor is proposed rather than extracting all the heat via the reactor exit gases. This is expected to give better operational control and flexibility and better overall efficiency.

8.8. Effect of sorbent particle size on CO₂ capture capacity of the calcium looping cycle (Cotton et al, Cranfield University)

The effect of particle size was evaluated and particles of 125-250 μ m found to be optimal. Smaller particles (<125 μ m) tended to agglomerate and also experienced higher losses. Larger particles (>250 μ m) exhibited lower activity.

8.9. Investigation on ceria and doped ceria supported oxygen carriers for CLC applications (Leion et al, Chalmers University)

Ceria and Gadolinia doped Ceria supported CuO, FeO and MnO carriers were produced using an extrusion process. The doped Ceria supported carriers showed

better performance than the un-doped. Cu materials had good activity iron less so but better than expected whilst Manganese based material showed very low reactivity. This latter is thought to be due to interaction between the oxides.

8.10. The influence of high temperature steam on the reactivity of CaO sorbent for CO₂ capture (Florin et al Cambridge University)

Experiments on 4 limestones show that steam at concentrations from as little as 0.1% up to 20% enhances activity of the sorbents. Beyond that concentration there was no further effect. The improvement correlates with reduced reduction in pore volume and BET surface area.

8.11. Pilot Plant results of the calcium looping process for CO₂ capture from power plant flue gas (Hawthorne et al IFK Stuttgart)

This poster complementing the presentation on hydrogen production in the same pilot plant. 500 hours of successful stable operation in this mode has been logged. A high capture efficiency of ~90% was achieved and full calcination of the sorbent. Steam was found to greatly enhance the carbonation reaction. Losses of sorbent were low at around 5% of the inventory per hour.

8.12. One dimensional modelling of chemical looping combustion in dual circulating fluidised bed system (Peltola et al , Lappeenanta University)

A model has been built to simulate CLC in a dual circulating bed system using Matlab and Simulink software. Reactors are modelled as a series of well mixed sections. Predictions of circulation rate and conversion etc. can be produced but validation against experimental results is needed.

8.13. Chemical looping combustion of solid fuels as a heat source for a regenerative Rankine cycle. (Gipperich et al, University of Siegen)

A CLC reactor system to feed a 450°C, 40 bar Rankine cycle is underdevelopment. Simulations have been carried out based on combustion of a solid beech with 21.5% moisture content using an FeTi oxygen carrier. Efficiencies are estimated to be 33.83% without and 30.46% with CO₂ compression. The equivalent using conventional combustion coupled to the same Rankine cycle would be 31.3% efficient dropping to only 19.94% for conventional post combustion capture making the process likely to be competitive in a carbon constrained situation.

8.14. Direct solid fuel CLV using biomass (Penthor et al Vienna University of Technology)

A model for a CLC reactor system in which the fuel reactor has several well mixed zones in series has been constructed. The concept is based around a reactor with

several narrowings which tend to divide it into zones of higher solid concentration. Biomass is a suitable fuel as it has lower ash content than coal and better char burn out. Also loss of char to the air reactor does not have the same GHG emission implications. The model can also handle segregation processes for solids and char. The novel reactor design may present opportunities for concentration and withdrawal of ash.

8.15. Alstom chemical looping technologies (Abdulally et al, Alstom Power)

Alstom Chemical looping combustion development status (Beal et al, Alstom Power)

The first poster outlines Alstom's involvement in CLC through the EU supported ÉCLAIR project and in CaL capture through a US DOE funded programme in which a "fast" bed reactor concept is used. The CLC programme is looking at arrangement of oxygen carriers and also at developing a carbon stripper to reduce carry back of char to the air reactor. The CaL programme is based around use of limestones and incorporates sorbent reactivation. Goals include competitive costs for CO₂ capture and economical H₂ or gas production.

The second poster outlines the status of development of the above projects. The 3 MWth DOE project at Windsor CT, USA started coal firing in June 2011. Hot commissioning of the 1MWth ÉCLAIR chemical combustion looping is due to start at Darmstadt in October with first operation expected soon after.

8.16. Towards simulation based design of a post combustion CO₂ capture reactor (Amini et al, SINTEF)

The poster describes construction of a simulation model of a carbonation reactor using the reaction of CO₂ with a potassium based sorbent. The poster shows how the characteristics of the process can be explored without the need to construct equipment. It is possible to investigate extreme conditions which could be difficult to test.

8.17. 3-D full loop simulation of a CFB carbonator with advanced EMMS scheme. (A. Nikolopoulos et al, CERTH)

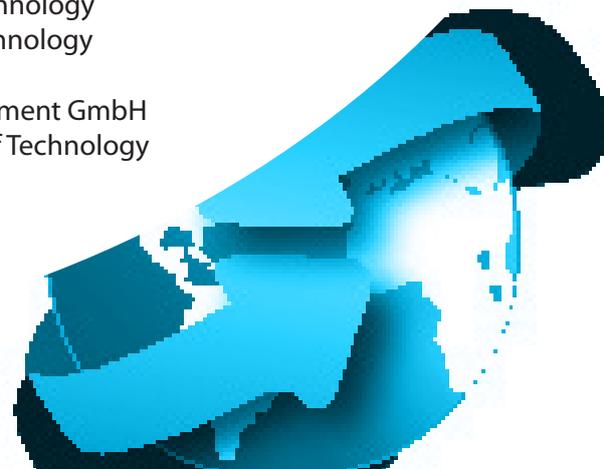
The cold flow model built by IFK Stuttgart has been simulated using 3-D CFD techniques. The advanced EMMS (energy-minimization multi-scale) scheme is used to take account of clustering effects of the particles. The full system was simulated with 286,753 elements and results of the simulation showed good agreement with the physical model behaviour of pressure profile and circulation flux to within 2%.



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Attendee List

Alberto Abad	CSIC
Carlos Abanades	CSIC
Iqbal Abdulally	
Juan Adanez	CSIC
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Olajumoke Ajao	University of Nottingham
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