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Analyzing Gas Turbine Performance Through Simulation and Performance Tests: Case Study of Gas Turbine Units in Jambi, Indonesia

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***Abstract* – The purpose of this research is to analyse and compare the performance of units 1 and 2 of the gas turbine (GT) power plant based on simulation results and tests in terms of performance, to identify factors causing a decrease in gas turbine performance, and provide recommendations to improve gas turbine. The study was carried out in GT units in Jambi, Indonesia. In this location, there are two identical GT units with a capacity of 34.25 megawatts electric (MWe). The analysis was carried out using three methods, namely performance test, inspection of the measurement instruments, and simulation of the thermodynamic performance using GT-Pro software. To improve the performance of the gas turbine, it is necessary to clean the compressor blades, online compressor washing or manual deposit cleaning on the compressor blades during the overhaul, calibrate manometers, and inspect the piping line of the differential pressure of Air Inlet Filter, and also carry out inspection and calibration of the exhaust gas thermocouple on numbers 1, 2, 5, and 8 of GT Unit 2. This research not only presents practical recommendations for improving the performance of GT in Jambi, Indonesia, but also contributes to the broader field of gas turbine technology. The findings and recommendations can be applied in the power generation industry worldwide, helping to enhance the efficiency and reliability gas turbine power plants.**

***Keywords* – Gas turbine, thermodynamic simulation, open cycle.**

1. Introduction

Gas turbines have gained increasing popularity in recent years due to their high efficiency, reliability, and flexibility [1]. They are used in various applications, such as power generation, aviation, and industrial processes [2]. Gas turbines also serve as ideal equipment to balance variable renewable energy sources such as wind and solar in power systems, given their ability to rapidly adjust power output [3], [4]. Gas turbine technology is extensively utilised in power generation, particularly in scenarios requiring rapid start-up. Gas-fired power plants are often used as peak plants to supplement the production from other energy sources or as baseload plants in regions rich in natural gas resources. The performance of gas turbines is influenced by fuel quality, turbine design, and operational conditions. High-quality fuels such as natural gas yield higher efficiency, while modern turbine design and combined-cycle systems can significantly enhance efficiency. Environmental factors such as temperature and humidity also impact the performance of gas turbines [5]. Superior fuels, such as natural gas, result in higher efficiency compared to lower quality fuels, which may lead to reduced efficiency and increased emissions [6], [7]. Turbine design is another key factor affecting the performance of gas-fired power plants [8]. The turbine design determines how much energy can be converted from fuel into electricity. Modern turbine designs, such as systems that use combined cycles that harness waste heat to generate additional electricity, can significantly increase the efficiency of gas-fired power plants [9].

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In addition to efficiency, other crucial factors for gas turbine performance in power plants include reliability, durability, and safety. These factors can influence the long-term viability and profitability of the power plant, as well as its impact on the surrounding environment and community [10]. Monitoring parameters such as power output, efficiency, exhaust gas flow rate, exhaust gas temperature, air temperature, pressure ratios, and airflow rates are necessary to assess the performance of gas turbine performance [11], [12], [13]. These parameters provide valuable information about the condition of the turbine, enabling operators to optimise its performance and identify efficiency degradation issues of efficiency [14]. Advances in sensor technology, data analytics, and control systems have revolutionised the monitoring and performance optimisation of gas turbines [15]. Modern gas turbines are equipped with various sensors that provide real-time performance data, enabling operators to quickly detect and resolve issues [16]. In recent years, data analytics and optimisation techniques have also advanced rapidly, enabling operators to predict and diagnose failures before they occur and optimise gas turbine performance in various operational conditions.

Among these techniques are machine learning algorithms [17], sophisticated data analysis, and artificial intelligence [18], [19]. With regular operational monitoring and maintenance, power plant units can prevent machine failures that could lead to accidents or major damage. Furthermore, monitoring gas turbine performance can aid operators in decision making, such as determining optimal timing for routine or periodic maintenance [20]. In facing the challenges of future energy needs, the monitoring and optimisation of gas turbine performance will become increasingly crucial to achieving clean, efficient, and sustainable energy sources [21]. This study will be conducted in open-cycle gas turbine units in Jambi, Indonesia. The location consists of two gas-fired power plants with a capacity of 34.25 MWe operating at a frequency of 50 Hz and using natural gas as fuel.

The objective of this research is to analyse and compare the performance of Units 1 and 2 of the gas-fired power plant based on simulation results and tests, specifically in terms of heat rate. The study aims to identify the factors that cause degradation in gas turbine performance and provide recommendations to improve gas turbine performance. This paper is divided into four parts: introduction, materials, methodology, and results.

Table 1. Gas turbine specification

Turbine		**Generator**		**Transformator**	
Type	General Electic MS 6001 B	Type	General Electric GA 3 Open	Type	AEG TL UN 7752
Power	34,250 kW	Capacity	46.863 kVA	Capacity	45,000 kVA
Speed	5094 rpm	Speed	3000 RPM	Cooling system	ONAN / ONAF
Base Exhaust Temp.	549 °C	Rated Voltage	11.500 Volt	Rated Voltage	11.5 / 150 kV
Inlet air pressure	2.5 in H20	Power Factor	0,8	Maximum Oil temperature	100 °C
Compressor stage	17	Frequency	2 Pole 3 phase 50 Hz	Ratio	2500 / 2 A
Turbine stage	3	Excitation voltage	125 Volt	Current rating	400 A

2. Materials and Method

In this study, the performance analysis is conducted through three methods: first, performance testing to measure the heat rate of units 1 and 2 of the gas-fired power plant with specifications indicated in Table 1, second, inspection of measuring instruments, and third, thermodynamic performance simulation using GT-Pro software.

2.1. Performance Testing

During performance testing, data are collected in accordance with the ASME PTC 22 standard for gas turbine performance testing [22]. The collected data includes parameters such as inlet air temperature, air filter pressure differential, fuel flow rate, exhaust gas temperature, self-use electrical energy, and electricity production, as indicated by the red points in Figure 1.

The heat rate testing for Units 1 and 2 of the gas-fired power plant was conducted at different times and under the following testing conditions:

a) Load patterns and testing duration are indicated in Table 2.

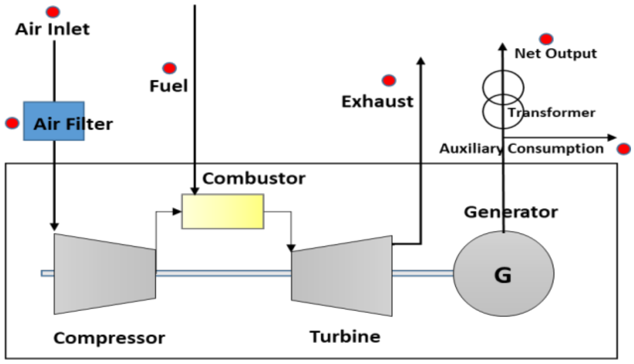


Figure 1. Performance data point schematic

a) The gas fuel used during the testing was natural gas with the composition specified in Table 3.

b) Net energy production data was collected from the kWh-meter transactions in the Generator Auxiliary Control (GAC) room, while gross energy production data was obtained from the gross kWh-meter in the Local Control Room. The self-use energy (UAT) was measured by the kWh-meter in the Motor Control Center (MCC) room.

Table 1. Performance test load setting

No	Unit	Day	Time	Load Setting
				MW
1	#2	1	10.00 – 11.00	15
2			11.30 – 12.30	22.5
3			13.30 – 14.30	30
4			15.00 – 16.00	Base Load (33.7)
5	#1	2	10.00 – 11.00	15
6			11.30 – 12.30	22.5
7			13.30 – 14.30	30

c) Load testing at base load setting was not performed on Unit 1 due to the temperature limit protection of the gas turbine being reached, preventing the load from increasing. The base load setting in the gas-fired power plant units depends on the exhaust temperature protection. For the GE MS-6001B type gas turbine in the Jambi power plant, the maximum load (peak load) that can be generated is 34,250 kW.

Table 2. Gas composition

Parameter	Gas	Value	
		Day 1	Day 2
Composition (%v)	Methane	88.83	88.45
	Ethane	4.15	4.02
	Propane	2.02	1.98
	i-Butane	0.39	0.37
	n-Butane	0.46	0.44
	i-pentane	0.11	0.1
	n-pentane	0.06	0.06
	Nitrogen	0.33	0.35
	Carbon Dioxide	3.56	4.13
HHV	Btu/scf	1037.04	1033.49

d) Gas fuel sampling was conducted twice during the testing period for Unit 1 and Unit 2, taken from the scrubber outlet before entering the gas turbine.

e) The heat rate calculation in this study was performed using the energy input - energy output method with equation (1). The compressor efficiency calculation was done using equation (2).

$$\boldsymbol{Net\ Plant\ Heat\ Rate\ (NPHR) =} \\ = \frac{\boldsymbol{Fuel\ flow\ x\ Fuel\ heating\ value}}{\boldsymbol{Nett\ Power\ Output}} \tag{1}$$

Where

Net Plant Heat Rate : Ratio of the energy needed to produce 1 kWh of energy (kkal / kWh)
Fuel flow : Fuel usage flow (kg/jam)
Fuel heating value : Fuel specific energy (kkal / kg)
Net Power Output : GTG gross output minus auxiliary power consumption (kWh)

$$\boldsymbol{\eta_c = \frac{T_{1c} + 273,15}{T_{2c} - T_{1c}}\ x \left[\left(\frac{Pcs + Pa}{Pa} \right)^{\frac{K-1}{K}} - 1 \right] x\ 100}$$

(1)

Where,

T_{1c} : Compressor inlet temperature
T_{2c} : Compressor outlet temperature
Pcs : Compressor discharge temperature
Pa : Ambient pressure
K : Specific heat ratio

2.2. Instrumentation Inspection

In this study, an analysis of the output values of the measuring instrument, such as differential pressure (DP) for Air Inlet Filter, exhaust gas turbine temperature profiles, and compressor discharge temperature is conducted.

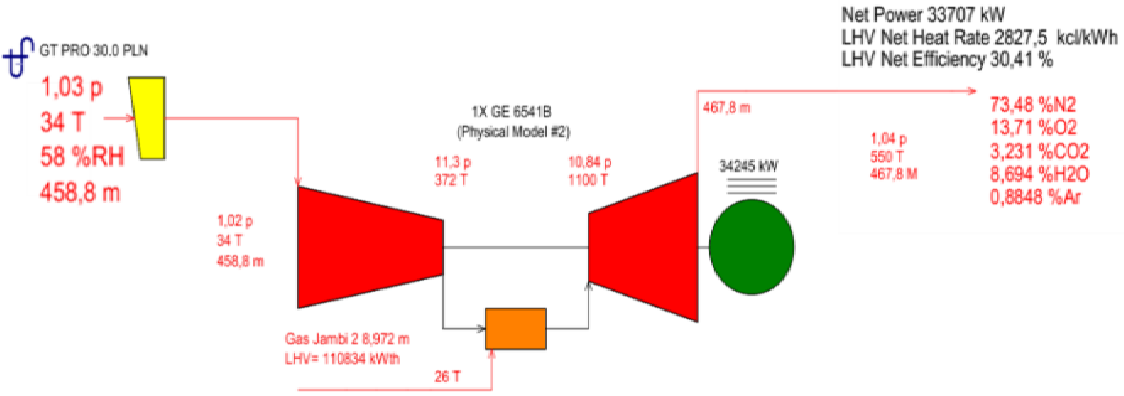


Figure 2. Thermoflow simulation model

2.3. Gas Turbine Performance Simulation

To assess the performance of the gas turbine and compare it with the manufacturer's design, a thermodynamic performance simulation of the gas turbine is conducted using GTPro software by Thermoflow Inc. [23].

The gas turbine model utilised in the simulation is the General Electric GE6541B gas turbine model available in the software database. The simulation incorporates the composition of air: nitrogen (N_2) 75.30%, oxygen (O_2) 20.20%, CO_2 0.02%, water (H_2O) 3.55%, and Argon (Ar) 0.90%.

2.4. Performance Test Preparation

The preparation in the execution of the test and performance analysis of the gas-fired power plant includes effective and efficient planning, as well as the ability to identify potential risks and obstacles that may arise during the work. Health and safety on the workplace are crucial, as every worker desires a safe working environment. In carrying out daily tasks, there are several factors that can potentially lead to workplace accidents. Therefore, prior to starting any work, coordination meetings for preparation, as depicted in Figure 3, should be held, together with inspections of the completeness of personal protective equipment and compliance with applicable occupational health and safety procedures. During the execution of the work, it is essential to ensure compliance with environmental regulations with respect to the results of the tasks performed.

Figure 3. Coordination meeting

3. Results and Discussion

In this study, the performance test results are then compared with the performance simulations using GT-Pro software. The results of each unit are also compared.

3.1. Performance Test Result Analysis

The results of plant heat rate calculations for Unit 1 of the gas-fired power plant are shown in Table 4, while the results for Unit 2 are shown in Table 5. The lowest value achieved for the Net Plant Heat Rate (NPHR) of Unit 1 during load testing at 29.94 MW is 3,155.36 kcal/kWh. The lowest value achieved for the Gross Plant Heat Rate (GPHR) of Unit 1 in the same load testing is 3,142.29 kcal/kWh.

Table 3. GTG unit 1 performance

Item	Code	Unit	Beban (MW)		
			15	22.5	30
Gross heat rate	HR_{GTG}	BTU/kWH	15,643.26	13,242.55	12,469.42
		kCal/kWh	3,942.10	3,337.12	3,142.29
Net heat rate	HR_{GTN}	BTU/kWH	15,770.41	13,312.34	12,521.28
		kCal/kWh	3,974.14	3,354.71	3,155.36
Gas flow rate	Gfgas	MSCF/h	232.00	302.00	360.00
Gas Fuel Gross heating value	HV_{gas}	btu/scf	1,037.04	1,037.04	1,037.04
Gas turbine gross power output	GTKWG	MWH	15.38	23.65	29.94
Gas turbine net power output	GTKWN	MWH	15.26	23.53	29.82
UAT	GTKWU	KWH	124.00	124.00	124.00
Specific Fuel Consumption	SFC	scf/kWh	15.085	12.770	12.024
Frequency	F	Hz	50.07	50.14	50.07
Exhaust Temperature	TTX	^{o}C	385.53	470.11	539.99
GT Efficiency	η_{GT}	%	21.81	25.77	27.36
GT compressor efficiency	η_{C}	%	81.98	82.57	83.01
GT compressor inlet air temperature	T1C	^{0}C	28.64	31.31	33.55
GT compressor outlet air temperatur	T2C	^{0}C	342.07	356.75	367.64
GT compressor outlet air pressure	PCS	kg/cm^{2} (A)	8.89	9.42	9.78
Ambien pressure	Pa	kg/cm^{2} (A)	1.03	1.03	1.03
Specific heat ratio	K		1.40	1.40	1.40
Air Inlet Differential Pressure	ΔP	kg/cm2 (A)	0.0055	0.0053	0.0050

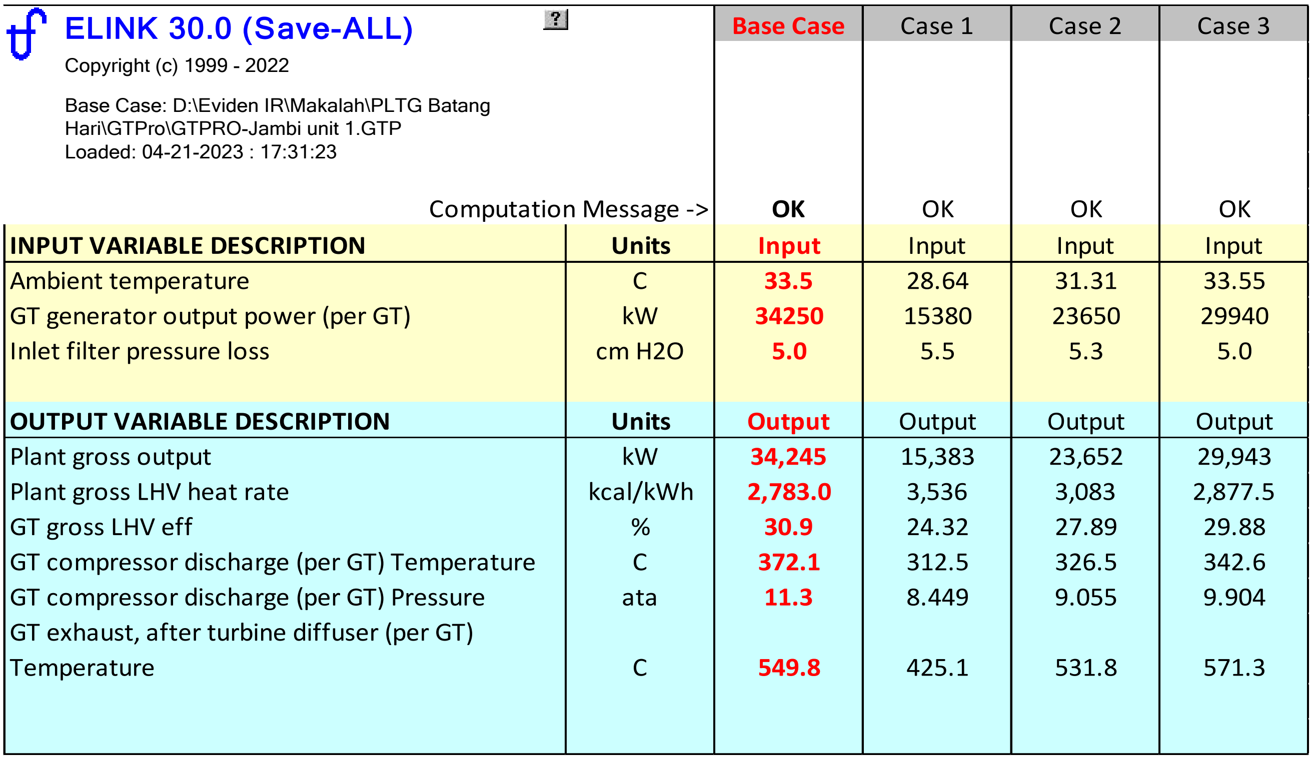
The lowest value achieved for the net plant heat rate (NPHR) of Unit 2 during the base load test at 33.78 MW is 2,933.87 kcal/kWh. The lowest value achieved for the gross plant heat rate (GPHR) of Unit 2 at the same base load testing is 2,922.06 kcal/kWh.

The higher heat rate values obtained during the testing compared to the simulation results indicate a performance degradation in both units. However, it should be noted that the simulation assumptions consider the gas turbine's new condition, while the tested units have been in operation for 20 years, resulting in performance degradation.

Table 5. GTG unit 2 performance

Item	Code	Unit	Beban (MW)			
			15	22.5	30	Base Load (33,7)
Gross heat rate	HR_{GTG}	BTU/kWH	15,124.32	12,862.08	11,913.20	11,595.46
		kCal/kWh	3,811.33	3,241.24	3,002.13	2,922.06
Net heat rate	HR_{GTN}	BTU/kWH	15,253.02	12,939.19	11,966.64	11,642.33
		kCal/kWh	3,843.76	3,260.68	3,015.59	2,933.87
Gas flow rate	Gfgas	MSCF/h	222.00	284.00	351.00	379.00
Gas Fuel Gross heating value	HV_{gas}	btu/scf	1,033.50	1,033.50	1,033.50	1,033.50
Gas turbine gross power output	GTKWG	MWH	15.17	22.82	30.45	33.78
Gas turbine net power output	GTKWN	MWH	15.04	22.68	30.31	33.64
UAT	GTKWU	KWH	128.00	136.00	136.00	136.00
Specific Fuel Consumption	SFC	scf/kWh	14.634	12.445	11.527	11.220
Frequency	F	Hz	50.10	50.14	50.24	50.20
Exhaust Temperature	TTX	^{o}C	395.72	447.89	524.80	556.00
GT Efficiency	η_{GT}	%	22.56	26.53	28.64	29.43
GT compressor efficiency	η_{C}	%	81.84	82.44	83.02	83.00
GT compressor inlet air temperature	T1C	^{0}C	30.26	31.21	32.67	32.10
GT compressor outlet air temperature	T2C	^{0}C	336.48	359.27	371.42	374.81
GT compressor outlet air pressure	PCS	kg/cm^{2} (A)	8.45	9.50	10.05	10.28
Ambien pressure	Pa	kg/cm^{2} (A)	1.03	1.02	1.02	1.02
Specific heat ratio	K		1.40	1.40	1.40	1.40
Air Inlet Differential Pressure	ΔP	kg/cm2 (A)	0.0045	0.0045	0.0045	0.0045

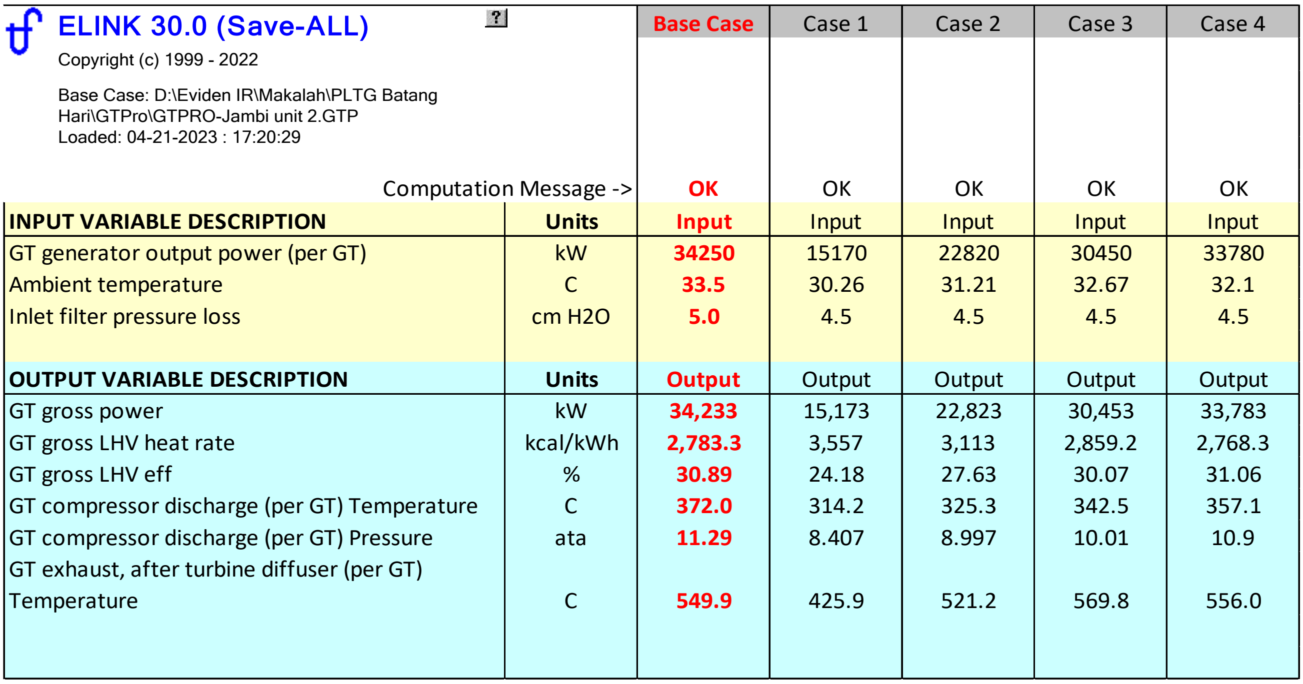
Table 4. GTG unit 1 simulation results



ELINK 30.0 (Save-ALL)
Copyright (c) 1999 - 2022
Base Case: D:\Eviden IR\Makalah\PLTG Batang Hari\GTPro\GTPRO-Jambi unit 1.GTP
Loaded: 04-21-2023 : 17:31:23

		Base Case	Case 1	Case 2	Case 3
	Computation Message ->	OK	OK	OK	OK
INPUT VARIABLE DESCRIPTION	**Units**	Input	Input	Input	Input
Ambient temperature	C	33.5	28.64	31.31	33.55
GT generator output power (per GT)	kW	34250	15380	23650	29940
Inlet filter pressure loss	cm H2O	5.0	5.5	5.3	5.0
OUTPUT VARIABLE DESCRIPTION	**Units**	Output	Output	Output	Output
Plant gross output	kW	34,245	15,383	23,652	29,943
Plant gross LHV heat rate	kcal/kWh	2,783.0	3,536	3,083	2,877.5
GT gross LHV eff	%	30.9	24.32	27.89	29.88
GT compressor discharge (per GT) Temperature	C	372.1	312.5	326.5	342.6
GT compressor discharge (per GT) Pressure	ata	11.3	8.449	9.055	9.904
GT exhaust, after turbine diffuser (per GT) Temperature	C	549.8	425.1	531.8	571.3

Table 5. GTG unit 2 simulation results



ELINK 30.0 (Save-ALL)
Copyright (c) 1999 - 2022
Base Case: D:\Eviden IR\Makalah\PLTG Batang Hari\GTPro\GTPRO-Jambi unit 2.GTP
Loaded: 04-21-2023 : 17:20:29

		Base Case	Case 1	Case 2	Case 3	Case 4
	Computation Message ->	OK	OK	OK	OK	OK
INPUT VARIABLE DESCRIPTION	**Units**	Input	Input	Input	Input	Input
GT generator output power (per GT)	kW	34250	15170	22820	30450	33780
Ambient temperature	C	33.5	30.26	31.21	32.67	32.1
Inlet filter pressure loss	cm H2O	5.0	4.5	4.5	4.5	4.5
OUTPUT VARIABLE DESCRIPTION	**Units**	Output	Output	Output	Output	Output
GT gross power	kW	34,233	15,173	22,823	30,453	33,783
GT gross LHV heat rate	kcal/kWh	2,783.3	3,557	3,113	2,859.2	2,768.3
GT gross LHV eff	%	30.89	24.18	27.63	30.07	31.06
GT compressor discharge (per GT) Temperature	C	372.0	314.2	325.3	342.5	357.1
GT compressor discharge (per GT) Pressure	ata	11.29	8.407	8.997	10.01	10.9
GT exhaust, after turbine diffuser (per GT) Temperature	C	549.9	425.9	521.2	569.8	556.0

A comparison of the compressor performance between Unit 1 and Unit 2 of the gas-fired power plant, particularly in terms of compressor discharge pressure (PCS), indicates that Unit 1's compressor blades are fouled and thus require cleaning. This can be achieved through online compressor washing or manually removing deposits from compressor blades during overhaul procedures [24].

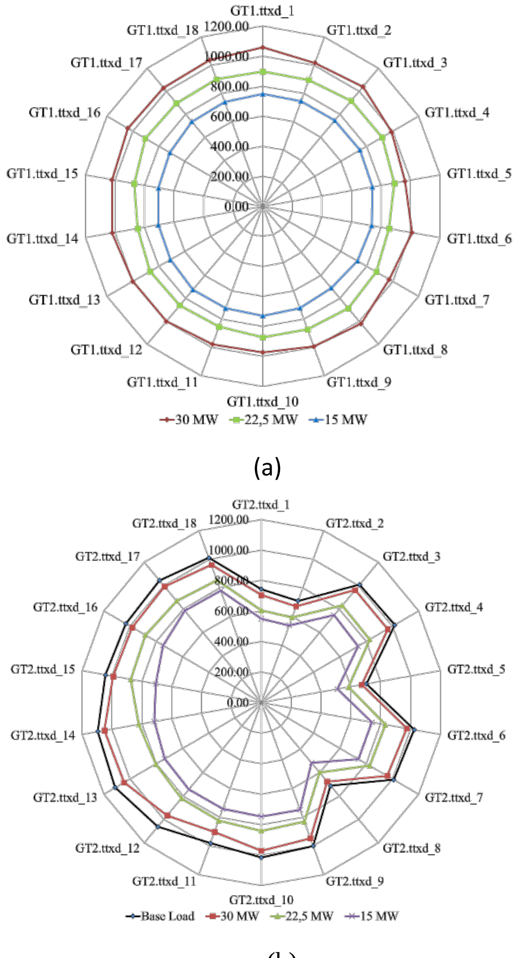
Regarding the differential pressure sensor, the data indicating the differential pressure in Unit 2 at each load level show any differences. This indicates a potential issue, such as a malfunction in the instrument or a blockage in the differential pressure filter pipe.

3.2. Instrument Inspection Result

In both Unit 1 and Unit 2 of the gas-fired power plant, there are 18 thermocouple sensors that measure the exhaust gas temperature on the exhaust side of the gas turbine. A comparison of the distribution of exhaust gas temperatures between Unit 2 and Unit 1 reveals an uneven temperature distribution at each load level. This indicates a possible failure in the functioning of these sensors, necessitating inspection and calibration of thermocouples 1, 2, 5, and 8. The uneven distribution are observed particularly in thermocouples 1, 2, 5, and 8, which display lower values compared to the other thermocouples, as depicted in Figure 4.

3.3. Gas Turbine Performance Simulation

Using the gas turbine model depicted in Figure 2, a simulation is conducted by adjusting several input parameters in the ELINK module available in the GT-Pro software. In the GT simulation, the input parameters include load percentage, differential filter pressure, and ambient air temperature. The simulation output is presented in Table 6. Meanwhile, the simulation output for Unit 2 in GT is shown in Table 7.



(a)

(b)

Figure 4. Gas turbine exhaust temperature profile (a) unit 1 dan (b) unit 2.

Comparison between the simulation results and the test data indicates that the performance degradation of the performance of the gas turbines of unit 1 and unit 2 is caused by a decline in compressor performance, as evidenced by an increase in heat rate, decrease in compressor discharge pressure and rise in exhaust temperature [25]. The reduction in compressor discharge pressure and the increase in exhaust temperature are attributed to the accumulation of contaminants, such as dust, on the compressor blades. This results in a decrease in mass airflow rate, leading to an increase in the temperature within the combustion chamber and, subsequently, to an elevation in exhaust temperature [26].

4. Conclusion

The simulation results show that the lowest plant heat rate achieved for unit 1 of the gas turbine is 2,877.5 kcal/kWh at a load of 29.94 MW, while the testing data indicates a value of 3,142.29 kcal/kWh. The lowest plant heat rate for Unit 2 is 2,768.3 kcal/kWh at base load, while the test data shows a value of 2,922.06 kcal/kWh. The decline in gas turbine performance can be attributed to the decreased compressor performance. The distribution of exhaust gas temperatures in Unit 2 is uneven compared to Unit 1. To improve the performance of the gas turbine, it is necessary to clean the compressor blades, calibrate the pressure gauges, inspect the piping channel of the Air Inlet Filter's differential pressure, and calibrate the exhaust gas thermocouples at positions 1, 2, 5, and 8 in Unit 2.

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References:

[1]. Abudu, K., Igie, U., Minervino, O., & Hamilton, R. (2021). Gas turbine efficiency and ramp rate improvement through compressed air injection. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 235*(4), 866–884. Doi: 10.1177/0957650920932083

[2]. Aldi, N., Casari, N., Morini, M., Pinelli, M., Spina, P. R., & Suman, A. (2018). Gas Turbine Fouling: A Comparison Among 100 Heavy-Duty Frames. *Journal of Engineering for Gas Turbines and Power, 141*(3), Article 3. Doi:10.1115/1.4041249

[3]. ASME PTC 22—Gas Turbine. (2013). ASME. Retrieved from: https://www.asme.org/codes-standards/find-codes-standards/ptc-22-gas-turbines [accessed: 04 June 2023].

[4]. Bhargava, R. K., Bianchi, M., De Pascale, A., Negri di Montenegro, G., & Peretto, A. (2007). Gas Turbine Based Power Cycles—A State-of-the-Art Review. In K. Cen, Y. Chi, & F. Wang (Eds.), *Challenges of Power Engineering and Environment*, 309–319. Springer. Doi: 10.1007/978-3-540-76694-0_56

[5]. Boyce, M. P. (2012). *Gas turbine engineering handbook* (4th ed). Elsevier/Butterworth-Heinemann.

[6]. Brooks, F. J. (2000). GE gas turbine performance characteristics. *GE Power Systems, Schenectady, NY.*

[7]. Burnes, D., & Camou, A. (2019). Impact of Fuel Composition on Gas Turbine Engine Performance. *Journal of Engineering for Gas Turbines and Power, 141*(10). Doi: 10.1115/1.4044238

[8]. Dixon, S. L., & Hall, C. (2013). *Fluid mechanics and thermodynamics of turbomachinery*. Butterworth-Heinemann.

[9]. Hanachi, H., Mechefske, C., Liu, J., Banerjee, A., & Chen, Y. (2018). Performance-Based Gas Turbine Health Monitoring, Diagnostics, and Prognostics: A Survey. *IEEE Transactions on Reliability, 67*(3), 1340–1363. Doi: 10.1109/TR.2018.2822702

[10]. Jones, R., Goldmeer, J., & Monetti, B. (2011). Addressing gas turbine fuel flexibility. *GE Energy*, *4601*, 1-20.

[11]. Kumar, N., Besuner, P., Lefton, S., Agan, D., & Hilleman, D. (2012). *Power plant cycling costs*. National Renewable Energy Lab.(NREL), Golden, CO (United States).

[12]. Kurz, R., & Brun, K. (2016). Gas turbine performance. In *Asia Turbomachinery & Pump Symposium. 2016 Proceedings.* Turbomachinery Laboratories, Texas A&M Engineering Experiment Station. Doi: 10.21423/R1W112

[13]. Li, Y. G. (2008). A genetic algorithm approach to estimate performance status of gas turbines. In *Turbo Expo: Power for Land, Sea, and Air*, *43123*, 431-440. Doi: 10.1115/GT2008-50175

[14]. Liu, Z., & Karimi, I. A. (2020). Gas turbine performance prediction via machine learning. *Energy, 192*, 116627. Doi: 10.1016/j.energy.2019.116627

[15]. Meher-Homji, C. B., & Bromley, A. (2004). Gas Turbine Axial Compressor Fouling And Washing. In *Proceedings of the 33rd turbomachinery symposium*. Texas A&M University. Turbomachinery Laboratories. Doi: 10.21423/R1S66R

[16]. Meher-Homji, C. B., Chaker, M. A., & Motiwala, H. M. (2001). Gas Turbine Performance Deterioration. In *Proceedings of the 30th turbomachinery symposium*. Texas A&M University. Turbomachinery Laboratories. Doi: 10.21423/R19Q1P

[17]. Tahan, M., Tsoutsanis, E., Muhammad, M., & Karim, Z. A. (2017). Performance-based health monitoring, diagnostics and prognostics for condition-based maintenance of gas turbines: A review. *Applied energy*, *198*, 122-144.
Doi: 10.1016/J.APENERGY.2017.04.048

[18]. Ogaji, S. O. T., Sampath, S., Singh, R., & Probert, S. D. (2002). Parameter selection for diagnosing a gas-turbine's performance-deterioration. *Applied Energy, 73*(1), 25–46. Doi: 10.1016/S0306-2619(02)00042-9

[19]. Swapan Basu, Ajay Kumar Debnath. (2019).
Power Plant Instrumentation and Control Handbook (2nd ed). Academic Press.
Doi: 10.1016/B978-0-12-819504-8.09011-9

[20]. Redl, C. (2018). *A word on flexibility: The German Energiewende in practice: How the electricity market manages flexibility challenges when the shares of wind and PV are high*. Agora. Retrieved from: https://www.agora-energiewende.de/en/publications/a-word-on-flexibility/ [accessed: 15 June 2023].

[21]. Roddy, D. (2010). *Advanced power plant materials, design and technology*. Elsevier.

[22]. Saravanamuttoo, H. I. H., Rogers, G. F. C., & Cohen, H. (2017). *Gas turbine theory* (7th ed). Pearson.

[23]. *Thermoflow Software Suite User Manual*. (2022). Thermoflow Inc. Retrieved from:
https://www.thermoflow.com/images/OVERVIEW.pdf [accessed: 15 June 2023].

[24]. Walsh, P. P., & Fletcher, P. (2004). *Gas turbine performance*. Blackwell science.

[25]. Zedda, M. (1999). *Gas turbine engine and sensor fault diagnosis.* [PHD thesis, Cranfield university]. https://dspace.lib.cranfield.ac.uk/handle/1826/9117

[26]. Zhang, X., Sugishita, H., Ni, W., & Li, Z. (2005). Economics and performance forecast of gas turbine combined cycle. *Tsinghua Science and Technology, 10*(5), 633–636.
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