A Parametric Study of Multi-Stage Chemical Looping Combustion for CO$_2$ Capture Power Plant

Hassan, Bilal, Tariq Shamim, and Ahmed F. Ghoniem. “A Parametric Study of Multi-Stage Chemical Looping Combustion for CO$_2$ Capture Power Plant.” Proceedings of the ASME 2012 Summer Heat Transfer Conference, 8-12 July, 2012, Rio Grande, Puerto Rico, ASME, 2012. © 2012 by ASME.

As Published
http://dx.doi.org/10.1115/HT2012-58597

Publisher
ASME International

Version
Final published version

Citable link
http://hdl.handle.net/1721.1/119437

Terms of Use
Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.
A PARAMETRIC STUDY OF MULTI-STAGE CHEMICAL LOOPING COMBUSTION FOR CO₂ CAPTURE POWER PLANT

Bilal Hassan and Tariq Shamim*
Mechanical Engineering Program
Masdar Institute of Science & Technology
Masdar City, Abu Dhabi, UAE
bhassan@masdar.ac.ae and tshamim@masdar.ac.ae

Ahmed F. Ghoniem
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
ghoniem@mit.edu

ABSTRACT

A thermodynamic model and parametric analysis of a natural gas fired power plant with carbon dioxide (CO₂) capture using multi-stage chemical looping combustion (CLC) are presented. CLC is an innovative concept and an attractive option to capture CO₂ with a significantly lower energy penalty than other carbon-capture technologies. The principal idea behind CLC is to split the combustion process into two separate steps (redox reactions) carried out in two separate reactors: an oxidation reaction and a reduction reaction, by introducing suitable metal oxide which acts as an oxygen-carrier that circulates between the two reactors.

In this study, an Aspen Plus model was developed by employing the conservation of mass and energy for all the components of the CLC system. In the analysis, equilibrium based thermodynamic reactions with no oxygen-carrier deactivation were considered. The model was employed to investigate the effect of various key operating parameters such as air, fuel and oxygen carrier (OC) mass flow rates, operating pressure, and waste heat recovery on the performance of a natural gas fired power plant with multi-stage CLC. Results of these parameters on the plant efficiency are presented. The analysis shows efficiency gain of more than 6% over that of conventional power plant with CO₂ capture technologies when CLC is integrated with the power plant.

INTRODUCTION

In view of the mounting evidence for global warming, the case for reducing carbon dioxide emissions from power plants has become more compelling. Traditional CO₂ capture technologies have significant energy penalty. Alternative technologies, such as chemical looping combustion (CLC) are more promising. Originally proposed by Richter and Knoche [1] as a scheme for improving combustion efficiency, CLC was later reconsidered for its inherent ability to capture CO₂ efficiently. The principle behind this technology is the combustion of fuel in a nitrogen free environment, which results in the production of stream of carbon dioxide and water only. Water can be condensed and CO₂ stream purified for storage or reuse.

The overall CLC process consists of two fluidized bed reactors interconnected in a single loop through which solid OC particles circulate. The reactors are termed the oxidation or air and reduction or fuel reactors, where oxidation and reduction refer to the metal oxide. The function of the OC particles is the transportation of oxygen from the air to the fuel reactor. Suitable OC particles include transition metals such as Iron, Nickel, Copper and Manganese.

In the air reactor, incoming compressed air reacts with the inbound metal oxygen carrier, oxidizing the metal to the corresponding metal oxide in an exothermic reaction. The solid product stream comprising the metal oxide is separated from the gas stream and transmitted to the reducing or fuel reactor and the high temperature gaseous product stream, consisting of nitrogen and un-reacted oxygen, is released into the environment after appropriate power extraction. A gaseous fuel (natural gas) is injected into the reduction reactor where it is combusted by the incoming lattice oxygen of the metal oxide producing CO₂ and water. The gaseous product stream can be easily stripped off the water by condensation. The remaining carbon dioxide is available for storage or use. In this reduction reaction, the metal oxide is reduced to the corresponding metal or metal oxide with lower oxygen ratio and is transferred back to the oxidizer reactor.

The reduction reaction could be exothermic or endothermic depending on the combination of metal and fuel used. However, as for any oxidation/reduction reaction the combined heat of reaction remains the same as in a conventional combustion reaction between fuel and air. CLC technology does not provide any advantage in enthalpy gain.
However, as will be shown, it offers a lower energy penalty for carbon capture and drop in NOx emissions given the lower reaction temperatures in air/oxidation reactor [2]. The equations below define the oxidation and reduction reactions in a CLC cell.

\[
\text{Me} + \frac{1}{2} \text{O}_2 \rightarrow \text{MeO} \quad \text{(Oxidation Reactor)}
\]

\[
\text{CH}_4 + 4 \text{MeO} \rightarrow \text{CO}_2 + 2\text{H}_2\text{O} + 4 \text{Me} \quad \text{(Reduction Reactor)}
\]

![Diagram of CLC process](image)

**Figure 1 Schematic representation of a generalized CLC cell.**

The prime requirement for an effective CLC loop is the stability of the OC particles under repeated oxidation/reduction reactions. To survive in the cyclic operation, the OC material should display chemical stability, mechanical strength, fluidizability, high melting points and resistance towards agglomeration. Since most OC’s deteriorate at high temperature and pressure environments, they are impregnated onto inert materials to decrease their vulnerability. Suitable combinations of active OC and inactive inert are being investigated [4,5]. However, increasing concentrations of inactive inert material (20-60%) results in reduced reactor temperatures and overall work outputs. The key performance parameters of a CLC based plant are strongly affected by the proportion of inert on the OC. This will be further examined in this article to quantitatively describe the reduction of plant work and thermal efficiency with increasing proportions of inactive inert.

CLC for power generation setups has been investigated in numerous studies. The prime target of these studies has been the enhancement of the plant efficiencies and comparing power plants with or without CLC technology. Brandvoll and Bolland [3] presented a scheme where the gaseous streams from air and fuel reactors were expanded in two separate gas turbines. The exhaust stream from the former was used in a steam generation bottoming cycle whereas the latter was sequentially cooled until water was condensed out of the stream resulting in pure CO2. Their analysis considered Nickel and NiO/Yttria-stabilized Zirconia (YSZ) as OC. Naqvi et al. [4] employed various CLC based power generation strategies in their studies. Their thermodynamic assessment of a steady state CLC based power generation model with negligible CO2 emissions found a maximum efficiency of 49.7%. A part load study of the plant was also performed [5]. Since CLC temperatures, in some situations, are low enough to compromise the gas turbine performance, Consonni [6] studied the possible benefits of a CLC power plant configuration with a fired burner in comparison to an unfired CLC scheme. Wolf et al. [7] and Wolf and Yan [8] performed a comparative analysis between a CLC and MEA based process for carbon capture in a conventional power plants. They concluded that the electrical efficiency of CLC is lower. However, when the cost of CO2 capture was added to conventional power plants, CLC provides better economy. They calculated 53% electrical efficiency at 1200°C, producing pure compressed CO2. Besides these system level research, efforts have been dedicated to reactor design, experimentation on prototype plants and selection of ideal OC materials.

These studies are based on specific combinations of power plant arrangements, fuels and OCs. However, the possible impact of key operation variables on overall plant thermal and exergic efficiencies needs to be further examined. It is essential to perform a parametric analysis to investigate the relationship between key input and output parameters in CLC. Ideal operating points for running CLC plants can also be examined further through such an analysis. The present study is motivated by recognizing this gap in literature. A system level model of a CLC based power plant was developed where key operating parameters were varied to investigate their impact on plant performance parameters. The results highlight areas critical to efficient and effective operation of a CLC based power plant.

**METHODOLOGY**

Simulations were performed on system level model of a CLC based power plant. A parametric analysis of the key input variables was performed and the corresponding effect on plant performance was accessed. Figure 2 represents a generalized schematic for the CLC based power plant used in the current analysis. The power plant model comprises two sequential CLC cells. In several researches cited [7], nickel has been favored as an OC, providing the basis for its usage in the current analysis.

Air is compressed and fed into the oxidizer reactor A. The gaseous product stream from oxidizer reactor A is passed through gas turbine GT-1A before being injected into the oxidizer reactor B. The oxidizer reactor B exit stream is expanded further in GT-1B before the exhaust waste heat is recovered by the reduction reactors A and B. For recovery of this exhaust energy, exhaust waste heat exchangers are used. This heat is beneficial in shifting the endothermic reactions in
the reduction reactors forward. The gas turbines GT-2A and GT-2B are located downstream of reducer reactors A and B respectively. The high temperature product solid streams from the oxidizers are used to heat the gaseous product streams from the reducers in the heat exchangers. This enables the turbine inlet temperatures downstream of the reduction reactors to be high enough for effective turbine operation.

![Schematic representation of the CLC based natural gas power plant used in current study.](image)

The power plant was modeled on the Aspen Plus V7.1 simulation engine as shown in Fig. 3. The reactors are modeled as equilibrium based (minimization of Gibbs free energy) reactions with no OC deterioration. The reaction kinetics and fluid dispersion velocities were not considered. Additional components such as compressors for fuel gas pressurization; separators for segregation of solid and gaseous outlet streams from the reactors; and converging OC loops were used to develop an overall system model. Complete separation of solid and gaseous product streams ejecting from the reactors is assumed in the separators.

The plant simulations provide results containing values of key stream temperatures, pressures and concentrations which are imported to an excel spreadsheet for tabulation of exergy. The total stream exergy flow is the summation of the thermo-mechanical and chemical exergies. The chemical exergies were tabulated through information derived from References [8] and [9]. The stream exergies can be used to calculate exergetic efficiencies through correlations described in Table 1.

The Aspen based model was validated by comparing the results with the work of Anheden and Svedberg [10] and excellent agreements were found (within 1%) as shown in Table 2.

The effect of air, fuel and OC mass flow rates; the fraction of exhaust waste heat recovered and pressure of CLC cells on thermal and exergetic efficiencies of the power plant were analyzed. To reduce the number of simulations, a base case scenario was developed where the mass flow rates of air and fuel were 180,000 kg/hr and 3600 kg/hr, respectively. The OC mass flow rates were 39,600 kg/hr and 11,600 kg/hr in Table 2 Validation of the current model with Anheden and Svedberg's work [10]. The stream names are as shown in plant schematic in Fig. 2.

| Ratio of Exergy of Stream over Exergy of Fuel Inlet Stream | Current Analysis (%) | Anheden and Svedberg’s Analysis (%) |
|----------------------------------------------------------|----------------------|--------------------------------------|
| Oxidizer A Inlet Stream                                  | 51.26                | 50.56                                |
| GT-1A Exhaust Stream                                     | 79.52                | 80.35                                |
| Oxidizer B Exit Stream                                   | 95.4                 | 95.81                                |
| Heat Exchanger A Inlet Stream from Oxidizer A            | 23.26                | 23.68                                |
| GT-2A Exhaust Stream                                     | 12.8                 | 12.69                                |
| GT-2B Exhaust Stream                                     | 8.2                  | 8.73                                 |
| Heat Exchanger B Inlet Stream from Oxidizer B            | 6.44                 | 6.49                                 |

![Power plant configuration represented in Aspen Plus. CLC cells are shown as grey circuits.](image)
oxidation reactors A and B, respectively. The pressures were 30 bar and 15 bar for the CLC cells A and B, respectively. During simulations, except the varied parameter, the other operating parameters were fixed at their base case values.

RESULTS AND DISCUSSION

The simulation is used to compare the efficiency of an optimized, natural gas based CLC power plant and a conventional power plant. The intent is to provide some process-based estimates for CLC benefits in comparison to traditional power plants. Results show that the thermal efficiency of the CLC-integrated power plant is 50.2% and is approximately 2% lower than that of the plant without CLC. This is in agreement with previous findings [2], which show a slight decrease in the thermal efficiency of the CLC-integrated power plant. However, the real advantage of the CLC is that the CO2 capture is built into the design. Considering that traditional, post-combustion CO2 capture technologies cost 8-10% efficiency drop, there is more than 6% efficiency gain with the CLC-integrated power plant. The CLC-integrated power plant has better exergic efficiency because of the way combustion is performed. Because of the low temperature combustion, CLC is closer to what is known as flameless combustion, which takes place at lower temperatures than conventional combustion, resulting in lower NOx emissions. The results of the parametric study regarding key operating variables on the plant performance are discussed below.

Effect of Fuel Mass Flow Rate

Figure 4 shows the effect of the fuel mass flow rate on various thermal and exergic efficiencies of the power plant. For the current conditions, stoichiometric mass flow rate of the fuel is 2700 kg/hr. The result shows that the plant thermal efficiency is maximum at this fuel flow rate. The plant thermal efficiency drops as the fuel supply is increased (fuel rich mixture) or decreased (fuel lean mixture) from the stoichiometric point owing to a drop in the overall work output.

Table 3 Comparison of a CLC-integrated power plant (with CO2 capture) with a conventional natural gas power plant (without CO2 capture).

|                      | CLC-Integrated Power Plant | Conventional Power Plant |
|----------------------|----------------------------|---------------------------|
| Fuel Exergy (kW)     | 49357                      | 49357                     |
| Air Exergy (kW)      | 0                          | 0                         |
| Exhaust Exergy (kW)  | 11255                      | 9300                      |
| Total Work Output (kW)| 20633                      | 21500                     |
| Total Irreversibilities (kW) | 17472                      | 18558                     |
| Overall Exergic Efficiency (%) | 64.60                      | 62.40                     |
| Overall Thermal Efficiency (%) | 50.19                      | 52.30                     |

Figure 2 Effect of incoming fuel mass flow rate on plant efficiencies.

With an increase of fuel supply, the exergic efficiencies of the reduction reactors increase, because of the lower irreversibilities in the reactions between metal oxide and fuel and an increase in exhaust exergy. The higher fuel mass flow rates also result in a drop in exergic efficiency of the oxidation reactor A. However, the fuel mass flow rate has little effect on the exergic efficiency of the oxidation reactor B. The significant effect on the oxidizer reactor A is primarily because the majority (75%) of the heat is recovered in the high pressure CLC loop. The temperature (thermal exergy) of the OC inlet stream to the oxidizer reactor A increases considerably as the fuel supply reaches stoichiometric conditions in the reducer reactor A resulting in an increase in input exergy. The output exergy stream does not increase proportionally and hence, the exergic efficiency of the oxidizer falls. Overall, the exergic efficiency of the total power plant increases with the increase of the fuel mass flow rate. The increasing plant exergic efficiency provides a false perception of decreasing irreversibilities. Plant irreversibilities increase with increasing fuel mass flow rate but have insignificant effect on the exergic efficiency due to the increasing amount of unburnt fuel. This fuel appears in the exhaust stream as chemical exergy resulting in a much higher output exergy and correspondingly overall exergic efficiency.

The increase of the fuel mass flow rate also affects various temperatures as shown in Fig.5. Since the reaction in the reduction reactors is endothermic, the increase of fuel mass flow rate decreases these reactor temperatures. The increase of the fuel supply and the corresponding increase of the reaction rate in the reducing reactors increase the availability of metal (nickel) for reaction in the oxidation reactors. This increases the reaction (exothermic) rate in the oxidation reactors and correspondingly the reactor temperatures increase as shown in the Fig. 5. However, beyond stoichiometric point, further increase in fuel supply rate does not affect the availability of metal to the oxidizer.
Hence, after reaching a maximum value (slightly in the rich region), the oxidation reactor temperatures are not influenced by further increase in the fuel supply rate.

Effect of Air Mass Flow Rate
Figure 6 shows the effect of the air mass flow rate on various thermal and exergic efficiencies of the power plant. On stoichiometric basis, the air to incoming metal (nickel) ratio is roughly 1.17. Hence, 39,600 kg/hr of incoming nickel metal shall be completely oxidized with 46,000 kg/hr of feed air. At this point, the oxidation reactor A temperature is maximum as shown in Fig. 7. The other temperatures are also at their peak values close to this point. The thermal efficiency of the plant rises with the air flow rate (beyond this point) because of an increase of the availability of high temperature working fluid (oxygen depleted air) for the gas turbines downstream of the oxidation reactors. After reaching a peak value, the thermal efficiency starts decreasing with a further rise of air supply. This drop is due to a significant reduction of the turbine inlet temperature at higher air mass flow rates.

The exergic efficiency of the plant decreases with increasing the air supply rate due to general increase in irreversibilities in the reactors. With initial limited supply of air, the amount of combustible species released in the exhaust is high resulting in high output exergies and overall exergic efficiency. However, the general increase in irreversibilities is primarily attributed to the drop in temperatures due to the increase in feed air supply rate. Also, air and fuel are the primary inlet exergies for the power plant. The increase in work output is impeded by the limits on the fuel but the inlet air stream exergy is increasing. This results in a reduction in plant exergic efficiency.

Effect of Oxygen Carrier Mass Flow Rate
Figure 8 shows the effect of the OC (nickel) mass flow rate on various thermal and exergic efficiencies of the power plant. For the current conditions, the stoichiometric mass flow rates of the OC are 52,800 kg/hr based on the chemical reaction in the reduction reactor (with fuel mass flow rate of 3600 kg/hr) and 153,900 kg/hr based on the chemical reaction in the oxidation reactor (with air mass flow rate of 180,000 kg/hr).

Result shows that the plant thermal efficiency rises with an increase of the OC mass flow rate because of the enhancement in reactions in both reactors. This continues until it reaches the stoichiometric amount of the OC based on the reaction with the fuel (abundant air supply). Beyond that a further increase in the OC mass flow rate has no significant effect on the thermal efficiency. While more OC could still be oxidized by the excess air in the oxidation reactor, this reaction is limited by the reduction reaction and its capacity to reduce MeO to Me (OC).
The overall plant exergic efficiency, in this particular case, is a function of the plant work output and exhaust stream exergy (as per correlation defined in Table 1) since the input exergies of fuel and air remain constant. Initially, with limited OC available for oxidizing the incoming fuel, the work output is low. However, the amount of unburnt fuel and combustible species appearing as chemical exergy in the exhaust stream are very high. This results in high initial plant exergic efficiency which drops as OC increases and work output stabilizes.

Effect of CLC Cell Pressure

Figure 10 shows the effect of the pressure of the CLC loops on the exergic and thermal efficiencies. The pressure ratio between the sequential high pressure and low pressure CLC loops is 0.5 and remains invariant in the current analysis. The results show that overall plant thermal efficiency increases with increasing the pressure. However, for higher pressures (beyond 55 Bar), the change in the thermal efficiency is minimal. This trend is explained by the rising air compressor input work which offsets the increase in plant work output resulting in a predominantly constant thermal efficiency at high pressures.

The component and overall exergic efficiencies show limited change with pressure rise. The exergic efficiencies are dependent on pressure and temperature variations through Le Chatelier’s principle. The oxidation reaction equilibrium shifts forward with an increase in pressure based on molar concentrations. However, higher CLC pressure requires higher compression which correspondingly results in increased feed air temperatures. Increased feed air temperatures shift the equilibrium backward for an exothermic oxidation reaction. The two counteracting effects prevent an appreciable change in exergic efficiency due to pressure variations. Similarly in the reduction reactors, increasing pressure shifts the reduction reaction equilibrium backwards.

Effect of Waste Heat Recovery

The waste heat recovery system recycles thermal energy from the exhaust of the oxidation reactor and supplies it to the reduction reactors to assist the endothermic reduction reaction. The major fraction of the exhaust energy (75%) is supplied to the reduction reactor in the high pressure CLC loop. The portion of the exhaust stream thermal energy reutilized by the plant is varied in our analysis. The remaining unused exhaust stream gases are released into the environment. The percentage of exhaust waste heat recovered (in graphs) represents the portion of the maximum possible recoverable waste heat, which is defined by the temperature drop from exhaust stream temperature to environment temperature.

The effect of the extent of exhaust heat recovered to the reduction reactors of the power plant on key efficiencies is represented in Fig. 12. The major portion of the recovered heat is transmitted to the high pressure CLC loop which results in a relatively larger temperature increase in this loop as shown in Fig. 13. The results show an increase of the overall thermal efficiency with increasing levels of heat recovered to the reducers. This is because of the higher gas turbine inlet temperatures and consequently greater cumulative work output for the same fuel supply.
The overall plant exergic efficiency also increases with an increase in the waste heat recovered, although, the change is small. Interestingly, the reduction reactor exergic efficiency decreases as shown in Fig. 12 with higher proportions of exhaust heat recovered. This is because of the incorporation of the recovered heat in the exergic efficiency definition (Table 1) as inlet feed exergy. Although the irreversibilities in the reduction reactor decrease (with higher operating temperatures), the exergic efficiency is shown to decrease (Fig. 12). The increase in input heat exergy to the reduction reactors is much larger in comparison to the corresponding decrease in irreversibilities. This results in a decrease in the reducer exergic efficiency. The overall plant irreversibilities are also reduced with increasing operating temperatures due to the higher levels of heat recovery and higher temperatures. Also, as the reduction reactor temperature rises, the need for heat exchangers to heat up the reduction reactor product streams for effective gas turbine performance is eliminated, making these heat exchangers redundant and reducing overall plant irreversibilities.

The recovered heat primarily affects the reduction reactor temperatures; however, due to the cyclic operation in a loop, the temperature of the oxidizers also increases as shown in Fig. 13. The increase in the oxidizer reactor temperature is much lower as compared to the reducer reactor temperature due to the abundant air supply. The air supply absorbs thermal energy from the feed streams without showing appreciable temperature rise due to its high mass flow rate.

Effect of Fraction of Inactive inert in oxygen carrier

Major research activities in CLC include investigations into reliable combinations of active OC and binding inert materials. The intent is to find material combinations which can provide acceptable levels of chemical stability, fluidizability, recurrent oxidation and reduction capability, capability to withstand high temperature and pressure environments and resist agglomeration. The active OC, usually a transition metal, is impregnated on the inactive inert which include materials such as Al₂O₃, Zirconium and silicon compounds [9]. Typical percentages of inert within the metal by mass are 20 to 60%. It would be interesting to investigate the effect of increasing concentrations of inert binding materials on plant operations. Figure 14 depicts the decrease in plant overall thermal efficiency and work output with corresponding increase in the concentration of inert binding material. The decrease in work output is not substantial and could be enumerated as 50-70 kW per 10% increase in concentration of inert binder. The minimal drop is associated to recirculation and enhanced exchange of thermal energy between the two looped reactors. Thereby, with endothermic
reduction reactions, higher masses of circulated OC results in higher thermal energy exchange and higher operating temperatures for the reduction reactor resulting in more work output. However, the mechanism for effective circulation of OC particles within the CLC loop (through the reactors) requires further investigation. In our analysis, the energy requirements for such a mechanism have not been taken into account. However, in practical implementation of the CLC power plant, this work shall substantially increase with higher masses of circulated OC.

CONCLUSION
A system level model was developed to analyze the CLC technology in terms of the effects on power plant performance of mass flow rates of fuel, air and OC; proportion of exhaust waste heat recovered; pressure of CLC cells and fraction of inactive inert in OC. Compared to a conventional power plant, the results shows approximately 2% decrease in the thermal efficiency of the CLC-integrated power plant. However, when the energy penalty of conventional CO$_2$ capture is considered, the CLC-integrated plant shows 6-8% efficiency gain. Furthermore, the CLC-integrated power plant has better exergic efficiency due to lower irreversibilities. Stoichiometric amount of OC with respect to fuel reaction is required to obtain the maximum plant thermal efficiency. However, the air supply should be roughly twice the stoichiometric amount to increase the high temperature working fluid and correspondingly attain maximum thermal efficiency. The maximum thermal efficiency of the CLC power plant in the parametric analysis has remained within the range of 50-52%. Although stoichiometric conditions result in high thermal efficiencies, they correspondingly mark the peak temperature points as well, which could possibly result in considerable OC degradation. It is worthwhile to mention that in order to perform a more refined assessment of CLC based power plants, the reaction kinetics and associated rate based factors need to be taken into account. In addition, the fluid mechanics and hydrodynamic aspects of the heterogeneous reaction between solid OC and gaseous fuel/air need to be considered as well.

ACKNOWLEDGEMENTS
The work is financially supported by the MIT/Masdar Institute Collaborative Research funds.

REFERENCES
[1] K. K. F. Richter H.J., "Reversibility of combustion processes," ACS Symposium, pp. 71-85, 1983.
[2] M. Ishida and H. Jin, "A novel chemical-looping combustor without NOx formation," Industrial & Engineering Chemistry Research, no. 35, pp. 2469-2472, 1996.
[3] O. Brandvoll and O. Bolland, "Inherent CO$_2$ capture using chemical looping combustion in a natural gas fired power cycle," Journal of Engineering for Gas Turbine and Power, no. 126, pp. 316-321, 2004.
[4] R. Naqvi, O. Bolland, O. Brandvoll, and K. Helle, "Chemical looping combustion analysis of natural gas fired power cycles with inherent CO$_2$ capture," in ASME Turbo Expo, Power for Land, Sea and Air, Vienna, Austria, 2004.
[5] R. Naqvi, J. Wolf, and O. Bolland, "Part-load analysis of a chemical-looping combustion (CLC) combined cycle with CO$_2$ capture," Energy, no. 32, pp. 360-370, 2007.
[6] S. Consonni, G. Lozza, G. Pelliccia, S. Rossini, and F. Saviano, "Chemical-looping combustion for combined cycles with CO$_2$ capture," Journal of Engineering for Gas Turbines and Power, no. 128, pp. 525-534, 2006.
[7] J. Wolf, "CO$_2$ mitigation in advanced power cycles—Chemical looping combustion and steam-based
gasification," KTH-Royal Institute of Doctoral Thesis, 2004.

[8] J. Wolf and J. Yan, "Parametric study of chemical looping combustion for trigeneration of hydrogen heat and electrical power with CO₂ capture," *International Journal for Energy Research*, vol. 29, pp. 739-753, 2005.

[9] M. A. J. Y. Jens Wolf, "Comparison of nickel- and iron-based oxygen carriers in chemical looping combustion for CO₂ capture in power generation," *Fuel*, 2004.

[10] "Calculation and Interpretation of the Standard Chemical Exergies of Elements Using the Chemical Reference Species," Bilgen Selçuk, Department of Chemistry, Karadeniz Technical University.

[11] R. Rivero and M. Garfias, "Standard chemical exergy of elements updated," Instituto Mexicano del Petro’leo, Grupo de Exergia, 2006.

[12] M. Anheden and G. Svedberg, "Energy analysis of chemical-looping combustion systems," *Energy Conversion & Management*, vol. 39, p. 1967–1980, 1998.

[13] T. Mattisson, M. Johansson, and M. Lyngfelt, "Reactivity of some metal oxides supported on alumina with alternating and oxygen–Application of chemical looping combustion," *Energy & Fuel*, 2003.

[14] M. M. Hossain and H. L. d. Lasa, "Chemical –Looping Combustion (CLC) for inherent CO₂ separations- a review," *Chemical Engineering Science*, 2008.