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Calculation of a 900 MW conceptual 700/720°C coal-fired power unit with an auxiliary extraction-backpressure turbine

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Abstract

This paper presents the calculations for various configurations of a 900 MW power unit for advanced 700/720°C ultra-supercritical steam parameters with a single and double steam reheat. The application of double steam reheat can improve power unit efficiency by 1.1%. The transition to such high steam parameters, especially the reheated steam temperature, involves thermodynamic and material problems related to high temperature differences in the feed water heaters. In relation to this, a concept is presented for the modification of the feed water heaters system by using an auxiliary extraction-backpressure turbine fed with steam from the cold reheat steam line. The steam from the bleeds and the turbine outlet is directed to feed water heaters, which in the classical system are fed from the intermediate pressure turbine. The efficiency improvement gained through use of an additional steam turbine is no higher than 0.2%. However, the greatest advantages of this solution are reduced temperature differences in the feed water heaters and a simplified structure of the IP part of the main turbine.

Keywords: Condensing coal-fired power units, Ultra-supercritical steam parameters, Double steam reheat, Auxiliary turbine

1. Introduction

Increasing both live and reheated steam parameters is definitely the best avenue for improving coal-fired power unit efficiency at the present time [1–3]. There are currently many power units in the world which operate at steam parameters reaching 27 MPa/600°C/620°C. A further significant rise in these parameters can only be achieved with completely new materials. To show possible ways ahead in coal technologies, the project "Thermie 700 Advanced Power Plant" was set up with a view to mastering the advanced ultra-supercritical parameters of 350–375 bar and 700/720°C [4]. This relates to the use of new nickel-based superalloys (Ni-alloys) in the production of critical components of boilers and turbines that are exposed to extremely high temperatures. The use of advanced ultra-supercritical parameters makes it possible to achieve net electricity generation efficiencies exceeding the 50% limit and to further reduce CO_2 emissions.

However, a substantial rise in the temperature

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of steam, especially reheated steam, aggravates the problem of temperature differences (bleed steam and saturation temperatures) in feed water heaters. This causes additional material and thermodynamic problems because together with the rise in the mean difference in the temperature of the heat-exchanging agents, the exergy losses rise too, which leads to a reduction in process effectiveness, or to an increase in heating steam consumption. Therefore, an improvement in the operation of feed water heater systems becomes a vital issue for ultra-supercritical power units in order to reduce exergy losses. To avoid this problem, in cycles with steam parameters of 600/620°C, a special system of cross-feeding with bleed steam of the high pressure feed water heaters is often used [5]. The steam from the first bleed of the intermediate pressure part of the turbine is directed first to a steam attemperator which constitutes the last high pressure regeneration stage, and then to the appropriate feed water heater. In advanced 700/720°C ultra-supercritical cycles, however, the temperature differences are even higher. Consequently, further modifications of the thermal cycle are necessary. The main purpose of this paper is to analyze the impact of cycle configuration modifications on the basic power unit operation indicators.

2. The 900 MW power unit for advanced 700/720°C ultra-supercritical parameters

Within the Strategic Research Programme—Advanced technologies for energy generation, research is being conducted to select the optimum structure and parameters for a conceptual 900 MW power unit for advanced ultra-supercritical parameters. This paper presents two concepts of the power unit configuration—with a single and double steam reheat. The balance calculations of the power units are performed using the commercial software package Ebsilon Professional v.10.0.

2.1. Basic parameters of the 900 MW power unit

Table 1 presents the basic parameters assumed for calculations of the 900 MW power unit with a single and double steam reheat. The values of pressure

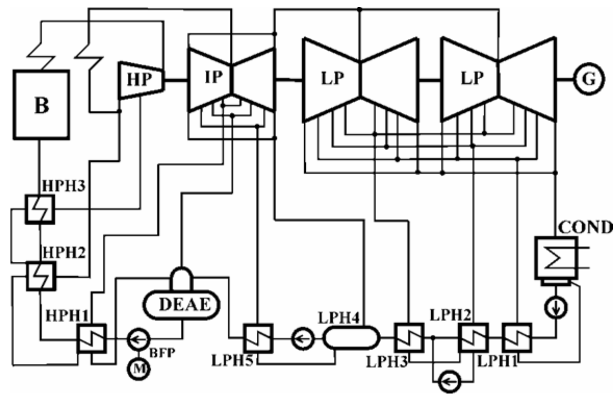

Figure 1: Simple diagram of a conceptual advanced ultra-supercritical power unit with single reheat, (B—boiler, HP—high pressure turbine, IP—intermediate pressure turbine, LP—low pressure turbine, G—generator, COND—condenser, LPH—low pressure feed water heater, DEAE-deaerator, BFP-boiler feed pump, HPH-high pressure feed water heater)

and the live and reheated steam temperatures are assumed based on [4]. It is assumed that in both cases the cycles feature the same gross electric power of 900 MW, the pressure in the condenser is the same and the efficiency of individual machines and facilities is identical. The power unit has a pulverized coal-fired boiler with an efficiency level of 94.5%. Internal efficiency of the LP turbine, presented in Table 1, is adjusted with Baumann's coefficient due to the wet steam flow losses. The power unit has a pulverized coal-fired boiler with an efficiency level of 94.5%.

2.2. The power unit with a single reheat

Fig. 2 presents a simplified diagram of the cycle with a single steam reheat. The system features a five-stage low pressure regeneration with an open feed water heater (LPH4) and a three-stage high pressure regeneration. The steam turbine is composed of a single flow HP part, a double-flow IP part and two double flow LP parts.

2.3. The power unit with double reheat

Fig. 2 presents a simplified diagram of the cycle with a double steam reheat. The use of the double steam reheat complicates the power unit structure, but makes it possible to substantially improve the electricity generation efficiency. In cycles with a double steam reheat, the steam dryness factor at the

Table 1: Basic parameters of the 900 MW power unit

Parameter	Single reheat	Double reheat	
Live steam parameters	35MPa/700°C	37.5MPa/700°C	
Reheated steam parameters	7.5MPa/720°C	13MPa/3MPa/720°C	
Gross electric power			900 MW
Pressure in the condenser			0.005 MPa
Feed water temperature	330°C	332°C	
Boiler efficiency			94.5%, flue gases temperature: 120°C
Internal efficiency of HP turbine			90%
Internal efficiency of IP turbine			92%
Internal efficiency of LP turbine			90%
Internal efficiency of pumps			85%
Generator efficiency			98.8%
Electric motors efficiency			97%
Fuel: hard coal			LHV=23 MJ/kg; moisture=0.09; ash=0.2; c=0.6; h=0.038; o=0.05; n=0.012; s=0.01

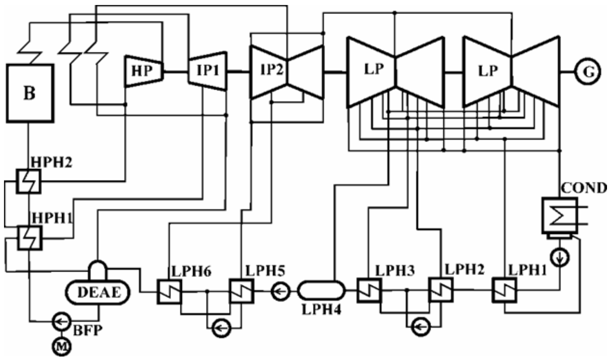

Figure 2: Simple diagram of a conceptual advanced ultra-supercritical power unit with double reheat (B—boiler, HP—high pressure turbine, IP—intermediate pressure turbine, LP—low pressure turbine, G—generator, COND—condenser, LPH—low pressure feed water heater, DEAE—deaerator, BFP—boiler feed pump, HPH—high pressure feed water heater)

turbine outlet is much higher, which causes a reduction in the wet steam flow losses and a rise in the efficiency of the LP turbine. The presented system features a six-stage low pressure regeneration with one open feed water heater (LPH4) and a two-stage high pressure regeneration. The intermediate pressure turbine is composed of two single flow parts IP1, and a double-flow part IP2. The IP1 outlet steam is directed to the boiler for second reheat. The last heat exchanger of the high pressure regeneration is fed from the cold reheat steam line and therefore the first reheat pressure determines the feed water temperature.

3. Configurations of a 900 MW power unit with an auxiliary turbine

A substantial rise in the temperature of steam, especially reheated steam (to 720°C), aggravates the problem of the difference between the bleed steam and the heated water temperatures in feed water heaters fed with bleeds from the intermediate pressure turbine, which are situated right after the steam reheater. In order to solve this problem, the company Elsam [4] patented a thermal cycle referred to as the "Master Cycle". The main idea of this cycle is to shift the bleeds from the intermediate pressure part of the main turbine to a separate extraction-backpressure turbine fed from the turbine high pressure turbine outlet before the first reheat. By keeping pressures in the bleeds at the same level, the temperature differences in the heaters fed from the auxiliary turbine are much lower. The auxiliary turbine outlet steam also gives off heat in the feed water system, causing a reduction in the heat transfer in the condenser. The auxiliary turbine is connected to an additional electric generator. The steam flow through the auxiliary turbine is rather unconventional because the steam mass flow at the first stage inlet is

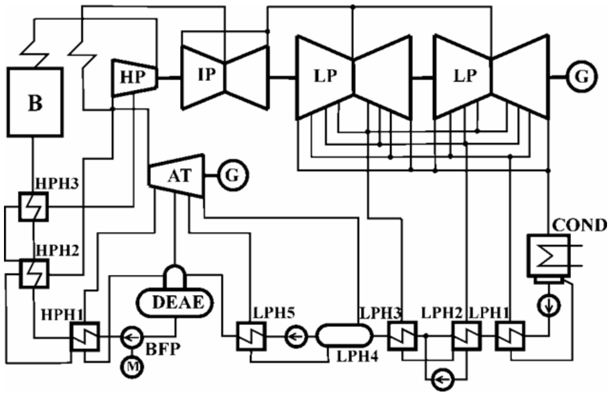

Figure 3: Simple diagram of a conceptual advanced ultra-supercritical power unit with single reheat SR_AT (AT—auxiliary turbine)

relatively large. However, the steam mass flow gets smaller as it passes through the subsequent stages (the steam flows into feed water heaters) so that in the last stages there is steam flowing to feed one feed water heater. This results in the blades in the last stages of the turbine not being very high. Owing to the use of an auxiliary turbine, the structure of the main turbine intermediate part, which has been deprived of bleeds, is much simpler and cheaper, which is essential since very costly construction materials (nickel alloys) have to be used. Lower steam temperatures at the auxiliary turbine bleeds—compared to the intermediate pressure part of the main turbine—result in an increase in the steam mass flow from these bleeds. This causes a reduction in the steam mass flow to the reheater, i.e. in lower costs of the reheated steam pipelines and of the reheater in the boiler, as well as in a reduction in the heat transfer in the turbine condenser.

3.1. The power unit with a single reheat and an auxiliary turbine

Fig. 3 presents a simplified diagram of the cycle with a single steam reheat and an extraction-backpressure turbine—AT. The auxiliary turbine is fed with steam from the cold reheat steam line. The steam from the bleeds and the AT outlet is directed to feed water heaters fed in the system without the AT (Fig. 4) from the IP part of the main turbine. Fig. 4 presents the expansion line in the main turbine (green) and in the auxiliary turbine (red) in an enthalpy-entropy chart. The auxiliary turbine AT

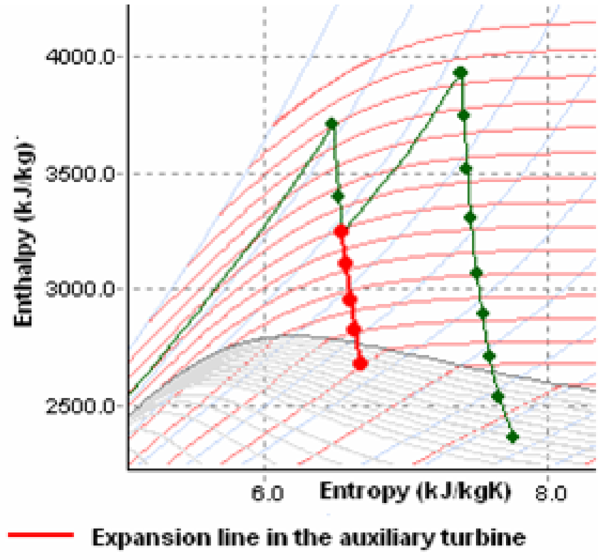

Figure 4: Expansion line in the main and the auxiliary turbine (SR_AT)

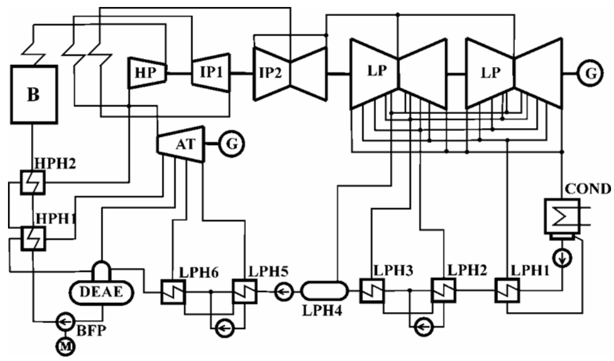

Figure 5: Simple diagram of a conceptual advanced ultra-supercritical power unit with double reheat DR_AT(1) (AT—auxiliary turbine)

steam outlet is located in the wet steam area.

3.2. The power unit with a double reheat and an auxiliary turbine in different configurations

For a system with a double steam reheat two configurations of the cycle with an auxiliary turbine were analysed. In one configuration (Fig. 5), the auxiliary turbine AT is fed from the first cold reheat steam line, and the steam from its bleeds and outlet is directed to feed water heaters fed in the system without the AT from the IP1 and IP2 turbine—DR_AT(1). In the other configuration (Fig. 6), the auxiliary turbine is fed from the second cold reheat steam line (from the IP1 outlet) and it has one bleed—DR_AT(2). Fig. 7 and Fig. 8 present expan-

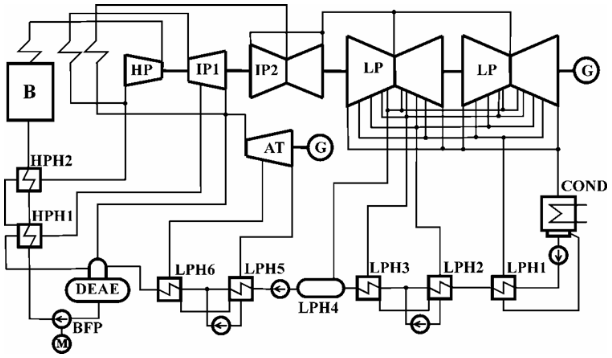

Figure 6: Simple diagram of a conceptual advanced ultra-supercritical power unit with double reheat DR_AT(2) (AT—auxiliary turbine)

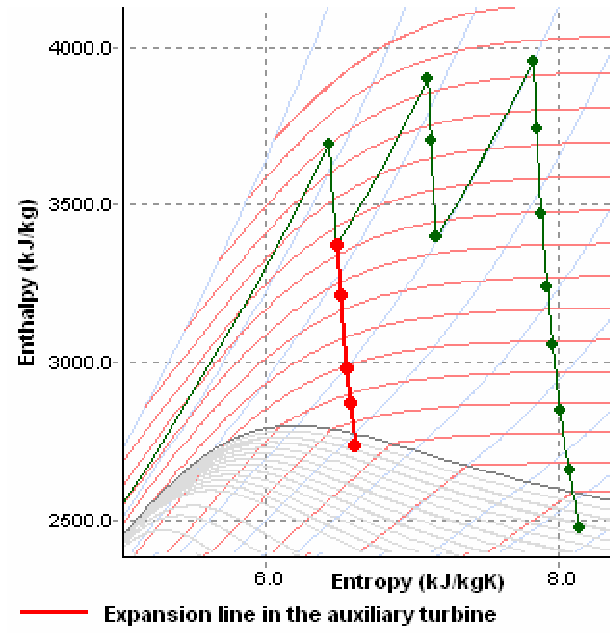

Figure 7: Expansion line in the main and the auxiliary turbine (DR_AT(1))

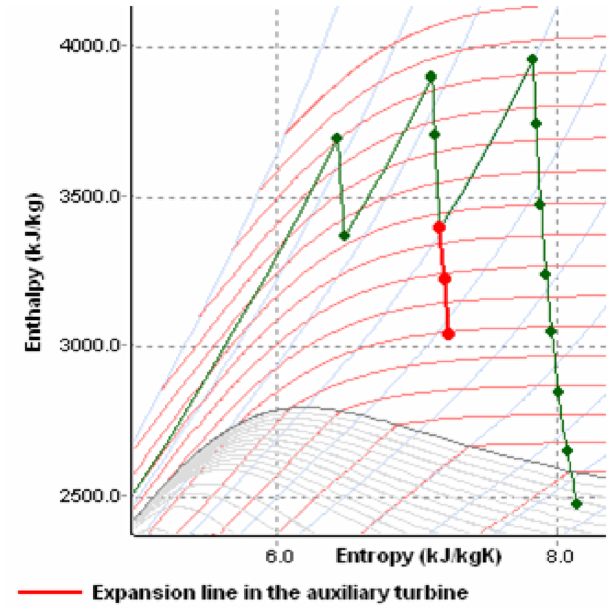

Figure 8: Expansion line in the main and the auxiliary turbine (DR_AT(2))

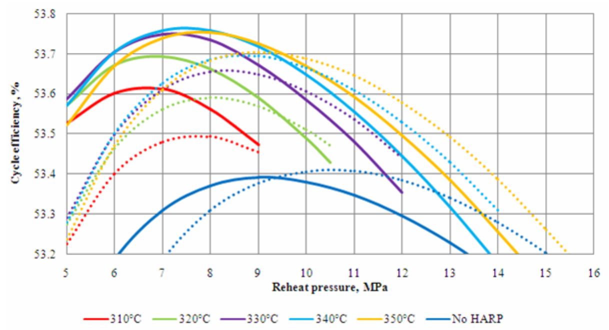

Figure 9: The impact of the feed water temperature and the reheat pressure on the cycle efficiency for the system configuration with an auxiliary turbine (solid lines) and without an auxiliary turbine (dotted lines)

sion lines in the main turbine (green line) and in the auxiliary turbine (red line) for both configurations.

4. Calculation results

The chart in Fig. 9 presents the impact of the reheated steam pressure at the boiler outlet on the efficiency of the 900 MW power unit cycle. The individual curves in the chart are determined for a constant temperature of the feed water, i.e. for a constant value of pressure at the HP turbine bleed, from which the last high pressure feed water heater HPH3 is fed. The solid lines relate to a system with an auxiliary turbine, the dotted lines to a system without the AT. The chart additionally shows a curve for system configuration without the last high pressure feed water heater HPH3 (without heater above the reheat point HARP—No HARP). In this configuration the feed water temperature depends on the reheat pressure. The lower the reheat pressure, the higher the increment in the efficiency of the system with the auxiliary turbine AT compared to the system without it. For pressure values exceeding about 9.5 MPa, the efficiency of the system with the AT is lower than the efficiency of the system without it.

The chart in Fig. 10 presents the impact of the second reheat pressure (at the boiler outlet) on the efficiency of the cycle of the power unit configuration

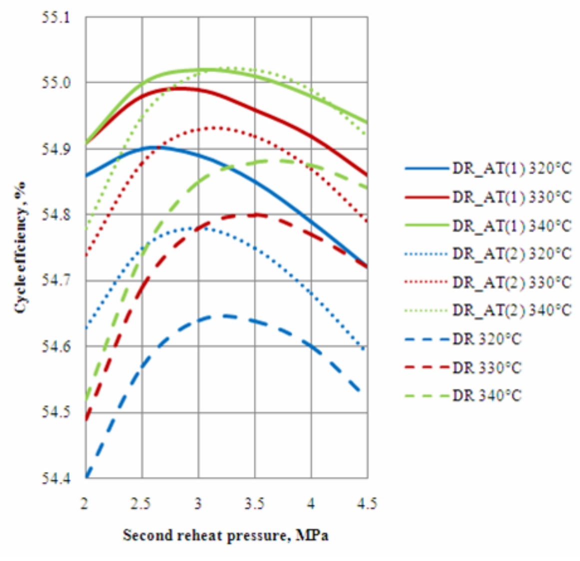

Figure 10: The impact of the second reheat pressure on the cycle efficiency

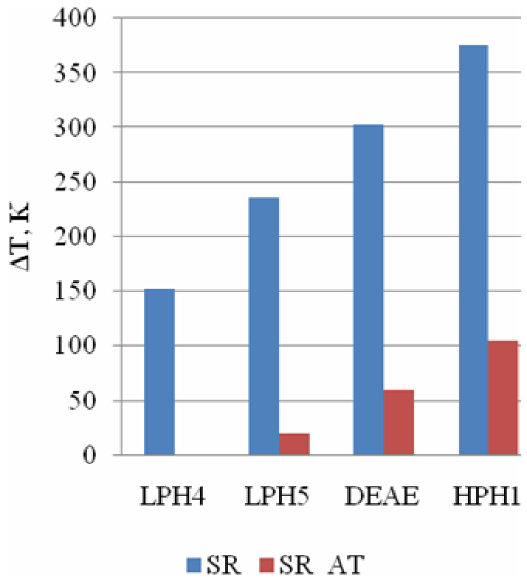

Figure 11: Temperature differences in the feed water heaters

with and without an auxiliary turbine. The individual curves in the chart are determined for a constant temperature of feed water, i.e. for a constant pressure value of the first reheat. In the case of systems with an auxiliary turbine, the optimum pressure of the second reheat is lower, compared to the system without the AT.

The basic operating indicates for all the analyzed configurations of the 900 MW power unit cycle are listed in Table 2. For all the configurations, the gross electric power of the unit is 900 MW. In cycles with an auxiliary turbine, the gross electric power of 900 MW is the total of the power capacities of the main generator and the auxiliary generator driven by the auxiliary turbine. The calculations of the net electric power of the unit take account of the demand for electric power of all the basic auxiliary devices: the boiler feed pump, the condensate pumps, the cooling water pumps, the air and flue gas fans and the coal pulverizers. The hard coal is pulverized in ring-ball mills with an electric energy consumption of 25 kWh/Mg. The net efficiency of the power unit with a single reheat is 48.6%. The application of a double steam reheat results in a net efficiency increase of 1.1%. If a system with a single reheat is expanded by adding an auxiliary turbine, the power unit net efficiency rises by 0.11%, and that of a system with a double reheat—by 0.18 and 0.15%.

In order to achieve the same power capacity of the unit in systems with an auxiliary turbine, it is necessary to increase the live steam mass flow because a smaller mass flow of steam is reheated. In the SR with AT and DR with AT(1) configurations, the mass flow of steam directed to the auxiliary turbine is, respectively, 19% and 23% of the live steam mass flow generated in the boiler. For the DR with AT(2) configuration, the steam mass flow to the turbine and the power capacity of the auxiliary turbine are substantially lower.

Fig, 11 and Fig. 12 present the differences between the temperatures of reheated steam at the inlet to the feed water heaters and the saturation temperatures in them. For the system configuration with a single reheat, the maximum temperature difference is over 350°C, and with a double reheat it exceeds 400°C. The use of an auxiliary turbine in variants SR_AT and DR_AT(1) reduces these differences significantly. In the DR_AT(2) variant, the temperature difference is eliminated in only two exchangers, but these are the ones where the problem is the greatest.

Fig, 13 and Fig. 14 present a characteristic parameter for individual feed water heaters—kA (kW/K), where k—the heat transfer coefficient, A—heat exchange area.

$$\dot{Q} = kA\Delta T_{log} \quad (1)$$

Table 2: Basic indices of the 900 MW power unit operation in various configurations

	SR	SR_AT	DR	DR_AT(1)	DR_AT(2)	Unit
Live steam mass flow	586.3	612.4	517.0	546.8	523.0	kg/s
Heat input to the cycle	1642.5	1636.2	1610.5	1601.8	1605.3	MW
Cycle efficiency	53.64	53.76	54.8	55.0	54.96	%
Gross power	900	900	900	900	900	MW
Gross efficiency	51.78	51.99	52.81	53.1	52.98	%
Net power	844.7	843.3	846.9	845.4	846.6	MW
Net efficiency	48.6	48.71	49.7	49.88	49.85	%
Electric power of the auxiliary turbine	-	40.3	-	44.9	10.7	MW
Steam mass flow to the auxiliary turbine	-	115.9	-	125.4	43.0	kg/s

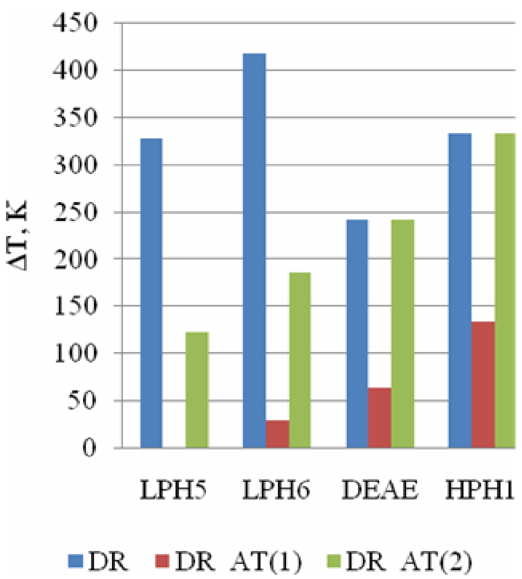

Figure 12: Temperature differences in the feed water heaters

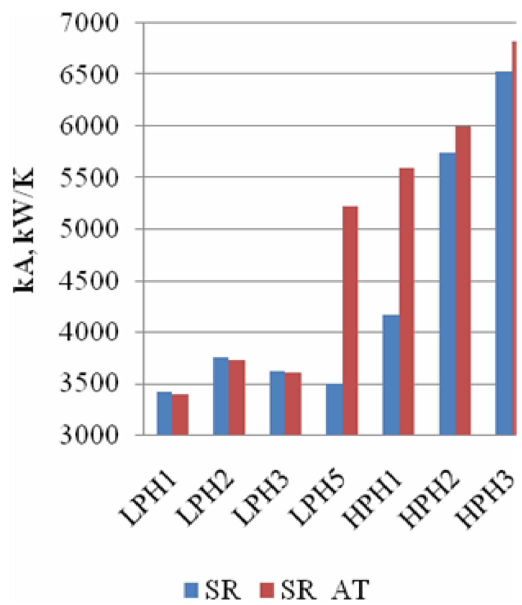

Figure 13: Feed water heaters—kA parameter

Assuming that the heat flows Q and heat transfers coefficients k in the feed water heaters are the same for the cycles with and without the auxiliary turbine, for the SR_AT and DR_AT(1) variants (according to (1)) there is a significant increase in the heat exchange area of the feed water heaters fed from the auxiliary turbine. This is caused by the reduction in the mean difference temperatures in these heaters. For the DR_AT(2) variant, the increase of this area is smaller.

5. Summary and conclusions

Raising the live and reheated steam parameters results in a substantial increase in electricity generation efficiency, which is essential in terms of curbing fossil fuel consumption and greenhouse gases emissions. The construction and operation of power units for advanced ultra-supercritical 700/720°C steam parameters will depend first and foremost on the results of research on construction materials that will be able to work over such a high range of temperature and pressure values. One of the aims is also to exceed

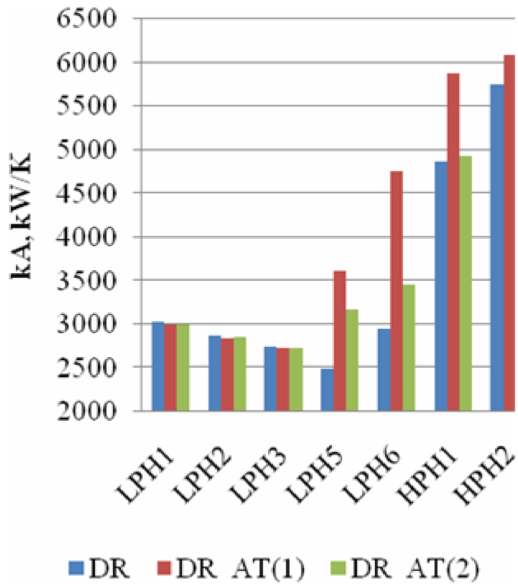

Figure 14: Feed water heaters—kA parameter

the 50% power unit net efficiency level, which will be difficult for systems with a single steam reheat to achieve. In Polish conditions, one of the barriers is the pressure level that may be obtained in the turbine condenser. There is great potential for further improvement in cycle efficiency through the modification of the power unit system by using a second steam reheat. This, however, involves a more complex structure of the steam boiler and the turbine itself. Another problem related to such high steam parameters is the significant temperature difference in the feed water heaters, especially in systems with a double steam reheat. This may be resolved by using an auxiliary extraction-backpressure turbine. Owing to the fact that the turbine is fed from the cold reheat steam line, the steam temperature at the bleeds, with the same pressure as at the intermediate pressure turbine bleeds, is much lower. This results in only small temperature differences in the heaters fed from this turbine, which reduces both exergy losses and the restrictions related to material problems. However, this involves an increase in the heat exchange area of the feed water heaters fed from the auxiliary turbine. The increments in efficiency related to the use of an auxiliary turbine are not high. For the two analyzed SR with AT and DR with AT(1) variants, the power capacity of the auxiliary turbine is high enough (40 and 45 MW, respectively) to drive the boiler feed pump.

Acknowledgments

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