Chemical Looping Combustion Kinetics

Utah Clean Coal Program Topical Report

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Task 16

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Disclaimer

Abstract

One of the most promising methods of capturing CO_2 emitted by coal-fired power plants for subsequent sequestration is chemical looping combustion (CLC). A powdered metal oxide such as NiO transfers oxygen directly to a fuel in a fuel reactor at high temperatures with no air present. Heat, water, and CO_2 are released, and after H_2O condensation the CO_2 (undiluted by N_2) is ready for sequestration, whereas the nickel metal is ready for reoxidation in the air reactor. In principle, these processes can be repeated endlessly with the original nickel metal/nickel oxide participating in a loop that admits fuel and rejects ash, heat, and water. Our project accumulated kinetic rate data at high temperatures and elevated pressures for the metal oxide reduction step and for the metal reoxidation step. These data will be used in computational modeling of CLC on the laboratory scale and presumably later on the plant scale. The oxygen carrier on which the research at Utah is focused is CuO/Cu_2O rather than nickel oxide because the copper system lends itself to use with solid fuels in an alternative to CLC called "chemical looping with oxygen uncoupling" (CLOU).

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Executive Summary

Chemical looping combustion (CLC) combined with CO_2 sequestration techniques is a promising method of producing adequate electric power from fossil fuels to meet the world's growing needs without contributing significantly to global warming. In CLC, oxygen is transferred chemically from combustion air to fuel (to produce heat, water, and captured CO_2) by means of an oxygen carrier catalyst (metal oxide). In classic CLC, metal oxide particles enter a fuel reactor in which a gaseous fuel such as syngas ($CO + H_2$) contacts the metal oxide and flameless combustion takes place at ~850°C. Thus combustion occurs in the absence of air with consequently no heating of nitrogen and no formation of nitrogen oxides. The term "looping" arises from the passage of the resulting metal particles into the air reactor in which the metal is reoxidized (at high temperature). The regenerated metal oxide then cycles back into the fuel reactor where it oxidizes more fuel and so on.

W.K. Lewis and E.R. Gilliland (1954)[1] and H.J. Richter and K.F. Knoche (1983)[2] were essential forerunners to Masaru Ishida and Hongguag Jin, who are the widely credited "inventors" of CLC. The present literature survey begins with the 1994 Ishida-Jin paper.[3] Conspicuous by its absence from this list of CLC papers in this literature review (with one exception) are titles with the CLOU acronym that stands for "chemical looping with oxygen uncoupling." This is a new concept introduced by Tobias Mattisson and coworkers at Chalmers University of Technology in Sweden for which refereed papers are beginning to appear in print.[4] CLOU permits combustion of solid fuels in gas-phase oxygen without resorting to an energy-intensive air separation unit. Three steps in two reactors are required: the first step occurs in an air reactor wherein a partially oxidized metal oxide such as copper(I) oxide captures oxygen from combustion air to form copper(II) oxide. In step two taking place in a fuel reactor, the copper(II) oxide releases molecular oxygen into the gas phase that in the third step (also in the fuel reactor) reacts with the fuel. So far, three metal oxide systems (Mn_2O_3/Mn_3O_4; CuO/Cu_2O; and Co_3O_4/CoO) appear suitable for the CLOU version of CLC. Rates of fuel conversion are much higher in CLOU compared to CLC, and the rate increases with increasing temperature[5].

The “immediate” goal of our Utah CLC research is the production of meaningful experimental rate data for small-particle copper oxide reduction and small-particle copper metal and copper (I) oxide reoxidation at temperatures on the order of 850°C that can be used in computer modeling of CLC applications. It is somewhat encouraging to note that few of the titles found in this literature survey mention rate studies of metal oxide reductions and metal particle oxidations carried out at high temperatures. None of these papers appears to report CLC experiments carried out at high pressures.

The original CLC experimental plan recognized that conversion of fuels to heat, water, and CO_2 would have attendant changes in gas volume that could be facilitated or at the very least elucidated by changing gas pressure. The premier laboratory tool for exploring mechanistic aspects of CLC would be a thermogravimetric analyzer (TGA). A high pressure TGA (TherMax 500) was ordered from Thermo Fisher Scientific, the only vendor of an adjustable pressure TGA at the time. Unfortunately, the TherMax 500 has never performed consistently up to specifications, and essentially all of the experimental CLC work reported from Utah so far has been carried out using generously gifted time on an atmospheric pressure TA Q500 TGA in the Department of Chemistry.

While the TA Q500 TGA lacks the capability of adjustable gas pressure, it has the enormous advantage of a smaller sample compartment (than the TherMax 500) that permits rapid heating and –especially – rapid cooling, and hence requires shorter time periods for completion of the experiments. Thus the TA Q500 TGA has been used to collect data under ambient pressure at several temperatures for the determination of the parameters of the reaction kinetics.

Nickel and copper metal powders were oxidized with compressed air from gas cylinders (TherMax) or delivered on the “house” line (TA Q500) under both isothermal and non-isothermal conditions. The oxidation process completed with good yields. A large number of experiments was executed and the numerical data analysis is in progress.

The investigation of the reduction of the metal oxides with H_2 as fuel is not complete, due to the problems with the TherMax 500 instrument. The limited data indicate the complete reduction of NiO, with good yield.

A spontaneous decomposition of CuO can be induced by switching the ambient atmosphere from air to N_2 at elevated temperatures. The TA Q500 was also used to simulate this “limited” CLC over times as long as thirty hours with a single charge of copper/copper oxide. An optimum temperature near 850°C was found for this prolonged CLC simulation. There was no support used for the copper/copper oxide oxygen carrier.

The Cu/CuO system was subjected to repeated sequences of temperature programmed oxidations and temperature programmed reductions with O_2 and H_2 in inert gas carriers. The reductions were very similar, but the oxidations varied during the sequence. This behavior is consistent with the observed changes of the oxidation and spontaneous decomposition cycles.

Literature Survey

Subtask 16.1

The work of W.K. Lewis and E.R. Gilliland (1954)[1] and H.J. Richter and K.F. Knoche (1983)[2] was the forerunner to that of Masaru Ishida and Hongguag Jin, who are the widely credited inventors of CLC[3]. Our literature survey began with the 1994 Ishida-Jin paper (see the Appendix for a list of the surveyed literature). The survey identified only one title that included CLOU (chemical looping with oxygen uncoupling), a new concept introduced by Tobias Mattisson and coworkers at Chalmers University of Technology in Sweden for which refereed papers are beginning to appear in print.[4] CLOU permits combustion of solid fuels in gas-phase oxygen without resorting to an energy-intensive air separation unit. Furthermore, few of the titles found in this literature survey mention rate studies of metal oxide reductions and metal particle oxidations carried out at high temperatures. More recently the CLC research community has been considering long-term experiments of 30 hours or more carried out with lab-scale fluidized bed CLC reactors rather than with simple TGAs[6,7]. Another growing dimension of CLC research is the computer modeling of the fuel and air reactors[8]. None of these papers appears to report CLC experiments carried out at high pressures.

Experimental Methods

We performed thermogravimetric analysis using the TherMax 500 and a TA Q500 and temperature-programmed oxidations and reductions using the Micromeritics ChemiSorb 2720. Thermogravimetric analysis is based on the observation of the weight of a solid sample suspended on a balance, enclosed in a temperature-controlled environment. To obtain the data necessary to describe the reaction-kinetics, the experiments can be executed under isothermal (constant temperature) and non-isothermal (programmed temperature changes) conditions. The experiment is always the observation of the weight (mass) and temperature of the sample as a function of time.

For isothermal experiments the sample is prepared under ambient conditions (temperature, pressure), and it is heated to the target temperature in an inert (N_2, He) atmosphere. When the target temperature is stabilized, the flow of the inert gas is replaced with flow of a reacting gas (air, H_2), and the change of the sample weight is recorded. The rate constant at the target temperature (k_T) is determined, according to an assumed reaction mechanism. The experiment is repeated at several temperatures, so that an Arrhenius plot ($\ln(k_T)$ vs $1/T$) can be constructed.

For non-isothermal experiments the sample is prepared under ambient conditions (temperature, pressure). The inert gas flow is terminated, and the system is switched to the reacting gas. The sample is heated to the target temperature according to a (linear) heating program (°C/min). The experiment is repeated several times, using different heating rates. The kinetic information is extracted by using the IsoKin program. This approach has no initial assumptions of the reaction mechanism.

The high pressure TGA apparatus purchased by the University of Utah from Thermo-Fisher (TherMax 500) was delivered and installed in January, 2008. However, the TherMax 500 has never operated satisfactorily, and fundamental problems remain unidentified. The hypothesis of the Thermo-Fisher support personnel had been “dirty” electrical power in the Merrill Engineering Building where the instrument is located. To remedy the situation, a new isolated electrical circuit was built for the instrument. The TGA continues to experience random failures although it is connected to the new circuit. During January – March 2009, the instrument was back at the manufacturer undergoing testing and investigations. When the instrument was reinstalled in mid-April 2009, the pressure control system was found to be inoperable. This has delayed experiments performed at pressures exceeding one atmosphere as well as all experiments involving “fuels” (syngas, hydrogen, etc.) that pose safety problems when the TGA sample is not in a fully enclosed environment. In spite of these handicaps, we have made significant progress in completing our experimental matrix using generously “loaned” time on an atmospheric pressure TGA in the Department of Chemistry.

The temperature programmed oxidations (TPO) and reductions (TPR) are experiments conducted by monitoring the composition of the gas before and after the reaction zone using a thermal conductivity detector (TCD). The TCD is used in gas chromatography to monitor the changes of the thermal conductivity of the gas exposed to the sample by splitting the incoming flow of the gas into the sample and reference cells. In the Micromeritics ChemiSorb 2720 the full gas flow is monitored, in a time-delayed manner by comparing the gas composition before and after the sample, respectively. To optimize the TCD signal the gas mixtures were chosen as ultra high purity (UHP) helium as the (neutral) carrier gas; 10% H_2 in UHP argon for the reduction experiments; and 5% O_2 in UHP helium for the oxidation experiments. During the experiment, the sample temperature is raised according to a linear heating program, and the consumption of the component of interest was measured by the TCD detector.

These techniques complement each other. The TGA data provide information about the changes in the solid, and the TPR/TPO experiments reveal the participation of the gases.

Results and Discussion

Subtask 16.3

Ni/NiO Experiments. The non-isothermal oxidation of Ni with air is shown in Figure 1. The observed 27.7% weight gain at the end of the reaction indicates the complete oxidation of the Ni to NiO (27.3% calculated weight gain). The oxidation occurred in a single process.

$$2Ni(s) + O_2(g) \rightleftharpoons 2NiO(s)$$

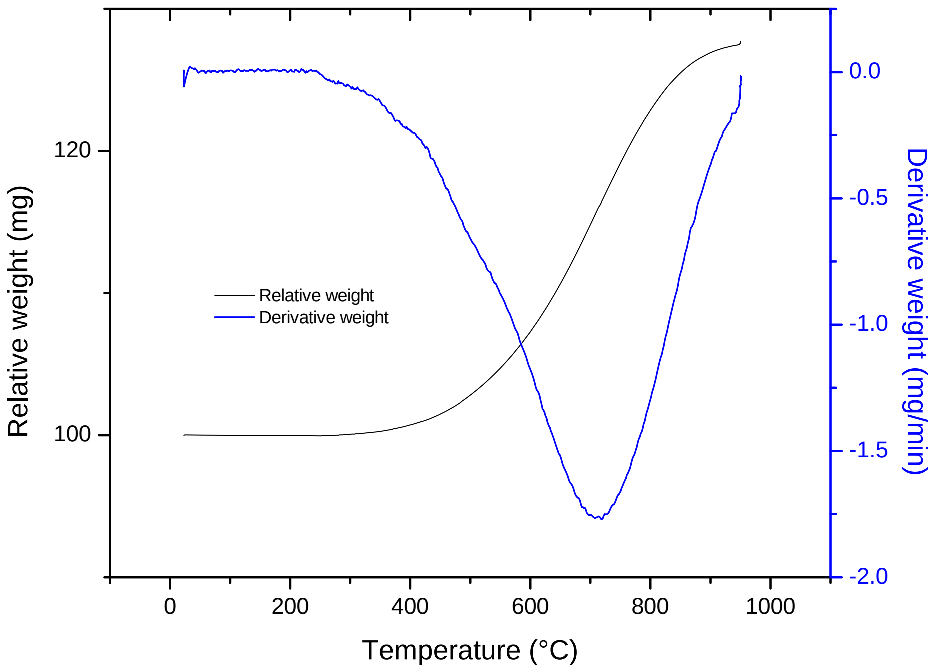

Figure 1. Non-isothermal oxidation of Ni with air

Figure 2 presents the isothermal oxidation of Ni with air at 950 °C. The reaction is complete. Similar isothermal data sets were collected for evaluation at several temperatures in the 600 – 950 °C range. After the completion of the experiment the sample was cooled under N_2, without any loss of weight. The minor change shown in the figure is due to the effect of the buoyancy on the mass, arising from the changing density of the air.

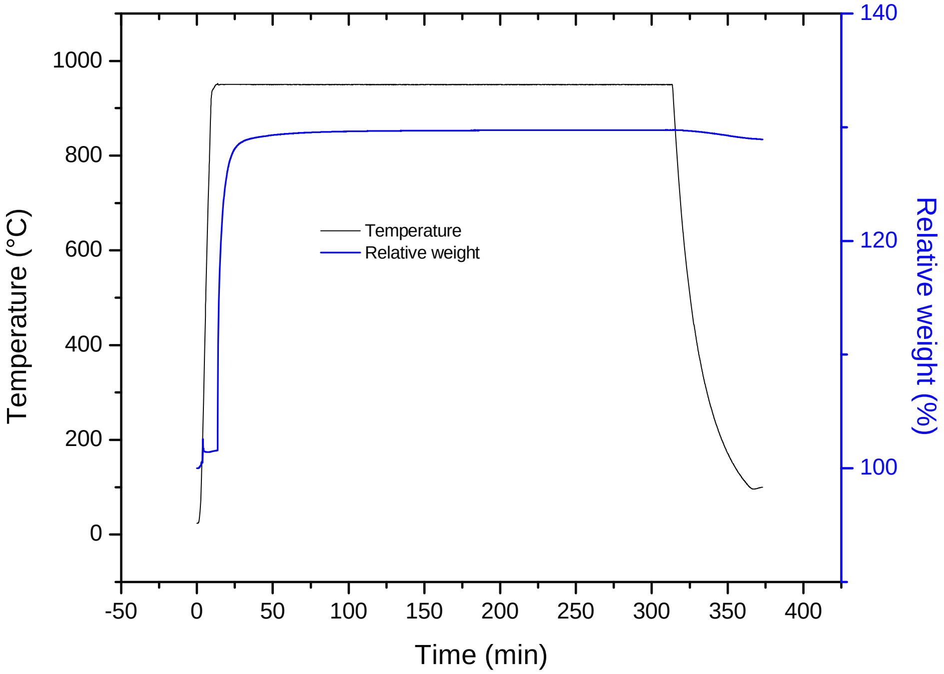

Figure 2. Isothermal oxidation of Ni with air at 950 °C

Figure 3 shows the reduction of NiO with 50% H_2 in N_2 as simulated fuel. The 19.3% weight loss is close to the 21.4% change expected for the complete reduction

$$NiO(s) + H_2(g) \rightleftharpoons Ni(s) + H_2O(g)$$

Interestingly, this reaction takes place at a comparatively low temperature.

The NiO/Ni system was subjected to a sequence of TPR/TPO/TPR. The raw data are presented in Figure 4. The signals of the repeated TPR experiments show remarkable differences. The signal strength between the first and second TPR experiments was reduced by about a factor of two. On the same scale of arbitrary units, the signal of the TPO was weak.

The reduction of NiO can be done at relatively “low” temperatures (<500 °C), repeatedly, but the oxidation of Ni is not immediately accomplished, even at “higher” temperatures (>900 °C). The variation of the consecutive TPR steps needs to be investigated to

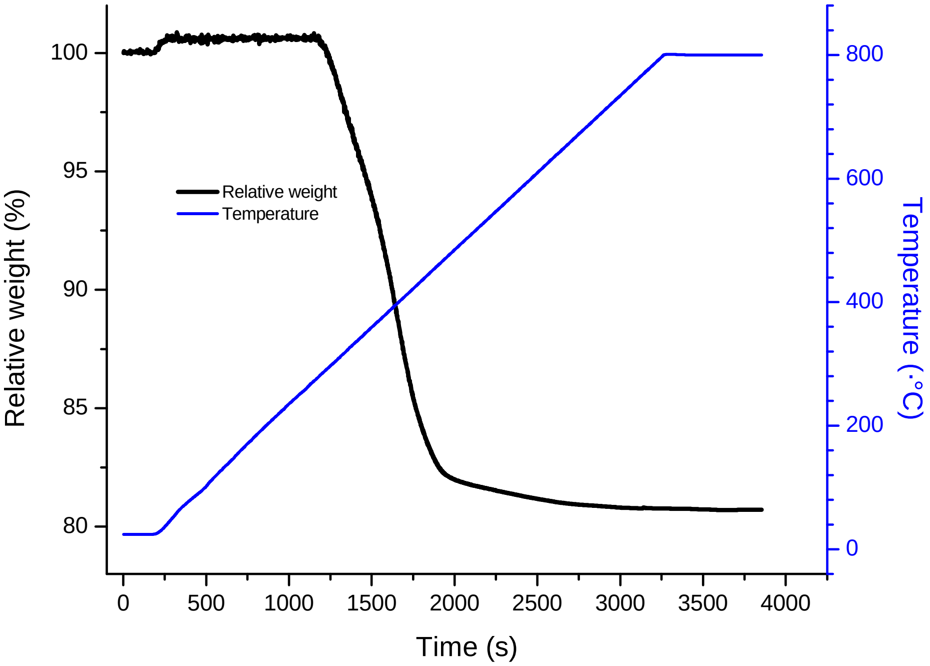

Figure 3. Reduction of NiO with 50% H_2

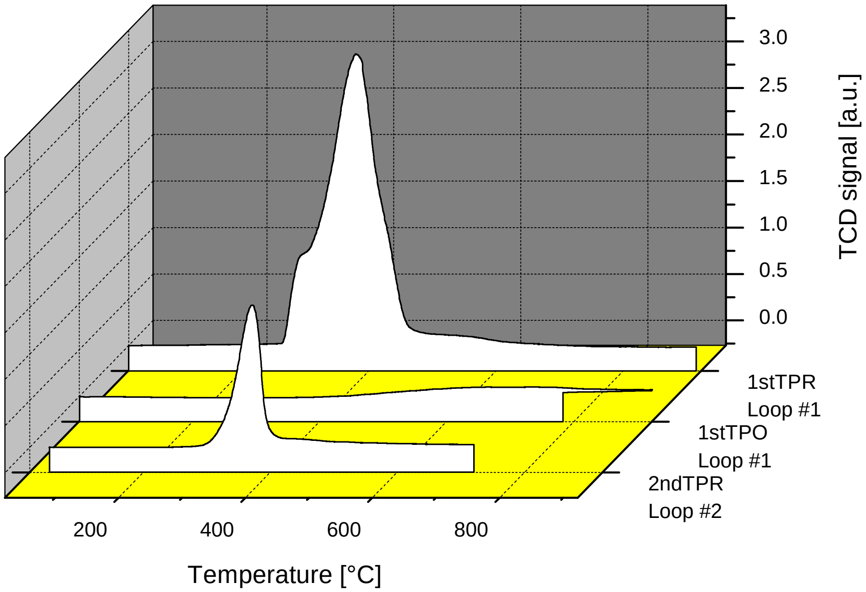

Figure 4. TPR/TPO/TPR sequence of NiO/Ni

understand the process. Is it a consequence of the incomplete oxidation, or is there something to learn about the behavior of the NiO/Ni system exposed to repeated reduction/oxidation cycles?

Cu/CuO Experiments. Figure 5 shows that the non-isothermal oxidation of Cu is not simple. The observed 24.3% weight gain is close to the expected 25.2%, but it does not occur in a single reaction. The difference is clearly indicated by the derivative curves. The three oxidation reactions of the copper

$$2Cu(s) + O_2(g) \rightleftharpoons 2CuO(s)$$

$$4Cu(s) + O_2(g) \rightleftharpoons 2Cu_2O(s)$$

$$2Cu_2O(s) + O_2(g) \rightleftharpoons 4CuO(s)$$

do not satisfactorily explain the observed trace, characterized by more than three steps. These steps are clearly revealed by considering the derivative of the weight change.

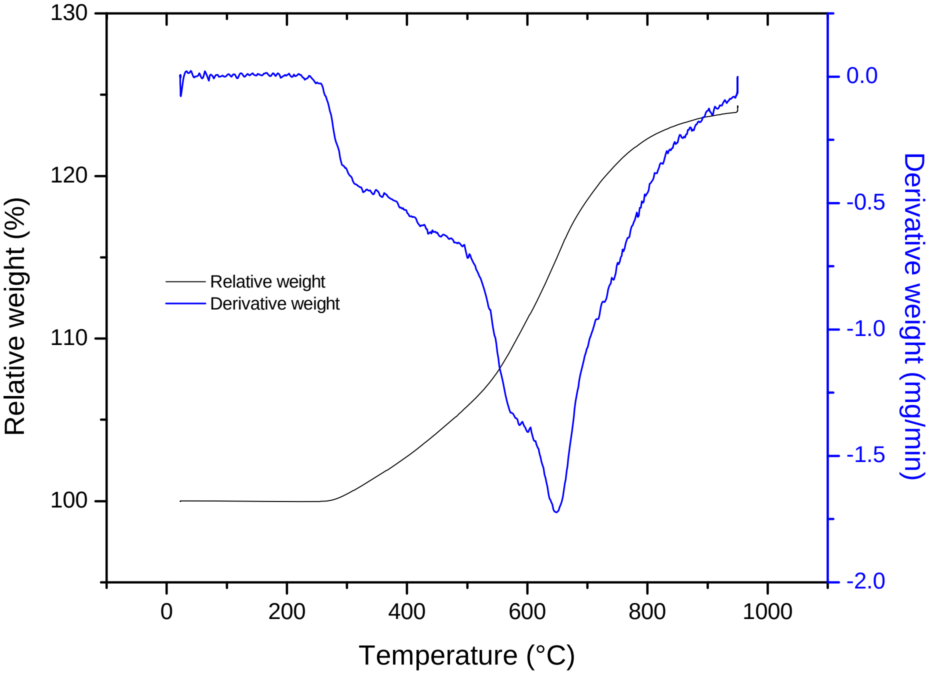

Figure 5. Non-isothermal oxidation of Cu with air

The changes expressed by the derivative weight in the 200 - 500°C temperature range show small, not well developed, but noticeable features. The features in the corresponding non-isothermal oxidation of Ni, depicted in Figure 1, shall be reconsidered, as well.

The isothermal oxidation of Cu with air at 950 °C as shown in Figure 6 was not yet complete after a 45-minute isothermal holding period. The weight gain was 22.5%. After the 45 minutes, the air was replaced with N_2, and the sample was allowed to cool. The change of gas immediately initiated a weight loss. In the absence of oxygen, the CuO decomposed. The decomposition is not complete because the temperature dropped quickly, and the reaction stopped.

Figure 7 shows the spontaneous decomposition of CuO under nitrogen. The CuO sample was heated at a rate of 5°C/min. When the sample temperature exceeded 770°C, decomposition occurred. The weight loss was approximately 10%. For the conversion of CuO to Cu metal the expected weight loss is 20.1%. The observed value is in good agreement with the 10.1% weight loss expected for the conversion of CuO into Cu_2O. Under the same experimental conditions NiO did not decompose.

Our systematic studies reveal that the best CuO/Cu_2O system yields are achieved in the 825 – 875 °C temperature range.

The oxygen carrying capability of the CuO/Cu_2O system was further investigated in simulated looping experiments with both Cu and CuO as starting materials. After 6 or 7 cycles the systems exhibited a consistently repeatable behavior, as shown in Figure 8. The weight changes indicate a swing between CuO and Cu_2O (129.2% and 115.8%, relative to 100% Cu, respectively). The oxidation segments with air were faster and more complete, as indicated by the constant weights, than the decomposition segments under N_2.

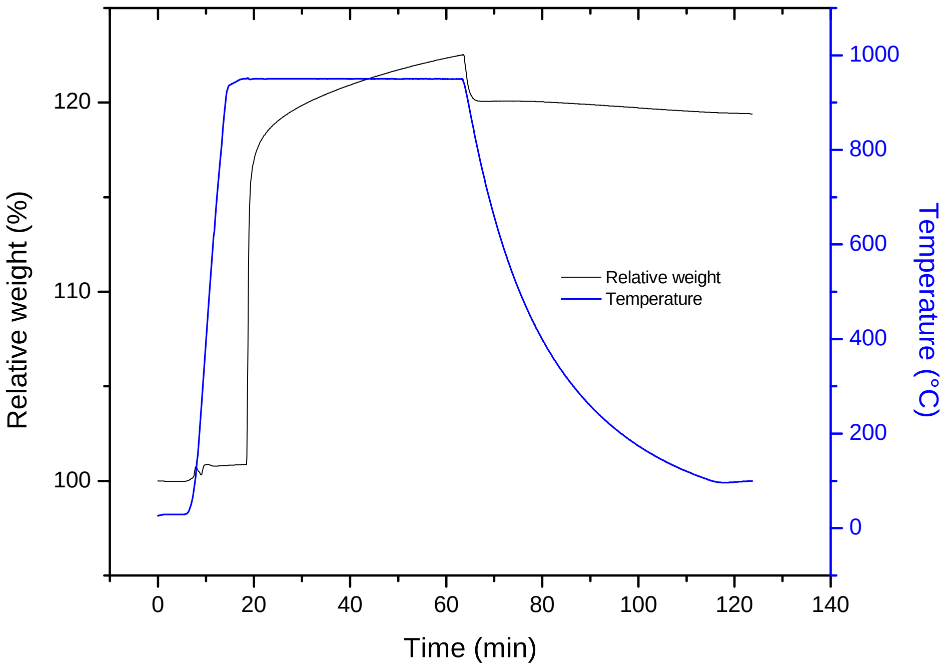

Figure 6. Oxidation of Cu with air at 950 °C

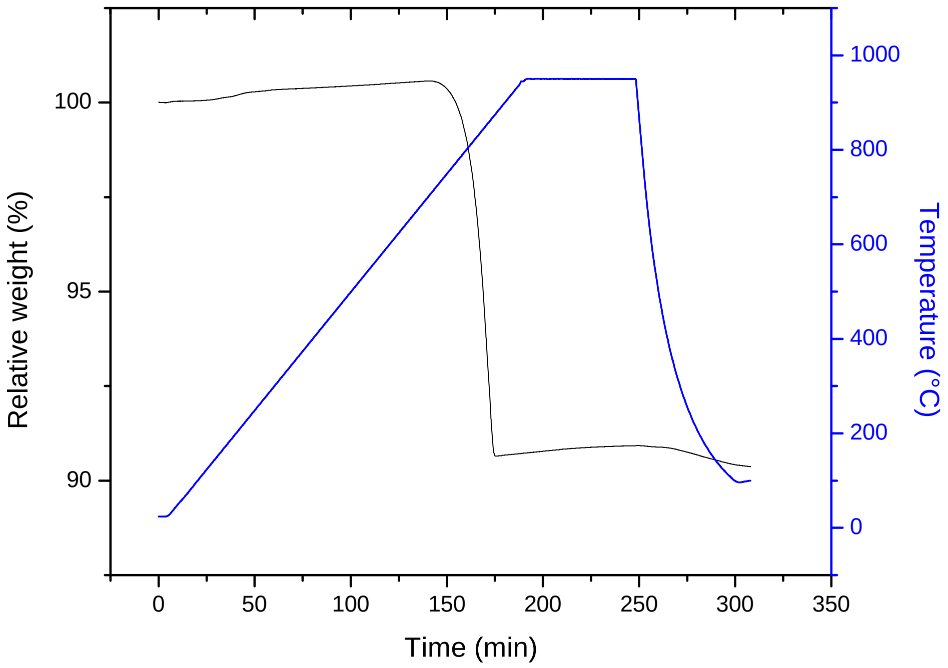

Figure 7. Decomposition of CuO in nitrogen

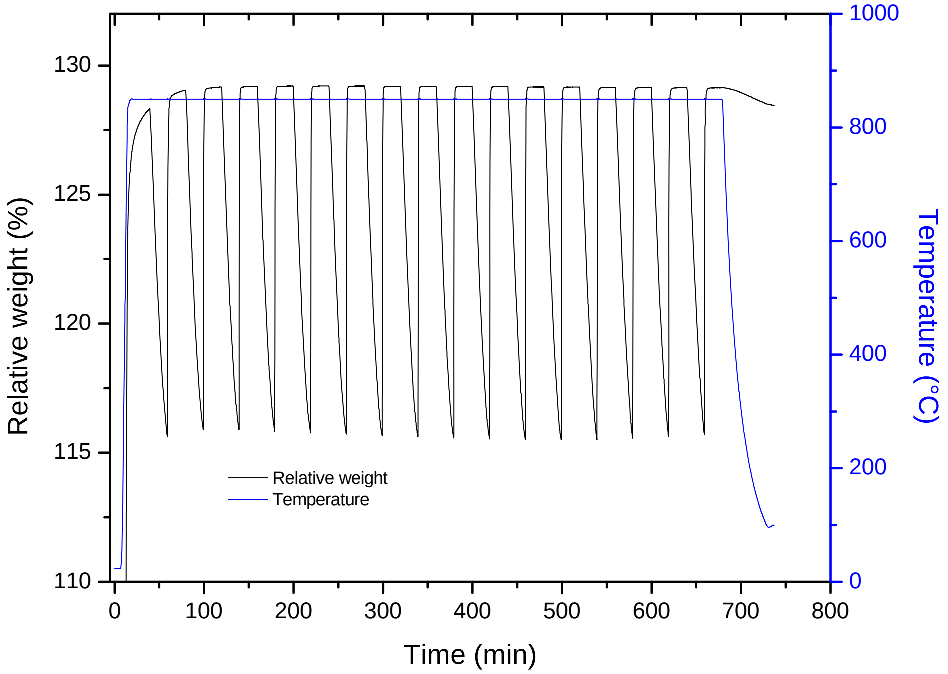

Figure 8. Looping of Cu/Cu_2O/CuO, with air and N_2

This behavior can be tuned, by selecting the reaction temperature and the times of exposure to the different gases. Figure 8 shows an experiment with 20 minutes under air exposure and 20 minutes under N_2. The oxidation cycles went to completion (for practical purposes), while the decomposition cycles did not. The looping was successfully extended up to 200 cycles.

The CuO/Cu system was studied using two CuO samples as starting material. Results of repeated sequences of TPR and TPO experiments are shown in Figure 9 and Figure 10. The plots labeled 1998, 1999, 2002, 2003 were observed using a technical grade CuO. The plots numbered 2011-2014 were observed using a high purity, “standard grade” CuO material. Due to the very different amplitudes the TPR and the TPO data are presented separately.

The traces in Figure 9 indicate several processes taking place. The reduction is complete below 500 °C as shown by the curves 1998, 2002, 2011, and 2013 in Figure 9.

Consequently, there is no need to carry out the looping at high temperatures. Possible reduction reactions are:

$$CuO(s) + H_2(g) \rightleftharpoons Cu(s) + H_2O(g)$$

$$2CuO(s) + H_2(g) \rightleftharpoons Cu_2O(s) + H_2O(g)$$

$$Cu_2O(s) + H_2(g) \rightleftharpoons 2Cu(s) + H_2O(g)$$

The sharp character of the peaks suggests that the process is dominated by the first reaction.

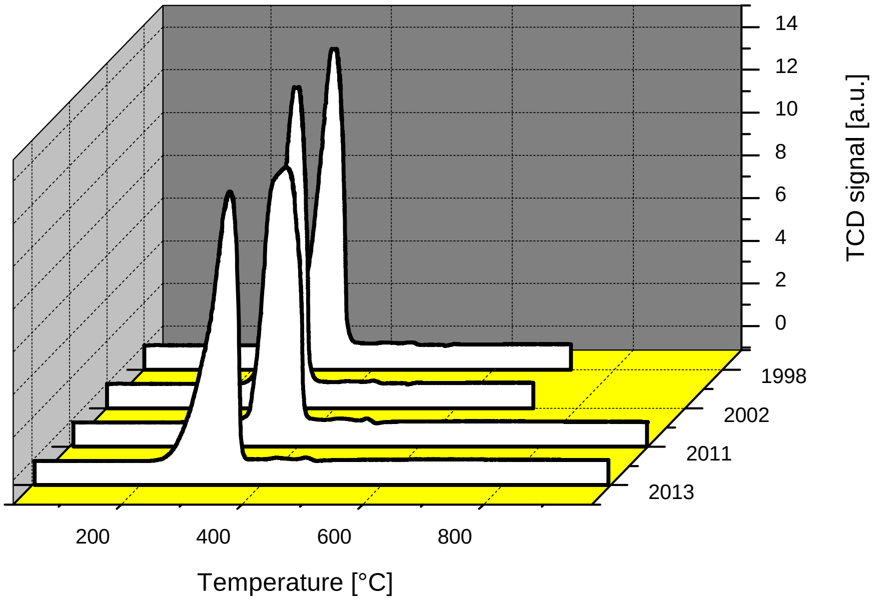

Figure 9. TPR sequences of CuO/Cu, using two materials

Figure 10 shows the TPO of the previously reduced samples (curves 1999, 2003, 2012, and 2014), and these produced at least four components in the traces. The events begin at low temperature (about 160°C) and last to above 900°C, indicated on the temperature ramp. The possible chemical reactions already described for the oxidation of the copper metal do not satisfactorily explain the observed traces.

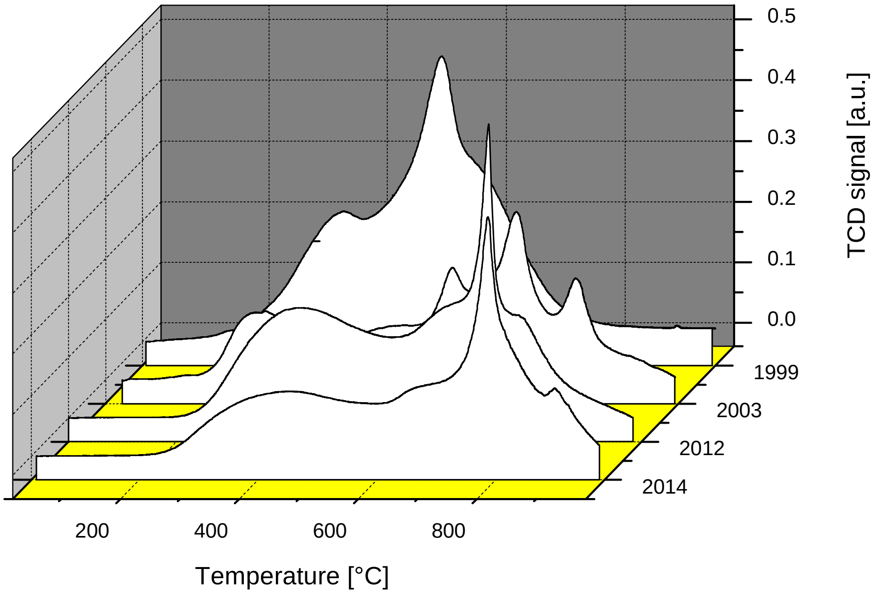

Figure 10. TPO sequences of CuO/Cu using two materials

Considering the extended “looping” using Cu/CuO with air and N_2, the TPR/TPO sequence was extended up to seven cycles. The TPO and TPR results of the Cu/CuO system are presented in Figure 11 and Figure 12, respectively. The observed TPO signal indicates a change in composition between the cycles until the results of the 6th and 7th TPO experiments became similar (Figure 11). The results of the TPR experiments did not show a similar trend. The first and the last TPR experiments presented in Figure 12 are almost identical. The reduction takes place at a relatively low temperature.

As we noted above, the NiO does not decompose in an inert atmosphere (in contrast to CuO), so a TGA experiment on the TherMax 500 using H_2 is required to complete a “loop.”

A small number of experiments was completed under elevated pressures. The decomposition of calcium oxalate is shown in Figure 13.

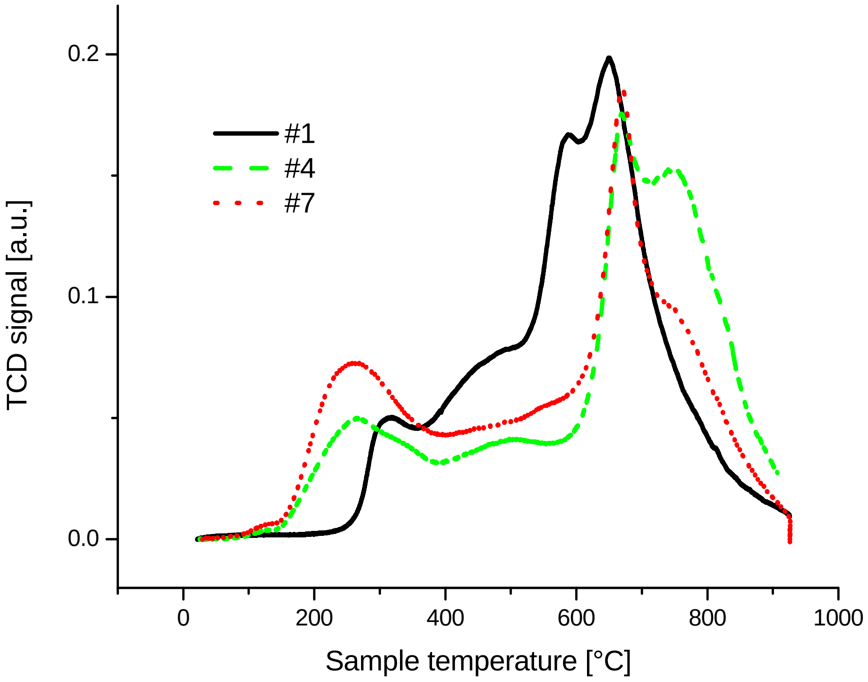

Figure 11. TPO sequence of Cu

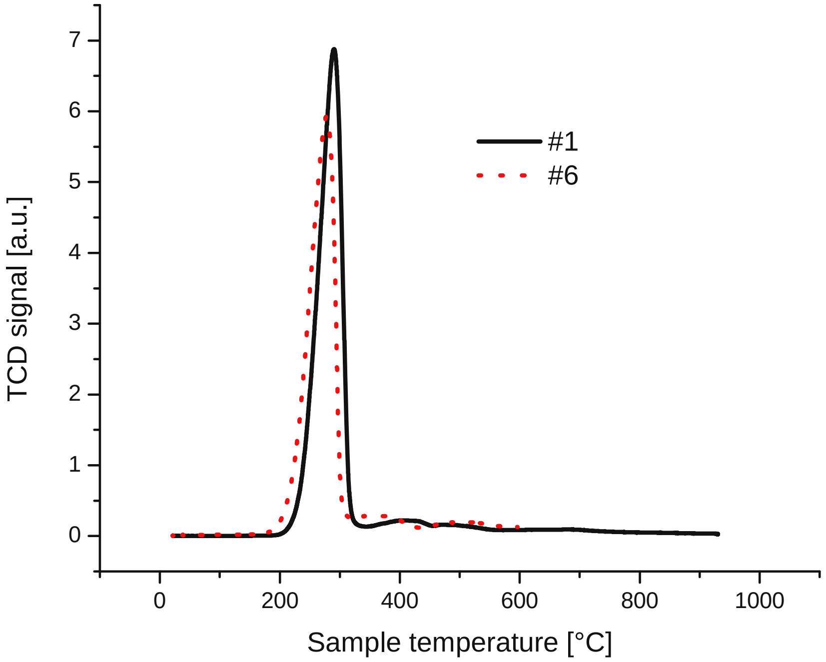

Figure 12. TPR sequence of CuO

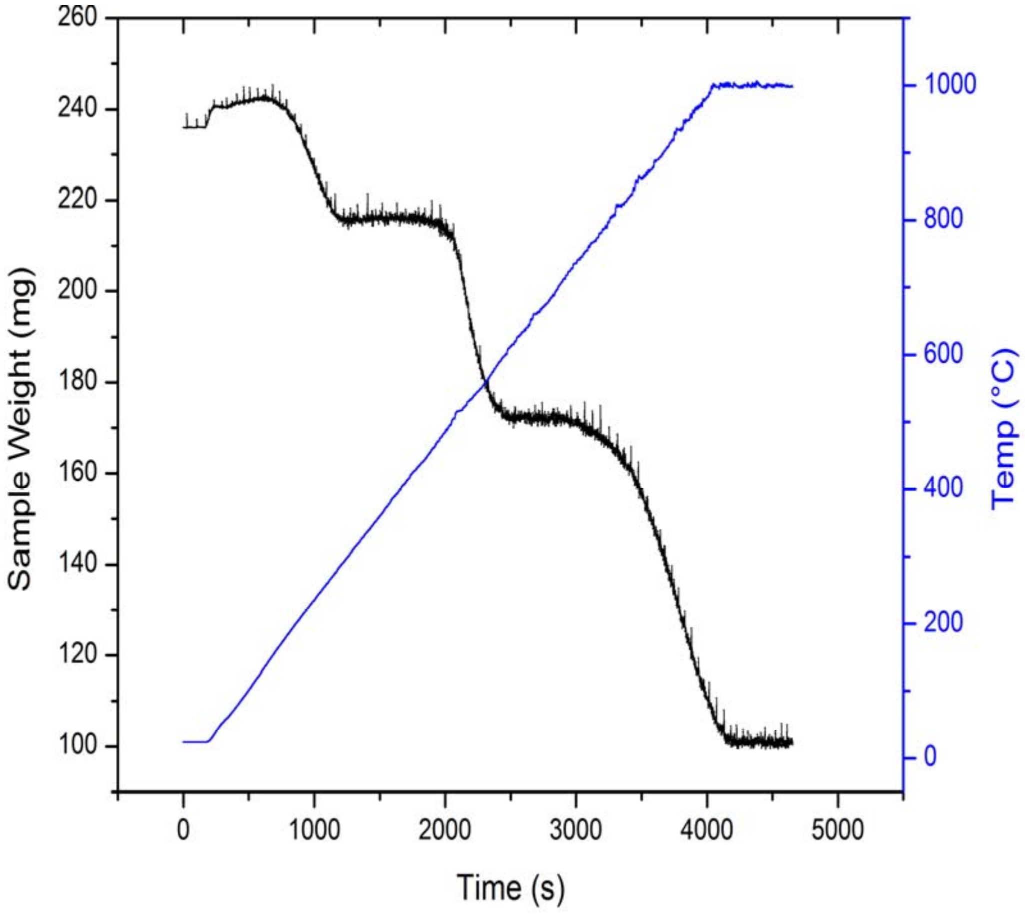

Figure 13. Calcium oxalate decomposition under N_2 at 100 psi

$Ca(COO)_2$ is an interesting model material because it decomposes in two steps. The gaseous products are CO and CO_2, respectively:

$$Ca(COO)_2 \rightarrow CaCO_3 + CO \rightarrow CaO + CO_2$$

Repeated experiments under different elevated pressures indicate the expected shift of the reaction temperatures toward higher temperatures with higher applied pressures.

A preliminary experiment with sodium chabazite, a potential support material, revealed no mass change after the initial loss of water.

During the course of the experiments, improvements were made to the instruments. An external gas mixing system, consisting of four mass-flow controllers to deliver gases under high pressure was developed to provide the reaction gas for the TherMax 500 apparatus. In the same instrument, the original sample holders are suspended by a metal wire as shown in Figure 14. This piece of wire is not durable, and it makes the cleaning of the quartz tedious. An all-quartz substitute sample holder, shown in Figure 15, was designed and fabricated in the Glass Shop of the Department of Chemistry, for a fraction of the commercial replacement cost.

Similarly, quartz replicas of the Pt sample holding pans were used in the TA Q500 instrument. The Pt pans were not suitable for the experiments, due to sintering of the metal samples.

Due to the problems with the high-pressure TGA, the original experimental plan for Subtask 16.3 required revision, as shown below. During the time period covered in this report the project objectives have also evolved. Based on our preliminary results and development of the CLC reported in the literature, we focused on the Cu/Cu_2O/CuO system and performed a great number of not originally proposed experiments, studying Cu as a potential oxygen carrier for CLC and the emerging technology of CLOU.

Variable	Number of Experiments	
	Planned	Executed
Char composition	2	0
Composition of syngas	3	0
Reaction temperature	4	Many
NiO/Ni particle size	2	1 with NiO, 1 with Ni
Composition of particle support	2	0
Pressure (1 atm total pressure)	1	Several

Since we have not yet executed the gaseous fuel experiments, the issue of char composition is premature. We now have the mass flow controllers in place to continuously vary the composition of a syngas. However, as noted above we cannot safely perform any experiment using syngas until the TGA apparatus is airtight.

We have recently discovered that a metal-metal oxide couple can effectively be used in repeated looping without any support.

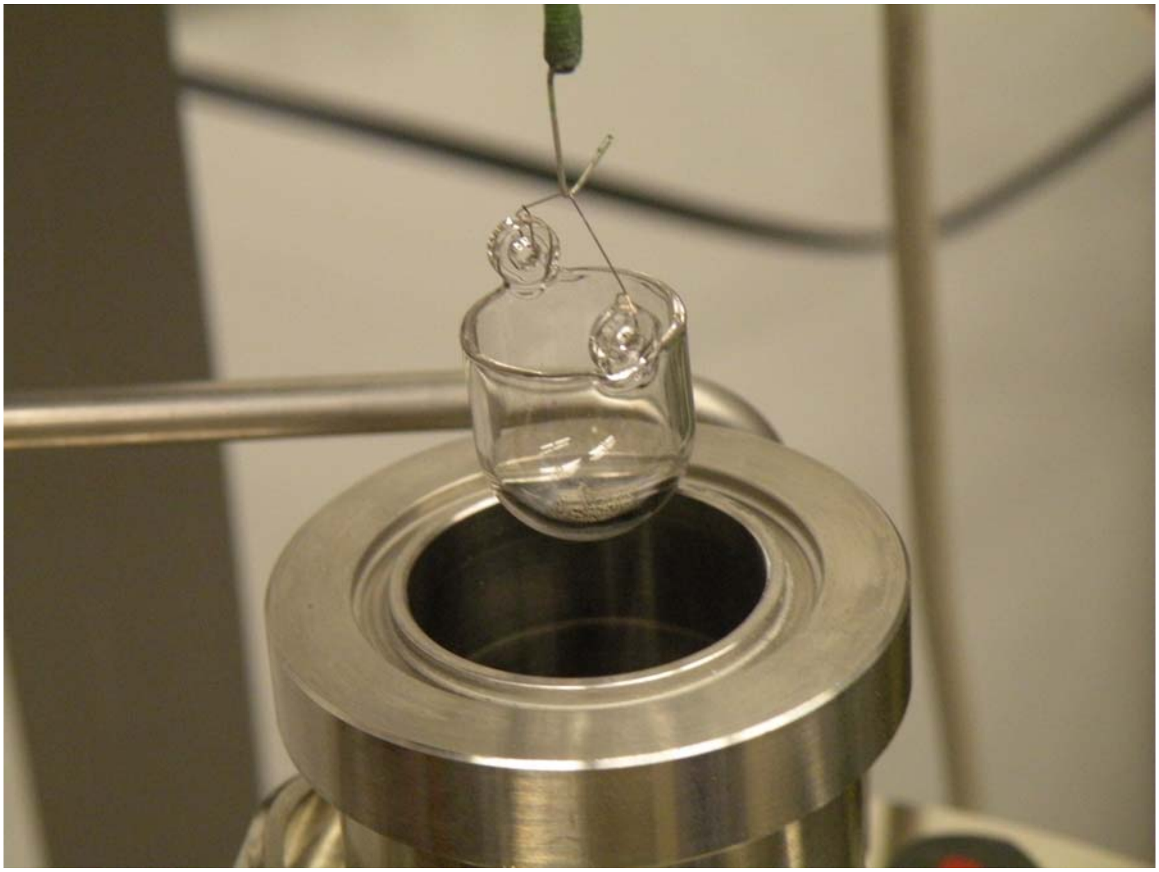

Figure 14. Ni produced from NiO by reduction with H_2 in the original sample holder

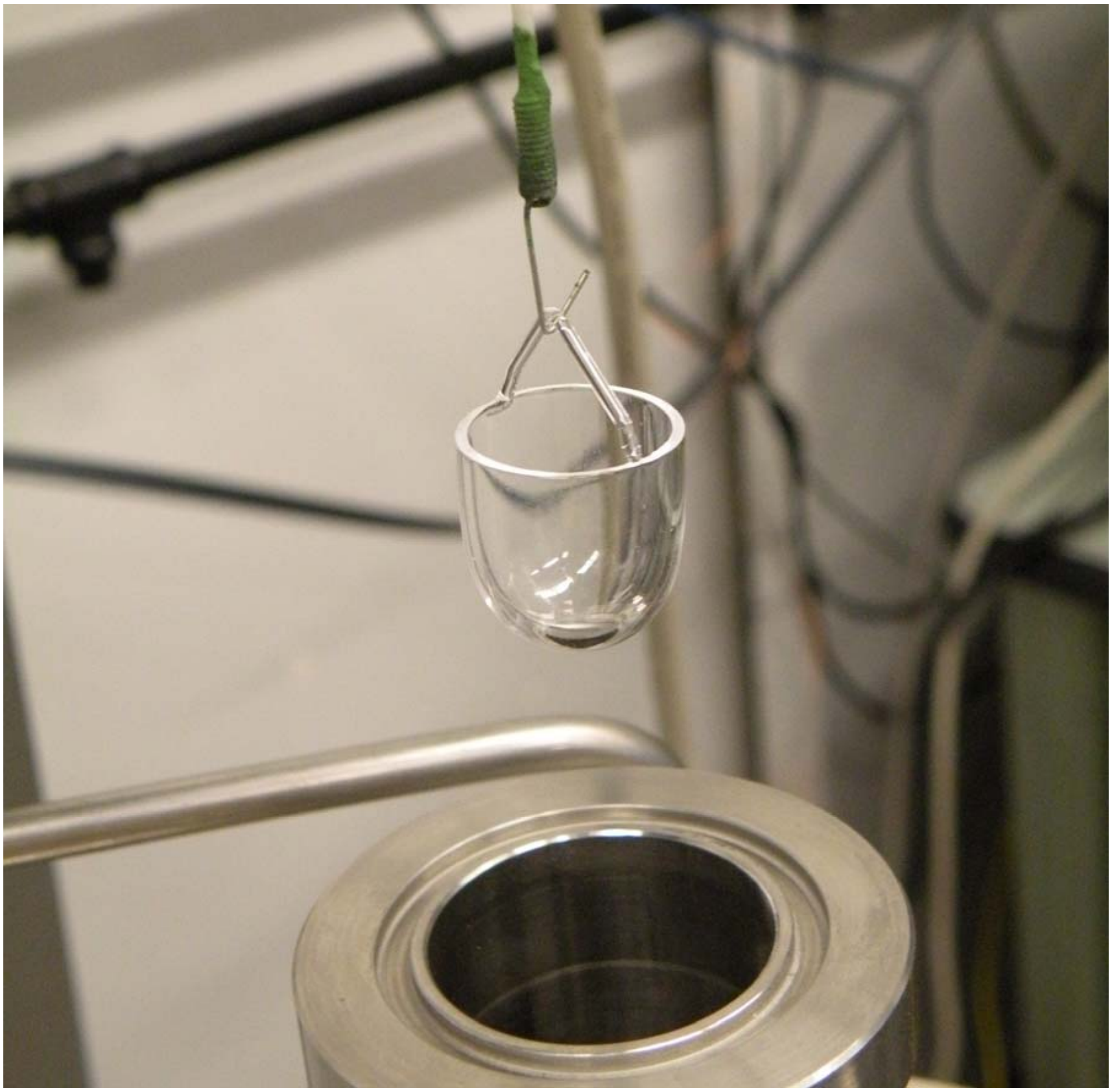

Figure 15. The all-quartz sample holder (bucket)

Conclusions

Many recent papers advance our understanding of chemical looping combustion. Often they report the use of TGA or small fixed-bed reactors in the search for an oxygen carrier that can be used successfully with gaseous fuels such as H_2, CO, or CH_4. Fewer publications so far report work with oxygen carriers that are effective in CLC of solid fuels. More recently the CLC research community has been considering long-term experiments of 30 hours or more carried out with lab-scale fluidized bed CLC reactors rather than with simple TGAs[5, 6]. Another growing dimension of CLC research is the computer modeling of the fuel and air reactors[8].

Further high-pressure TGA studies in CLC research will be useful for the measurement of chemical rate constants over a wide range of temperatures (up to 1000°C) and gas pressures up to 1000 psi, which could be of interest for reducing the size of the air reactor, the fuel reactor, and the amount of oxygen carrier. When the temperature readings are well calibrated and dependable confidence intervals for the activation energies have been established[9] the TGA will provide essential rate data needed in computer modeling of CLC.

Ni oxidation experiments in air revealed complete oxidation of Ni to NiO in a single process. The limited data for the reduction of NiO with 50% H_2 in N_2 indicate the complete reduction of NiO at a comparatively low temperature (below 500°C).

Cu oxidation experiments in air revealed a more complex oxidation process reflecting in part the multiple oxidation states of Cu. CuO undergoes decomposition to yield oxygen gas and Cu_2O under nitrogen at elevated temperatures, in contrast to NiO which does not decompose at temperatures of interest. In addition, the TA Q500 was used to simulate limited cycling of the oxidation/decomposition of copper oxide over times as long as thirty hours with a single charge of unsupported copper/copper oxide in order to determine the stability of the oxygen carrier for use in CLC. An optimum temperature near 850°C was found for this prolonged CLC simulation. Finally, the Cu/CuO system was subjected to repeated sequences of temperature-programmed oxidations and temperature-programmed reductions with O_2 and H_2 in inert gas carriers. The reduction cycles were reproducible, but the oxidations varied during the sequence. This behavior is consistent with the observed changes of the oxidation and spontaneous decomposition cycles.

Acknowledgements

This material is based upon work supported by the Department of Energy under Award Number DE-FC26-06NT42808.

Many of the reported experiments were carried out on the TGA (a TA Q500 instrument, professionally maintained by Ms. Jeramie Jergins) in Professor Charles A. Wight’s laboratory in the Department of Chemistry, at the University of Utah.

The IsoKin computer program provided to us – implementing the isoconversional analysis of kinetic data – was developed by Professor Charles A. Wight.

List of Graphics

List of Abbreviations and Symbols

Abbreviations:

CLC: Chemical Looping Combustion

CLOU: Chemical Looping Combustion, with Oxygen Uncoupling

MFC: Mass Flow Controller

TCD: Thermal Conductivity Detector

TGA: Thermogravimetric Analysis (as an experimental method), or
Thermogravimetric Analyzer (as an instrument)

TPO: Temperature Programmed Oxidation

TPR: Temperature Programmed Reduction

UHP: Ultra High Purity (the best commercially available gas)

Symbols:

T: Temperature

k_T: Rate constant of a reaction, at a given temperature (T)

References

1. Lewis, W. K.; Gilliland, E. R. Production of Pure Carbon Dioxide. 2665972, 1954.

2. Richter, H. J.; Knoche, K. F., Reversibility of combustion processes. *ACS Symp. Ser.* **1983,** 235, (Effic. Cost.: Second Law Anal. Processes), 71-85.

3. Ishida, M.; Jin, H., A new advanced power-generation system using chemical-looping combustion. *Energy* **1994,** 19, (4), 415-422.

4. Mattisson, T.; Lyngfelt, A.; Leion, H., Chemical-looping with oxygen uncoupling for combustion of solid fuels. *Int. J. Greenhouse Gas Control* **2009,** 3, (1), 11-19.

5. Leion, H. Capture of CO_2 from Solid Fuels using Chemical-Looping Combustion and Chemical-Looping with Oxygen Uncoupling. Thesis for the Degree of Doctor of Philosophy, Chalmers University of Technology, Göteborg, 2008.

6. Shen, L.; Wu, J.; Xiao, J.; Song, Q.; Xiao, R., Chemical-Looping Combustion of Biomass in a 10 kWth Reactor with Iron Oxide As an Oxygen Carrier. *Energy Fuels* **2009,** 23, (5), 2498-2505.

7. Chandel, M. K.; Hoteit, A.; Delebarre, A., Experimental investigation of some metal oxides for chemical looping combustion in a fluidized bed reactor. *Fuel* **2009,** 88, (5), 898-908.

8. Deng, Z.; Xiao, R.; Jin, B.; Song, Q.; Huang, H., Multiphase CFD modeling for a chemical looping combustion process (fuel reactor). *Chem. Eng. Technol.* **2008,** 31, (12), 1754-1766.

9. Vyazovkin, S.; Wight, C. A., Estimating Realistic Confidence Intervals for the Activation Energy Determined from Thermoanalytical Measurements. *Anal. Chem.* **2000,** 72, (14), 3171-3175.

Appendix

Titles of CLC papers reported on the Scopus.com database for the interval 1994 to May 15, 2009

Appendix

Titles of CLC papers reported on the Scopus.com database for the interval 1994 to May 15, 2009

Article title	Authors	Year	Journal	Cited
A new advanced power-generation system using chemical-looping combustion	Ishida, M., Jin, H.	1994	*Energy* 19 (4), pp. 415-422	76 times
A fundamental study of a new kind of medium material for chemical-looping combustion	Ishida, M., Jin, H., Okamoto, T.	1996	*Energy and Fuels* 10 (4), pp. 958-963	62
CO2 recovery in a power plant with chemical looping combustion	Ishida, M., Jin, H.	1997	*Energy Conversion and Management* 38 (SUPPL. 1), pp. S187-S192	28
Kinetic behavior of solid particle in chemical-looping combustion: Suppressing carbon deposition in reduction	Ishida, M., Jin, H., Okamoto, T.	1998	*Energy and Fuels* 12 (2), pp. 223-229	53
Exergy analysis of chemical-looping combustion systems	Anheden, M., Svedberg, G.	1998	*Energy Conversion and Management* 39 (16-18), pp. 1967-1980	45
Development of a novel chemical-looping combustion: Synthesis of a looping material with a double metal oxide of CoO-NiO	Jin, H., Okamoto, T., Ishida, M.	1998	*Energy and Fuels* 12 (6), pp. 1272-1277	58
Development of a novel chemical-looping combustion: Synthesis of a solid looping material of NiO/NiAl2O4	Jin, H., Okamoto, T., Ishida, M.	1999	*Industrial and Engineering Chemistry Research* 38 (1), pp. 126-132	80
Novel gas turbine cycle with hydrogen-fueled chemical-looping combustion	Jin, H., Ishida, M.	2000	*International Journal of Hydrogen Energy* 25 (12), pp. 1209-1215	25
Investigation of a novel gas turbine cycle with coal gas fueled chemical-looping combustion	Jin, H., Ishida, M.	2000	*American Society of Mechanical Engineers, Advanced Energy Systems Division (Publication) AES* 40, pp. 547-552	1

Ni based mixed oxide materials for CH4 oxidation under redox cycle conditions	Villa, R., Cristiani, C., Groppi, G., Lietti, L., Forzatti, P., Cornaro, U., Rossini, S.	2003	*Journal of Molecular Catalysis A: Chemical* 204-205, pp. 637-646	53
Effect of temperature on reduction reactivity of oxygen carrier particles in a fixed bed chemical-looping combustor	Ryu, H.-J., Bae, D.-H., Jin, G.-T.	2003	*Korean Journal of Chemical Engineering* 20 (5), pp. 960-966	15
Characteristics of the NiO/hexaaluminate for chemical looping combustion	Song, K.S., Seo, Y.S., Yoon, H.K., Cho, S.J.	2003	*Korean Journal of Chemical Engineering* 20 (3), pp. 471-475	11
Reactivity of some metal oxides supported on alumina with alternating methane and oxygen - Application for chemical-looping combustion	Mattisson, T., Järdnäs, A., Lyngfelt, A.	2003	*Energy and Fuels* 17 (3), pp. 643-651	54
Carbon deposition characteristics and regenerative ability of oxygen carrier particles for chemical-looping combustion	Ryu, H.-J., Lim, N.-Y., Bae, D.-H., Jin, G.-T.	2003	*Korean Journal of Chemical Engineering* 20 (1), pp. 157-162	10
Multicycle reduction and oxidation of different types of iron oxide particles-application to chemical-looping combustion	Mattisson, T., Johansson, M., Lyngfelt, A.	2004	*Energy and Fuels* 18 (3), pp. 628-637	53
Inherent CO2 capture using chemical looping combustion in a natural gas fired power cycle	Brandvoll, Ø., Bolland, O.	2004	*Journal of Engineering for Gas Turbines and Power* 126 (2), pp. 316-321	18
Selection of oxygen carriers for chemical-looping combustion	Adánez, J., De Diego, L.F., García-Labiano, F., Gayán, P., Abad, A., Palacios, J.M.	2004	*Energy and Fuels* 18 (2), pp. 371-377	84

Principle of cascading utilization of chemical energy	Jin, H.-G., Wang, B.-Q.	2004	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 25 (2), pp. 181-184	1
Reduction and oxidation kinetics of a copper-based oxygen carrier prepared by impregnation for chemical-looping combustion	García-Labiano, F., De Diego, L.F., Adánez, J., Abad, A., Gayán, P.	2004	*Industrial and Engineering Chemistry Research* 43 (26), pp. 8168-8177	20
A new type of coal gas fueled chemical-looping combustion	Jin, H., Ishida, M.	2004	*Fuel* 83 (17-18), pp. 2411-2417	33
A two-compartment fluidized bed reactor for CO2 capture by chemical-looping combustion	Kronberger, B., Johansson, E., Löffer, G., Mattisson, T., Lyngfelt, A., Hofbauer, H.	2004	*Chemical Engineering and Technology* 27 (12), pp. 1318-1326	15
Investigation of Fe2O3 with MgAl2O 4 for chemical-looping combustion	Johansson, M., Mattisson, T., Lyngfelt, A.	2004	*Industrial and Engineering Chemistry Research* 43 (22), pp. 6978-6987	26
Hydrogen production from reforming of natural gas for stationary PEMFC	Xu, Y., Xie, X., Wang, Z., Wang, Y., Mao, Z., Wang, S.	2004	*Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 55 (SUPPL.), pp. 26-33	0
Development of Cu-based oxygen carriers for chemical-looping combustion	De Diego, L.F., García-Labiano, F., Adánez, J., Gayán, P., Abad, A., Corbella, B.M., Palacios, J.M.	2004	*Fuel* 83 (13), pp. 1749-1757	36
Comparison of iron-, nickel-, copper- and manganese-based oxygen carriers for chemical-looping combustion	Cho, P., Mattisson, T., Lyngfelt, A.	2004	*Fuel* 83 (9), pp. 1215-1225	89

Investigation of a novel gasification chemical looping combustion combined cycle	Xiang, W.-G., Di, T.-T., Xiao, J., Shen, L.-H.	2004	*Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering* 24 (8), pp. 170-174	11
Redox characteristics of various kinds of oxygen carriers for hydrogen fueled chemical-looping combustion	Lee, J.-B., Park, C.-S., Choi, S.-I., Song, Y.-W., Kim, Y.-H., Yang, H.-S.	2005	*Journal of Industrial and Engineering Chemistry* 11 (1), pp. 96-102	9
Simulation of mass and energy balances of a chemical-looping combustion system	Kronberger, B., Löffler, G., Hofbauer, H.	2005	*Clean Air* 6 (1), pp. 1-14	6
Fluidized-bed reactor systems for chemical-looping combustion with inherent separation of CO2	Johansson, E.	2005	*Doktorsavhandlingar vid Chalmers Tekniska Hogskola* (2367)	0
Impregnated CuO/Al2O3 oxygen carriers for chemical-looping combustion: Avoiding fluidized bed agglomeration	de Diego, L.F., Gayán, P., García-Labiano, F., Celaya, J., Abad, A., Adánez, J.	2005	*Energy and Fuels* 19 (5), pp. 1850-1856	29
Characterization study and five-cycle tests in a fixed-bed reactor of titania-supported nickel oxide as oxygen carriers for the chemical-looping combustion of methane	Corbella, B.M., De Diego, L.F., García-Labiano, F., Adánez, J., Palacios, J.M.	2005	*Environmental Science and Technology* 39 (15), pp. 5796-5803	7
Parametric study of chemical looping combustion for tri-generation of hydrogen, heat, and electrical power with CO2 capture	Wolf, J., Yan, J.	2005	*International Journal of Energy Research* 29 (8), pp. 739-753	9
Development and characterisation of oxygen-carrier materials for chemical-looping combustion	Cho, P.	2005	*Doktorsavhandlingar vid Chalmers Tekniska Hogskola* (2287)	0

La0.8Sr0.2Co0.2Fe0.8O 3-δ as a potential oxygen carrier in a chemical looping type reactor, an in-situ powder X-ray diffraction study	Readman, J.E., Olafsen, A., Larring, Y., Blom, R.	2005	*Journal of Materials Chemistry* 15 (19), pp. 1931-1937	3
Comparison of nickel- and iron-based oxygen carriers in chemical looping combustion for CO2 capture in power generation	Wolf, J., Anheden, M., Yan, J.	2005	*Fuel* 84 (7-8), pp. 993-1006	29
A new principle of synthetic cascade utilization of chemical energy and physical energy	Jin, H., Hong, H., Wang, B., Han, W., Lin, R.	2005	*Science in China, Series E: Technological Sciences* 48 (2), pp. 163-179	10
The performance in a fixed bed reactor of copper-based oxides on titania as oxygen carriers for chemicel looping combustion of methane	Corbella, B.M., De Diego, L., García, F., Adánez, J., Palacios, J.M.	2005	*Energy and Fuels* 19 (2), pp. 433-441	22
Carbon formation on nickel and iron oxide-containing oxygen carriers for chemical-looping combustion	Cho, P., Mattisson, T., Lyngfelt, A.	2005	*Industrial and Engineering Chemistry Research* 44 (4), pp. 668-676	37
Design and fluid dynamic analysis of a bench-scale combustion system with CO2 separation-chemical-looping combustion	Kronberger, B., Lyngfelt, A., Löffler, G., Hofbauer, H.	2005	*Industrial and Engineering Chemistry Research* 44 (3), pp. 546-556	17
Temperature variations in the oxygen carrier particles during their reduction and oxidation in a chemical-looping combustion system	García-Labiano, F., De Diego, L.F., Adánez, J., Abad, A., Gayán, P.	2005	*Chemical Engineering Science* 60 (3), pp. 851-862	17
Simulation of coal gasification chemical looping combustion	Xiang, W., Di, T., Xiao, J., Shen, L.	2005	*Dongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Southeast University (Natural Science Edition)* 35 (1), pp. 20-23	3

Creating a synergy effect by using mixed oxides of iron- and nickel oxides in the combustion of methane in a chemical-looping combustion reactor	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Energy and Fuels* 20 (6), pp. 2399-2407	11
Investigation of chemical looping combustion by solid fuels. 2. Redox reaction kinetics and product characterization with coal, biomass, and solid waste as solid fuels and CuO as an oxygen carrier	Cao, Y., Casenas, B., Pan, W.-P.	2006	*Energy and Fuels* 20 (5), pp. 1845-1854	14
Thermal analysis of chemical-looping combustion	Jerndal, E., Mattisson, T., Lyngfelt, A.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 795-806	17
Investigation of Mn3O4 with stabilized ZrO2 for chemical-looping combustion	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 807-818	4
Combustion of syngas and natural gas in a 300 W chemical-looping combustor	Johansson, E., Mattisson, T., Lyngfelt, A., Thunman, H.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 819-827	18
Recovery combining chemical-looping combustion with low-temperature solar thermal energy	Hong, H., Jin, H.-G., Yang, S.	2006	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 27 (5), pp. 729-732	1
Investigation of chemical looping combustion by solid fuels. 1. Process analysis	Cao, Y., Pan, W.-P.	2006	*Energy and Fuels* 20 (5), pp. 1836-1844	17
In situ gasification of coal using steam with chemical looping: A technique for isolating CO2 from burning a solid fuel	Dennis, J.S., Scott, S.A., Hayhurst, A.N.	2006	*Journal of the Energy Institute* 79 (3), pp. 187-190	15

Use of NiO/NiAl2O4 particles in a 10 kW chemical-looping combustor	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Industrial and Engineering Chemistry Research* 45 (17), pp. 5911-5919	14
A novel solar-hybrid gas turbine combined cycle with inherent CO 2 separation using chemical-looping combustion by solar heat source	Hong, H., Jin, H., Liu, B.	2006	*Journal of Solar Energy Engineering, Transactions of the ASME* 128 (3), pp. 275-284	2
Research Status and Progress of Chemical-Looping Combustion	Li, Z.-S., Han, H.-J., Cai, N.-S.	2006	*Dongli Gongcheng/Power Engineering* 26 (4), pp. 538-543	1
Using steam reforming to produce hydrogen with carbon dioxide capture by chemical-looping combustion	Rydén, M., Lyngfelt, A.	2006	*International Journal of Hydrogen Energy* 31 (10), pp. 1271-1283	10
A 300 W laboratory reactor system for chemical-looping combustion with particle circulation	Johansson, E., Mattisson, T., Lyngfelt, A., Thunman, H.	2006	*Fuel* 85 (10-11), pp. 1428-1438	32
Chemical-looping combustion for combined cycles with CO2 capture	Consonni, S., Lozza, G., Pelliccia, G., Rossini, S., Saviano, F.	2006	*Journal of Engineering for Gas Turbines and Power* 128 (3), pp. 525-534	2
Chemical looping combustion using NiO/NiAl2O4: Mechanisms and kinetics of reduction - Oxidation (Red-Ox) reactions from in situ powder X-ray diffraction and thermogravimetry expirements	Readman, J.E., Olafsen, A., Smith, J.B., Blom, R.	2006	*Energy and Fuels* 20 (4), pp. 1382-1387	17
Chemical-looping combustion in a 300 W continuously operating reactor system using a manganese-based oxygen carrier	Abad, A., Mattisson, T., Lyngfelt, A., Rydén, M.	2006	*Fuel* 85 (9), pp. 1174-1185	29

Synthesis and redox properties of NiO/NiAl2O4 oxygen carriers for hydrogen-fueled chemical-looping combustion	Song, Y.-W., Lee, J.-B., Park, C.-S., Hwang, G.-J., Choi, S.-I., Yang, H.-S., Kim, Y.-H.	2006	*Journal of Industrial and Engineering Chemistry* 12 (2), pp. 255-260	3
Defluidization conditions for a fluidized bed of iron oxide-, nickel oxide-, and manganese oxide-containing oxygen carriers for chemical-looping combustion	Cho, P., Mattisson, T., Lyngfelt, A.	2006	*Industrial and Engineering Chemistry Research* 45 (3), pp. 968-977	20
Performance in a fixed-bed reactor of titania-supported nickel oxide as oxygen carriers for the chemical-looping combustion of methane in multicycle tests	Corbella, B.M., De Diego, L.F., García-Labiano, F., Adánez, J., Palacios, J.M.	2006	*Industrial and Engineering Chemistry Research* 45 (1), pp. 157-165	11
Characterization and performance in a multicycle test in a fixed-bed reactor of silica-supported copper oxide as oxygen carrier for chemical-looping combustion of methane	Corbella, B.M., de Diego, L., García-Labiano, F., Adánez, J., Palacios, J.M.	2006	*Energy and Fuels* 20 (1), pp. 148-154	12
Effect of pressure on the behavior of copper-, iron-, and nickel-based oxygen carriers for chemical-looping combustion	García-Labiano, F., Adánez, J., de Diego, L.F., Gayán, P., Abad, A.	2006	*Energy and Fuels* 20 (1), pp. 26-33	25
Redox investigation of some oxides of transition-state metals Ni, Cu, Fe, and supported on SiO2 and MgAl2O4	Zafar, Q., Mattisson, T., Gevert, B.	2006	*Energy and Fuels* 20 (1), pp. 34-44	17
Synthesis and redox properties of NiO/NiAl2O4 oxygen carriers for hydrogen-fueled chemical-looping combustion	Song, Y.-W., Lee, J.-B., Park, C.-S., Hwang, G.-J., Choi, S.-I., Yang,	2006	*Journal of Industrial and Engineering Chemistry* 12 (2), pp. 255-260	3

Study and improvement of the regeneration of metallic oxides used as oxygen carriers for a new combustion process	Roux, S., Bensakhria, A., Antonini, G.	2006	*International Journal of Chemical Reactor Engineering* 4, pp. 1-14	0
Creating a synergy effect by using mixed oxides of iron- and nickel oxides in the combustion of methane in a chemical-looping combustion reactor	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Energy and Fuels* 20 (6), pp. 2399-2407	11
Investigation of chemical looping combustion by solid fuels. 2. Redox reaction kinetics and product characterization with coal, biomass, and solid waste as solid fuels and CuO as an oxygen carrier	Cao, Y., Casenas, B., Pan, W.-P.	2006	*Energy and Fuels* 20 (5), pp. 1845-1854	14
Thermal analysis of chemical-looping combustion	Jerndal, E., Mattisson, T., Lyngfelt, A.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 795-806	17
Investigation of Mn3O4 with stabilized ZrO2 for chemical-looping combustion	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 807-818	4
Combustion of syngas and natural gas in a 300 W chemical-looping combustor	Johansson, E., Mattisson, T., Lyngfelt, A., Thunman, H.	2006	*Chemical Engineering Research and Design* 84 (9 A), pp. 819-827	18
Recovery combining chemical-looping combustion with low-temperature solar thermal energy	Hong, H., Jin, H.-G., Yang, S.	2006	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 27 (5), pp. 729-732	1
Investigation of chemical looping combustion by solid fuels. 1. Process analysis	Cao, Y., Pan, W.-P.	2006	*Energy and Fuels* 20 (5), pp. 1836-1844	17

Chemical looping combustion in a 10 kWth prototype using a CuO/Al2O3 oxygen carrier: Effect of operating conditions on methane combustion	Adánez, J., Gayán, P., Celaya, J., De Diego, L.F., García-Labiano, F., Abad, A.	2006	*Industrial and Engineering Chemistry Research* 45 (17), pp. 6075-6080	24
Use of NiO/NiAl2O4 particles in a 10 kW chemical-looping combustor	Johansson, M., Mattisson, T., Lyngfelt, A.	2006	*Industrial and Engineering Chemistry Research* 45 (17), pp. 5911-5919	14
In situ gasification of coal using steam with chemical looping: A technique for isolating CO2 from burning a solid fuel	Dennis, J.S., Scott, S.A., Hayhurst, A.N.	2006	*Journal of the Energy Institute* 79 (3), pp. 187-190	15
Chemical looping combustion in a 10 kWth prototype using a CuO/Al2O3 oxygen carrier: Effect of operating conditions on methane combustion	Adánez, J., Gayán, P., Celaya, J., De Diego, L.F., García-Labiano, F., Abad, A.	2006	*Industrial and Engineering Chemistry Research* 45 (17), pp. 6075-6080	24
Performance research on new oxygen carrier CaSO4 used in chemical-looping combustion	Zheng, Y., Wang, B.-W., Song, K., Zheng, C.-G.	2006	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 27 (3), pp. 531-533	9
The use of NiO as an oxygen carrier in chemical-looping combustion	Mattisson, T., Johansson, M., Lyngfelt, A.	2006	*Fuel* 85 (5-6), pp. 736-747	41
A quantitative comparison of gas turbine cycles with CO2 capture	Kvamsdal, H.M., Jordal, K., Bolland, O.	2007	*Energy* 32 (1), pp. 10-24	15
Mapping of the range of operational conditions for Cu-, Fe-, and Ni-based oxygen carriers in chemical-looping combustion	Abad, A., Adánez, J., García-Labiano, F., de Diego, L.F., Gayán, P., Celaya, J.	2007	*Chemical Engineering Science* 62 (1-2), pp. 533-549	31

Chemical-looping combustion using syngas as fuel	Mattisson, T., García-Labiano, F., Kronberger, B., Lyngfelt, A., Adánez, J., Hofbauer, H.	2007	*International Journal of Greenhouse Gas Control* 1 (2), pp. 158-169	8
Multi-stage chemical looping combustion (CLC) for combined cycles with CO2 capture	Naqvi, R., Bolland, O.	2007	*International Journal of Greenhouse Gas Control* 1 (1), pp. 19-30	0
Part-load analysis of a chemical looping combustion (CLC) combined cycle with CO2 capture	Naqvi, R., Wolf, J., Bolland, O.	2007	*Energy* 32 (4), pp. 360-370	2
The preliminary experimental study of the energy release principle in the energy system integrating methanol-chemical looping combustion and low-temperature solar thermal energy	He, P., Hong, H., Jin, H.-G., Yu, Z.-A.	2007	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 28 (2), pp. 181-184	1
Reaction kinetics of freeze-granulated NiO/MgAl2O4 oxygen carrier particles for chemical-looping combustion	Zafar, Q., Abad, A., Mattisson, T., Gevert, B.	2007	*Energy and Fuels* 21 (2), pp. 610-618	8
Performance study of an oxygen-bearing iron oxide-based combined cycle system featuring integrated coal-gasification chemical-looping combustion	Mou, J.-M., Xiang, W.-G., Di, T.-T.	2007	*Reneng Dongli Gongcheng/Journal of Engineering for Thermal Energy and Power* 22 (2), pp. 149-153	0
Chemical looping combustion of coal in interconnected fluidized beds of CaSO4 oxygen carrier	Shen, L.-H., Xiao, J., Xiao, R., Zhang, H.	2007	*Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering* 27 (2), pp. 69-74	6
Titania-supported iron oxide as oxygen carrier for chemical-looping combustion of methane	Corbella, B.M., Palacios, J.M.	2007	*Fuel* 86 (1-2), pp. 113-122	15

Performance investigation of Ni-based CLC gasification combined cycle	Xiang, W., Di, T.	2007	*Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 58 (7), pp. 1816-1821	1
Reactivity and stability of Co-Ni/Al2O3 oxygen carrier in multicycle CLC	Hossain, M.M., De Lasa, H.I.	2007	*AIChE Journal* 53 (7), pp. 1817-1829	6
Packed bed reactor technology for chemical-looping combustion	Noorman, S., Van Sint Annaland, M., Kuipers, H.	2007	*Industrial and Engineering Chemistry Research* 46 (12), pp. 4212-4220	1
Application of Fe2O3/Al2O3 Composite Particles as Oxygen Carrier of Chemical Looping Combustion	He, F., Wang, H., Dai, Y.	2007	*Journal of Natural Gas Chemistry* 16 (2), pp. 155-161	1
Chemical-looping combustion of simulated synthesis gas using nickel oxide oxygen carrier supported on bentonite	Siriwardane, R., Poston, J., Chaudhari, K., Zinn, A., Simonyi, T., Robinson, C.	2007	*Energy and Fuels* 21 (3), pp. 1582-1591	5
The use of iron oxide as oxygen carrier in a chemical-looping reactor	Abad, A., Mattisson, T., Lyngfelt, A., Johansson, M.	2007	*Fuel* 86 (7-8), pp. 1021-1035	28
Operation of a 10 kWth chemical-looping combustor during 200 h with a CuO-Al2O3 oxygen carrier	de Diego, L.F., García-Labiano, F., Gayán, P., Celaya, J., Palacios, J.M., Adánez, J.	2007	*Fuel* 86 (7-8), pp. 1036-1045	17
Chemical looping combustion of coal in interconnected fluidized beds	Shen, L., Zheng, M., Xiao, J., Zhang, H., Xiao, R.	2007	*Science in China, Series E: Technological Sciences* 50 (2), pp. 230-240	7

Solution combustion synthesized oxygen carriers for chemical looping combustion	Erri, P., Varma, A.	2007	*Chemical Engineering Science* 62 (18-20 SPEC. ISS.), pp. 5682-5687	4
Co - Ni / Al2 O3 oxygen carrier for fluidized bed chemical-looping combustion: Desorption kinetics and metal-support interaction	Hossain, M.M., Sedor, K.E., de Lasa, H.I.	2007	*Chemical Engineering Science* 62 (18-20 SPEC. ISS.), pp. 5464-5472	7
Solid waste management of a chemical-looping combustion plant using Cu-based oxygen carriers	García-Labiano, F., Gayán, P., Adánez, J., De Diego, L.F., Forero, C.R.	2007	*Environmental Science and Technology* 41 (16), pp. 5882-5887	1
The use of petroleum coke as fuel in chemical-looping combustion	Leion, H., Mattisson, T., Lyngfelt, A.	2007	*Fuel* 86 (12-13), pp. 1947-1958	17
Reduction kinetics of Cu-, Ni-, and Fe-based oxygen carriers using syngas (CO + H2) for chemical-looping combustion	Abad, A., García-Labiano, F., de Diego, L.F., Gayán, P., Adánez, J.	2007	*Energy and Fuels* 21 (4), pp. 1843-1853	12
Hydrodynamics of interconnected fluidized beds for chemical-looping combustion	Wu, J., Shen, L., Xiao, J., Lu, H.	2007	*Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 58 (11), pp. 2753-2758	1
Reduction of iron oxide as an oxygen carrier by coal pyrolysis and steam char gasification intermediate products	Yang, J.-B., Cai, N.-S., Li, Z.-S.	2007	*Energy and Fuels* 21 (6), pp. 3360-3368	3
Spinel-supported oxygen carriers for inherent CO2 separation during power generation	Erri, P., Varma, A.	2007	*Industrial and Engineering Chemistry Research* 46 (25), pp. 8597-8601	5
Reduction and oxidation kinetics of Mn3O4/Mg-ZrO2 oxygen carrier particles for chemical-looping combustion	Zafar, Q., Abad, A., Mattisson, T., Gevert, B., Strand, M.	2007	*Chemical Engineering Science* 62 (23), pp. 6556-6567	2

Novel oxygen-carrier materials for chemical-looping combustion and chemical-looping reforming; LaxSr1-xFeyCo1-yO3-δ perovskites and mixed-metal oxides of NiO, Fe2O3 and Mn3O4	Rydén, M., Lyngfelt, A., Mattisson, T., Chen, D., Holmen, A., Bjørgum, E.	2008	*International Journal of Greenhouse Gas Control* 2 (1), pp. 21-36	4
Sol-gel-derived NiO/NiAl2O4 oxygen carriers for chemical-looping combustion by coal char	Zhao, H., Liu, L., Wang, B., Xu, D., Jiang, L., Zheng, C.	2008	*Energy and Fuels* 22 (2), pp. 898-905	1
Investigation of gasification chemical looping combustion combined cycle performance	Xiang, W., Wang, S., Di, T.	2008	*Energy and Fuels* 22 (2), pp. 961-966	2
Thermodynamic investigation of carbon deposition and sulfur evolution in chemical looping combustion with syngas	Wang, B., Yan, R., Lee, D.H., Liang, D.T., Zheng, Y., Zhao, H., Zheng, C.	2008	*Energy and Fuels* 22 (2), pp. 1012-1020	1
Clean combustion of solid fuels	Wang, J., Anthony, E.J.	2008	*Applied Energy* 85 (2-3), pp. 73-79	7
Progress in carbon dioxide separation and capture: A review	Yang, H., Xu, Z., Fan, M., Gupta, R., Slimane, R.B., Bland, A.E., Wright, I.	2008	*Journal of Environmental Sciences* 20 (1), pp. 14-27	11
Using continuous and pulse experiments to compare two promising nickel-based oxygen carriers for use in chemical-looping technologies	Johansson, M., Mattisson, T., Lyngfelt, A., Abad, A.	2008	*Fuel* 87 (6), pp. 988-1001	5
Multiphase CFD-based models for chemical looping combustion process: Fuel reactor modeling	Jung, J., Gamwo, I.K.	2008	*Powder Technology* 183 (3), pp. 401-409	1
Solid fuels in chemical-looping combustion	Leion, H., Mattisson, T., Lyngfelt, A.	2008	*International Journal of Greenhouse Gas Control* 2 (2), pp. 180-193	12

The use of petroleum coke as fuel in a 10 kWth chemical-looping combustor	Berguerand, N., Lyngfelt, A.	2008	*International Journal of Greenhouse Gas Control* 2 (2), pp. 169-179	7
Solid looping cycles: A new technology for coal conversion	Anthony, E.J.	2008	*Industrial and Engineering Chemistry Research* 47 (6), pp. 1747-1754	9
Utilization of chemical looping strategy in coal gasification processes	Fan, L., Li, F., Ramkumar, S.	2008	*Particuology* 6 (3), pp. 131-142	1
Chemical looping combustion of coal based on NiO oxygen carrier	Gao, Z., Shen, L., Xiao, J.	2008	*Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 59 (5), pp. 1242-1250	0
New strategies for conquering environmental challenges	[No author name available]	2008	*Power* 152 (7)	0
Chemical-looping combustion - a thermodynamic study	McGlashan, N.R.	2008	*Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 222 (6), pp. 1005-1019	0
Reactivity and stability of Ni/Al2O3 oxygen carrier for chemical-looping combustion (CLC)	Sedor, K.E., Hossain, M.M., de Lasa, H.I.	2008	*Chemical Engineering Science* 63 (11), pp. 2994-3007	5
NiO/NiAl2O4 oxygen carriers prepared by sol-gel for chemical-looping combustion fueled by gas	Zhao, H.-B., Liu, L.-M., Xu, D., Zheng, C.-G., Liu, G.-J., Jiang, L.-L.	2008	*Journal of Fuel Chemistry and Technology* 36 (3), pp. 261-266	0
Reduction kinetics of a fluidizable nickel-alumina oxygen carrier for chemical-looping combustion	Sedor, K.E., Hossain, M.M., De Lasa, H.I.	2008	*Canadian Journal of Chemical Engineering* 86 (3), pp. 323-334	4

Hydrogen production from the steam-iron process with direct reduction of iron oxide by chemical looping combustion of coal char	Yang, J.-B., Cai, N.-S., Li, Z.-S.	2008	*Energy and Fuels* 22 (4), pp. 2570-2579	0
Chemical-looping combustion and chemical-looping reforming in a circulating fluidized-bed reactor using Ni-based oxygen carriers	Rydén, M., Lyngfelt, A., Mattisson, T.	2008	*Energy and Fuels* 22 (4), pp. 2585-2597	0
Development and performance of Cu-based oxygen carriers for chemical-looping combustion	Chuang, S.Y., Dennis, J.S., Hayhurst, A.N., Scott, S.A.	2008	*Combustion and Flame* 154 (1-2), pp. 109-121	2
Chemical-looping combustion (CLC) for inherent CO2 separations-a review	Hossain, M.M., de Lasa, H.I.	2008	*Chemical Engineering Science* 63 (18), pp. 4433-4451	2
Effect of support on reactivity and selectivity of Ni-based oxygen carriers for chemical-looping combustion	Gayán, P., de Diego, L.F., García-Labiano, F., Adánez, J., Abad, A., Dueso, C.	2008	*Fuel* 87 (12), pp. 2641-2650	4
Design and operation of a 10 kWth chemical-looping combustor for solid fuels - Testing with South African coal	Berguerand, N., Lyngfelt, A.	2008	*Fuel* 87 (12), pp. 2713-2726	7
Development of novel two-interconnected fluidized bed system	Ryu, H.-J., Park, Y.-C., Jo, S.-H., Park, M.-H.	2008	*Korean Journal of Chemical Engineering* 25 (5), pp. 1178-1183	0
A mechanistic investigation of a calcium-based oxygen carrier for chemical looping combustion	Shen, L., Zheng, M., Xiao, J., Xiao, R.	2008	*Combustion and Flame* 154 (3), pp. 489-506	4
The reaction of NiO/NiAl2O4 particles with alternating methane and oxygen	Mattisson, T., Johansson, M., Jerndal, E., Lyngfelt, A.	2008	*Canadian Journal of Chemical Engineering* 86 (4), pp. 756-767	1

Chemical looping and coal	[No author name available]	2008	*Power* 152 (10)	0
A novel energy conservation process for zero emission of carbon dioxide: Chemical looping combustion	Wang, Q., Cheng, Y., Wu, C., Jin, Y.	2008	*Progress in Chemistry* 20 (10), pp. 1612-1620	0
160 h of chemical-looping combustion in a 10 kW reactor system with a NiO-based oxygen carrier	Linderholm, C., Abad, A., Mattisson, T., Lyngfelt, A.	2008	*International Journal of Greenhouse Gas Control* 2 (4), pp. 520-530	5
Natural gas combustion characteristics in a chemical-looping combustor with three different oxygen carrier particles	Ryu, H.-J., Jin, G.-T., Jo, S.-H., Park, M.-H.	2008	*Journal of Chemical Engineering of Japan* 41 (7), pp. 716-720	0
The use of ilmenite as an oxygen carrier in chemical-looping combustion	Leion, H., Lyngfelt, A., Johansson, M., Jerndal, E., Mattisson, T.	2008	*Chemical Engineering Research and Design* 86 (9), pp. 1017-1026	1
Advances in oxygen carriers in chemical-looping combustion technology	Liu, Y.-X., Zhang, J., Sheng, C.-D., Zhang, Y.-C., Yuan, S.-J.	2008	*Xiandai Huagong/Modern Chemical Industry* 28 (9), pp. 27-32	0
Investigation into decomposition behavior of CaSO4 in chemical-looping combustion	Tian, H., Guo, Q., Chang, J.	2008	*Energy and Fuels* 22 (6), pp. 3915-3921	0
Reduction of CaSO4 oxygen carrier with CO in chemical-looping combustion	Zheng, M., Shen, L., Xiao, J.	2008	*Huagong Xuebao/Journal of Chemical Industry and Engineering (China)* 59 (11), pp. 2812-2818	0
Synthesis gas generation by chemical-looping reforming in a batch fluidized bed reactor using Ni-based oxygen carriers	de Diego, L.F., Ortiz, M., Adánez, J., García-Labiano, F., Abad, A., Gayán, P.	2008	*Chemical Engineering Journal* 144 (2), pp. 289-298	0

Chemical looping combustion of coal derived synthesis gas over copper-based oxygen carrier	Tian, H., Siriwardane, R.V., Veser, G., Simonyi, T., Liu, T., Solunke, R.	2008	*2008 AIChE Spring National Meeting, Conference Proceedings*	0
Use of coal as fuel for chemical-looping combustion with Ni-based oxygen carrier	Gao, Z., Shen, L., Xiao, J., Qing, C., Song, Q.	2008	*Industrial and Engineering Chemistry Research* 47 (23), pp. 9279-9287	0
Multiphase CFD modeling for a chemical looping combustion process (fuel reactor)	Deng, Z., Xiao, R., Jin, B., Song, Q., Huang, H.	2008	*Chemical Engineering and Technology* 31 (12), pp. 1754-1766	0
A chemical intercooling gas turbine cycle with chemical-looping combustion	Zhang, X., Han, W., Hong, H., Jin, H.	2008	*Energy* Article in Press	0
Effect of temperature on reduction of CaSO4 oxygen carrier in chemical-looping combustion of simulated coal gas in a fluidized bed reactor	Song, Q., Xiao, R., Deng, Z., Shen, L., Xiao, J., Zhang, M.	2008	*Industrial and Engineering Chemistry Research* 47 (21), pp. 8148-8159	0
Chemical-looping combustion of methane with CaSO4 oxygen carrier in a fixed bed reactor	Song, Q., Xiao, R., Deng, Z., Zhang, H., Shen, L., Xiao, J., Zhang, M.	2008	*Energy Conversion and Management* 49 (11), pp. 3178-3187	2
Multicycle study on chemical-looping combustion of simulated coal gas with a CaSO4 oxygen carrier in a fluidized bed reactor	Song, Q., Xiao, R., Deng, Z., Zheng, W., Shen, L., Xiao, J.	2008	*Energy and Fuels* 22 (6), pp. 3661-3672	2
Chemical-looping combustion of coal-derived synthesis gas over copper oxide oxygen carriers	Tian, H., Chaudhari, K., Simonyi, T., Poston, J., Liu, T., Sanders, T., Veser, G., Siriwardane, R.	2008	*Energy and Fuels* 22 (6), pp. 3744-3755	0

Diffusional effects in nickel oxide reduction kinetics	Erri, P., Varma, A.	2009	*Industrial and Engineering Chemistry Research* 48 (1), pp. 4-6	0
Syngas combustion in a chemical-looping combustion system using an impregnated Ni-based oxygen carrier	Dueso, C., García-Labiano, F., Adánez, J., de Diego, L.F., Gayán, P., Abad, A.	2009	*Fuel* Article in Press	0
Numerical simulation of chemical looping combustion process with CaSO4 oxygen carrier	Deng, Z., Xiao, R., Jin, B., Song, Q.	2009	*International Journal of Greenhouse Gas Control* Article in Press	0
Modeling of a 120 kW chemical looping combustion reactor system using a Ni-based oxygen carrier	Kolbitsch, P., Pröll, T., Hofbauer, H.	2009	*Chemical Engineering Science* 64 (1), pp. 99-108	0
Clean hydrogen production and electricity from coal via chemical looping: Identifying a suitable operating regime	Cleeton, J.P.E., Bohn, C.D., Müller, C.R., Dennis, J.S., Scott, S.A.	2009	*International Journal of Hydrogen Energy* 34 (1), pp. 1-12	0
Chemical-looping with oxygen uncoupling for combustion of solid fuels	Mattisson, T., Lyngfelt, A., Leion, H.	2009	*International Journal of Greenhouse Gas Control* 3 (1), pp. 11-19	1
NiO/NiAl2O4 oxygen carriers for chemical looping combustion fueled by coal	Zhao, H.-B., Liu, L.-M., Xu, D., Zheng, C.-G., Liu, G.-J., Jiang, L.-L.	2009	*Ranshao Kexue Yu Jishu/Journal of Combustion Science and Technology* 15 (1), pp. 22-27	0
Oxidation of CaS with O2 for oxygen carrier regeneration in chemical-looping combustion	Zheng, M., Shen, L., Gao, Z., Xiao, J.	2009	*Huanjing Kexue Xuebao / Acta Scientiae Circumstantiae* 29 (2), pp. 330-338	0

Methane combustion in a 500 Wth chemical-looping combustion system using an impregnated ni-based oxygen carrier	Adánez, J., Dueso, C., Diego, L.F.D., García-Labiano, F., Gayán, P., Abad, A.	2009	*Energy and Fuels* 23 (1), pp. 130-142	1
Progress of energy system with chemical-looping combustion	Jin, H., Hong, H., Han, T.	2009	*Chinese Science Bulletin* 54 (6), pp. 906-919	0
Reactivity of a CaSO4-oxygen carrier in chemical-looping combustion of methane in a fixed bed reactor	Song, Q., Xiao, R., Deng, Z., Shen, L., Zhang, M.	2009	*Korean Journal of Chemical Engineering* 26 (2), pp. 592-602	0
Nickel- and copper-based oxygen carriers for chemical looping combustion	Hoteit, A., Chandel, M.K., Delebarre, A.	2009	*Chemical Engineering and Technology* 32 (3), pp. 443-449	0
Syngas combustion characteristics of four oxygen carrier particles for chemical-looping combustion in a batch fluidized bed reactor	Ryu, H.-J., Shun, D., Bae, D.-H., Park, M.-H.	2009	*Korean Journal of Chemical Engineering* 26 (2), pp. 523-527	0
Hydrogen production from coal using coal direct chemical looping and syngas chemical looping combustion systems: Assessment of system operation and resource requirements	Gnanapragasam, N.V., Reddy, B.V., Rosen, M.A.	2009	*International Journal of Hydrogen Energy* 34 (6), pp. 2606-2615	0
The sustainable capability research of the metal oxygen carrier	Jiang, J., Jin, J., Duan, H.-W., Chen, L.	2009	*Kung Cheng Je Wu Li Hsueh Pao/Journal of Engineering Thermophysics* 30 (3), pp. 505-508	0
Design of a chemical looping combustor using a dual circulating fluidized bed reactor system	Kolbitsch, P., Pröll, T., Bolhar-Nordenkampf, J.	2009	*Chemical Engineering and Technology* 32 (3), pp. 398-403	0

Investigation of different NiO/NiAl2O4 particles as oxygen carriers for chemical-looping combustion	Jerndal, E., Mattisson, T., Lyngfelt, A.	2009	*Energy and Fuels* 23 (2), pp. 665-676	0
Long-term integrity testing of spray-dried particles in a 10-kW chemical-looping combustor using natural gas as fuel	Linderholm, C., Mattisson, T., Lyngfelt, A.	2009	*Fuel* Article in Press	0
Oxygen carriers for chemical looping combustion of solid fuels	Rubel, A., Liu, K., Neathery, J., Taulbee, D.	2009	*Fuel* 88 (5), pp. 876-884	0
Experimental investigation of some metal oxides for chemical looping combustion in a fluidized bed reactor	Chandel, M.K., Hoteit, A., Delebarre, A.	2009	*Fuel* 88 (5), pp. 898-908	0
Chemical-looping with oxygen uncoupling using CuO/ZrO2 with petroleum coke	Mattisson, T., Leion, H., Lyngfelt, A.	2009	*Fuel* 88 (4), pp. 683-690	1
Reduction and oxidation kinetics of Co-Ni/Al2O3 oxygen carrier involved in a chemical-looping combustion cycles	Hossain, M.M., de Lasa, H.I.	2009	*Chemical Engineering Science* Article in Press	0
Characterization of chemical looping pilot plant performance via experimental determination of solids conversion	Kolbitsch, P., Proll, T., Bolhar-Nordenkampf, J., Hofbauer, H.	2009	*Energy and Fuels* 23 (3), pp. 1450-1455	0
Experimental validation of packed bed chemical-looping combustion	Noorman, S., van Sint Annaland, M., Kuipers, J.A.M.	2009	*Chemical Engineering Science* Article in Press	0
Effect of fuel gas composition in chemical-looping combustion with Ni-based oxygen carriers. 2. Fate of light hydrocarbons	Adánez, J., Dueso, C., De Diego, L.F., García-Labiano, F., Gayán, P., Abad, A.	2009	*Industrial and Engineering Chemistry Research* 48 (5), pp. 2509-2518	1

Effect of fuel gas composition in chemical-looping combustion with Ni-based oxygen carriers. 1. Fate of sulfur	García-Labiano, F., De Diego, L.F., Gayán, P., Adánez, J., Abad, A., Dueso, C.	2009	*Industrial and Engineering Chemistry Research* 48 (5), pp. 2499-2508	1
Experiments on chemical looping combustion of coal with a NiO based oxygen carrier	Shen, L., Wu, J., Xiao, J.	2009	*Combustion and Flame* 156 (3), pp. 721-728	1
NiO/Al2O3 oxygen carriers for chemical-looping combustion prepared by impregnation and deposition-precipitation methods	Gayán, P., Dueso, C., Abad, A., Adanez, J., de Diego, L.F., García-Labiano, F.	2009	*Fuel* 88 (6), pp. 1016-1023	0
Nickel on lanthanum-modified γ-Al2O3 oxygen carrier for CLC: Reactivity and stability	Hossain, M.M., Lopez, D., Herrera, J., de Lasa, H.I.	2009	*Catalysis Today* 143 (1-2), pp. 179-186	0