

*Article*

# Simulation of Process Structure and Operating Parameters on the Efficiency of the Chemical Looping Combustion Combined with Humid Air Turbine Cycle Using Statistical Experimental Design

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**Abstract.** This study's objective is to investigate the process structure and operating variables that affect the efficiency of the CLC combined with humid air turbine (HAT) unit to produce electricity. The investigation was carried out by using the Aspen Plus program with Peng-Robinson-Boston-Mathias (PR-BM) thermodynamics properties. In this study, the process structure and operating parameters were investigated. The process structure was related to process configuration, which reflected the number of compressor stages. The operating parameters were pressure, airflow rate, and compression methods. The four investigated responses consist of LHV efficiency, power production from the air reactor, work of air compressors, and air compressor discharge temperature. The 3<sup>k</sup> factorial experimental design was employed. After that, the result was analyzed by the analysis of variance (ANOVA). The result showed that the highest LHV efficiency was at 55.87 % when seven stages of compressors were used and the operating condition was at 15 atm of pressure in the air reactor, air compression using method 3, and 61,000 kmol/hr of airflow rate. The pressure and the method of compression highly affected LHV efficiency, as shown by their p-values. The pressure had the highest effect on LHV efficiency. The high pressure provided high power production. Method 3 provided the highest discharged temperature from the air compressor, which was the reason for the high power production in the air reactor. The compression ratio of the last compressor would be 65% of the pressure in the air reactor. Moreover, the efficiency could be improved to 57.67% by increasing the loading of Ni on the oxygen carrier from 25% to 40%. The benefit of the paper will be preliminary data for operation and investment decisions on a CLC power production because this result has not yet been demonstrated.

**Keywords:** Chemical looping combustion, power generation, optimize LHV efficiency, multistage compressor operation, Ni oxygen carrier, HAT cycle.

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## 1. Introduction

The environmental crisis and natural resource depletion are key factors that stimulate the development of combustion technology. The CO<sub>2</sub> in the environment was analyzed in the study of Kiyoki for evaluating the real crisis. [1] In conventional combustion, fuel and air react with each other directly. For power generation, its system efficiency without carbon capture and storage system (CCS) is only 25%. [2] Therefore, the combustion process to produce electricity should be improved, and the process should become greener electricity production. Many power production systems have high energy conversion efficiency. The efficiency of the gas turbine combined cycle (GTCC) is 60. After the post-combustion process, efficiency is reduced by 8-10% due to the energy penalty in CO<sub>2</sub> capture operation. [3] The combined cycle of natural gas without the CCS has an efficiency of 58%. [4] However, the CCS process will reduce its efficiency by 10%. [5]

Chemical looping combustion (CLC) is a novel technology that could help the issue of CO<sub>2</sub> management. With this technology, the power generation will be environmentally friendly and be more efficient due to less energy penalty for the CCS. The CLC has two reactors connecting, air and fuel reactors. In the air reactor, metal is oxidized by the air to produce metal oxide as an oxygen carrier. The oxygen carrier is transported from the air reactor to the fuel reactor and combusted directly with fuel. The products of the combustion are heat, carbon dioxide, and steam, which is easy to separate. There are two main components in flue gas, which are CO<sub>2</sub> and H<sub>2</sub>O. The water is separated from the flue gas by condensation, and the remainder is high purity of CO<sub>2</sub>. Finally, the spent oxygen carrier is returned to regenerate in the air reactor, and the process is continued as a cycle. CLC process is a high LHV efficiency for power production. It was not pure O<sub>2</sub> needed for high combustion efficiency. It was easily CO<sub>2</sub> separation because there was only water and CO<sub>2</sub> in the flue gas. [6] CLC process that uses H<sub>2</sub> as a fuel obtained very high LHV efficiency: 63.5%. [7] The efficiency of CLC with the combined cycle is 51% and increases to 53% when increasing the temperature from 1,000 °C to 1,200 °C [8]. The multiple pressure levels of turbines which could utilize the heat in the exhaust gas from the turbine and reduce the loss of energy were investigated because of high efficiency. The maximum efficiency of Ibrahim's study was 55.2% [9], and Brandvoll's study was 55.9. [10]

Many researchers studied the operating conditions to improve system efficiency. The countercurrent gas-solid flow pattern, low moisture content of feeding biomass, the temperature of fuel reactor (> 600 °C), low pressure (<40 atm) in the fuel reactor increased the conversion of oxygen carrier [2]. From the study of Brandvoll and Bolland, the five parameters for operating the reactors were studied; temperature inlet of air and fuel, the temperature of reactors, temperature inlet to a turbine, temperature outlet from reactors, and pressure of reactor. [10] These

parameters were studied by one factor at a time approach (OFAT). The high temperature and pressure led to the high efficiency of the system. The optimum efficiency of their study was 55.9%.

Olaleye and Wang studied CLC with the HAT cycle for power production, which reached 57% LHV efficiency. [11] They investigated four effects including of 1) effect of humidified air to fuel ratio on the concentration of CO, 2) effect of fuel flow on NiO conversion, 3) effect of temperature inlet of fuel on the LHV efficiency, and 4) effect of inlet and outlet of air reactor on LHV efficiency. In the study of Basavaraja and Jayanti, 4 case studies were investigated the optimum operating condition when the fuel was changed. [12] The operating temperature of the reactor was slightly changed because of the fuel types. The use of supercritical steam for power production also increased the net efficiency of natural gas to 43.11% because this steam boiler was operated in high pressure operating condition (240 bar). In the study of Ibrahim and Rahman, the reheat cycle with a combined cycle for power production was investigated. [9] The types of gas and steam turbines were investigated by adjusting the compression ratio between 10-30 using the OFAT technique. The result indicated that the optimum compression ratio was 19, which provided the highest thermal efficiency. In the study of Jiménez, the three parameters, the turbine inlet temperature (TIT), the reduction temperature, and the pressure of the air and fuel reactor were investigated for optimization by OFAT. [13] Ishida and Jin modified the power production process to improve system efficiency. [14] The modified power generation system called CLSA had a multistage of compressors and humid air production like the HAT cycle. This improvement increased LHV efficiency to 55.1%. Ibrahim studied the types of CLC and types of oxygen carriers for power generation. [15] The results indicated that the LHV efficiency of CLC with the HAT cycle using Ni as an oxygen carrier was 56.08%. The CLC with the HAT cycle for power production was investigated. Olaleye and Wang [16] used OFAT to study 4 parameter effects including of 1) fuel inlet temperature, 2) inlet and outlet temperature of air reactor, 3) effect of humid air and Ni flow rate, and 4) effect of air to oxygen carrier ratio on LHV efficiency. Nevertheless, it could not explain the relation of all effects. All variables affected each other and could not separately investigate. Fun et al. [17, 18] studied CLC operated with combined cooling, heating, and power production (CCHP-CLC). The LHV efficiency of the process obtained 58.20% in summer and 60.34% in winter. This process was suitable for some countries that had enough different temperatures by season change. In other combination processes, the CLC with solid oxide fuel cells (SOFCs) gained very high LHV efficiency that was 63-70 % [19] because chemical energy from fuel was directly converted to electricity. SOEC was solid oxide electrolysis that high efficiency for H<sub>2</sub> production. [20] The combination of SOEC in CLC obtain 56% efficiency. [21] Power and H<sub>2</sub> were produced from this process in the same time. However, it was

operated in lab scale because high scale of SOFC and SOEC were needed.

There were some limitations to the previous study, as explained above. The CLC with the HAT cycle was high efficiency, which is suitable for all countries when compared to the CCHP-CLC system. Furthermore, it was a higher capacity than SOFC and SOEC for power production because the included SOFC and SOEC systems need scale development. The previous study investigated each variable individually or varied only one variable with constant other variables. All of the parameters that will affect each other could not separately be studied. The factorial design will solve this issue. It was a tool to design an experiment to obtain the lowest case study with systematic. For this study,  $3^k$  factorial design was used for systematically study. Even though the CLC with the HAT cycle had been studied, it was only the parameter of operation of CLC: temperature, pressure, and flowrate for CLC. The literature investigation of the compression operation of the multistage compressor in the HAT cycle that operated with the CLC process still had not been systematically studied. The HAT cycle operation was significant because it included multistage compressors and the heat exchanger network of the power plant. The workload of the compressor was critical to the LHV efficiency of the system. The operation of the HAT cycle would be investigated in this study. This study aims to perform a systematic study of the four independent input variables, which are the pressure of air reactor, number stages of air compressors, methods of air compression, and airflow rate on the LHV efficiency. The four responses consist of LHV efficiency, power production from air reactor, work of air compressors, and air compressor discharge temperature. The benefit of this work is the optimum operating condition for the highest power production by CLC with the HAT cycle. The study would lead to more understanding of how higher efficiency for power production using the CLC process could be obtained. The  $3^k$  factorial results would be represented to the connection of all factors in this process. Furthermore, it would represent the correlation of parameters and other components in the system. The well understanding of each component in the system, the more practical operation and the better development of the CLC system in the future.

## 2. Process Description

In this study, the CLC process with the HAT cycle was developed under a process simulator environment, so-called ASPEN PLUS. The study was carried out using the thermodynamics properties of the Peng- Robinson-Boston- Mathias (PR- BM) method that is suitable for handling both fluid and solid systems. The PR- BM is one type of equation of state that was modified for a more precise prediction of a multiphase system [22] and was selected in many solid-gas simulation studies. [15] Natural gas was the fuel and NiO on  $Al_2O_3$  support was the oxygen carrier. The properties of natural gas was shown in

Table 1. In this study, the operating conditions of CLC with the HAT cycle for power production were carried out, followed the Petriz- Prieto's work [15]. Their LHV efficiency case was 56.60%, while their base case efficiency was 55.88%.

Table 1. Aspen Plus model and parameters.

Thermodynamics properties		PR-BM
Ni/ $Al_2O_3$	Flow rate (kmol/hr)	48658.04
	Mol fraction (-)	0.25/0.75
	Temperature ( $^{\circ}C$ )	1350
	Pressure (atm)	1
Natural gas	Flow rate (kg/s)	14.2
	Temperature ( $^{\circ}C$ )	25
	Pressure (atm)	20
Composition of natural gas	Nitrogen	0.28
	Carbon dioxide	0.70
	Methane	89.51
	Ethane	5.92
	Propane	2.36
	n-Butane	0.40
	i-Butane	0.56
	n-Pentane	0.08
i-Pentane	0.13	
Hexane	0.06	

The process diagram was shown in Fig. 1. Air was introduced into the multistage compressors (C-101, C102, and C-103) to produce the high- pressure air and sent to the air reactor. The compressed air was the high temperature which was reduced temperature by cooling water using at the inter-cooler. Water was introduced into the inter-cooler (HX-101 and HX -102) for reduced heat from the compressed air. This reason provided the reduction of work consumption in compressors. Water received heat from the outlet of the turbine until it became the steam in the preheating section. After that, the compressed air and steam were used to produce humid air. The humid air was introduced into the air reactor.

The CLC process, including air (AR-101) and fuel reactors (FR-101), works together as a cycle. In the air reactor, metal is oxidized by high- pressure air to produce metal oxide as an oxygen carrier. The temperature inlet of metal into the air reactor has already been investigated. At 1350  $^{\circ}C$ , it is the optimum temperature to obtain the highest efficiency. The Ni and  $Al_2O_3$  are fed into the air reactor with the mole ratio of 0.25:0.75 at 1350  $^{\circ}C$ . The oxygen carrier is transported from the air reactor to the fuel reactor and is combusted with fuel. The natural gas was preheated at the preheating section. After that, natural gas was introduced into the fuel reactor. The products of the combustion are heat,  $CO_2$  and steam ( $H_2O$ ).  $H_2O$  is

separated from flue gas by condensation (CSR-101). The high pressure and high-temperature discharge gas from the air reactor and fuel reactor are sent to the turbine (TURB-101, TURB-102) for power production. The spent oxygen carrier is returned to the air reactor for regeneration.

### 3. Experimental Design

The factorial experimental design was selected to perform this parametric study to investigate the effect of all parameters with minimum cases. [23] The 3<sup>k</sup> factorial experimental design was selected to achieve the optimum output when the case studies might not behave linearly. Since pressure plays a significant role in system efficiency, the studies of the pressure effect on the CLC process were mentioned by a few research works [24], [15], and [25]. In this study, the investigation of the pressure effect was extended to include the pressure levels, number of compressor stages in the process, and methods of air compressions before feeding to the air reactor for the CLC with the HAT cycle. Four operating input variables, which were the pressure of air reactor, number of air compressor

stages, method of air compression and airflow rate, were explored. The four responses which extremely effect on LHV efficiency consist of LHV efficiency, power production from air reactor, work of air compressors and air compressor discharge temperature. There were 81 cases in total to be simulated and evaluated the outputs. Table 2 shows the values of these four input variables employed in the study.

Table 2. The values of four input variables employed in 3<sup>k</sup> factorial design.

	Name	Units	Low value	Middle value	High value
A	Pressure of air reactor	atm	5	10	15
B	Number of compressors	Number	3	5	7
C	Air compression method	-	Method 1	Method 2	Method 3
D	Air flow rate	kmol /hr	58000	59500	61000

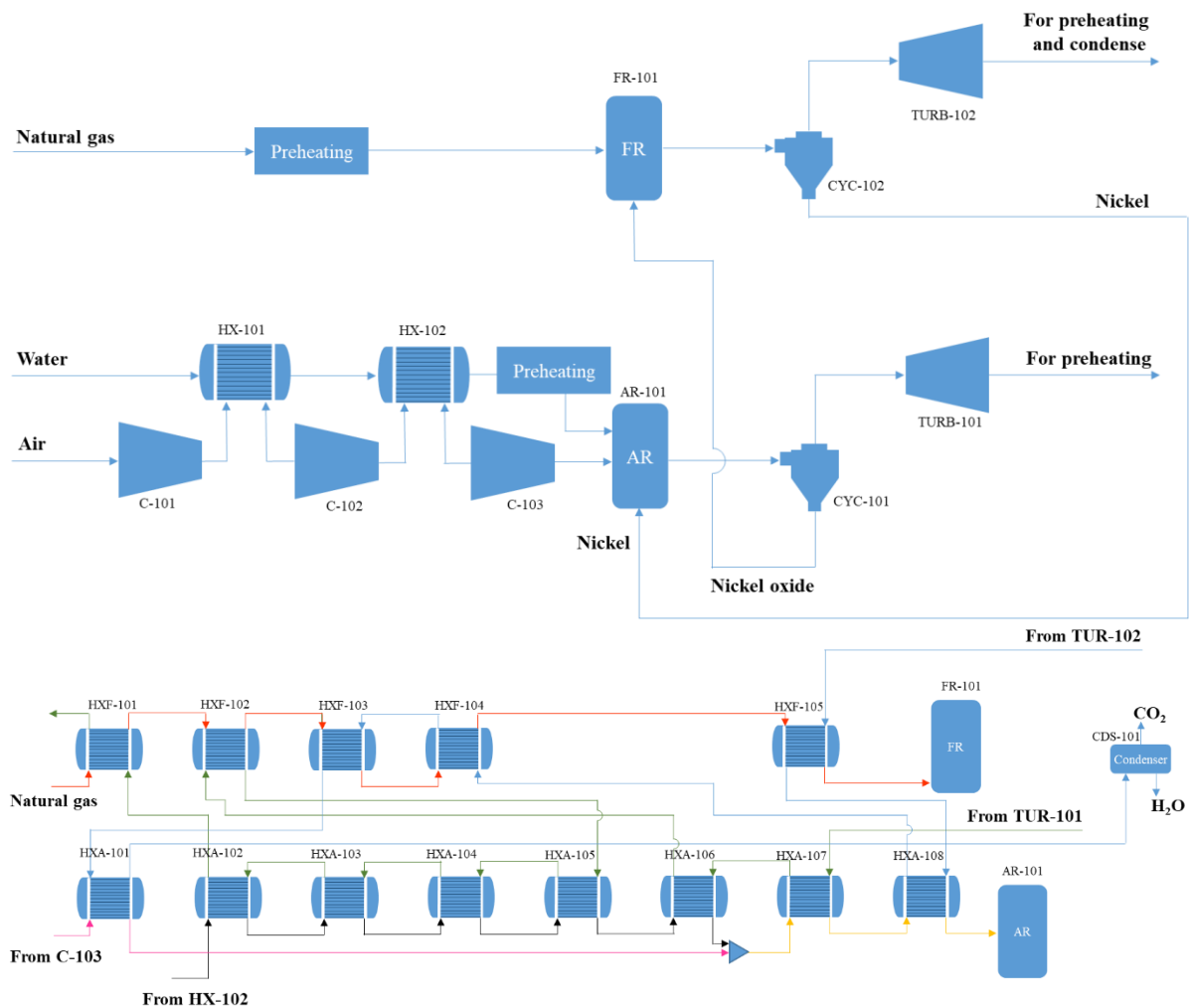


Fig. 1. The flowchart of CLC for power production system and flow chart of the preheating section.

### 3.1. LHV Efficiency

LHV efficiency shows the efficiency of the net power production system which was divided by the lower heating value of the fuel.

$$\text{LHV efficiency}(\%) = \frac{\text{Power production from air and fuel reactor (kW)} - \text{Work of air compressor (kW)} - \text{Work of water pump (kW)}}{\text{Lower heating value of fuel (kW)}} \times 100 \quad (1)$$

### 3.2. Method of Air Compression

The operation of a multistage compressor using in this kind of system has never been studied. This investigation will express the significance and effect of the operation on the efficiency. Due to the HAT cycle, many compressors are being used. The compression ratio is an important parameter of a compressor. It is the ratio of the outlet pressure to those of the input stream to the compressor.

$$\text{Compression ratio} = \frac{\text{Pressure outlet}}{\text{Pressure inlet}} \quad (2)$$

The compression ratio has the effects on the discharge temperature of the air compressor, the heat to be transferred to cooling water, and the work consumed by the air compressor. When the compression ratio is high, it implies the work supplied to the compressor is large and the outlet pressure and temperature from the compressor are also high. Typically, the compressor ratio is recommended to be less than 3 to avoid the high work consumption and high temperature of the outlet gas from the compressor [26, 27]. However, in this study, the heat in outlet gas from the compressor could utilize elsewhere in the system. Therefore, a high compression ratio might not present a negative effect, as shown in typical processes. Since the number of compressors would be installed in the system to achieve the desired pressure, there are several alternatives for setting up the compression ratio among compressors in this proposed power production system. In this study, three arrangements of air compression among the compressors installed in the system were studied their effects on the set of response variables. These arrangements are as followed:

Method 1: the pressure increase in the first compressor would be 65% of the total pressure in the air reactor; the rest of the pressure increment was distributed equally among the downstream compressors.

Method 2: the compression ratio was the same value for all compressors in the system.

Method 3: the pressure increased by the last compressor would be 65% of the pressure in the air reactor. The rest of the pressure increment was distributed equally among the upstream compressors.

## 4. Results and Discussion

The developed model of CLC with HAT cycle as indicated above was employed to investigate the effects of four independent input variables: the pressure of air reactor, the number of air compressor stages, method of air compression and airflow rate, on the LHV efficiency, power production from air reactor, work of air compressor and air compressor discharge temperature. The model was investigated according to the conditions specified in Table 2, with a 3<sup>k</sup> factorial design. There were 81 cases to be simulated. All case studies were conducted with the same thermodynamics properties and model parameters, as shown in Table 1. Their results of the simulation were summarized in Table 3. The result shows that the maximum efficiency and maximum power production are 55.87% and 503.88 MW, respectively, which correspond to simulation run numbers 81 and 75. In these two cases, three operating variables are the same: air reactor pressure at 15 atm., method 3 of air compression, an airflow rate of 61,000 kmole/hr. The different input variable is the number of compressor stages. The run numbers 75 and 81 used 3 and 7 stages of compressions, respectively.

On the contrary, the response variables that might reflect the reduction of system efficiency and power production are work consumed by compressors and the discharge temperature of the outlet gas from the compressor. The results show that the case that consumed the least power for driving compressors and the discharge temperature of the air compressor are the run numbers 16 and 7, respectively. Although these simulation cases seem to possess less parasitic power, they do not provide the maximum power production or maximum LHV efficiency for the system. Therefore, it implies that it is not straightforward to select the operating condition of these input variables to achieve optimal power production. Therefore, the effect on each output variable was investigated in detail as follows.

Table 3. Results of 3<sup>k</sup> factorial design.

	Variable 1	Variable 2	Variable 3	Variable 4	Responses			
Case	A	B	C	D	Efficiency	Power production from air reactor	Work of compressors	Temperature discharge of air compressor
No.	atm	Number	Ratio	kmol/hr	%	MW	MW	°C
1	5	3	Method 1	58000	48.188	347.113	92.700	136.34
2	10	3	Method 1	58000	52.726	433.031	147.807	207.45
3	15	3	Method 1	58000	52.512	467.154	183.376	207.46
4	5	5	Method 1	58000	48.219	347.073	92.449	136.08
5	10	5	Method 1	58000	52.754	432.978	147.560	207.45
6	15	5	Method 1	58000	52.621	467.149	182.636	207.44
7	5	7	Method 1	58000	48.226	347.067	92.399	136.03
8	10	7	Method 1	58000	52.758	432.957	147.511	207.45
9	15	7	Method 1	58000	52.642	467.149	182.491	207.45
10	5	3	Method 2	58000	48.747	349.223	91.018	161.52
11	10	3	Method 2	58000	53.962	436.384	142.763	247.62
12	15	3	Method 2	58000	55.225	479.925	177.726	306.47
13	5	5	Method 2	58000	48.695	347.893	90.041	147.05
14	10	5	Method 2	58000	53.866	433.817	140.852	226.67
15	15	5	Method 2	58000	55.142	476.607	174.975	279.14
16	5	7	Method 2	58000	48.672	347.324	89.626	140.85
17	10	7	Method 2	58000	53.822	432.712	140.046	217.62
18	15	7	Method 2	58000	55.324	475.840	172.972	252.64
19	5	3	Method 3	58000	48.930	353.106	93.659	204.24
20	10	3	Method 3	58000	54.305	445.207	149.263	320.25
21	15	3	Method 3	58000	55.655	492.339	187.228	397.18
22	5	5	Method 3	58000	48.962	353.063	93.398	203.92
23	10	5	Method 3	58000	54.335	445.151	148.999	319.89
24	15	5	Method 3	58000	55.684	492.270	186.957	396.80
25	5	7	Method 3	58000	48.968	353.053	93.346	203.86
26	10	7	Method 3	58000	54.341	445.137	148.947	319.82
27	15	7	Method 3	58000	55.690	492.258	186.905	396.73
28	5	3	Method 1	59500	48.526	351.919	95.214	138.54
29	10	3	Method 1	59500	52.814	437.663	151.839	207.44
30	15	3	Method 1	59500	51.703	466.391	188.107	207.46
31	5	5	Method 1	59500	48.557	351.884	94.965	138.29
32	10	5	Method 1	59500	52.850	437.664	151.596	207.45
33	15	5	Method 1	59500	51.814	466.385	187.348	207.44
34	5	7	Method 1	59500	48.564	351.878	94.914	138.24
35	10	7	Method 1	59500	52.861	437.660	151.515	207.46
36	15	7	Method 1	59500	51.835	466.383	187.199	207.45
37	5	3	Method 2	59500	49.114	354.238	93.541	163.09
38	10	3	Method 2	59500	54.207	442.242	146.961	250.92
39	15	3	Method 2	59500	45.388	424.686	190.374	344.93
40	5	5	Method 2	59500	49.055	352.874	92.575	148.94

	Variable 1	Variable 2	Variable 3	Variable 4	Responses			
Case	A	B	C	D	Efficiency	Power production from air reactor	Work of compressors	Temperature discharge of air compressor
No.	atm	Number	Ratio	kmol/hr	%	MW	MW	°C
41	10	5	Method 2	59500	54.140	439.912	145.081	230.47
42	15	5	Method 2	59500	54.944	480.521	180.229	279.15
43	5	7	Method 2	59500	49.029	352.288	92.165	142.88
44	10	7	Method 2	59500	54.081	438.735	144.304	221.72
45	15	7	Method 2	59500	54.360	475.216	178.889	252.64
46	5	3	Method 3	59500	49.312	358.207	96.164	204.81
47	10	3	Method 3	59500	54.598	451.246	153.307	321.08
48	15	3	Method 3	59500	55.766	498.220	192.349	398.26
49	5	5	Method 3	59500	49.344	358.164	95.905	204.50
50	10	5	Method 3	59500	54.628	451.185	153.045	320.72
51	15	5	Method 3	59500	55.792	498.133	192.085	397.89
52	5	7	Method 3	59500	49.350	358.154	95.853	204.43
53	10	7	Method 3	59500	54.634	451.172	152.993	320.65
54	15	7	Method 3	59500	55.798	498.112	192.029	397.81
55	5	3	Method 1	61000	48.798	356.302	97.745	140.94
56	10	3	Method 1	61000	52.040	436.634	156.060	207.44
57	15	3	Method 1	61000	50.899	465.667	192.838	207.46
58	5	5	Method 1	61000	48.829	356.265	97.498	140.69
59	10	5	Method 1	61000	52.094	436.630	155.692	207.45
60	15	5	Method 1	61000	51.013	465.660	192.059	207.44
61	5	7	Method 1	61000	48.833	356.239	97.448	140.65
62	10	7	Method 1	61000	52.108	436.632	155.597	207.46
63	15	7	Method 1	61000	51.036	465.663	191.907	207.45
64	5	3	Method 2	61000	49.318	358.200	96.114	165.02
65	10	3	Method 2	61000	54.070	445.741	151.388	255.53
66	15	3	Method 2	61000	54.763	488.189	189.129	318.66
67	5	5	Method 2	61000	49.276	356.961	95.161	151.20
68	10	5	Method 2	61000	53.809	442.315	149.730	236.75
69	15	5	Method 2	61000	54.029	480.001	185.925	279.15
70	5	7	Method 2	61000	49.255	356.415	94.756	145.27
71	10	7	Method 2	61000	53.677	440.742	149.057	228.74
72	15	7	Method 2	61000	53.375	474.615	184.974	252.63
73	5	3	Method 3	61000	49.478	361.870	98.701	205.55
74	10	3	Method 3	61000	54.824	456.845	157.371	321.96
75	15	3	Method 3	61000	55.843	503.882	197.490	399.36
76	5	5	Method 3	61000	49.508	361.822	98.445	205.24
77	10	5	Method 3	61000	54.851	456.775	157.116	321.62
78	15	5	Method 3	61000	55.869	503.803	197.233	399.01
79	5	7	Method 3	61000	49.515	361.814	98.393	205.18
80	10	7	Method 3	61000	54.860	456.780	157.064	321.55
81	15	7	Method 3	61000	55.875	503.791	197.179	398.93

#### 4.1. The Effect on LHV Efficiency

The power production efficiency is defined by Eq. (1). The system with high efficiency reflects the worthiness of fuel usage. The highest obtained LHV efficiency was 55.875% from case 81 at 15 atm. Compared with the study of Brandvoll and Bolland, the optimum LHV efficiency was 55.9% at 20 bars [10]. The LHV efficiency was 46.4% when the process was operated at 20 bar with the rice straw process [13]. From Table 3, if focused on the case studies with the LHV efficiency higher than 55.5%, these simulation case numbers are 21, 24, 27, 48, 51, 54, 75, 78, and 81. As observed, the similarity among these cases is that the air reactor pressure is operated at 15 atm. The method of air compression is method 3, but the airflow rate and the number of compressor stages can be varied. In other words, the airflow rate and the number of compression stages might have less affected on the system efficiency. Table 4, the analysis of variance (ANOVA), can confirm the former statement. The table indicates that air reactor pressure (A), method of air compression (C) and their interaction between air reactor pressure and method of air compression (AC) have significantly affected on the efficiency of the system, since their p-value was lower than 0.05.

It was found that the impact of both variables on efficiency is the same for methods 2 and 3, but not method 1. Air compression methods 2 and 3 provide higher system efficiency when the air reactor pressure is higher. However, method 3 provides higher system efficiency than method 2. On the contrary, air compression method

1 provides higher system efficiency up to 10 atm of air reactor pressure. Beyond this pressure, system efficiency becomes lower. The reason for method 3 and high air reactor pressure gained high efficiency is that method 3 carries out a high compression ratio in the last reactor before feeding the air to the air reactor. The outlet gas from the compressor will be at a high temperature, which enhances the capability of the gas stream to carry more water into the air reactor. The high temperature of the air reactor provided the high LHV efficiency, which was consistent with the study of Olaleye and Wang [11] and the study of Surywanshi [28]. Table 5 shows the discharge temperature of the air compressor as the function of air reactor pressure and method of compression. When the air reactor pressure is high, the discharge temperature of the air compressor is also high. Compression method 3 provides a higher discharge temperature of the air compressor than the other two methods. The different carrying capacity of the outlet compressor gas stream to carry water into the air reactor under different compression methods and reactor pressure is also shown in Table 5. At low air reactor pressure, a high quantity of water could be fed to the reactor, and all compression methods had quite the same water carrying capacity. However, with different compression methods, compression method 3 still could maintain quite higher water carrying capacity in the gas stream than the other compression methods. This higher water carrying capacity could produce more power in the system and led to higher efficiency.

Table 4. The ANOVA for the LHV efficiency.

	Sum of		Mean	F	p-value	
Variables & Interaction	Squares	df	Square	Value	Prob > F	
A-Pressure of air reactor	411.15	2	205.57	177.25	< 0.0001	significant
B-Number of compressors	1.76	2	0.88	0.76	0.4741	
C-Compression method	68.91	2	34.45	29.71	< 0.0001	significant
D-Air flow rate	1.17	2	0.59	0.51	0.6059	
AB	3.87	4	0.97	0.83	0.5103	
AC	25.01	4	6.25	5.39	0.0011	significant
AD	10.38	4	2.59	2.24	0.0788	
BC	2.53	4	0.63	0.54	0.7038	
BD	4.92	4	1.23	1.06	0.3859	
CD	6.32	4	1.58	1.36	0.2607	
Residual	55.67	48	1.16			
Cor Total	591.68	80				



Table 5. The temperature discharge of air compressor, water flow rate and temperature discharge of air turbine.

Case	Pressure (atm)	Method of air compressor	Temperature discharge of air compressor (°C)	Water flow rate (kg/hr)	Temperature discharge of air turbine (°C)
61	5	Method 1	140.65	348850.44	971.06
62	10	Method 1	207.46	247829.04	805.16
63	15	Method 1	207.45	185210.46	715.38
70	5	Method 2	145.27	349489.62	971.10
71	10	Method 2	228.74	258838.56	806.16
72	15	Method 2	252.63	206281.26	717.66
79	5	Method 3	205.18	369025.38	972.35
80	10	Method 3	321.55	301811.22	809.92
81	15	Method 3	398.93	275018.58	724.50

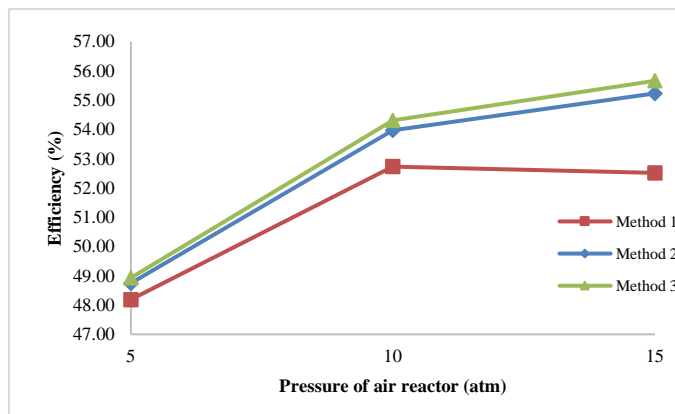


Fig. 2. The effect of the pressure of the air reactor and air compression method on LHV efficiency.

#### 4.2. The Effect on Power Production from the Air Reactor

The power is produced from passing hot gas from the fuel reactor and hot air from the air reactor through turbines and generators. The power gained from the fuel reactor was similar for all cases since the mass flow rate of the reactants fed into the fuel reactor was constant. Thus, the focus will be on the power produced by the air reactor effluent. From Table 3, it was found that simulation case number 75 has the highest power production. When focusing on the case studies with the power production higher than 500 MW, these simulation case numbers are 75, 78, and 81. The operating conditions of these simulation cases are at high air reactor pressure (A), high airflow rate (D), and method 3 of air compression (C) with any number of compression stages (B). The simulation shows that the number of compression stages does not show a significant effect on power production. Table 6 also confirms the same conclusion relating to the impact of input variables on power production. The variables A, C, D, and AC are the variables that have affected power production. The air reactor pressure, the method of

compression, and the airflow rate have affected power production. Figure 3 shows that power production increases with the increase of air reactor pressure, which was consistent with the study of Kvamsdal. Kvamsdal found that the high pressure in the air reactor provided the high efficiency of the system [29]

. It also shows the interaction between air reactor pressure and the method of compression on power production. The combination of high reactor pressure and method 3 of air compression gives the highest power production among the other combination. The reason that the system obtained high power production is related to the conditions of the air that are fed to the turbine. The above information shows the synergistic effect of the selected air reactor pressure and the proper outlet temperature resulted from the air compressor method, leading to high power production. The increase in airflow rate increases the mass inlet to the turbine. The higher mass flow rate inlet to the turbine then increases the power production from the air reactor (Fig. 4). This result was consistent with the study of Li and Shen that the increase of airflow rate increased the performance of the air reactor and CLC process [30].

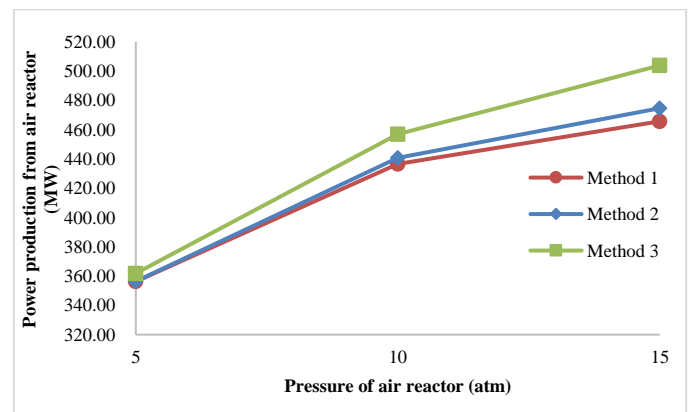


Fig. 3. The effect of the pressure of air reactor and air compression method on the power production from the air reactor.

Table 6. The ANOVA for the power production from the air reactor.

	Sum of		Mean	F	p-value	
Variables & Interaction	Squares	df	Square	Value	Prob > F	
A-Pressure of air reactor	222623.11	2	111311.55	2562.26	< 0.0001	significant
B-Number of compressors	18.24	2	9.12	0.21	0.8114	
C-Compression method	4684.68	2	2342.34	53.92	< 0.0001	significant
D-Air flow rate	728.32	2	364.16	8.38	0.0008	significant
AB	109.03	4	27.26	0.63	0.6453	
AC	1705.31	4	426.33	9.81	< 0.0001	significant
AD	269.65	4	67.41	1.55	0.2024	
BC	39.02	4	9.75	0.22	0.9234	
BD	187.98	4	46.99	1.08	0.3761	
CD	267.14	4	66.79	1.54	0.2064	
Residual	2085.25	48	43.44			
Cor Total	232717.72	80				

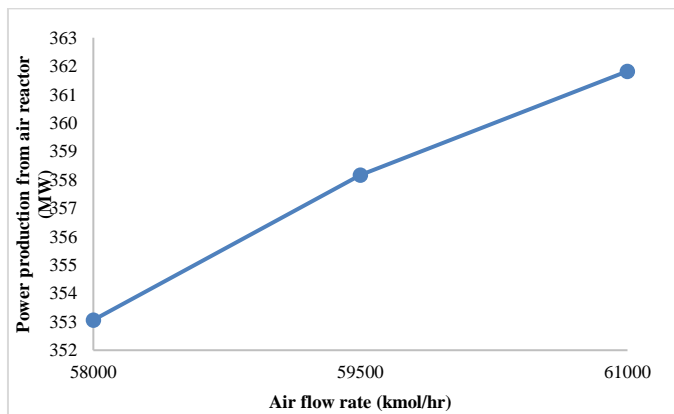


Fig. 4. The effect of airflow rate on the power production from the air reactor.

This study indicated that the high temperature obtained from method 3 provided the high temperature and the high power production from the air reactor. This result was confirmed the result of Jiménez. [13] Their result also indicated that the reactor temperature should be as high as possible for providing the high conversion of an endothermic reaction.

Detail investigation was conducted to understand what has happened in the process. The power extracted from the turbine is related to the pressures and temperature of the input stream and output streams of the turbine. The outlet pressure of the effluent from the turbine also determines the temperature of the effluent. In the simulation cases, it has shown that with the proper combination of air reactor pressure and the methods of air compression, more power can be extracted from the turbine. As mentioned before, air compression method 3 raises the temperature of the stream fed into the air reactor significantly, especially at high-pressure, compared to the other methods, as shown in Table 5. The increase of reactor temperature raises the potential to add more water

into the inlet stream of the turbine. In turn, it increases the density of the hot air before sending it to the air reactor and the turbine for power extraction, respectively. The inlet temperature of the turbine was not changed with pressure and methods of air compressor, which was kept at 1425 °C. The outlet temperatures of the turbine decrease with the increase in pressure, as shown in Table 5. The differences in inlet and outlet temperatures are more pronounced when the air reactor pressure is high. Thus, more work can be extracted by the turbine.

Moreover, to confirm the effect of water inlet in the air reactor, simulation studies were conducted with different amounts of water added to the air reactor, as shown in Table 7. The first row of data in Table 7 is the simulation result obtained from case number 81, which is the case with the highest system efficiency. The results show that the produced power decreases with the decrease of the water inlet. Subsequently, the efficiencies decrease as well. On the contrary, the work of the compressors increases, as will be described in the next section.

#### 4.3. The Effect on Work Consumed by Compressors

Typically, the work required by compressors in the system will be subtracted from the total power produced in the system. The workload of the compressor was 25.8-44.8% of power production, as calculated in Table 3. Accordingly, the investigation of compressor operation was critical to study. Thus, one normally will intend to reduce the work consumed by the compressors in the system to obtain a system with high efficiency. From the simulation result shown in Table 3, the case with the lowest work consumption of the compressors is case number 16. The work required by the compressors is 89.63 MW, while the work required by the compressors for the case number with the highest efficiency is 197.49. However, the case with the lowest work consumption of the compressors, like case number 16, is not the operating condition with the highest efficiency. Thus, to obtain the

optimum operating condition for the system, it is not straight forward. There are the numbers of operating variables that promote power production and the others demote power production. In this section, the effects of input variables on work consumed by the compressors will be described.

Table 8 shows the analysis of variance (ANOVA) when the work required by the compressors is the response of the system in Table 3. It shows that all main input variables (A, B, C, D) affect the work needed by the compressors and the interactions of AB, AC, AD, and BC also affect the work required by the compressors. From the analysis, it was found that when the number of compressors increases, the required work decreases slightly. Different air compression methods affect the compressor work. In this study, method 3 requires the highest work; method 2 requires the least work, and method 1 is in the middle of the two methods. The increase in the stage of compression decreased work consumption, which was consistent with Naqvi and Bolland's study. [8]

The analysis of the experimental design also shows that the interactions of air reactor pressure with the

number of compressors (B), compression methods (C), and airflow rate (D) affects the compressor work as shown in Fig. 5 –Fig. 7. Figure 5 shows that the compressor work increases with the increase of air reactor pressure. Compression method 3 consumed work slightly higher than the other two methods. Figure 6 shows that method 2 consumes the least energy among three arrangements due to evenly distributed pressure ratios. Furthermore, the work consumption of the compressor was lowest at the 7 stages. This result was consistent with Nyberg and Thern's work [31] in that the increase of compressor stages decreased the work consumption of air compression and increased the amount of humid. Figure 7 shows that the compressors consume more energy with increased airflow rates, consistent with Naqvi and Bolland [8] and Khan's work [32].

However, the increase of high-density airflow rates could produce more work by the turbine. Thus, in this case, there is a tradeoff between work consumed by the air compressor and more dense air to pass through the turbine to produce power.

Table 7. The effect of water fed to air reactor and turbine on the power production and efficiency of the system.

% Water flow rate of case 81	Water flow rate (kg/hr)	Power production from air reactor (MW)	Efficiency (%)	Work of compressor (MW)
100%	275,252	503.79	55.875	197.18
90%	247,726	493.33	54.290	197.67
80%	220,201	482.71	52.673	198.20
70%	192,676	472.01	51.036	198.79

Table 8. The ANOVA for the work of the compressor.

Variables & Interaction	Sum of Squares	Df	Mean Square	F Value	p-value Prob > F	
A-Pressure of air reactor	117138.38	2	58569.19	65440.75	< 0.0001	significant
B-Number of compressors	32.15	2	16.07	17.96	< 0.0001	significant
C-Compression method	702.13	2	351.07	392.25	< 0.0001	significant
D-Air flow rate	852.21	2	426.10	476.10	< 0.0001	significant
AB	11.56	4	2.89	3.23	0.02	
AC	131.79	4	32.95	36.81	< 0.0001	significant
AD	67.30	4	16.82	18.80	< 0.0001	significant
BC	32.60	4	8.15	9.11	< 0.0001	significant
BD	2.57	4	0.64	0.72	0.5836	
CD	3.90	4	0.97	1.09	0.3729	
Residual	42.96	48	0.89			
Cor Total	119017.55	80				

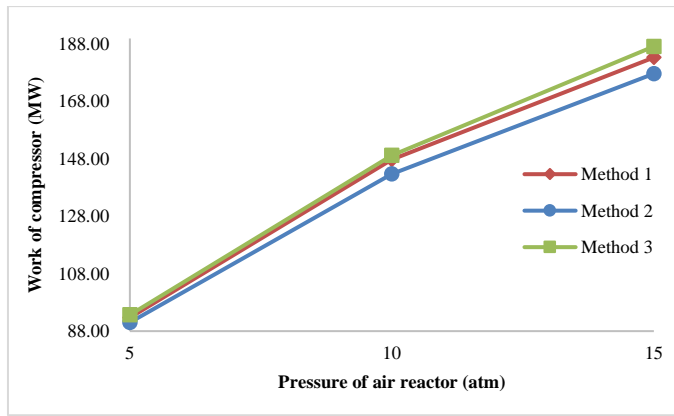


Fig. 5. The effect of the pressure of the air reactor and air compression method on the work of the compressors.

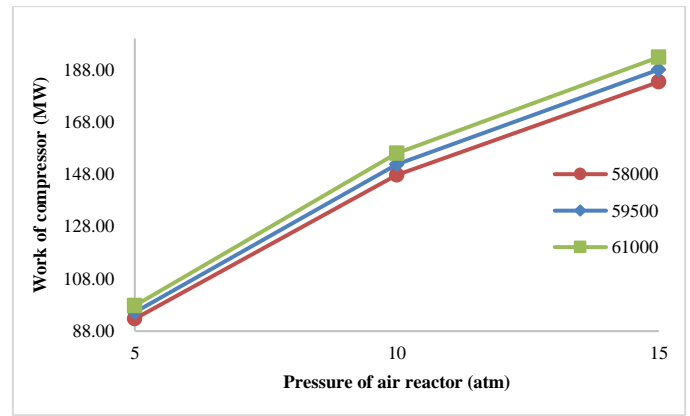


Fig. 7. The effect of the pressure of air reactor and air flow rates on the work of the compressors.

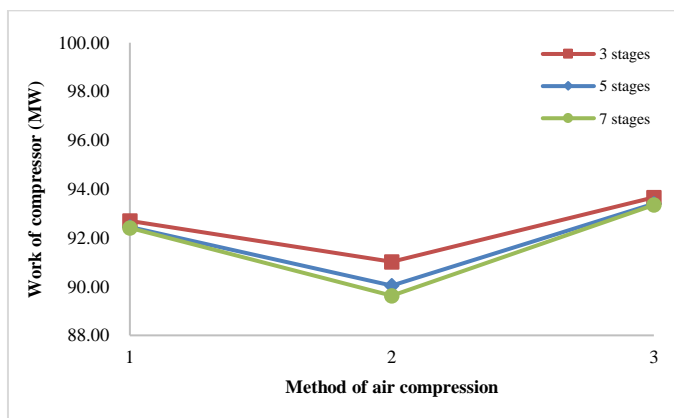


Fig. 6. The effect of the number of compressors and air compression method on the work of the compressors.

#### 4.4. Effect on Discharge Temperature of Air Compressor

The discharge temperature of the air compressor is the fourth response of the experimental design, as shown in the last column of Table 3. The simulation case number with the highest discharge temperature is case number 75 and that with the lowest discharge temperature is case number 7. The highest and lowest discharge temperatures are 399.36 and 136.03°C, respectively. The discharge temperature of the air compressor was affected by air reactor pressure (A) and the method of compression (C). On the contrary, the discharge temperature of the air compressor decreases when the number of compressors (B) increases. The airflow rates do not have an apparent effect on the discharge temperature of the air compressor.

Table 9 shows that the input variables: A, B, C, and their interactions: AB, AC, and BC have affected on discharge temperature of the air compressor. These temperatures could affect the downstream unit operation, in this study, the air reactor. The higher discharge temperature implies that the system needs less external energy supply.

Table 9. The ANOVA for the discharge temperature of the air compressor.

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
A-Pressure of air reactor	244847.52	2	122423.76	2787.98	< 0.0001	significant
B-Number of compressors	2526.75	2	1263.37	28.77	< 0.0001	significant
C-Compression ratio	214353.74	2	107176.87	2440.76	< 0.0001	significant
D-Air flow rate	146.45	2	73.23	1.67	0.1994	
AB	735.77	4	183.94	4.19	0.0055	significant
AC	35894.44	4	8973.61	204.36	< 0.0001	significant
AD	66.41	4	16.60	0.38	0.8232	
BC	4856.17	4	1214.04	27.65	< 0.0001	significant
BD	56.83	4	14.21	0.32	0.8608	
CD	96.25	4	24.06	0.55	0.7013	
Residual	2107.74	48	43.91			
Cor Total	505688.07	80				

Figures 8 – 10 show the relationship between the discharge temperature of the air compressor and input variables and their interactions. Figure 8 shows that besides the increase of the discharge temperature with the increase of the air reactor pressure, the lesser the number of staged compressors also leads to the higher discharge temperature. Typically, the higher number of staged compressors will lead to a lower discharge temperature. Air compression method 3 provides the highest discharge temperature of the air compressor among the three arrangements. However, Fig. 9 implies that the discharge temperature of the air compressor is dependent on how compression methods are arranged. Method 2 represents a typical operation. That is, the compression ratios are the same for all compressors in the system. Thus, heat from hot air exchanges to cooling water among the intercoolers in the system evenly, while this is not the case of method 1 and 3. The discharge temperature of method 3 was the highest, as shown in Fig. 10.

The higher discharge temperature led to the higher temperature of the air reactor, the higher power production and the higher net efficiency, which was consistent with the studies of Han [4] and Khan [33]. In Khan's study, the higher temperature inlet to the turbine provided higher net efficiency. [33] When the temperature inlet of the turbine was 900 and 1,200 °C, the net efficiency was 48.5 and 53%, respectively.

## 5. Further Efficiency Improvement

From Table 3, case number 81 has the highest LHV efficiency in this study. To improve the efficiency further, the researchers focused on the %Ni and %Al<sub>2</sub>O<sub>3</sub> loadings on the oxygen carrier. Huijun et al. showed that higher %Ni loading increases carbon conversion [34]. Huijun et al. and Ishida et al. demonstrated that NiO loading increases syngas consumption [34, 35]. It was found that 50% NiO loading on Al<sub>2</sub>O<sub>3</sub> obtained the highest conversion of syngas and carbon in biomass. The ratio of NiO: NiAl<sub>2</sub>O<sub>4</sub> 0.6:0.4 was rapidly reduced by H<sub>2</sub> [34].

Thus, in this study, the chemical looping systems with various compositions of Ni and Al<sub>2</sub>O<sub>3</sub> loadings on the oxygen carrier were simulated to observe the responses of system efficiency. For the base case, Ni: Al<sub>2</sub>O<sub>3</sub> was 25:75 mole ratio and Ni is fed into the air reactor at the feed rate of 908,469 kg/hr. The Ni compositions were varied from 10% to 60% Ni loading. The increase of Ni loading was done by reducing the amount of Al<sub>2</sub>O<sub>3</sub> in the oxygen carrier. Figure 11 shows the effect of %Ni loading on LHV system efficiency. It was noted that the LHV system efficiencies increased with the increases of %Ni loading from 10% to 40%. Then the LHV efficiencies started decreasing when %Ni loading was beyond 40%.

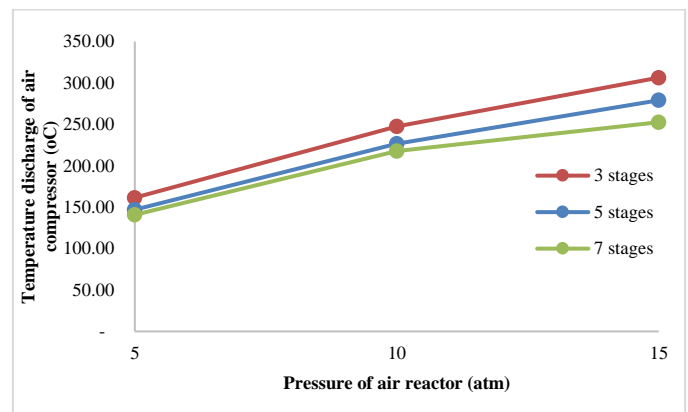


Fig. 8. The effect of the pressure of air reactor and number of compressors on discharge temperature of air compressor.

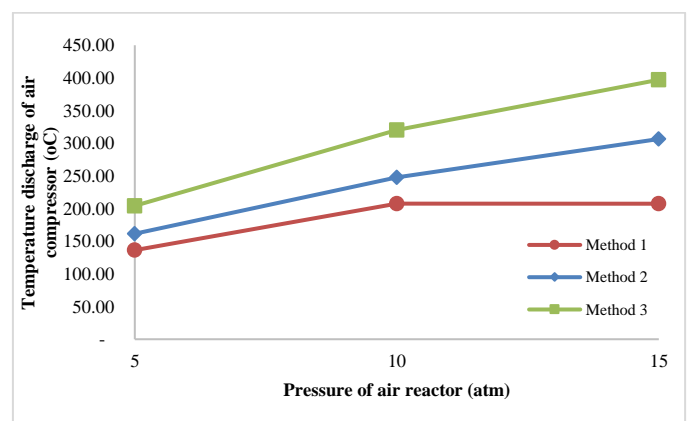


Fig. 9. The effect of the pressure of the air reactor and air compression method on the temperature discharge of air compressor.

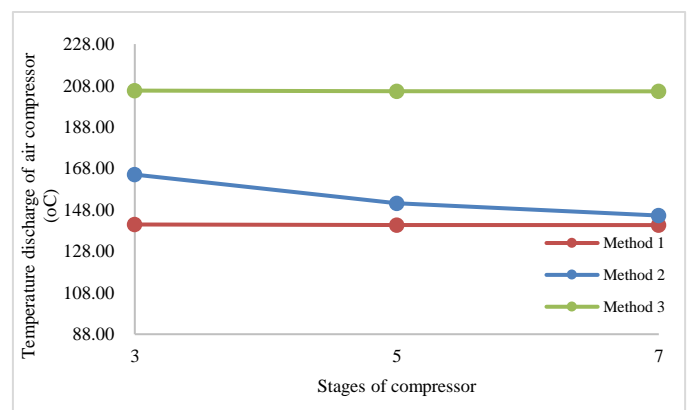


Fig. 10. The effect of the number of compressors and air compression method on the discharge temperature of the air compressor.

The change in the NiO percentage in the oxygen carrier has changed the amount of Al<sub>2</sub>O<sub>3</sub> in the oxygen carrier. Typically, Al<sub>2</sub>O<sub>3</sub> is an inert material and it acts as a supporter providing more surface for the reaction. Furthermore, the temperature of the Al<sub>2</sub>O<sub>3</sub> in the air reactor was higher than that in the fuel reactor. The Al<sub>2</sub>O<sub>3</sub>

also acted as a heat carrier from the air reactor to the fuel reactor for supporting the reaction. By increasing the amount of Ni loading, the amount of  $\text{Al}_2\text{O}_3$  in the oxygen carrier decreased and the heat transport between the two reactors became less. Consequently, the compensation for those loss heat, NiO and  $\text{Al}_2\text{O}_3$  should be fed to the fuel reactor at high temperature.

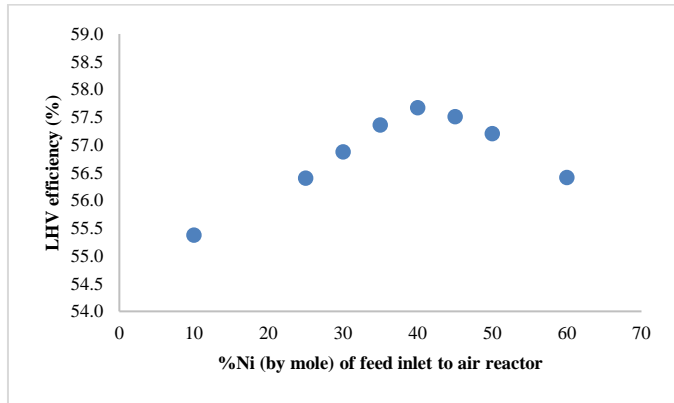


Fig. 11. The effect of % Ni loading on LHV system efficiency.

On the contrary, the temperature in the air reactor increased due to less amount of  $\text{Al}_2\text{O}_3$  to absorb excess heat from the reaction (Fig. 12). This higher temperature in the air reactor temporarily led to higher power production, as shown in Fig. 13, which led to higher efficiency. With the higher temperature, the work consumed by the compressor in the air reactor section also increased, which drag the system efficiency in the opposite direction. The other factor observed from changing Ni loading is the water absorbed in the gas fed to the air reactor and the work required by the air compressors. The water absorbed in the feed gas to the turbine was reduced with the increase of the Ni loading because the NiO and  $\text{Al}_2\text{O}_3$  will be a high temperature at a low water flow rate, even though the temperature of the air reactor had increased. The work required by air compressors increased with the %Ni loading, shown in Fig. 14. Accordingly, the % Ni beyond 40% led to a decrease in LHV efficiency. These counter effects of higher temperature of the feed gas and the lower density of the gas with more work required by the compressors on the turbine performance have shown the optimum point to be 40% Ni loading on oxygen carrier. From the investigation, it was found that the maximum LHV efficiency was 57.67% when the operating conditions are at the airflow rate of 61,000 kmol/hr, 0.4% Ni loading by a mole on oxygen carrier, the pressure of 15 atm in the air reactor, with 7 stages of compressors using method 3 for the air compression. The LHV efficiency in this study was higher than Petriz-Prieto's work [15], which was 56.08%. The air compression method and Ni percentage by mole in the oxygen carrier were explored. The Ni loading percentage of Petriz-Prieto's work was 25%, but the suitable %Ni loading observed in this study was 40%.

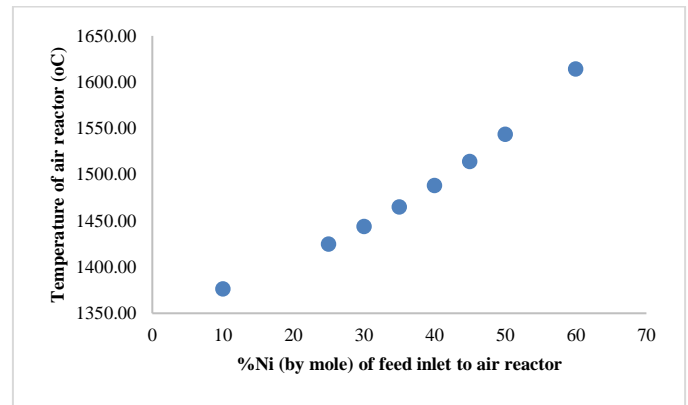


Fig. 12. The effect of % Ni loading on the temperature of the air reactor.

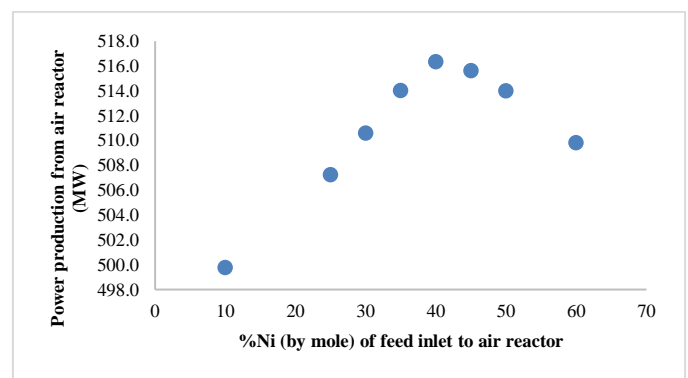


Fig. 13. The effect of %Ni loading on power production from the air reactor.

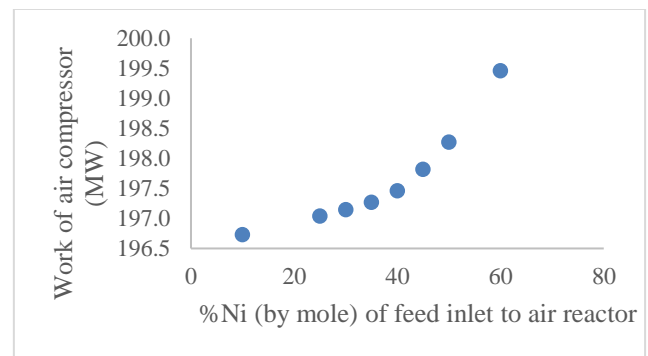


Fig. 14. The effect of %Ni loading on work of air compressor.

## 6. Conclusion

This study's objective is to investigate the process structure and the operating variables that affected the efficiency of the CLC combined with the HAT unit to produce electricity. The high LHV efficiency represented the worthiness of the use of fuel. Four operating variables; the pressure of the air reactor, number of air compressor stages, methods of air compression and airflow rate were investigated their effects on four responses; the lower



heating value (LHV) efficiency, power production from air reactor, work of air compressor and air compressor discharge temperature. The result showed that the highest LHV efficiency was at 55.87 % when 7 stages of compressors were implemented and the operating condition was at 15 atm of the pressure in the air reactor, method 3 for air compression and 61,000 kmol/hr of airflow rate. It is the first time that the HAT cycle was operated with the CLC process. Moreover, the process efficiency could be improved to 57.67% by increasing the % Ni loading by mole on the oxygen carrier from 25% to 40%.

The state of the art of this study was a deep explanation of the effect of the process structure and operating parameters. A well understanding of the CLC process with the HAT cycle then provided better efficiency improvement. The LHV system efficiency increased since the power production increased. The power production increased due to the increase of pressure and airflow rate of the air reactor and the decrease of work done by the air compressor. The increase of the pressure and airflow rate directly impacts power production since higher pressure and mass flow rate drove the turbine to produce more power. The increase in the number of air compressor stages decreased the work required by air compressors due to the heat removal between each stage within multistage air compressors. The increase of water flow rate to be mixed with air fed into the reactor increased mass flow rate to the turbine and also decreased the work required by the air compressors. The method of compression is a new parameter of CLC with a multistage compressor that was investigated in this study. Compression method 3 promoted the power production from the air reactor section because the method improved the density of the gas fed to the turbine by allowing more water to be added to the hot gas. The systematic 3<sup>k</sup> experimental design results obtain the highest LHV efficiency of CLC with the HAT cycle with minimum case studies.

## Acknowledgments

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