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Heat management in Gas Switching Combustion for power production with integrated CO_2 capture

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Abstract

Gas Switching Combustion (GSC) is a promising new process concept for energy efficient power production with integrated CO_2 capture. In comparison to conventional Chemical Looping Combustion (CLC) carried out in fluidized beds, the GSC concept will be substantially easier to design and scale up, especially under pressurized conditions. One potential drawback of the GSC concept is the gradual temperature variation over the transient process cycle which leads to a drop in electric efficiency of the plant. This article investigates heat management strategies to mitigate this issue both through simulations and experiments. Promising results are reported both through the dilution of air with nitrogen and through the concentrated injection of air.

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Keywords: Gas Switching Combustion, Chemical Looping Combustion, CO_2 *capture, Fluidized bed reactor.*

1. Introduction

Chemical Looping Combustion (CLC) is a promising concept for power production with integrated CO_2 capture [1]. The CLC concept often utilizes two fluidized bed reactors, an air reactor and a fuel reactor, to achieve flameless combustion of coal or natural gas in such a way that a pure stream of CO_2 is produced after steam condensation. This is achieved by circulating an oxygen carrier material between the two reactors. In the air reactor, the oxygen carrier is oxidized by air after which it is transferred to the fuel reactor where it is again reduced by the fuel in absence of nitrogen.

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The primary advantage of the CLC concept relative to other CO_2 capture processes is that it can achieve close to 100% CO_2 capture with a very low energy penalty [2-10]. As a result, CLC appears to be a highly promising concept for new fossil fuel power stations with integrated CO_2 capture. However, scale-up of pressurized CLC technology capable of achieving competitive efficiencies with gaseous fuels has been relatively slow, primarily due to challenges related to the circulation of solids between the reactors and separation of solids from the gas streams at high temperatures and pressures.

As a result, several simplified reactor configurations have been proposed to circumvent these challenges. One such reactor configuration is the packed bed system [11-13]. In this concept the oxygen carrier material is stationary and exposed to alternate streams of air and fuel. In this way, fossil fuel combustion with integrated CO_2 separation is achieved in a very simple reactor configuration which is simple to scale up and pressurize. Due to the transient nature of this concept, a cluster of reactors is required to supply a steady stream of hot gasses to the downstream power cycle and CO_2 compression equipment. The primary technical uncertainty introduced by this configuration is the need for a high temperature (~1200 °C) valve system to regulate the reactor outlet streams.

Other challenges facing the packed bed CLC concept include the need for a shaped oxygen carrier material and the need for a complete reactor shutdown in order to replace spent oxygen carrier material. If the natural mineral, ilmenite, is used as oxygen carrier, the process requires pure nitrogen in the heat removal stage as well as the execution of a material activation procedure each time new material is loaded. These challenges can be overcome by simply using a bubbling fluidized bed instead of a packed bed reactor. This concept, called Gas Switching Combustion (GSC), was experimentally demonstrated recently and proved to be simple to operate autothermally with a high CO_2 separation efficiency [14]. The GSC concept can use cheap natural mineral ore as oxygen carrier without pellets manufacture costs and feed this ore to the reactor when needed without the need for shutdown. When using ilmenite, air can be used in the heat removal stage and a material activation procedure is only required once during reactor startup after which gradual additions of fresh material will be activated during normal operation. In addition, a fluidized bed configuration also opens the possibility of in-situ gasification of solid fuels during the fuel stage which promises to ultimately be the lowest cost application of the CLC principle.

On the other hand, good mixing in the fluidized bed would result in more undesired mixing between gasses when switching between stages relative to the plug flow achieved in the packed bed, thereby reducing the CO_2 capture efficiency. In addition, the fines generation from mechanical attrition in the fluidized bed would intuitively be larger than the fines generation from thermal and chemical stresses imposed by the sharp temperature and reaction fronts in packed bed CLC. Fines generation is an important general challenge in using high pressure fluidized beds for power production using a combined cycle due to the need for high temperature filtering systems for protecting the gas turbine. More work is required to assess the magnitude of this challenge.

Another drawback of the fluidized bed concept is the gradual temperature variation over the cycle – an increase during oxidation followed by a decrease during heat removal and reduction. This temperature variation causes the average temperature fed to the gas turbine to be significantly lower than the maximum operating temperature of the reactor, thereby lowering plant efficiency. As a result, some advanced heat management strategies are required to minimize the temperature variation across the cycle. These strategies will be discussed in this paper, both via modelling (large scale reactor modelling combined with process simulation) and experiments (lab-scale demonstration).

2. Methodology

Due to space restrictions, the methodology will be referred to prior papers. The reactor simulation methodology is based on the filtered approach from the group of Sundaresan at Princeton University [15]. The equation system for the hydrodynamics (drag, solids stresses and wall corrections) are reported in

[16] where it was also validated against experiments, while filtered reaction rate closures were taken from [17]. The reactions simulated are given below and kinetic data was taken from [18]. As a conservative assumption, the reaction rate constant was made inversely proportional to the pressure as observed for three different oxygen carrier materials in [19]:

$$H_2 + Fe_2O_3 \rightarrow 2FeO + H_2O$$
$$CO + Fe_2O_3 \rightarrow 2FeO + CO_2$$
$$O_2 + 4FeO \rightarrow 2Fe_2O_3$$

Information about the process modelling can be gathered from the following prior publications: [20]. The process simulation integrates the GSC concept into an Integrated Gasification Combined Cycle (IGCC) power cycle to calculate the electric efficiency, CO_2 avoidance and energy penalty relative to a reference IGCC plant without CO_2 capture.

The experimental setup is described in [14]. The primary difference is the use of a blanket insulation material which made reactor maintenance substantially easier, but also led to greater heat losses compared to the particulate insulation used previously.

3. Results and discussion

Results will be presented in two main parts: modelling of the commercial scale system and experimental demonstration through lab scale experiments.

3.1. Simulations

From a process efficiency viewpoint, the primary challenge with the GSC system is the gradual temperature variation over the cycle. This effect is shown in Figure 1 where a temperature variation across the cycle of 350 °C is observed. This temperature variation both reduces the electric efficiency of the plant and increases thermal wear on the turbine.

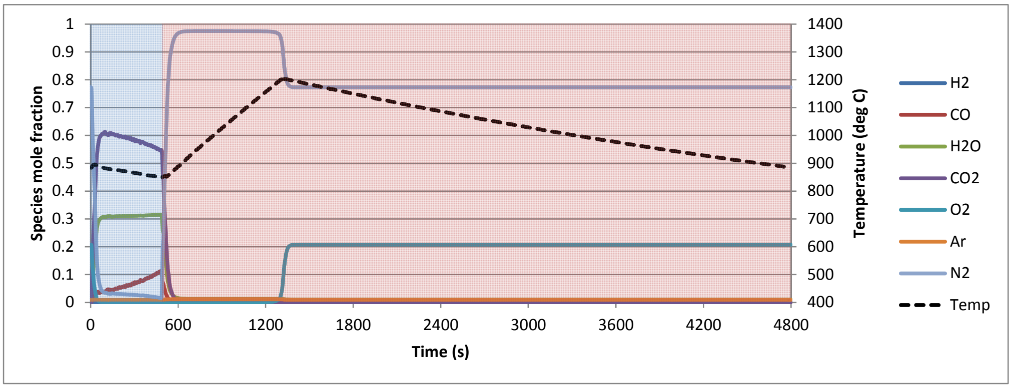


Figure 1: Temperature and gas composition of the reactor outlet stream over one full redox cycle. The blue area (first 480 s) represents the fuel stage (reduction) and the red area represents the air stage (oxidation).

An additional challenge is the reduction stage that now takes place at relatively low temperatures. Given that a cheap natural mineral (ilmenite) is used which is not as reactive as more expensive synthetic materials, this implies that some fuel slip can take place during the reduction stage. This fuel slip is also shown in Figure 1 where an increasing amount of CO can be observed during the fuel stage due to a gradual reduction in temperature and increase in oxygen carrier conversion.

One way of reducing this temperature variation is to dilute with nitrogen during the air stage. This can be done either by feeding a constant fraction of nitrogen throughout the air stage or by only introducing the fraction of nitrogen required to keep the reactor at its maximum temperature over most of the air stage. The effect of these modifications is shown in Figure 2.

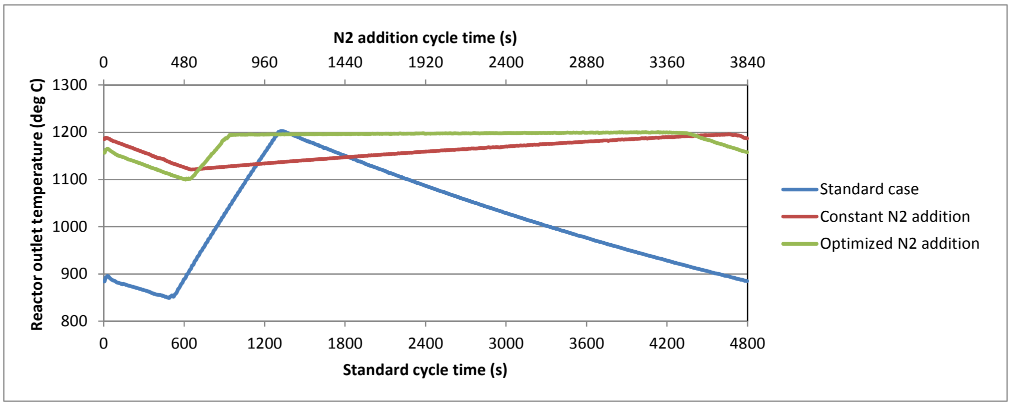


Figure 2: Temperature variation of the reactor outlet stream for three different operating procedures: the standard case (identical to Figure 1), a case with a constant addition of N_2 in the air stage, and a case with N_2 addition optimized to keep the reactor at its maximum operating temperature for as long as possible.

The effect of these improvements on the overall electric efficiency of the process is shown in Figure 3. It is clear that the addition of N_2 substantially improved the electric efficiency of the plant. Moving from constant N_2 addition to optimized N_2 addition only delivered a small improvement though. It should also be noted that the standard case electric efficiency was calculated by including oxidation of the unconverted CO after the reactor via a small amount of additional oxygen from the air separation unit. Due to the much higher temperatures at which the fuel stage takes place in the N_2 addition cases, this treatment was not required as fuel slip was negligible.

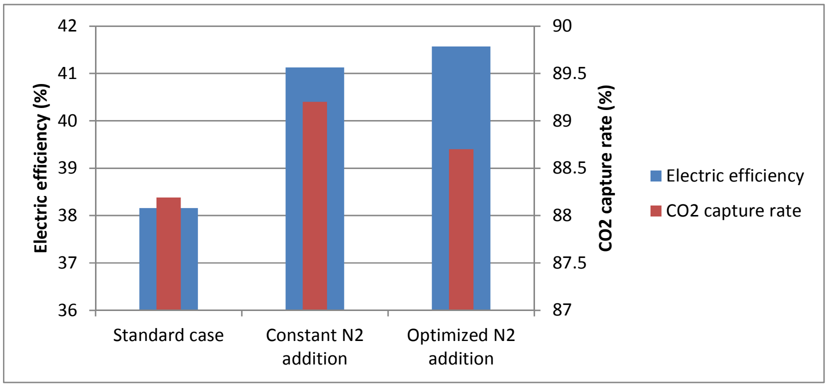


Figure 3: Power plant efficiency and CO capture performance for the three different operating procedures illustrated in Figure 2.

The addition of N_2 during the air stage therefore appears to be an excellent way in which to improve the GSC power cycle performance. However, implementing this strategy in practice implies additional process complexity in the form of a N_2 recycle loop similar to the requirements of the packed bed CLC process. One way in which this challenge can be overcome is to inject the majority of air into the reactor in a very concentrated manner via a lance while the remainder is fed through the distributor to keep the entire bed fluidized. Since the gas/solid heat transfer rate is typically some orders of magnitude faster than the oxidation reaction rate and mixing in fluidized bed reactors is generally very good, such a concentrated air injection can theoretically extract the necessary heat while allowing most oxygen to exit the reactor without reacting. This configuration can potentially achieve the same outcome as the N_2 dilution achieved in Figure 3 without the need for a separate N_2 recycle loop.

3.2. Experiments

The three cases shown in Figure 2 were tested in a lab-scale reactor in order to evaluate the practical feasibility of implementing these strategies to achieve autothermal operation in practice. In addition to these three cases, another case where 80% of the air was injected via a concentrated injection point 0.1 m above the distributor was included in order to assess the feasibility of reducing the temperature variation without having to recycle N_2.

Due to large heat losses from the reactor, the operation had to be carried out at relatively low temperatures. The principle remains the same as at high temperatures, however, and the highly reactive Ni-based oxygen carrier employed ensured that fuel slip was not significant (pure CO was used as fuel).

The resulting transient temperature profiles from each case are depicted in Figure 4 where it is clearly shown that the favorable effect of N_2 addition could be reproduced in experiments. The case with concentrated injection also showed an improvement relative to the standard case, albeit not as great as the addition of N_2. The favorable effect of the concentrated air injection can possibly be increased by implementing this strategy in a 3D system instead of the pseudo-2D reactor setup used in this study. A 3D geometry would give the gas one more degree of freedom in which to slip past the solids, thereby reducing the quality of gas/solid contact.

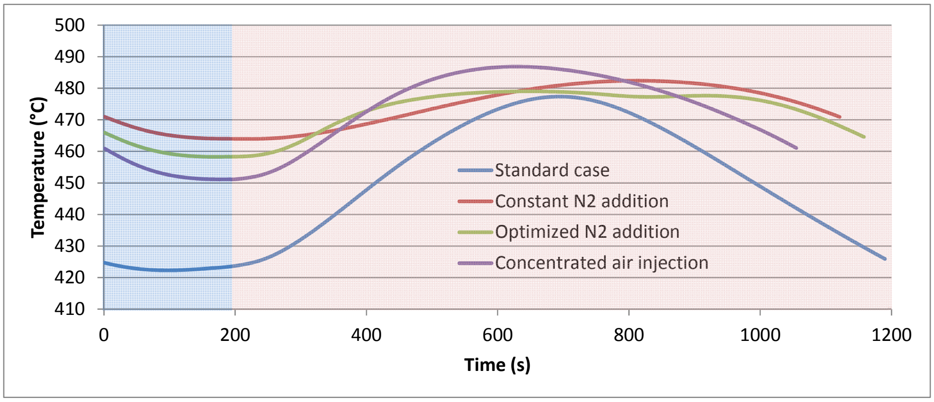
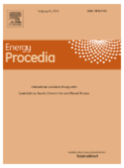


Figure 4: Experimental data of the transient temperature variation across the GSC cycle using different heat management strategies. The blue area represents the fuel stage (reduction) and the red area represents the air stage (oxidation).

4. Summary and conclusions

This paper addresses one important challenge posed by the GSC concept: the gradual variation of reactor temperature over the cycle which leads to reduced electric efficiencies and possible fuel slip. It was shown that heat management strategies using N_2 addition during the air stage could significantly increase electric efficiency (from 38.2% to 41.6%) and reduce fuel slip. In addition, the strategy of a concentrated air injection was also discussed and tested experimentally with promising results. This strategy could potentially increase the electric efficiency of the GSC power cycle without the need for a N_2 recycle stream. The GSC concept therefore remains a promising candidate for rapid upscaling and deployment of efficient and cost effective CO_2 capture technology when a favorable policy environment finally emerges.



Biography

Shahriar Amini is the Research Director of Flow Technology Department in SINTEF Materials and Chemistry, Norway. He is managing national and international projects with a focus on energy conversion technologies with integrated CO_2 capture. He has a PhD in Chemical Engineering from University of New South Wales, Australia.

References

[1] J. Adanez, A. Abad, F. Garcia-Labiano, P. Gayan, L.F. de Diego, Progress in Chemical-Looping Combustion and Reforming technologies, Progress in Energy and Combustion Science, 38 (2012) 215-282.
[2] Brandvoll, O. Bolland, Inherent CO2 capture using chemical looping combustion in a natural gas fired power cycle, Journal of Engineering for Gas Turbines and Power, 126 (2004) 316-321.
[3] S. Consonni, S. Rossini, F. Saviano, G. Lozza, G. Pelliccia, Chemical-Looping Combustion for Combined Cycles With CO2 Capture, Journal of Engineering for Gas Turbines and Power, 128 (2006) 525-534.
[4] C.-C. Cormos, Evaluation of iron based chemical looping for hydrogen and electricity co-production by gasification process with carbon capture and storage, International Journal of Hydrogen Energy, 35 (2010) 2278-2289.
[5] B. Erlach, M. Schmidt, G. Tsatsaronis, Comparison of carbon capture IGCC with pre-combustion decarbonisation and with chemical-looping combustion, Energy, 36 (2011) 3804-3815.
[6] G. Lozza, P. Chiesa, M.C. Romano, P. Savoldelli, Three Reactors Chemical Looping Combustion For High Efficiency Electricity Generation With CO2 Capture From Natural Gas, ASME Turbo Expo 2006, 2006.
[7] R. Naqvi, O. Bolland, Multi-stage chemical looping combustion (CLC) for combined cycles with CO2 capture, International Journal of Greenhouse Gas Control, 1 (2007) 19-30.
[8] R. Naqvi, J. Wolf, O. Bolland, Part-load analysis of a chemical looping combustion (CLC) combined cycle with CO2 capture, Energy, 32 (2007) 360-370.
[9] M. Sorgenfrei, G. Tsatsaronis, Design and evaluation of an IGCC power plant using iron-based syngas chemical-looping (SCL) combustion, Applied Energy, 113 (2014) 1958-1964.
[10] J. Wolf, M. Anheden, J. Yan, Comparison of nickel- and iron-based oxygen carriers in chemical looping combustion for CO2 capture in power generation, Fuel, 84 (2005) 993-1006.
[11] S. Noorman, F. Gallucci, M. van Sint Annaland, J.A.M. Kuipers, A theoretical investigation of CLC in packed beds. Part 2: Reactor model, Chemical Engineering Journal, 167 (2011) 369-376.
[12] V. Spallina, F. Gallucci, M.C. Romano, P. Chiesa, G. Lozza, M. van Sint Annaland, Investigation of heat management for CLC of syngas in packed bed reactors, Chemical Engineering Journal, 225 (2013) 174-191.
[13] H.P. Hamers, F. Gallucci, P.D. Cobden, E. Kimball, M. van Sint Annaland, A novel reactor configuration for packed bed chemical-looping combustion of syngas, International Journal of Greenhouse Gas Control, 16 (2013) 1-12.
[14] A. Zaabout, S. Cloete, S. Johansen, M. Van Sint Annaland, F. Gallucci, S. Amini, Experimental demonstration of a novel gas switching combustion reactor for power production with integrated CO2 capture, Industrial & Engineering Chemistry Research, In press (2013).
[15] Y. Igci, A.T. Andrews, S. Sundaresan, S. Pannala, T. O'Brien, Filtered two-fluid models for fluidized gas-particle suspensions, AIChE Journal, 54 (2008) 1431-1448.
[16] S. Cloete, S.T. Johansen, S. Amini, Evaluation of a filtered model for the simulation of large scale bubbling and turbulent fluidized beds, Powder Technology, 235 (2013) 91-102.
[17] W. Holloway, S. Sundaresan, Filtered models for reacting gas–particle flows, Chemical Engineering Science, 82 (2012) 132-143.
[18] A. Abad, J. Adánez, A. Cuadrat, F. García-Labiano, P. Gayán, L.F. de Diego, Kinetics of redox reactions of ilmenite for chemical-looping combustion, Chemical Engineering Science, 66 (2011) 689-702.
[19] F. García-Labiano, J. Adánez, L.F. de Diego, P. Gayán, A. Abad, Effect of Pressure on the Behavior of Copper-, Iron-, and Nickel-Based Oxygen Carriers for Chemical-Looping Combustion, Energy & Fuels, 20 (2005) 26-33.
[20] V. Spallina, M.C. Romano, P. Chiesa, F. Gallucci, M. van Sint Annaland, G. Lozza, Integration of coal gasification and packed bed CLC for high efficiency and near-zero emission power generation, International Journal of Greenhouse Gas Control, Submitted (2014).