PROCESS MODELLING AND TECHNO-ECONOMIC ANALYSIS OF NATURAL GAS COMBINED CYCLE INTEGRATED WITH CALCIUM LOOPING

by

Maria ERANS, Dawid P. HANAK, Jordi MIR, Edward J. ANTHONY, and Vasilije MANOVIC*

Combustion and Carbon Capture and Storage Centre,
Cranfield University, Bedford, Bedfordshire, UK

Original scientific paper
DOI: 10.2298/TSCI151001209E

Calcium looping is promising for large-scale CO_2 capture in the power generation and industrial sectors due to the cheap sorbent used and the relatively low energy penalties achieved with this process. Because of the high operating temperatures the heat utilisation is a major advantage of the process, since a significant amount of additional power can be generated from it. However, this increases its complexity and capital costs. Therefore, not only the energy efficiency performance is important for these cycles, but also the capital costs must be taken into account, i. e. techno-economic analyses are required in order to determine which parameters and configurations are optimal to enhance technology viability in different integration scenarios. In this study the integration scenarios of calcium looping and natural gas combined cycles are explored. The process models of the natural gas combined cycles and calcium looping CO_2 capture plant are developed to explore the most promising scenarios for natural gas combined cycles-calcium looping integration with regard to efficiency penalties. Two scenarios are analysed in detail, and show that the system with heat recovery steam generator before and after the capture plant exhibited better performance of 49.1% efficiency compared with that of 45.7% when only one heat recovery steam generator is located after the capture plant. However, the techno-economic analyses showed that the more energy efficient case, with two heat recovery steam generators, implies relatively higher cost of electricity, 44.1 €/MWh, when compared to that of the reference plant system (33.1 €/MWh). The predicted cost of CO_2 avoided for the case with two heat recovery steam generators is 29.3 € per tonne of CO_2.

Key words: *natural gas combined cycles, calcium looping, efficiency penalty, techno-economic analysis*

Introduction

Mitigation of CO_2 emissions is required in order to limit the global concentration of CO_2 to 450 ppm_v by 2050 [1]. However, energy demand is expected to grow and the burning of fossil fuels is likely to continue in the medium-term future. Therefore, it is important to find viable routes to achieve CO_2 emission limits before the development and deployment of new, less carbon-intensive sources of energy becomes dominant in our global energy mix. One widely considered approach for reducing CO_2 emissions in the short to mid-term is carbon capture and

* Corresponding author; e-mail: v.manovic@cranfield.ac.uk

Published by VINČA Institute of Nuclear Sciences

storage (CCS) [2, 3]. CCS technology is based on avoiding the emission of CO_2 to the atmosphere; instead the carbon dioxide stream is captured and stored in a safe location [4].

Of the carbon capture technologies amine-based scrubbing is the closest to the market and can be deployed in the short term because of its easy retrofit in current power stations [3]. In fact, the first large-scale plant of its kind was commissioned in late 2014 [5, 6]. However, given the high cost of amine scrubbing, alternative technologies are being developed using solids as adsorption material, and among these options, calcium looping (CaL) [7] seems to be one of the most promising and competitive processes to decarbonise power generation and carbon-intensive industries. The main advantages of CaL are relatively low energy penalties [8] and the widely available and cheap sorbent (typically limestone) [9].

CaL technology comprises two interconnected fluidised bed reactors and uses lime (CaO) as a CO_2 carrier regenerable at high temperatures [10]. In the first reactor, the CO_2 present in the flue gas reacts with the sorbent to produce $CaCO_3$, *i. e.* saturated sorbent, which is transferred to the second reactor where it is regenerated at high temperature, producing a nearly pure concentrated CO_2 stream. After regeneration, the sorbent is transferred again to the first reactor to start the new cycle. The additional advantage of this process is the almost zero waste material produced in some scenarios as spent sorbent can be reused, for example, in the cement industry [11]. Although CaL is estimated to be 60% less costly than amine technology [9] and cheaper than other emerging technologies (chilled ammonia and membrane separation) [12], there are challenges that need further investigation before fully scaling-up the technology. Namely, it is well known that sorbents experience reactivity decay with increasing numbers of reaction cycles, mainly due to sintering [13].

Usually in carbon capture technologies, energy is spent in order to remove the CO_2 from the flue gas, which results in lower power plant output. However, in calcium looping, the high temperatures in both reactors allow an exceptional opportunity for heat integration in order to increase the power output of the integrated power-capture plant system. The efficiency penalty expected for calcium looping is between 7-10% points, but it can be reduced to levels as low as 5% [10, 14-17]. Heat can be recovered from both hot gas and solid streams, but as the carbonation reaction is exothermic, heat generated in the carbonator can also be used to produce additional steam for a secondary steam cycle [18, 19].

Natural gas combined cycle (NGCC) plants use natural gas as fuel, which is a mixture of gaseous hydrocarbons. The main component is methane, but it usually contains some traces of sulphur, nitrogen, and CO_2, among other components including higher hydrocarbons [20]. It is a relatively clean fuel used for electricity generation, which accounts for 21% of electricity generated worldwide [21]. Moreover, the efficiency of this kind of plant can achieve values up to 60% [22].

The NGCC consists of two power cycles in series in order to achieve a high overall efficiency of the plant. In this study a detailed analysis of NGCC plants is performed, pointing out the main parameters and key challenges. The aim of this paper is to develop process models of the NGCC plant as well as the CaL plant, integrate them, and to compare the results (thermal efficiency) from different integration scenarios. In addition a techno-economic analysis of two most viable configurations was carried out. The main idea is to evaluate at the same time both the thermal efficiencies of the NGCC-CaL systems and the cost of electricity and CO_2 avoided taking into account different complexities considered in the integration scenarios. It should be noted that although in previous studies efficiency penalties, sorbent performance and key process parameters have been analysed, this work also provides insight into the economics of the NGCC-CaL process.

Model development

Natural gas combined cycle (NGCC) power plant

The model of the NGCC was developed using the European Benchmark Taskforce (EBTF) data and the work performed by Manzolini *et al.* [20]. The configuration of the process comprises two gas turbines plus a single steam cycle.

This configuration is used because of the flexibility given by being able to operate with only one gas turbine or both of them, depending on the electricity demand. It provides extra flexibility that cannot be achieved with only one gas turbine [23].

For the modelling of the gas turbine the GasTurb® was used, due to its more accurate calculation options. The gas turbine was modelled in this software in order to satisfy the conditions imposed by the EBTF; blade cooling was also taken into account. The nominal speed of the gas turbine is 1800 rpm, and as the input parameters for the fuel the data for natural gas were extracted from Manzolini *et al.* [20]. The main air and natural gas inlet conditions are shown in tab. 1, followed by tab. 2 revealing the gas turbine operating parameters.

The rest of the power plant, as well as the capture plant and the compression stage have been modelled using Aspen Plus®. For modelling purposes the combustor was assumed to be a stoichiometric reactor (RStoic), which takes into account the stoichiometry of the oxidation of the fuel in order to calculate the outlet conditions. The HRSG was assumed to have three different pressure turbines and a set of heat exchangers in order to get a more accurate prediction. The parameters for the HRSG are specified in tab. 3.

The variables studied in the validation of the model are temperature and pressure at the exit of the turbine and power produced by the gas turbines and the HRSG, as well as the efficiency of the plants. These values can be found in tabs. 4 and 5.

Table 1. Air and natural gas inlet conditions

Air		Natural gas	
Temperature, [ºC]	15	Temperature, [ºC]	160
Pressure, [bar]	1	Pressure, [bar]	70
Mass flow, [kgs^{-1}]	650	Mass flow, [kgs^{-1}]	15.3

Table 2. Gas turbine main parameters

Parameter	Value
Turbine inlet temperature, [ºC]	1360
Pressure ratio in the compressor, [–]	18.1
Compressor efficiency, [%]	85
Turbine efficiency, [%]	94.15
Mechanical efficiency, [%]	99.6
Combustor temperature, [ºC]	1443
Combustor pressure, [bar]	70
Mole flow at exit, [molh^{-1}]	84251.5
Temperature at exit, [ºC]	604
Vapour fraction, [–]	1

Table 3. Main parameters of the HRSG of the reference plant

Parameter	Value
High-pressure turbine	
Inlet pressure, [bar]	120
Reheat temperature, [ºC]	500
Isentropic efficiency, [%]	94
Intermediate-pressure turbine	
Inlet pressure, [bar]	28
Reheat temperature, [ºC]	291
Isentropic efficiency, [%]	91
Low-pressure turbine	
Inlet pressure, [bar]	5
Isentropic efficiency, [%]	90
Condenser pressure, [bar]	0.048

Table 4. Validation of gas turbine

Parameter	Aspen Plus	EBTF	Error, [%]
Gas turbine outlet temperature, [°C]	604	608	0.65
Power generated by gas turbine, [MW]	277	280	1.07
Power generated by steam turbine, [MW]	265	269.9	1.8

Table 5. Validation parameters of the steam cycle

Parameter	Aspen Plus	EBTF	Error, [%]
Power generated, [MW]	819.9	829.9	1.3
Net efficiency LHV, [%]	57.7	58.3	1.1

Capture plant

The flue gas from the NGCC enters the carbonator, which is assumed to be a stoichiometric reactor for modelling purposes, with three degrees of freedom: sorbent conversion, temperature, and pressure. The carbonator temperature is maintained between 580-700 °C, which is the optimal capture temperature range due to the trade-off between the equilibrium forces and the reaction kinetics [24, 25]. The calcination occurs at more than 900 °C, in a chamber that is modelled as a Gibbs reactor, where extra fuel is burned in an O_2/CO_2 atmosphere to generate heat required for the endothermic calcination reaction [14, 26]. As the sorbent conversion decreases during the carbonation/calcination cycles, the fresh sorbent make-up is considered.

This model uses the semi-empirical correlation for maximum average conversion shown in eq. (1) [27]. The carbonation conversion and the CO_2 capture level are calculated by eqs. (2) and (3).

$$X_{\text{ave}} = (F_0 + F_R r_0) f_{\text{calc}} \left[\frac{a_1 f_1^2}{F_0 + F_R f_{\text{carb}} f_{\text{calc}} (1 - f_1)} + \frac{a_2 f_2^2}{F_0 + F_R f_{\text{carb}} f_{\text{calc}} (1 - f_2)} + \frac{b}{F_0} \right] \tag{1}$$

$$\Delta X_{\text{carb}} = f_{\text{calc}} f_{\text{carb}} X_{\text{ave}} \tag{2}$$

$$E_{\text{CO}_2} = \frac{F_R}{F_{\text{CO}_2}} \Delta X_{\text{carb}} \tag{3}$$

This model has been verified elsewhere [28], and the main parameters are shown in tab. 6.

Integration of the NGCC and the CaL plant

The ASU was not implemented in the model, and the energy needed to produce pure oxygen was assumed to be 200 kWh/t of O_2 [29]. Depending on the technology, there are certain ranges of efficiency penalties that are accepted, for calcium looping that is from 8% to around 12% points [14, 30]. In this work efficiency penalties are used as a benchmark to compare configurations [31, 32]. The following cases are studied in more detail. In Case 1 the capture plant is placed immediately after the gas turbine exit point, and the gas is directly transferred to the carbonator. It should be noted that this configuration is not suitable for the retrofit scenario as the capture plant would be built between the turbine and the HRSG, which is in real plants just one piece of equipment. On the other hand, in Case 2, the capture plant was located after the HRSG to allow retrofitting of existing plants. The HRSG exit gas, which is at 147 °C, is preheated to 564 °C with the CO_2 stream from calciner. The efficiency penalty results related to two main integration cases considered in this study are presented in tab. 7. These results show that for Case 2 more power is generated compared with both Case 1 and the reference plant, while the net plant efficiency drops in both cases with CaL when compared to the reference plant. The energy penalty for Case 1 is substantially higher than the one for Case 2 due to the higher net plant efficiency in Case 2.

Table 6. Summary of key operating conditions of the calcium looping plant

Parameter	Value
Carbonator temperature, [°C]	650
Calciner temperature, [°C]	900
Carbonated sorbent fraction, [–]	0.70
Calcined sorbent fraction, [–]	0.95
Fluidising fan pressure increase, [mbar]	150
Excess oxygen, [$\%_{vol}$]	2.5
Relative fresh limestone make-up rate*, [–]	0.05

Relative fresh limestone make-up rate is defined as ratio of fresh limestone make-up and sorbent looping rate.

Techno-economic analysis

The prices used in this techno-economic analysis have been taken from [33-37].

In addition to thermal efficiency, both cost of electricity [€$MW^{-1}h^{-1}$] and CO_2 avoided [€/tCO_2] are the main parameters of the process that this study aims to evaluate, and they are the main drivers for the final recommendations of this study. Equation (4) is used to calculate the cost of electricity, the annuity factor is calculated with eq. (5), and the cost of CO_2 avoided is quantified with eq. (6).

Table 7. NGCC plant output and efficiency

Parameter	Reference plant without CO_2	Plant with CO_2 capture	
		Case 1	Case 2
Net plant output, [MW]	819.9	906.8	1025.4
Net plant efficiency, LHV, [%]	57.7	45.7	49.1
Efficiency penalty, [% points]	n/a	12.0	8.6

$$COE = \frac{TPC\,\Psi}{P\,T_{\mathrm{eq}}} + \frac{Y_F}{\overline{\eta}} + \frac{U_{\mathrm{fix}}}{P\,T_{\mathrm{eq}}} + u_{\mathrm{var}} \tag{4}$$

$$\Psi = \frac{q-1}{1-q^{-n}} \tag{5}$$

$$\text{Cost of avoided t CO}_2 = \frac{COE_{\mathrm{capture}} - COE_{\mathrm{ref}}}{\left(\dfrac{\mathrm{CO_2}}{\mathrm{kWh}}\right)_{\mathrm{ref}} - \left(\dfrac{\mathrm{CO_2}}{\mathrm{kWh}}\right)_{\mathrm{capture}}} \tag{6}$$

Operational parameters

No technical or operational issues are considered, so it is assumed that the plant is running at full capacity all the time (8760 h per year).

One of the most sensitive parameters is the fuel price which can fluctuate greatly. According the Energy Information Administration [38], natural gas prices have varied substantially such that they were 8.5 €/GJ in 2005, 3.5 €/GJ in 2009, and 2.4 €/GJ in 2011. Currently prices are at 3.5 €/GJ [38] while many studies use a value of 3-9 €/GJ. In this study, the current price will be used followed by a sensitivity analysis in order to evaluate the impact of the fuel price and allow the chance to compare it with other literature data.

Table 8. Total costs for the NGCC plant without CO_2 capture

Costs	Value
Equipment cost, [M€]	206.7
Delivery + Install, [M€]	122.8
Direct costs, [M€]	329.5
Indirect costs at 14%, [M€]	46.1
EPC, [M€]	375.6
TPC, [M€]	431.9
Specific investment, [€$kW^{-1}h^{-1}$]	526.8

Table 9. Main economic values *COE* and cost of avoided CO_2

Parameter	Reference plant	Case 2
EPC (Dir. + Indir.), [M€]	375.6	715.6
Owner costs (5%), [M€]	18.8	35.8
Contingency (10%), [M€]	37.6	71.6
TCI, [M€]	431.9	822.9
TCI (specific), [€kW^{-1}]	526.8	802.5
Fuel price, [€GJ^{-1}]	3.5	3.5
Annual fuel cost, [M€a^{-1}]	157.1	250.5
Fixed O&M, [M€a^{-1}]	24.4	45.7
Variable O&M, [M€a^{-1}]	1.4	14.6
Variable O&M, [€$MW^{-1}h^{-1}$]	0.2	1.6
COE, [€$MW^{-1}h^{-1}$]	33.1	44.1
Cost of CO_2 avoided, [€/tCO_2 avoided]		29.3

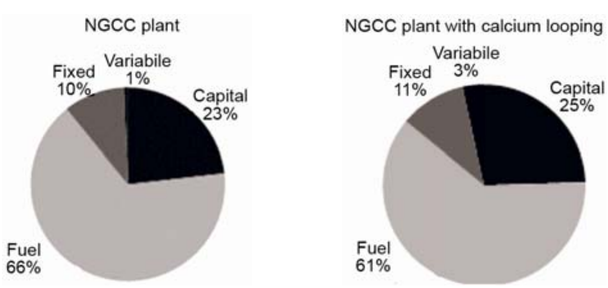


Figure 1. Breakdown of the costs for the reference case and the CaL case

Other consumable costs used in this analysis are: fresh water 6 €/m^3, cooling water 0.35 €/m^3, and fresh limestone 8 €/t. However, since these prices differ in an open range between studies, an analysis considering these variations is carried out here.

Cost of electricity and cost of avoided CO_2

The total costs for the 820 MW_e NGCC plant without CO_2 capture are specified in tab. 8.

In tab. 9 the most important economic values are found for the reference plant and Case 2 as well as the fuel price, the cost of electricity (*COE*), and cost of CO_2 avoided.

Discussion

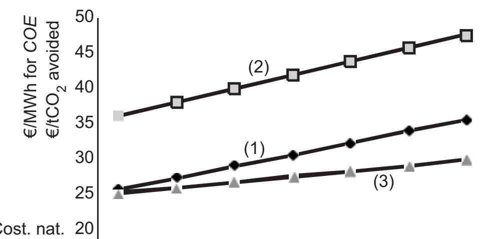
The difference between the costs of the reference power plant and the plant with calcium looping can be seen in fig. 1.

While the *COE* increases from 33.1 €/MWh to 44.1 €/MWh, which is a growth of approximately 33%, it can be seen how the capital investment increases when the capture is implemented. Fixed costs are also augmented by 2% points, due to the extra water consumption plus the necessity of a sorbent make-up flow.

Nevertheless, fuel price is in both cases the most critical variable when it comes to the final cost of electricity. Speaking about the CO_2 avoidance cost (29.3 €/tCO_2), it is highlighted that in this case the system does not require any ash or sulphur removal treatments. Also when comparing the results to plants with similar electric output but using other types of capture systems, such as amines, the price becomes substantially lower for the CaL case, with avoided cost for novel amine scrubbing technologies of 38.0 €/tCO_2 [39].

In order to obtain more reliable results for different fuel price scenarios, a sensitivity analysis for the fuel price is carried out and it is shown in fig. 2.

As can be seen from fig. 2, the fact that natural gas is used also for combustions in the calciner makes the *COE* rise faster in the capture containing system than in the reference plant. It is also shown that the COE_{cap} and the COE_{ref} are more affected by the cost of fuel whilst the cost of CO_2 avoided is affected in a less dramatic manner.



Cost. nat. gas (€/GJ)	2.5	2.75	3	3.25	3.5	3.75	4
(1) COE_{ref}	26.9	28.4	30	31.5	33.1	34.7	36.2
(2) COE_{cap}	36.7	38.6	40.4	42.2	44.1	45.9	47.7
(3) $CO_{2\ avoid}$	26.4	27.1	27.8	28.6	29.3	30	30.8

Figure 2. Costs *vs.* fuel price

Conclusions

This work shows that adding an additional steam cycle decreases the energy penalty substantially from 12% to 8.6%, due to the high temperatures reached in the carbonator and the calciner. Therefore, this heat must be utilized in order to achieve a competitive energy penalty comparable to other technologies such as amine scrubbing.

The techno-economic analysis results have shown a potential future for this combination of fuel and technology. While the capital costs of the plant increase considerably, the improved efficiency combined with the capture capacity of the process ensures that the *COE* remains at a very acceptable range, and is certainly lower than the costs obtained with other technologies, *e. g.* with novel amine technologies the COE is 78.5 €/MWh [39], while in this work these costs are as low as 44.1 €/MWh. It can also be concluded that the fuel cost is the most critical parameter and the idea of using natural gas for the calciner is a viable option, since it avoids future costs for the sorbent regeneration due to sulphur contamination and impurities treatments in the flue gas of the reference plant. Our results have shown costs rapidly increase when the fuel price raises, but gas provisions for the time window where this option is considered appear to be acceptably low.

Nomenclature

a_1 – model fitting parameter, [28]
a_2 – model fitting parameter, [28]
b – model fitting parameter, [28]
E_{CO_2} – CO_2 capture level in the carbonator [–]
F_{CO_2} – CO_2 flow rate entering the carbonator [$kmols^{-1}$]
F_R – CaO looping rate [$kmols^{-1}$]
F_0 – fresh limestone make-up rate, [$kmols^{-1}$]
f_1 – model fitting parameter, [28]
f_2 – model fitting parameter, [28]
f_{calc} – calcination reaction extent, [–]
f_{carb} – carbonation reaction extent, [–]
n – amortization, [years]
P – power output, [MW]
q – one plus the average discount rate per annum, [–]
r_0 – fraction of never calcined limestone in the system, [–]
T_{eq} – utilization time at rated power output, [hours per year]
U_{fix} – fixed cost of operation, maintenance, and administration, [€]
U_{var} – variable cost of operations, maintenance and administration, [€]
X_{ave} – average sorbent conversion, [–]
X_{calc} – sorbent conversion in the calciner, [–]
X_{carb} – sorbent conversion in the carbonator, [–]
Y_F – fuel price, [$€MJ^{-1}$]
ΔX_{carb} – carbonation conversion, [–]

Greek symbols

ψ – annuity factor, [–]
$\bar{\eta}$ – average plant net efficiency, [–]

Acronyms

ASU – air separation unit

CaL – calcium looping
CCS – carbon capture and storage
COE – cost of electricity
EBTF – European benchmark task force
EPC – engineering, procurement and construction
HRSG – heat recovery steam generator
NGCC – natural gas combined cycle
O&M – operation & maintenance
TCI – total capital investment
TPC – total plant cost

References

[1] ***, Climate Change 2007: Mitigation: Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, U K, and New York, USA, 2007

[2] MacDowell, N., *et al.*, An Overview of CO_2 Capture Technologies, *Energy Environ. Sci., 3* (2010), 11, pp. 1645-1669

[3] He, M. T., *et al.*, Green Carbon Science: Scientific Basis for Integrating Carbon Resource Processing, Utilization, and Recycling, *Angew. Chem., Int., 52* (2013), 37, pp. 9620-9633

[4] ***, Technology Roadmap: Carbon Capture and Storage, International Energy Agency, Paris, France, 2013

[5] ***, Boundary Dam Integrated Carbon Capture and Sequestration Demonstration Project, GCCSI, http://bit.ly/1iVXjVQ

[6] ***, Carbon Capture and Sequestration Technologies at MIT, Boundary Dam Fact Sheet: Carbon Dioxide Capture and Storage Project, http://bit.ly/Q7lSIG

[7] Shimizu, T., *et al.*, A Twin Fluid-Bed Reactor for Removal of CO_2 from Combustion Processes, *Chem. Eng. Res. Des., 77* (1999), 1, pp. 62-68

[8] Romano, M. C., Modelling the Carbonator of a Ca-Looping Process for CO_2 Capture from Power Plant Flue Gas, *Chem. Eng. Sci., 69* (2012), 1, pp. 257-269

[9] MacKenzie, A, *et al.*, Economics of CO_2 Capture Using the Calcium Cycle with a Pressurized Fluidized Bed Combustor, *Energy Fuels, 21* (2007), 2, pp. 920-926

[10] Romeo, L. M., *et al.*, Oxyfuel Carbonation/Calcination Cycle for Low Cost CO_2 Capture in Existing Power Plants, *Energy Conversion and Management*, *49* (2008), 10, pp. 2809-2814

[11] Boot-Handford, M. E., *et al.*, Carbon Capture and Storage Update, *Energy Environ. Sci., 7* (2014), 1, pp. 130-189

[12] Zhao, M., *et al.*, A Review of Technoeconomic Models for the Retrofitting of Conventional Pulverised--Coal Power Plants for Post-Combustion Capture (PCC) of CO_2. *Energy Environ. Sci., 6* (2013), 1, pp. 25-40

[13] Blamey, J., *et al.*, The Calcium Looping Cycle for Large-Scale CO_2 Capture, *Prog. Energy Combust. Sci., 36* (2010), 2, pp. 260-279

[14] Martínez, I., *et al.*, Integration of a Ca-Looping System for CO_2 Capture in an Existing Power Plant, *AIChEJ*, 57 (2011), 9, pp. 2599-2607

[15] Abanades, J. C., *et al.*, Fluidized Bed Combustion Systems Integrating CO_2 Capture with CaO, *Environ. Sci.and Tech.*, *39* (2005), 8, pp. 2861-2866

[16] Romeo, L. M., *et al.*, Optimizing Make-up Flow in a CO_2 Capture System Using CaO, *Chemical Engineering Journal, 147* (2009), 2-3, pp. 252-258

[17] Vorrias, I., *et al.*, Calcium Looping for CO_2 Capture from a Lignite Fired Power Plant, *Fuel, 113* (2013), Nov., pp. 826-836

[18] Berstad, D., *et al.*, NGCC Post-Combustion CO_2 Capture with Ca/Carbonate Looping: Efficiency Dependency on Sorbent Properties, Capture Unit Performance and Process Configuration, *Int. J. Greenh. Gas Control*, *24* (2014), pp. 43-53

[19] Berstad, D., *et al.*, Post-Combustion CO_2 Capture from a Natural Gas Combined Cycle by Cao/$CaCO_3$ Looping, *Int. J. Greenh. Gas Control*, *11* (2012), pp. 25-33

[20] Manzolini, G., *et al.*, CO_2 Capture in Natural Gas Combined Cycle with SEWGS. Part A: Economic Assessment, *Int. J. Greenh. Gas Control, 12* (2013), pp. 502-509

[21] ***, Natural Gas Combined Cycle Gas Turbine Power Plants. New Resource Characterization for the Fifth Power Plan, Northwest Power Planning Council, Portland, Ore., USA, 2002

[22] Rao, A. D., *Combined Cycle Systems for Near-Zero Emission Power Generation*, Woodhead Publishing, Cambridge, UK, 2012.

[23] Farmer, R., de Biasi, B., *Gas Turbine World Handbook*, Gas Turbine World, Fairfield, Conn., USA, 2010
[24] Lu, D. Y., *et al.*, Ca-Based Sorbent Looping Combustion for CO_2 Capture in Pilot-Scale Dual Fluidized Bed, *Fuel Proc. Tech., 89* (2008), 12, pp. 1386-1395
[25] Valverde, J. M., A Model on the CaO Multicyclic Conversion in the Ca-Looping Process, *Chem. Eng. Journal, 228* (2013), pp. 1195-1206
[26] Valverde, J. M., *et al.*, CO_2 Multicyclic Capture of Pretreated/Doped CaO in the Ca-Looping Process. Theory and Experiments, *Physical Chemistry Chemical Physics, 15* (2013), 28, pp. 11775-11793
[27] Rodríguez, N., *et al.*, Average Activity of CaO Particles in a Calcium Looping System, *Chem. Eng. Journal, 156* (2010), 2, pp. 388-394
[28] Hanak, D. P., *et al.*, Modelling and Comparison of Calcium Looping and Chemical Solvent Scrubbing Retrofits for CO_2 Capture from Coal-Fired Power Plant, *Int. J. Greenh. Gas Control, 42* (2015), Nov., pp. 226-236
[29] Romano, M. C., *et al.*, Ultra-High CO_2 Capture Efficiency in CFB Oxyfuel Power Plants by Calcium Looping Process for CO_2 Recovery from Purification Units Vent Gas, *Int. J. Greenh. Gas Control, 18* (2013), Oct., pp. 57-67
[30] Page, S. C., *et al.*, Carbon Capture and Storage: Fundamental Thermodynamics and Current Technology, *Energy Policy, 37* (2009), 9, pp. 3314-3324
[31] Versteeg, P., Rubin, E. S., Technical and Economic Assessment of Ammonia-Based Post-Combustion CO_2 Capture, *Energy Procedia, 4* (2011), Sep., pp. 1957-1964
[32] Rao, A. B., Rubin, E. S., A Technical, Economic, and Environmental Assessment of Amine-Based CO_2 Capture Technology for Power Plant Greenhouse Gas Control, *Environ. Sci. and Tech., 36* (2002), 20, pp. 4467-4475
[33] Martínez, I., *et al.*, Integrated Combined Cycle from Natural Gas with CO_2 Capture Using a Ca-Cu Chemical Loop, *AIChE Journal, 59* (2013), 8, pp. 2780– 2794
[34] Manzolini, G., *et al.*, CO_2 Capture in Integrated Gasification Combined Cycle with SEWGS – Part B: Economic Assessment, *Fuel, 105* (2013), Mar., pp. 220-227
[35] Kehlhofer, R., *et al.*, *Combined-Cycle Gas & Steam Turbine Power Plants*, Pennwell Books, Tulsa, Okla., USA, 2009
[36] Figueroa, J. D., *et al.*, Advances in CO_2 Capture Technology – The US Department of Energy's Carbon Sequestration Program, *Int. J. Greenh. Gas Control, 2* (2008), 1, pp. 9-20
[37] Peters, M. S., *et al.*, *Plant Design and Economics for Chemical Engineers,* vol. 5*,* McGraw-Hill, New York, USA, 2002
[38] ***, Annual Energy Outlook, International Energy Agency, Washington DC, USA, 2015
[39] Manzolini, G., *et al.*, Economic Assessment of Novel Amine Based CO_2 Capture Technologies Integrated in Power Plants Based on European Benchmarking Task Force Methodology, *Applied Energy, 138* (2015), C, pp. 546-558

Paper submitted: October 1, 2015
Paper revised: October 2, 2015
Paper accepted: October 10, 2015