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Off-Design Analysis of the GRAZ Cycle Performance

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ABSTRACT

The Japanese World Energy Network Program (WE-NET) was focused on establishing a global energy system. Within frames of the program, hydrogen was meant to be a medium transferring energy from renewable energy sources to a place of its utilisation. The program target was, among others, to implement power plant stations of very high efficiency based on so-called hydrogen-fuelled gas turbines.

Several conceptual solutions have been evaluated and analysed so far but a so-called GRAZ cycle has been treated as the basic concept in the WE-NET Program. Static characteristics of the GRAZ cycle were elaborated. Part-load and over-load performance characteristics were calculated and analysed to show control possibilities of the cycle. According to the authors' knowledge, such an approach to the Graz cycle was carried out for the first time.

NOMENCLATURE

modules:
CDP – condensate pump; COMB – hydrogen-fuelled combustion chamber; COND – condenser; EX – heat exchanger; FWP – feed water pump. HHPT, HPT – high-high- and high-pressure turbine stage group, respectively; HRSG – heat recovery steam generator; G (or GEN) – electric generator; LP – low-pressure part; LPT – low-pressure turbine stage group, T – turbine stage group;

parameters:
m - mass flow, n – rotational speed, P – power (mechanic or electric), p – pressure, Q – heat power, T – temperature;

indexes:
0 – nominal condition, *C* – Carnot cycle related, *g* – refers to heat exchanger (hot side), *HHV* – high heat value, *LHV* – low heat value, *max* – maximal value, *min* – minimal value, *R* – Rankine cycle related, *w* – refers to heat exchanger (cold side), á - refers to outlet (outflow), ù - refers to inlet (inflow).

INTRODUCTION

The WE-NET Program concerns, among others, establishing a global energy network using renewable energy based on utilisation of hydrogen as a secondary clean energy carrier. Production cost of hydrogen, however, is relatively high, which requires designing a power system of much higher thermal efficiency compared to conventional power units. It was required to achieve the above 60%HHV thermal efficiency (it means above 71% LHV). Nowadays, thermal efficiency of the most advanced combined cycles (natural gas – fuelled) is close to 60% LHV (54% HHV) and is comparable to 50.4%HHV, assuming that hydrogen fuel is used. It was obvious that the efficiency should be increased by about 10 percent points, which was equivalent to about 20% in comparison with the most efficient contemporary power plant units. To meet such a requirement was a very serious technological challenge (a qualitative change, not only quantitative). The aim was to build a full-scale 500MW_e power plant unit. To achieve this, it was essential, apart from increasing working medium temperature at the turbine's inlet to 1973 K (at present, it was equal to 1773 K), to implement a new approach (different from a traditional one) for both conceptual design of the system (its configuration and working parameters) and to develop detailed construction solutions. The issue was challenging and potentially beneficial.

Taking the above into account, the main issue was to identify a proper cycle concepts and evaluate their performance characteristics. Due to its advantageous features, the GRAZ cycle was treated as a basic concept in the WE-NET Program (Mouri, 2001). However, during the research conducted by the authors several other concepts were analysed (Iki, et. al., 1999), (Miller et al., 2002). The research included, among others, the following main items:
(i) cycle identification and assessment, (ii) cycle selection, (iii) comparison of selected cycle performance in nominal state under the same reference conditions. The GRAZ cycle off-design performance characteristics are presented in this paper.

THE GRAZ CYCLE

A combined steam cycle with steam recirculation, proposed by prof. Herbert Jericha is called the GRAZ cycle.

The GRAZ cycle was an interesting combination of the Brayton and Rankine concepts. The Brayton cycle was applied as a topping cycle (high parameters zone) in half-closed arrangement, and was coupled to the Rankine cycle operating as bottoming cycle (low parameters zone).

Basically, the cycle consists of one combustor, three turbine parts, heat recovery steam generator, condensing part and compressor. Thermal efficiency achieved in the cycle amounts to 61% HHV (version without cooling). A flow diagram and basic flow parameters of the GRAZ cycle were shown in Fig. 1.

As in other cycle concepts of this type, the only one working medium (steam) was used for both topping and bottoming cycle. Replacement of an external firing (as in the Rankine steam cycle) by a direct firing (similar to gas turbines or piston engines) was also a characteristic feature. The combustion takes place inside a cooling steam flow, which reduces combustion temperature to 1973 K. Combustion process of hydrogen-oxygen mixture was assumed to be stoichiometric.

An original concept, which distinguishes the GRAZ cycle from others, was a bleed of partially cooled down working fluid from the Brayton cycle (point 8 of flow diagram, Fig.1) and its utilisation as

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working fluid in the Rankine cycle (points 8, 9, 12, Fig.1). Thus, this cycle is sometimes called the topping-extraction cycle. Efficiency benefit in this case comes from substantial decrease of compression load in the Brayton cycle, because big amount of working fluid (more than a half) reaches high pressure in a feed-water pump (points 12, 10 – Fig.1), instead of being compressed in a compressor.

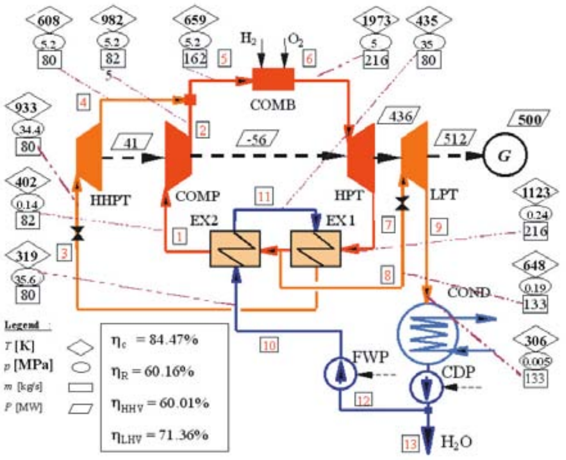

Fig. 1. Flow diagram and calculation results for the GRAZ cycle

NOMINAL CONDITIONS

Analysis of the GRAZ cycle under nominal conditions was conducted for the following values of parameters:
(i) compressor stages group internal efficiency 0.9, (ii) turbine stages group internal efficiency 0.9, (iii) combustor efficiency 0.99, (iv) heat exchanger pressure loss 0.043, (v) combustor pressure loss 0.05, (vi) pump efficiency 0.9, (vii) electric generator efficiency 0.99, (viii) cycle overall mechanical efficiency 0.99, (ix) overall power output 500MW_e, (x) temperature after combustor 1973 K, (xi) condenser pressure 0.005MPa, (xii) condensate temperature 306 K. Working medium parameters were calculated using the ITC-PAR calculation procedures (Kiryk, 2002), based on the NIST/ASME steam property tables.

The GRAZ cycle performance under nominal conditions was analysed based on maximal overall thermal efficiency criteria (minimum 60%HHV for the 500MW_e class unit).

It was possible to increase the GRAZ cycle efficiency by adding to the basic configuration a compressor inter-stage cooling and recuperation (high-temperature regeneration). Nevertheless, it should to be pointed out that implementing the GRAZ cycle would require introducing, in a different range, cooling systems of the hottest elements, which includes turbine blade cooling. Usually, the implementation of such cooling radically decreases overall cycle efficiency, so it is especially important that the cycle has got certain efficiency "reserves" (above 60%HHV).

During this research, a modified version of the GRAZ cycle was chosen. The GRAZ cycle was additionally equipped with the following items: (i) an inter-stage cooling system by condensate injection in the steam compressor, (ii) additional heat exchanger – regenerator - to heat steam flow at the inlet to the combustor, (iii) "classic" two-stage regenerative heating system with a deaerator.

In order to analyse cycle performance under changed conditions, a simple version of the system was chosen (Fig. 1). This way, we can concentrate on basic issues. Operation of cooling system and additional regeneration system under changed conditions can be taken into account in the next step.

OFF-DESIGN ANALYSIS

Part-load analysis was an important issue and it should be taken into account when designing and defining operational characteristics. Results of the cycle behaviour analysis under part-load conditions should support defining the cycle structure and its nominal parameters, as well as constructional solutions and characteristics of a given sub-system. It could happen that calculation results based on nominal conditions analysis (e.g. by use of maximum efficiency criteria) are not useful from the operation point of view. It was possible that specific working conditions of the cycle performance could be present, so its proper operation was only possible in a very narrow range of parameters, different from nominal ones, and so it was not possible that the cycle performance could adapt to the power output change. Thus, in the extreme case, starting up the cycle was practically not possible at all. It should be stressed that no complex analysis of the GRAZ cycle part-load operation has been published so far.

Part-load operation characteristic research can be reduced mainly to conditions of co-operation between turbo machines, the heat exchange element and other equipment. The regenerative heat exchangers set in the GRAZ cycle provided a kind of link between low- and high-pressure part of the cycle. A specific feature of this study was the existence of many bonds and limits. Bonds were defined mainly by the cycle configuration and properties of devices, together with their characteristics. Limits usually result from boundary values of working parameters. Thus, studying conditions of co-operation of the cycle can be reduced to description and analysis of all possible operational stages for which bonds and limits were fulfilled.

In order to define a mathematical model, the cycle flow diagram ought to be divided into specific modules. As a result, a supplementary diagram was worked out. Individual elements and with connections between them (input/output parameters) were shown in this diagram. Overall combination makes up a mathematical model structure scheme, shown in the Fig. 2.

Basic off-design analysis of the GRAZ cycle worked out here was limited only to a single-shaft version with constant rotational speed. So, it was necessary to stress that a condensing turbine module (LPT) was formally isolated in the Fig. 2, though according to the concept of dividing the GRAZ cycle into low-pressure and high-pressure part, the LPT module was assigned to the low-pressure part (NP). Isolating the LPT module was done for two reasons:
(i) the analysed GRAZ cycle concept was a single-shaft version cycle so the LPT turbine was placed in sequence power generation in mechanical sense and was one of element when summing up mechanical power generated on shaft-ends of particular turbine stage group and (ii) because of using the same elementary mathematical model (turbine stage group), describing the module's performance.

Mathematical model of the GRAZ cycle was formulated as a very complex and strongly non-linear algebraic equation set. Due to the complex structure of the GRAZ cycle, solving this model was difficult. There were inter-connections between main flow streams (collectors, distributors in the flow stream paths), while a split ratio was unknown and is to be found.

A complexity and number of equations of this kind of mathematical model induces to introduce a decomposition of the equation set into relevant equation sub-sets out of which each of them can be solved with different method. It is necessary then to keep a modular arrangement of the mathematical model, especially taking into account a fact that a number of modules are repeated.

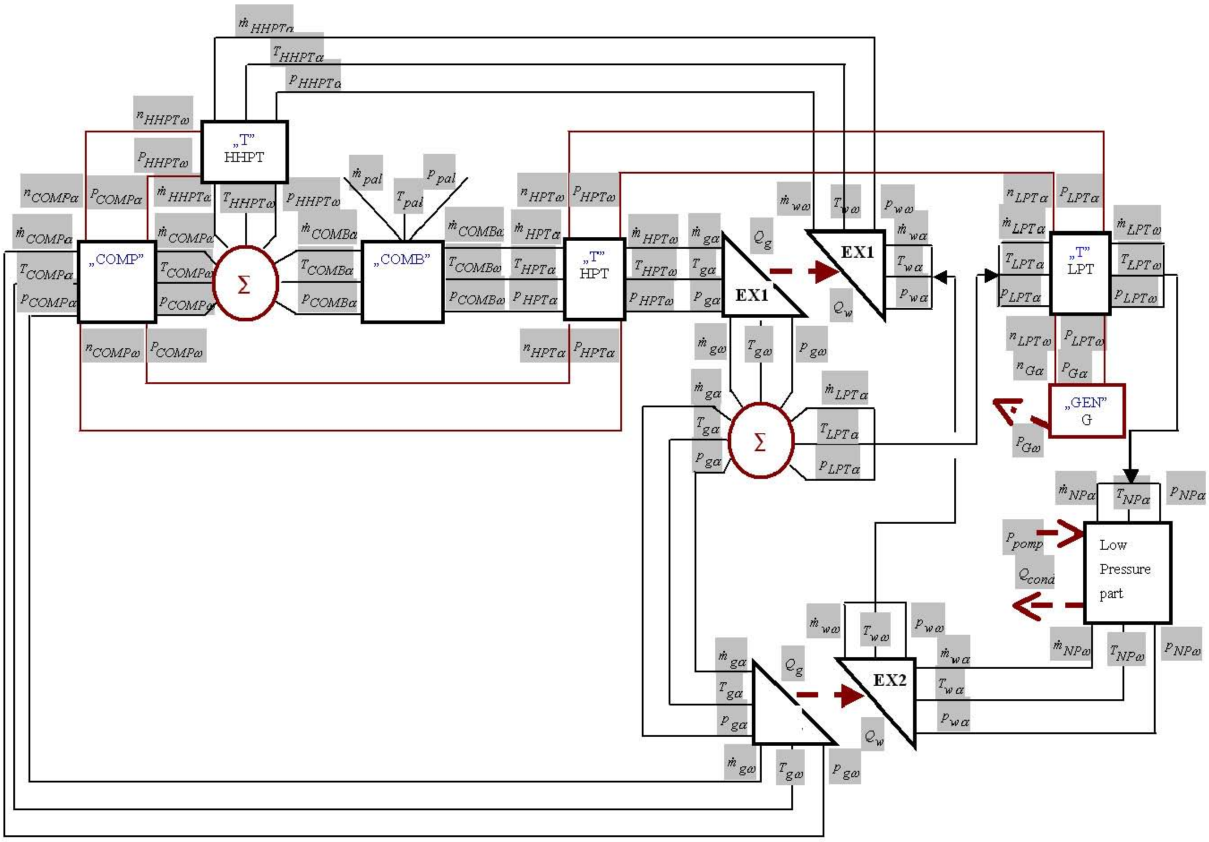

Fig. 2. Structure scheme of the Graz cycle's mathematical model

The equation set should be divided in such a way that equation sub-sets would be connected by possibly minimal number of common variables - so called - coordination variables. Additionally, equation sub-sets should be coherent with mathematical models of particular devices. In this way it is possible to formulate general modules modelling devices' performance which makes a possibility to study different structures made of typical modules. General concept of calculations realization for hydrogen gas turbine cycles like the GRAZ cycle is shown on the Fig. 3.

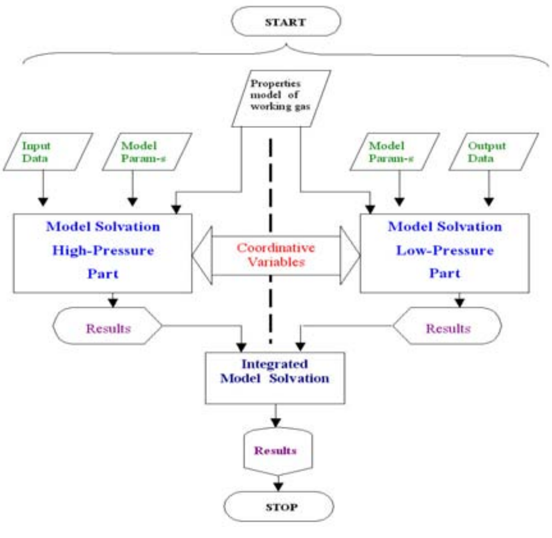

Fig. 3. Structure Scheme of performing calculations for GRAZ cycle

Mathematical models of individual elements of the system (modules) were presented by (Kiryk, 2002) and (Miller et al., 2001). In particular, a model of turbine stage group was given by Miller (2000).

Mathematical model of a steam compressor requires some additional remarks. Such a compressor is a new and virtually unknown element introduced in the GRAZ cycle. To our knowledge, this type of the compressor has not been used till now, and its implementation would require separate design work. For the purpose of mathematical modelling, several assumptions were taken, on the basis of the analogy of flow properties of superheated steam and gas, taking into consideration the possibility of applying several constructional ideas known from air compressors. Fig. 3 shows compressor characteristics used in the research.

In the case of compressor operating with constant, rated rotational speed – and simulating GRAZ cycle operation – the compressor characteristic is needed only to find out, whether operating conditions being examined (reduced flow and compression) are attainable by changing blade angle and how it will reduce the compressor efficiency.

It seems that under the circumstances assuming compressor characteristic of Fig. 3 is acceptable.

PERFORMANCE STATIC CHARACTERISTICS

In order to solve the mathematical model of the GRAZ cycle, a specific sequence-iteration program was developed based on modelling experience for "classic" condensing turbine sets.

The GRAZ cycle power output was changed affecting main circulating mass-flow (feed steam flow change) or changing temperatures after combustor (combustion temperature change), or both (combined method). Results obtained are shown in Figs. 5

through 15. The first case could be treated as a quantitative regulation method, the second one as a qualitative one and the third as a combined quantitative and qualitative.

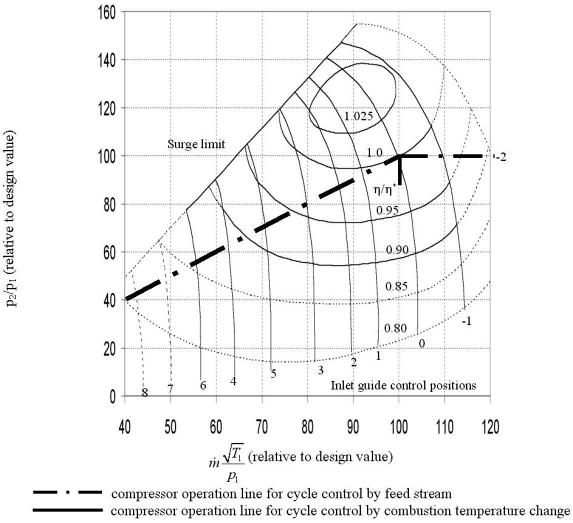

Fig. 4. Compressor characteristic: variable inlet vane angle

Regulation was possible on the working medium mass-flow side (by compressor outlet mass-flow) and by changing hydrogen-oxygen mixture supplied to combustors (fuel mass-flow). When changing the main circulating mass-flow, pressures change accordingly. To follow these pressure changes, the cycle should be provided with two valves – at the inlets of HHPT and LPT turbines, respectively. There is a kind of analogy here with the accumulation work mode. The influence of this regulation concept on the GRAZ cycle performance was simulated using the program under different part-load and over-load conditions. Calculations, if possible, were performed within the range from 20% to 120% of the nominal point.

When performing calculations, the following constraints and limits were taken into consideration:

(i) Compressor characteristics working range for the variable inlet vane angle.

(ii) Maximal temperature of the cycle (combustor outlet temperature 1973 K).

(iii) Minimal temperature difference in the heat exchanger, to ensure proper heat exchange conditions.

(iv) Stoichiometric ratio of fuel and oxygen, to ensure steadiness of the combustion process.

Input data for these calculations were: (i) compressor outlet mass flow, (ii) combustor outlet temperature, and (iii) condenser cooling conditions. Apart from sequential calculations, iteration loops were required to define work conditions of heat exchangers (EX1, EX2) and work conditions between the compressor (COMP) and the high-high-pressure turbine (HHPT).

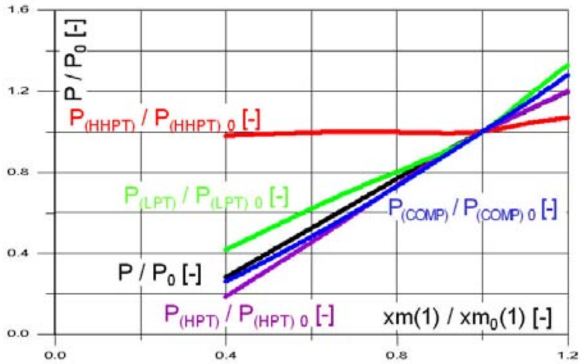

Fig. 5. The GRAZ cycle's p art load characteristics (feed steam flow change): relative power vs. relative feed steam flow

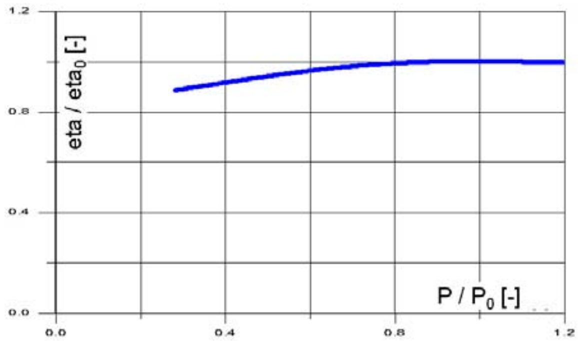

Fig. 6. The GRAZ cycle's part load characteristics (feed steam flow change): thermal efficiency vs. relative power

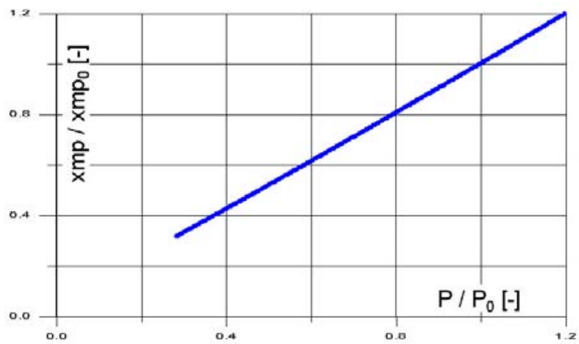

Fig. 7. The GRAZ cycle's part load cha racteristics (feed steam flow change): fuel mass-flow vs. relative power

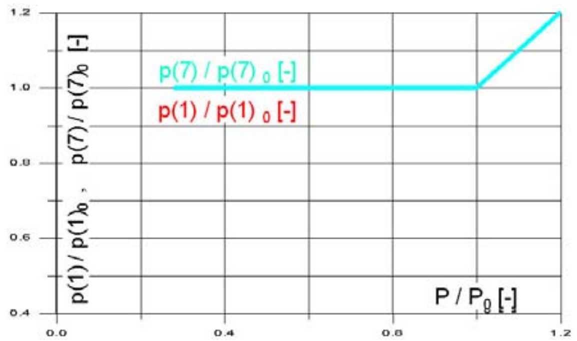

Fig. 8. The GRAZ cycle's part load characteristics (feed steam flow change): pressure vs. relative power

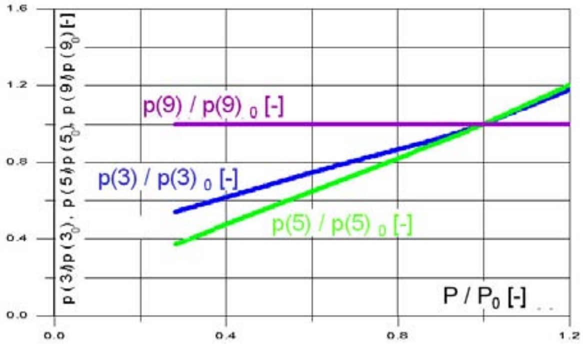

Fig. 9. The GRAZ cycle's part load characteristics (feed steam flow change): pressure vs. relative power

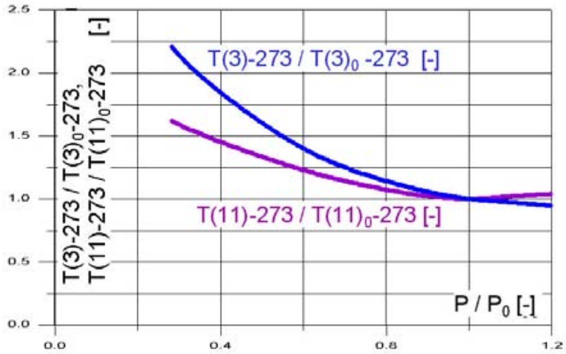

Fig. 10. The GRAZ cycle's part load characteristics (feed steam flow change): temperature vs. relative power

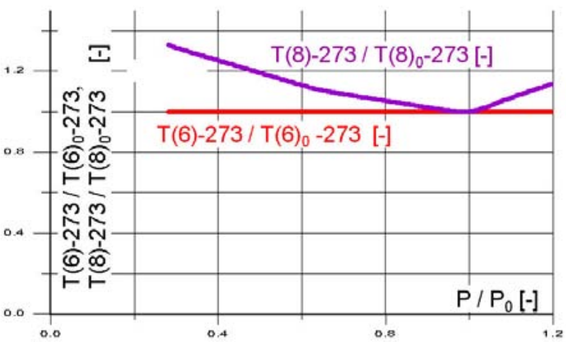

Fig. 11. The GRAZ cycle's part load characteristics (feed steam flow change): temperature vs. relative power

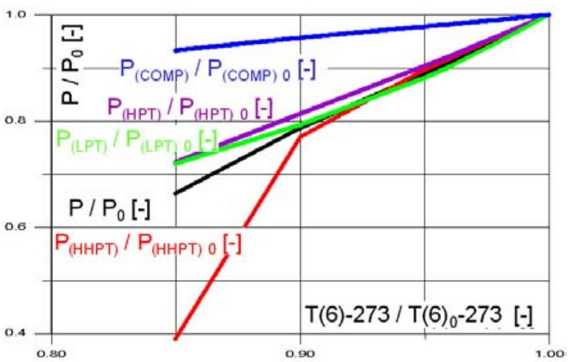

Fig. 12. The GRAZ cycle's part load characteristics (combustion temperature change): relative power vs. combustion temperature

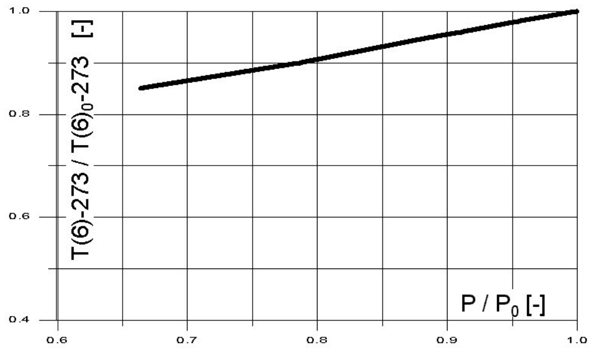

Fig. 13. The GRAZ cycle's part load characteristics (combustion temperature change): combustion temperature vs. relative power

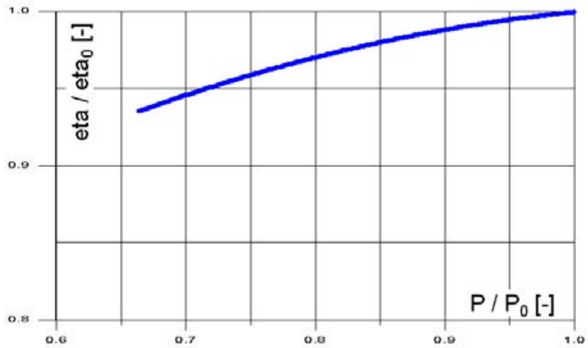

Fig. 14. The GRAZ cycle's part load characteristics (combustion temperature change): thermal efficiency vs. relative power

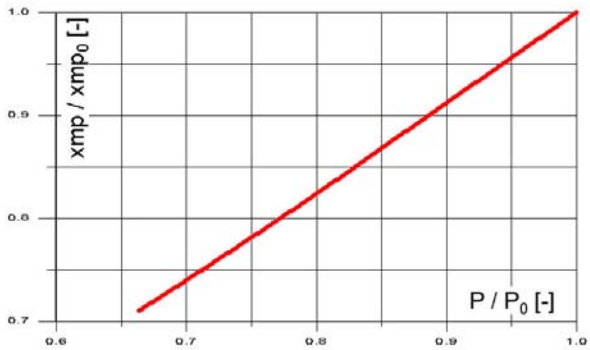

Fig. 15. The GRAZ cycle's part load characteristics (combustion temperature change): fuel mass flow vs. relative power

Combustion temperature change characteristics (Figs. 11 through 15) show that it was possible to operate only within very limited range of changes (P/P_oº(0.65 ; 1.0>). Change of combustion temperature with constant feed steam flow cause close to linear power output change.

As it is shown in Figs. 5 through 10, feed steam flow change with constant combustion temperature was accompanied by virtually linear change of power output, as well as linear pressure change in the cycle. In this case, regulation was possible down to 37% of P/P_o and in over-load conditions. Overall thermal efficiency varies only slightly within a wide range of the power output values (it was almost constant). Stable overall thermal efficiency was very important characteristic of the GRAZ cycle. The overall thermal efficiency change was bigger when regulation by feed steam flow change was used.

Combustion temperature change has less impact on changes of the overall thermal efficiency. However, it could be applied within very limited operational range of the cycle performance. Hence, a combined method was possible to consider – the main regulation would be done by changing feed steam flow together with changing combustion temperature for compensation regulation.

SUMMARY

Specific calculation program has been worked out for the GRAZ cycle to define static characteristics and part-load analysis under different off-design working conditions. This analysis was done for the single-shaft version with constant rotational speed. It was found that GRAZ cycle has good operational properties for part-load, stable efficiency and acceptable properties for overload. Results obtained for the GRAZ cycle basic off–design performance characteristics seem to be, in our opinion, the first results published in this field.

Investigations should be continued on possible increase of operational flexibility of the system by applying multi-shaft cycle concept.

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