INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 6, Issue 2, 2015 pp.201-226
Journal homepage: www.IJEE.IEEFoundation.org

Process simulation and maximization of energy output in chemical-looping combustion using ASPEN plus

Xiao Zhang, Subhodeep Banerjee, Ling Zhou, Ramesh Agarwal

Department of Mechanical Engineering & Materials Science, Washington University in St. Louis, 1 Brookings Drive, St. Louis, MO 63130, USA.

Abstract
Chemical-looping combustion (CLC) is currently considered as a leading technology for reducing the economic cost of CO_2 capture. In this paper, several process simulations of chemical-looping combustion are conducted using the ASPEN Plus software. The entire CLC process from the beginning of coal gasification to the reduction and oxidation of the oxygen carrier is modeled and validated against experimental data. The energy balance of each major component of the CLC process, e.g., the fuel and air reactors and air/flue gas heat exchangers is examined. Different air flow rates and oxygen carrier feeding rates are used in the simulations to obtain the optimum ratio of coal, air, and oxygen carrier that produces the maximum power. Two scaled-up simulations are also conducted to investigate the influence of increase in coal feeding on power generation. It is demonstrated that the optimum ratio of coal, air supply, and oxygen carrier for maximum power generation remains valid for scaled-up cases with substantially larger coal feeding rates; the maximum power generation scales up linearly by using the process simulation models in ASPEN Plus. The energy output from four different types of coals is compared, and the optimum ratio of coal, air supply and oxygen carrier for maximum power generation for each type of coal is determined.

Keywords: Carbon capture; Process simulation; Chemical-looping combustion; Maximum energy output; Optimization; Scaled-up simulation.

1. Introduction
Coal-fired power plants contribute to significant CO_2 emissions; this reality has driven research in recent years on investigation of combustion processes that can capture CO_2 with reduced energy penalty. One technology that is showing great promise for high-efficiency low-cost carbon capture is the Chemical-Looping Combustion (CLC) process. In contrast to other methods for CO_2 separation from flue gas such as oxy-combustion, chemical absorption, and physical adsorption, the CLC is an advanced technology that creates and captures an almost pure and concentrated CO_2 stream with relatively less energy requirement [1, 2]. Several theoretical and experimental studies have demonstrated the potential of CLC to capture almost pure CO_2 very efficiently [3-6]. CLC employs a dual fluidized bed system with circulating fluidized bed process where an oxygen carrier (OC) is used as a bed material providing the oxygen for combustion in the fuel reactor. The reduced OC is then transferred to a second bed and re-oxidized by the atmospheric air [7-9] in an air reactor before it is returned to the fuel reactor to complete the loop. Because of the absence of air in the fuel reactor, the combustion products are not diluted by

other gases (e.g., N_2), resulting in high purity CO_2 available at the outlet of the fuel reactor. Thus, the CLC process for power generation provides a sequestration-ready CO_2 stream directly after combustion, without the need for using costly gas separation techniques to purify CO_2 from the flue stream. CLC therefore holds significant promise as a next generation combustion technology due to its potential for pre-capturing almost pure CO_2 emission with very limited effect on the efficiency of the power plant.

ASPEN Plus is a process simulation software that simulates chemical processes at system level using basic engineering relationships such as mass and energy balance, and multi-phase and chemical reaction models. It consists of flow sheet simulations to calculate stream properties such as flow rate and mass composition given various chemical processes and operating conditions. In this paper, a system level model of CLC process is developed to conduct parametric studies for optimal energy output.. These studies provide valuable insight into the design and operating conditions required in an industrial-scale CLC plant and to assess the feasibility of deploying CLC as an economically viable solution for electricity generation and carbon capture.

2. Validation of the CLC process simulation with experiment

The CLC process simulation in ASPEN Plus was validated against the experimental work of Sahir et al [10]. The physical and chemical properties of the Colombian coal used as the solid fuel in the experiment are summarized in Table 1.

Table 1. Physical and chemical properties of Colombian coal

Proximate Analysis (wt. %)				Ultimate Analysis (wt. %)					Energy
Moisture	Volatile matter	Fixed carbon	Ash	C	H	N	S	O	LHV (MJ/kg)
3.3	37.0	54.5	5.2	80.7	5.5	1.7	0.6	11.5	29.1

The schematic of the flow sheet for this simulation is shown in Figure 1. The coal is first pulverized and dried before it is pressurized and introduced into a shell gasifier to be partially oxidized to form syngas. The molar ratio of steam and carbon is maintained at unity for the process model. The syngas composition at the gasifier outlet is 34.5% CO, 50.3% H_2, 12.3% H_2O, and 2.4% CO_2. The syngas is converted completely to CO_2 and H_2O in the fuel reactor while the Fe_2O_3 in the oxygen carrier is reduced to Fe_3O_4. The oxygen carrier material used is a mixture of 60 wt. % Fe_2O_3 and 40 wt. % inert Al_2O_3 as support. The outflow from the fuel reactor is a concentrated stream of H_2O and CO_2. After condensing the stream, high purity CO_2 is obtained. The reduced oxygen carrier is fed into the air reactor where the oxidation reaction takes place with an 80% conversion of Fe_3O_4 to Fe_2O_3.

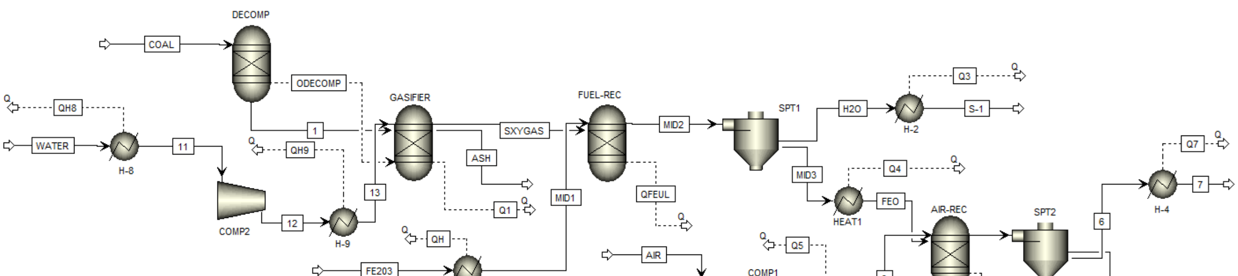

Figure 1. Flow sheet of the CLC model in ASPEN Plus

The various process models used in the ASPEN Plus shown in flow sheet in Figure 1 are summarized in Table 2. The coal devolatilization is defined by the RYIELD reactor, followed by the gasification of coal represented by the RGIBBS reactor. Another RGIBBS reactor defines the actual syngas combustion and the corresponding reduction of the oxygen carrier. These blocks together represent the fuel reactor. The flow sheet within the ASPEN Plus simulation package cannot model this entire reaction with one reactor. As a result, the fuel reactor simulation is broken down into several different reactor simulations. The air reactor is also modeled as an RGIBBS reactor.

Table 2. Process models used in different parts of the CLC process in ASPEN Plus

Name	Model	Function	Reaction formula
DECOMP	RYIELD	Coal devolatilization	Coal → volatile matter + char
BURN	RGIBBS	Gasification	Char + volatile matter → CO_2 + H_2O
FUEL-R	RSTOIC	Carrier reduction reaction	$3Fe_2O_3 + CO/H_2 \rightarrow 2Fe_3O_4 + CO_2/H_2O$
AIR-R	RSTOIC	Carrier oxidation reaction	$4Fe_3O_4 + O_2 \rightarrow 6Fe_2O_3$

For the purpose of validation, the energy balance of the CLC process model was analyzed using the input values from the experiment of Sahir et al [10]. The input values and the energy requirements for the various units and streams in Figure 1 are presented in Table 3; this will be referred to as the baseline case in rest of the paper. Energy is consumed mainly in the compressor processes. Compressed air is required in the air reactor to regenerate Fe_2O_3 from Fe_3O_4. The air compressor for the combustor compresses air to 18atm. Another compressor is used to compress the steam for the gasifier. There is a large amount of energy produced in the air reactor, but the fuel reactor needs to be supplied with energy. This is because the net heat work in the fuel reactor is the summation of the heat work from the DECOMP, GASIFER, and FUEL-R blocks. Although FUEL-R produces energy because of the combustion of syngas, the combined energy requirement of DECOMP and GASIFIER are more than the energy produced in FUEL-R. Summing the energy requirements of each individual stream, the total energy obtained from the CLC process is 554.2 kW.

Table 3. Input values and energy balance for the baseline case corresponding to the experiment of Sahir et al. [10]

Input values	Coal (kg/h)	100
	Steam (kg/h)	140
	Air Flow Rate (kg/h)	71
	Temperature of Fuel Reactor (ºC)	950
	Temperature of Air Reactor (ºC)	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921
	Al_2O_3 in the System (kg/h)	3951
	Particle Density (kg/m³)	3200
Energy Balance (kW)	Fuel reactor	-161.8
	Air reactor	688.0
	Cool air reactor exhaust	135.4
	Cool flue gas	148.3
	Cool OC for air reactor	40.9
	Reheat OC for fuel reactor	-42.7
	Heat steam	-69.8
	Heat air	-184.1
	Net	554.2

The results shown in Table 3 for the baseline case with a coal feed rate of 100 kg/h are in excellent agreement with those reported by Sahir et al [10]. These calculations validate our CLC model developed in ASPEN Plus.

3. Investigation of the effect of various parameters on the energy output of the CLC process simulation

With the successful validation of the process simulation of the CLC experiment of Sahir et al in the previous section, the ASPEN Plus simulation is expanded to consider the effect of varying the air flow rate and the oxygen carrier feeding rate. Additional scaled-up simulations are also conducted to determine these effects on an industrial scale power plant.

3.1 Effect of varying the air flow rate on energy output of baseline case with 100 kg/h coal feeding rate

The recent paper of Mukherjee et al. [11] suggests that it is favorable to operate the air reactor of the CLC process at higher temperatures with excess air supply in order to achieve higher power efficiency.

In order to evaluate the effect of air supply on energy output, we consider the baseline case of Table 3 and vary the air flow rate. The results are presented in Figure 2 and Table A1. From Figure 2, it can be seen that with an increase in the air flow rate, the net energy output increases and achieves a maximum for a certain air flow rate. If the air flow rate is further increased from its maximum value (i.e., value corresponding to maximum energy output), the energy output starts decreasing albeit very slowly. This result implies that there exists a certain rate of air supply around 900 kg/h to obtain the maximum energy output for 100 kg/h of coal supply. At this flow rate in the air reactor, 131.06 kW of additional energy is generated, which is 23.6% more than the baseline case given in Table 2 indicating that the reaction in the air reactor is not complete for the baseline case. Excess air supply ensures the 80% conversion of Fe_3O_4 to Fe_2O_3.

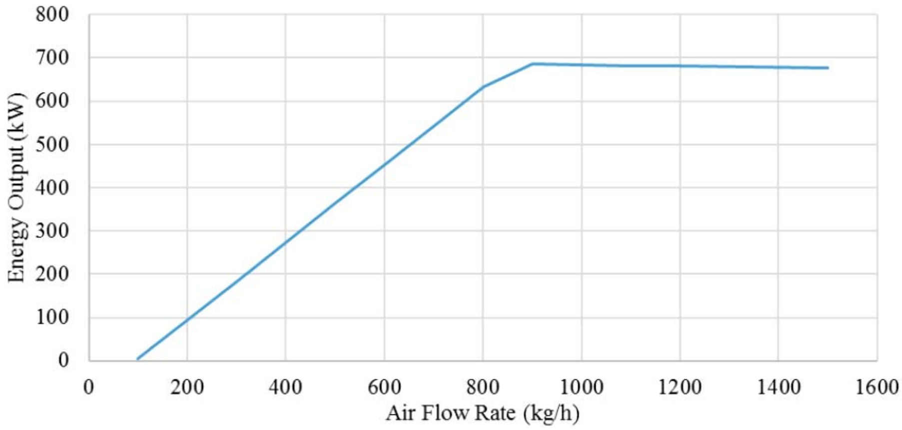

Figure 2. Energy output for various air flow rates for 100 kg/h of coal supply

3.2 Effect of varying the oxygen carrier feeding rate on energy output of baseline case with 100 kg/h coal feed rate

The oxygen carrier (OC) plays a vital role in the CLC process; it reacts with the syngas in the fuel reactor and reacts with the air in the air reactor. Both of these reactions contribute a large amount to the net energy output. Figure 3 and Tables A1–A6 present the energy output for different OC feeding rates in the system with varying air flow rates. As expected, Figure 3 shows that for a given air flow rate, a higher OC feeding rate yields more energy output. However, when the OC feeding rate increases above a certain threshold value, the marginal increase in energy output by increasing the OC rate becomes extremely small. The red line in Figure 3 represents the baseline case (Fe_2O_3 at 5921 kg/h), for which the maximum energy output is 685.26 kW with 900 kg/h air flow rate. For the threshold Fe_2O_3 rate of 7000 kg/h, the maximum energy output of 824.33 kW occurs at the 1000 kg/h air flow rate. 138.97 kW of additional energy output is obtained by increasing the OC rate from 5921 kg/h to 7000 kg/h. Therefore, for maximum energy output with a coal feeding rate of 100 kg/h, the optimum rates of air flow and OC feeding are 1000 kg/h and 7000 kg/h respectively. In other words, the optimum ratio of Coal: Air: OC is 1: 10: 70.

3.3 Scaled-up simulation

Scaling up is an essential step for the realization and optimization of industrial-scale power plants. Two different scaled-up simulations were conducted to investigate the relationship between the coal feeding rate and energy output. The first scaled-up simulation employed the initial values of the baseline case and the other was based on the optimum values of coal: air supply: oxygen carrier rate. The details of the scaled-up simulations are given in Table A7 and Table A8 respectively. In both cases, the coal feeding rate is scaled up by a factor of up to 12. The OC feeding rate and air supply rate are also scaled-up accordingly to meet the demand of the increased coal feeding. Other modeling parameters such as the reactor efficiency and coal decomposition rate are considered unchanged for both the scaled up simulations. The total thermal power output for the scaled-up simulations is summarized in Figure 4 and Table 4 below. From Figure 4, it can be seen that the total power output increases linearly with increase in coal feeding rate. Considering the principles of energy and mass balance on which the ASPEN Plus modeling is based, linearity in the scaled-up results is expected since the non-linear effects (e.g., the energy loss at multiple locations in the flow sheet) are omitted in the modeling process.

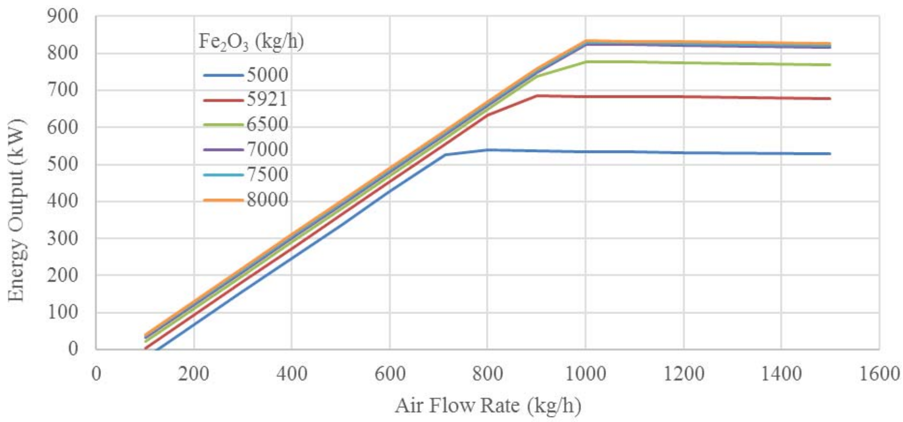

Figure 3. Energy output for various oxygen carrier feeding rates and air flow rates for 100 kg/h of coal supply

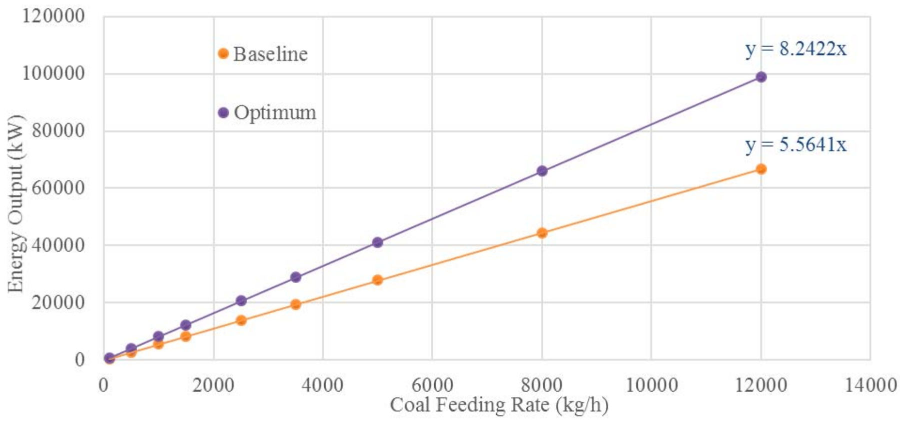

Figure 4. Energy output of two scaled-up simulations for various coal feeding rates

Table 4. Results of two scaled-up simulations for different ratios of Coal: Air: OC

Coal (kg/h)		100	500	1000	1500	2500	3500	5000	8000	12000
Energy output (kW)	Baseline	554.2	2782	5564	8346	13910	19474	27820	44513	66769
	Optimum	824.2	4121	8242	12363	20606	28847	41211	65936	98907

Based on these scaled-up simulations, the energy output for the baseline case is given by the equation

$$\text{Energy output} = 5.5641 \times \text{Coal feeding rate} \quad (1)$$

and the energy output for the optimum case is given by the equation

$$\text{Energy output} = 8.2422 \times \text{Coal feeding rate} \quad (2)$$

3.4 Validation of optimum values of air flow rate and oxygen carrier feeding rate for scaled-up simulation

To demonstrate that the optimum values of air flow rate and OC feeding rate for maximum energy output are valid for the scaled-up simulations, four more cases with 12,000 kg/h coal feeding rate and varying rates of air flow and OC were studied, which are presented in Figure 5 and Tables A9-A11. Figure 5 shows that the maximum energy output occurs at 120,000 kg/h of air flow rate, and 840,000 kg/h of

Fe_2O_3 feeding rate. This suggests that the optimum ratio of Coal: Air: OC in the system still holds for the scaled-up simulations; it is given by

Coal feeding rate: Air flow rate: OC feeding rate=1:10:70 (3)

Equation (3) is an important relationship among these three input parameters for obtaining the maximum energy output from a CLC-based power plant. This relationship can be used for the initial estimates in designing a CLC-based industrial-scale power plant.

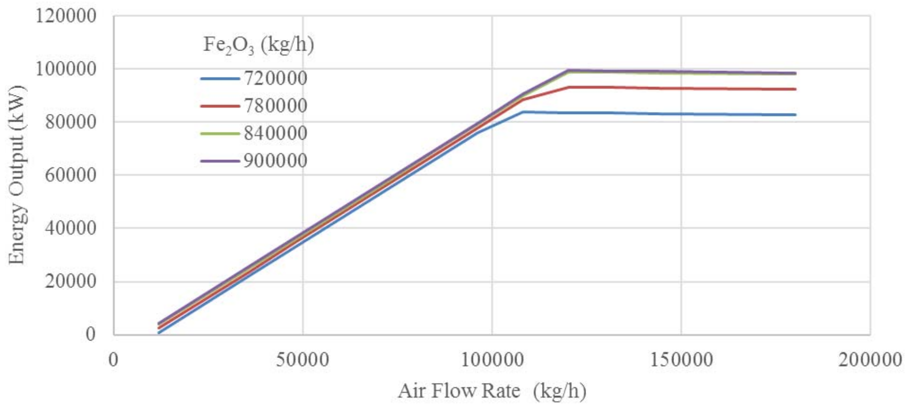

Figure 5. Energy output for different airflow rates and OC rates for a 12000 kg/h coal feeding rate

4. Energy output of different types of coals

All the results above are dependent on the certain type of coal, the Colombian coal of which the physical and chemical properties are listed in Table 1. Now it is interesting to investigate the performance of different types of coal. Four types of coals are used in this paper which are Colombian, Bituminous, Anthracite and Lignite. The proximate analysis and ultimate analysis of Colombian coal is given in Table 1 and that of other three coals are summarized in Table 5.

Table 5. Physical and chemical properties of bituminous, anthracite and lignite coals

Coal name	Proximate Analysis (wt. %)				Ultimate Analysis (wt. %)						Energy
	Moisture	Volatile matter	Fixed carbon	Ash	C	H	N	S	O	Ash	LHV (kJ/kg)
Bituminous	2.3	33.0	55.9	8.8	65.8	3.3	1.6	0.6	17.6	11.1	21899
Anthracite	1.0	7.5	59.9	31.6	60.7	2.1	0.9	1.3	2.4	32.6	21900
Lignite	12.6	28.6	33.6	25.2	45.4	2.5	0.6	5.2	8.5	37.8	16250

4.1 Effect of varying the air flow rate on energy output of four types of coals with 100 kg/h coal feeding rate

Again in order to evaluate the effect of air supply on energy output, we conduct the same process modeling as described in section 3.1 by varying the air flow rate with coal feeding rate of 100 kg/h for four different types of coals. The results are presented in Figure 6 and Table A1 for Colombian coal and in Tables A12-A14 for Bituminous, Anthracite and Lignite coal. From Figure 6, it can be seen that with an increase in air flow rate, all four types of coal show the same trend that net energy output increases and achieves a maximum for a certain air flow rate. Every coal type has a different inflection point which corresponds to the maximum energy output on the y-axis for a certain air flow rate shown on x-axis. It can be seen that the inflection point is different depending upon the type of coal which is expected because of different properties of the coals as given in Table 5. By qualitative analysis, one can infer that higher the concentration of fixed carbon in a coal gives more fuel to burn, and the higher concentration of volatile matter and ash cost less energy to decompose the coal. Next, we determine the optimal ratio of Coal: Air: OC for the other three types of coal.

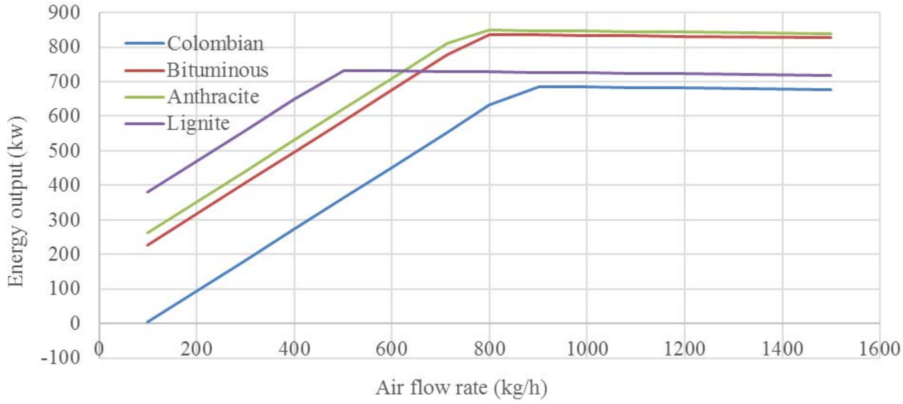

Figure 6. Energy output for various air flow rates for 100 kg/h of four types of coals

4.2 Effect of varying the oxygen carrier feeding rate on energy output of four types of coals with 100 kg/h coal feeding rate

The effect of varying the oxygen carrier feeding rate on energy output of Colombian coal was shown in Figure 3 and Tables A1-A6. The results of other three types of coal, Bituminous, Anthracite and Lignite are presented in Figures 7-9 and Tables A12-A24. As expected, as with the Colombian coal, there is the maximum energy output based on optimal coal feeding rate: air flow rate: OC feeding rate for Bituminous, Anthracite and Lignite coal as well. Table 6 summarizes the maximum energy output and optimal ratio of Coal: Air: OC for four types of coal with 100 kg/h coal feed rate.

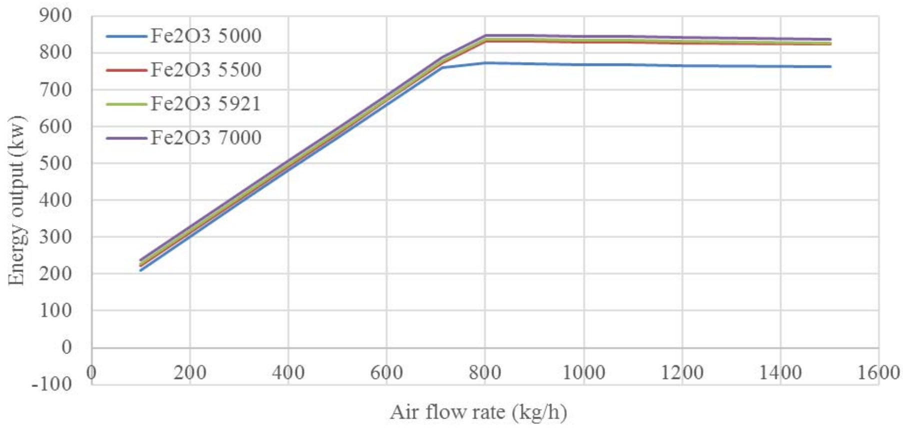

Figure 7. Energy output for various oxygen carrier feeding rates and air flow rates for 100 kg/h of Bituminous coal

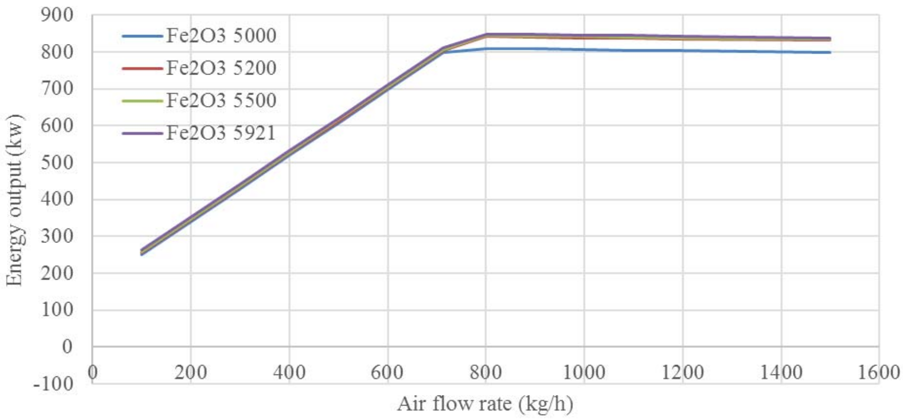

Figure 8. Energy output for various oxygen carrier feeding rates and air flow rates for 100 kg/h of Anthracites coal

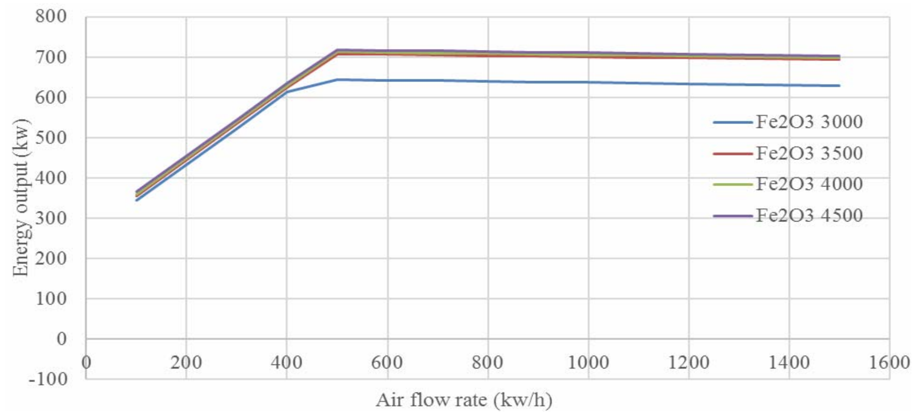

Figure 9. Energy output for various oxygen carrier feeding rates and air flow rates for 100 kg/h of Lignite coal

Table 6. Maximum energy output and optimal ratio of Coal: Air: OC for four types of coal with 100 kg/h coal feed rate

Coal Name	Maximum Energy (kw)	Optimal Ratio of Coal: Air: OC
Colombian	824.229	1: 70: 10
Bituminous	832.373	1: 55: 8
Anthracite	841.258	1: 52: 8
Lignite	707.905	1: 35: 5

5. Conclusions

In this paper, ASPEN Plus is employed to model and study the complete CLC process from the coal gasification to the reduction and eventual re-oxidation of the oxygen carrier (OC). The CLC process model is validated against the experiment of Sahir et al [10] and shows good agreement between the experimental data and the simulation results. Based on further studies on the effect of varying air flow rates and OC feeding rates, it is found that the maximization of energy output from CLC can be accomplished by using the optimum ratio of Coal: Air: OC in the system equal to 1: 10: 70 for Colombian coal. Compared to the baseline case based on the experiment of Sahir et al [10], a net increase in power of 48% can be obtained by increasing the air flow rate by 40.25% and the OC feeding rate by 18.22% to attain this optimum ratio for the Colombian coal for the given coal feeding rate of 100kg/h. Scaled-up simulations are also conducted using different coal feeding rates. The results show that the total power output is linear with increase in coal feeding rate. In general, such linearity is not expected for actual industrial-level scale-up since the ASPEN Plus system modeling software neglects miscellaneous energy losses in the system due to changes in the hydrodynamic characteristics of the two fluidized bed reactors. To account for the changes in the hydrodynamics characteristics, detailed hydrodynamic simulations are needed using the computational fluid dynamics software. Three other types of coal (Bituminous, Anthracite, and Lignite) are also investigated, and the optimal ratio of coal: airflow: OC is determined for each of these coal types. There are other parameters that may also influence the energy output such as the temperature and pressure of the reactors, particle size, etc., which are not investigated in this paper.

Reference

[1] Cuadrat A., Abad A., de Diego L.F. (2012) Prompt considerations on the design of chemical-looping combustion of coal from experimental tests, Fuel 97, pp. 219-232.

[2] Wang J., Anthony E.J. (2008) Clean combustion of solid fuels, Applied Energy 85 (2), pp. 73-79.

[3] Gnanapragasam N.V., Reddy B.V., Rosen M.A. (2009) Hydrogen production from coal using coal direct chemical looping and syngas chemical looping combustion systems: assessment of system operation and resource requirements, Int. J. Hydrogen Energy 34 (6), pp. 2606-2615.

[4] Adánez J., Gayán P., Celaya J. (2006) Chemical looping combustion in a 10 kWth prototype using a CuO/Al2O3 oxygen carrier: Effect of operating conditions on methane combustion, Industrial & Engineering Chemistry Research 45 (17), pp. 6075-6080.

[5] Arjmand M., Azad A.M., Leion H., Lyngfelt A., Mattisson T. (2011) Prospects of Al2O3 and MgAl2O4-supported CuO oxygen carriers in chemical-looping combustion (CLC) and chemical-looping with oxygen uncoupling (CLOU), Energy & Fuels 25 (11), pp. 5493-5502.
[6] Leion H., Lyngfelt A., Johansson M., Jerndal E., Mattisson T. (2008) The use of ilmenite as an oxygen carrier in chemical-looping combustion, Chemical Engineering Research and Design 86 (9), pp. 1017-1026.
[7] Leion H., Mattisson T., Lyngfelt A. (2009) Using chemical-looping with oxygen uncoupling (CLOU) for combustion of six different solid fuels, Energy Procedia 1 (1), pp. 447-453.
[8] Mattisson T., Lyngfelt A., Leion H. (2009) Chemical-looping with oxygen uncoupling for combustion of solid fuels, Int. J. Greenhouse Gas Control 3 (1), pp. 11-19.
[9] Cuadrat A., Abad A., Adánez J., de Diego L.F. (2012) Behavior of ilmenite as oxygen carrier in chemical-looping combustion, Fuel Processing Technology 94 (1), pp. 101-112.
[10] Sahir A.H., Cadore A.L., Dansie J.K. (2012) Process analysis of chemical looping with oxygen uncoupling (CLOU) and chemical looping combustion (CLC) for solid fuels, 2nd International Conference on Chemical looping, Darmstadt, Germany.
[11] Mukherjee S., Kumar P., Hosseini A. (2014) Comparative assessment of gasification based coal power plants with various CO_2 capture technologies producing electricity and hydrogen Energy & Fuels 28 (2), pp. 1028-1040.

Appendix

Table A1. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5921/3951 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-161.8	-161.8	-161.8	-161.8	-161.8	-161.8
	Air Reactor	96.498	289.5	386	482.49	578.99	688
	Cool air reactor exhaust	18.996	56.988	75.985	94.981	113.98	135.4
	Cool flue gas	148.3	148.3	148.3	148.3	148.3	148.3
	Cool OC for air reactor	40.9	40.9	40.9	40.9	40.9	40.9
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	4.57	183.92	273.59	363.26	452.93	554.2
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-161.8	-161.8	-161.8	-161.8	-161.8	-161.8
	Air Reactor	771.99	829.67	829.79	829.93	830.07	830.49
	Cool air reactor exhaust	151.97	173.08	197.33	221.58	245.83	318.57
	Cool flue gas	148.33	148.33	148.33	148.33	148.33	148.33
	Cool OC for air reactor	40.9	40.9	40.9	40.9	40.9	40.9
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-68.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	632.3	685.26	683.81	682.37	681.94	676.63

Table A2. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5000/3000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-183.2	-183.2	-183.2	-183.2	-183.2	-183.2
	Air Reactor	96.498	289.5	386	482.49	578.99	688
	Cool air reactor exhaust	18.996	56.999	75.985	94.981	113.98	135.4
	Cool flue gas	142.63	142.63	142.63	142.63	142.63	142.63
	Cool OC for air reactor	32.792	32.792	32.792	32.792	32.792	32.792
	Reheat OC for fuel reactor	-34.27	-34.27	-34.27	-34.27	-34.27	-34.27
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	-22.21	157.14	246.8	336.47	426.14	527.41
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-183.2	-183.2	-183.2	-183.2	-183.2	-183.2
	Air Reactor	700.66	700.79	700.93	701.11	701.21	701.64
	Cool air reactor exhaust	155.86	180.1	204.35	228.6	252.85	325.59
	Cool flue gas	142.63	142.63	142.63	142.63	142.63	142.63
	Cool OC for air reactor	32.792	32.792	32.792	32.792	32.792	32.792
	Reheat OC for fuel reactor	-34.27	-34.27	-34.27	-34.27	-34.27	-34.27
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	538.05	536.6	535.16	533.77	532.29	527.99

Table A3. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 6500/4500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	6500	6500	6500	6500	6500	6500
	Al_2O_3 in the System (kg/h)	4500	4500	4500	4500	4500	4500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-148.4	-148.4	-148.4	-148.4	-148.4	-148.4
	Air Reactor	96.498	289.5	386	482.49	578.99	688.04
	Cool air reactor exhaust	18.996	56.999	75.985	94.981	113.98	135.4
	Cool flue gas	151.96	151.96	151.96	151.96	151.96	151.96
	Cool OC for air reactor	45.781	45.781	45.781	45.781	45.781	45.781
	Reheat OC for fuel reactor	-47.71	-47.71	-47.71	-47.71	-47.71	-47.71
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	21.473	200.83	290.49	380.16	469.83	571.14

Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	6500	6500	6500	6500	6500	6500
	Al_2O_3 in the System (kg/h)	4500	4500	4500	4500	4500	4500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-148.4	-148.4	-148.4	-148.4	-148.4	-148.4
	Air Reactor	771.99	868.49	910.81	910.94	911.07	911.49
	Cool air reactor exhaust	151.97	170.97	192.91	217.16	241.41	314.15
	Cool flue gas	151.96	151.96	151.96	151.96	151.96	151.96
	Cool OC for air reactor	45.781	45.781	45.781	45.781	45.781	45.781
	Reheat OC for fuel reactor	-47.71	-47.71	-47.71	-47.71	-47.71	-47.71
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	649.18	738.85	777.29	775.85	774.41	770.1

Table A4. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 7000/5000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7000	7000	7000	7000	7000	7000
	Al_2O_3 in the System (kg/h)	5000	5000	5000	5000	5000	5000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-139.6	-139.6	-139.6	-139.6	-139.6	-139.6
	Air Reactor	96.498	289.5	386	482.49	578.99	688.04
	Cool air reactor exhaust	18.996	56.999	75.985	94.981	113.98	135.4
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	50.175	50.175	50.175	50.175	50.175	50.175
	Reheat OC for fuel reactor	-52.19	-52.19	-52.19	-52.19	-52.19	-52.19
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	31.917	211.27	300.93	390.6	480.28	581.58
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7000	7000	7000	7000	7000	7000
	Al_2O_3 in the System (kg/h)	5000	5000	5000	5000	5000	5000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-139.6	-139.6	-139.6	-139.6	-139.6	-139.6
	Air Reactor	771.99	868.49	949.41	949.52	949.66	950.07
	Cool air reactor exhaust	151.97	170.97	190.81	215.06	239.31	312.05
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	50.175	50.175	50.175	50.175	50.175	50.175
	Reheat OC for fuel reactor	-52.19	-52.19	-52.19	-52.19	-52.19	-52.19
	Heat steam	-69.8	-69.8	-69.8	-69.8	-68.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	659.62	749.29	824.23	822.77	822.33	817.02

Table A5. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 7500/5500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7500	7500	7500	7500	7500	7500
	Al_2O_3 in the System (kg/h)	5500	5500	5500	5500	5500	5500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-134.6	-134.6	-134.6	-134.6	-134.6	-134.6
	Air Reactor	96.498	289.5	386	482.49	578.99	688.04
	Cool air reactor exhaust	18.996	56.999	75.985	94.981	113.98	135.4
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	54.647	54.647	54.647	54.647	54.647	54.647
	Reheat OC for fuel reactor	-56.67	-56.67	-56.67	-56.67	-56.67	-56.67
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	36.942	216.3	305.96	395.63	485.3	586.61
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7500	7500	7500	7500	7500	7500
	Al_2O_3 in the System (kg/h)	5500	5500	5500	5500	5500	5500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-134.6	-134.6	-134.6	-134.6	-134.6	-134.6
	Air Reactor	771.99	868.49	949.41	949.52	949.66	950.07
	Cool air reactor exhaust	151.97	170.97	190.81	215.06	239.31	312.05
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	54.647	54.647	54.647	54.647	54.647	54.647
	Reheat OC for fuel reactor	-56.67	-56.67	-56.67	-56.67	-56.67	-56.67
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	664.65	754.32	829.25	827.8	826.35	822.04

Table A6. CLC process simulation results for different air flow rates with Colombian coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 8000/6000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	8000	8000	8000	8000	8000	8000
	Al_2O_3 in the System (kg/h)	6000	6000	6000	6000	6000	6000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	-129.6	-129.6	-129.6	-129.6	-129.6	-129.6
	Air Reactor	96.498	289.5	386	482.49	578.99	688.04
	Cool air reactor exhaust	18.996	56.999	75.985	94.981	113.98	135.4
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	59.121	59.121	59.121	59.121	59.121	59.121
	Reheat OC for fuel reactor	-61.15	-61.15	-61.15	-61.15	-61.15	-61.15
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.47	-103.3	-129.1	-154.9	-184.1
	Net	41.968	221.32	310.98	400.66	490.33	591.63

Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	8000	8000	8000	8000	8000	8000
	Al_2O_3 in the System (kg/h)	6000	6000	6000	6000	6000	6000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	-129.6	-129.6	-129.6	-129.6	-129.6	-129.6
	Air Reactor	771.99	868.49	949.41	949.52	949.66	950.07
	Cool air reactor exhaust	151.97	170.97	190.81	215.06	239.31	312.05
	Cool flue gas	153.71	153.71	153.71	153.71	153.71	153.71
	Cool OC for air reactor	59.121	59.121	59.121	59.121	59.121	59.121
	Reheat OC for fuel reactor	-61.15	-61.15	-61.15	-61.15	-61.15	-61.15
	Heat steam	-69.8	-69.8	-69.8	-69.8	-68.8	-69.8
	Heat air	-206.6	-232.4	-258.2	-284.1	-309.9	-387.3
	Net	669.67	759.34	834.28	832.82	832.38	827.07

Table A7. Scaled-up simulation results for different coal feeding rates using the baseline ratios of air flow rate and oxygen carrier flow rate from the experiment of Sahir et al [10]

Initial values	Coal (kg/h)	100	500	1000	1500	2500
	Water (kg/h)	140	700	1400	2100	3500
	Air Flow Rate (kg/h)	713	3565	7130	10695	17825
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	30000	60000	90000	150000
	Al_2O_3 in the System (kg/h)	3951	20000	40000	60000	100000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200
Energy balance (KW)	Fuel Reactor	-161.8	-800.8	-1602	-2402	-4.004
	Air Reactor	688	3440.2	6880.4	10321	17.201
	Cool air reactor exhaust	135.4	677.22	1354.4	2031.7	3.3861
	Cool flue gas	148.3	744.09	1488.2	2232.3	3.7205
	Cool OC for air reactor	40.9	207.26	414.52	621.77	1.0363
	Reheat OC for fuel reactor	-42.7	-216.2	-432.3	-648.5	-1.081
	Heat steam	-69.8	-349.1	-698.3	-1047	-1.746
	Heat air	-184.1	-920.6	-1841	-2762	-4.603
	Net	554.2	2782	5564.1	8346.1	13910
Initial values (continued)	Coal (kg/h)	3500	5000	8000	12000	
	Water (kg/h)	4900	7000	11200	16800	
	Air Flow Rate (kg/h)	24955	35650	57040	85560	
	Temperature of Fuel Reactor (ºC)	950	950	950	950	
	Temperature of Air Reactor (ºC)	935	935	935	935	
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	210000	300000	480000	720000	
	Al_2O_3 in the System (kg/h)	140000	200000	320000	480000	
	Particle Density (kg/m³)	3200	3200	3200	3200	
Energy balance (KW) (continued)	Fuel Reactor	-5.606	-8.008	-12.81	-19.22	
	Air Reactor	24.081	34.402	55.043	82.564	
	Cool air reactor exhaust	4.7405	6.7722	10.836	16.253	
	Cool flue gas	5.2087	7.4409	11.906	17.858	
	Cool OC for air reactor	1.4508	2.0726	3.3161	4.9742	
	Reheat OC for fuel reactor	-1.513	-2.162	-3.459	-5.188	
	Heat steam	-2.444	-3.491	-5.586	-8.379	
	Heat air	-6.444	-9.206	-14.73	-22.09	
	Net	19474	27820	44513	66769	

Table A8. Scaled-up simulation results for different coal feeding rates using the optimum ratios of air flow rate and oxygen carrier flow rate

Initial values	Coal (kg/h)	100	500	1000	1500	2500
	Water (kg/h)	140	700	1400	2100	3500
	Air Flow Rate (kg/h)	1000	5000	10000	15000	25000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7000	35000	70000	105000	175000
	Al_2O_3 in the System (kg/h)	5000	25000	50000	75000	125000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200
Energy balance (KW)	Fuel Reactor	-139.6	-698.2	-1484	-2226	-3711
	Air Reactor	949.41	4747	9108.1	13662	22770
	Cool air reactor exhaust	190.81	954.06	1929.1	2893.7	4822.9
	Cool flue gas	153.71	768.54	1519.6	2279.4	3799
	Cool OC for air reactor	50.175	250.87	457.81	686.72	1144.5
	Reheat OC for fuel reactor	-52.19	-261	-477.1	-715.7	-1193
	Heat steam	-69.8	-349.1	-698.3	-1047	-1746
	Heat air	-258.2	-1291	-2582	-3873	-6456
	Net	824.23	4121	8242.3	12363	20606
Initial values (continued)	Coal (kg/h)	3500	5000	8000	12000	
	Water (kg/h)	4900	7000	11200	16800	
	Air Flow Rate (kg/h)	35000	50000	80000	120000	
	Temperature of Fuel Reactor (ºC)	950	950	950	950	
	Temperature of Air Reactor (ºC)	935	935	935	935	
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	245000	350000	560000	840000	
	Al_2O_3 in the System (kg/h)	175000	250000	400000	600000	
	Particle Density (kg/m³)	3200	3200	3200	3200	
Energy balance (KW) (continued)	Fuel Reactor	-5195	-7421	-11874	-17811	
	Air Reactor	31878	45541	72865	109297	
	Cool air reactor exhaust	6752	9645.7	15433	23150	
	Cool flue gas	5318.6	7598.1	12157	18235	
	Cool OC for air reactor	1602.3	2289.1	3662.5	5493.7	
	Reheat OC for fuel reactor	-1670	-2386	-3817	-5725	
	Heat steam	-2444	-3491	-5586	-8379	
	Heat air	-9038	-12912	-20659	-30988	
	Net	28847	41211	65936	98907	

Table A9. CLC process simulation results for different air flow rates with Colombian coal at 12000 kg/h and Fe_2O_3/Al_2O_3 at 780000/540000 kg/h

Initial values	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	12000	36000	48000	60000	72000	84000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	780000	780000	780000	780000	780000	780000
	Al_2O_3 in the System (kg/h)	540000	540000	540000	540000	540000	540000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW)	Fuel Reactor	-17811	-17811	-17811	-17811	-17811	-17811
	Air Reactor	11580	34740	46320	57899	69479	81059
	Cool air reactor exhaust	2279.6	6838.7	9118.2	11398	13677	15957
	Cool flue gas	18235	18235	18235	18235	18235	18235
	Cool OC for air reactor	5493.7	5493.7	5493.7	5493.7	5493.7	5493.7
	Reheat OC for fuel reactor	-5725	-5725	-5725	-5725	-5725	-5725
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-3099	-9296	-12395	-15494	-18593	-21692
	Net	2573.3	24095	34855	45616	56376	67137

Initial values (continued)	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	96000	108000	120000	132000	144000	180000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	780000	780000	780000	780000	780000	780000
	Al_2O_3 in the System (kg/h)	540000	540000	540000	540000	540000	540000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW) (continued)	Fuel Reactor	-17811	-17811	-17811	-17811	-17811	-17811
	Air Reactor	92639	104219	109297	109313	109329	109379
	Cool air reactor exhaust	18236	20516	23150	26059	28969	37698
	Cool flue gas	18235	18235	18235	18235	18235	18235
	Cool OC for air reactor	5493.7	5493.7	5493.7	5493.7	5493.7	5493.7
	Reheat OC for fuel reactor	-5725	-5725	-5725	-5725	-5725	-5725
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-24790	-27889	-30988	-34087	-37186	-46482
	Net	77898	88658	93271	93098	92925	92408

Table A10. CLC process simulation results for different air flow rates with Colombian coal at 12000 kg/h and Fe_2O_3/Al_2O_3 at 840000/600000 kg/h

Initial values	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	12000	36000	48000	60000	72000	84000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	840000	840000	840000	840000	840000	840000
	Al_2O_3 in the System (kg/h)	600000	600000	600000	600000	600000	600000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW)	Fuel Reactor	-16757	-16757	-16757	-16757	-16757	-16757
	Air Reactor	11580	34740	46320	57899	69479	81059
	Cool air reactor exhaust	2279.6	6838.7	9118.2	11398	13677	15957
	Cool flue gas	18445	18445	18445	18445	18445	18445
	Cool OC for air reactor	6021	6021	6021	6021	6021	6021
	Reheat OC for fuel reactor	-6263	-6263	-6263	-6263	-6263	-6263
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-3099	-9296	-12395	-15494	-18593	-21692
	Net	3826.8	25348	36109	46869	57630	68390
Initial values (continued)	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	96000	108000	120000	132000	144000	180000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	840000	840000	840000	840000	840000	840000
	Al_2O_3 in the System (kg/h)	600000	600000	600000	600000	600000	600000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW) (continued)	Fuel Reactor	-16757	-16757	-16757	-16757	-16757	-16757
	Air Reactor	92639	104219	113929	113943	113959	114009
	Cool air reactor exhaust	18236	20516	22897	25807	28717	37446
	Cool flue gas	18445	18445	18445	18445	18445	18445
	Cool OC for air reactor	6021	6021	6021	6021	6021	6021
	Reheat OC for fuel reactor	-6263	-6263	-6263	-6263	-6263	-6263
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-24790	-27889	-30988	-34087	-37186	-46482
	Net	79151	89912	98904	98730	98556	98039

Table A11. CLC process simulation results for different air flow rates with Colombian coal at 12000 kg/h and Fe_2O_3/Al_2O_3 at 900000/660000 kg/h

Initial values	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	12000	36000	48000	60000	72000	84000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	900000	900000	900000	900000	900000	900000
	Al_2O_3 in the System (kg/h)	660000	660000	660000	660000	660000	660000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW)	Fuel Reactor	-16154	-16154	-16154	-16154	-16154	-16154
	Air Reactor	11580	34740	46320	57899	69479	81059
	Cool air reactor exhaust	2279.6	6838.7	9118.2	11398	13677	15957
	Cool flue gas	18445	18445	18445	18445	18445	18445
	Cool OC for air reactor	6557.7	6557.7	6557.7	6557.7	6557.7	6557.7
	Reheat OC for fuel reactor	-6801	-6801	-6801	-6801	-6801	-6801
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-3099	-9296	-12395	-15494	-18593	-21692
	Net	4429.8	25951	36712	47472	58233	68993
Initial values (continued)	Coal (kg/h)	12000	12000	12000	12000	12000	12000
	Water (kg/h)	16800	16800	16800	16800	16800	16800
	Air Flow Rate (kg/h)	96000	108000	120000	132000	144000	180000
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	900000	900000	900000	900000	900000	900000
	Al_2O_3 in the System (kg/h)	660000	660000	660000	660000	660000	660000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (KW) (continued)	Fuel Reactor	-16154	-16154	-16154	-16154	-16154	-16154
	Air Reactor	92639	104219	113929	113943	113959	114009
	Cool air reactor exhaust	18236	20516	22897	25807	28717	37446
	Cool flue gas	18445	18445	18445	18445	18445	18445
	Cool OC for air reactor	6557.7	6557.7	6557.7	6557.7	6557.7	6557.7
	Reheat OC for fuel reactor	-6801	-6801	-6801	-6801	-6801	-6801
	Heat steam	-8379	-8379	-8379	-8379	-8379	-8379
	Heat air	-24790	-27889	-30988	-34087	-37186	-46482
	Net	79754	90515	99507	99333	99159	98642

Table A12. CLC process simulation results for different air flow rates with Bituminous coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5921/3951 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	72.119	72.119	72.119	72.119	72.119	72.119
	Air Reactor	96.498	289.497	385.995	482.494	578.993	688
	Cool air reactor exhaust	18.996	56.988	75.985	94.981	113.978	135.4
	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	41.082	41.082	41.082	41.082	41.082	41.082
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.823	-77.469	-103.29	-129.12	-154.94	-184.1
	Net	227.436	406.781	496.452	586.124	675.796	777.065
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	72.119	72.119	72.119	72.119	72.119	72.119
	Air Reactor	752.554	752.667	752.812	752.951	753.091	753.515
	Cool air reactor exhaust	153.029	177.277	201.524	225.772	250.02	322.764
	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	41.082	41.082	41.082	41.082	41.082	41.082
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	836.762	835.299	833.868	832.432	830.996	826.695

Table A13. CLC process simulation results for different air flow rates with Anthracite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5921/3951 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	116.145	116.145	116.145	116.145	116.145	116.145
	Air Reactor	96.498	289.497	385.995	482.494	578.993	688
	Cool air reactor exhaust	18.996	56.988	75.985	94.981	113.978	135.4
	Cool flue gas	127.834	127.834	127.834	127.834	127.834	127.834
	Cool OC for air reactor	41.132	41.132	41.132	41.132	41.132	41.132
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.823	-77.469	-103.29	-129.11	-154.94	-184.1
	Net	262.282	441.627	531.298	620.97	710.642	811.911
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	116.145	116.145	116.145	116.145	116.145	116.145
	Air Reactor	728.287	728.416	728.553	728.692	728.832	729.257
	Cool air reactor exhaust	154.351	178.599	202.847	227.094	251.342	324.086

(continued)	Cool flue gas	127.834	127.834	127.834	127.834	127.834	127.834
	Cool OC for air reactor	41.132	41.132	41.132	41.132	41.132	41.132
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.58	-232.41	-258.23	-284.05	-309.88	-387.34
	Net	848.663	847.216	845.778	844.341	842.905	838.605

Table A14. CLC process simulation results for different air flow rates with Lignite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5921/3951 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	246.014	246.014	246.014	246.014	246.014	246.014
	Air Reactor	96.498	289.497	385.995	475.591	475.716	475.872
	Cool air reactor exhaust	18.996	56.988	75.985	95.357	119.605	147.005
	Cool flue gas	115.4	115.4	115.4	115.4	115.4	115.4
	Cool OC for air reactor	41.649	41.649	41.649	41.649	41.649	41.649
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.823	-77.46	-103.29	-129.11	-154.94	-184.1
	Net	380.234	559.579	649.25	732.395	730.944	729.34
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5921	5921	5921	5921	5921	5921
	Al_2O_3 in the System (kg/h)	3951	3951	3951	3951	3951	3951
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	246.014	246.014	246.014	246.014	246.014	246.014
	Air Reactor	475.994	476.136	476.278	476.42	476.563	476.992
	Cool air reactor exhaust	168.101	192.349	216.596	240.884	265.092	337.836
	Cool flue gas	115.4	115.4	115.4	115.4	115.4	115.4
	Cool OC for air reactor	41.649	41.649	41.649	41.649	41.649	41.649
	Reheat OC for fuel reactor	-42.7	-42.7	-42.7	-42.7	-42.7	-42.7
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.58	-232.41	-258.23	-284.05	-309.88	-387.34
	Net	728.072	726.638	725.204	723.811	722.338	718.042

Table A15. CLC process simulation results for different air flow rates with Bituminous coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5000/3000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140

	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	57.719	57.719	57.719	57.719	57.719	57.719
	Air Reactor	96.498	289.497	385.995	482.494	578.993	688
	Cool air reactor exhaust	18.996	56.988	75.985	94.981	113.978	135.4
	Cool flue gas	134.734	134.734	134.734	134.734	134.734	134.734
	Cool OC for air reactor	32.792	32.792	32.792	32.792	32.792	32.792
	Reheat OC for fuel reactor	-34.273	-34.273	-34.273	-34.273	-34.273	-34.273
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.46	-103.29	-129.11	-154.94	-184.1
	Net	210.843	390.188	479.859	569.531	659.203	760.472
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	57.719	57.719	57.719	57.719	57.719	57.719
	Air Reactor	700.662	700.794	700.932	701.072	701.213	701.639
	Cool air reactor exhaust	155.856	180.104	204.352	228.6	252.848	325.591
	Cool flue gas	134.734	134.734	134.734	134.734	134.734	134.734
	Cool OC for air reactor	32.792	32.792	32.792	32.792	32.792	32.792
	Reheat OC for fuel reactor	-34.273	-34.273	-34.273	-34.273	-34.273	-34.273
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.58	-232.41	-258.23	-284.05	-309.88	-387.34
	Net	771.104	769.66	768.223	766.788	765.353	761.053

Table A16. CLC process simulation results for different air flow rates with Bituminous coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5500/3500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5500	5500	5500	5500	5500	5500
	Al_2O_3 in the System (kg/h)	3500	3500	3500	3500	3500	3500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	67.705	67.705	67.705	67.705	67.705	67.705
	Air Reactor	96.498	289.497	385.995	482.494	578.993	688.037
	Cool air reactor exhaust	18.9963	56.9989	75.985	94.981	113.978	135.4
	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	37.159	37.159	37.159	37.159	37.159	37.159
	Reheat OC for fuel reactor	-38.752	-38.752	-38.752	-38.752	-38.752	-38.752
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8

	Heat air	-25.82	-77.46	-103.29	-129.11	-154.94	-184.12
	Net	223.047	402.4029	492.063	581.735	671.407	772.693
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5500	5500	5500	5500	5500	5500
	Al_2O_3 in the System (kg/h)	3500	3500	3500	3500	3500	3500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	67.705	67.705	67.705	67.705	67.705	67.705
	Air Reactor	752.554	752.677	752.812	752.951	753.091	753.515
	Cool air reactor exhaust	153.029	177.277	201.524	225.773	250.02	322.764
	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	37.159	37.159	37.159	37.159	37.159	37.159
	Reheat OC for fuel reactor	-38.752	-38.752	-38.752	-38.752	-38.752	-38.752
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.58	-232.41	-258.23	-284.05	-309.88	-387.34
	Net	832.373	830.92	829.479	828.044	826.607	822.306

Table A17. CLC process simulation results for different air flow rates with Bituminous coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 7000/5000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7000	7000	7000	7000	7000	7000
	Al_2O_3 in the System (kg/h)	5000	5000	5000	5000	5000	5000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	82.8	82.8	82.8	82.8	82.8	82.8
	Air Reactor	96.498	289.497	385.995	482.494	578.993	688.037
	Cool air reactor exhaust	18.9963	56.9989	75.985	94.981	113.978	135.4
	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	50.577	50.577	50.577	50.577	50.577	50.577
	Reheat OC for fuel reactor	-52.192	-52.192	-52.192	-52.192	-52.192	-52.192
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-25.82	-77.46	-103.29	-129.11	-154.94	-184.12
	Net	238.12	417.4759	507.136	596.808	686.48	787.766
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	7000	7000	7000	7000	7000	7000
	Al_2O_3 in the System (kg/h)	5000	5000	5000	5000	5000	5000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	82.8	82.8	82.8	82.8	82.8	82.8
	Air Reactor	752.554	752.677	752.812	752.951	753.091	753.515
	Cool air reactor exhaust	153.029	177.277	201.524	225.772	250.02	322.764

(continued)	Cool flue gas	137.064	137.064	137.064	137.064	137.064	137.064
	Cool OC for air reactor	50.577	50.577	50.577	50.577	50.577	50.577
	Reheat OC for fuel reactor	-52.192	-52.192	-52.192	-52.192	-52.192	-52.192
	Heat steam	-69.8	-69.8	-69.8	-69.8	-69.8	-69.8
	Heat air	-206.58	-232.41	-258.23	-284.05	-309.88	-387.34
	Net	847.446	845.993	844.552	843.116	841.68	837.379

Table A18. CLC process simulation results for different air flow rates with Anthracite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5000/3000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	104.05	104.05	104.05	104.05	104.05	104.05
	Air Reactor	96.50	289.50	386.00	482.49	578.99	688.04
	Cool air reactor exhaust	19.00	56.99	75.99	94.98	113.98	135.44
	Cool flue gas	126.59	126.59	126.59	126.59	126.59	126.59
	Cool OC for air reactor	32.79	32.79	32.79	32.79	32.79	32.79
	Reheat OC for fuel reactor	-34.27	-34.27	-34.27	-34.27	-34.27	-34.27
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.12
	Net	249.03	428.37	518.05	607.72	697.39	798.72
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5000	5000	5000	5000	5000	5000
	Al_2O_3 in the System (kg/h)	3000	3000	3000	3000	3000	3000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	104.05	104.05	104.05	104.05	104.05	104.05
	Air Reactor	700.66	700.79	700.93	701.07	701.21	701.64
	Cool air reactor exhaust	155.86	180.10	204.35	228.60	252.85	325.59
	Cool flue gas	126.59	126.59	126.59	126.59	126.59	126.59
	Cool OC for air reactor	32.79	32.79	32.79	32.79	32.79	32.79
	Reheat OC for fuel reactor	-34.27	-34.27	-34.27	-34.27	-34.27	-34.27
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	809.29	807.85	806.41	804.97	803.54	799.24

Table A19. CLC process simulation results for different air flow rates with Anthracite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5200/3200 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140

	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5200	5200	5200	5200	5200	5200
	Al_2O_3 in the System (kg/h)	3200	3200	3200	3200	3200	3200
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	108.71	108.71	108.71	108.71	108.71	108.71
	Air Reactor	96.50	289.50	386.00	482.49	578.99	688.04
	Cool air reactor exhaust	19.00	56.99	75.99	94.98	113.98	135.44
	Cool flue gas	127.83	127.83	127.83	127.83	127.83	127.83
	Cool OC for air reactor	34.53	34.53	34.53	34.53	34.53	34.53
	Reheat OC for fuel reactor	-36.07	-36.07	-36.07	-36.07	-36.07	-36.07
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.12
	Net	254.88	434.22	523.89	613.57	703.24	804.57
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5200	5200	5200	5200	5200	5200
	Al_2O_3 in the System (kg/h)	3200	3200	3200	3200	3200	3200
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	108.71	108.71	108.71	108.71	108.71	108.71
	Air Reactor	728.29	728.42	728.55	728.69	728.83	729.26
	Cool air reactor exhaust	154.35	178.60	202.85	227.09	251.34	324.09
	Cool flue gas	127.83	127.83	127.83	127.83	127.83	127.83
	Cool OC for air reactor	34.53	34.53	34.53	34.53	34.53	34.53
	Reheat OC for fuel reactor	-36.07	-36.07	-36.07	-36.07	-36.07	-36.07
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	841.26	839.81	838.37	836.94	835.50	831.20

Table A20. CLC process simulation results for different air flow rates with Anthracite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 5500/3500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5500	5500	5500	5500	5500	5500
	Al_2O_3 in the System (kg/h)	3500	3500	3500	3500	3500	3500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	111.73	111.73	111.73	111.73	111.73	111.73
	Air Reactor	96.50	289.50	386.00	482.49	578.99	688.04
	Cool air reactor exhaust	19.00	56.99	75.99	94.98	113.98	135.40
	Cool flue gas	127.83	127.83	127.83	127.83	127.83	127.83
	Cool OC for air reactor	37.03	37.03	37.03	37.03	37.03	37.03
	Reheat OC for fuel reactor	-38.75	-38.75	-38.75	-38.75	-38.75	-38.75
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80

	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.12
	Net	257.71	437.06	526.73	616.40	706.07	807.36
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	5500	5500	5500	5500	5500	5500
	Al_2O_3 in the System (kg/h)	3500	3500	3500	3500	3500	3500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	111.73	111.73	111.73	111.73	111.73	111.73
	Air Reactor	728.29	728.42	728.55	728.69	728.83	729.26
	Cool air reactor exhaust	154.35	178.60	202.85	227.09	251.34	324.09
	Cool flue gas	127.83	127.83	127.83	127.83	127.83	127.83
	Cool OC for air reactor	37.03	37.03	37.03	37.03	37.03	37.03
	Reheat OC for fuel reactor	-38.75	-38.75	-38.75	-38.75	-38.75	-38.75
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	844.09	842.65	841.21	839.77	838.34	834.04

Table A21. CLC process simulation results for different air flow rates with Lignite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 3000/1000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	3000	3000	3000	3000	3000	3000
	Al_2O_3 in the System (kg/h)	1000	1000	1000	1000	1000	1000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	212.04	212.04	212.04	212.04	212.04	212.04
	Air Reactor	96.50	289.50	386.00	420.42	420.60	420.72
	Cool air reactor exhaust	19.00	56.99	75.99	98.36	122.61	150.01
	Cool flue gas	113.10	113.10	113.10	113.10	113.10	113.10
	Cool OC for air reactor	15.47	15.47	15.47	15.47	15.47	15.47
	Reheat OC for fuel reactor	-16.35	-16.35	-16.35	-16.35	-16.35	-16.35
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.10
	Net	344.13	523.48	613.15	644.13	642.73	641.09
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	3000	3000	3000	3000	3000	3000
	Al_2O_3 in the System (kg/h)	1000	1000	1000	1000	1000	1000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	212.04	212.04	212.04	212.04	212.04	212.04
	Air Reactor	420.84	420.98	421.13	421.27	421.41	421.84
	Cool air reactor exhaust	171.11	195.36	219.60	243.85	268.10	340.84

(continued)	Cool flue gas	113.10	113.10	113.10	113.10	113.10	113.10
	Cool OC for air reactor	15.47	15.47	15.47	15.47	15.47	15.47
	Reheat OC for fuel reactor	-16.35	-16.35	-16.35	-16.35	-16.35	-16.35
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	639.82	638.39	636.96	635.52	634.09	629.79

Table A22. CLC process simulation results for different air flow rates with Lignite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 3500/1500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	3500	3500	3500	3500	3500	3500
	Al_2O_3 in the System (kg/h)	1500	1500	1500	1500	1500	1500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	221.47	221.47	221.47	221.47	221.47	221.47
	Air Reactor	96.50	289.50	386.00	475.59	475.72	475.87
	Cool air reactor exhaust	19.00	56.99	75.99	95.36	119.61	147.01
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	19.83	19.83	19.83	19.83	19.83	19.83
	Reheat OC for fuel reactor	-20.83	-20.83	-20.83	-20.83	-20.83	-20.83
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.10
	Net	355.74	535.09	624.76	707.91	706.45	704.85
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	3500	3500	3500	3500	3500	3500
	Al_2O_3 in the System (kg/h)	1500	1500	1500	1500	1500	1500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	221.47	221.47	221.47	221.47	221.47	221.47
	Air Reactor	475.99	476.14	476.28	476.42	476.56	476.99
	Cool air reactor exhaust	168.10	192.35	216.60	240.88	265.09	337.84
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	19.83	19.83	19.83	19.83	19.83	19.83
	Reheat OC for fuel reactor	-20.83	-20.83	-20.83	-20.83	-20.83	-20.83
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	703.58	702.15	700.71	699.32	697.85	693.55

Table A23. CLC process simulation results for different air flow rates with Lignite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 4000/2000 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713

	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	4000	4000	4000	4000	4000	4000
	Al_2O_3 in the System (kg/h)	2000	2000	2000	2000	2000	2000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	226.51	226.51	226.51	226.51	226.51	226.51
	Air Reactor	96.50	289.50	386.00	475.59	475.72	475.87
	Cool air reactor exhaust	19.00	56.99	75.99	95.36	119.61	147.01
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	24.31	24.31	24.31	24.31	24.31	24.31
	Reheat OC for fuel reactor	-25.31	-25.31	-25.31	-25.31	-25.31	-25.31
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.10
	Net	360.77	540.11	629.79	712.93	711.48	709.88
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	4000	4000	4000	4000	4000	4000
	Al_2O_3 in the System (kg/h)	2000	2000	2000	2000	2000	2000
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	226.51	226.51	226.51	226.51	226.51	226.51
	Air Reactor	475.99	476.14	476.28	476.42	476.56	476.99
	Cool air reactor exhaust	168.10	192.35	216.60	240.88	265.09	337.84
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	24.31	24.31	24.31	24.31	24.31	24.31
	Reheat OC for fuel reactor	-25.31	-25.31	-25.31	-25.31	-25.31	-25.31
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	708.61	707.17	705.74	704.35	702.87	698.58

Table A24. CLC process simulation results for different air flow rates with Lignite coal at 100 kg/h and Fe_2O_3/Al_2O_3 at 4500/2500 kg/h

Initial values	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	100	300	400	500	600	713
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935
	Fe_2O_3 flow in the Fuel Reactor (kg/h)	4500	4500	4500	4500	4500	4500
	Al_2O_3 in the System (kg/h)	2500	2500	2500	2500	2500	2500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW)	Fuel Reactor	231.54	231.54	231.54	231.54	231.54	231.54
	Air Reactor	96.50	289.50	386.00	475.59	475.72	475.87
	Cool air reactor exhaust	19.00	56.99	75.99	95.36	119.61	147.01
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	28.78	28.78	28.78	28.78	28.78	28.78
	Reheat OC for fuel reactor	-29.79	-29.79	-29.79	-29.79	-29.79	-29.79
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-25.82	-77.47	-103.29	-129.12	-154.94	-184.10
	Net	365.79	545.14	634.81	717.96	716.50	714.90
Initial values (continued)	Coal (kg/h)	100	100	100	100	100	100
	Water (kg/h)	140	140	140	140	140	140
	Air Flow Rate (kg/h)	800	900	1000	1100	1200	1500
	Temperature of Fuel Reactor (ºC)	950	950	950	950	950	950
	Temperature of Air Reactor (ºC)	935	935	935	935	935	935

	Fe_2O_3 flow in the Fuel Reactor (kg/h)	4500	4500	4500	4500	4500	4500
	Al_2O_3 in the System (kg/h)	2500	2500	2500	2500	2500	2500
	Particle Density (kg/m³)	3200	3200	3200	3200	3200	3200
Energy balance (kW) (continued)	Fuel Reactor	231.54	231.54	231.54	231.54	231.54	231.54
	Air Reactor	475.99	476.14	476.28	476.42	476.56	476.99
	Cool air reactor exhaust	168.10	192.35	216.60	240.88	265.09	337.84
	Cool flue gas	115.40	115.40	115.40	115.40	115.40	115.40
	Cool OC for air reactor	28.78	28.78	28.78	28.78	28.78	28.78
	Reheat OC for fuel reactor	-29.79	-29.79	-29.79	-29.79	-29.79	-29.79
	Heat steam	-69.80	-69.80	-69.80	-69.80	-69.80	-69.80
	Heat air	-206.59	-232.41	-258.23	-284.06	-309.88	-387.35
	Net	713.63	712.20	710.76	709.37	707.90	703.60

Xiao Zhang is a M.S. student in the department of Mechanical Engineering & Materials Science at Washington University in St. Louis, USA. He holds a B.E. degree in Thermal Energy and Power Engineering from Chongqing University. His research interests are in the applications of computational fluid dynamics and chemical looping combustion. He plans to pursue Ph.D. at Washington University in St. Louis in January 2015.
E-mail address: xiaozhang@wustl.edu

Subhodeep Banerjee is a Ph.D. student in the department of Mechanical Engineering & Materials Science at Washington University in St. Louis, USA. He holds a B.S. degree in Aerospace Engineering from University of Michigan, Ann Arbor and a M.S. degree in Aerospace Engineering from University of Southern California. His research interests are in the application of computational fluid dynamics in the study of chemical looping combustion and wind energy.
E-mail address: sb13@wustl.edu

Ling Zhou received both M.S and PhD in fluid machinery engineering from Jiangsu University in China.His research interests are in the application of computational fluid dynamics and optimization to the study of fluid machinery, including the multiphase flow and flow visualization. He recently wasa visitor in the department of Mechanical Engineering and Materials Science at Washington University in St. Louis, USA where he worked on chemical looping combustion.
E-mail address: lingzhoo@hotmail.com

Ramesh Agarwal is the William Palm Professor of Engineering in the department of Mechanical Engineering & Materials Science at Washington University in St. Louis. He has a PhD from Stanford University. His research interests are in Computational Fluid Dynamics and Renewable Energy Systems.
E-mail address: rka@wustl.edu