



TWO-SHAFT GAS TURBINE TEACHING AND TESTING STATION

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Abstract

The station was established as part of a project co-financed by the European Union with the funds of the European Regional Development Fund as part of the Infrastructure and Environment Operational Programme titled: “Establishment of state-of-the-art technical infrastructure for the Engineers of the Future learning programme at the Gdańsk University of Technology” executed in 2013-2015.

Keywords: gas turbine, teaching station, testing station

Designations

h - enthalpy reduction

m - mass flow

n - shaft rotational speed

p - pressure

t - temperature

C - compressor

CC - combustion chamber

CT - compressor turbine

EB - eddy current brake

PT - power turbine

cycle points

0 - air inlet

1 - compressor inlet

2 - compressor outlet

3 - combustion chamber outlet

3' - crossover between turbines

4 - turbine outlet

5 - stack outlet

indexes

b - barometer

f - fuel

n - overpressure, leakages

p - negative pressure

s - isentropic change

T - turbine

γ - cooling

1. Introduction

Gas turbines are commonly used in aviation, land transport (locomotives, cars), military applications (tanks), in shipbuilding and for powering electric generators and other working machinery. When compared to other engines, gas turbines weigh less, their motions are more flexible, and their investment costs are lower despite relatively low efficiency. In many cases gas turbines prove to be more economical.

When designing gas turbines the main emphasis is placed on increasing their efficiency and, as a result, reducing their fuel consumption. Efficiency is increased mainly through the use of increasingly higher upper temperatures of the cycle by means of introducing new heat-resistant materials and improving the system of high-temperature sections cooling.

2. Two-shaft gas turbine

A two-shaft arrangement is usually used in aircraft propulsion, where a separate part of the turbine is designated solely for the compressor powering.

A set comprising a compressor, a combustion chamber and a compressor turbine performs the function of a gas generator. Its task involves the generation of hot compressed gas with parameters p_3 , t_3 which converts some of its heat energy into mechanical energy as part of an expansion process taking place in the compressor turbine. The role of a gas generator in a gas turbine set is similar to the role of a steam boiler with a feed pump in a steam turbine unit. Further expansion takes place over the power turbine, releasing its output to the receiver. In the discussed arrangement air as the working medium is drawn from the atmosphere and returns in the form of exhaust gas, which is why such cycles are called open cycles. They are most commonly used in gas turbines.

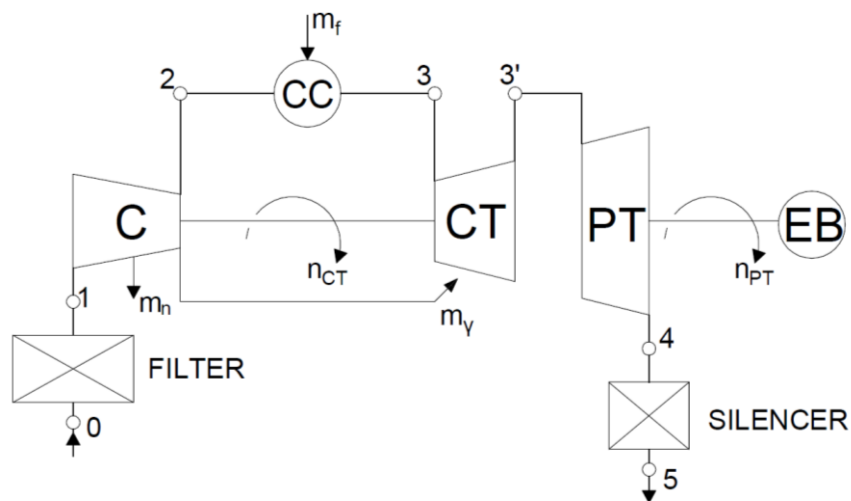


Fig. 1. Diagram of a two-shaft gas turbine

2.1. Turbine real cycle

Fig. 2 shows a real, simple, open cycle on an i - s diagram. In this arrangement air is drawn into the compressor through the filter increasing the pressure loss, which is why air pressure upstream of the turbine set in point 1 is slightly lower than atmospheric pressure.



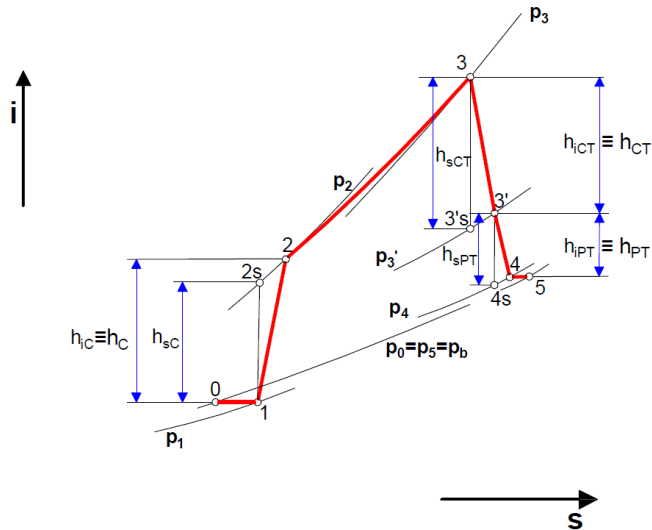


Fig. 2. Real, simple, open cycle of a two-shaft gas turbine

The compressor compresses air from point 1 to the highest pressure of the cycle, point 2. Air from behind the compressor is fed to the combustion chamber, reduced by cooling air jet m_γ and leakage air jet m_n . Liquid fuel is supplied to the combustion chamber where it evaporates, mixes with air and burns, releasing its heat to exhaust gas. At the combustion chamber outlet, point 3, exhaust gas pressure is reduced by pressure losses. Exhaust gas expands in the compressor turbine to pressure $3'$. The compressor turbine powers the compressor. Further expansion to pressure exceeding atmospheric pressure (point 4) takes place in the power turbine powering the receiver. The pressure drop from point 4 to point 5 (atmospheric pressure) is required due to exhaust gas flow resistance in the silencer and the stack.

3. Experiment on a turbine engine

The gas turbine installed at the testing station at the Department of Automatics and Turbine Propulsion at the Faculty of Ocean Engineering and Ship Technology is a lightweight, aircraft type turbine used for powering a helicopter [1, 2]. It operates as a simple cycle with cooling – Fig. 1 and 2.

The gas turbine includes (see: Fig. 1 and 3):

- compressor C — comprising seven axial stages and one radial stage,
- combustion chamber CC – comprising the CC casing with a spiral housing, with air tubes, a flame tube, a working injector and an ignition device,
- compressor turbine CT – axial, single-stage turbine,
- power turbine PT – axial, two-stage turbine,
- eddy current brake EB – directly connected to the turbine shaft.





Img 1. View of a two-shaft gas turbine

The power turbine was connected with the power receiver, the eddy current brake. The compressor turbine and the power turbine are kinematically separate turbines. Exhaust gas from the power turbine (point 4) is released to the atmosphere through the stack.

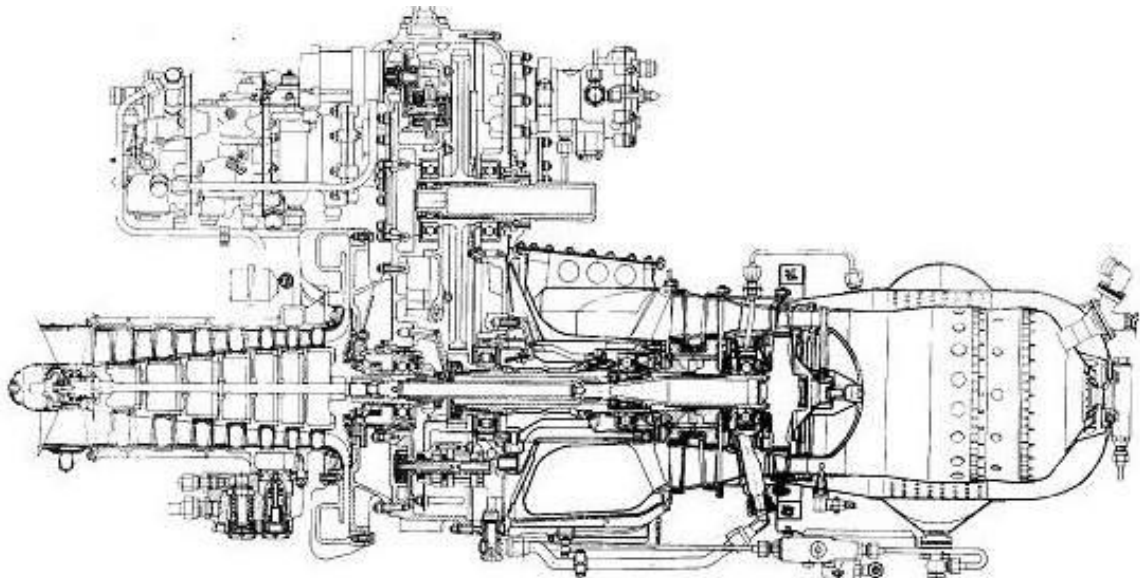


Fig. 3. GTD-350 turbine cross-section [4]

Almost all of the CT capacity is used to power the compressor (some of the CT capacity is used to power auxiliary generators, cover friction losses, etc.). The output of the

power turbine is released to the output shaft via a gear-motor. Some of the air from behind the compressor m_7 is drawn for cooling the parts operating at a high temperature, i.e. turbines rotor discs, vanes and the first bearing of the CT shaft. Cooling air does not operate in the CT, while in the crossover between the CT and the PT it mixes with exhaust gas and expands in the power turbine, thus increasing the PT working stream. The engine is fuelled by a fuel system that also performs the role of a governing system. The governing and fuel system comprises a piston fuel pump (powered by the transmission from the turbocharger shaft) and a series of devices ensuring the correct operation of the engine. The most important devices are the turbines rotational speed governors. The CT speed governor is a mechanical and centrifugal type governor used for setting (gas lifting) and maintaining speed n_{CT} over a full load range, i.e. from the idle run to the maximum, starting run. The power turbine speed governor interferes in the operation of the engine when speed n_{PT} approaches its maximum threshold. The turbine engine is equipped with an anti-surge valve located downstream of the sixth stage of the compressor. It opens automatically during the turbine operation close to the idle run. Its task is to protect the compressor against a surge. In case of low capacity the compressor would operate under surge conditions, which is why its capacity is increased in order to safely distance it from the unstable area. Excess air from behind the compressor is released by the valve to the atmosphere. At higher loads the valve closes automatically. The gas turbine is equipped with its own lubrication system with forced oil circulation intended for lubricating and removing heat from the bearings of all supports and drives of the engine.

Air to the engine is drawn from outside of the laboratory building, while the exhaust gas outlet is directed to the stack adjacent to the building, Img 2a and b.

a)



b)



Img 2. Air inlet (a) and exhaust gas outlet (b) of the turbine engine

A start-up system is used for starting up the engine. A starter-generator is connected to the turbocharger shaft using a toothed gear and during the start-up of the turbine it rotates the CT shaft. Then the compressor supplies air to the CC, and the fuel pump supplies fuel m_f . At the first start-up stage the fuel stream is fed to the ignition and start-up device located in the CC. The sprayed fuel is ignited by a spark plug, the thermal power of the CC increases, speed n_{CT} increases which results in an increase in the air jet and the engine entering the idle run. After approximately 30 seconds from the start-up of the start-up apparatus, the starter and the spark plug power supply switches off automatically. Now, combustion in the CC takes place as a result of self-ignition, the starter operates as a generator.

By shutting off the fuel supply to the injector the engine is shut down.

4. Measuring station

The measurement station of the gas turbine is shown in *Img 3*. The station was equipped with control systems, measurement systems and auxiliary equipment, including an eddy current brake, as well as control, measurement, visualization and data archiving software designed and delivered by ODIUT Automex sp. z o.o.¹ It includes a turbine engine² connected with the eddy current brake. The engine draws air from outside of the building through a suction pipeline at the beginning of which a filter is installed, while exhaust gas from the PT is released to the atmosphere through an outlet stack combined with a silencer, *Img 2*. The eddy current brake is water cooled in a closed-cycle system.



Img 3. Two-shaft gas turbine testing and teaching station

The turbine is controlled from a sound isolated booth. The engine may be loaded directly – by interfering with the turbine fuel system using an acceleration lever or indirectly – using the eddy current brake. The setting of the acceleration lever and the brake may be changed at the same time using electronic control, *Fig. 4*.

¹ ODIUT Automex sp. z o.o. designed and equipped the turbine station. All screenshots come from the company's own design.

² The GTD-350 turbine engine in the property of the Gdańsk University of Technology was modernised and prepared for the tests in accordance with the instructions of the Department of Automatics and Turbine Propulsion by WSK "PZL-Rzeszów" spółka S.A.

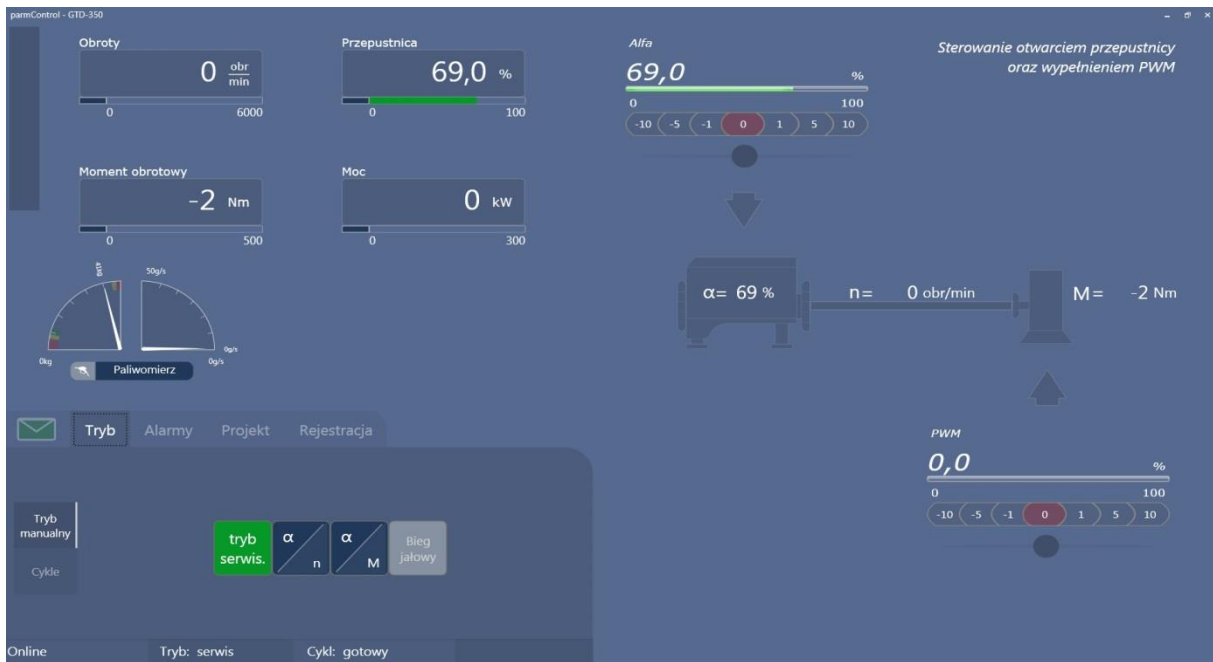


Fig. 4. Station control screen [3]

The design of the brake and its control makes the proportional loading of the brake possible, for a constant rotational speed of the brake, constant torque and square characteristics ($M \sim n^2$), Fig. 4 – input by the brake operation mode.

The engine is controlled from the control booth using digital controllers (control module) connected with a CAN bus that makes it possible to simultaneously control a two-dimensional object: a gas turbine and an eddy current brake, as well as a measurement module, using a computer system, Img 4 and Fig. 4.



Img 4. Control booth for the gas turbine measuring station

During the operation of the station, the operator can monitor selected parameters of the engine operation on the display. A sample screenshot is given in Fig. 5.



Fig. 5. Sample turbine engine station operation parameters monitored by the operator [3]

The engine was adapted to experiments by introducing additional measuring points to the standard equipment of the engine. The possibility of measuring the parameters of exhaust gas (temperature and static pressure) between the compressor turbine and the power turbine, as well as the gas stream at the power turbine outlet (temperature and pressure) was introduced, together with air measurement at the compressor outlet.

The redevelopment of the station made it possible to simultaneously measure the thermal field downstream of the combustion chamber (in 32 measuring points along the entire perimeter of the exhaust gas inflow to the compressor turbine); in the crossover between the turbines (in 12 measuring points along the entire flow perimeter); downstream of the power turbine along the 1/2 of the flow perimeter in 12 points.

The station enables the measurement of static characteristics, as well as dynamic characteristics with a short signals sampling time.

4.1. Instrumentation and measuring methods

The measurement system registers all of the parameters of the gas turbine station. Measurement signals from measurement sensors are collected and transmitted to the computer (to the measurement module), while it is possible to save them in binary files. The sampling frequency of measurement signals of the torque and the rotational speed of the break amounts to 50 Hz, with 100 Hz for the remaining measurement signals. It is possible to determine static characteristics and dynamic curves. The system was designed in such a way that the parameters can be monitored in their numerical form (a digital display) and in the form of curves on a computer screen. Data is stored in the computer memory and can be imported into other external software.

Only those measurement instruments that will be used for the measurement of the static and dynamic characteristics of the engine will be described below. Some of the instruments are doubled.

Table 1 lists selected measured parameters of the gas turbine and their ranges.

Table 1 Measured parameters of the turbine engine operation and their ranges

No.	Description	Designation	Range of values
1	Barometric pressure	p_b	950-1030 [hPa]
2	Negative pressure at the compressor inlet	p_{1p}	0-0.015 [MPa]
3	Air overpressure downstream of the compressor	p_{2n}	0-1 [MPa]
4	Exhaust gas overpressure downstream of the compressor turbine	$p_{3'n}$	0-0.5 [MPa]
5	Exhaust gas overpressure downstream of the power turbine	p_{4n}	0-300 [MPa]
6	Pressure drop at the metering orifice	Δp_d	0-0.015 [MPa]
7	Ambient air temperature	t_0	-50 - 50 [°C]
8	Air temperature downstream of the compressor	t_2	0 -300 [°C]
9	Cycle upper temperature (downstream of the combustion chamber)	t_3	0 -1200 [°C]
10	Gas temperature downstream of the compressor turbine	$t_{3'}$	0 -1000 [°C]
11	Gas temperature downstream of the power turbine	t_4	0 -700 [°C]
12	Turbocharger rotor rotational speed	n_{CT}	0-45000 [obr/min]
13	Power turbine rotor rotational speed	n_{PT}	0-24000 [obr/min]
14	Brake torque	M_{EB}	0-600 [kN]
15	Fuel flow rate	m_f	0-200 [l/h]

Fig. 5 shows a measurement diagram of the gas turbine station. The measuring points designated with numbers in circles in the description correspond with the measuring points given in Fig. 5.

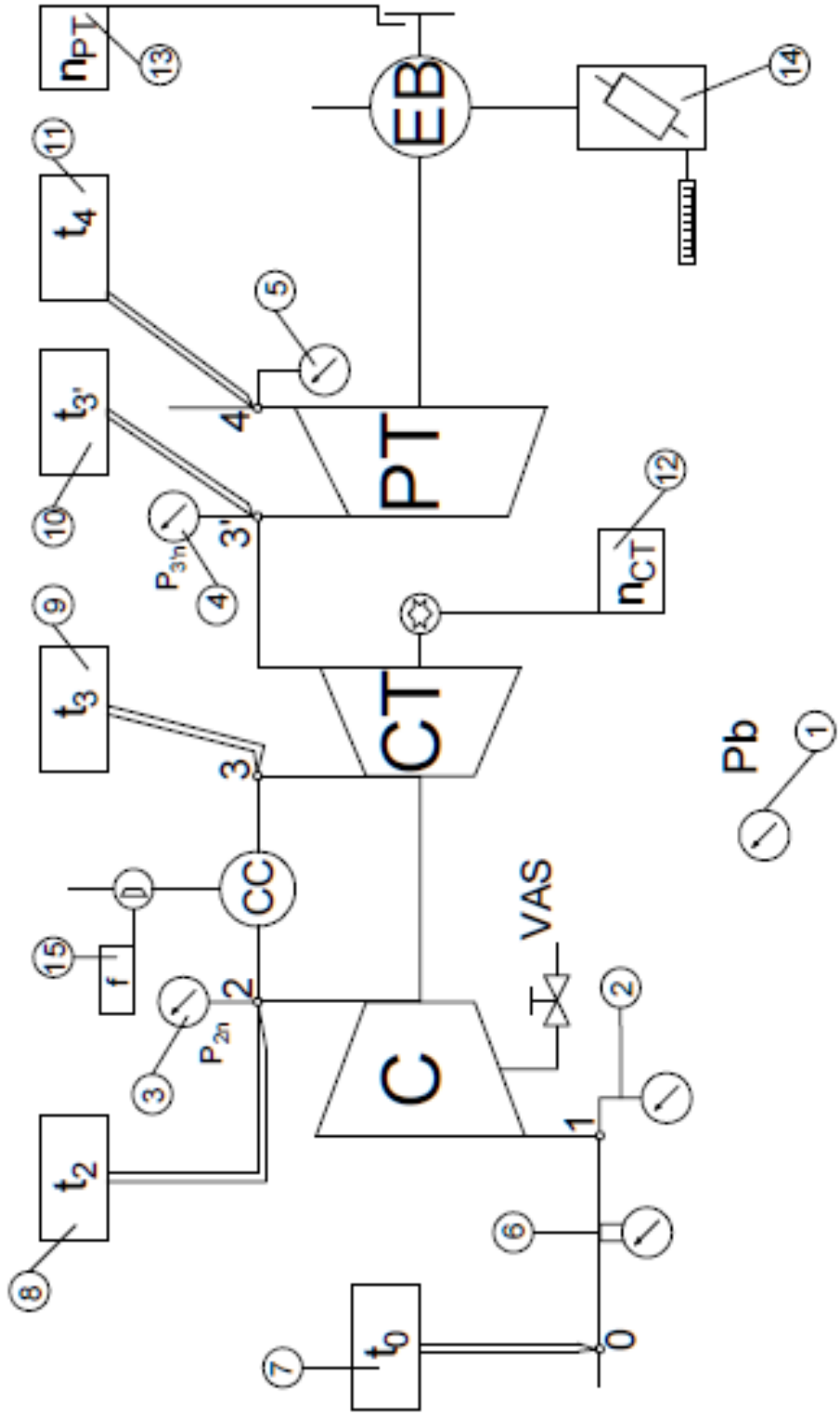
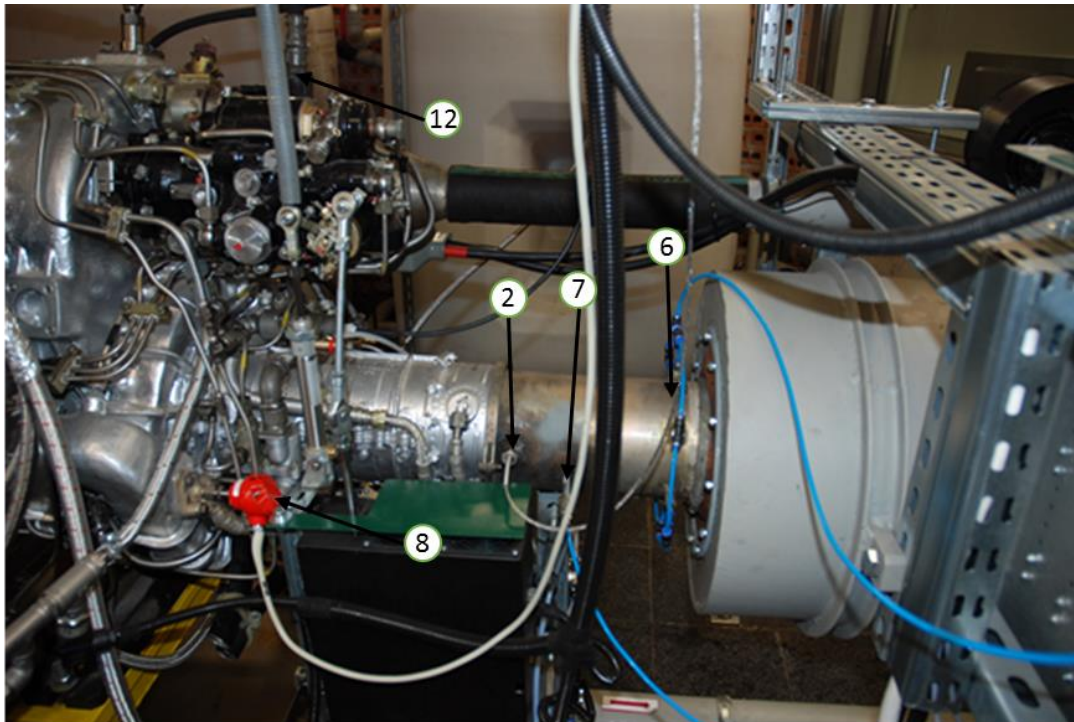
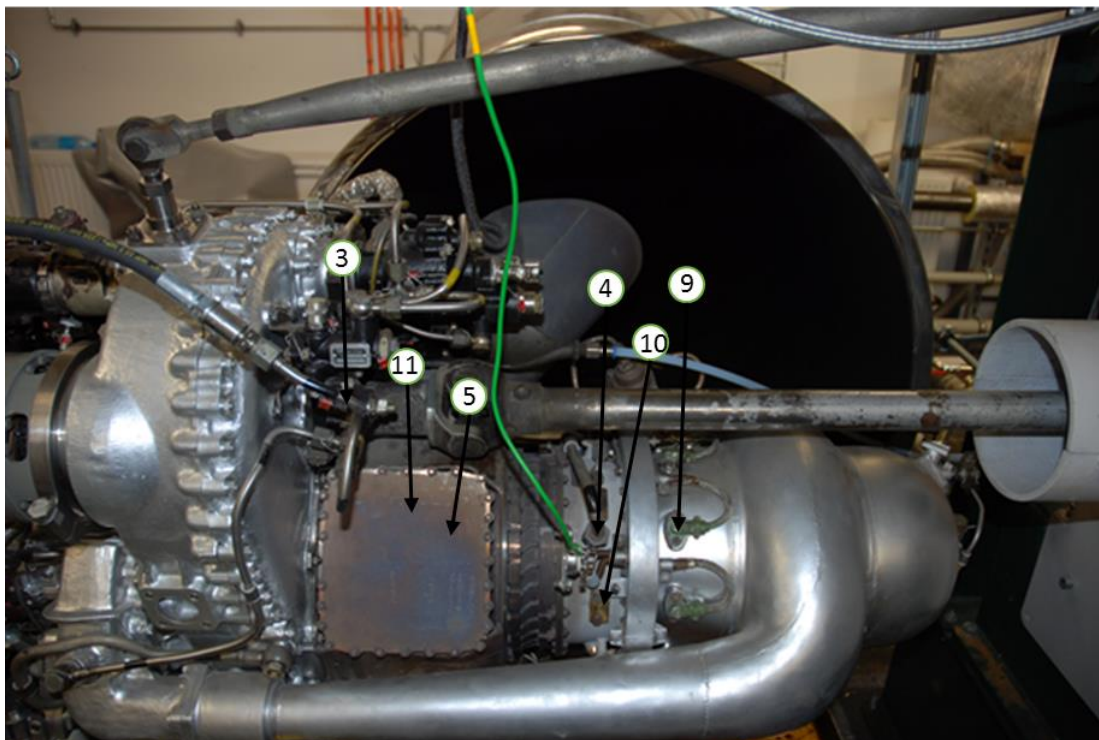


Fig. 5. Measurement diagram of the gas turbine station



Img 5. Gas turbine measuring points

2 – negative pressure at the compressor inlet; 7 – ambient air temperature; 6 – pressure drop at the metering orifice; 8 – air temperature downstream of the compressor; 12 – turbocharger rotor rotational speed



Img 6. Gas turbine measuring points; 3 – air overpressure downstream of the compressor; 4 – overpressure downstream of the compressor turbine; 5 – exhaust gas overpressure downstream of the power; 9 – temperature downstream of the turbine; combustion chamber; 10 – gas temperature downstream of the compressor; 11 – gas temperature downstream of the turbine; power turbine

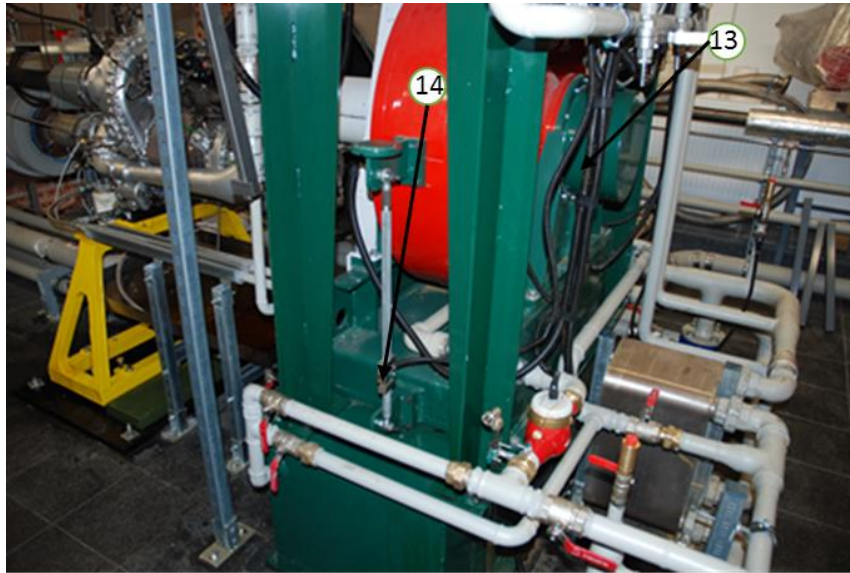
a)



b)



*Img 7. Gas stream temperature measuring thermocouples
a) single-point with a covered junction b) four-point with a covered junction*



*Img 8. Gas turbine measuring points
13 – Brake rotor rotational speed; 14 – Brake torque*

Pressure measurement at the station:

a) barometric pressure

Pressure p_b is measured using pressure gauge ① located in the engine test house;

b) pressure at the compressor inlet

Static pressure drop is defined as a difference between atmospheric pressure and pressure measured immediately upstream of the compressor blade system. The value of this pressure is determined using the measurement of barometric pressure ① and the measurement of negative pressure in the pipeline upstream of the compressor p_{1p} ②, Fig. 5 and Img 5, while pressure upstream of the compressor equals $p_1 = p_b - p_{1p}$;

c) air pressure downstream of the compressor

Overpressure p_{2n} is measured in the pipeline downstream of the compressor (static pressure) ③, Img 5. Pressure downstream of the compressor is determined using dependence $p_2 = p_b + p_{2n}$;

d) pressure downstream of the compressor turbine

Static overpressure p_{3n} of exhaust gas is measured in the crossover between the turbines ④, Img 6. Pressure of the stream between the turbines is determined using dependence $p_3 = p_b + p_{3n}$;

e) exhaust gas pressure downstream of the power turbine

The measurement took place immediately downstream of the power turbine, in the outlet covers of the turbine stack, Img 6. Overpressure p_{4n} (static) is collected from two measuring points ⑤. Pressure downstream of the power turbine is determined using dependence $p_4 = p_b + p_{4n}$;

f) pressure drop at the metering orifice

Pressure drop at the metering orifice installed on the compressor inlet air pipeline Δp_d ⑥ is an average of six measuring points, Img 5. This measurement is used to determine mass air flow at the compressor inlet;

Air and exhaust gas temperature measurement:

a) air temperature at the turbine set inlet

Measurement of t_0 using a PT100 resistance thermometer ⑦ installed in the compressor inlet pipeline, Img 5;

b) air temperature downstream of the compressor

Temperature t_2 ⑧ is measured using a single-point, uncovered chromel-alumel type thermocouple in the pipeline, immediately downstream of the compressor, Img 5;

c) cycle upper temperature (downstream of the combustion chamber)

Gas temperature t_3 ⑨ is an average of 8 measuring points distributed symmetrically on the perimeter in the inlet ring to the guide vanes of the CT (mid-height), Img 6. Chromel-alumel type single-point thermocouples with a covered junction act as the measuring sensors, Img 7a. Special four-point thermocouples with an uncovered junction are used for measuring the thermal field downstream of the combustion chamber, Img 7b. This measurement is taken in 32 points distributed symmetrically in the outlet cross-section of the combustion chamber;

d) gas temperature downstream of the compressor turbine

The measurement of temperature t_3 is an average of 4 measuring points distributed along the perimeter in the crossover between the turbines ⑩. Single-point thermocouples, Img 7a, identical to the ones used for the measurement of temperature downstream of the combustion chamber, were used for this measurement. The thermal field in the crossover between the turbines is measured in 16 points with four-point thermocouples, Img 7b, as described in section c;

e) gas temperature downstream of the power turbine

Gas temperature t_4 is measured in 4 points in the outlet channel (along the $\frac{1}{2}$ of the outlet ring perimeter), immediately downstream of the rotor blades of the last stage of the PT ⑪. The measurement using chromel-alumel type four-point thermocouples with an uncovered junction is an average of 16 points, as described in section c. With a separate reading of each point of the thermocouple it is possible to measure the thermal field on the $\frac{1}{2}$ of the outlet surface area of the power turbine;

Rotational speed measurement

a) compressor turbine rotational speed

The measurement of rotational speed (12) n_{CT} , Img 6 and 8, is made using a tachogenerator with which a standard engine is equipped, driven by the toothed gear of the CT turbocharger shaft. The shaft rotational speed is given in RPM, Hz or percentage value;

b) power turbine rotational speed measurement

The value of (13) n_{PT} is measured using a magnetoelectric speed transducer installed on the eddy current brake rotor, Img 8, or a tachogenerator powered by the power turbine shaft through a mechanical transmission gear, Img 6. The shaft rotational speed is given in RPM, Hz or percentage value;

Water brake torque measurement

Torque (14) M_{EB} is measured indirectly through the measurement of force on the arm of the water brake. For this purpose a force strain gauge and a measuring bridge were used.

Measurement of an air jet drawn in by the compressor

Air jet m_c is measured at the compressor inlet using a metering orifice. Pressure drop at the orifice Δp_d (6 – Fig. 5) and negative pressure in the pipeline upstream of the orifice p_{1p} (2). Mass air jet at the compressor inlet is determined using the following formula:

$$m_c = 13,18 \cdot A^{5/7} \cdot \sqrt{1 - A^{2/7}} \quad [\text{kg/s}]$$

$$\text{where } A = 1 - \frac{\Delta p_d}{p_1}$$

Measurement of fuel stream supplied to the combustion chamber

A turbine flowmeter (15) installed on the pipeline supplying fuel to the fuel pump was used for the measurement of stream m_f . Flow rate reading in kg/s.

4.3. Visualization of measurement results

The teaching and measurement station is equipped with measurement and recording instrumentation that makes it possible to measure static and dynamic characteristics.

In order to display the dynamic characteristics on the screen, parameters that are to be displayed on the graph must be selected from the table of measured parameters, Fig. 7. Dynamic characteristics are performed in the function of time; sample dynamic characteristics are given in Fig. 8. Any number of measured parameters in the function of time may be displayed on a single graph.

Static characteristics graphs are a second option. For this purpose parameters must be selected from the list of measured values, Fig. 7 and the first selected variable is marked on the horizontal axis of the static characteristics graph in the function in which the static characteristics is determined. A sample static characteristics graph is given in Fig. 9.

The file containing the recorded experimental data may be exported to any external software and there properly processed.

5. Conclusion

The gas turbine teaching and testing station located at the Department of Automatics and Turbine Propulsion at the Faculty of Ocean Engineering and Ship Technology of the Gdańsk University of Technology is fully automated. The start-up of the turbine set is automatic, while an automatic governing system is responsible for the turbine operation. All the parameters of the engine are registered from the moment of the turbine start-up until its shut down. The relevant parameters of the gas turbine are set on the engine by entering the set value of the CT compressor turbine rotational speed within the range between the minimum speed (idle run) and the maximum speed (equivalent to the start-up range). The receiver load is met by the eddy current brake that makes it possible to set the correct characteristics.

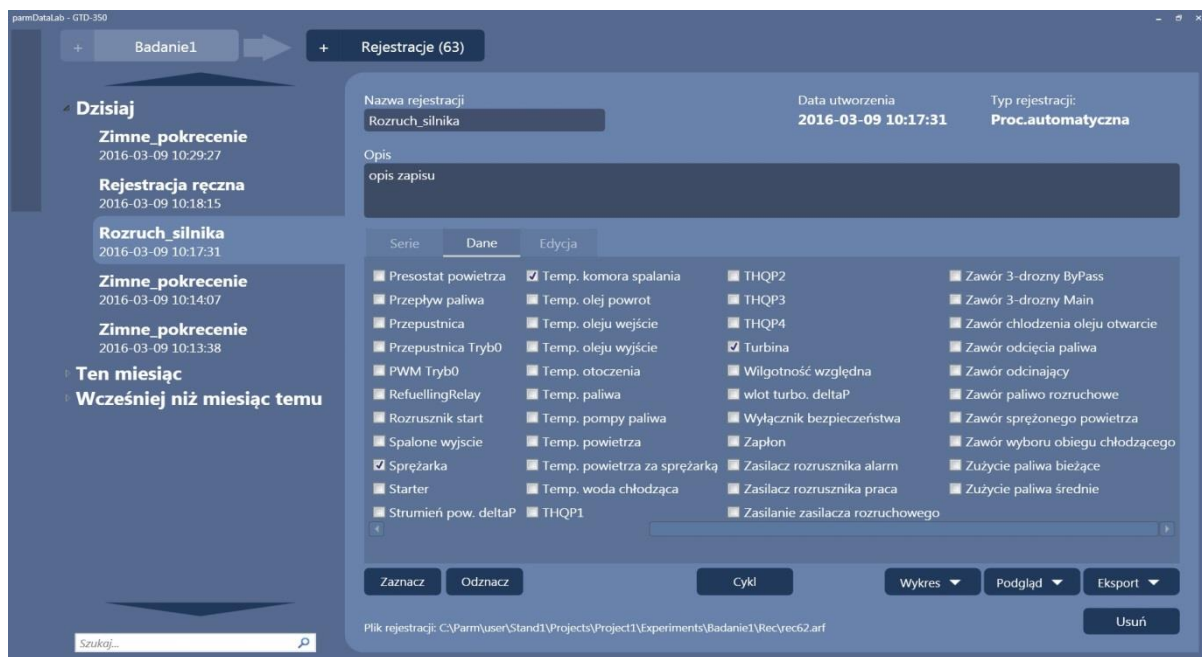


Fig. 7. List of parameters measured at the gas turbine station [3]

Measurement data is archived and may be exported to a different software. Static, as well as dynamic characteristics may be tested at the station.

Additional sensors were installed on the gas turbine that enable the sampling of their data at high frequencies. The modernisation of a standard turbine engine makes it possible to measure the parameters at any point of the gas turbine system. The used recording instrumentation, including special measuring sensors dedicated to this station, make operation over the entire field of permissible characteristics of the gas turbine possible. This is a unique gas turbine station on a national scale. It was put into operation at the Gdańsk University of Technology in 1974, while in 2014-2015 it was completely redeveloped and equipped with state-of-the-art measuring and recording technology and IT solutions.

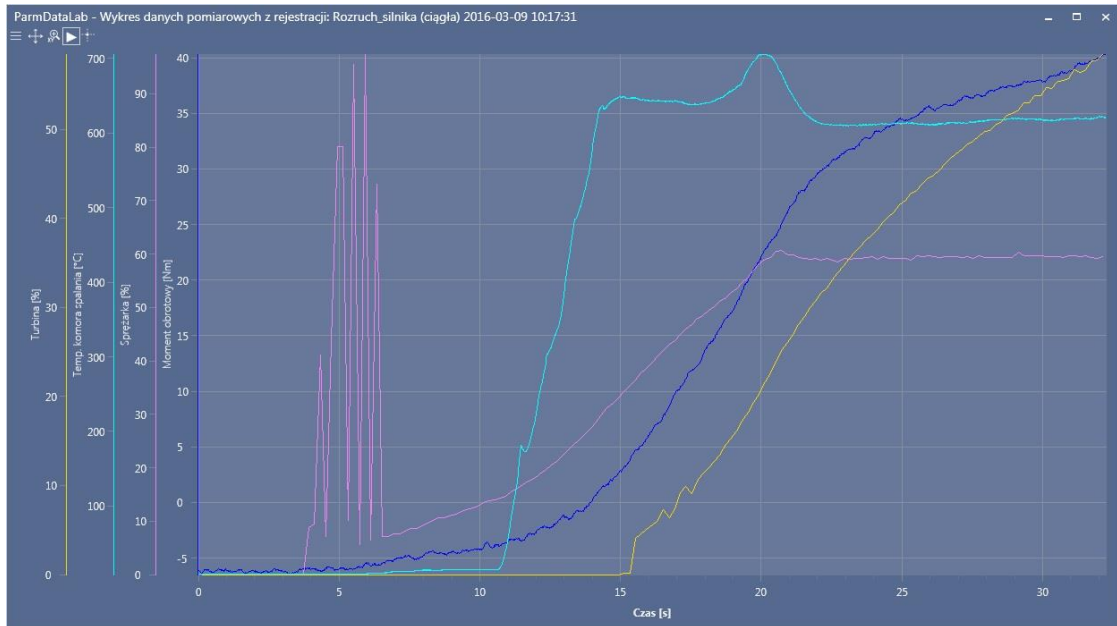


Fig. 8. Dynamic characteristics [3]

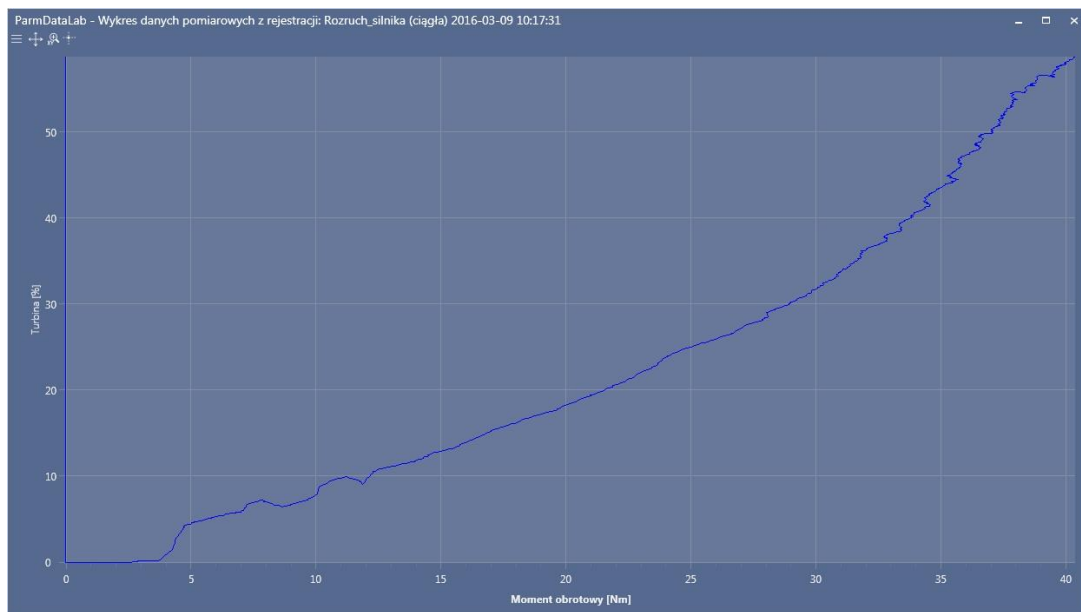


Fig. 9. Static characteristics [3]

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