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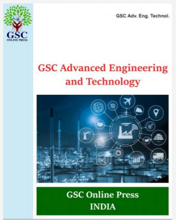

(Research Article)

Energy and exergy analysis of a simple gas turbine combined with linde cycle and N_2 injected into the compressor of the gas turbine

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Abstract

In this paper, we investigated a thermodynamic model of the regeneration gas turbine cycle with nitrogen supplied during the compression process. A suitable quantity of nitrogen that comes from the air separation cycle (Linde cycle) is injected between the stages of the compressor where it is evaporated, then the nitrogen and air mixture enters into the combustion chamber where it is burned and expanded in the turbine. We used this method to reduce greenhouse gases and improve gas turbine efficiency. In this work, we evaluated the operational data of the regeneration gas turbine cycle and the maximum amount of nitrogen that can be injected into the compressor. We also investigated the performance variation due to nitrogen spray into the compressor, and the effect of varying ambient temperature on the performance of gas turbines (thermal efficiency, power), as well as a comparison between the normal gas turbine cycle, and the remodelled compression cycle. The exergy analysis shows that the injection of the nitrogen will increase exergy destruction. The results demonstrated an 8% increase in the efficiency of the cycle, furthermore, CO_2 emission decreased by 11% when the nitrogen was injected into the compressor.

Keywords: Gas Turbine; Exergy Analysis; Exergy Destruction; Ipsepro; Linde Cycle.

Nomenclature

Cp_g	Gas specific heat at constant pressure	S	Entropy
h	Specific enthalpy	s	Specific entropy
I	Irreversibility	S_{gen}	Entropy generation
m_a	Air mass flow rate	T	temperature (K)
m_f	Fuel mass flow rate	To	Environment temperature (K)
m_g	Gas mass flow rate	φ	Exergy
m_N	Nitrogen mass flow rate	η	cycle efficiency
P	pressure	η_s	Compressor isentropic efficiency
R_g	Gas constant		

1. Introduction

Gas turbine technology is commonly used with several methods. In recent years, different modification has been used to improve gas turbine performance. Several methods show success in improving and maintaining the performance of the gas turbine cycle with steam injected at various points in the cycle [5]. For several years, the injection of steam into the combustion chamber has demonstrated a common way to improve the performance of gas turbine power plants, increasing both the efficiency and the power output due to increased mass flowing through the turbine while at the

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same time reducing NOx emissions [2,3, 4]. Emissions such as NO, CO2, O2, and HC are reduced when the engine runs with steam injection [6]. In this paper, we used the simple gas turbine with regeneration combined with the air separation cycle (Linde cycle) to reduce the emissions and increase the power output, whereas part of the nitrogen produced from the Linde cycle is injected into the compressor of the gas turbine. This redesign process shows a significant reduction in emissions. The new design pertains to all gas turbine sizes. It also can be applied as an upgrade to existing units. This process can increase efficiency to 40%, compared to about 32% for simple gas turbines. The programming of the performance model for the gas turbine was developed utilizing the software IPSEpro [7].

2. System Analysis

In May 1895, Carl von Linde performed an experiment in his laboratory in Munich that resulted in his invention of the first continuous process for the liquefaction of air based on the Joule-Thomson refrigeration effect and the principle of countercurrent heat exchange.

This idea marked the breakthrough for cryogenic air separation. For his experiment, the air was compressed from 20 to 60 bars in the compressor and cooled in the water cooler to ambient temperature. The precooled air was fed into the counter-current heat exchanger, further cooled down, and expanded in the expansion valve (Joule-Thomson valve) to liquefaction temperature. The gaseous content of the air was then warmed up again in the heat exchanger and fed into the suction side of the compressor. The hourly yield from this experiment was approximately three liters of liquid air [1]. After separation, the resulted nitrogen is divided into two parts, one part is injected into the heat exchanger to be used as a coolant and the other is injected into the compressor to enhance the performance of the cycle. After the air-nitrogen mixture is discharged from the compressor, it entered the combustion chamber where it is burned with CH4 and combustion takes place. The high-pressure gas exits the combustion chamber at a very high temperature (up to 1100°C). The exhaust gas then passes through the turbine, giving it a part of the energy to spin the compressor, the Linde cycle, and the power for a generator to produce electricity. Figure 1 shows a simplified schematic of a regeneration gas turbine with Linde air separation cycle.

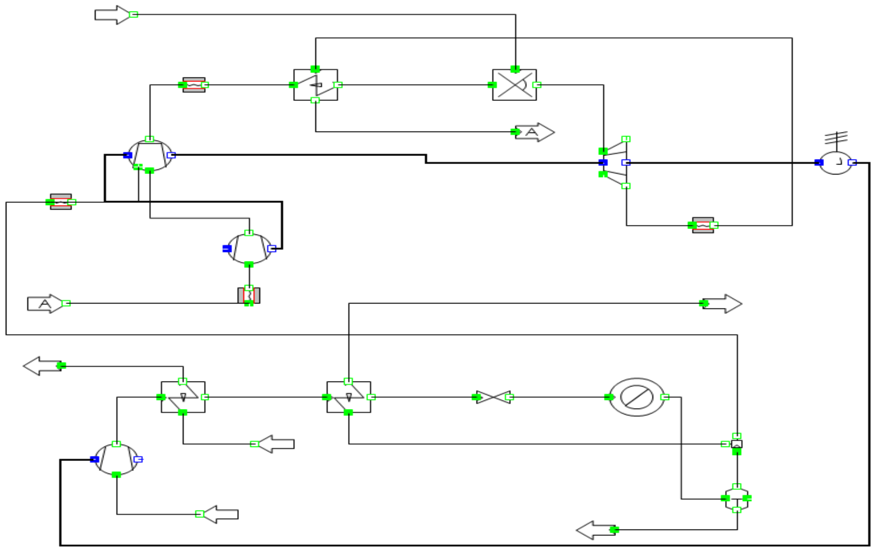

Figure 1 Simple gas turbine with Linde air separation cycle

3. Thermodynamic Analysis

This work presents energy and exergy analysis for the nitrogen injected into the compressor of the regeneration gas turbine cycle. The analysis investigated the cycle performance due to changes in the ambient temperatures and nitrogen injected flow rate.

3.1. Assumptions

The following assumptions are made to simplify the calculations however they can be refined to reach more real solutions. The main assumptions are:

Methane (CH_4) gas enters a steady-flow adiabatic combustion chamber at 25°C and 25bar.

Table 1 Design Parameters

Design Parameters	**Value**
Ambient temperature T_a	15^{o}C
Inlet pressure P_{air}	1bar
Mass of the air m_{air}	932 kg/s
The input data for the compressor	
Compressor isentropic efficiency η_s	0.87
Compressor mechanical efficiency η_m	0.98
Pressure ratio P_2/P_1	18
Pressure drop in the combustion chamber (ΔP)	0.1 bar
The input data for the turbine:	
Turbine mechanical efficiency η_m	0.99
Turbine isentropic efficiency η_s	0.9
Turbine inlet exhaust gas temperature T_{max}	1100 ºC
The characteristics of the heat exchanger are:	
The pressure drop of the hot temperature side	0.1 bar
The pressure drop of the low-temperature side	0.1 bar

4. Energy Destruction in the Gas turbine Cycle

The conventional first law analysis of any thermodynamic system determines the energy distribution across the system boundaries but does not explain the means of energy degradation that cause decreases in the power output of the system, for this reason, the second law of thermodynamics used to analyze the cycle. The exergy analyses for the gas turbine components have been performed to determine the energy loss caused by irreversible processes. Exergy analysis usually predicts the thermodynamic performance of an energy system and the efficiency of the system components by quantifying the entropy generation of the components. This analysis provides a tool for the optimal design and operation of complex thermal systems. The exergy and irreversibility equations for each component are written as follows [8],

Compressor: The exergy and irreversibility in the compressor is given by

$$\Delta\varphi = \left(\left((m_a * h_1) + (m_N * h_N)\right) - \left((m_N + m_a) * h_2\right)\right) - 298 * \left(\left((m_a * s_1) + (m_N * s_N)\right) - \left((m_N + m_a) * s_2\right)\right) \qquad (1)$$

$$I = T_0 * \left[\left((m_a + m_N) * s_2\right) - \left[(m_a * s_a) + (m_N * s_N)\right]\right] \qquad (2)$$

Combustion Chamber: As an approximation, the virtual power is used to calculate the exergy of the combustor component [8]. The exergy balance and exergy loss due to irreversibility in the combustion chamber are given by:

$$\varphi_{c.c} = Q_{in} + T_o S_{gen} \qquad (3)$$

$$I_{c\cdot c} = T_0 S_{gen} \qquad (4)$$

Where

$$S_{gen} = \left(\dot{m}_a + \dot{m}_f\right)\left(c_p ln \frac{T_3}{T_2}\right) - \frac{\dot{Q}_{in}}{T_{av}} \qquad (5)$$

And T_{av}= average (T_3, T_2)

Turbine

The exergy loss due to irreversibility in the gas turbine is given by:

$$\varphi_T = m_g(h_3 - h_4) - T_o m_g(s_3 - s_4) \qquad (6)$$

$$I_{GT} = m_g T_o (s_4 - s_3) \qquad (7)$$

where

$$(s_4 - s_3) = C_{Pg} ln \frac{T_4}{T_3} - R_g ln \frac{P_4}{P_3} \qquad (8)$$

and

$$R_g = C_{Pg} \frac{(\gamma - 1)}{\gamma} \qquad (9)$$

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5. Discussion

Based on the thermodynamic equations shown above, we displayed graphically the effect of ambient temperature on the power output, efficiency, and the destruction of exergy due to irreversibility in various components of the gas turbine, with and without nitrogen injection into the compressor. The following figures show the change in the performance of the gas turbine with changing ambient temperature. Exergy destruction is obtained from the exergy analysis. Figure 2 shows the Linde cycle compressor work increasing because of increasing air inlet into the Linde cycle.

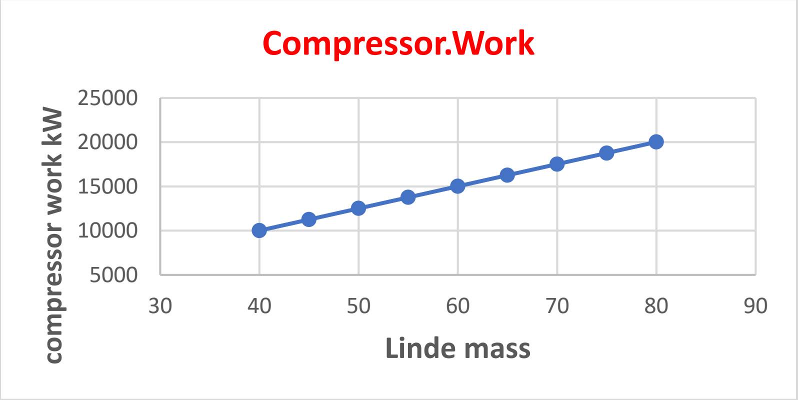


Figure 2 Linde compressor work with Linde inlet air flow rate kg/s

Figure 3 shows the variation of the cycle efficiency at a different Linde cycle inlet mass flow rate.

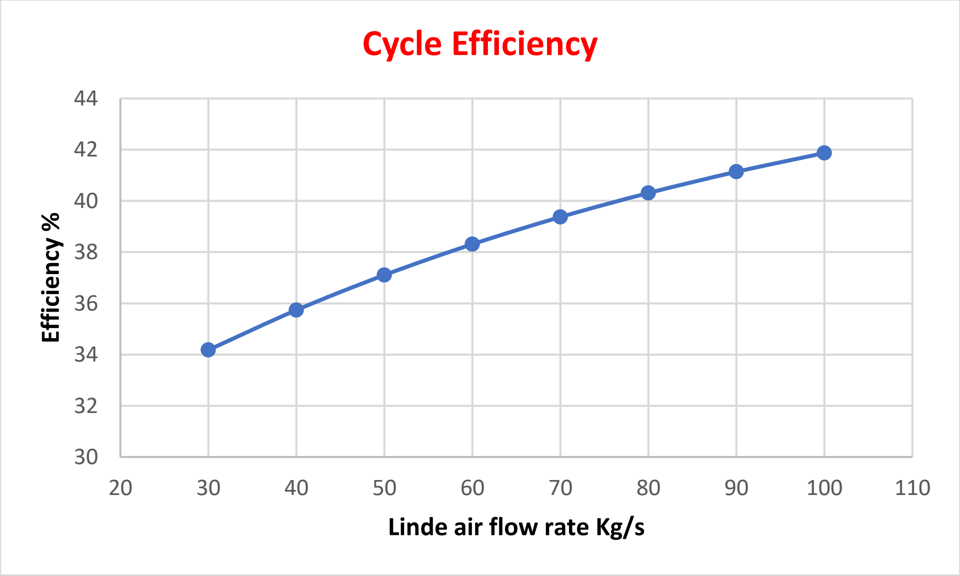


Figure 3 Cycle efficiency with Linde inlet air flow rate

The following figure shows the increase in the power output as Linde cycle inlet mass is increased.

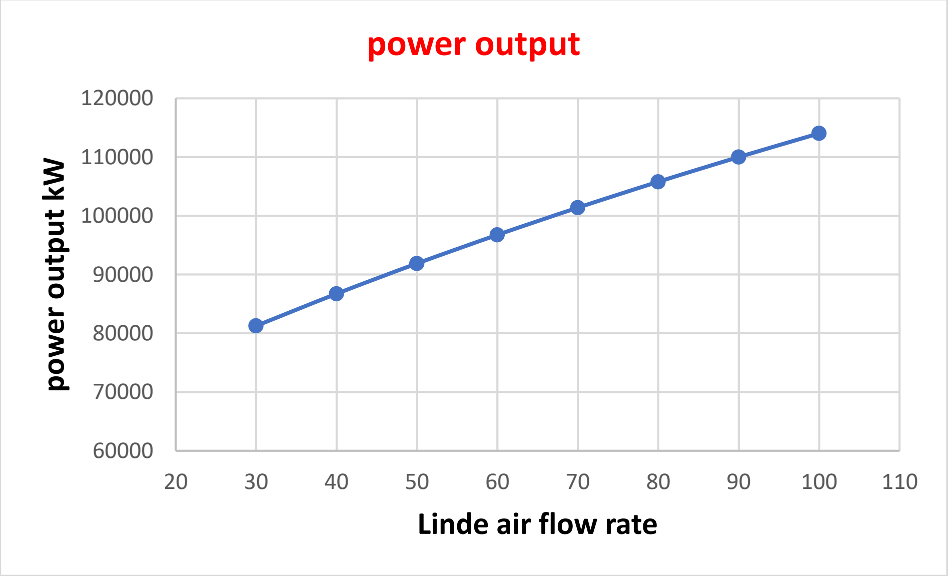


Figure 4 Cycle power output with Linde inlet air flow rate

We can see in figure 5 the effect of nitrogen injection on the cycle power output. With an increase in Linde cycle inlet air from 40 kg/s to 80 kg/s, the cycle power output reduces as the inlet flow rate increases.

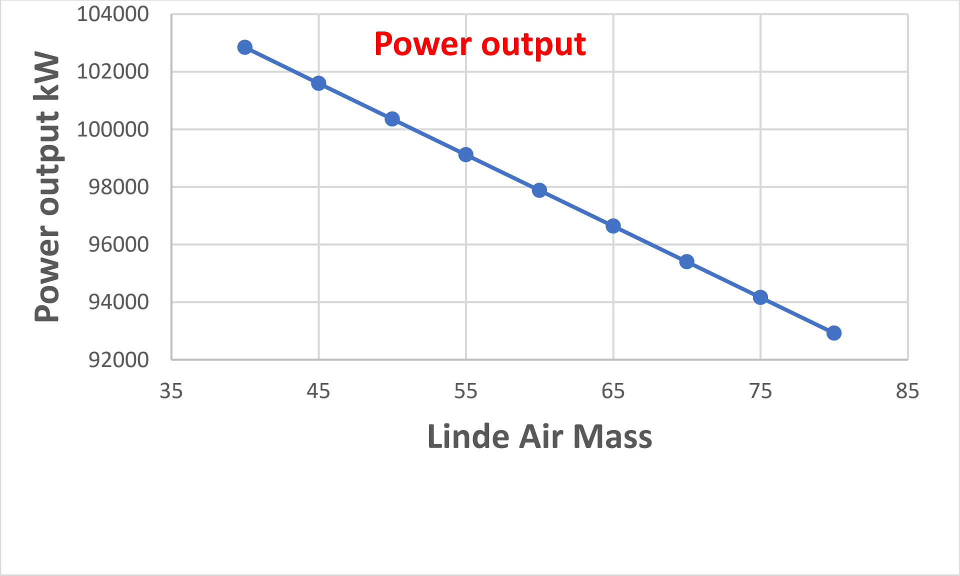


Figure 5 Cycle power output with Linde inlet air flow rate at N2= 30 kg/s

Figure 6 shows the variation of the power output with both ambient temperature and nitrogen mass injected into the gas turbine compressor. At the lowest amount of nitrogen mass (14 kg/s) the power output is lowest and as the nitrogen mass increases, the power increases. There is a similar behavior in the cycle efficiency that we can see in figure 7, as nitrogen injection increases, the cycle efficiency increases.

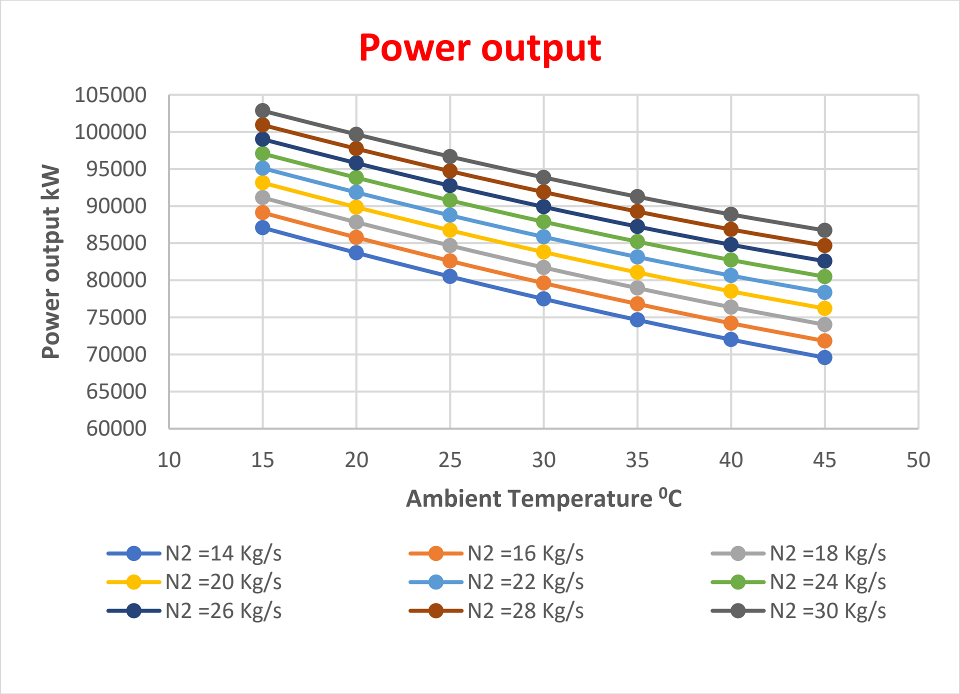


Figure 6 The power output of the cycle with ambient temperature at different Nitrogen mass flow

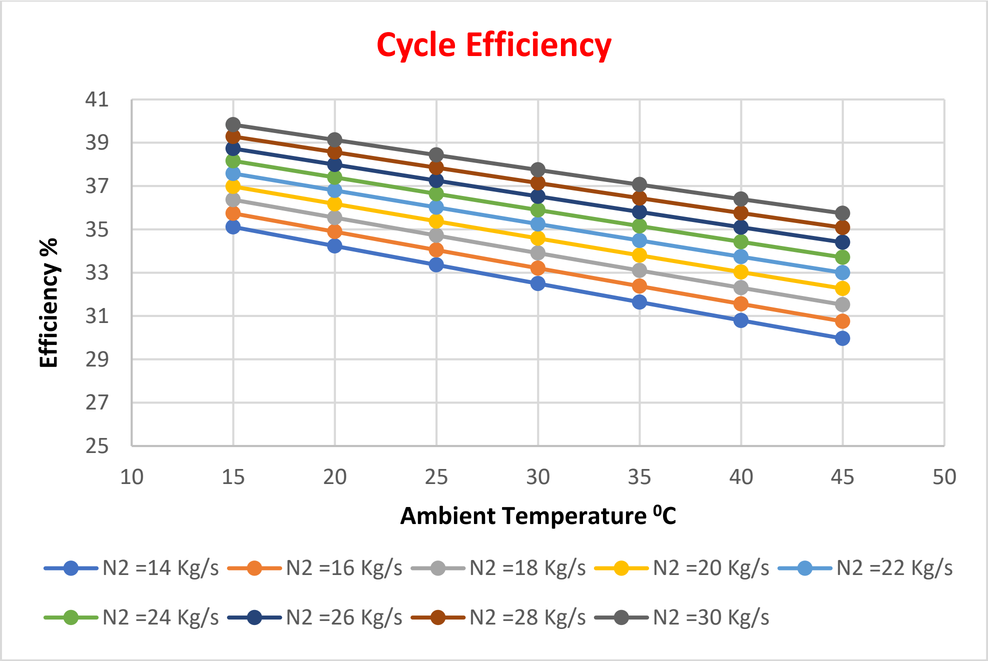


Figure 7 The efficiency of the cycle with ambient temperature at different Nitrogen mass flow

The effect of the ambient temperature on the power output of the simple cycle and the regeneration cycle injected with 30 kg/s nitrogen is shown in figure 8. This figure shows a significant increase in the power output with the use of a large amount of nitrogen injected into the compressor, thus leading to an improvement in cycle power output by 7.8 %.

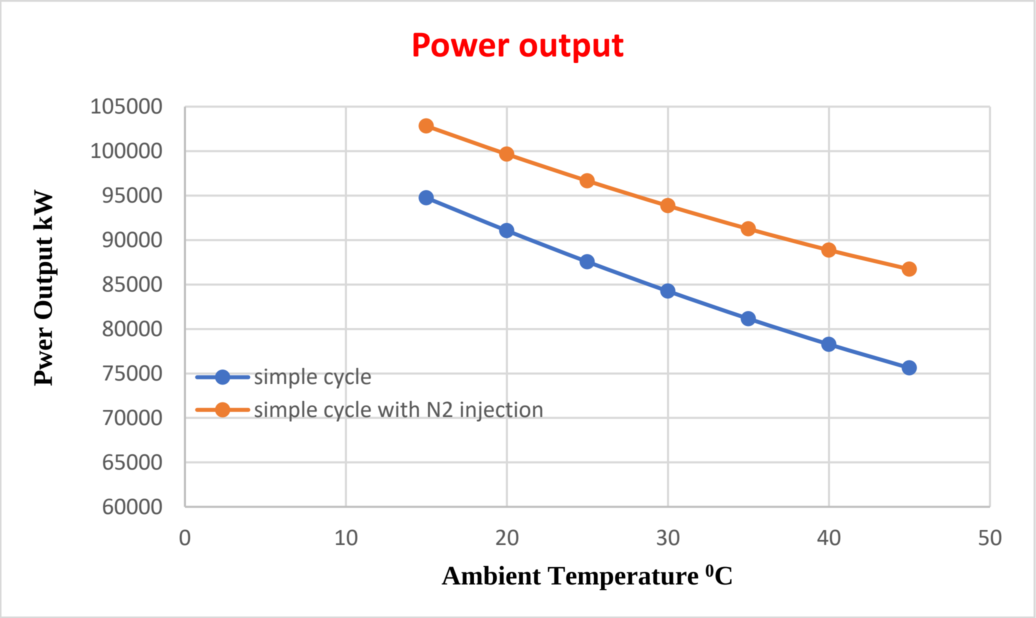


Figure 8 The power output of the simple cycle and simple cycle with N2 injection at N2 = 30kg/s with an ambient temperature

This figure shows a significant increase in cycle efficiency with the use of a large amount of nitrogen injected into the compressor which leads to an improvement in the cycle efficiency by 8 %.

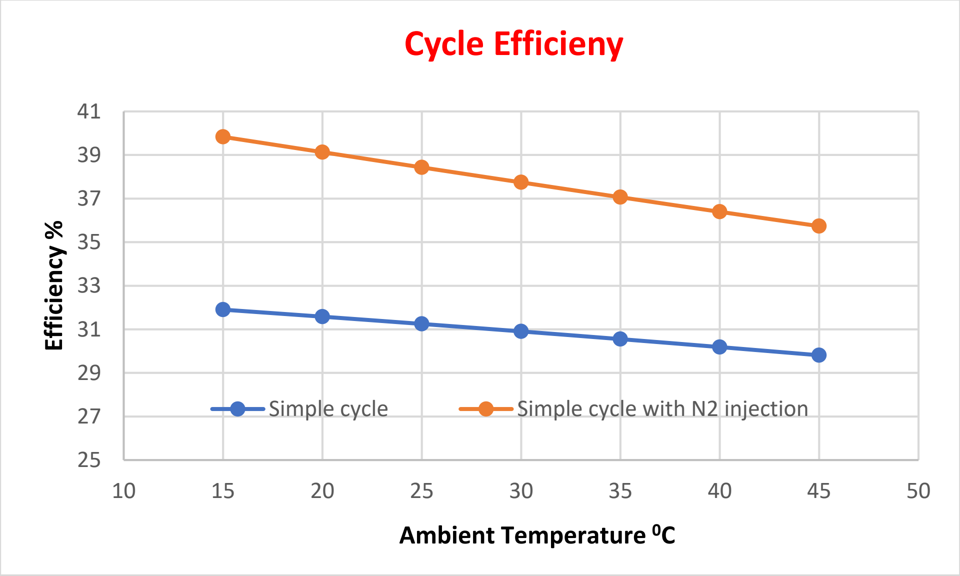


Figure 9 The efficiency of the simple cycle and combined cycle at N2 = 30kg/s with an ambient temperature

The nitrogen injected into the compressor also results in a significant reduction in the fuel flow rate. Figure 10 demonstrates the fuel consumption in two cases.

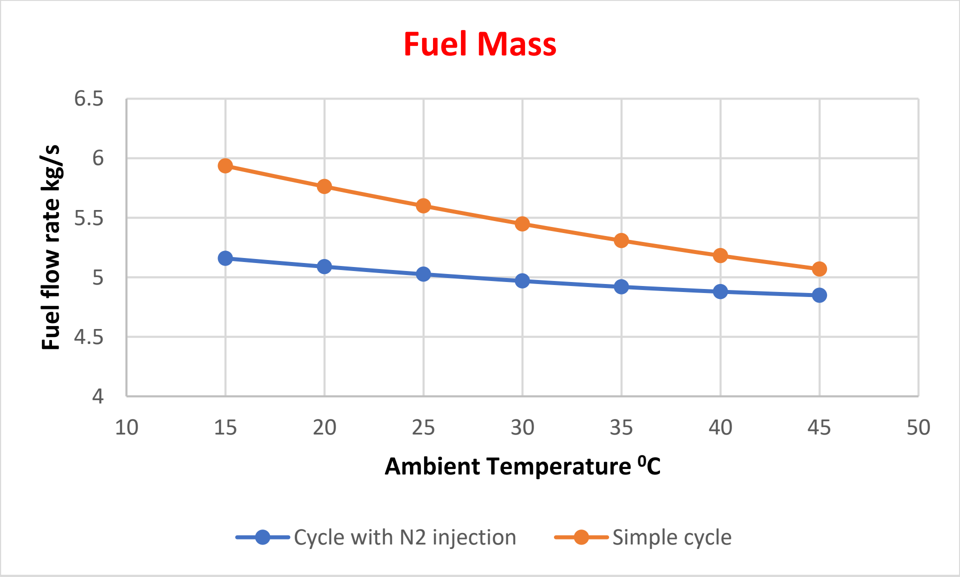
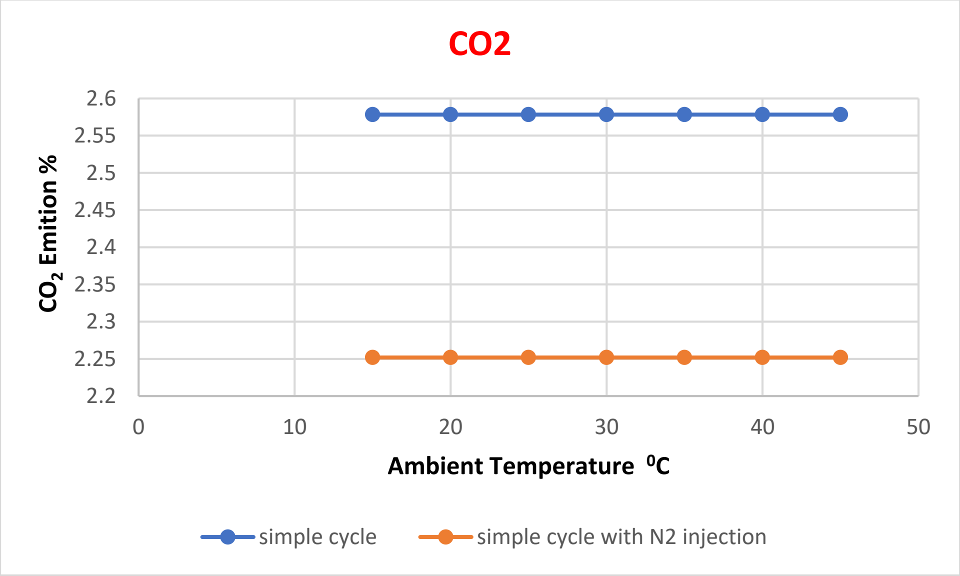


Figure 10 The efficiency of the cycle with ambient temperature at different Nitrogen mass flow

The amount of CO2 in the exhaust is affected by the nitrogen that we injected into the compressor as shown in figure 11. There is a clear effect of the nitrogen mass flow on the CO2 emission. When we injected nitrogen, the CO2 in the exhaust will be lower.



6. Conclusion

We carried out an analysis of the energy and exergy for the regeneration gas turbine combined with the air separation cycle (Linde cycle). The simulation program IPSEpro was used to successfully simulate the cycle. The power output and efficiency were highest at cooler temperatures of the day and lowest at the hottest temperatures of the day when they are needed most. We injected nitrogen between the stages of the gas turbine compressor, increasing the flow rate through the turbine. This method causes an increase in the power output of the gas turbine and an increase in electric efficiency. This gas turbine can reach an electrical efficiency of up to 40%, this improvement also came with the benefit of reducing CO2 emissions. Based on the above analysis, there are limitations on the amount of nitrogen that we can inject into the compressor, the following conclusions are made at different ambient temperature. We can improve the cycle performance as nitrogen cools the compressor. The exergy analysis gives a calculation of the losses that occur in the different cycle components. More exergy losses occur in the compressor due to irreversibility and this issue must be reduced with advanced modern technology. The optimum turbine inlet temperature and pressure ratio should be the next focus of the study for minimizing the total exergy losses in all the components.

Compliance with ethical standards

Disclosure of conflict of interest

All authors declare that no conflict of interest is exist.

References

[1] Air separation plants, “History and technological progress in the course of time”, http://www.linde-engineering.com.

[2] Bathie, W.W., ―Fundamentals of Gas Turbines‖, Second Edition, John Wiley & Sons, Inc, USA, ISBN 0-471-31122-7, 1996.

[3] Bouam A, Dadda A and Kadi R, ―Evaluation of Gas Turbine Performances and NOx and CO Emissions during the Steam Injection in the Upstream of Combustion Chamber‖, J Nucl Ene Sci Power Generat Technol 2017; Vol: 6 Issue 4.

[4] Maria Jonssona, Jinyue Yan, ―Humidified gas turbines—a review of proposed and implemented cycles‖ Energy, 2005; 30:1013–1078

[5] Massimiliano Renzi, Camilla Riolfi, Marco Baratieri, ―Influence of the Syngas Feed on the Combustion Process and Performance of a Micro Gas Turbine with Steam Injection‖, Energy Procedia, May 2017; Volume 105, Pages 16651670.

[6] P. P. Patnaik, S. K. Acharya, etc, ―Experimental investigation on CI engine performance using steam injection and ferric chloride as catalyst‖, Engineering Science and Technology, an International Journal, December 2016 Volume 19, Issue 4:Pages 2073-2080.

[7] Simulation Technology, "IPSEpro Process Simulator", Manual Version 7, 2016.

[8] Sonntag R.and Van Wylen G. ―Introduction to Thermodynamics Classical and Statistical‖ John Wiley, ISBN: 0471614270, 3rd edition, 1991.