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MODELING AND SIMULATION OF AN OPERATING GAS TURBINE USING MODELICA LANGUAGE

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This article uses Modelica to model and simulate the operating Gas Turbine (GT) in a combined cycle power plant in Ras-Djinet, Algeria. The modeling and simulation have been validated based on the data collected from this operating power plant. Details of GT modeling using Modelica language and ThermoPower library have been presented. Furthermore, the simulation results have been discussed in this article. The model has been examined in two different cases: the temperature effect and the reduction in fuel flow at a steady state. Besides, a comparison between the reel and simulation results for a different amount of fuel has been investigated. The accuracy of these simulations is noted and proven by the coherence of the simulation results with the experimental data collected from the power plant company.

1. INTRODUCTION

Modeling and simulation are becoming more important since engineers need to analyze increasingly complex systems composed of many components from different domains [1]. A large variety of modeling and simulation environments is available today, and it becomes more attractive every year with the tendency concerning the simulation of complex and heterogeneous systems. Modeling complex physical systems requires complete mathematical modeling to define the system behavior and, at the same time, structure concepts for the models' description. Modeling of power plant processes may be approached using different points of view, depending on the purpose for which the model is intended. Plant components may be classified first by looking at the subsystem they belong to, then considering the nature of the process transformations they implement [2]. Therefore, modeling power units by aggregating component models is very convenient because it reflects the physical plant layout and enhances the reuse of modeling tools.

Recently, object-oriented and non-causal modeling has been one of the most researched items in modeling and simulation. The object-orientation concepts enable an easy adaptation of the behavior and properties of an existing system in different contexts. These concepts are the foundation of the Modelica language [3–5]. Using knowledge of experts in the domain, encoded in simulation tools and libraries with different levels of details, to build models that closely reflect the actual behavior of the system is the main principle of Modelica language [3–5]. In this article, the Modelica language concept will be presented, followed by a citation of the main objectives of the Modelica tool. Hence, a dynamic simulation of a Gas turbine operating in a combined cycle power plant will be simulated in Modelica by considering different simulation states. The simulation results will be compared to the experimental ones.

2. GAS TURBINE

The Gas turbine is the principal and crucial part of the design of power plant generation [6]. It plays a significant role in the CCGT power plant. It can be considered the most crucial equipment in the plant since it provides almost two third part of the power production (GT produces about 60 %, while 40 % is provided by a steam turbine (ST), at base load) and supplies the thermal energy needed by the steam cycle. Therefore, it represents the most influential element in the efficiency of the power plant. Furthermore, the GT can operate independently, even if components of the plant are shut down for maintenance or if only a part of the unit's total capacity is necessary. The three main elements of the GT are coupled as follows; a compressor coupled to a turbine and a combustion chamber in between [7]. Air under atmospheric conditions enters the compressor, which is then compressed to a required pressure level for combustion. Because of the adiabatic compression, the air undergoes an increase in temperature and pressure. In the combustion chamber (combustor), the air is mixed with fuel and burned under constant pressure to produce thermal energy. High temperature and high-pressure gases are expanded in the turbine, generating mechanical power to drive the compressor and the coupled electrical generator [6].

3. MODELICA LANGUAGE

Building models that closely reflect the system's actual behavior starts from the knowledge expert encoded in simulation tools and libraries with different levels of detail. This principle is the basis of Modelica language, which allows for a detailed and object-oriented description of individual components. Therefore, it can be used to generate models of large systems automatically.

Modelica is an object-oriented language for modeling various and large, complex systems. It is suitable for multi-domain modeling, for instance, automotive, mechatronic models, robotics, and aerospace applications involving mechanical, electrical, hydraulic control, and state machine subsystems [5].

Modelica is a declarative modeling language freely available, maintained, and conserved by the Modelica Association [8]. Models in Modelica are mathematically described by differential, algebraic, and discrete equations. In addition to the declarative aspect, Modelica provides support for a causal connection that enables building models with a structure corresponding to the physical system. Thereby, the components elaboration is based on the object-oriented modeling method, each component is described using differential-algebraic equations, and then the components are connected via a-causal connection equations to create the

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complete model [9]. Modelica can solve various problems in terms of differential-algebraic equations (DAEs), describing the behavior of continuous variables utilized to efficiently handle large models with more than one hundred thousand equations [8,9].

Commercial software products such as MathModelica [10] or Dymola [11] can acquire the simulation using Modelica. However, there are also open-source projects like the OpenModelica(OMEdit) (www.openmodelica.org), which is an open-source Modelica-based modeling and simulation environment intended for industrial as well as academic usage [12].

4. OBJECT MODELING IN MODELICA

Modelica is the concept of multi-domain modeling, which gathers different aspects of the physical system and encapsulates them in the same model [13]. The Modelica language is well-established for modeling complex systems in various manufacturing domains [3]. Casella F. [14], from his personal experience and based on published literature, states that the following steps can summarize the standard workflow of state-of-the-art Modelica tools.

- The Modelica code is parsed; classes are expanded, instantiated, and eventually brought into the so-called flat form.
- Structural analysis of the differential-algebraic equations (DAEs) is performed to solve them efficiently for the state derivatives and algebraic variables. This process includes equation ordering (BLT transformation), may require symbolic index reduction, and usually involves extensive symbolic processing, as well as the use of advanced techniques such as tearing or reshuffling for solving sub-systems of equations efficiently. In most cases, numerical solvers are required for linear and non-linear systems of algebraic equations.
- The code, which is the result of the previous step, is linked to some well-tested, general-purpose dense Ordinary Differential Equation (ODE) solver, including root-finding algorithms to handle state events in the case of hybrid models.

5. THERMOPOWER LIBRARY

ThermoPower is an open-source library developed by Francesco Casella, at the Politecnico di Milano, for the dynamic modeling of thermal power plants [15]. The library provides the essential components for modeling power plants (turbines, heat exchangers, drum boilers, pipes, valves, *etc.*), providing a high level of detail and accuracy. ThermoPower library has been validated against experimental data-based physical systems [16], and each component in the library has been tested in different configurations. In addition, the ThermoPower library has been validated for dynamic plant simulation and controlling system and optimization.

The library features, together with the Modelica language, make ThermoPower to be an attractive option for developing accurate models of thermal power systems and CCGT plants. The library has been developed conferring to the following main principles [16,17]:

1. The model components are derived from the first principal equations (mass, energy, and momentum balance) or acknowledged empirical correlations.
2. The model interface is independent of the modeling assumption adopted for each component to achieve full modularity.
3. The level of detail of the models is flexible.
4. The inheritance mechanism is used with limitations to maximize the code readability and modifiability.

6. GT MODELING USING OMEDIT-OPENMODELICA

The main idea of this research is to build a reliable GT model simulated in Modelica (OMEdit-OpenModelica) and compare the simulation results to the reel ones. The model is constructed by using the ThermoPower library. The main component used in this model is the pressure drop (*dP*) model, which is a lumped model that computes a punctual pressure drop. When the pressure drop is computed, the fluid is assumed incompressible, and no thermal energy losses to the environment are considered further. The source pressure, the source mass flow, and the sink pressure are connected to the GT_ISO unit.

The GT_ISO unit model in the ThermoPower library requires introducing the parameters under ISO conditions. According to the ISO standards 3977-2 (Gas Turbines - Procurement - Part2: Standard Reference Conditions and Ratings), the ISO ambient conditions for the industrial gas turbine are designated as follows [18]:

– Ambient temperature 15 °C (59 F).
– Relative humidity 60 %.
– Ambient pressure 1.013 bar.

However, in our case, the parameters collected from the power plant company are not at ISO condition. So, in this situation, some calculations are needed to find a solution that permits the use of the GT_ISO unit. The proposed solution exploits the named "correction curve of the power output" that represents the output power correction factors as a function of the ambient temperatures. The following sections of this article present the necessary calculations to get the parameters at ISO conditions.

7. SIMULATIONS, RESULTS, AND DISCUSSION

7.1. DESCRIPTION OF THE COMBINED CYCLE GAS TURBINE PLANT OF RAS_DJINET

The combined cycle gas turbine (CCGT) power plant of RAS-DJINET, situated at the seaside in Boumerdes (Algeria), is designed to produce a total output power of 1131.1 MW. The RAS-DJINET plant consists of three single-shaft combined cycle gas turbine units, each producing almost 400 MW. The CCGT unit consists of one gas turbine associated with one heat recovery steam generator (HRSG) and one steam turbine with high performances (3 levels of pressure), and a typical hydrogen-cooled generator [19] located on the same shaft between the gas turbine (GT) and the steam turbine (ST). The Gas turbines are designed to use natural gas as the base fuel, while diesel fuel is held as the backup fuel. The electrical generator is coupled directly to the Gas Turbine; however, it is coupled with Steam Turbine through Self Shifting and Synchronizing (SSS) Clutch. This CCGT is designed to operate under the following ambient conditions [19]:

– Ambient Temperature: 35 °C,
– Relative Humidity: 76 %,
– Barometric Pressure: 1.013 bar,
– Frequency: 50 Hz,

– Fuel Gas Lower Heating Value: 45001.3 KJ/Kg,
– Generator Terminal Power Factor: 0.9.

7.2 CALCULATION OF THE POWER UNDER ISO CONDITIONS

Changes in ambient temperature impact the full load power and heat rate of a gas turbine, but also part-load performance and optimum turbine speed [20,21]. Manufacturers typically provide performance maps that describe these relationships for ISO conditions. However, when these characteristic maps are not accessible, the correction curves may be used as the primary way to get some information about the engine, for instance, the correction curve of the power output. This characteristic curve is used in the power plant as a meaningful way to get the output power under ISO conditions from that acquired at any ambient temperature.

Figure 1 shows the correction curve, which represents correction coefficients as a function of the ambient temperatures. The Y-axis represents the ratio between power output at any temperature and power output at the reference temperature. The reference temperature for the curve is 15 °C (59 F); for that reference temperature, the gas turbine power output correction factor can be taken as one. The output power correction factor increases for temperatures above the reference temperature (15 °C) and vice versa.

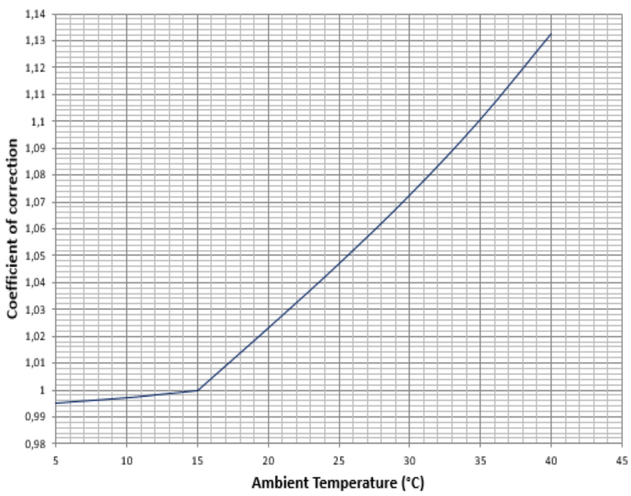

Fig. 1 – The correction curve of the power.

For different values of temperature, we present the corresponding GT_output power at full load and the calculated output power under ISO conditions, which is a result of the multiplication of each value of output power by its corresponding correction factor extracted from the correction curve presented in Fig. 1. The calculated output power under ISO conditions using the correction curve is represented in Table 1.

Table 1

The calculated power under ISO conditions using the correction curve.

Ambient Temperature(°C)	GT_OutputPower (MW)	GT_OutputPower_ISO (MW)
11.46	288.26	287.69
15.55	279.60	280.16
20.56	275.06	282.22
22.57	272.16	282.51
25.31	265.44	279.24
29.00	258.90	277.32
31.30	255.80	276.77

With the same procedure of using the correction curve presented in fig.1. the calculated output power under ISO conditions for different loads is represented in Table 2.

Table 2

The calculated power under ISO conditions for different loads

Ambient Temperature(°C)	Load (%)	GT_Output Power (MW)	GT_Power_ISO (MW)
11.46	100	288.26	287.69
20.56	95	275.06	282.22
14.90	65	186.38	186.38
15.00	62	179.84	179.84
14.90	45	129.25	129.25
06.00	20	62.24	61.98

7.3 GT MODEL DETAILS AND VALIDATION

Using a graphical model, the model is constructed by positioning icons that represent the models of the components, as shown in Fig. 2, then connecting the different components of the model, namely the source Pressure, the source mass flow, the pressure drop, the GT_ISO unit and the sink pressure, after that introducing the parameter values in dialogue boxes.

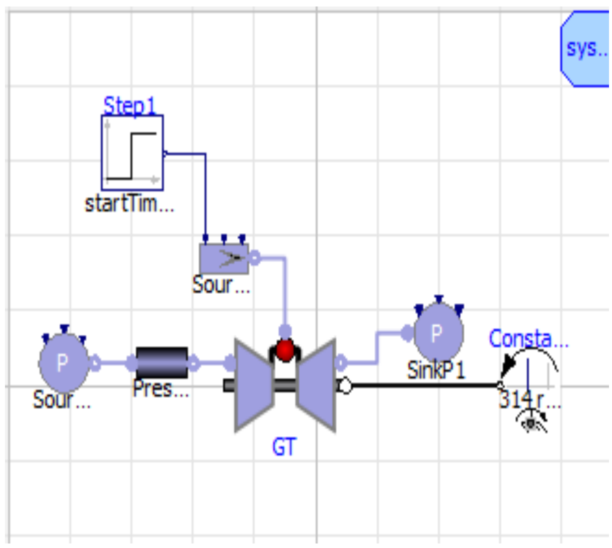

Fig. 2 – Simulated gas turbine model.

The gas turbine_ISO unit model is used when only one performance curve is known under ISO conditions: 15 °C temperature and 1.013 bar pressure at the air inlet, and nominal rotational speed. The parameters of the data table, presented in Table 3, must be introduced in the text view (editor) of the simulating Modelica model. While the other parameters may be introduced in the text view or the parameters table. These parameters are tabulated into the matrix Data table, from the minimum value to the maximum one. These parameters include:

1. Zero loss power output in ISO conditions,
2. Heat input in ISO conditions,
3. Pressure ratio,
4. Inlet air flow rate in ISO conditions.

Table 3

The Parameters of the data table

Load (%)	GT_Power_ISO (MW)	Heat input (MW)	Pressure ratio	Inlet air flow rate (kg/s)
100	287.69	698.86	19.01	568.90
95	282.22	678.16	18.16	546.05
65	186.38	661.06	13.22	403.64
62	179.84	653.86	13.08	333.84
45	129.25	397.36	10.98	327.57
20	61.98	333.84	9.62	325.23

The validation of the GT model has been made by strictly comparing its responses to the variation of the input signals with the ones obtained by experimental actual data. Remind that the GT data are derived from the operating power plant of Ras_Djinet. The model has been investigated in two different cases: the temperature effect and the reduction of fuel flow at a steady state.

First case: Simulation at 15°C and 35°C:

The simulations deal with the steady state for two different temperatures, 15 °C, and 35 °C, Fig.3 and Fig.4. It has been noted that the GT output power for zero losses is more important than the net output power. The simulated GT's Net output power (Pout) increases from 267.528 MW, at 15 °C, to 267.992 MW at 35 °C. While the output power for zero losses (ZL Pout) increases from 281.608 MW to 282.097 MW, which is not far from the actual maximum power the operating GT provides (287 MW). These increases are because the GT performance is affected by the ambient temperature.

On the other hand, the simulation results in Fig.5 showed that; at 15°C the output power for zero loss power, referred to ISO conditions (ZL Pout _ISO), is around 292.345 MW, while at 35 °C the output power is around 291.958 MW. The GT is simulated at the standard condition with no losses. So, it is noted that the output power is more critical for 15°C. It is crucial to mention that the examined GT is designed to work at 35 °C. We can also mention that the obtained results are still around their rated value.

The different values of the output power at full load, simulated at 15 °C and 35 °C, are represented in Table 4.

Table 4

The output power at full load

Ambient temperature (°C)	Pout (MW)	ZL Pout (MW)	ZL Pout _ISO (MW)
At 15°C	267.53	281.61	292.34
At 35°C	267.99	282.09	291.96

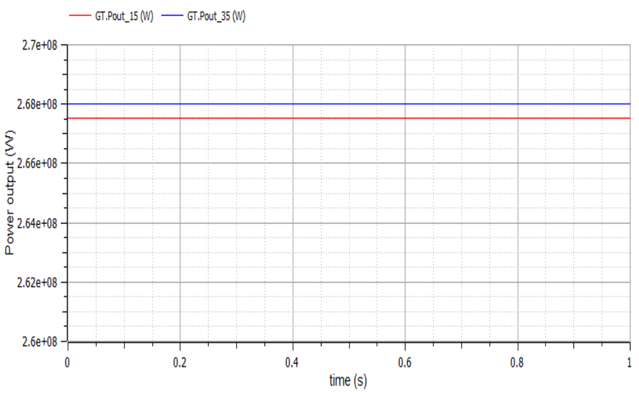

Fig. 3 – The GT output power

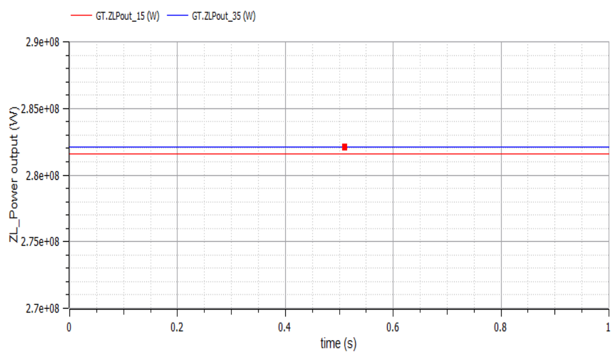

Fig. 4 – The GT output power for zero loss power.

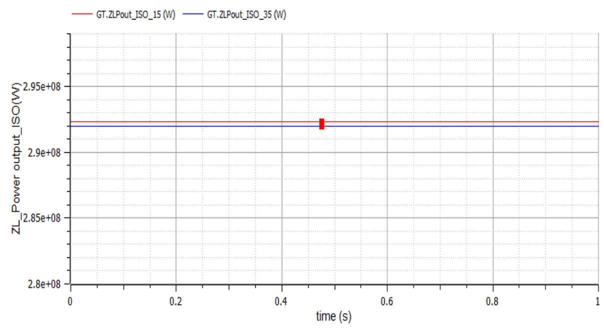

Fig. 5 – The GT output power for zero loss power, referred to ISO conditions.

The second case: The simulations deal with a step reduction in fuel at t = 3 s. The simulation results are presented in figures below.

In this case, the model is simulated starting from a steady state condition, and the fuel flow rate is reduced by 30 % at time t = 3 s. The simulation results showed that each parameter of the GT, namely the output power, the pressure ratio, the heat input, and turbine torque, is affected by this reduction in the fuel flow, as shown in Fig. 6 to Fig. 9, respectively. Figure 6 shows a comparison among the three mean powers, namely the net output power (Pout), which decreases from 267.992 to 267.315 MW; the output power for zero loss (ZLPout) decreases from 282.097 to 281.385 MW at time 3 s, while the output power for zero loss referred to ISO conditions (ZLPout_ISO) decreases from 291.958 to 291.087 MW. It can be noted that the rate of the reduction of the output power at t= 3 s is approximately the same.

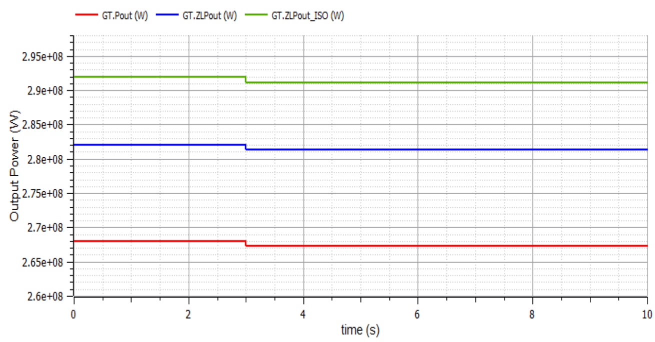

Fig. 6 – Comparison of the three considered GT output power.

On the other hand, the heat input, referred to ISO conditions, goes from 733.09 to 728.04 MW. The heat input decreases from 708.33 to 703.77 MW. While the pressure ratio goes from 19.72 to 19.58, and the net torque acting on the turbine decreases from 853478 to 851323 N.m. The obtained results are illustrated in Figs. 7 to 9, respectively. The simulation results show and confirm the simulated GT model's sensitivity to this fuel reduction.

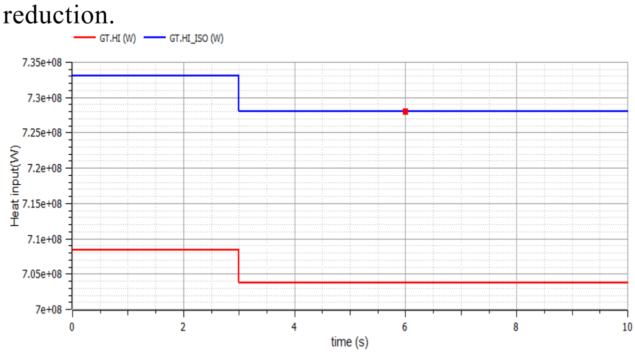

Fig. 7 – The heat input

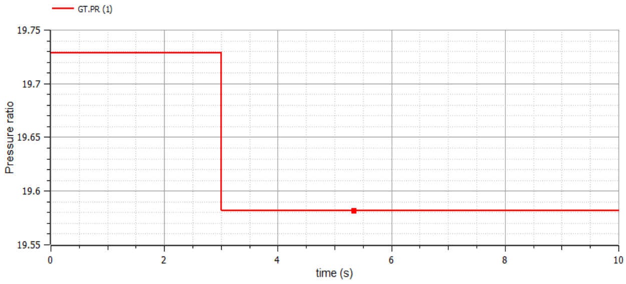

Fig. 8 – The pressure ratio

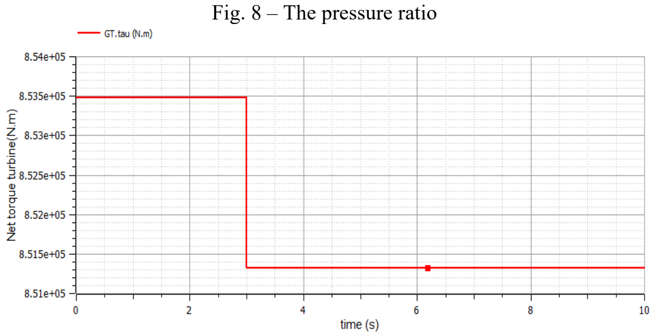

Fig. 9 – The turbine torque

7.4 COMPARISON BETWEEN THE REEL AND SIMULATION RESULTS

Table 5 compares the output power of the GT obtained from the simulation study and the reel values obtained from the power company. The calculated error between the simulation results for a different amount of the injected fuel and the actual experimental values is given in (%). It can be noted that the error is stuck between 2.77 % and 7%. These results are satisfactory since they are close to the values collected from the power plant company.

Table 5

The calculated error of simulation (at 15 °C)

Amount of Fuel (kg/s)	Real value of the output power (W)	The obtained output Power by Simulation (W)	Error (%)
7.31	61.98 e 6	6.41745e+07	3.54
8.71	129.25e6	1.25663e+08	2.77
10.45	179.84e6	1.70518e+08	5.18
10.92	186.38e6	1.77157e+08	4.94
14.52	279.24e6	260.543 e+08	6.69
14.86	282.23e6	2.62973e+08	6.82
15.53	287.69 e6	2.67528e+08	7.00

The calculated errors in simulation for the obtained power output at 35 °C are presented in Table 6. The same thing as in the last case, the simulation results are compared to the real ones. The calculated error between the obtained and the actual values are stuck between 1.78 % and 6.84 %. Therefore, the results are more satisfactory in this case than those calculated at 15 °. However, they remain in the same range.

Table 6

The calculated error of simulation (at 35 °C)

Amount of Fuel (kg/s)	Real value of the output Power (W)	The obtained output Power by Simulation (W)	Error (%)
7.31	61.98 e 6	6.30895e+07	1.78
8.71	129.25e6	1.25109e+08	3.20
10.45	179.84e6	1.70647e+08	5.11
10.92	186.38e6	1.77111e+08	4.97
14.52	279.24e6	2.60988e+08	6.53
14.86	282.23e6	2.63426e+08	6.66
15.53	287.69 e6	2.67992e+08	6.84

8. CONCLUSION

This article has considered a case study where the gas turbine model is simulated using Modelica language. To show the performance of the simulated GT model, the obtained simulation results have been compared with the experimental data getting from the power plant company of RAS-DJINET.

– The validation of the GT model has been made by strictly comparing its responses to the variation of the ambient temperature in two different cases namely at 15°C and 35°C with the experimental actual data.
– The validation of the GT model has been examined by its sensitivity responses to a reduction in fuel flow at a steady state.
– The validation also has been investigated by comparing its responses to the variation of the amount of fuel with the experimental data.
– The accuracy of these simulations has been inspected, and the simulation error doesn't exceed 7% in the worst case.

Therefore, the simulation results of the GT model based on Modelica language are coherent with the data collected from the power plant company.

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REFERENCES

1. D. Talah, H Bentarzi, Modeling and Analysis of Heavy-Duty Gas Turbine Based on Frequency Dependent Model, International Conference on Electrical Engineering (ICEE), Istanbul, Turkey, 25-27 (Sept. 2020).
2. D. Flynn, Thermal power plant simulation and control, **43**, IET, 2003.
3. H. Elmqvist, S.E. Mattsson, M. Otter, Modelica – a language for physical system modeling, visualization and interaction. In Proceedings of the IEEE international symposium on computer aided control system design, pp. 630-639 (August 1999).
4. P. Fritzson, P. Aronsson, P. Bunus, V., Engelson, L., Saldamli, H. Johansson, A. Karström, *The open source Modelica project*, Proc. 2nd International Modelica Conference, pp. 18-19 (March 2002).
5. J.-c. Park, *Modeling and Simulation of Selected Distributed Generation Sources and Their Assessment,* Graduate Theses, Dissertations, and Problem Reports, pp. 989 (1999).
6. D. Talah, H. Bentarzi, *Ambient temperature effect on the performance of gas turbine in the combined cycle power plant*, Algerian Journal of Environmental Science and Technology (2021).
7. D. Talah, H. Bentarzi, *Comparative study on modeling of heavy duty gas turbines*, 7th International Conference on Renewable Energies, Sousse-Tunisia (December 2019).
8. ***Modelica Association. The Modelica Association, https://www.modelica.org/.
9. A. Tica, *Design, Optimization and Validation of Start-Up Sequences of Energy Production Systems*, Doctoral dissertation, Supélec (2012).
10. M. Jirstrand, J. Gunnarsson, P. Fritzson, *MathModelica – a new modeling and simulation environment for Mathematica* (1999).
11. D. Brück, H. Elmqvist, S.E Mattsson, H. Olsson, *Dymola for multi-engineering modeling and simulation*, Proc. of Modelica, Citeseer (March 2002).
12. S.A. Asghar, S. Tariq, *Design and Implementation of a User-Friendly OpenModelica Graphical Connection Editor* (2010).
13. N. Petchers, Combined Heating, Cooling & Power Handbook: Technologies & Applications.: The Fairmont Press, Inc, Georgia, 2002.
14. F. Casella, *Simulation of large-scale models in Modelica: State of the art and future perspectives*, 11th Int. Modelica Conf., pp. 459-468 (2015).

15. F. Casella, F. Schiavo, *Modelling and simulation of heat exchangers in Modelica with finite element methods*, Proc. 3rd Int. Modelica Conference (November 2003).
16. F. Casella, A. Leva, *Object-oriented modelling & simulation of power plants with Modelica*, 44th IEEE Conference on Decision and Control (December 2005).
17. F. Casella, F. Pretolani, *Fast start-up of a combined cycle power plant: a simulation study with Modelica*. Proc, 5th Int. Modelica Conference, pp. 3–10, Vienna, Austria (4–6 September 2006).
18. K.A.B. Pathirathna, *Gas turbine thermodynamic and performance analysis methods using available catalog data*, 2013.
19. ***Ras_Djinet power plant Documentation.
20. R. Kurz., K. Brun, *Gas turbine performance,* In Asia Turbomachinery & Pump Symposium. Proceedings. Turbomachinery Laboratories, A&M Engineering Experiment Station, Texas (2016).
21. I. Meriche, A. Chemoul, T.E. Boukelia, *Analyse 4E (énergetique–exergétique–économique-environnementale) d'une centrale thermique à vapeur*, Rev. Roum. Sci. Techn. – Électrotechn. Et Énerg., **67**, *2*, pp. 199-205 (2022).