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Comparative thermodynamic analysis of quasi-nonstationary operation of one and two power units with capacity of 370 MW operating in cogeneration

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Abstract

This paper undertakes a comparison of annual, quasi-nonstationary operation of one and two power units with a capacity of 370 MW operating in cogeneration used to feed heaters connected in a series. The comparison encompasses the thermal parameters of the steam in turbine extractions used to feed the heaters, the potential for achieving district hot water parameters behind the heaters and the energy efficiency of the steam bleed from one and two power units.

Keywords: power unit, CHP, repowering, useful heat,

1. Introduction

Combined heat and power is one of the most important ways of producing energy in an ecological and economic way, as was reflected by EU Directive 2012/27/EU of 25 October 2012 on energy efficiency. Poland is one of the countries in which the ratio of the heat production in combined heat and power systems to the total heat production in central heat sources is at a high level. In 2011 it accounted for 64% of the total heat production. Although this ratio may appear high, there is still considerable scope to expand the use of cogeneration.

One important way to develop the CHP system involves repowering power units in baseload power plants. In this case a standard large power unit, which is capable of concurrently producing heat and power, has a different structure from a standard combined heat and power system including an extraction-condensing turbine in the power plant. In this case the production of heat is considerably smaller even in the period corresponding to its peak demand in relation to the total production of electricity. In addition, it is possible to completely compensate the loss of electrical output as a result of implementing cogeneration, which is an economically viable enterprise [1–4]. However, a major problem associated with repowering a unit in a baseload power plant is the appropriate selection of steam extractions in the steam turbine to be used to feed heaters from among the extractions used for feeding steam regeneration reheaters [1, 3]. Another important problem is choosing the appropriate number of units to participate in steam production for heating purposes. The adaptation of a single unit in a power plant is the cheapest alternative in terms of cost, but an emergency source is also needed, and this cost has to be accounted for. A steam header or emergency water boiler can be investigated as an emergency source. One other aspect that needs to be factored in is that when the repowered unit is in shutdown, the heat delivered from the emergency source will have low exergy efficiency and, consequently, the specific cost of heat will be higher. One alternative is to repower two or more units in a power plant so that more units are adapted for heating purposes. While this entails greater investment cost, the economic efficiency will be considerably higher. Consequently, it is necessary to undertake a comparative analysis of the adaptation of various numbers of units in a power plant. This should logically include quasi-nonstationary operation resulting from the operation of the power plant in the power and frequency regulation system of the Polish Power System (PPS), which corresponds to the annual, hourly output of electricity production in specific units overlapping with

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the hourly output of demand for district heating corresponding to actual ambient temperatures. This paper contains a thermodynamic comparison between heater supply from one and two power units.

2. Thermodynamic calculations

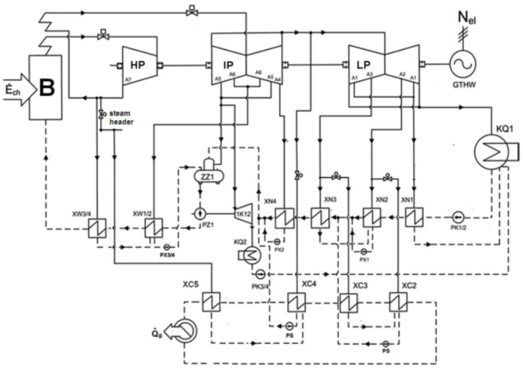

Figure 1: Diagram of a 370 MW unit adapted to cogeneration (B—steam boiler, HP, IP, LP—high-, intermediate- and low-pressure section of the turbine, GTHW—generator, A1, A2, A3, A4, A5, A6, A7—turbine extractions, KQ1, KQ2—condensers in the main and auxiliary turbines, XN1, XN2, XN3, XN4—low-pressure regeneration reheaters, XW1/2, XW 3/4—high-pressure regeneration reheaters, XC2, XC3, XC4, XC5—heaters, PZ1—main feedwater pump, 1K12—steam turbine used to feed PZ1, PK—condensate pumps, PX, PS—condensate pumps, ZZ1—feedwater tank)

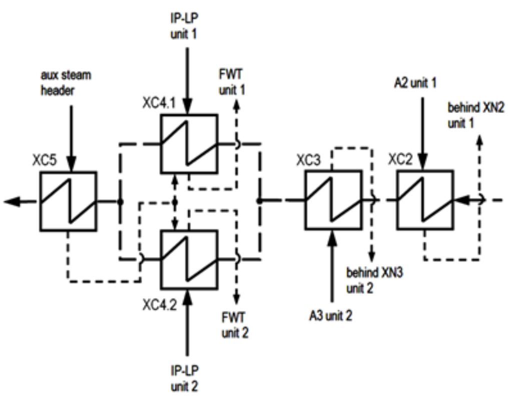

Figure 2: Configuration of heaters with steam bleed from two power units

Thermodynamic calculations for the case of steam bleed from one and two power unit into the heaters are based on the mathematical model presented in [2]. For the case of steam bleed from a single unit, steam is extracted from A2, A3 extractions, the crossoverpipe located between the low- and intermediate-pressure sections of the turbine and the steam header with steam bleed from the exhausts of the high-pressure sections of the turbines (Fig. 1) of all four units in the power plant. For the case of steam bleed from two units, the steam used to feed the XC2 heater is extracted from one of the units and from the other unit to feed into XC3 heater. XC4 heater is divided into two concurrently operating heaters—XC4.1 and XC4.2 (Fig. 2). This is aimed at maintenance of required temperatures of network hot water for the case when one of the repowered units is shut down. In both alternatives, XC5 heater plays the role of emergency peak heater and the steam to feed it is extracted from the auxiliary steam header. It was assumed that the pressure in it was constant at 1.8 MPa.

The analyzed units operate in the power and frequency regulation of the Polish Power System and their electrical output is varied according to the requirements of the system. In most cases it means that they operate with a capacity which is close to maximum during the day peak period and at minimum capacity during the night valley. A comparison of the thermodynamic parameters was undertaken for two values of electrical output—the maximum of 380 MW and the minimum of 180 MW. This paper also contains a comparison of the specific uses of the chemical energy of the fuel calculated for the actual, annual output of electricity and heat production for the cases of steam bleed from one and two repowered units.

The thermal power was adopted in accordance with the linear qualitative regulation chart (Fig. 3, 12, 13, dash-dot line) on the assumption that its maximum value is equal to $\dot{Q}_{c\,max}$ = 220MW, and the power needed for domestic hot water is equal to $\dot{Q}_{dhw}$ = 15MW. Due to the need to achieve the temperature of domestic hot water of +55°C, it was assumed that the minimum temperature of network hot water was equal to +70°C for the range of ambient temperatures from 20°C do +2.6°C and the temperature of return water was +41.7°C. Within this temperature range, the volume of heat delivered was regulated through varying the volume of network hot water flow.

2.1. Results of selected thermodynamic calculations for operating the units with electrical output of 180 MW

The following figures: 3–7 present the saturation temperatures and volumes of steam extracted to feed XC2, XC3, XC4 heaters (for operation with a single unit) and

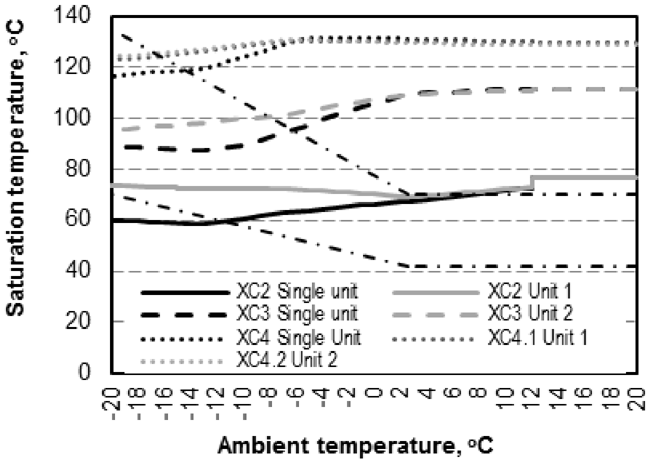

Figure 3: Relation between saturation temperature before XC2, XC3, XC4 (XC4.1, XC4.2) heaters and ambient temperature for steam bleed from one and two units used to feed heaters

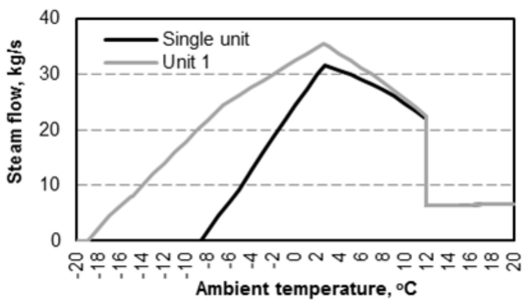

Figure 4: Relation between steam extraction into XC2 heater and ambient temperature for two alternatives of heater feeding (from one and two power units)

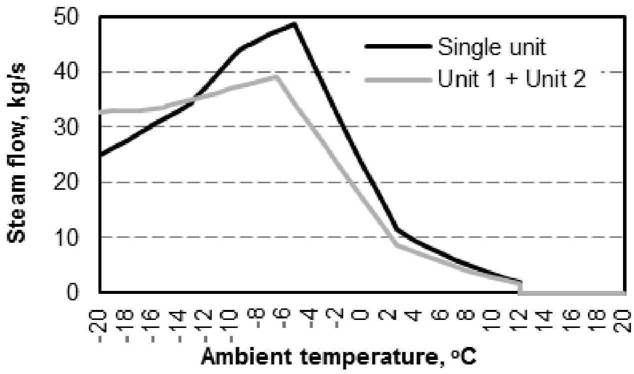

Figure 5: Relation between steam extraction into XC3 heater for feeding this heater from one and two power units

XC4.1, XC4.2 heaters (for the operation with two units) as a function of ambient temperatures. For the case of the operation of two power units, the period of shutdown of one of the repowered units and steam bleed from the other unit are not accounted for.

As one can note, the use of two power units to bleed

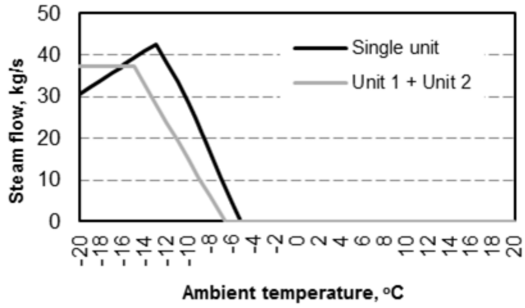

Figure 6: Relation between volume of steam used to feed into XC4 heater for steam extraction from one and two power units (for steam extraction from two power units the feed into XC4 heater is the sum of steam flow into XC4.1 and XC4.2 heaters)

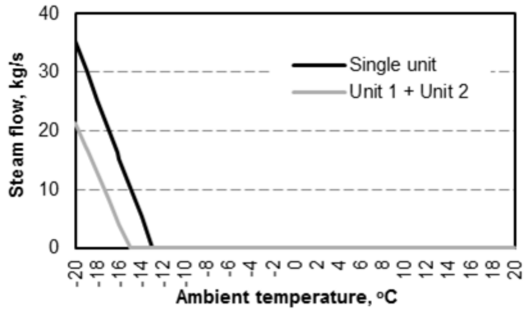

Figure 7: Relation between volume of steam used to feed into XC5 heater for steam extraction from one and two power units (for steam bleed from two units the feed into XC5 heater

steam for feeding heaters results in lower drops of steam saturation temperatures before the heaters. The largest differences in this respect are registered for the case of steam bleed from A2 extraction. For ambient temperatures above +2.6°C, these differences are small and do not exceed 2°C. Below this temperature the extraction of steam to feed XC3 heater increases and for operation with a single unit the pressure drop in A3 extraction augments the pressure drop in A2 extraction, thus reducing its saturation temperature. This results in a smaller range of application of XC2 heater for steam extraction from A2, as it is smaller than for the case of heater feeding from two power units. A similar tendency is known to occur for the case of XC3 heater. The values of the pressure in it and the corresponding saturation temperature are affected by the pressure in the crossoverpipe which joins the intermediate- and low-pressure sections of the turbine. Due to the fact that for the case of steam extraction from two units, XC4 heater is divided into two heaters (XC4.1 and XC4.2) operating in a parallel system, the steam is extracted from two units and it brings a lower pressure drop in the IP-LP crossoverpipe in each unit.

Figs 4-7 illustrate steam bleed to feed XC2, XC3, XC4 heaters (and the alternative with XC4.1 and XC4.2 heaters for the steam bleed in parallel from two units) as a function of the ambient temperature. Due to the steam bleed in parallel to feed XC4 and XC5 for the case of steam extracted from two units, the volumes of steam used to feed them are added.

By analyzing the flow of steam during heater feeding from a single unit, one can note that for the case of its operation at minimum electrical output, it is sufficient to use A2 extraction to heat network hot water to the required temperature of +70°C only in the summer season (Fig. 4, black line). The highest value of steam flow into XC2 heater occurs for the ambient temperature of +2.6°C and is equal to around 31.5 kg/s. For further decrease of ambient temperatures, the flow of stream from extraction A2 decreases and becomes zero for the temperature of −8.6°C. Extraction A3 (Fig. 5, black line) starts to be used for steam bleeding for ambient temperature below +12°C. For the temperature of −5.2°C it achieves its maximum at 48.7 kg/s, and subsequently decreases to the value of 24.8 kg/s. The decrease of steam bleed from extraction A3 is caused by the decrease of pressure in it and its corresponding saturation temperature. This, in turn, results in the need to bleed steam to feed XC4 heater for the purposes of heating hot water to the required temperature for ambient temperature below −5°C (Fig. 6, black line). This flow increases and gains a maximum of 42.6 kg/s for the ambient temperature of −12.9°C, and subsequently, decreases to reach a minimum of 30.6 kg/s as a result of the decrease in temperature of steam saturation. Below the temperature of −12.9°C it is necessary to additionally include steam feed from the auxiliary steam header into XC5 heater. Its maximum value is equal to 35.3 kg/s for the minimum investigated ambient temperature.

The parallel steam bleed from two power units to feed the heaters is characterized by a larger steam flow into XC2 heater (Fig. 4, grey line), whose maximum value occurs for the ambient temperature of +3°C and is equal to 35.5 kg/s. As one can note, this heater is capable of heating water over the entire range of the variable ambient temperatures. This leads to the limitation of steam bleed from A3 extraction in comparison to feeding heaters from a single unit (Fig. 5) for the range of ambient temperatures from +12°C to −13°C. For ambient temperatures below −13°C, the flow of steam in this case is greater than for the alternative with steam extraction from a single unit due to the higher temperatures of steam saturation. The volumes of steam feed into XC4.1, XC4.2 heaters are added and presented as a single flow (Fig. 6) in order to make it easier to compare it with the values for the XC4 heater. For ambient temperature above −16°C, its value is smaller than for steam flow into XC4 heater. Below this temperature, the volume of steam used to feed XC4.1 and XC4.2 exceeds the flow of steam into XC4 heater due to the higher saturation temperatures in the crossoverpipes. The extraction of steam to feed XC5 heater is made up by the sum total of steam extracted from both repowered units, and its value is smaller than for the case of steam bleed from a single unit (Fig. 7).

2.2. *Results of selected thermodynamic calculations for power unit operation with electrical output of 380 MW*

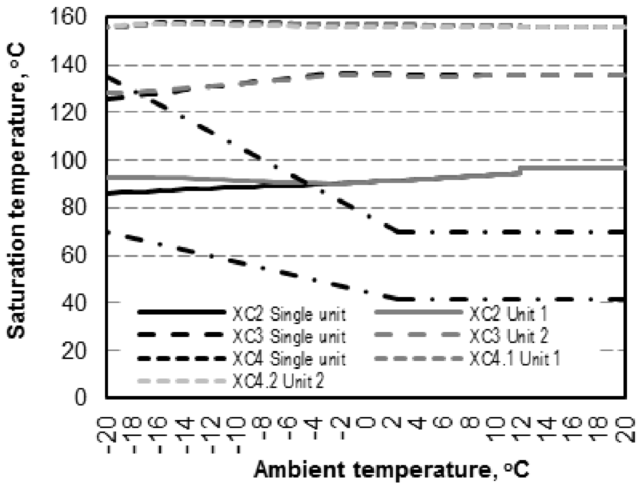

Figure 8: Relation between saturation temperature before XC2, XC3, XC4 (XC4.1, XC4.2) heaters and ambient temperature for steam bleed from one and two units used to feed heaters

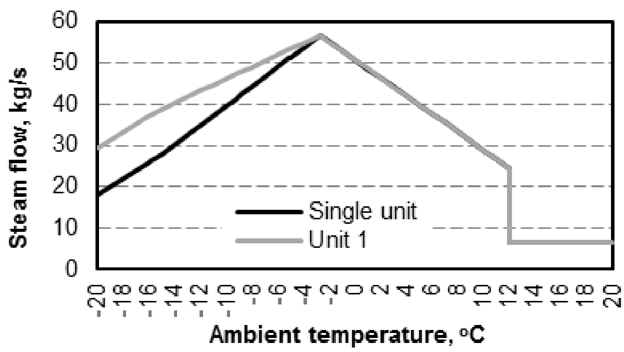

Figure 9: Relation between steam flow into XC2 heater and ambient temperature for heater feeding from one and two power units

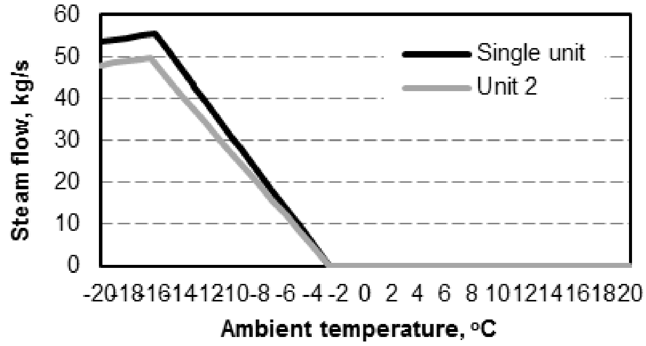

Figure 10: Relation between steam flow into XC3 heater and ambient temperature for heater feeding from one and two power units

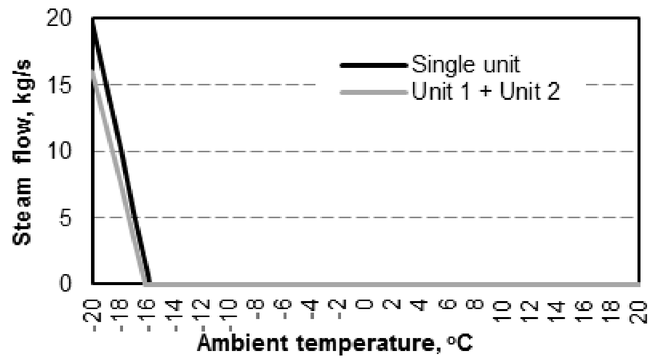

Figure 11: Relation between extraction steam flow into XC4 heater and ambient temperature for heater feeding from one and two power units (for steam extraction from two units the volume extracted into XC4 is made up by the total of flows into XC4.1 and XC4.2)

Figs. 8–11 present the relations between saturation temperatures of extraction steam and volumes of steam feed into the heaters and ambient temperature for feeding heaters from one and two power units. As in the case of the operation of the unit with the output of 180 MW for operation with steam bleed from two units, the case of the shutdown of one of the repowered units and steam extraction from the other unit is not accounted for.

As one can note, compared to the operation of the power unit at minimum electrical output, the drop in the saturation temperature of the steam used to feed the heaters is considerably smaller. The largest difference between the case of heater feeding from one and two units is found for the steam extracted from A2 extraction and it is equal to around 7°C. For steam bleed from A3 extraction this difference does not exceed 3°C and the course of the saturation temperatures in the IP-LP crossoverpipe is nearly identical.

Compared to operation with small loads, the smaller differences between the saturation temperatures of the steam extracted to feed the heaters while feeding them from a single power unit and two power units result in similar volumes of steam extracted into the heaters. In this respect, the largest difference is noted for the case of steam bleed to feed XC2 heater and for the ambient temperature of −20°C it is equal to around 11.5 kg/s (Fig. 9). As a consequence of greater steam extraction to feed XC2 heater and bigger production of heat in it, the extraction of steam from A3 extraction and IP-LP crossoverpipe is smaller (Fig. 11). In addition, due to the fact that the temperature of the steam in the IP-LP crossoverpipe allows the maximum temperature of 135°C to be achieved for both heater feeding alternatives, there is no need to bleed steam from the steam header.

2.3. Comparison of thermodynamic effectiveness for heater feeding from one and two power units

A comparison of the thermodynamic effectiveness of various ways of feeding heaters can be made by comparing the specific uses of the chemical energy of the fuel needed for the production of heat:

$$\beta_{CH} = \frac{E_{ch}^{CHP} - E_{ch}^{non-CHP}}{Q_c} \qquad (1)$$

where: E_{ch}^{CHP}– use of chemical energy of fuel for operation of a power unit in cogeneration, $E_{ch}^{non-CHP}$– use of chemical energy of fuel for condensing operation, Q_c– total heat production.

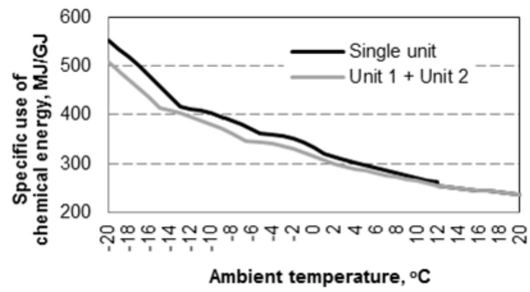

Figure 12: Relation between specific use of chemical energy of fuel and ambient temperature for steam feeding from one and two power units into the heaters (power unit operating at the output of 180 MW)

The lower the specific use of the chemical energy of fuel needed for the production of heat (Eq. 1), the higher the effectiveness of heat production and the lower the specific cost of heat. Figs 12, 13 illustrate the relation between the specific use of the chemical energy of the fuel and ambient temperature for the operation of the power unit at the electrical output of 180 MW and 380 MW. For the case of heater feeding from two units, the specific use

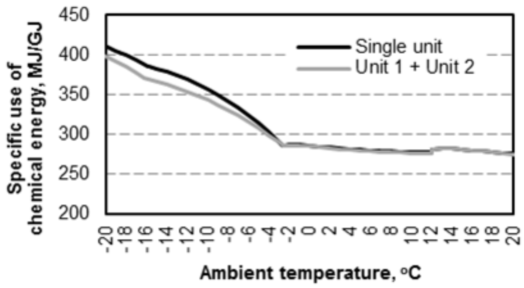

Figure 13: Relation between specific use of chemical energy of fuel and ambient temperature for steam feeding from one and two power units into the heaters (power unit operating at the output of 380 MW)

of the chemical energy of the fuel is given by the sum total of the use of additional chemical energy of the fuel in the two units per total heat production. In order to indicate the differences between the various ways in which the system operates, the case for the operation with two units does not account for the period when one of the repowered units is shut down and the heaters steam feed comes from the other unit only.

The feeding of heaters in a parallel system from two power units is characterized by the smaller specific use of the chemical energy of the fuel for heat production. The largest differences are noted for the lowest range of ambient temperature and operation of the power unit at the minimum output.

Table 1 contains a summary of annual production of electricity, use of the chemical energy of fuel, production of heat in the heaters and mean annual gross efficiency for feeding heaters from one and two repowered units and for its condensing operation. Since the calculations are conducted for the actual electrical output to meet the demand of the Polish national grid, the system operating in parallel accounts for the period when one of the units is shut down and the heater feeding is performed by the other unit. The investigation also includes the case in which both repowered units are shut down and the steam is extracted from the 1.8 MPa steam header. The specific use of the chemical energy of the fuel therefore does not account for (item 8, Table 1) but does account for (item 9, Table 1) for the heat extracted to feed XC5 heater from the 1.8 MPa steam header with steam feeding from the remaining unrepowered units.

The thermodynamic calculations indicated that the production of heat in the repowered units was 444 785 MWh for single unit heater feeding and 548 855 MWh for feeding them from two units. This was equivalent to 78.9% and 98.4% of the total heat production. The remaining volume of heat production from the unrepowered units was extracted by the 1.8 MPa steam header located between the units. The mean annual gross efficiency of the repowered units was 48.0% for the case of heater feeding from a single unit and 47.3% and 42.4% for the two units used to feed the heaters in a parallel system, respectively. The efficiency of feeding heaters from a single unit is greater due to the smaller volume of electricity produced during its condensing operation.

This paper also includes a calculation of the specific use of the chemical energy of the fuel for heat production in the XC5 heater which is fed in the period of emergency from the 1.8 MPa steam header by the unrepowered units, whose mean annual value is 750 MJ/GJ. This value is considerably higher than the values obtained for the case of heater feeding from one and two units due to the fact that the steam in the header is collected from the exhausts of the high-pressure sections of the turbines. By accounting for the annual production of heat, which needs to be in part delivered from the unpowered units, it is possible to reach conclusions about the specific uses of the chemical energy of the fuel for total heat production (item 10., Table 1). As can be seen, accounting for the emergency feeding of XC5 heater results in the specific use of fuel for heat production in the heaters with steam feed from two units being considerably smaller than the value obtained for feeding heaters from a single unit.

3. Conclusion

- For the case of feeding heaters from one unit, the increase in its overall gross efficiency is 7.6% compared to condensing operation (item 12, Table 1). For the case of feeding heaters from two units, the increase in the efficiency of the unit used to feed XC2, XC4.1 and XC5 heaters is 6.9%, while the efficiency is 2.0% higher for the one used to feed steam into XC3, XC4.2 and XC5 heaters. The higher efficiency of the unit during steam extraction from a single unit is due to the smaller volume of condensing steam in the condenser.

- Without accounting for the heat extracted from the 1.8 MPa steam header to feed XC 5 heater (item 7, Table 1) during the shutdown period of the repowered units, the specific use of the chemical energy of the fuel for the production of heat by the repowered units (item 8, Table 1) is lower for the case of heaters being fed by one of the units. This is due to the higher ratio of heat production in XC2 heater during heater feeding from a single unit. This ratio is

Table 1: Comparison of selected thermodynamic parameters for steam extraction from one and two repowered units (* these calculations do not account for energy losses associated with unit start-up and shutdown cycles)

No.	Parameter	Steam extraction from one unit	Steam extraction from two units
1.	Electricity production in the repowered units, MWh	2 002 067	2 002 067
			2 214 861
2.	Use of the chemical energy of the fuel by repowered units during its operation in cogeneration, MWh	5 103 382	5 084 361
			5 562 528
3.	Use of the chemical energy of the fuel by repowered units during its condensing operation, MWh	4 975 074	4 975 074
			5 503 071
4.	Use of the chemical energy of the fuel by repowered units for heat production (item 2–item 3), MWh	128 308	109 287
			59 457
5.	Use of the chemical energy of the fuel for production of heat in XC5 heater by unrepowered units used to feed 1.8 MPa steam header, MWh	84 701	6 650
6.	Production of heat in heaters with steam extraction from repowered units (item 6a + item 6b + item 6c + item 6d), MWh	444 785	403 457
			145 398
6a.	XC2 heater, MWh	383 471	398 596
6b.	XC3 heater, MWh	57 390	142 116
6c.	XC4 heater (XC4.1, XC4.2), MWh	3 820	4 861
			3 282
6d.	XC5 heater, MWh	104	0
7	Production of heat in XC5 heater with steam extraction from 1.8 MPa steam header by the unrepowered units, MWh	112 935	8 867
8.	Specific use of the chemical energy of the fuel for heat production by repowered units (item 4/ item 6), MJ/GJ	288	307
9.	Specific use of the chemical energy of the fuel for heat production in XC5 heater with steam extraction from 1.8 MPa steam header by the unrepowered unit (item 5/ item 7), MJ/GJ	750	750
10.	Specific use of the chemical energy of the fuel for total heat production ((item 4 + item 5)/(item 6 + item 7)), MJ/GJ	382	314
11.	Total gross efficiency during condensing operation * (item 1/ item 3), %	40.4	40.4
12.	Total gross efficiency during operation in cogeneration (item 1 + item 6)/ item 2), %	48.0	47.3
			42.4

then 86.2%, while for the case of in parallel feeding from two units it is 72.6%.

- The fact of accounting for heat production in XC5 heater (item 7, Table 1) during the shutdown of the repowered units results in considerably smaller specific use of the chemical energy of the fuel needed for total production of heat (item 10, Table 1) for the case of heaters being fed from two units. This is due to the smaller heat production in XC5 heater (item 6d, 7, Table 1).

- The calculations made in this paper prove that the most beneficial alternative from the thermodynamic perspective is based on heater feeding from two units. However, this solution involves greater investment cost due to the need to repower two units. For this reason, it would be necessary to undertake an economic analysis aimed at determining the most economical alternative for repowering a power plant.

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