OFF-DESIGN FLOW ANALYSIS OF COGENERATION STEAM TURBINE WITH REAL PROCESS DATA

by

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This paper presents the concept of reconstruction of the existing coal-fired combined heat and power plant to comply with new European environmental policies. The existing coal-fired boiler will be replaced by two new dual pressure heat recovery steam generators, which will utilize the exhaust gas heat from two new gas turbines. The steam from the heat recovery steam generators will be fed to the existing steam turbine. After the reconstruction, the nominal turbine inlet steam mass-flow of 40 kg/s will be reduced to 30 kg/s. During periods of low heat demand, only one gas turbine and one heat recovery steam generator will be in operation and the live steam mass-flow may drop even to 12 kg/s. Prior to the reconstruction, dedicated tests of the existing steam turbine were carried out using the steam from the existing coal-fired boiler. The goal of the test was to verify the viability of operation with such an extremely low mass-flow. The results of tests show that such operation is possible but inefficient from a power generation point of view. Besides this, the turbine control algorithm needs to be accommodated to this extreme operating regime and additional measures like displacement of the extraction points and steam cooling will be required to control the temperature of the steam extractions. The novelty of this paper is using real pre-reconstruction process data for the assessment of feasibility and efficiency of the post-reconstruction operation of a combined heat and power turbine.

Key words: *cogeneration, control valves, exhaust gas, heat recovery, steam turbine*

Introduction

In order to meet European environmental policies and to stay in operation older thermal power plants must be upgraded. Cleaner energy production is closely associated with large investments. Older coal-fired power plants are lowering the emissions of harmful gases like CO_2 and NO_x by, for example, incorporating machine learning algorithms for the control of the combustion process and introduction of primary and secondary measures for NO_x reduction: enhancing the distribution of combustion air, the introduction of cold flue gas recirculation, such as incorporation of selective catalytic reduction, and selective non-catalytic reduction of NO_x, *etc.* The other possibility is the replacement of the existing coal-based technology with more environment friendly technology. Environment friendly technologies ena-

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ble the generation of heat and power with less greenhouse gas emissions. This is usually associated with large investment cost.

In this particular case of combined heat and power plant (CHP), the existing coal-fired boiler is being replaced by two gas turbines (GT) and two heat recovery steam generators (HRSG). Only the existing extraction condensing steam turbine will be preserved. Two HRSG will feed the steam to the turbine. A schematic representation of the planned natural-gas-fired combined gas-steam CHP cycle is shown in fig. 1.

Similar cases were studied also by several authors. Akbari *et al.* [1] evaluated using the supply boiler for repowering the existing natural gas-fired steam power plant. The results show that use of HRSG with higher pressure levels causes an imbalance in the mass-flow rate of steam in steam turbines and different parts of the existing boiler. Agbor *et al.* [2] integrated techno-economic and environmental assessments of sixty scenarios for co-firing biomass with coal and natural gas. The results reveal that the fully paid-off coal-fired power plant co-fired with forest residues and natural gas is very attractive option. Vojdani *et al.* [3] developed a techno-economic-environmental assessment and multi-objective optimization of a triple pressure HRSG.

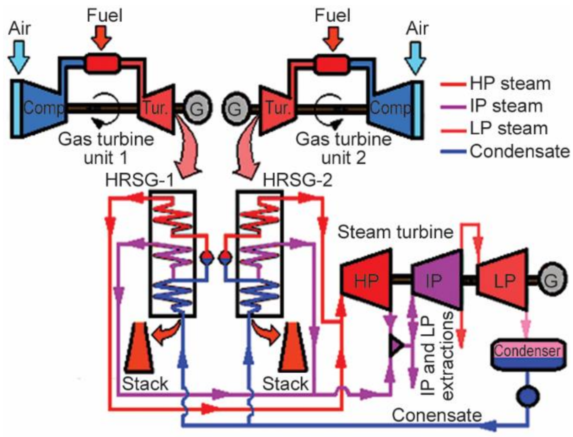

Figure 1. Natural-gas-fired combined gas-steam CHP cycle

The HRSG uses the exhaust gas heat from the GT for the production of high pressure (HP) and intermediate pressure (IP) steam. The HP steam is fed to the steam turbine while IP steam may be either fed to the IP turbine or employed directly for district heating or distributed to steam consumers. The steam production of HRSG is depending on the GT load. At maximal load, one GT consumes 2.78 kg/s of natural gas and the GT generator generates 54.4 MW of electricity. At the minimum load, one GT consumes 1.74 kg/s of natural gas and the GT generator generates 27.2 MW of electricity. Table 1 shows HP and IP steam parameters generated by HRSG at minimum and maximum GT load.

Table 1. Steam parameters of each HRSG depending on the GT load [4, 5]

Name	HP steam	IP steam
Flow	12-17 kg/s	2-3.5 kg/s
Temperature	505-525 °C	250-270 °C
Pressure	90-95 bar	8-9.5 bar

The IP steam and low pressure (LP) steam extraction pressures are controlled by throttling of IP and LP control valves [6]. Besides the IP and LP extractions, there exists also a so called HP extraction, fig. 2, which was used for regenerative feed water heating in the past but is currently not active. The pressure of HP extraction is sliding and depends on the turbine operating regime.

To verify the readiness and to identify the eventual hardware or software related modifications needed for the smooth and effective operation of the steam turbine in the combined gas-steam cycle at off-design extremely low steam flow, two-phase test was carried out.

Some other authors also researched this area. Arakelyan *et al.* [7] presented some aspects of steam turbine performance by numerical modelling of the hydrodynamic process. Cao *et al.* [8] presented the effects of water droplets on last-turbine stage blades at low steam flow. Mambro *et al.* [9] analyzed heat transfer in the last rotor stage of the steam turbine at minimal steam flow. Using computation modelling, Elmekawy *et al.* [10] examined condensing steam flows in LP steam turbines. Xinggang *et al.* [11] investigated condensing flow in the last stage of LP nuclear steam turbine. Cao *et al.* [12] presented strain-life estimation of the last stage blade of the steam turbine during low volume flow conditions. So far, we are not aware of any studies analyzing the behavior and the performance of an extraction condensing steam turbine operating at off-design extremely low steam flows in CHP.

The goal of this study was to assess if the existing steam turbine is capable of relatively efficient and reliable operation with extremely low inlet steam flow during minimum load of the topping gas-turbine cycle. The test was executed before the installation of GT and HRSG took place. The HP steam needed for the test was generated with the existing coal-fired boiler. The originality of this paper is the prediction of the feasibility and efficiency of post-reconstruction operation using pre-reconstruction equipment and process data.

Operation and test description

The steam turbine power output is controlled by the throttling of HP control valves. The desired IP and LP pressure of extracted steam is controlled by throttling of the IP and LP control valves. The steam that is not extracted from the turbine through IP and LP extractions exits through the exhaust of the turbine into the condenser. A schematic representation of the steam turbine control valves with steam extractions is shown in fig. 2. The HP extraction is designed for feeding the regenerative feedwater heater but is currently not used. The CHP operation principle and the thermodynamics specifications of the steam turbine had also been described in [5, 13]. The basic data of the existing steam turbine are shown in tab. 2. The values shown in fig. 2 are not representative of this particular test.

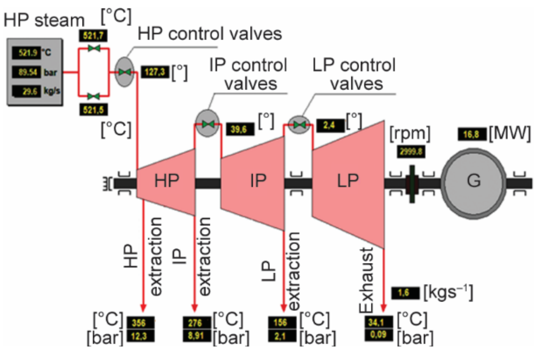

Figure 2. Steam turbine control valves with steam extractions

Test was executed in two phases. During the first phase the default algorithm for automatic control of HP, IP, and LP valves was engaged with no manual intervention. As described below, this phase has proven that the default algorithm will need to be accommodated to the operation with extremely low steam flow. During the second phase the HP, IP, and LP

Table 2. Basic data of the existing steam turbine [14]

Existing steam turbine type	Action type, extraction condensing, with two controlled pressure and one sliding-pressure steam extractions
HP steam pressure	Nominal: 92 bar, maximal continuous: 111 bar
HP steam temperature	Nominal: 520 °C, maximal continuous: 530 °C
Steam flow through HP turbine	Nominal: 40 kg/s, maximal: 62 kg/s
Steam flow through IP turbine	Nominal: 25 kg/s, maximal: 37 kg/s
Steam flow through LP turbine	Nominal: 20 kg/s, maximal: 28 kg/s

valves control was partly automatic and partly manual to mimic the future automatic control algorithm for the operation with extremely low steam flow. Measured data were recorded at one-minute intervals using the supervisory control and data acquisition system [15].

The first phase was performed in order to determine the adequacy of the automatic control algorithm and the responsiveness of HP, IP, and LP control valves. As mentioned before, the amount of HP steam, entering the steam turbine, is controlled using HP control valves to obtain the desired power output of the generator, while IP and LP control valves control the pressure of the extracted IP and LP steam [16]. The first phase commenced by slowly throttling the inlet steam flow with HP control valves. When steam flow dropped to 14 kg/s, the automatic control of IP and LP control valves was no longer able to maintain the desired pressure of extracted steam. At that point, the test was cancelled due to excessive steam pressure fluctuations. The duration of this first phase of the test was 720 minutes. Trends of steam temperature, pressure and flow during the first phase are shown in fig. 3(a).

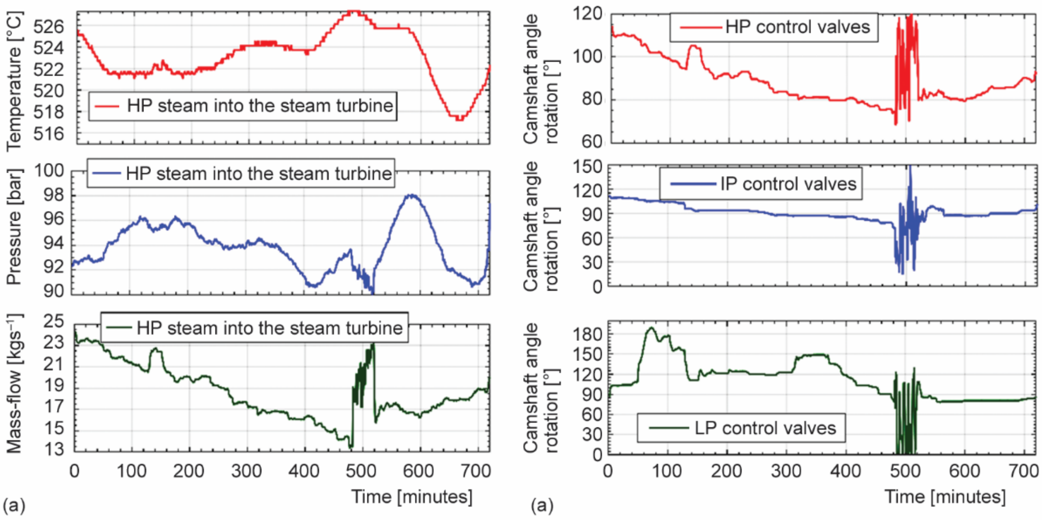

Figure 3. First phase: (a) parameters of HP steam and (b) positions of control valves

The HP, IP, and LP control valves are camshaft driven. The rotation angles of the HP, IP, and LP camshafts for the first phase of measurements are shown in the diagrams in fig. 3(b). The camshaft rotation angle of 0° corresponds to a fully closed position and the rotation angle of 260° corresponds to the fully open position. Figure 4(a) shows the pressure of IP, LP, and exhaust steam. Excessive fluctuations of pressure at about 500 minutes are caused by stochastic response of the turbine control system when the inlet steam flow dropped below 14 kg/s. Except for the beginning of the first phase, when HP steam temperature was decreasing, a tendency of increasing the temperature of LP extraction and exhaust steam was present. The temperature trends of IP, LP, and exhaust steam during the first phase are shown in fig. 4(b).

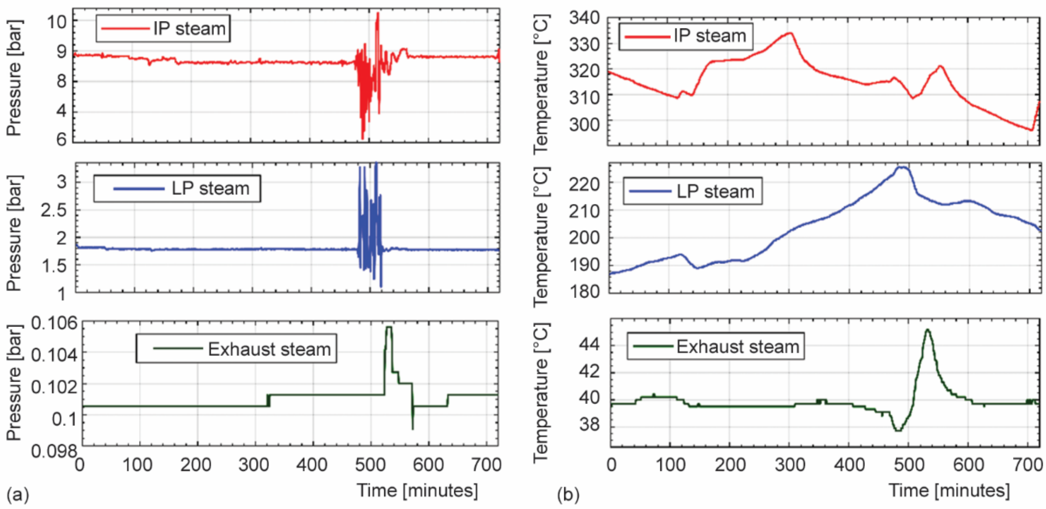

Figure 4. First phase: steam pressure (a) and temperature (b)

The generator power output and the condensate mass flow during the first phase are shown in fig. 5.

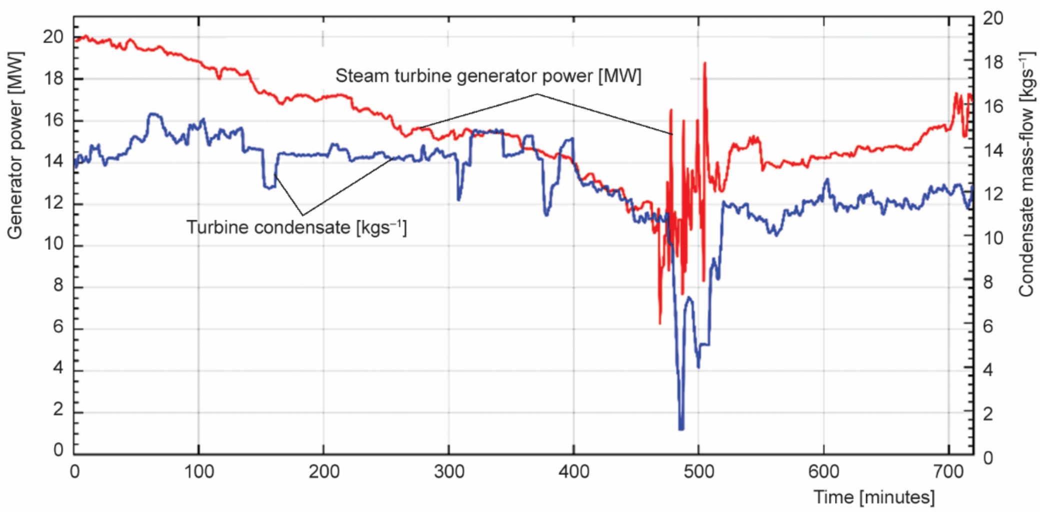

Figure 5. First phase: generator power output and turbine condensate mass-flow

Due to the unfavorable results of the first phase of the test, the second phase was planned in a different manner and divided into three consequent periods. The automatic turbine control was gradually introduced in the respective periods of the second phase.

During the first period, 0-30 minutes, only the control of the HP control valves was actively maintaining the inlet steam flow between 12 kg/s and 14 kg/s. Both IP and LP control valves were manually set to a fully open position meaning that no steam left the turbine through IP and LP extractions and that the exhaust-steam mass flow was equal to the inlet steam mass flow.

During the second period, 30-120 minutes, the automatic control of the LP control valves was activated to enable the extraction of LP steam while the IP control valves were still manually set to fully open position. Gradually, the LP control valves became almost completely closed and almost all steam was extracted through the LP extraction. Only 0.7 kg/s of steam was still passing through the remaining LP turbine stages.

The parameters of HP steam for the duration of the second phase are shown in fig. 6(a) and the positions of control valves in fig. 6(b).

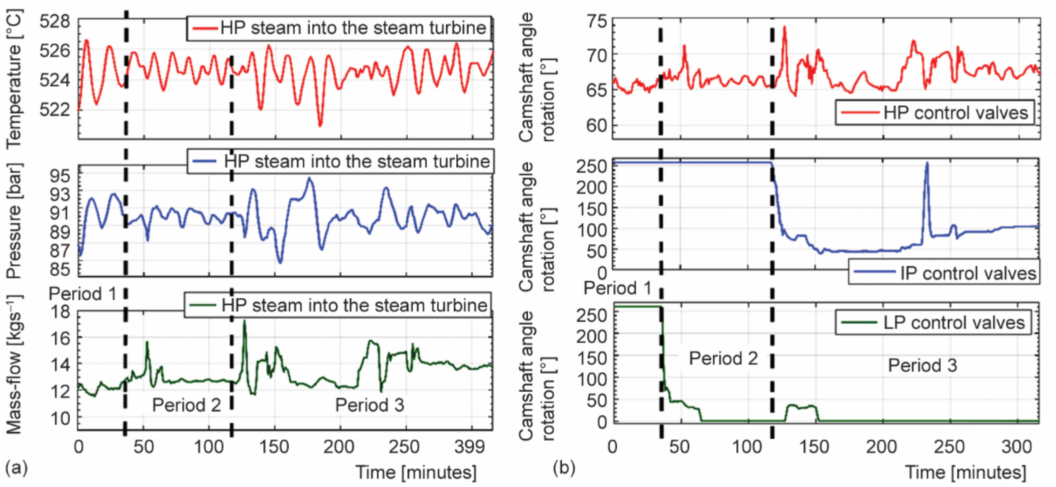

Figure 6. Second phase: (a) parameters of HP steam and (b) positions of control valves

During the third period, from 120 minutes onwards, the control of IP control valves was also activated to maintain the desired pressure and flow of the IP extraction. From this point on, the turbine automatic control system was capable of maintaining stable operation of the steam turbine.

Figure 7(a) shows the IP, LP, and exhaust steam pressure during the second phase of the test. The increase of LP steam pressure may be observed when the LP valve was activated and the increase of IP steam pressure may be observed when the control of the IP valves was activated.

After activation of IP control valves, a mass flow of 3 kg/s of IP steam was extracted from the steam turbine. Besides the increase of pressure, the increase of temperature of both LP and IP extractions can be observed, fig. 7(b).

After respective activations of IP and LP extractions, the power output dropped, which can be seen from fig. 8.

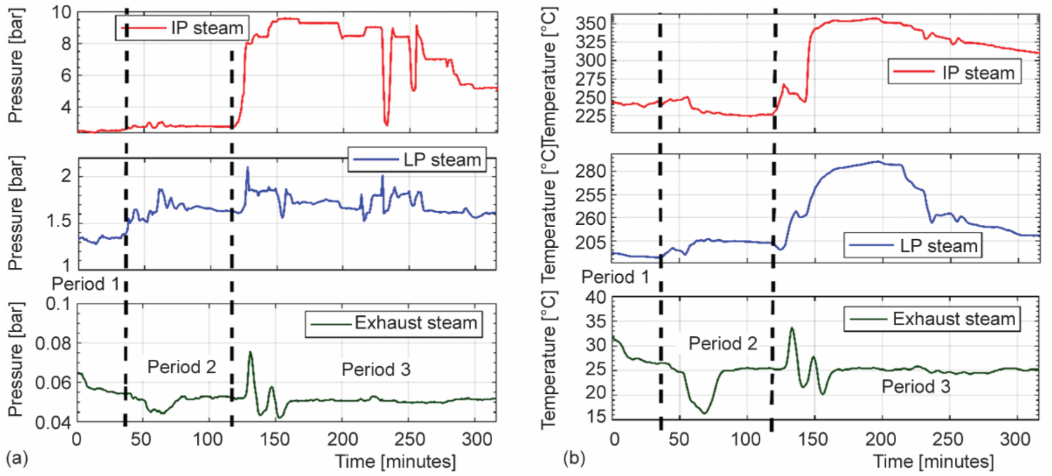

Figure 7. Second phase: steam pressure (a) and temperature (b)

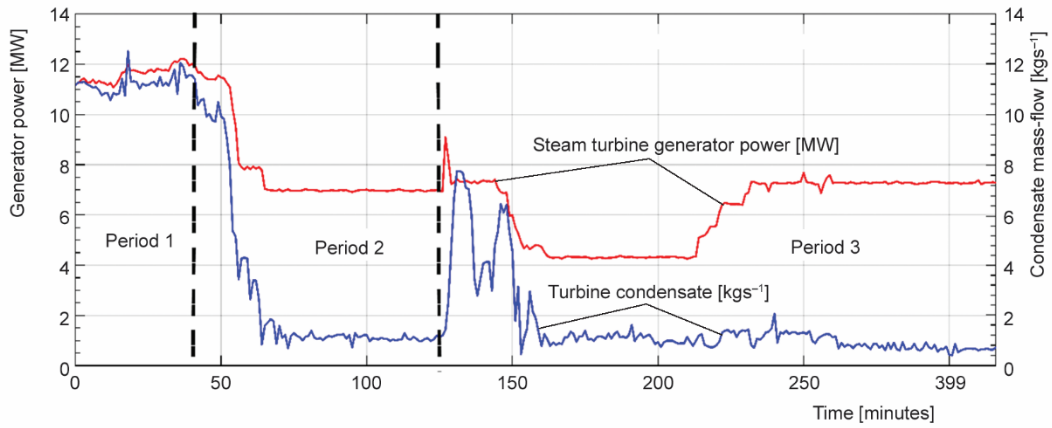

Figure 8. Second phase: generator power output and turbine condensate mass-flow

Analysis of test results

The increase of temperature of LP and IP steam after activation of IP control valves can be explained by the fact that extreme throttling is required in HP inlet valves to keep the HP steam mass-flow very low. This causes the origin of the steam expansion to move towards lower pressure. Additionally, the isentropic efficiency of turbine stages decreases due to low steam velocity and distorted steam flow through turbine blading. Both effects cause the intersection of the expansion curve and extraction pressure to move towards a higher temperature compared to operation with nominal inlet steam flow. The steam expansion curves of corresponding operating regimes are presented in fig. 9.

The analysis shows that operation in the condensing mode and in CHP mode with automatic control of only LP valve (IP valve fully open) is possible with no need for any major modification despite extremely low inlet steam flow. Nevertheless, during the CHP regime with the employment of both IP and LP extractions, the automatic control algorithm of valves

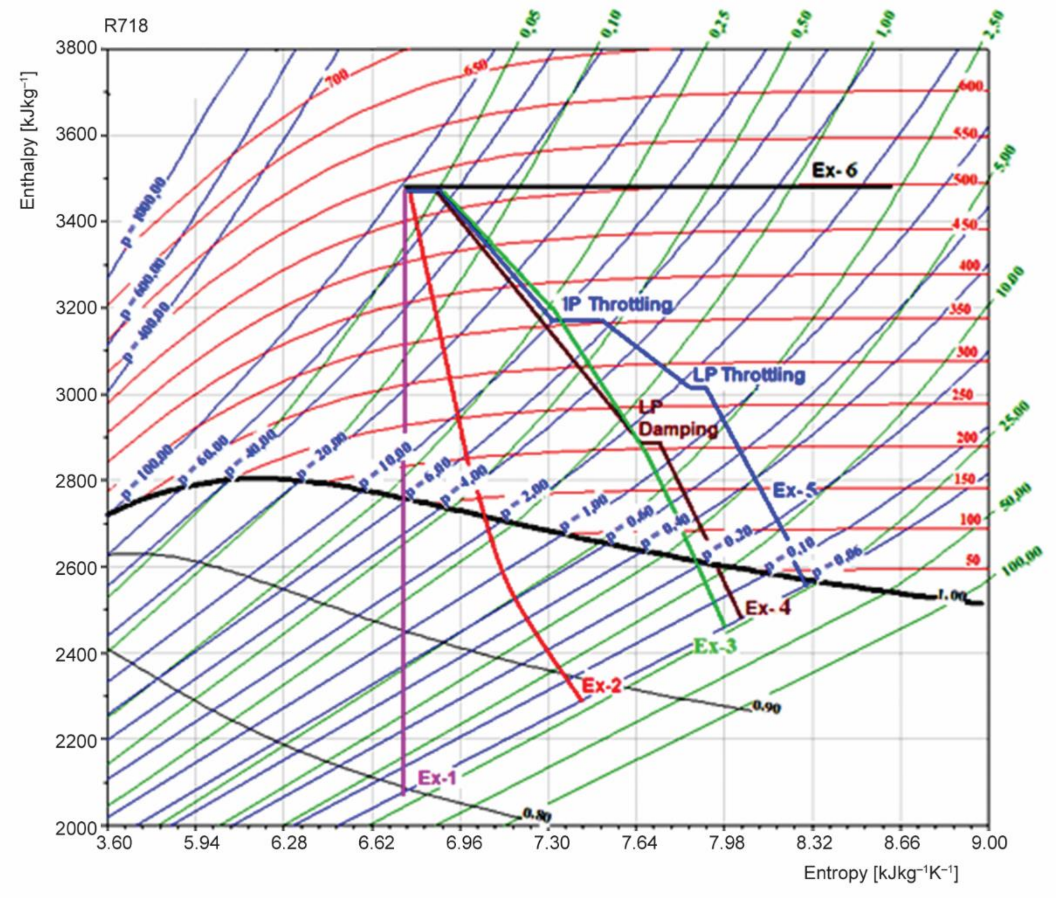

Figure 9. Steam expansion curves; *Ex-1 - theoretical isentropic expansion, Ex-2 - polytropic expansion, condensing mode, nominal steam flow, Ex-3 - polytropic expansion, steam mass-flow 12.5 kg/s, condensing mode, IP and LP control valves fully open, Ex-4 - polytropic expansion, steam mass-flow 12.5 kg/s, CHP mode, IP control valve fully open, automatic control of LP valve, Ex-5 - polytropic expansion, steam mass-flow 12.5 kg/s, CHP mode, automatic control of IP and LP valve, Ex-6 - theoretical isenthalpic expansion (throttling), no technical work generated*

fails. Besides this, the temperature of IP steam exceeds the limit of 290 °C which is imposed by the consumer of the extracted IP steam. Therefore, the algorithm tor automatic control of HP, IP, and LP valves will need so be modified and certain hardware adaptations will be required to control the temperature of IP steam. Three possible solutions are:

– default IP extraction may be used with additional cooling of the extracted steam,
– the HP extraction may be used with additional cooling of the extracted steam, and
– the HP live steam may be extracted upstream the turbine with additional cooling and reduction of pressure.

A schematic representation of feasible modifications needed for IP steam generation is shown in fig. 10.

Off-design flow analysis of cogeneration steam turbine with real process data shows that more throttling is required in inlet steam turbine control valves. This greatly affects the

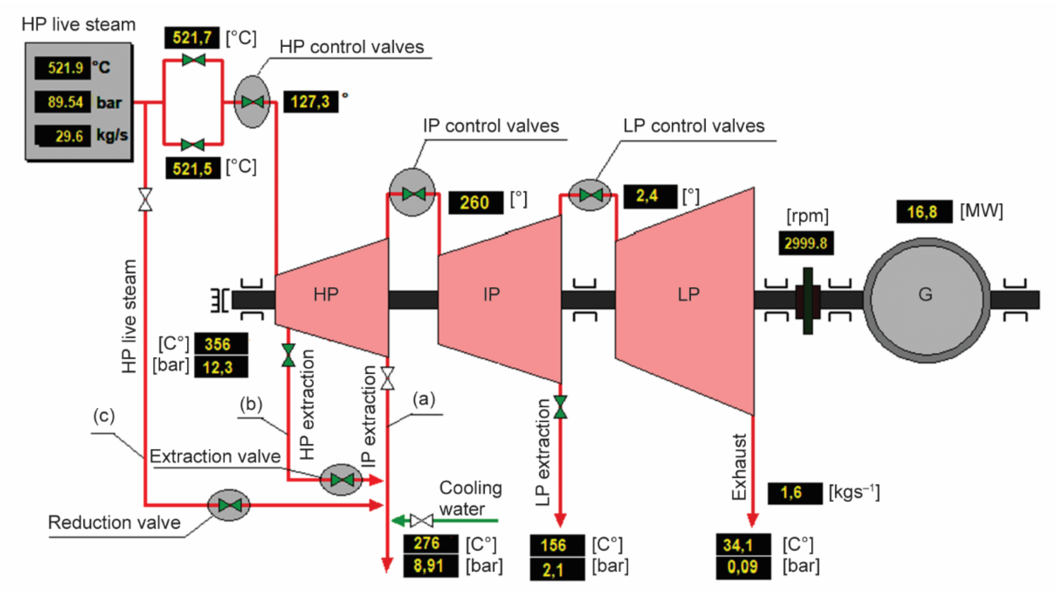

Figure 10. Schematic representation of feasible solutions for IP steam temperature control

power output of the turbine and its isentropic efficiency. Additional throttling in the IP control valves, which is required for maintaining of the IP steam pressure, further reduces the performance of the steam turbine. If the steam was extracted through HP extraction instead of through the IP extraction, less throttling in the IP control valves would be required. At the lowest inlet steam flow the use of live HP steam with the subsequent reduction of pressure and temperature becomes the least inefficient mode of IP steam generation. Therefore, as the inlet steam flow reduces, the optimum IP steam extraction point moves upstream the default IP extraction point. It even moves upstream the turbine for the lowest of steam flows.

Conclusions

According to the results of the test, the adaptation of the algorithm for automatic control of turbine inlet and extraction valves is needed to avoid stochastic response of the valves when steam inlet flow drops below 14 kg/s.

Due to excessive throttling in HP and IP valves during steam inlet flow of less than 14 kg/s, the temperature of the extracted IP steam exceeds the temperature required by the steam consumers. To avoid excessively high steam temperatures and the deterioration of turbine performance, the location of IP steam extraction may be moved upstream the default IP extraction point, even upstream the turbine inlet valves with in the case of the lowest inlet steam flow. In this last case, subsequent pressure reduction will be required. Regardless of the location of the IP steam extraction point, additional cooling of steam will be required.

Other authors in this field. Lu *et al.* [17] and Agrež *et al.* [18] also analyzed steam throttling in steam turbine valves and concluded the amount of entropy generated during thermodynamic transformation is closely related to the degree of steam throttling. Wang *et al.* [19], Mambro *et al.* [20], and Guo *et al.* [21] analyzed the steam turbine at minimum flows, where they also found increased entropy generation and a consequently decreased cycle efficiency. As already mentioned, the expansion curves for various modes of steam turbine operation constructed using the real process data confirm exactly this. Using the results of this test, the control of turbine valves and steam extractions will be accommodated for low-steam flow operation so that the deterioration of isentropic efficiency will be minimized.

The presented test proved that, despite few unavoidable but relatively minor modifications, the existing condensing extraction steam turbine with the nominal inlet steam flow of 40 kg/s can operate even with an off-design extremely low steam flow of 12 kg/s but at the expense of isentropic efficiency and power output. Considering that the turbine is primarily dedicated for the combined heat and power generation, that substantial investment costs for the replacement of the turbine were avoided and that only a minor portion of yearly heat and electricity will be generated in this mode of operation, the aforementioned deterioration of performance may be tolerated.

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Nomenclature

CHP – combined heat and power plant
GT – gas turbines
HP – high pressure
HRSG – heat recovery steam generators
IP – intermediate pressure
LP – low pressure

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