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Model of an ANSALDO V94.2 gas turbine from Lublin Wrotków Combined Heat and Power Plant using GateCycle^{TM} software

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Abstract

This paper concerns the model of the ANSALDO V94.2 gas turbine for variable operating conditions from CHP Lublin Wrotków. General Electric GateCycle^{TM} software was used to build the model. The gas turbine modeling methods used in the software were described. To assess the model, computations were performed for 40% and 70% load for 0.9, 14 and 30°C ambient temperature and 100% load for -20, 0.9, 14, 15 and 30°C ambient temperature. The results were compared with available heat balances of the object. The paper also discusses the theory of gas turbines, considering the sensitivity of the thermodynamic cycle.

Keywords: Gas turbine, Brayton cycle, Mathematical modeling, GateCycle

1. Introduction

A gas turbine is a heat engine which consists of a compressor, a combustion chamber and an expander. Cold air is compressed in the axial compressor and the fuel-air mixture is burned in the combustion chamber. Then hot flue gases transmute the energy into rotary motion of the expander, which propels the compressor and the power generator. The power of the turbine less the power of the compressor is called the effective power of the gas turbine. A schematic of the gas turbine is shown in Fig. 1.

There are a few indices which describe thermodynamically the gas turbine. For example:

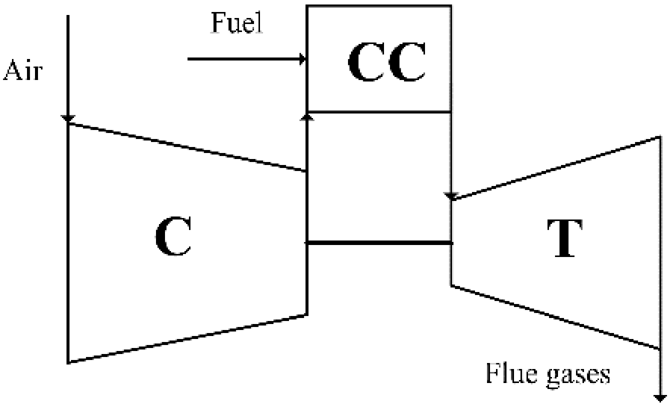

Figure 1: Schematic of a gas turbine, C—compressor, T—expander, CC—combustion chamber

- compression ratio—ratio of air pressure after compressor to the pressure before the compressor;
- ratio of the highest to the lowest temperature;
- thermal efficiency—ratio of the effective power

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of gas turbine to the power delivered in fuel;

- power index—ratio of the internal power of gas turbine to the power of gas turbine [1].

The ideal gas turbine cycle, with internal combustion, is the Brayton cycle. It consists of two isentropic processes—air compressing and expanding of flue gases and two isobaric processes - delivering and rejecting heat. However, the actual cycle of the gas turbine differs from the ideal. The Joule-Brayton cycle includes all major losses.

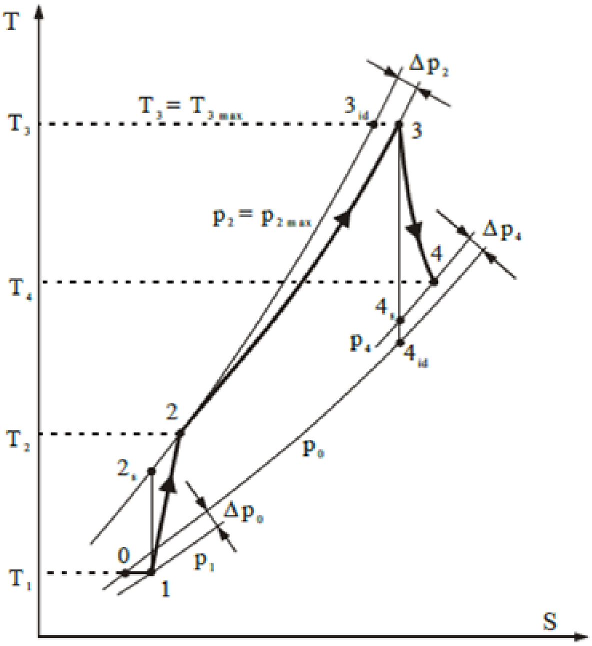

Figure 2: Joule-Brayton Cycle [2]

As is shown in Fig. 2, point 0 represents ambient air parameters. In the cross-section of the inlet to the compressor it has lower pressure (point 1) because of losses in connecting channels and the air filter. There are also pressure losses in the combustion chamber and exhaust manifold. Moreover, due to irreversibility, compression and expansion are not isentropic processes [3].

The foregoing cycles are related to the simple gas turbine cycle. There are other cycles, which may be divided for example according to the implemented thermal cycle and the flow of the working medium. Thermal cycles may be simple or combined. Combined cycles have implemented systems to recover heat from flue gases (for example a heat recovery steam generator, which is used to produce steam for the Rankine cycle) and/or, for other complex gas turbine cycles, systems for intercooling or additional interstage heating of the working medium. In addition, cycles divided by the flow of working medium are: open cycles, closed cycles or half-closed cycles.

2. Cycle sensitivity

The gas turbine is characterized by the sensitivity of its performance based on cycle parameters. This arises from the power index:

$$\varphi = \frac{N_i}{N_T} = 1 - \frac{\pi^m}{\theta \cdot \eta_K \cdot \eta_T}$$

This is the ratio of gas turbine internal power to its whole power and, as is shown in the above relation, it is a function of compression ratio π, ratio (θ) of the maximum temperature T_3 to the minimum temperature T_1 and efficiency of compressor (η_K) and gas turbine (η_T). Increasing the temperature ratio θ results in higher cycle efficiency and unit power. However, the absolute effect of temperature T_1 is θ times greater than the temperature T_3. Unit power can also be increased due to increases in turbine and compressor efficiency. Furthermore, an increase in these parameters with a simultaneous drop in the compression ratio makes the power index increase, which reduces cycle sensitivity. In the simple cycle it is in the range of 0.3–0.4. This means that two thirds of gas turbine power drives the compressor and only one third is the internal power of gas turbine. Low internal power causes sensitivity to disturbances in system work and changes in components' characteristics. For the system it is also important to properly design the inlet and outlet manifolds, because of the pressure losses that occur, which have a significant impact on efficiency and unit power.

Ambient conditions also have a significant impact on turbine performance. Variations affect air density and thereby the mass flowing to the compressor. The greatest impact is caused by changes in ambient temperature: decrease to -20°C can increase

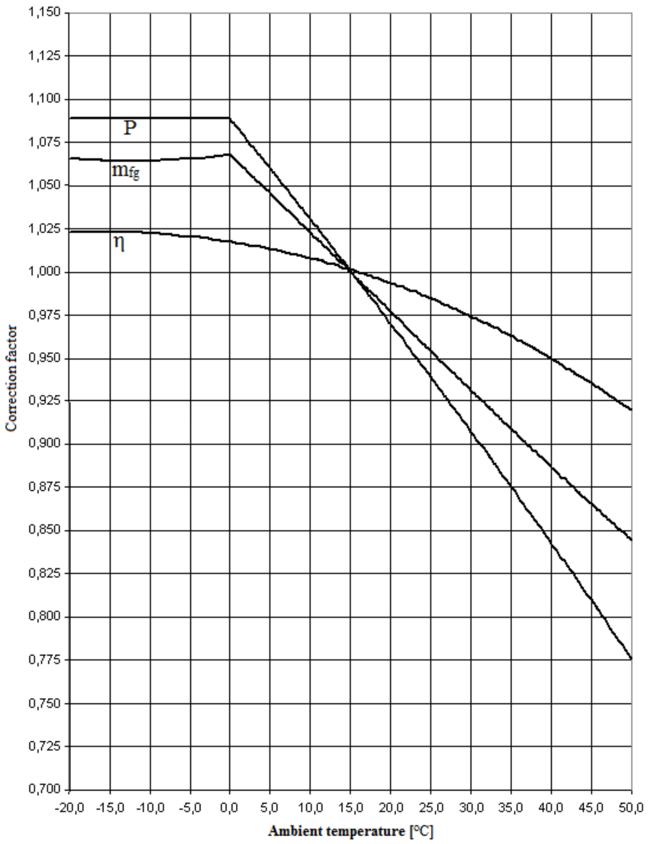

Figure 3: Correction curve for the influence of ambient temperature, P—power, m_{fg}—flue gas mass flow, η—efficiency [4]

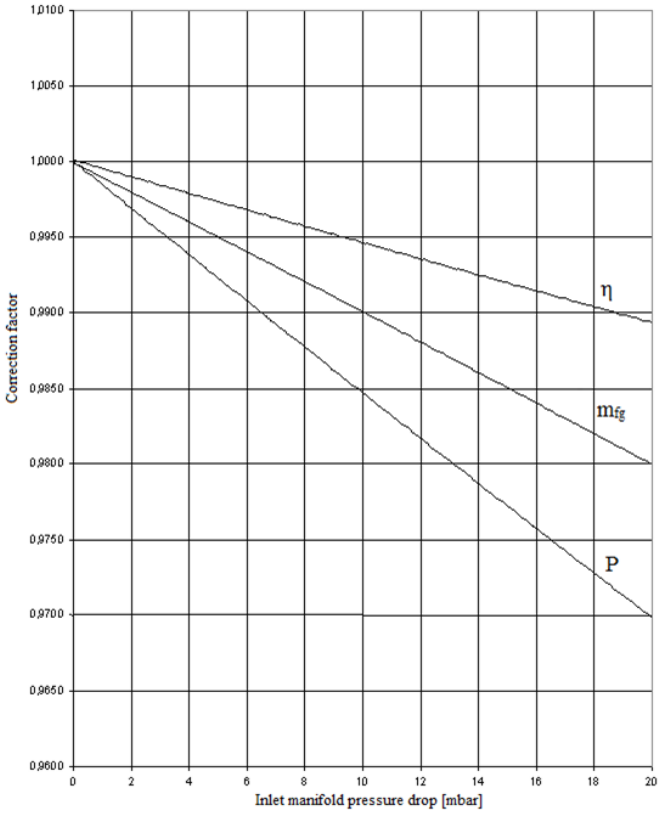

Figure 4: Correction curve for the influence of inlet pressure drop, P—power, m_{fg}—flue gas mass flow, η—efficiency [4]

power to 120% compared to ISO conditions. However, it is not always allowed to achieve such power, because of the need to use a greater power generator, which may not always be economically justified. Moreover, an increase in gas turbine power may also be caused by higher ambient pressure. Recently, no attention was paid to the influence of air humidity. However, since power boosting or emissions reduction systems are used, where water or steam is injected into the system, air humidity is more important due to its influence on gas turbine performance. Rising air humidity decreases air density and gas turbine power. Nevertheless, air humidification may increase turbine power. Preparation of an adequate water mist, in addition to raising air humidity, also decreases air temperature. Falling ambient air temperature has a greater influence than falling air humidity on increasing air density and because of that turbine power rises. Therefore, standard reference ambient conditions were established (ISO conditions [5]: $p = 101.325\,\text{kPa}$, $T = 15°\text{C}$, $\varphi = 60\%$) for which gas turbine performance ratings are stated. With these standard conditions, there is a possibility of comparing their performance. Above are examples of correction curves (Fig. 3, 4) for the ANSALDO V94.2 gas turbine. They are used to determine gas turbine performance (power, efficiency, flue gas flow and its temperature) for various ambient conditions and other parameters. The gas turbine vendor creates them with its own standards. Sometimes correction curves for the influence of variable rotary speed, degradation of the gas turbine and change of fuel LHV are also delivered [3, 6].

3. Model building

Mathematical models can be used to establish the characteristics of the object, as well as the technical and economic optimization. For this purpose are used own and the commercial computational codes. There are many articles devoted to this subject, such as: [7–9].

The turbine modeled here is the biggest in Poland and works in CHP Lublin Wrotków. The total electric output of the plant is 231 MW with 185 MW of thermal power. The ANSALDO turbine is a single hull, single shaft structure composed of a 16-stage axial compressor and a 4-stage axial turbine. It is equipped with two silo combustion chambers. In each combustion chamber, there are 8 hybrid burners designed to work with gas and oil fuel.

To run computations GateCycle^{TM} software was used. The GateCycle^{TM} application is a PC-based software application used for design and performance evaluation of thermal power plant systems at both design and off-design points. The GateCycle^{TM} application combines an intuitive, graphical user interface with detailed analytical models for the thermodynamic, heat-transfer and fluid-mechanical processes within power plants, allowing design and simulation studies of any complexity.

The construction of the model begins with choosing the appropriate elements (icons) in the “Equipment toolbox”, that symbolize the various system components such as turbines, pumps, valves, heat exchangers, etc. Once all the items have been selected they should be combined to form a logical whole. They are combined according to the direction of the flow of streams. Then the calculation method for each element and the appropriate amount of data should be entered. There are three possible methods to build the gas turbine model:

1. Standard GT—one icon represents the whole gas turbine. It allows a simplified model of a single shaft turbine to be built. There is also a library with more than 100 turbines along with saved correction curves. This allows a model to be built to determine performance for conditions other than ISO or for variable load without the need for detailed data from the vendor.
2. Data gas turbine—one icon represents the entire turbine. The most frequently used method. It does not require large amounts of input data. It allows a library of correction curves to be built, which make it possible to construct a turbine model for variable operating conditions.
3. Separate elements—the most advanced method. The model is built with separate components (compressor, combustion chamber, turbine, etc.). It is possible to build more advanced systems such as CAES, IGCC, HAT and others.

Table 1: Reference values [4]

Ambient conditions	
Relative humidity	0.6
Inlet pressure, kPa	101.325
Inlet temperature, °C	15
Performance data	
Rated exhaust flow, kg/s	514.4
Rated exhaust temperature, °C	546.3
Rated heat rate, kJ/kW-sec	2.9656
Rated power, MW	154
Operating conditions	
Power factor	0.85
Relative rotation speed	1
Inlet pressure drop, mbar	9.8
Outlet pressure drop, mbar	33.5
Fuel conditions	
Fuel pressure, kPa	2500
Fuel temperature, °C	10
Fuel LHV, kJ/kg	48820

In the GateCycle^{TM} a gas turbine library is included with a few manufactured by ANSALDO. None of them have parameters similar to V94.2. Considering the availability of data for the ANSALDO V94.2 turbine, including correction curves, method number 2 was chosen to build the model. There are a few calculation methods. It is possible to input the expected power, heat rate, to bypass turbine, idle load, match the performance of the turbine to another model and another method, which uses the correction curves. The latter method was used. "Curve Set Editor" was used to create a new set of correction curves. The reference values for ambient conditions, turbine performance, operating conditions and fuel parameters should be provided in it. They are shown in Table 1. Correction curves are based on the entered correction factors or temperature differences. In addition, the appropriate interpolation method should be selected.

Correction curves were entered in the model reflecting the influence of: pressure drop in inlet and outlet duct, ambient conditions, fuel LHV, relative rotation speed, turbine degradation and variable load. However, for variable turbine load, ready-curves were not available and the data entered were based on the available heat balances for various loads and ambient temperatures.

In addition to the "Data gas turbine" icon, two "GAS" icons representing air and fuel intakes were also used, as well as "EXH" representing exhaust outlet [1, 10, 11].

4. Calculation examples

To verify the correctness of the model heat balances of the CHP were used. These are the cases:

- 40% and 70% load for 0.9, 14 and 30°C ambient temperature,
- 100% load for -20, 0.9, 14, 15 and 30°C ambient temperature.

To demonstrate the example results, the following charts show changes in flow and temperature of the turbine flue gas and power as a function of the ambient temperature for various loads and for computations and design points.

The graph of exhaust gas temperature as a function of the ambient temperature (Fig. 5) shows that the computation results generally correspond to the values of the design points for all loads. There are only small deviations. These may be due to an aberration in reading the correction factors from correction charts, rounding by the software or interpolation of a factor instead of the software reading it direct from the tables.

Greater changes can be seen in the chart of exhaust flow as a function of the ambient temperature for 100% load (Fig. 6). This error was caused by different correction factors used in the heat balance for this case. Other cases seem to be the same as in the previous chart. The results of computations and design points overlap each other.

The results for power change for the variable ambient temperature (Fig. 7) also correspond to each other and mostly differ only slightly. The reasons for these differences are the same as above. The results which deviate from each other to a greater extent are in the same range of temperatures and for the same load as for the exhaust gas flow. The difference results from the heat balance assumption of maximum

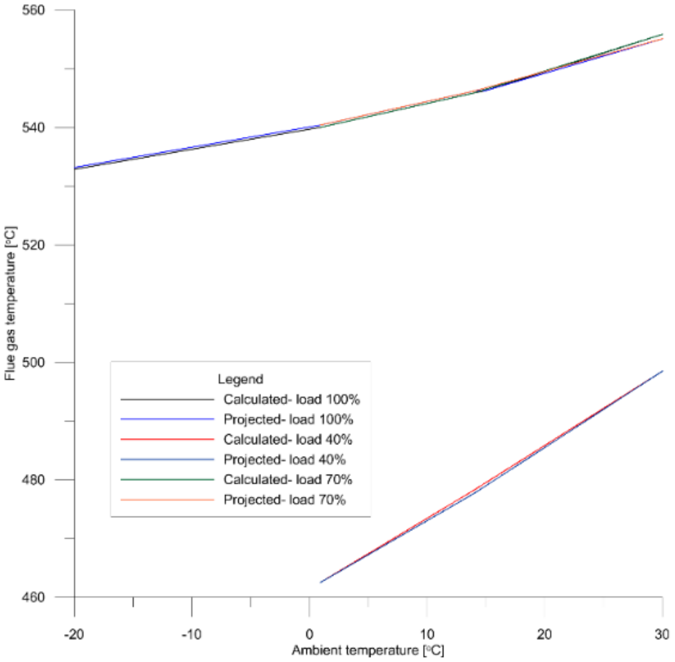

Figure 5: Comparison of the influence of ambient temperature and variable load on flue gas temperature

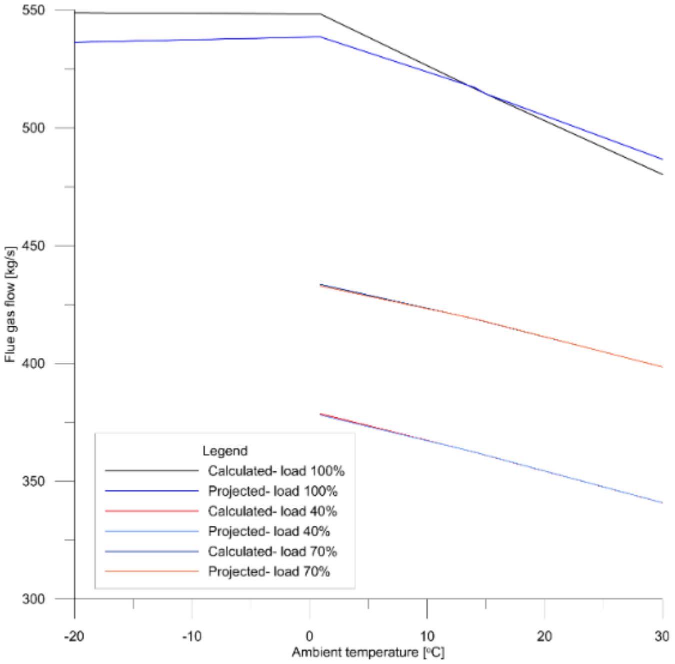

Figure 6: Comparison of the influence of ambient temperature and variable load on flue gas mass flow

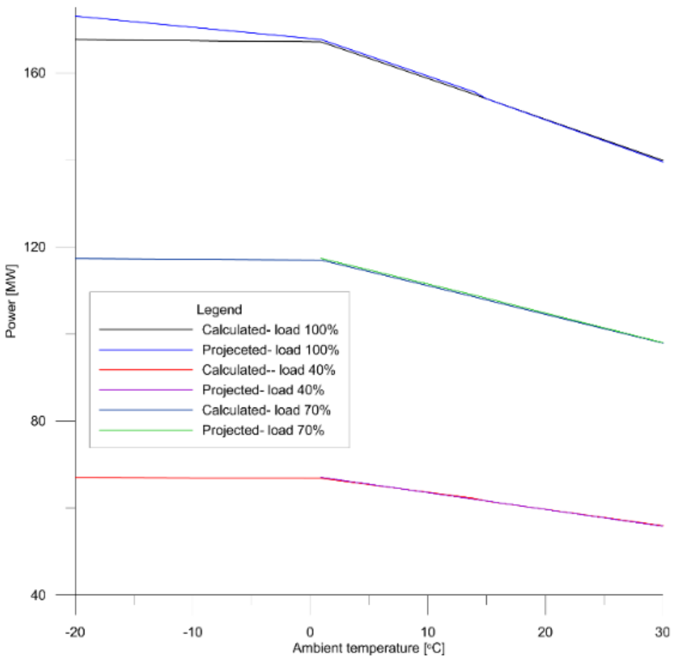

Figure 7: Comparison of the influence of ambient temperature and variable load on power

turbine power as the maximum mechanical power, instead of the power which will be generated by the generator.

In addition, during the computations a "warning" may appear, which is caused by specifying only the LHV of the fuel without stating its composition. Thus the software assumes its default composition, which calorific value differs from the setpoint. However, this does not affect the results of the computations.

5. Conclusions

This paper discusses the construction of the ANSALDO V94.2 gas turbine model for variable operating conditions. For this purpose GateCycle^{TM} software and the design data of the turbine were used. For the computations a method based on correction curves was selected. Tables of correction factors were used reflecting the influence of: pressure drop in inlet and outlet duct, ambient conditions, LHV of the fuel, relative rotation speed, turbine degradation and variable load. The curves for different loads were not available. Therefore, in order to build arrays of these coefficients available heat balances of the CHP were used. Only changes in efficiency tables were selected by default. In order to present the results of model computations, they were compared with the heat balances. Mostly, the results overlap each other and there are only small deviations, which however are not primarily caused by properties of the model. Therefore, it can be concluded that the model is working properly.

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