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RESEARCH ARTICLE

Development of a digital twin of the capstone C30 micro gas turbine unit

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ABSTRACT

This article presents the results of developing a mathematical model of the Capstone C30 micro-GTU in SimInTech, on the basis of which a digital twin was developed. It allows obtaining the values of the supplied electric power, turbine rotor speed, fuel pressure after the booster compressor, gas temperature after the turbine and exhaust gas temperature from sensors installed on the micro-GTU. These values are compared with the parameters calculated in the mathematical model and displayed to the operator for further analysis. The paper presents the structure of the digital twin of the Capstone C30 micro-GTU.

Keywords: digital twin; micro-GTU; Capstone C30; SimInTech

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1. Introduction

In recent decades, the issue of transition to high-tech production has become very relevant. Due to the fact that information technologies are developing at a tremendous speed, it becomes possible to collect, store, transmit and analyze large amounts of data, therefore, the concept of the Industrial Internet of Things (IIOT) is actively used in industry, which ensures the automation of the enterprise, combines measured values and allows remote control of the technological process[1]. One of the elements of IIOT can be a digital twin (DT). The concept of a digital twin was first defined by Michael W. Grives[2]. The development of digital twins is currently underway in the Russian Federation[3-4].

The pace of digitalization is also growing in education, where the same technologies are often used. Digital data can be used in training engineering personnel and allows students to gain experience in interacting with equipment, interference in the operation of which can entail significant risks, including financial losses and a threat to human life and health. There are already examples of work that describe the use of digital data for training operational and dispatch personnel of automated industrial complexes[5], modeling installations for educational purposes[6] or laboratories[7].

In order to reduce the costs associated with the operation and repair of equipment, as well as to improve the efficiency of facilities in the energy sector, the concept of digital twins is being actively implemented. The development of a digital twin for new or already operated equipment will help to cope with the task. A mathematical model, which is part of a digital twin, is able to calculate optimal operating modes to improve equipment performance. There is a growing interest in the possibility of using cloud computing and big data technologies (Big Data) for industrial automation[8-10]. This technology is often used in the development of digital twins using predictive diagnostics, which can facilitate the timely detection of possible defects at early stages of development[11]. Big data technologies will allow structuring data, finding dependencies and correlations in a large volume of data constantly coming from sensors.

Figure 1 shows a typical structural diagram of a digital twin[12]. It includes the following components: an object with sensors installed on it to measure operational parameters, a database of measured and controlled values of technological processes, a reference mathematical (simulation) model in which the technological parameters of the object's operation in various operating modes are calculated, and a data analysis system. The result of the digital twin's operation is a comparison of data obtained from the APCS database with the calculated parameters from the mathematical model, and the output of the comparison results to the operator in a convenient form for subsequent analysis in real time.

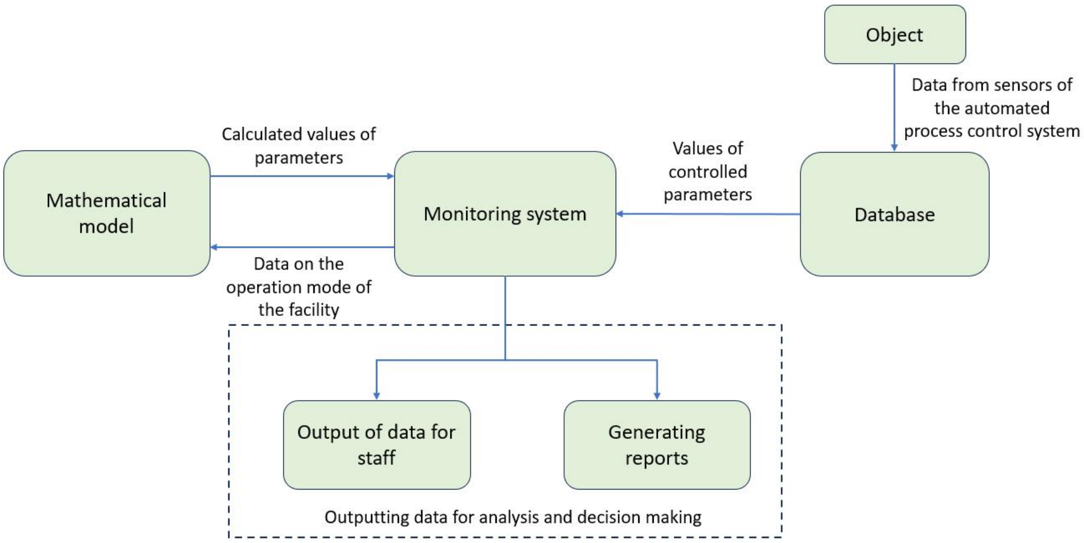

Figure 1. Structural diagram of a digital twin.

One of the Russian digital twin products for thermal power plants is the PRANA forecasting and remote monitoring system[11]. Thanks to the precise adjustment of the mathematical model included in it, it is possible to achieve accurate forecasts for the timing of the operational parameters going beyond the established limits. The mathematical model is developed based on the obtained array of data on the state of the object and its technological parameters. The mathematical model uses technologies for processing big data and predictive diagnostics technologies. As a result of the digital twin's operation, it is possible to predict the state of the equipment, due to which the number of emergency situations decreases, which means that it is possible to switch to maintenance based on the technical condition.

The article[13] describes in detail the development of a mathematical model of the General Electric LM2500 gas turbine engine, and then, based on it, a digital twin is developed that compares the measured operating parameters with the calculated values. During the operation of the digital twin, the temperature and pressure at the inlet and outlet of the compressor and turbine and the rotation speed of the turbine rotor are monitored. A user interface is also developed that displays all operating parameters, as well as the comparison results. The developed mathematical model describes the change in parameters quite accurately, as can be judged by the error of less than 1.5%.

The article[14] describes in detail the development of a digital twin of a 320 MW thermal power plant based on Thermoflo w software , which has built-in models of a steam turbine and a boiler. The developed mathematical model is verified based on the results of the power unit operation and has an error in calculating the operating parameters of less than 2%. The result of the digital twin operation is the calculated optimal operating mode of the power unit in the modes of generating electric and thermal energy from the point of view of minimal costs for their production. The digital twin of the power unit will help to effectively operate the power unit in conditions of fluctuating prices for thermal and electric energy.

The article[15] describes the development of a digital twin of a steam boiler, the mathematical model of which uses machine learning technologies. The mathematical model calculates the parameters of the working bodies of the air and steam-water tracts of the boiler, as well as coal mills and burners. The developed digital twin is used to predict changes in process parameters in real time. The result of the digital twin is the optimal operating mode of the boiler in order to reduce operating costs.

The article[16] describes the development of a digital twin of a steam turbine, the mathematical model of which is based on operational data. The verification of the mathematical model was carried out on the operational parameters of a 330 MW steam turbine operating at subcritical steam parameters and a 1000 MW steam turbine operating at supercritical steam parameters. After verification, errors within 1% were obtained.

The paper[17] describes the concept and structure of constructing a digital twin for a low-power turbogenerator unit based on an implicit-pole synchronous generator. The digital twin is based on an adaptive network based on a fuzzy inference system (ANFIS), which is one of the variants of hybrid neuro-fuzzy networks. A fuzzy controller with an auto-tuning unit is a fuzzy logical inference system with modules for identifying a digital model of the RG unit and for coordinated tuning of the excitation controller and speed controller[18]. The proposed concept is based on representing an object as a multi-connected structure with a certain number of input and output parameters and connections formed on the basis of experimental data. The studies were carried out on a computer model of a turbogenerator unit with an excitation controller and a speed controller with a capacity of 3125 kVA and a voltage of 10 kV, connected to the electric power system. The model is implemented in the MATLAB system. Based on the obtained experimental data, a fuzzy model of rotor speed control was constructed and optimized using the developed program. The results showed high accuracy (the standard deviation was less than 0.008) and practical suitability of the developed program for constructing individual links of the digital twin of the plant. The proposed algorithms can be used in further research aimed at the industrial implementation of digital twins of plants, as well as for solving the problem of setting up automatic regulators of low-power synchronous generators.

As a result of the literature review, it was found that most articles are devoted to the development of digital twins of large-capacity energy facilities. The development of digital twins for distributed and small-scale energy is not so active and is a pressing task. This article describes the process of developing a digital twin (DT) for the Capstone micro gas turbine unit From 30.

2. Research object

The object of research for the development of the (DT) is the Capstone micro-GTU C 30 (power 30 kW).

Figure 2 shows the basic diagram of a 30 kW micro gas turbine plant. The air and fuel consumption are 0.3 kg/s and 0.003 kg/s, respectively. The temperature of the combustion products at the turbine inlet is 800-900 °C, and the temperature of the exhaust gases is 260-300 °C.

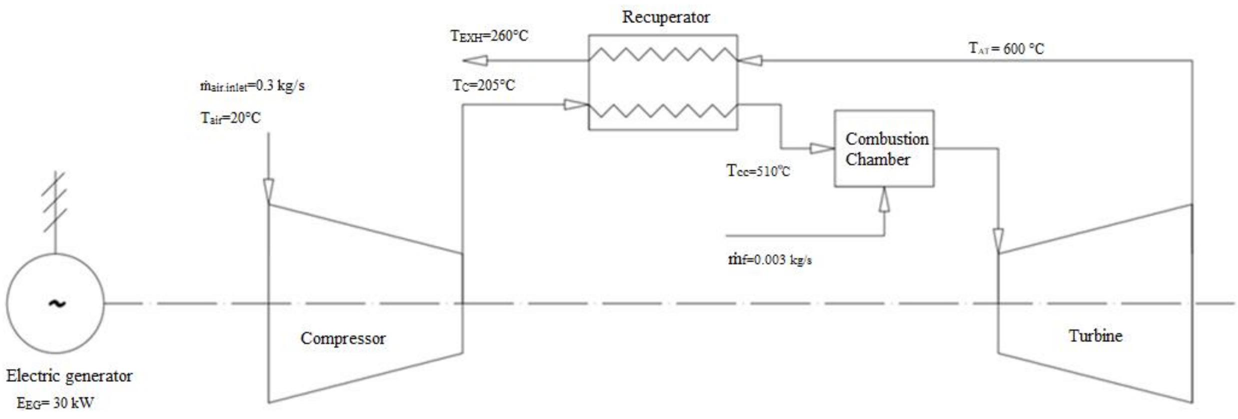

Figure 2. Schematic diagram of the Capstone C30 micro-GTU.

Capstone Remote Monitoring System " (Capstone Remote Monitoring Software) – special software required for reading values from sensors installed on the micro-GTU. It can also be used to perform the following functions: dispatching, control, recording trends, receiving notifications about accidents by e-mail. The controlled parameters are: gas temperature after the turbine, fuel pressure at the outlet of the booster compressor, turbine power and turbine rotor speed. Additionally, a thermocouple was installed on the exhaust of the micro-GTU to control the temperature of the exhaust gases.

3. Development of the structure of the digital twin and development of the mathematical model of the capstone C30 micro-gtu

In order to obtain a digital twin, it is necessary to link together 3 parts: the operating parameters of the installation, read using Capstone software Remote , the value of the temperature of the exhaust gases and the developed mathematical model. In order to link all the data, it was decided to develop a digital twin in SimInTech. Data obtained using Capstone Remote , are saved as a CSV file and read using existing ready-made blocks in SimInTech . The value of the temperature of the exhaust gases is obtained by polling the thermocouple by the OPC server, and is sent to SimInTech using a special ready-made block. **Figure 3** shows the structural diagram of the digital twin of the micro-GTU

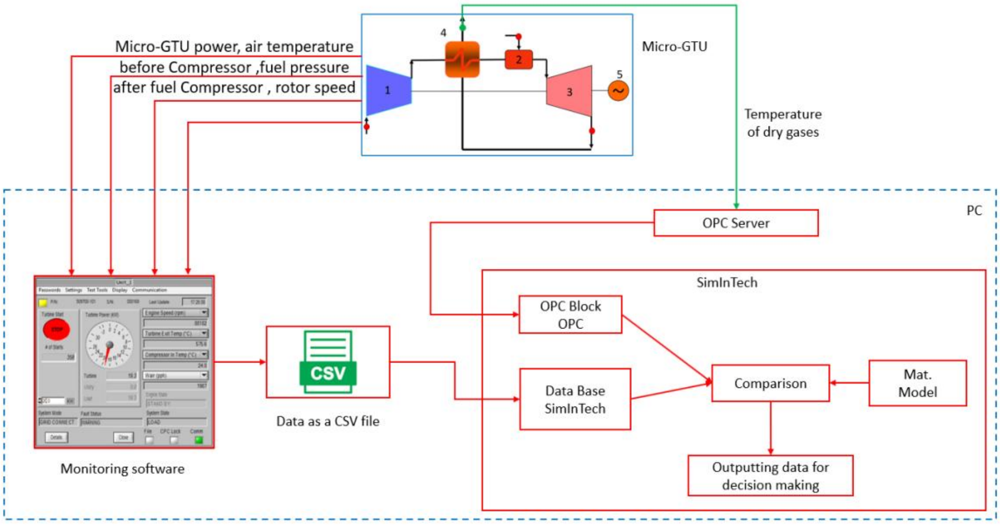

Figure 3. Structure of a digital twin.

1 – air compressor, 2 – combustion chamber, 3 – gas turbine, 4 – recuperator, 5 – electric generator

The SimInTech development environment does not contain ready-made calculation blocks for building a mathematical model of a micro-GTU, so for further calculations, calculation blocks were created to determine the properties of air, natural gas and components of combustion products. Based on the developed calculation blocks, models of a compressor, combustion chamber, turbine and recuperator were built. **Figure 4** shows a block diagram of the mathematical model of the Capstone C30 micro-GTU. Based on the measured parameters from the unit, the excess air coefficient is determined, taking into account which the composition of the combustion products is recalculated . Next, the enthalpy of the exhaust gases, the enthalpy after the combustion chamber, recuperator, compressor and turbine are calculated, after which the electric power of the entire unit and its efficiency are calculated. Taking into account the power of the unit, the temperature after the turbine and the temperature of the exhaust gases are calculated, after which they are compared with the measured parameters.

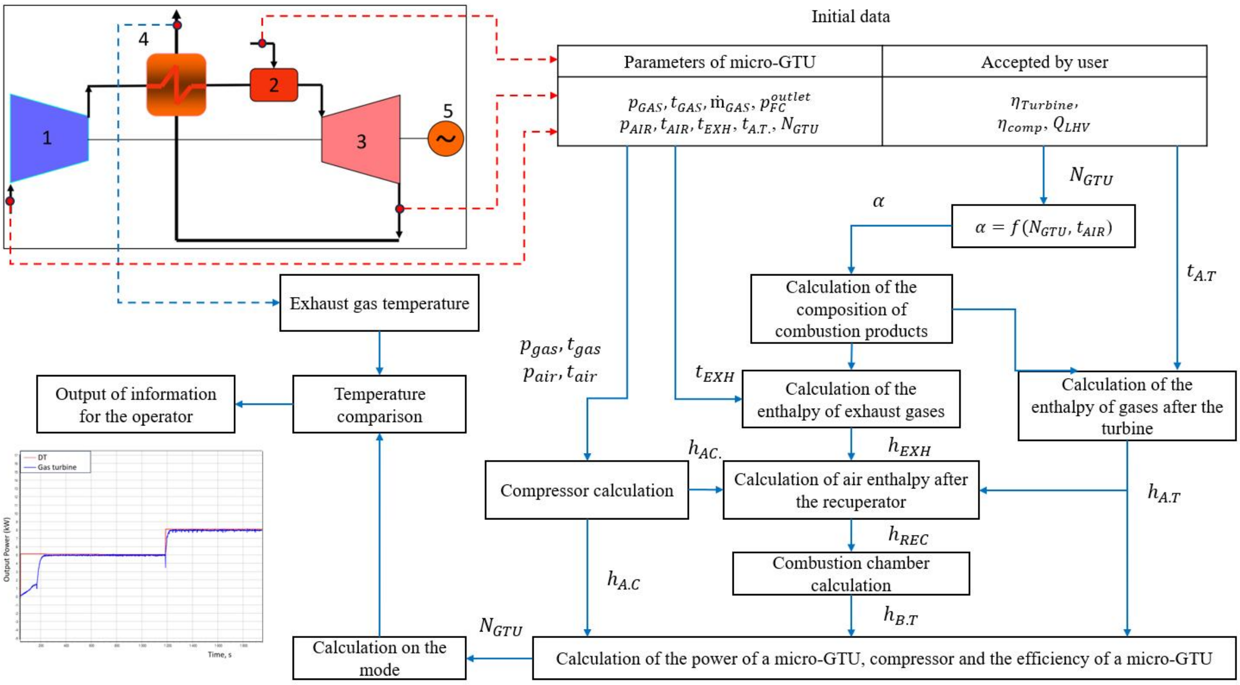

Figure 4. Block diagram of calculation of parameters in the mathematical model of micro-GTU

1 – air compressor, 2 – combustion chamber, 3 – gas turbine, 4 – recuperator, 5 – electric generator.

Reading data from the OPC server and comparing it with the calculated value is performed using 3 characteristic blocks: the OPC server data reading block, the results comparison block, and the data output block (**Figure 5**) . The data output block states that if the temperatures being compared differ from each other by no more than 2 degrees, the operator receives the message “Temperature within normal limits”, and if the temperatures being compared differ from each other by more than 2 degrees, the operator receives the message “Temperature has increased” or “Temperature has decreased”, depending on the sign.

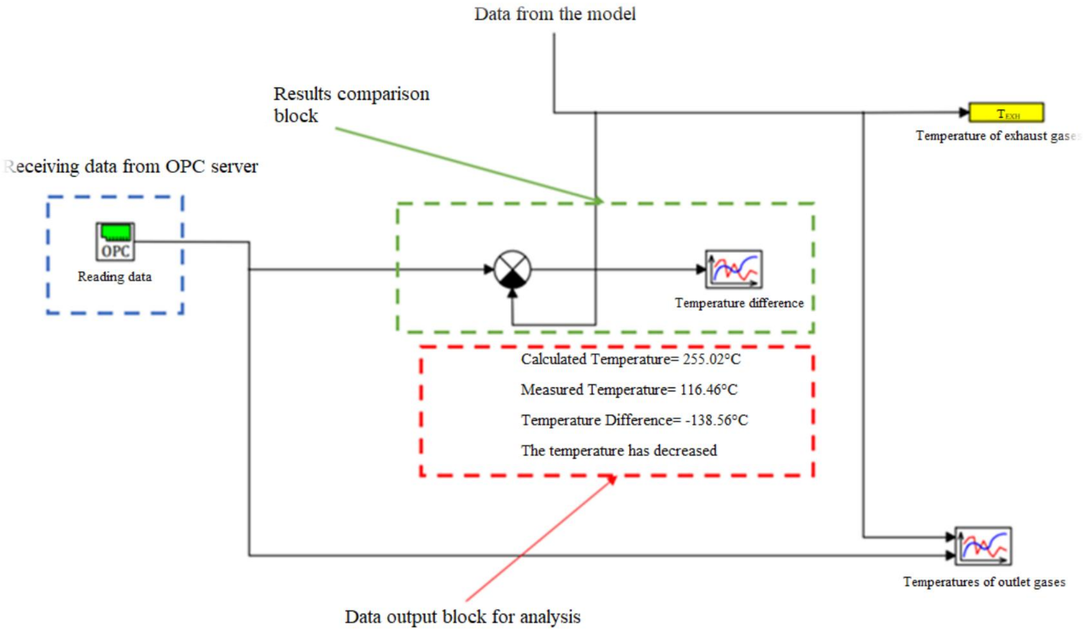

Figure 5. Block for importing the temperature of exhaust gases from a micro-GTU into SimInTech.

Since the data obtained using Capstone Remote , are saved as a CSV file as a data line, then in order to obtain this data in SimInTech a script was developed that extracts the necessary data from each line, creates a signal in the project database in SimInTech and assigns them the current value. Then the read parameters of the installation can be compared with the calculated parameters in real time.

4. Verification of the digital twin of the capstone C30 micro-gtu

To verify the mathematical model, a micro-GTU test was conducted in three modes: 10 kW, 15 kW and 18 kW. The results of changing the parameters of the Capstone C30 micro-gas turbine unit (power, gas temperature at the turbine outlet, gas temperature at the GTU outlet and gas pressure at the booster compressor outlet) are shown in **Figure 6**. The graphs presented have 4 zones: 1 – power 10 kW, 2 – power 15 kW, 3 – power 18 kW, 4 – unloading the unit to 0 kW.

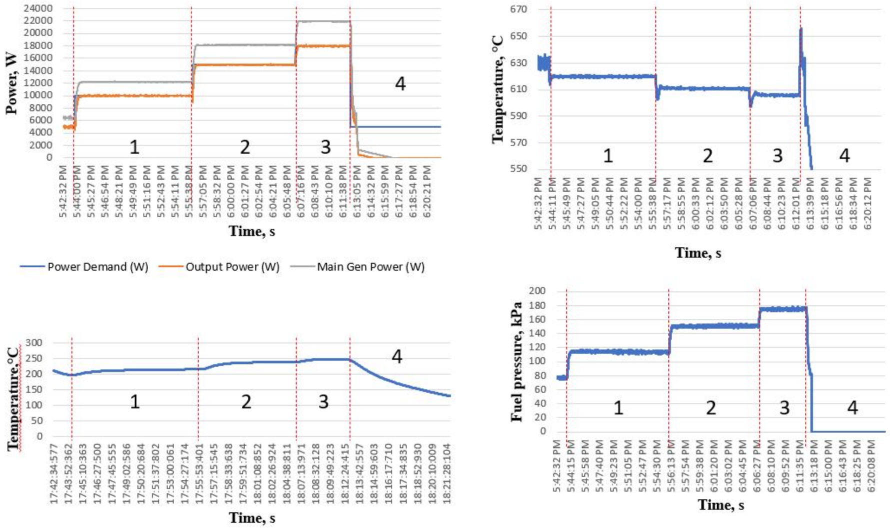

Figure 6. Micro-GTU test results.

Table 1 shows a comparison of the micro-GTU power values and exhaust gas temperature obtained in SimInTech with the values obtained as a result of tests. The deviation of the parameters does not exceed 0.05%, which indicates the adequacy of the created mathematical model of the micro-GTU Capstone C30 in SimInTech.

Table 1. Verification of the mathematical model of micro-GTU.

Parameter	Tests	SimInTech	Error
Exhaust gas temperature,℃	23 8.9	239	- 0 .04 %
Useful capacity of GTU, MW	15.56	15.552	0.05%

5. Checking the performance of the digital twin of the capstone C30 micro-gtu

To check the operability of the developed digital twin, micro-GTU tests were conducted at 5, 8, 10 and 12 kW. **Figure 7** shows a graph of the dependence of the released power on time, and **Figure 8** shows a graph of the dependence of the exhaust gas temperature on time.

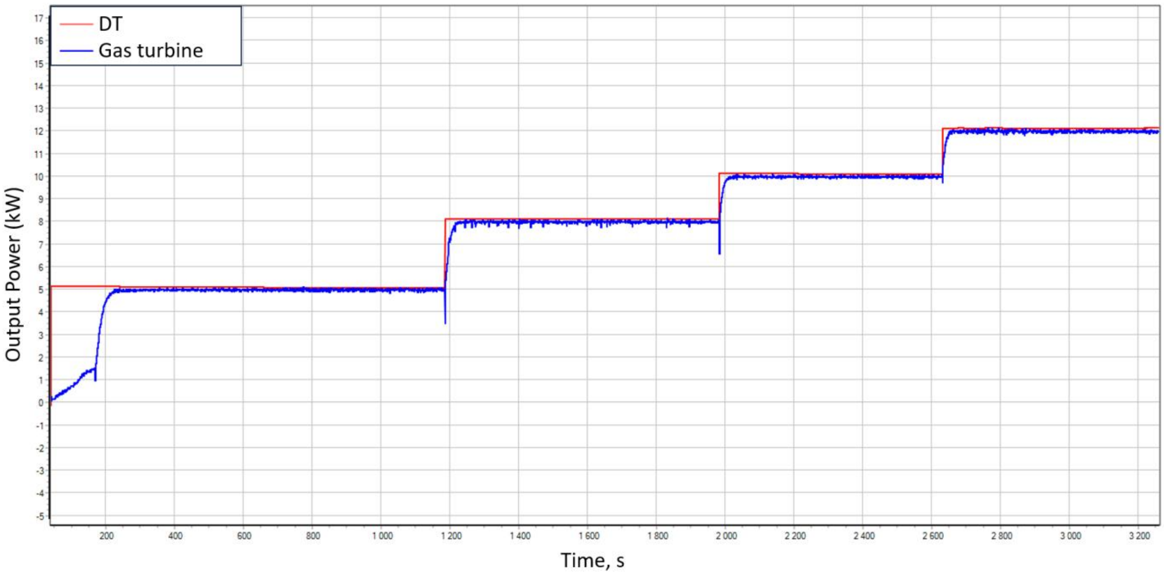

Figure 7. Output power, KW.

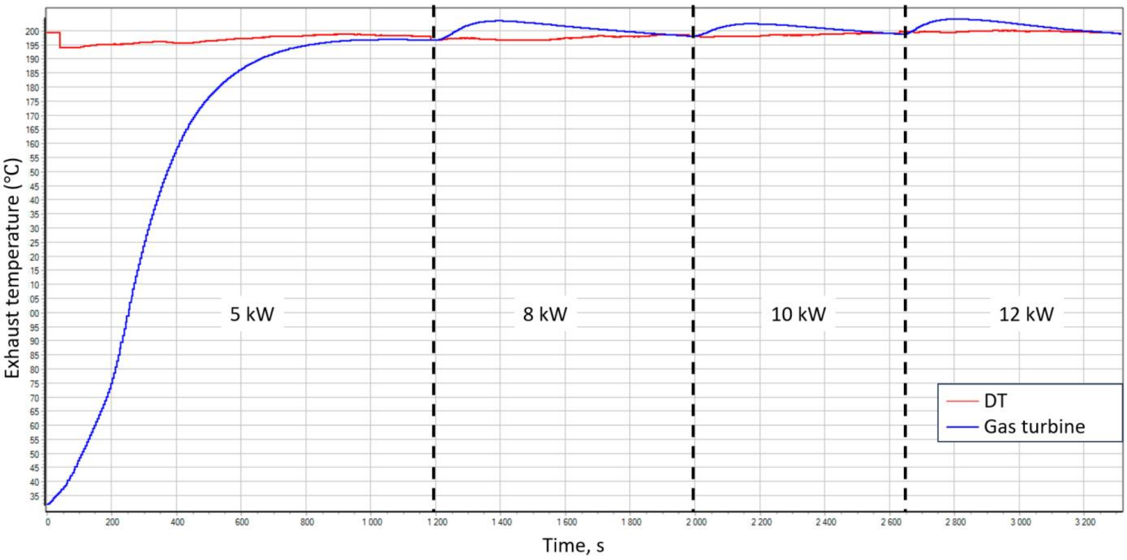

Figure 8. Exhaust gas temperature, °C.

From the graph of the released power, it can be seen that the microturbine from a cold state reaches the 5 kW mode in about 250 seconds. The transition from one load mode to another is about 50-60 seconds. After the microturbine reaches a steady-state operating mode, the deviation of the calculated value from the measured value is less than 1%.

On the graph of the exhaust gas temperature dependence, it can be seen that the mode is reached in much more time, since the thermocouple is very inertial. Thus, the time between start-up and reaching the 5 kW mode is approximately 1200 seconds, and the transition from one mode to another takes from 600 to 800 seconds. The mathematical model also takes into account the change in the temperature of the outside air entering the microturbine compressor. After the microturbine reaches the steady-state mode, the deviation of the calculated value of the exhaust gas temperature from the measured one is less than 0.5 °C.

Capstone micro-GTU CD C 30 allows measuring the temperature of exhaust gases, the temperature at the turbine outlet and the released electric power during its operation and comparing them with the calculated values obtained in the mathematical model. Thus, in the case of a strong difference between the operating temperature of exhaust gases and the calculated one, it is possible to draw conclusions about the possible occurrence of defects during the operation of the micro-GTU. For example, an increase in the temperature at the exhaust of the micro-GTU may indicate that foreign objects have entered the unit, or corrosion damage to the blades has begun, or contamination of the recuperator surface has occurred.

6. Conclusion

1. of the Capstone micro-GTU has been developed and verified C 30 for calculation and subsequent comparison with operating parameters of the following quantities: released electrical power, turbine rotor speed, fuel pressure after the booster compressor, gas temperature after the turbine and exhaust gas temperature.
2. of Capstone micro-GTU developed C 30, providing a comparison of operating parameters with values calculated in a mathematical model.
3. When testing the performance of the developed digital twin of the Capstone micro-GTU C 30 as a result of comparing the calculated values with the operating parameters, the following was obtained:
    - The error in calculating the supplied electrical power is less than 1%.
    - The error in calculating the temperature of gases after the turbine is less than 0.5%.
    - The error in calculating the temperature of the exhaust gases is less than 0.5 °C.

Author Contributions

Conceptualization, OSK and RAN; methodology, OSK; software, CDA; validation, CDA, OMV; formal analysis, OSK; investigation, CDA, OMV; resources, OSK; writing—original draft preparation, CDA and ZOV; writing—review and editing, OSK; visualization, OMV; supervision, OSK; project administration, OSK; funding acquisition, OSK. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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