

# Simulation of a NGCC Power Generation Plant for the Production of Electricity from CO<sub>2</sub> Emissions Part II: SNGCC Power Plant

Asfaw Gezae Daful, Zin Eddine Dadach\*

Department of Chemical and Petroleum Engineering, Higher Colleges of Technology, Abu Dhabi, UAE

Email: \*zdadach@hct.ac.ae

**How to cite this paper:** Daful, A.G. and Dadach, Z.E. (2020) Simulation of a NGCC Power Generation Plant for the Production of Electricity from CO<sub>2</sub> Emissions Part II: SNGCC Power Plant. *Journal of Power and Energy Engineering*, 8, 53-62.  
<https://doi.org/10.4236/jpee.2020.88004>

**Received:** July 13, 2020

**Accepted:** August 22, 2020

**Published:** August 25, 2020

Copyright © 2020 by author(s) and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

## Abstract

The objective of the first part of the investigation was to use Aspen Plus software and the Redlich-Kwong-Soave equation of state in order to simulate an adiabatic methanation reactor for the production of synthetic natural methane (SNG) using 1 kg/hr of carbon dioxide. In this paper, we define the Synthetic Natural Gas Combined Cycle (SNGCC) as a combined cycle power plant where the fuel is synthetic natural gas (SNG) produced by a methanation reactor. The feed of the methanation reactor is the recycled stream of carbon dioxide of a CO<sub>2</sub> capture unit treating the flue gas of the SNGCC power plant. The objective of the second part of the investigation is the utilization of Aspen plus software with SRK equation of state for the simulation of the SNGCC power plant. The metallurgical limitation of the gas turbine was fixed at 1300°C in this investigation. For effective absorption by amine solutions, the molar percentage of CO<sub>2</sub> in the flue gas should be higher than 10%. Moreover, in order to reduce technical problems linked to oxidative degradation of amine in the CO<sub>2</sub> capture plant, the percentage of O<sub>2</sub> in the flue gas should also be lower than 5%. To reach this goal, the primary air for combustion has 10% excess air (compared to stoichiometric air) and 37% of the flue gas leaving the SNGCC is recirculated as the secondary air for cooling the turbine. As a result, the concentration of CO<sub>2</sub> and O<sub>2</sub> of the flue gas entering the CO<sub>2</sub> capture unit were respectively equal to 10.2% and 2.01%. The simulation results of the SNGCC power plant indicate that 6.6 MJ of electricity are produced for each kg of carbon dioxide recycled from the CO<sub>2</sub> capture unit of the power plant. In other terms, the production of the 24.88 kg/hr of synthetic natural gas (SNG) consumes 62.36 kg/hr of recycled carbon dioxide and 16.4 kg/hr of hydrogen. The SNG produced by the methanation reactor of the power plant generates 114 kW of electricity. It is assumed in this paper that the hydrogen needed for the methanation of carbon dioxide is a product of a catalytic reforming plant that produces gasoline from heavy naphta fraction of an atmospheric distillation unit of crude oil.

---

## Keywords

Synthetic Natural Gas Combined Cycle (SNGCC)

---

### 1. Introduction

Even with the visible consequences of global warming, fossil fuels will still be the main energy sources leading to an ever-increasing amount of carbon dioxide released into the atmosphere. The use of renewable energies and Carbon capture and storage (CCS) technologies are already being utilized as ways to reduce greenhouse gas emissions. In addition to these known technologies, various techniques are also under investigation to slow down global warming by converting carbon dioxide emissions into more useful products. CO<sub>2</sub> methanation was found to be one such vital reaction of converting CO<sub>2</sub> to useful fuel, like methane, using different catalysts. The growing desire amongst some countries for independence from natural gas imports along with the growing prices for natural gas have strongly revived activities in the field of synthetic natural gas production from coal and biomass. Especially in the United States and China, huge efforts have been made to increase SNG production [1]. The produced SNG can not only be distributed in the natural gas network, but can also be stored.

As natural gas (NG) is the cleanest fossil fuel for electricity production, the Natural Gas Combined Cycle (NGCC) power generation plant is the best technology to meet the ever growing energy needs of the United Arab Emirates and reduce the country's environmental impact. However, even with the UAE's massive total of proven natural gas reserves, the country still needs to import natural gas in order to satisfy the energy market [2]. Utilizing carbon dioxide emissions for the production of synthetic natural gas (SNG) will therefore be valuable to contribute to the sustainable production of electricity in the United Arab Emirates. In a previous paper, an adiabatic methanation reactor was simulated for the production of synthetic natural methane (SNG) using 1 kg/hr of carbon dioxide [2].

The originality of this second part of the investigation is the simulation of the SNGCC (Synthetic Natural Gas Combined Cycle) power plant where the synthetic natural gas (SNG) of the methanation reactor is utilized as fuel for the power plant in order to produce electricity. The resulting flue gas emissions from the power cycle are treated in a CO<sub>2</sub> capture unit and the concentrated carbon dioxide is recycled as feed of the methanation reactor.

### 2. Methodology

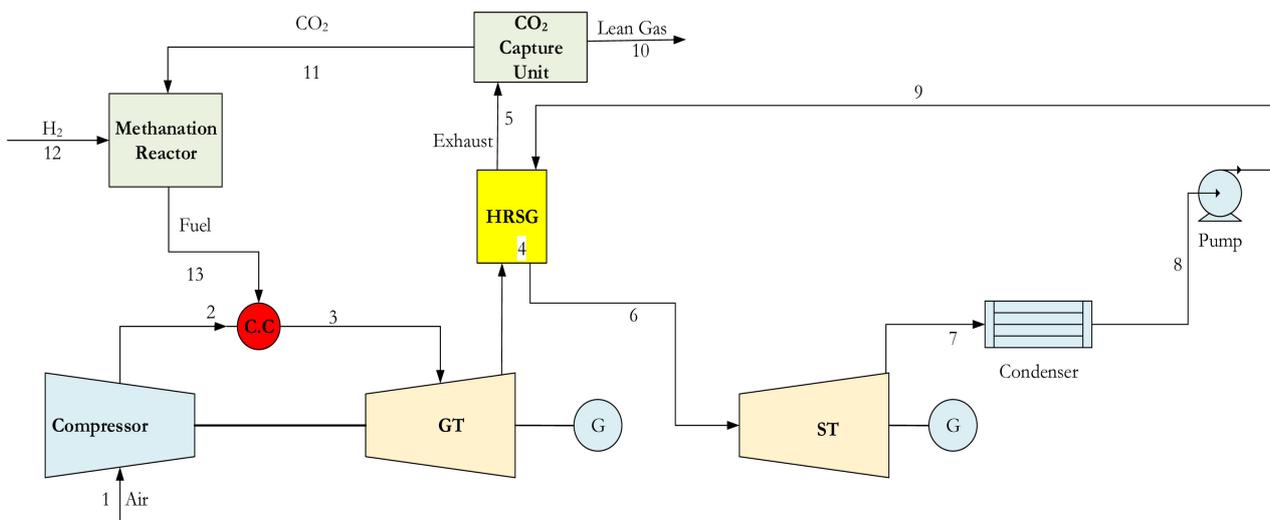
#### 2.1. Description of a Typical Synthetic Natural Gas Combined Cycle (SNGCC) Power Plant

In this paper, we define the Synthetic Natural Gas Combined Cycle (SNGCC) as

a combined cycle power plant where the fuel is synthetic natural gas produced by a methanation reactor. The feed of the methanation reactor is the recycled stream of carbon dioxide of a CO<sub>2</sub> capture unit treating the flue gas of the SNGCC. As shown in **Figure 1**, the simplified SNGCC (Synthetic Natural Gas Combined Cycle) power plant is divided into eight different control volumes: 1) Air Compressor, 2) Combustor (CC), 3) Combustion Turbine Generator (GT), 4) Steam Turbine Generator (ST), 5) Heat Recovery Steam Generator (HRSG), 6) Condenser, 7) Pump and 8) Methanation reactor.

Following the process flow diagram: 1) Fresh air enters the compressor. 2) It is then compressed to a higher pressure. Upon leaving the compressor, air enters the combustion system, where it is mixed with the Synthetic Natural Gas (13) produced by the methanation reactor where recycled carbon dioxide (11) from the carbon dioxide unit reacts with hydrogen (12). It is assumed in this paper that the hydrogen needed for the methanation of carbon dioxide is a product of a catalytic reforming plant that produces gasoline from heavy naphta fraction of an atmospheric distillation unit of crude oil.

The combustion process occurs essentially at constant pressure. The exhaust gas (3) leaves the combustor and enters the Combustion Turbine Generator (CT). In the turbine section, the flue gas is expanded to produce electricity. The flue gas leaves the CT at high temperature. This first part of the power plant is called the Open Cycle Gas turbine (OCGT). In the second part of the SNGCC, the hot stream from the gas turbine (4) will generate steam in a Heat Recovery Steam Generator (HRSG). The steam cycle consists of a HRSG, Steam Turbine Generator (ST), condenser, and pump to form a Rankine cycle for electricity production. Water (9) enters the HRSG at high pressure and the resulting steam (6) produces electricity in the steam turbine generator (ST). The saturated steam (7) leaving the steam turbine is first condensed (8) and then its pressure increased (9) before returning to the HRSG. The de-aerator of the steam cycle is



**Figure 1.** Schematic representation of a Synthetic Natural Gas Combined Cycle (SNGCC).

not included in this investigation. The exhaust gas (5) leaving the HRSG is treated in a CO<sub>2</sub> capture unit where lean gas (10) is sent to the atmosphere.

## 2.2. Preliminary Calculations

The objective of the preliminary calculations is to determine the amount of excess air needed for the combustion of the synthetic natural gas (SNG) obtained in the first part of this investigation.

### 2.2.1. Mass Flowrate of the Synthetic Natural Gas

Fresh air at ambient temperature is first compressed to 40 atm. then mixed with the synthetic natural gas (SNG) in the combustor of the gas turbine. It is assumed that combustion is complete and all the carbons in SNG convert to CO<sub>2</sub>. The operating conditions of the synthetic natural gas are shown in **Table 1**.

### 2.2.2. Stoichiometric Air

The stoichiometric combustion is a theoretical point in which the optimum amount of oxygen and fuel mix generates the most heat possible and maximum combustion efficiency is achieved. Natural gas mixes with compressed air in the combustor and it is assumed that combustion is completed and all the carbons converted to CO<sub>2</sub>. It is also assumed that only the following combustion reaction takes place in the combustor:



Knowing the value 17.2 of the mass Air-Fuel Ratio (AFR) for methane, 240.8 kg/hr. of stoichiometric air has to be added to 17.3 kg/hr. of synthetic natural gas stream for complete combustion. Moreover, for a turbine using natural gas, 10% of excess air is usually added to the stoichiometric air for combustion [3]. Excess Air (EA) is expressed as a percentage increase over the stoichiometric requirement and is defined as;

$$\text{EA} = \frac{\text{Actual AFR} - \text{Stoichiometric AFR}}{\text{Stoichiometric AFR}} \times 100\% \quad (2)$$

It is sometimes convenient to use the Excess Air Ratio (EAR) defined as:

**Table 1.** Operating conditions of the synthetic natural gas.

P (Atm)	40		
T (°C)	250		
H <sub>2</sub> : CO <sub>2</sub>	3.5		
Flow rates	kmol/hr.	kg/hr.	%mol.
CH <sub>4</sub>	1.345	21.58	94.7
H <sub>2</sub>	0	0	0
CO <sub>2</sub>	0.08	3.3	5.3
CO	4.9E-06	1.3e-04	0
Total	1.425	24.88	100

$$\text{EAR} = \frac{\text{Actual AFR}}{\text{Stoichiometric AFR}} \quad (3)$$

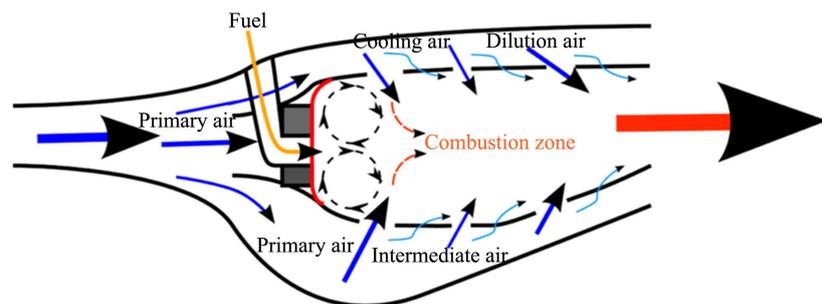
Using Equation (3) and for 10% excess air, the optimum value of the mass AFR is 18.92. The corresponding optimum mass flowrate of primary air for combustion only is 264.88 kg/hr.

### 2.2.3. Total Mass Air Needed for the Combustion

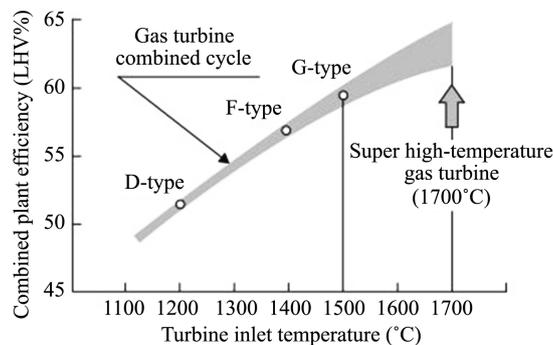
As shown in **Figure 2**, the primary air of the gas turbine is the main combustion air. This air is mixed with the synthetic natural gas (SNG) for combustion. Intermediate air is defined as the air injected into the combustion zone. This air completes the reaction processes and cools down the combustion gases. On the other hand, dilution air is injected at the end of the combustion chamber to cool down the combustion gases before they enter the turbine stages.

### 2.3. Metallurgical Limitations of the Gas Turbine

The net output of the gas turbine increases with the temperature of the exhaust gas but it is limited by the metallurgical limitation for the gas turbine being utilized. Turbine blades are subjected to stress from centrifugal force and fluid forces that can cause fracture or yielding. High temperatures could make the blades even more susceptible to failures and to corrosion. Depending on the metallurgical limitation of the blades and whether there is a cooling system, the temperature in the gas turbines could vary from 800 °C to 1700 °C. According to **Figure 3**, the NGCC type is located between the D and F types with a flue gas temperature around 1300 °C.



**Figure 2.** Different air flow paths in gas turbine [4].



**Figure 3.** Turbine inlet temperature and combined plant efficiency [5].

For effective absorption by amine solutions, the molar percentage of CO<sub>2</sub> in the flue gas should be higher than 10%. Moreover, in order to reduce technical problems linked to oxidative degradation of amine in the CO<sub>2</sub> capture plant, the percentage of O<sub>2</sub> in the flue gas should also be lower than 5%. To achieve this goal, it is supposed that the primary air (with 10% excess air for combustion) includes both the primary air and intermediate air and the secondary air is the dilution air. Part of the flue gas leaving the SNGCC is recirculated as the secondary air for cooling the turbine.

The positive effects of Flue Gas Recirculation (FGR) on the composition of the flue gas have also been investigated [6] [7] [8] [9]. Akram *et al.* [7] studied the effects of recirculating part of flue gas in a 100 KW (plus 150 KW hot water) CHP gas turbine Turbec T100. Their preliminary results indicate that a recirculation ratio of 0.45 increased the molar percentage of CO<sub>2</sub> from 1.5% to 3.0% and the molar percentage of O<sub>2</sub> decreased from 18.2% to 16.0%. Their results show also that recycling part of the flue gas decreases NO<sub>x</sub> emissions by decreasing the flame temperature. Using a natural gas-fired power plant of 700 MW, the results presented by Bolland and Saether [6] show that, using a recirculation ratio of 0.4, the molar percentage of CO<sub>2</sub> increased from 3.3% to 5.5% and the molar percentage of O<sub>2</sub> decreased from 13.8% to 9.8%.

In this study, the temperature of the combustion gases is 1923°C. Therefore, thirty seven percent (37%) of flue gas had to be recycled as secondary air in order to cool the combustion gases until 1330°C before entering the turbine. The exhaust gases leave the gas turbine at atmospheric pressure and 689°C. Notably, as a result of recycling 37% of the flue gas, the concentration of CO<sub>2</sub> and O<sub>2</sub> of the flue gas entering the CO<sub>2</sub> capture unit are respectively equal to 10.2% and 2.01%.

### 3. Results of the Simulation of the SNGCC Power Plant

As shown in **Figure 4**, a 114 kW-synthetic natural gas combined cycle (SNGCC) is simulated in this study using Aspen Plus software. The results of the simulation will be divided in the three following sections of the power plant.

#### 3.1. The Methanation Reactor

For this objective, 408.9 kg/hr of fresh air at local atmospheric conditions (40°C) is compressed up to 40 bars in a three-stage compressor with intercooling at 40°C. The adiabatic efficiency of 85% is selected for the compressors [5]. As a result, air compressor consumes 53.65 kW. For simplicity, the Carbon dioxide capture unit is simulated as a column splitter. The lean flue gas is released into the atmosphere and the 62.36 kg/hr. of Carbon dioxide (95% mol. CO<sub>2</sub>, 5% mol. H<sub>2</sub>O) is fed into the methanation reactor. The flowrate of hydrogen gas needed for the methanation of carbon dioxide is 16.4 kg/hr. After removing water, 24.88 kg/hr. of synthetic natural gas (SNG) is produced by the methanation reactor at 40 bars and 250°C.

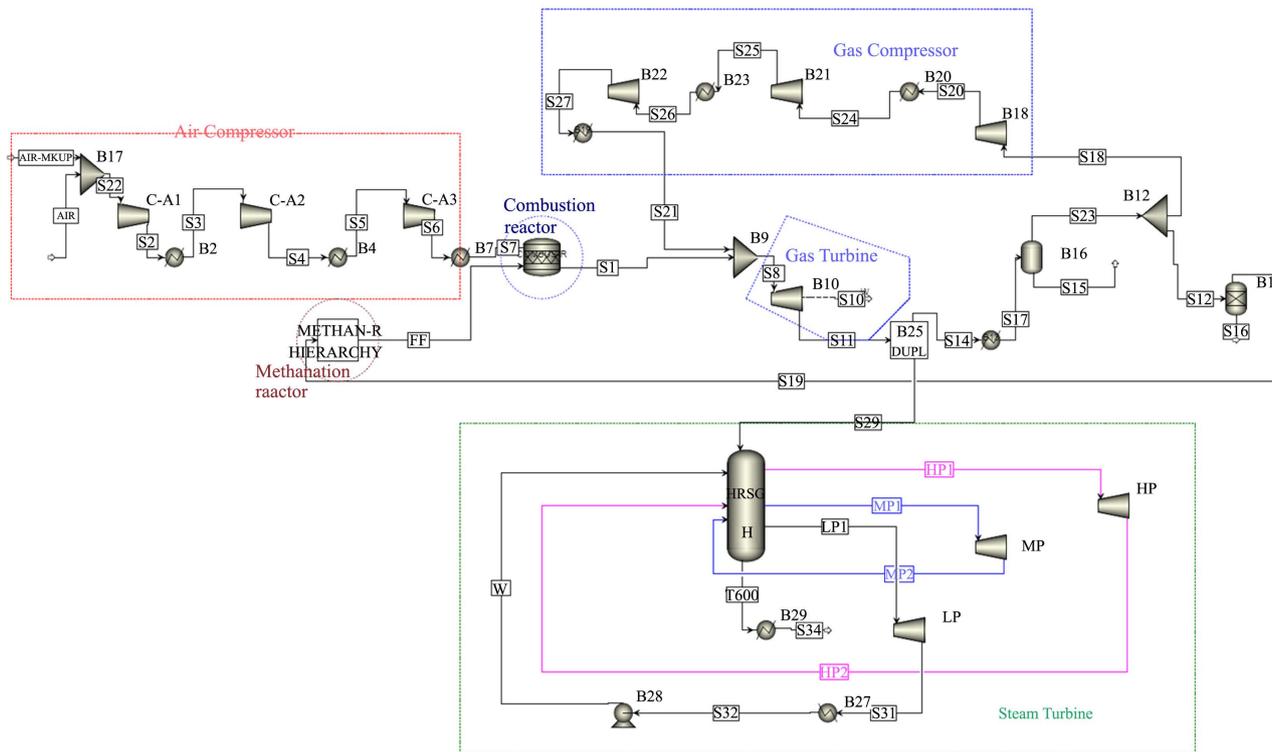


Figure 4. Aspen simulated SNGCC power plant.

### 3.2. The Gas Turbine

SNG (Synthetic Natural Gas) mixes with primary air in the combustor and it is assumed that combustion is complete and all the carbons in SNG converted to  $\text{CO}_2$ . The temperature of the combustion gases is  $1923^\circ\text{C}$ . After leaving the Heat Recovery Steam Generator (HRSG), the flue gas is cooled from  $70^\circ\text{C}$  to  $40^\circ\text{C}$  and 67% are recycled in order to be utilized as a cooling system for the gas turbine. Therefore, the pressure of the recycled flue gas is increased from 1bar to 40 bars using a three-stage compressor with intercooling at  $40^\circ\text{C}$ . For this duty, the corresponding compressor consumes 32.81 kW. Recycled cooled flue gas is mixed with the flue gas of the combustor to cool the combustion gases until  $1330^\circ\text{C}$  before entering the turbine. The Combustion Turbine produces 159.67 kW.

### 3.3. The Steam Turbine

The exhaust gases leave the gas turbine at atmospheric pressure and  $689^\circ\text{C}$ . The flue gas enters the HRSG in order to produce 135 kg/hr. of steam at three levels of pressure: high pressure (HP) steam (173 Bars,  $600^\circ\text{C}$ ), an intermediate pressure (IP) steam (65 bars,  $565^\circ\text{C}$ ), and a low pressure (LP) steam (2 bars,  $350^\circ\text{C}$ ) with double reheat. The adiabatic efficiency of the turbine, generator, and condensate pump are selected as 75%, 94%, 65% respectively [10]. The medium pressure steam (IP) is heated from  $457^\circ\text{C}$  to  $565^\circ\text{C}$  and the low pressure steam (LP) is heated from  $222^\circ\text{C}$  to  $350^\circ\text{C}$ . The power produced by the steam turbine is 8.78 kW (HP), 24.15 kW (MP) and 8.13 kW (LP).

## 4. Analysis of Results and Conclusions

In the second part of this investigation, Aspen plus software with SRK equation of state were utilized for the simulation of a Synthetic Natural Gas Combined Cycle (SNGCC). In the first section of this paper, preliminary simulation was performed in order to find the suitable percentage of the recycled flue gas for optimum conditions of the carbon capture unit of the power plant. Our results show that with a recycling 37% of the flue gas, the concentration of CO<sub>2</sub> and O<sub>2</sub> of the flue gas entering the CO<sub>2</sub> capture unit were respectively equal to 10.2% and 2.01%.

The simulation results indicate 6.6 MJ of electricity was produced for each kg of carbon dioxide recycled from the CO<sub>2</sub> capture unit of the power plant. The production of the 24.88 kg/hr of synthetic natural gas (SNG) consumed 62.36 kg/hr of recycled carbon dioxide and 16.4 kg/hr of hydrogen. The SNG produced by the methanation reactor of the power plant generated 114 kW of electricity. It is assumed in this paper that the hydrogen needed for the methanation of carbon dioxide is a product of a catalytic reforming plant that produces gasoline from the heavy naphtha fraction of an atmospheric distillation unit of crude oil.

It can be conclude that: 1) the flue gas composition with a FGR ratio of 0.37 was suitable for an effective absorption of carbon dioxide by amine solutions and 2) Limiting the temperature of the flue gas entering the gas turbine at 1330°C, the Combustion Turbine produced 159.67 kW. 3) The production of electricity from the steam turbine is respectively 8.78 kW (HP), 24.15 kW (MP) and 8.13 kW (LP). 4) The compressors for ambient air and the recycled flue gas were respectively 53.65 kW and 32.81 kW. In conclusion, the SNGCC power plant produced 6.6 MJ of electricity are produced for each kg of carbon dioxide recycled from the CO<sub>2</sub> capture unit of the power plant.

## Acknowledgements

The authors wish to thank the Higher Colleges of Technology of the UAE for supporting this research project.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

- [1] Sudiro, M. and Bertucco, A. Synthetic Natural Gas (SNG) from Coal and Biomass: A Survey of Existing Process Technologies. *Open Issues and Perspectives*.
- [2] Daful, A.G. and Dadach, Z.E. (2019) Simulation of a NGCC Power Generation Plant for the Production of Electricity from CO<sub>2</sub> Emissions Part I: The Methanation Reactor. *Journal of Power and Energy Engineering*, **7**, 1-14.  
<https://doi.org/10.4236/jpee.2019.77001>
- [3] Piper, J.E. (1999) Operations and Maintenance Manual for Energy Management.

---

Library of Congress Catalogues, 93.

- [4] Koff, B.L. (2004) Gas Turbine Technology Evolution: A Designer's Perspective. *Journal of Propulsion and Power*, **20**. <https://doi.org/10.2514/1.4361>
- [5] Ishikawa, M., Terauchi, M., Komori, T. and Yasuraoka, J. (2008) Development of High Efficiency Gas Turbine Combined Cycle Power Plant. Mitsubishi Heavy Industries, Ltd., *Technical Review*, 45.
- [6] Bolland, O. and Sæther, S. (1992) New Concepts for Natural Gas Fired Power Plants Which Simplify the Recovery of Carbon Dioxide. *Energy Conversion and Management*, **33**, 467-475. [https://doi.org/10.1016/0196-8904\(92\)90045-X](https://doi.org/10.1016/0196-8904(92)90045-X)
- [7] Akram, M., Khandelwal, B., Blakey, S. and Wilson, C.W. (2013) Preliminary Calculations on Post Combustion Carbon Capture from Gas Turbines with Flue Gas Recycle. *Proceedings of ASME Turbo Expo 2013: Turbine Technical Conference and Exposition (GT2013)*, San Antonio, 3-7 June 2013. <https://doi.org/10.1115/GT2013-94968>
- [8] Røkke, P.E. and Hustad, J.E. (2005) Exhaust Gas Recirculation in Gas Turbines for Reduction of CO<sub>2</sub> Emissions; Combustion Testing with Focus on Stability and Emissions. *International Journal of Thermodynamics*, **8**, 167-173.
- [9] Abu Zahra, M.R.M. (2009) Carbon Dioxide Capture from Flue Gas. PhD Dissertation, Delft University of Technology, The Netherlands.
- [10] Allahyari, N. (2013) Economic Evaluation of Capturing CO<sub>2</sub> from Natural Gas Power Plant and Injecting CO<sub>2</sub> for Enhanced Oil Recovery as an Integrated System. Ms. Thesis, University of Regina (Canada), Regina.

## Nomenclature

AFR	Air Fuel Ratio
C	Condenser
CC	Combustor
CCS	Carbon Capture & Storage
CT	Combustion Turbine
EA	Excess Air (%)
EAR	Excess Air Ratio
EOR	Enhanced Oil Recovery
FGR	Flue Gas Recirculation
HP	High pressure (bars)
HRSG	Heat Recovery Heat Generator
IEA	International Energy Agency
IP	Intermediate Pressure (bars)
IPCC	Intergovernmental Panel on Climate Change
LP	Low pressure (bars)
NG	Natural Gas
NGCC	Natural Gas Combined Cycle
SNG	Synthetic Natural Gas
SNGCC	Synthetic Natural Gas Combined Cycle
SRK	Soave Redlich-Kwong
ST	Steam Turbine