https://doi.org/10.36375/prepare_u.iiche.a367

[International Conference on Advances in Chemical and Material Sciences (ACMS-2022) – On the occasion of Platinum Jubilee Year of Indian Institute of Chemical Engineers]

Performance Analysis of CLC Integrated GT Power Cycle: Effect of Cycle Operating Parameters

Wasim Akram*[a], Sanjay[b], M A Hassan[c]

[a]*Mechanical Engg. Dept., National Institute of Technology Jamshedpur 831014, India*
[b,c]*Mechanical Engg. Dept., National Institute of Technology Jamshedpur 831014, India*

*****Email id- *wasimmech786@gmail.com*

Abstract

Chemical looping combustion (CLC) has emerged as a novel combustion technology for power generating stations and industrial applications with inherent CO_2 capture, which avoids energy penalty being imposed as compared to its competing technology. CLC is an indirect combustion technology taking place in two reactors namely air and fuel reactors, transfer of oxygen takes place between reactors with the help of metal oxide as an oxygen carrier. Here, hydrocarbon fuel reacts with metal oxide in the fuel reactor producing CO_2 and H_2O streams as products which subsequently expanded to a CO_2 turbine, where after the H_2O is separated by condensing and CO_2 is available for industrial purposes. Reduced metal oxides which transfer to air reactor react with O_2 (from the air) and re-oxide themselves for next subsequent cycle. The CLC system essentially replaces the gas turbine and exhibits added advantage of separating oxidation products CO_2 and H_2O (exiting fuel reactor) which is free from NOx. Depleted air (N_2 + excess O_2) exiting from the air reactor is the working fluid for the expansion turbine generating power.

This article reports the potential of a CLC integrated gas turbine-based plant as an alternative for a conventional gas turbine plant. CLC system uses CH4 as fuel and NiO as an oxygen carrier operating between 1100-1300°C to compute the performance. The performance of the CLC integrated plant is computed by varying parameters such as turbine inlet temperature (TIT), and compressor pressure ratio (r_{pc}). In the proposed cycle configuration maximum electrical efficiency achieved is 35.88% at 1450 K and r_{pc}=18.

Keywords: CLC, Oxygen carrier, Gas turbine, carbon capture, sequestration

Nomenclature

AR	Air Reactor
CLC	Chemical looping combustion
r_{pc}	Compressor pressure ratio
CO_2	Carbon dioxide
Cu	Copper
DMEA	Diethaloamine
h	Enthalpy (kJ/kg)
ΔH	Change in enthalpy
FR	Fuel reactor
C_nH_{2m}	Hydrocarbon fuel
ΔH_{red}	Heat absorbed/released during reduction (kJ)
ΔH_{oxid}	Heat absorbed/released during oxidation (kJ)
ΔH^{o}_{react}	Heat absorbed/released during reaction (kJ)
Fe	Iron
CH_4	Methane
Mn	Manganese
Me_yO_x	Metal oxide
$\dot{m}$	mass flow rate (kg/s)
MEA	Monoethaloamine
N_2	Nitrogen
NiO	Nickel oxide
Ni	Nickel
NO_x	Oxide of Nitrogen
O_2	Oxygen
p	Pressure
c_p	Specific heat (kJ/kgK)

e	exit
f	fuel
g	gas
gt	gas turbine
m	mechanical
j	number of stream
net,gt	net-work
pt	plant
p	polytropic
P	product
R	Reactant

Greek symbol

ŋ	efficiency

https://doi.org/10.36375/prepare_u.iiche.a367

1. Introduction

Modernization of society and the industrial age has been heavily dependent on the use of fossil fuels by mankind in general and its reduction or replacement to reduce greenhouse emissions for sustainable development will require extraordinary efforts [1]. Capture and sequestration of CO_2 could be the long-term solution to reduce the accumulation of greenhouse gases in the earth's atmosphere. It would help in the smooth transition of our dependency on fossil fuels to sustainable alternatives like solar energy, wind energy, tidal energy, nuclear energy, etc. Fossil fuels are still available in plenty underneath the earth's crust, and hence fossil fuel-based power utilities would continue to power the development of mankind. Fossil fuel-based power utilities account for 68% of total electricity generated today and are likely to continue to contribute around 65% by 2035 [2-3]. Removal of CO_2 from flue gas using amine-based chemical absorption method [5-6].

- Fuel de-carbonization means fossil fuel should be converted into CO_2 and H_2 and removed before being fed into the combustion chamber [7], [8].
- Oxy-combustion, which means pure oxygen has fed into a combustion chamber for combustion where nearly pure CO_2 obtained by condensing water vapor [9], [10].

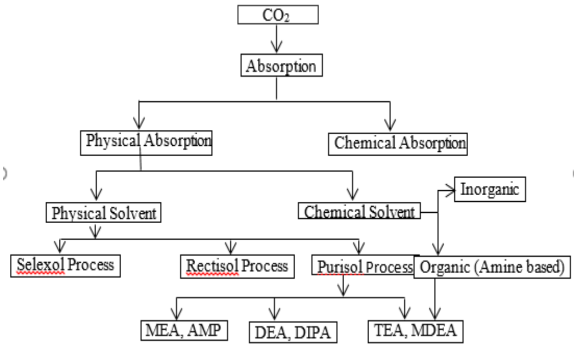

Figure 1 shows the classification of CO_2 capture technology based on the physical and chemical absorption process which further distributed based on solvents [11].

Chemical looping technology (CLC)

CLC is a novel CO_2 capture technology in which fuel is combusted without any direct contact with air, i.e. indirect combustion process[12]. CLC combustor consists of two reactors, a fuel and an air reactor as in figure 2. Transfer of oxygen takes place between the fuel reactor and air reactor with the help of an oxygen carrier. In a fuel reactor, as the name suggests, fuel is introduced in a gaseous form where it is allowed to react with an oxygen carrier i.e a metal oxide Me_yO_x. The reaction between hydrocarbon and oxygen carrier (basically a metal oxide) Me_yO_x is given as equation 1.

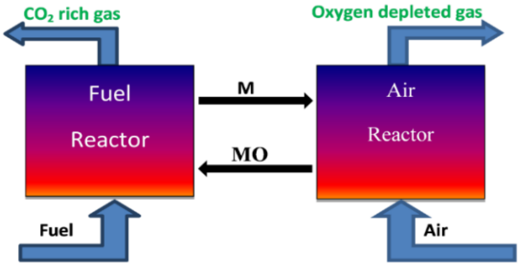

Figure 2 Schematic diagram of chemical looping combustion system

$$(2n+m)\ Me_yO_x + C_nH_{2m} \rightarrow (2n+m)\ Me_yO_{x-1} + m\ H_2O + n\ CO_2 + \Delta H_{red} \qquad (1)$$

Gases exiting the fuel reactor contain CO_2 and H_2O vapor which further can be physically separated by condensing steam, resulting in the production of a pure CO_2 stream. Metal oxide (Me_yO_x) which is reduced by reacting with hydrocarbon, and is then transferred to the air reactor where it is allowed to react with oxygen in the air and is re-oxidized for the subsequent cycle. The reaction that takes place in the air reactor is shown in equation 2.

$$Me_yO_{x-1} + 0.5\ O_2 \rightarrow Me_yO_x + \Delta H_{oxid} \qquad (2)$$

The exhaust gases coming out from the air reactor may contain any unreacted O_2 and N_2. The reduction reaction is generally endothermic as depicted in equation 1 whereas, the oxidation reaction can be both either exothermic or endothermic (equation 2). The summation of total heat evolved during the above reactions would be equal to the heat generated in conventional combustion. The advantage of the CLC system is that there is no heat loss during redox reaction and overall heat generated is equal to the heat produced during conventional combustion with the added advantage of CO_2 capture without any extra energy penalty [14]. The CLC system depicted in figure 2 can be configured in a number of ways based on types of fuels, physical and chemical characteristics of metal oxide, operating conditions, and types of reactors. Reactors can be of different configurations like fixed bed reactors, fluidized bed reactors, and pressurized bed reactors. In this article, we have adopted a fluidized bed reactor with metal oxide pneumatically transported continuously from one reactor to the other. The effectiveness of the CLC system mainly depends on the reactivity of the oxygen carrier, its oxygen-carrying capacities to name a few. Often metal oxide is used along with supporting material to enhance reactivity, reduce agglomeration and increase crushing strength which is out of scope for this article.

Table 1 Reduction and oxidation reactions of various metal oxides with their values at 25°C [14]

Metal	Type of reaction	Reaction equations	ΔH°_{react}(kJ)
Ni	RR	$4\,NiO + CH_4 \leftrightarrow CO_2 + 2\,H_2O + 4\,Ni$	175.7
	OR	$4\,Ni + 2\,O_2 \leftrightarrow 4\,NiO$	-978
Mn	RR	$12\,Mn_2O_3 + CH_4 \leftrightarrow CO_2 + 2\,H_2O + 8\,Mn_3O_4$	-379.5
	OR	$8\,Mn_3O_4 + 2\,O_2 \leftrightarrow 12\,Mn_2O_3$	-422.8
Fe	RR	$12\,Fe_2O_3 + CH_4 \leftrightarrow CO_2 + 2\,H_2O + 8\,Fe_3O_4$	230.9
	OR	$8\,Fe_3O_4 + 2\,O_2 \leftrightarrow 12\,Fe_2O_3$	-1033.2
Cu	RR	$8\,CuO + CH_4 \leftrightarrow CO_2 + 2\,H_2O + 4\,Cu_2O$	-517.5
	OR	$4\,Cu_2O + 2\,O_2 \leftrightarrow 8\,CuO$	-284.8
	Overall	$CH_4 + 2\,O_2 \leftrightarrow CO_2 + 2\,H_2O$	-802.3

Table 1 lists different oxygen carriers and their heat of reaction. It may be noted that most of the oxygen carriers except copper exhibit both endothermic and exothermic reactions in fuel reactor and air reactor respectively. In this paper, nickel oxide is used as an oxygen carrier and allowed to react with methane and the ensuring reduction reaction which takes place in the fuel reactor reduces nickel oxide (NiO) to nickel with carbon dioxide and water vapor as products of the reduction reaction. The reduction of nickel oxide is an endothermic reaction (equation 3).

$$4\,NiO + CH_4 \leftrightarrow CO_2 + 2\,H_2O + 4\,Ni - 175.7\ kJ \tag{3}$$

NiO requires 175.7 kJ of energy to combust one mole of methane. However, oxidation (in an air reactor) of any metal is an exothermic reaction that compensates heat required by an endothermic reduction reaction. Heat released during oxidation of Ni per mole of methane 978 kJ as per equation 4, so overall heat released during CLC is equal to heat liberated after combustion of 1 mole of CH_4 in a conventional combustion chamber.

$$4\,Ni + 2\,O_2 \leftrightarrow 4\,NiO + 978\ kJ \tag{4}$$

Transition metal groups are considered to be a more suitable choice for oxygen carriers in the CLC system. Also one can consider iron, copper, manganese oxide, etc. as an alternative of NiO. In this article, NiO has been considered an oxygen carrier due to its superior oxygen-carrying capacity per mole of metal. Table 2 shows oxygen-carrying capacity of various transition metal oxides per mole of metal of which NiO exhibits the highest value of oxygen-carrying capacity of 0.5. The larger value of oxygen-carrying capacity leads to that less quantity of inventory required per unit of power generated.

Table 3 Input data for CLC integrated gas turbine cycle [15]

Parameter	Symbol	Units
Ambient temperature	T_{amb} =25	°C
Gas properties	Specific heat Cp=f(T)	kJ/kg K
	Enthalpy $h = \int cp(T)\,dT$	kJ/kg
Compressor	Polytropic efficiency (η_{pc})=92.0	
	Mechanical efficiency (η_{m})=98.5	%
Lowest heating value of fuel	50000	kJ/kg
Gas turbine	Polytropic efficiency (η_{pt})=92.0	%
	Exhaust pressure =1.08	bar
	Turbine blade temperature = 1123	K
Alternator efficiency	η_{alt}= 98.5	%
Composition at reactor outlet	Chemical equilibrium	
Fuel	Methane (CH_4)	
Oxygen carrier	Ni, NiO	
Excess oxygen at air reactor	50	%

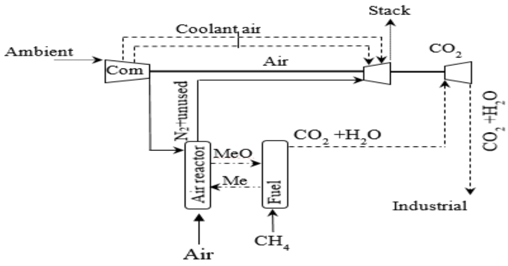

Figure 3 Schematic diagram of CLC integrated gas turbine cycle

2. System configuration

Figure 3 shows a schematic diagram of the CLC integrated gas turbine power cycle. Ambient air is ingested into the axial flow compressor and is compressed to raise its pressure and temperature. The high-pressure air is allowed to enter into the air reactor where activated metal combines with oxygen of the air to form metal oxide. This reaction is exothermic and the air (depleted of oxygen) exiting the air reactor is allowed to expand in the air turbine. The metal oxide is allowed to transport pneumatically from the air reactor to the fuel reactor where a reduction reaction between the metal oxide and fuel (methane) takes place. The products of the reduction reaction are at elevated temperature (which is lower than air exit temperature) from the air reactor and are allowed to expand in a separate expansion turbine (CO_2 turbine). The air exiting both the turbines contains significant thermal energy and may be used for district heating in a separate loop. The CO_2-rich loop (from the CO_2 turbine) after providing district heating gets cooled and may be compressed and transported for industrial use. However, it's pointed out that the thermodynamic analysis of district heating has not been considered in this paper to focus on the improvement potential of CLC. Performance of the integrated CLC-GT plant has been calculated based on the computer code written in c language for gas turbine cycle plant later extended to CLC integrated CLC system [15], [16]. Johansson et al. have reported that around 2% of the CO_2 generated in the fuel reactor goes to the air reactor along with reduced metal but this minor leakage is not considered in this paper during the calculation of power generated by gas turbine [18].

Table 1 Input data for CLC integrated gas turbine cycle [15]

3. Performance parameters

The performance of estimation of CLC integrated gas turbine-based cycle, includes $W_{net,gt}$, Work ratio (%), Wpl and η_{pl}

$$W_{net,gt} = W_{gt} - \frac{W_c}{\eta_m} \tag{19}$$

$$Work\ ratio(\%) = \frac{W_{net,gt}}{W_{gt}} * 100 \tag{20}$$

$$W_{pl} = \eta_{alt} * W_{net,gt} \tag{21}$$

$$\eta_{pl} = \frac{W_{pl}*100}{m_f*LHV} \qquad (22)$$

4. Validation of the mathematical model

The efficiency of the developed mathematical model of CLC integrated basic gas turbine cycle (BGT) have been validated with the author previous work on the BGT cycle at a specified r_{pc} and TIT of 16 and 1450 K respectively shown in table 4.

Table 4 validation of the model with the work of Sanjay et.at.[15]

Compressor pressure ratio (r_{pc})	Turbine inlet temperature (TIT)	Sanjay et.al. [14] (without CO_2 capture) Efficiency(%)	Present model (With CO_2 capture) Efficiency(%)
16	1450 K	35.81	35.95

5. Results and discussions

The influence of turbine inlet temperature on CLC integrated gas turbine-based cycle on plant performance has been computed using computer code written in C programming language. The mathematical model has been validated by the work of Sanjay et.al. [15]. Performance curves have been plotted using results obtained from modeling, governing equations, and input parameters (table 3).In the present work, the conventional combustor is replaced with a CLC reactor and its effect on the performance of the CLC integrated gas turbine-based cycle has been analyzed by varying various parameters. The results obtained have been plotted and discussed systematically as below.

5.1 Effect of compressor pressure ratio and turbine inlet temperature on specific work

Figure 4 shows a bar graph plotted between various turbine inlet temperatures and specific work at different compressor pressure ratios. It has been seen that specific work of plant increases with increasing TIT due to flue gas available at a higher temperature for work extraction. However, specific work decreases with increasing r_{pc} because increment in r_{pc} increases compression work resulting in reduced specific work. The optimum value of specific work obtained at TIT=1450 K and r_{pc}=16 is 338.34 kJ/kg.

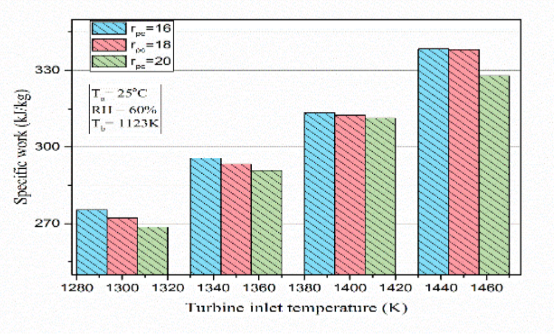

Figure 4 Effect of turbine inlet temperature and compressor pressure ratio on specific work.

5.2 Effect of compressor pressure ratio and turbine inlet temperature on work ratio: -

Effects of turbine inlet temperature and r_{pc} on work ratio for CLC integrated gas turbine plant have been shown in figure 5. It can be concluded from the bar graph that work-ratio increases with turbine inlet temperature due to a higher level of specific energy content in working fluid on account of higher TIT. At TIT of 1450 K, the maximum work ratio achieved by CLC integrated gas turbine power plant is 45.55 % (r_{pc} =16).

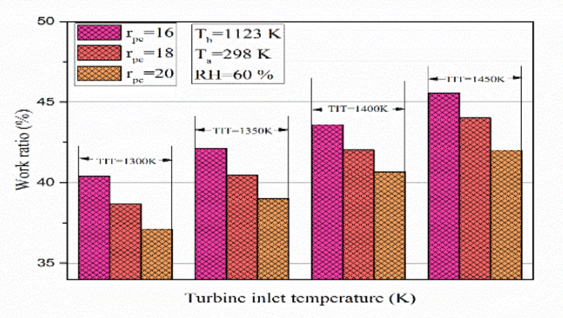

Figure 5 Effect of variation of TIT and r_{pc} on work ratio

5.3 Effect of compressor pressure ratio and turbine inlet temperature on efficiency

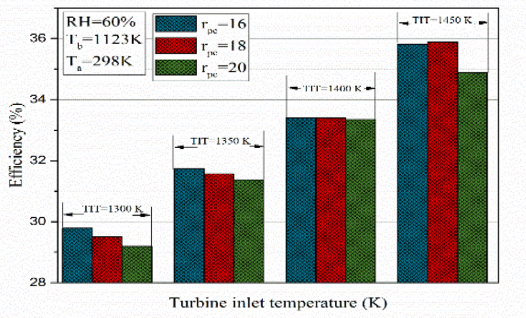

Figure 6 effect of TIT on turbine efficiency at various r_{pc}

Figure 6 depicts graph thermal efficiency for varying values of compressor pressure ratio versus turbine inlet temperature. The efficiency of the CLC integrated system increases due to an increase in specific work with increasing turbine inlet temperature of the flue gas results in higher heat content. It can be observed that the efficiency of CLC integrated gas turbine-based plant increases with increasing TIT at a constant compressor pressure ratio, the maximum efficiency achieved being 35.95% at TIT=1450 K and r_{pc}=18.

6. Conclusion

CLC integrated gas turbine-based plant has the potential to offer the best possible replacement for conventional gas turbine plants fired by fossil fuels. CLC integrated system generates electricity with minimal greenhouse emission without any extra energy penalty, since the depleted air which is the working fluid of the thermodynamic cycle separated from the combustion products. Performance of CLC integrated gas turbine configuration shows, it achieves maximum electrical efficiency of 35.88 % at TIT=1450 K and r_{pc}=18 which is comparable with conventional gas turbine configuration capturing CO_2 (both chemical and physical capture technologies). The maximum specific work obtained from the CLC integrated GT system is 338.34 kJ/kg whereas the maximum work ratio obtained from the above cycle is 45.55 % (r_{pc} =16) at 1450 K

References

[1] R. H. Williams, “Toward zero emissions for transportation using fossil fuels,” *Transp. Res. Board, Washington, DC*, 2002.

[2] E. (Energy I. Administration), *International Energy Outlook*, vol. 0484, no. July. 2010.

[3] A. M. Ranjekar and G. D. Yadav, “Dry reforming of methane for syngas production: A review and assessment of catalyst development and efficacy,” *J. Indian Chem. Soc.*, vol. 98, no. 1, p. 100002, 2021, doi: 10.1016/j.jics.2021.100002.

[4] D. G. Chapel, C. L. Mariz, and J. Ernest, “Recovery of CO2 from Flue Gases : Commercial Trends,” *Can. Soc. Chem. Eng. Annu. Meet.*, p. 17, 1999, [Online]. Available: http://www.canadiancleanpowercoalition.com/pdf/AS10 - 2b3.pdf.

[5] S. Chakravarti, A. Gupta, and B. Hunek, “Advanced technology for the capture of carbon dioxide from flue gases,” in *First National Conference on Carbon Sequestration, Washington, DC*, 2001, vol. 2001, pp. 15–17.

[6] T. Andersen, H. M. Kvamsdal, and O. Bolland, “Gas turbine combined cycle with CO2-capture using auto-Thermal reforming of natural gas,” *Proc. ASME Turbo Expo*, vol. 2, pp. 1–8, 2000, doi: 10.1115/2000-GT-0162.

[7] G. Lozza and P. Chiesa, “Natural Gas Decarbonization to Reduce CO2 Emission From Combined Cycles: Part A�Partial Oxidation,” in *Turbo Expo: Power for Land, Sea, and Air*, 2000, vol. 78552, p. V002T04A014.

[8] T. Kiga *et al.*, “Characteristics of pulverized-coal combustion in the system of oxygen/recycled flue gas combustion,” *Energy Convers. Manag.*, vol. 38, pp. S129--S134, 1997.

[9] R. J. Allam, N. W. Ivens, C. Road, B. Road, and W. Lothian, “THROUGH OXYFUEL COMBUSTION I]! ill I1 !,” vol. I, pp. 69–74, 2003.

[10] W. Akram, Sanjay, and M. A. Hassan, “Chemical looping combustion with nanosize oxygen carrier: a review,” *Int. J. Environ. Sci. Technol.*, 2020, doi: 10.1007/s13762-020-02840-8.

[11] W. K. Lewis, E. R. Gilliland, and R. R. Paxton, “Low-Temperature Oxidation of Carbon,” *Ind. \& Eng. Chem.*, vol. 46, no. 6, pp. 1327–1331, 1954.

[12] M. Ishida and H. Jin, “A new advanced power-generation system using chemical-looping combustion,” *Energy*, vol. 19, no. 4, pp. 415–422, 1994, doi: 10.1016/0360-5442(94)90120-1.

[13] A. Lyngfelt and C. Azar, “Proceedings of minisymposium on carbon dioxide capture and storage,” 1999.

[14] S. Consonni, G. Lozza, G. Pelliccia, S. Rossini, and F. Saviano, “Chemical-looping combustion for combined cycles with CO2 capture,” *J. Eng. Gas Turbines Power*, vol. 128, no. 3, pp. 525–534, 2006, doi: 10.1115/1.1850501.

[15] Sanjay, O. Singh, and B. N. Prasad, “Thermodynamic modelling and simulation of advanced combined cycle for performance enhancement,” *Proc. Inst. Mech. Eng. Part A J. Power Energy*, vol. 222, no. 6, pp. 541–555, 2008, doi: 10.1243/09576509JPE593.

[16] A. K. Mohapatra and Sanjay, “Thermodynamic assessment of impact of inlet air cooling techniques on gas turbine and combined cycle performance,” *Energy*, vol. 68, pp. 191–203, 2014, doi: 10.1016/j.energy.2014.02.066.

[17] E. Johansson, A. Lyngfelt, T. Mattisson, and F. Johnsson, “Gas leakage measurements in a cold model of an interconnected fluidized bed for chemical-looping combustion,” *Powder Technol.*, vol. 134, no. 3, pp. 210–217, 2003, doi: 10.1016/S0032-5910(03)00125-6.

[18] J. M. Smith, *Introduction to chemical engineering thermodynamics*, vol. 27, no. 10. 1950.

[19] D. A. Lewandowski, *Combustion Chemistry*. 2018.

[20] A. H. Shapiro, *The dynamics and thermodynamics of compressible fluid flow*, no. BOOK. John Wiley \& Sons, 1953.

[21] I. G. Rice, “A comparative study of the influence of different means of cooling on the

https://doi.org/10.36375/prepare_u.iiche.a367

performance of a combined (gas and steam turbine) cycle,” *J. Eng. Gas Turbines Power*, vol. 107, no. 1, p. 243, 1985, doi: 10.1115/1.3239691.