A Comparative Study of Performance of Al-Khairat Gas Turbine Power Plant for Different Types of Fuel

Hayder Jawad Kadhim¹, Thualfaqir J. Kadhim¹, Mohammed H Alhwayzee¹

¹ Mechanical Engineering Department, College of Engineering, University of Kerbala, Iraq

Abstract. In this work, the effect of various types of fuels on the performance and efficiency of Al-Khairat gas turbine power plant in Kerbala City, Iraq has been investigated. The plant contains 10 General Electric Frame 9E gas turbine units, each of around 125 MW. Three fuels were used in this study: crude oil, natural gas, and biomass gasification producer (synthesis) gas. Currently, liquid crude oil is used as fuel for this plant. For comparison purposes, this power plant was simulated utilizing Aspen-Hysys software. Hysys simulation modelled in accordance with experimental power plant conditions and data was applied and showed high validity. Due to this validity, the plant’s efficiency and performance were calculated. Similarly, plant efficiency and performance for the other two fuels were also calculated. Furthermore, many important parameters that affect plant efficiency and performance for these three fuels (ambient temperature, pressure ratio, CO₂ emission gases, heat rate and fuel consumption) were also investigated. Compared to the other two fuels, results show that the use of natural gas is the optimal choice for the plant, due to its increase of station efficiency and productivity, by approximately 3.12% and 10% respectively. At the same time, it reduced fuel consumption by 6% and produced less emission greenhouse gas.

Keywords: Gas turbine cycle, power plant performance and productivity, thermal efficiency, fuel consumption, emissions, Crude oil fuel, Natural gas fuel, Biogas fuel.

1. Introduction

The gas turbine converts the energy (heat) obtained from fuel to generate mechanical power. Gas turbines are currently widely used in the field of electric generation in Iraq. There are many factors and consideration that guide the selection of the type of fuel to feed the gas turbine plant, including the price and quality of fuel, local availability, environmental and governmental dictates.

The fuels of gas turbines can be classified as liquid or gaseous. Common liquid fuels are kerosene, diesel, crude oil and heavy oil; gaseous fuels include natural gas, liquid natural gas, hydrogen, refinery gas and biomass gasification (synthesis) gas. While natural gas has been the fuel of choice for the operation of gas stations, most gas turbines in Iraq operate on crude oil because it’s very cheap, regardless of the negative effects it generates.
Many researchers have studied different types of power plant and this has highlighted the role played by the gas turbine. Nag and P.K summed up their study by stating that the current optimum choice among power generation systems was the gas turbine, due to the cheap price of the fuel used, easy maintenance, small size compared to other systems, and because the initiation of operations does not take long. Also, gas turbines have the potential to use multiple types of fuel [1]. Lamfon and Najjar studied the performance of a gas turbine plant of 23.7 MW which worked at ambient conditions of temperature 30 to 45°C. When the air entering the gas turbine is cold, the output power is improved by 11% [2].

Dawoud et al. have presented the results of investigation of two gas turbine plants in Oman, and have shown that reduction of the air temperature at the inlet of the gas turbine, using fog cooling, leads to 11.4% more output electric power [3].

When the gas turbines are designed and manufactured, the use of certain fuels will have a profound impact upon both the design of machine and the materials that are used in the manufacture of gas turbine parts [4]. The researchers noted in [5] [6] that the type of fuel used in gas turbine directly affects the overall efficiency. Cengel, A.Y. and Boles indicated that the latest gas turbine produced by General Electric can work with inlet temperature of 1425 °C and 136 to achieve efficiency of about 39.5% and output power of 282 MW for a simple cycle [7]. Wafaa, E has concluded that the power output and efficiency in gas turbine power generation plant is affected by the ambient temperature [8]. Saravanamutto et al. concluded that a gas turbine’s temperature effect curve depends on the parameters of its cycle, efficiencies of components and mass flow rate of air inlet [9]. The researchers in [10] have reported that the output power and thermal efficiency of gas turbine plants are increased when using natural gas as fuel, compared to other fuels, and they have noticed that carbon emissions are relatively less when using natural gas as fuel compared with other fuels. The results of research by Farouk, N., & Sheng, L. showed that the thermal efficiency of the plant is higher when liquefied petroleum gas is used, rather than light diesel oil [11].

In this study, three different fuel types – crude oil, natural gas and biomass gasification (synthesis) gas – were used to study their effects on the performance of Al-Khairat power plant in the city of Kerbala, Iraq. This plant uses liquid crude oil. The Aspen Hysys package was used to simulate this power plant and according to the field data, the applied software gives high validity. After simulation, plant efficiency and performance were determined. In addition, and for comparison purposes, many relevant parameters were investigated. The results show that natural gas fuel gives high performance compared with two other types.

2. Materials and methodology

2.1 Power plant components

The open Brayton cycle is the basic principle of the gas turbine, where both compression and expansion processes occur in rotating machinery. Figure 1a illustrates. Most gas turbines consist of three parts; compressor, combustion chamber, and turbine, as shown in Figure 1b. Air at ambient temperature enters the compressor, where its pressure and temperature are raised. The compressed air proceeds into the combustion chamber, where fuel is burned at constant pressure. The temperature of air is fired to a high temperature (T3) and the resulting hot gases enter the expansion turbine where they generate useful work, and exhaust gases leave the turbine. The part of the work developed by the gases passing through the turbine is used to run the compressor and the remaining 30 – 35% is used to generate electrical energy [13].
Figure 1: Schematic of: a) Brayton cycle and b) Simple gas turbine.

2.2 Power plant field data

Field data for the gas turbine unit (Unit 2 GT43 - frame 9E) for two months, January and June, were used for this research. These experimental field data were collected and are described in Table 1. The average daily operating variables were analysed and mean values calculated. The main fuel of the unit is liquid crude oil and the back-up fuel is light distillate (LDO).

Table 1: Average operating parameters of Al Khairat gas turbine power plant (Unit 2 GT43)

| Operating parameters | Data in January | Data in June |
|----------------------|-----------------|--------------|
|                      |                 |              |
Active power 80 MW  76.5 MW
Inlet air RH (relative humidity) 35%  11.2%
Mass flow rate of air m’a 350.5 kg/s  335.8 kg/s
Temperature of intake air T1 19 °C  45 °C
Pressure of intake air P1 101.3 kPa  911.7 kPa
Exit temperature of air compressor T2 327 °C  356 °C
Exit pressure of air from the compressor P2 1013 kPa  911.7 kPa
Fuel (crude oil) mass flow rate $\dot{m}_f$ 6.1 kg/s  6 kg/s
Temperature of fuel Tf 35 °C  40 °C
Pressure of fuel gas Pf 3000 kPa  3000 kPa
Turbine pressure P3 1012.9 kPa  911.64 kPa
Turbine temperature T3 1025 °C  1007 °C
Exhaust temperature T4 443 °C  514 °C
Lower heating value LHV 43300 kJ/kg  43300 kJ/kg
Compressor isentropic efficiency 88%  88%
Turbine isentropic efficiency 85%  85%
Specific heat capacity of air Cpa 1.005 kJ/kg K  1.005 kJ/kg K
Specific heat capacity of gas Cpg 1.15 kJ/kg K  1.15 kJ/kg K
Pressure ratio 10  9
Thermal efficiency 31.9%  30.9%

2.3 Gas turbine modeling using HYSYS

Aspen HYSYS (or simply, HYSYS) version-10 is an engineering software suite. It can be used in the design and simulation of a very wide range of chemical and mechanical systems, especially regarding the fuel, gas and oil industry. Very complex processes can be modeled using HYSYS. The simulation model of simple gas turbine was built, the model consisting of three main parts: compressor, combustion chamber, and turbine as shown in Figure 2. Air enters the compressor under ISO conditions ($T_1 = 15^\circ C, \quad P_1 = 101.3$kpa and $\text{RH} = 60\%$). There is no drop in pressure at inlet and exhaust, the pressure drop in the combustion chamber is about 2%.

![Flow chart of a simple gas turbine model using Aspen HYSYS.](image-url)
The simulation was carried out using three types of fuel, crude oil (which is used in the plant), natural gas and synthesis gas, to determine the differences in performance of the gas turbine and to predict the extent of production that can be generated by using different types of fuel under different operating conditions [14]. The following assumptions have been adopted in this simulation; the composition of air inlet was 21% oxygen and 79% nitrogen; the Peng-Robinson (PR) fluid package is used as it has a robust database and equations, which can generate better predictions of equilibrium for hydrocarbon systems [15]. The modeling fuels’ composition, natural gas and bio-syngas, and properties of liquid crude oil are shown in Table 2a and 2b, respectively.

### Table 2: a) Compositions of bio-syngas [17] and natural gas fuels [18], b) Specifications of crude oil [18].

| Composition | bio-syngas | natural gas |
|-------------|------------|-------------|
| H2          | 61.9%      | -           |
| CO2         | 2.8%       | -           |
| CO          | 26.2%      | -           |
| CH4         | 6.9%       | 100%        |
| N2          | 1.8%       | -           |
| H2O         | 0.4%       | -           |

- Lower heating value LHV*, Amount of heat liberated by the complete combustion of a unit volume of fuel  
- *LHV

### (b)

| Specification | Crude oil |
|---------------|-----------|
| Specific gravity at 15 °C | 0.8572 |
| Viscosity @ 21 °C | 9.7 Cst |
| Viscosity @ 37.8°C | 6.69 Cst |
| API gravity* | 33.6 |
| Flash point** | 138 °C |

*API American Petroleum Institute standards  
**Flash point The lowest temperature at which vapours of crude oil starts to flash.

### 2.4 Theoretical equations of some performance parameters of gas turbine unit

#### 2.4.1 Equation of net power of gas turbine

The net power of the gas turbine, \( Power \) is calculated from the Equation (1) in kW units [7]:

\[
Power = w_t - w_c
\]  
(1)

Where:
- \( w_t \) - Work produced by turbine.
- \( w_c \) - Work consumed by compressor.

#### 2.4.2 Equation of the overall thermal efficiency.

The overall thermal efficiency (\( \eta_{th} \)) can be determined by Equation (2) [7]:

\[
\eta_{th} = \frac{Power}{\left(m_f\right)\times (LHV)}
\]  
(2)

Where:
- \( m_f \) - Mass flow rate of fuel (kg/s).  
- \( LHV \) - Fuel lower heating value (kJ / kg).
2.4.3 Equation of specific fuel consumption SFC

The specific fuel consumption (SFC) is obtained by Equation (3) in kg/kWh units [7]:

\[ SFC = \frac{m_f \cdot 3600}{\text{Power}} \] ............ (3)

2.4.4 Equation of the heat rate, HR

Heat rate (HR) is the consumed heat to produce “unit energy” of electricity. It can be determined by Equation (4) in kJ/kWh units [7]:

\[ HR = \frac{3600}{\eta_{th}} \] ............(4)

3 Results and discussions

The performance of the power plant was established by simulation using ASPEN HYSYS, version-10 software to obtain the turbine and compressor work. Other parameters, such as specific fuel consumption, rate of heat, net power, and thermal efficiency, were calculated. The comparative analysis of the simulated results is shown in Table 3.

| Item                  | Crude oil | Natural gas | Syngas | Units   |
|-----------------------|-----------|-------------|--------|---------|
| Compressor power      | 115.9     | 133.2       | 63.05  | MW      |
| Turbine power         | 192.6     | 227.1       | 107.4  | MW      |
| Net power             | 76.71     | 93.89       | 44.35  | MW      |
| Thermal efficiency    | 28.87     | 31.27       | 30.44  | %       |
| Specific fuel consumption | 0.2815   | 0.23005     | 0.474725 | kg/kWh |
| Heat rate             | 12192.413 | 11143.7     | 13197.36 | kJ/kWh |
| Total mass flow rate  | 356.5     | 408.9       | 190.7  | kg/s    |
| Temperature of intake air | 45        | 45          | 45     | °C      |
| Exhaust temperature   | 512.8     | 504.1       | 513.6  | °C      |

3.1 Impact of ambient air temperature on net power output

Figure 3 shows the influence of inlet air temperature on plant productivity for three fuel types. It can be seen that with an increase of inlet air temperature from 0 °C to 60 °C, the power output decreases by approximately 9.14% for natural gas, 10.2% for crude oil and 9.63% for synthesis gas. This is because, with an increase in ambient inlet air temperature, air mass flow and density decrease which affects the pressure ratio and the compressor and turbine work, and ultimately the power output.
3.2 Impact of ambient air temperature on thermal efficiency

Figure 4 shows the influence of the inlet air temperature on the plant’s thermal efficiency for three fuel types. It was clear that as the inlet air temperature increased, from 0 °C to 60 °C, there was a decrease in thermal efficiencies, approximately 3.15% for natural gas, 3.3% for synthesis gas and 3.13% for crude oil. This is due to the reduction in power output and a slight increase in specific fuel consumption.

3.3 Impact of ambient air temperature on fuel consumption

Figure 5 shows the influence of the inlet air temperature on the specific fuel consumption (SFC) of the plant, for three fuel types. It was found that the fuel consumption rate increased by approximately 9.6% for synthesis gas, 9.1% for natural gas and 10.2% for crude oil as the ambient inlet temperature reached 60 °C. This was due to a reduction in the pressure ratio (PR) and turbine work, which made it necessary to increase the mass flow rate of fuel to keep the turbine inlet temperature (TIT) constant.
3.4 Impact of ambient air temperature on the heat rate (HR)

Figure 6 illustrates the effect of the inlet air temperature on the heat rate for three different types of fuel. An increase in inlet air temperature from 0 °C to 60 °C increased the heat rate about 9.6% for syngas, 10.2% for crude oil and 9.1% for natural gas. This is because the compressor needs more power when intake air is at a high temperature, with an increase in specific fuel consumption. It can be seen that the bio-syngas had higher fuel heat rate than natural gas and crude oil.

3.5 Impact of pressure ratio on net power output

Figure 7 shows the influence of the compressor’s pressure ratio on the power output of the gas turbine. It is notable that increasing compression ratio will increase thermal efficiency and exert a positive effect on the power output. This is due to the increase in the turbine inlet temperature (TIT) while reaching the optimal value, which then starts to decrease because higher pressure ratios lead to a higher maximal turbine inlet temperature (TIT) and this temperature must not exceed the temperature that the turbine blades can withstand (around 1300°C, in practice). Therefore, practical pressure ratios are between 5 and 20.
3.6 Impact of ambient air temperature on the CO₂ composition in flue gas

The produced amount of carbon dioxide emissions, relative to the temperature of ambient inlet air, is illustrated for all types of fuel in Figure 8. The variation of ambient inlet air temperature decreases CO₂ emission: this is due to the increase in the amount of air entering the compressor at high ambient temperatures. This excess air increases the amount of oxygen to the combustion. It was found that turbines operating on natural gas emit relatively less CO₂ gas, compared to other fuels [16].

4 Conclusion

The performance and efficiency of Frame 9E gas turbine in Al-Khairat power plant, for three diverse types of fuel, have been compared using Aspen HYSYS. These fuels are liquid crude oil, natural gas, and biomass gasification producer (synthesis) gas. It has been found that, as the ambient inlet air temperature increased to 50°C, the efficiency and net power output of the plant decreased by approximately 3% and 10%, respectively for the fuels considered in the study. More specifically, plant efficiency and net power output for natural gas were higher as compared to other types of fuel.
addition, it has been noted that the volume emission of CO$_2$, in the case of using natural gas as fuel, was relatively less compared to other fuels.

References

[1] Nag, P.K. Power plant engineering. New Delhi: Tata McGraw-Hill Publishing Company Limited, 2008.

[2] Lamfon NJ, Najjar YS, Akyurt M. Modeling and simulation of combined gas turbine engine and heat pipe system for waste heat recovery and utilization. *Energy conversion and Management*. 1998 Jan 1;39(1-2):81-6.

[3] Dawoud B, Zurigat YH, Bortmany J. Thermodynamic assessment of power requirements and impact of different gas-turbine inlet air cooling techniques at two different locations in Oman. *Applied Thermal Engineering*. 2005 Aug 1; 25(11-12):1579-98.

[4] D.M. Todd, GE combined cycle experience. 33rd GD Turbine State-of-the-Art Tech Seminar, Paper No. GER3585A, 1989

[5] Young SK, Jong JL, Tong SK, and Jeong LS. Effects of syngas type on the operation and performance of gas turbine in integrated gasification combined cycle, *Energy Conversion & Management* 2011; 52, p 2262-2273.

[6] Vittorio V. Prediction of fuel impact associated with performance degradation in power plants. *Energy* 2008; 33, p. 213-223.

[7] Cengel, A.Y. and Boles, A.M. Thermodynamics an engineering approach New York: McGraw-Hill. 2008.

[8] Wafaa E. effect of air temperature on the efficiency of gas turbines in Gerri power plant, 2010. *ISSN (Print):1694-0784*.

[9] Saravanamuttoo, H., Rogers, G., Cohen, H. and Straznicky. *Gas Turbine Theory*. New York: Prentice Hall, 2009.

[10] Basha M, Shaahid SM, Al-Hadhrami L. Impact of fuels on performance and efficiency of gas turbine power plants. *Energy Procedia*. 2012 Jan 1; 14:558-65.

[11] Farouk N, Sheng L. Effect of Fuel Types on the Performance of Gas Turbines. *International Journal of Computer Science Issues (IJCSCI)*. 2013; 10(1):436.

[12] Meher-Homji CB, Zachary J, Bromley AF. Gas Turbine Fuels-System Design, Combustion,
And Operability. *In: Proceedings of the 39th Turbomachinery Symposium* 2010. Texas A&M University. Turbomachinery Laboratories.

[13] Orhorhoro EK, Orhorhoro OW. Simulation of Air inlet Cooling system of a Gas Turbine Power Plant. *ELK Asia Pacific Journal of Applied Thermal Engineering*. 2016; 1(2).

[14] E.N. Achimnole, E.K. Orhorhoro, M.O. Onogbotsere. Simulation of Gas Turbine Power Plant Using High Pressure Fogging Air Intake Cooling System. International Journal of Emerging Engineering Research and Technology (2017) Volume 5, Issue 5, pp. 16-23

[15] Biliyok C, Yeung H. Evaluation of natural gas combined cycle power plant for post-combustion CO2 capture integration. *International Journal of Greenhouse Gas Control*. 2013 Nov 1; 19:396405.

[16] Basha M, Shaahid SM, Al-Hadhrami L. Impact of fuels on performance and efficiency of gas turbine power plants. *Energy Procedia*. 2012 Jan 1; 14:558-65.

[17] Chaouki Ghenai. Combustion of Syngas Fuel in Gas Turbine Can Combustor. Hindawi Publishing Corporation. *Advances in Mechanical Engineering*, 2010, Article ID 342357, 13 pages.

[18] Ministry of Electricity, Al-Khairat gas turbine power plant - Kerbala City, Iraq.