Stand for exhaust-driven turbogenerators testing

Stanowisko do badania turbogeneratorów

WOJCIECH MIĄSKOWSKI
KRZYSZTOF NALEPA
PRZEMYSŁAW KOWALCZYK
KAMIL ADAMOWICZ *

Presented is the designing procedure of the research and teaching stand for testing of exhaust-driven turbogenerators. The SolidWorks environment was used in the design process. The necessary engineering analyses were carried out, such as: conceptual consideration, calculations of the turbogenerator thermodynamic circuit, energy balance, device efficiency calculations, strength calculations of the structure frame, etc. The strength calculations were carried out using SolidWorks software with Simulation package.
KEYWORDS: turbogenerator, supply system, blast chamber, test stand

Power stations with gas turbines belong to the group of fast developing power installations [2]. Turbogenerator, also called a turbine set, consists of a gas turbine and an electricity generator. The essence of the turbogenerator's operation is the conversion of chemical energy of fuel to enthalpy, enthalpy to mechanical energy, and then to electric energy.

A gas turbine is an impeller device, and its essential element is a rotor with profiled vanes called a vane ring. The working medium exerts on the rotor blades the pressure converted to the rotor torque. The energy transfer process of rotating machines uses the basic laws and principles of fluid dynamics, and the working medium and its kinetic energy are of great importance here [6].

A large part of the currently constructed gas turbines is made in a simple system or its modification (fig. 1). In a straight line, the air drawn from the surroundings by the compressor is pumped into the combustion chamber, where the compressed air is mixed with the fuel, and then its combustion. The resulting working medium gets into the turbine, where the enthalpy of the exhaust is converted into the rotational motion of the turbocharger shaft, while driving the compressor.
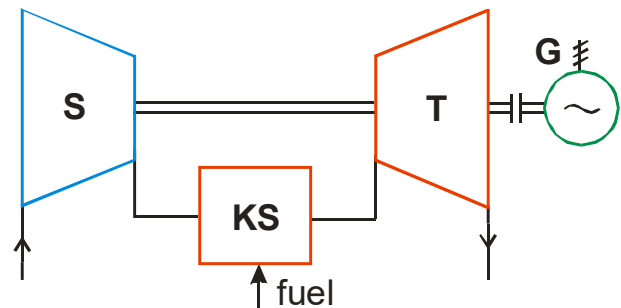

Fig. 1. Diagram of a gas turbine set in a straight line: S - compressor, KS - combustion chamber, T - turbine, G - electric generator

The power generated on the turbocharger shaft is transferred to the generator shaft, converting mechanical energy into electric one. The disadvantage of this solution is that the exhaust gas leaving the turbine remains unused. The second disadvantage is the difficulty of connecting the turbocharger shaft with the generator due to the very high rotational speed of the shaft, reaching up to 150,000 rpm [8]. Therefore, it is rather a turbo-generator's operating scheme than the model used in practice.

An example of a simple system modification (described eg in [1,2,4,5]) is the use of an additional element in the form of another low-pressure turbine, which uses expanded exhaust gas discharged from the first - high - pressure turbine. In this solution, the generator is connected to a low-pressure turbine, which further facilitates the coupling of these two elements, because the rotational speed of the second turbine is much smaller (about 20,000 rpm).

Purpose and scope of work

The aim of the work is to design and then build a research and teaching station for testing gas turbo-sets. It will be equipped with a turbine set, power supply system, lubrication and cooling systems, modular support frame, control and control equipment, etc. The whole structure is to meet the conditions needed to convert chemical energy of fuel (fumes) into electricity while ensuring the universality of the stand.

The most important design assumptions:
• achieved output power ~1 kW,
• use of propane-butane gas as fuel,

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* Dr inż. Wojciech Miąskowski (wojciech.miaskowski@uwm.edu.pl), dr inż. Krzysztof Nalepa (krzysztof.nalepa@uwm.edu.pl), inż. Przemysław Kowalczyk (przemeo197@wp.pl), inż. Kamil Adamowicz (k.adamov@o2.pl) – Wydział Nauk Technicznych, Uniwersytet Warmińsko-Mazurski

- obtaining on the shaft of a high-pressure turbine up to 140000 rpm,
- temperature of gases at the outlet from the chamber not higher than 900 °C,
- average flow velocity of the stream in the chamber not higher than 20 m/s,
- mounting the chamber so that it does not undergo plastic deformation (does not load statically), and that it has the ability to perform thermal elastic deformations,
- modular construction of the site allowing for testing of various objects.

Concept analysis

Conceptual analysis was carried out for individual construction nodes of the proposed position. This article presents considerations regarding the two most important elements conditioning the correct operation of the entire turbo-generator system. First, the focus was on the turbo-generator's work system, and then on the turbine power supply system resulting from the combustion of fuel.
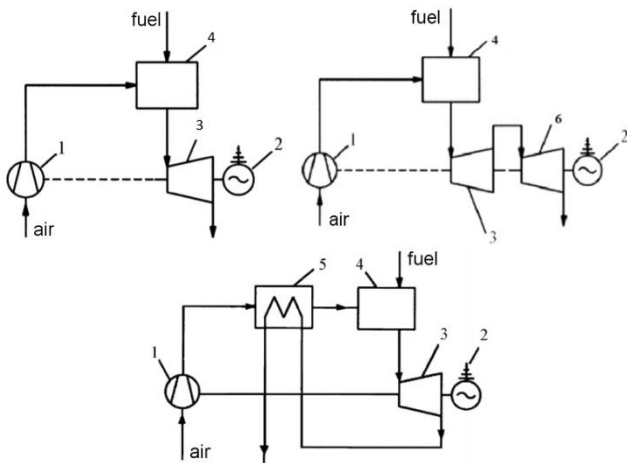
Fig. 2. Diagrams of the concept of work systems for gas turbo-sets: 1 - compressor, 2 - generator, 3 - turbine, 4 - combustion chamber, 5 - heat exchanger, 6 - low-speed turbine

Three propositions of the turbo-generator work system were adopted, as shown in Figure 2. Concept 1 is based on a solution in which the turbine set works in a straight system. Concepts 2 and 3 are so-called complex systems, the second proposition is characterized by the use of two turbines, and the third uses the heat of exhaust gases to increase the temperature of the air pumped by the compressor to the combustion chamber.

After a conceptual analysis based on accepted criteria - such as system efficiency, complexity, overall dimensions and construction cost - it was decided to implement the project based on concept 2. For the project, the K03-2072 turbocharger (BorgWarner) was selected. The compressor's operational characteristics obtained information (rotational speed, efficiency, mass flow and compression) necessary for further conceptual and design work on the remaining elements of the turbine set and the entire stand.

The main element of the turbo-generator power supply system is the combustion chamber [3]. It is crucial to design it properly, because the energy of the exhaust gases produced in the combustion chamber will be directly used to drive the turbo-generator [7], and consequently - to the production of electricity.

Concepts of the turbocharger-combustion chamber layout:
- Concept A (fig. 3a) - a straight-flow tubular combustion chamber with a fuel nozzle mounted on the turbocharger,

- Concept B (fig. 3b) - a tube combustion chamber with a reverse flow and a fuel nozzle mounted on the turbocharger,
- Concept C (fig. 3c) - a straight-flow combustion chamber and a fuel injector, attached to the frame of the structure and connected to the turbocharger,
- Concept D (fig. 4) - a straight combustion ring with fuel injectors mounted on the turbine.
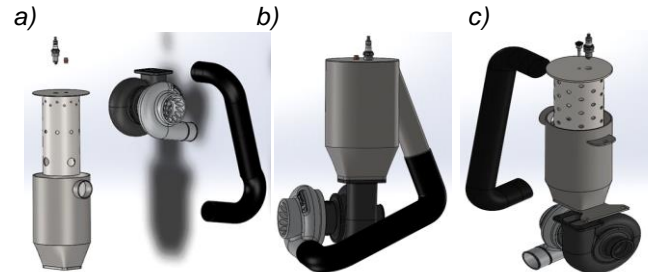
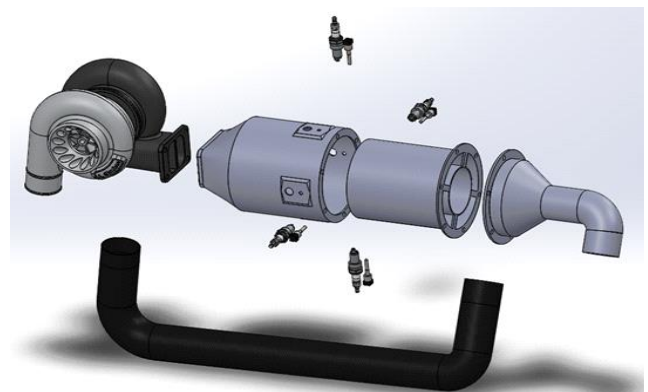Fig. 3. Concepts A, B and C of the main element of the power supply system

Fig. 4. Concept of the main element of the power supply system: D

Based on conceptual analysis, option A was chosen for further work.

After selecting the concept, calculations necessary to design the power supply system, in particular the combustion chamber, were carried out.
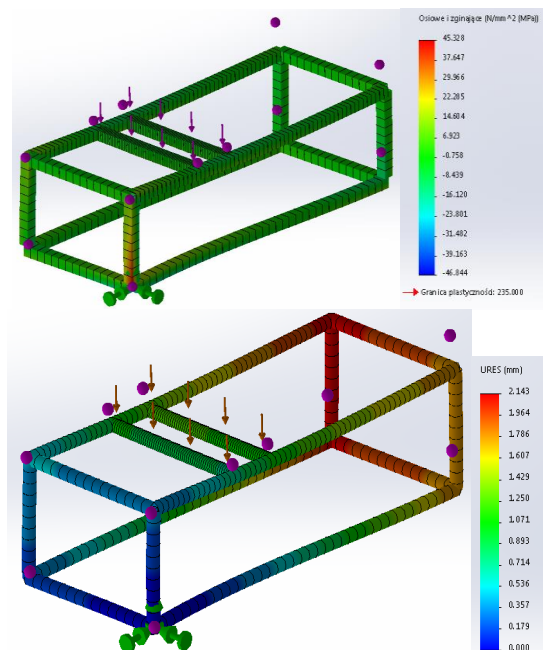
Fig. 5. Graph of stresses and displacements of the upper frame with visible boundary conditions

Simulation analysis of selected job elements

Finite element method was used to check the behavior of elements in conditions close to normal working conditions.

Static analyzes were carried out in the SolidWorsk 2016 environment with the addition of Simulation for the combustion chamber elements operating under the influence of high temperature and for the upper frame to which the turbine set will be attached.

The frame model was loaded statically (fig. 5) with forces coming from the mass of individual elements of the designed turbine set. Then, the attachment was added at the nodes and the mesh was applied.

A beam mesh was used to analyze the static frame. The mesh was compacted in the critical areas of the frame. The force coming from the weight of the turbine set was 250 N. The maximum stress value in the analyzed frame did not exceed 50 MPa (45,328 MPa) (fig. 5).

The flame tube was subjected to static analysis with the participation of temperature. The combustion chamber is attached to the frame so that no external forces act on it, and the only aggravating factor is the temperature reaching 1000 °C. A solid mesh was placed on the flame tube (fig. 6).
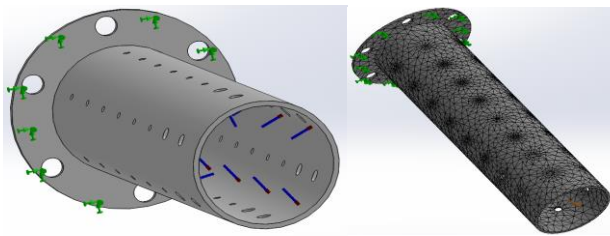

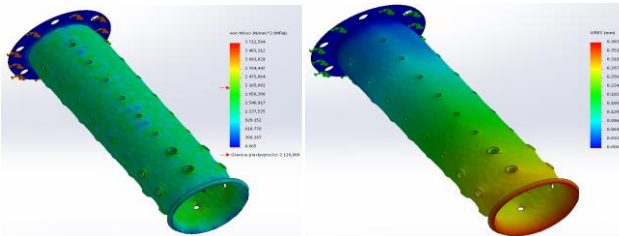Fig. 6. Flame pipe with preset boundary conditions (including thermal load) and a solid mesh

Fig. 7. Graphs of stresses and displacements of the flame tube

The analysis shows that the maximum displacement of the flame tube under the influence of high temperature did not exceed 0.4 mm (fig. 7).

Construction of the site

Fig. 8 shows the 3D model of the station made in the SolidWorks program. The frame made of 40 × 40 × 3 mm steel profiles has a modular structure that forms the foundation of the entire structure. On the bottom frame there is space for the gas cylinder (1) and oil lubrication system (2). Additional brackets and brackets are attached to the upper frame, on which a high-pressure turbocharger (3) connected to the combustion chamber (4) and - directly after the turbocharger - a power turbine (5) connected by means of a belt transmission with an electric power generator (6).
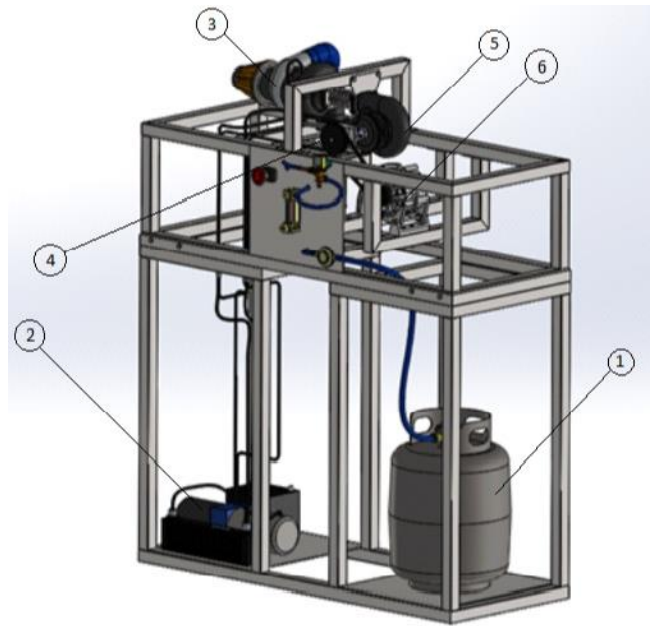

Fig. 8. 3D model of the station

Conclusions

Thanks to continuous improvement of the structure by adding additional elements, devices and development of control systems, gas turbines are becoming more and more efficient and become an important alternative to smaller power steam turbo-sets.

The concept that best suits the assumed criteria is a model of a gas turbo-generator operating in a complex system with two turbines. This solution facilitates the coupling of the turbine shafts and the electricity generator. The first turbine is connected to the compressor and the other is an independent power turbine. The designs of the combustion chamber and the selection of compressors were supported by calculations and simulation tests. In a real turbo-generator model, measuring equipment should be installed to measure: temperature, pressure, mass flow rate, torque, etc.

At the presented stage of works, technical documentation of the turbine set together with power supply, lubrication and cooling systems was made.

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