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The analysis of parameters of the cryogenic oxygen unit cooperating with power plant to realize oxy-fuel combustion

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Abstract The paper examines from the thermodynamic point of view operation of coal fired power unit cooperating with the cryogenic oxygen unit, with a particular emphasis on the characteristic performance parameters of the oxygen unit. The relatively high purity technical oxygen produced in the oxygen unit is then used as the oxidant in the fluidized bed boiler of the modern coal fired power unit with electric power output of approximately 460 MW. The analyzed oxygen unit has a classical two-column structure with an expansion turbine (turboexpander), which allows the use of relatively low pressure initially compressed air. Multivariant calculations were performed, the main result being the loss of power and efficiency of the unit due to the need to ensure adequate driving power to the compressor system of the oxygen generating plant.

Keywords: Coal power unit with oxyfuel combustion; Two-column cryogenic oxygen unit; Mathematical modelling of thermal systems

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1 Introduction

This study presents the results of the thermodynamic analysis of operation of the cryogenic oxygen unit in cooperation with a coal fired power plant where oxygen combustion takes place. Combustion takes place in the supercritical fluidized-bed boiler in a technical oxygen mixed with partly re-circulated combustion gases comprising mainly CO_2. Such a large concentration of carbon dioxide (CO_2) in combustion gases simplifies the process of any sequestration, recovery, transport, and subsequently permanent storage of CO_2, or may facilitate easier management of this gas in another way. The argument in favour of the cryogenic method of separating air into oxygen and nitrogen is the need to ensure a large stream of oxygen with a considerably high degree of purity, which must be supplied to ensure the appropriate combustion conditions. Cryogenic technology uses the difference in temperatures in the condensation of gases and a low distillation temperature (around 90.15 to 80.15 K) to separate air into technical oxygen, which is then conducted to the oxygen combustion process, and into waste nitrogen, which is a by-product. In the conditions of a cryogenic oxygen unit the compressor plays an important role, compressing air which is subjected to rectification and which is the element consuming the most energy in such an oxygen unit. A small portion of the driving power may be recovered in the expansion turbine in the oxygen unit, and its effect on energy consumption in the installation has been presented in this study. The two column structure oxygen unit was examined, which is currently the installation most frequently used for production of large quantities of oxygen of a purity of 95–96%. The choice of the cryogenic separation method of air into oxygen and nitrogen can be justified by the need to ensure large streams of oxygen of a considerably high degree of purity totalling almost 95% [4–6], which must be supplied to ensure the appropriate combustion conditions in the fluidized bed boiler of a modern coal fired power unit of around 460 MW (Fig. 1).

For the purposes of the analysis, i.e., in order to assess the cooperation of the power plant with the oxygen system the mathematical model of the power plant was worked out, taking into account all the more important elements of the power plant in terms of thermodynamics. The mathematical model of the power plant contains 335 equations and it is based on the substance balances, energy balances, equations of the characteristics of the important elements of the power plant and equations of the H_2O state. Equations of the substance and energy balances were formed for the basic elements and central points of the unit using typical simplified assumptions. In the calculations the EES (Engineering Equation Solver) commercial software package [12] was used, which enables simulation of the power plant operation under examination and the assessment of operation of additional elements enabling the oxygen combustion process to take place. The results of calculations of the stream of air flowing into the turbo expander calculated in the Aspen Plus, commercial chemical process optimilisation sofware [13] in the study [10] were also used.

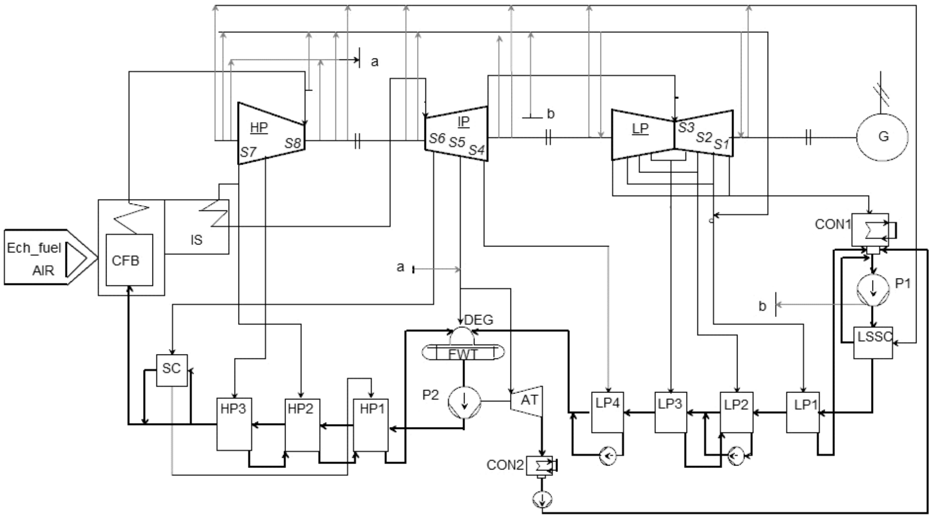

Figure 1: Scheme of the supercritical power plant under examination: Ech_fuel – chemical energy of fuel, CFB – circulating fluidized bed boiler, IS – interstage superheater, HP, IP, LP – high, intermediate, and low pressure section of the steam turbine, respectively, S1–S8 – bleeding steam from the main turbine, G – electricity generator, CON1 – main condenser, P1 – condensate pump, LSSC – labyrinth seal steam condenser, LP1–4 – low pressure preheaters, CON2 – auxiliary turbine condenser, AT – auxiliary turbine, DEG – degasifier, FWT – feed water tank, P2 – feed water pump, HP1–HP3 – high pressure preheaters, SC – steam cooler.

2 Oxygen unit supplying the coal fired power plant with technological oxygen

2.1 Choice of structure and characteristic parameters of the oxygen unit

The separation processes of air may generally be divided into low temperature (cryogenic) and non-cryogenic, which include adsorptive, chemical, membrane mechanisms and ion transport membrane (ITM) [1–3]. The analysed oxygen unit produces technical oxygen with a temperature similar to its surroundings, of atmospheric pressure or somewhat higher and 96% purity. An interesting characteristics of the installation in question is the use of a two shaft compressor with three stages, with double cooling interstage and with final cooling, despite the fact that the ratio of maximum and minimum pressure is barely around 6. The paper presents the calculation results of the effect of temperature difference in the condenser-evaporator of the oxygen unit, oxygen pressure at the outflow from the oxygen unit and the value of the 'outer' oxygen ratio excess calculated classically for the boiler (the real 'inner' oxygen ratio excess in combustion chamber is a little greater because of recirculation combustion gases with small oxygen contents) on the driving power and efficiency of the system: coal fired energy power unit – oxygen generating unit. The mathematical model for the whole system consists of the model of power unit and a very simplified model of the oxygen unit [11]. For the known parameters of the steam boiler operation the demanded oxygen stream is calculated. The air stream inflowing to the oxygen unit compressor is calculated from air and oxygen mass balances assuming the oxygen share in technology oxygen and in waste nitrogen. Demanded oxygen unit compressor driving power is then calculated after assuming temperature difference in the condenser-evaporator of the oxygen unit and oxygen pressure at the outflow from the oxygen unit. The calculated electric power of the power plant unit is then reduced by taking into account the electric power needed for compressor propulsion. Additionally there was worked out a simplified mathematical model of the oxygen unit based on equations of mass and energy balances for main elements of this unit and for assumptions typical for this type of installation [10,11]. This model was used only for estimation the power possible to obtain from the turboexpander in oxygen unit. Also the other possibilities of minimizing the oxygen unit own energy requirements were examined. The effect of the value of pressure after subsequent stages of compressor on its driving power was analysed. Because of the use of a cooling agent which acts as a medium in the compressor cooling system the heat removed by this fluid (water) can be partially introduced into the system of the power plant behind the main condenser, what causes a slight increase of the power and efficiency of the power plant.

Low-temperature technology is commonly used in industrial oxygen units. This technology uses mentioned difference in temperatures of condensation of gases and distillation (in the region of around 90.15 to 80.15 K) in low temperatures which results in separation of air into technical oxygen, flowing next to the oxygen combustion process and for waste nitrogen, which is a by-product. In order to achieve thermal parameters similar to those in the boiler, during the traditional method of fluidized-bed combustion, there has been used a mixture of technical oxygen and recirculated combustion gases containing mainly CO_2 (Fig. 2), the content of which in the combustion gases may reach 98% [7,8].

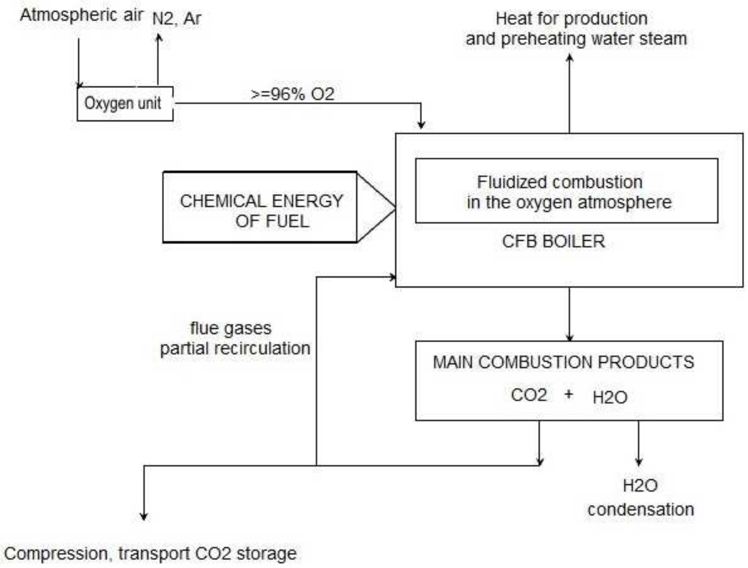

Figure 2: Flow chart of course of substances and products of carbon combustion in a fluidized bed in technical oxygen with partial recycling of combustion gases.

Separation of the mixture of gases requires external work [9], therefore the compressor plays an important role in the cryogenic oxygen unit, compress-

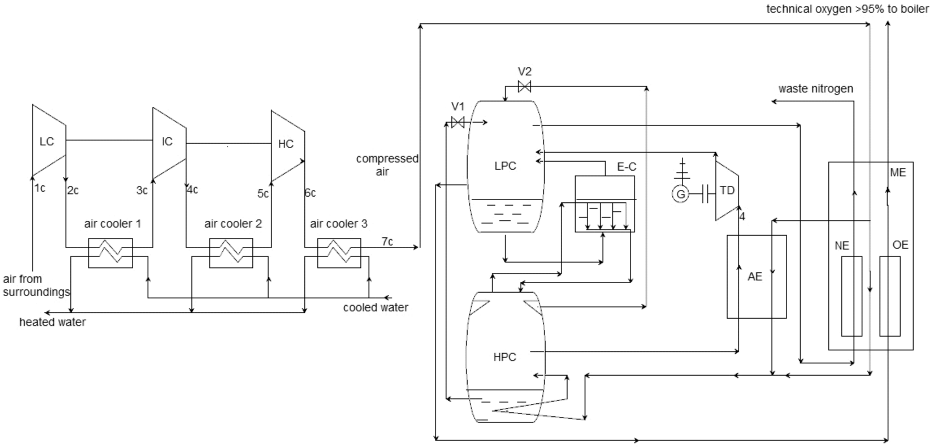

Figure 3: Oxygen production system using the two column method: LC, IC, HC – low, intermediate, and high pressure compressor section, respectively, 1c – ambient air before the first compression section, 2c – outlet air from the first compressor section, 3c – air after the first stage of compressor cooled in air cooler 1, 4c – outlet air from the second compressor section, 5c – air after the second stage of compressor cooled in air cooler 2, 6c – outlet air from the third compressor section, 7c – outlet air after the third stage of compressor cooled in air cooler 3, V1, V2 – throttling valves, LPC – low pressure rectification column, HPC – high pressure rectification column, E-C – heat exchanger 'evaporator – condenser', G – electric generator, TD – turbodetander (turbine expander), AE – auxiliary heat exchanger, ME – main heat exchanger for cooling the compressed air using technical oxygen (NO) and and waste nitrogen (NE).

ing air which is subjected to rectification and which, as already pointed out, is the most energy-consuming element in such oxygen unit. A small portion of the driving power may be recovered in the turbo expander of the oxygen unit. It is however a small share in relation to the energy-consumption during air compression. The double column oxygen unit [1] was examined, and it is presently the most frequently used installation to produce large oxygen streams of a 95–96% purity. There are proposals to build a three column oxygen unit [7], in which the work of the air compressor would be less by about 15%, however such systems are not yet used in industry. The simplified flow chart of the cryogenic double column oxygen unit has been set out in Fig. 3. Additional elements have been omitted such as pollution removal devices, off-take small amounts of liquid oxygen, final compression of technical oxygen, initial cooling of air using waste nitrogen and also recovery of inert gases. Using an additional heat exchanger for initially cooling of air, e.g., using waste nitrogen, 'improves' the general balance of the cryogenic oxygen unit, however this exchanger does not have any significant effect on the energy-consumption needed for the oxygen production. Figure 3 shows the oxygen unit together with the scheme of the compressor, compressing air to the pressure of around 0.55–0.6 MPa. The oxygen unit, as already mentioned, produces technical oxygen with a temperature similar to that of the surroundings, of an atmospheric pressure or somewhat higher and of a content of pure oxygen of 96%. At this relatively low pressure of air flowing to the unit it is essential to install a turbo expander. The expander closes the balance of energy for the cryogenic oxygen unit. The sum of enthalpy of the stream of compressed air and an 'undesired' stream of heat from the surroundings is greater than the overall enthalpy of streams of technical oxygen and waste nitrogen. This is due to the temperature of outlet and inlet gases which enthalpy, due to the low pressure, is not dependent on their pressure. The surplus energy is extracted from this system as the internal energy of the turbo expander. If the turbo expander is used there are various variants for its introduction into the structure, and the scenario presented in Fig. 3 is one of the possible ones. This case has an additional advantage involving the way in which the main heat exchangers (ME) cool the stream of compressed air.

2.2 Analysis of the compression system of the oxygen unit

Irreversible adiabatic compression has been assumed in the model of the air compression system. The stream of air which should be supplied to the compressor was calculated using stoichiometric equations based on the demand for oxygen for given output and efficiency of the boiler. The calculations were performed for several values of cooled air temperature after the first and the second compression stages (T3 and T5 correspondingly) and the constant pressure required for the oxygen unit equal to 0.55 MPa. In the compressor, after the third compressor section, 0.6 MPa pressure is obtained, however during further flow of compressed air through the exchanger causing its cooling there is a fall in the discharge pressure P7 to around 0.55 MPa. Because of such distribution of pressure in the compressor system the required pressure value is obtained for the correct functioning of the oxygen unit.

The graphs (Fig. 4) show the effect of pressures after the first and the second compression stage P2 and P4 on the compressor driving power. The graphs have been carried out for various values of characteristic temperatures. The assumption for the calculations was the identical internal efficiency of the individual parts of the compressor. Pressure drops in air coolers were assumed at a level of 0.001 MPa.

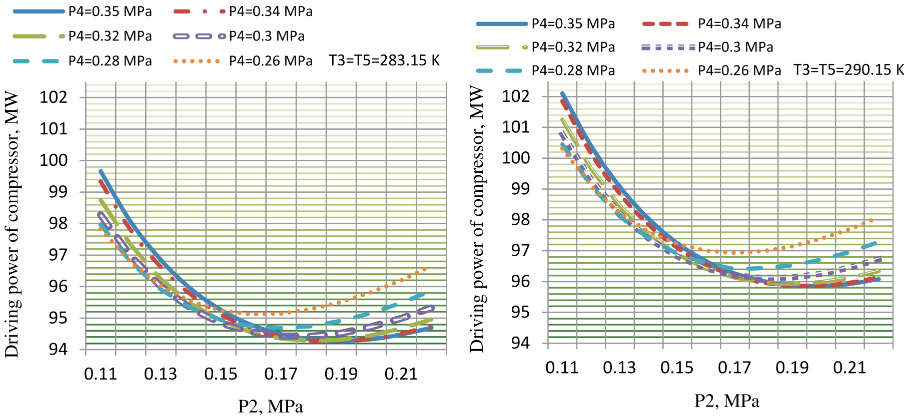

Figure 4: Dependence of compressor driving power on pressure P2 and P4, for P6= 0.6 MPa, and T3=T5=283.15 K and 290.15 K.

The above results indicate the important effect of temperatures T3 and T5 on the compressor driving power. These temperatures are indicated respectively in Fig. 3 as 3c and 5c. Other temperatures marked as 1s, 2s, 4s and 6s are as follows: temperature T1 is the ambient temperature, while the temperatures T2, T4 and T6 are the actual temperatures after the adiabatic compression in the first, second and third stage of compression and their values are derived from the pressure ratios in the various stages of compression. The lower the temperature after interstage cooling, the compression system is less energy-consuming, as it is obvious.

For the compressor being considered, the temperature of the cooling water was assumed at the level of 283.15 K, which corresponds with the temperature of air incoming to the compressor. Furthermore, the air of an initial pressure of 0.1 MPa is compressed, as mentioned earlier, to pressure P6=0.6 MPa, so that at the inflow to the oxygen unit the pressure was 0.55 MPa. An important parameter affecting the driving power of the compressor are the pressure losses in air coolers mentioned earlier. For the compressor under consideration they are up to 0.034 MPa and they increase its driving power. The pressure values after compression stages, according to pressure ratios P2/P1=P4/P3=P6/P5, are correspondingly: after the first compression stage P2=P3=0.1817 MPa and after the second stage P4=P5=0.3302 MPa, however such values of pressure cause higher inner driving power of the compressor equal to 112.4 MW, than for the optimal interstage pressures P2opt and P4opt, where the compressor driving power falls by 4.5 MW. For P2opt on the level 0.28 MPa and P4opt equal to 0.45 MPa the value of compressor driving power equals to 108 MW for the stream of compressed air 458 kg/s.

2.3 The oxygen unit own energy requirements

From substantial balance equations for the entire oxygen unit and for the assumed composition of technical oxygen and waste nitrogen, a stream of compressed air necessary to obtain the appropriate stream of oxygen element was calculated. For the known air stream and the value of pressure before and after the compressor, it is possible to define its driving power. The required pressure of compressed air depends on the required pressure of technical oxygen leaving the oxygen unit and on the difference in temperatures, and therefore pressure difference, in the evaporator-condenser. The set of balance equations for the entire oxygen unit, together with the appropriate state equations for the two-phase and two-element solution oxygen – nitrogen, is necessary only for calculation of the power obtained from the expander. Cold air, which is initially heated in the auxiliary exchanger, flows into the expander having the pressure as in the high pressure rectification column. The calculations of the turbo expander power were made for the stream of air flowing to it in a maximum quantity of 20% of the main stream of air feeding the oxygen unit (no) and as a result only small power of around 2 MW was obtained [10]. The power of the turbo expander does not significantly affects the reduction of the power consumed by the oxygen unit.

From the point of view of energy consumption for oxygen production, the ratio of pressure for subsequent compression stages and the ratio no/(z13n13), that is, the ratio of the stream of the air being compressed to the oxygen stream conducted to the boiler are important. The value of the ratio no/(z13n13) as a function of participation of oxygen in waste nitrogen z14 and in technical oxygen z13 is presented in Fig. 5. Kmoles stream of pure oxygen in the technical oxygen are described as z13n13 and kmoles stream of technical oxygen as n13.

The effect of the participation of oxygen element z13 on the ratio no/(z13 n13) is negligible in the range z13=0.91–0.99. However, it is important the participation of oxygen element in waste nitrogen, that is, z14, as with

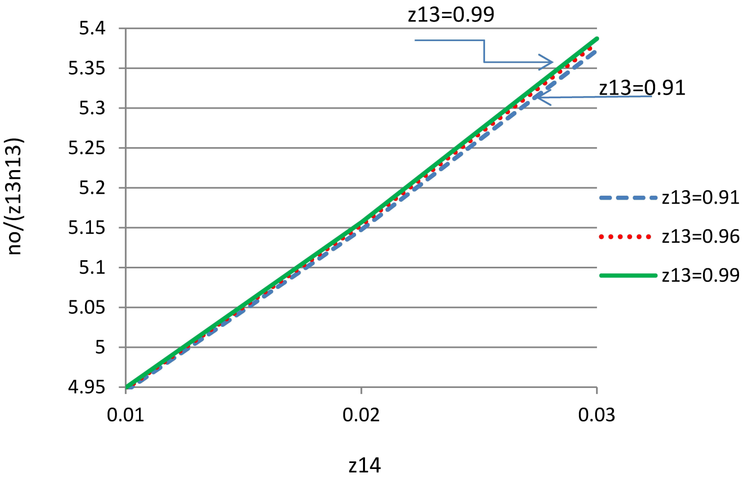

Figure 5: Dependence of ratio no/(z13n13) on the participation of oxygen in waste nitrogen z14 and in technical oxygen z13.

its increase from 1 to 3% the ratio no/(z13n13) increases 1.087 times, and thereby the driving power of the compressor increases by around 9%. During analyzing the parameters of operation of the oxygen installation, pressure in the rectification column LPC is assumed as dependent on the requirements of the boiler installation, in which coal will be combusted in oxygen atmosphere. In the conducted analysis the oxygen pressure of $1.25p_{ot}$ was assumed, therefore the pressure of air supplied to the cryogenic unit process should be 0.55 MPa. Higher final pressure of oxygen has a considerable effect on the power and efficiency of the coal unit, what is presented in Fig. 6.

Pressure in the high-pressure, HPC, rectification column has been selected as depending on the pressure in LPC (Fig. 3), so that in the evaporator-condenser E-C appears a minimum temperature difference of 3 K. That means that the temperature under which nitrogen condenses should be so much higher than the vaporization temperature of oxygen. A higher difference in temperatures would have a disadvantageous affect on the energy-consumption of the process (Fig. 7), as it would be necessary to supply air under increased pressure, what is presented in Fig. 8.

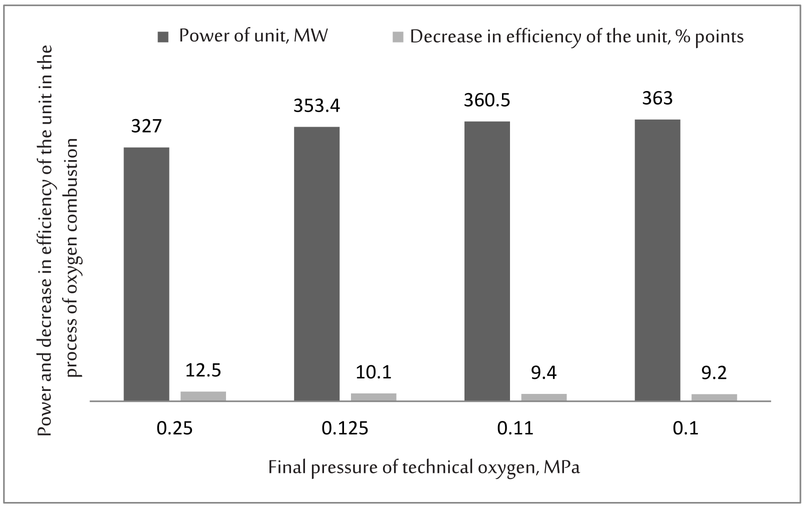

Figure 6: Effect of final pressure of technical oxygen on the power and efficiency of the power plant integrated with the oxygen unit.

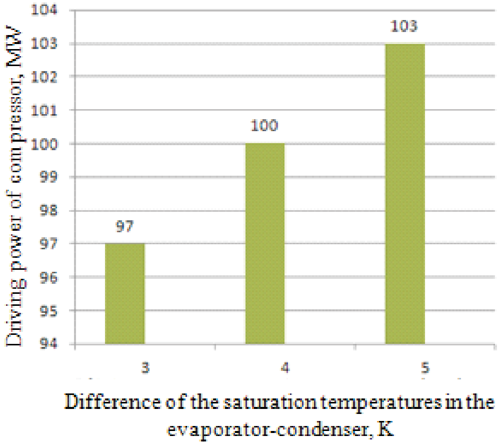

Figure 7: Effect of difference in temperatures of saturation in the evaporator-condenser on energy consumption during oxygen production.

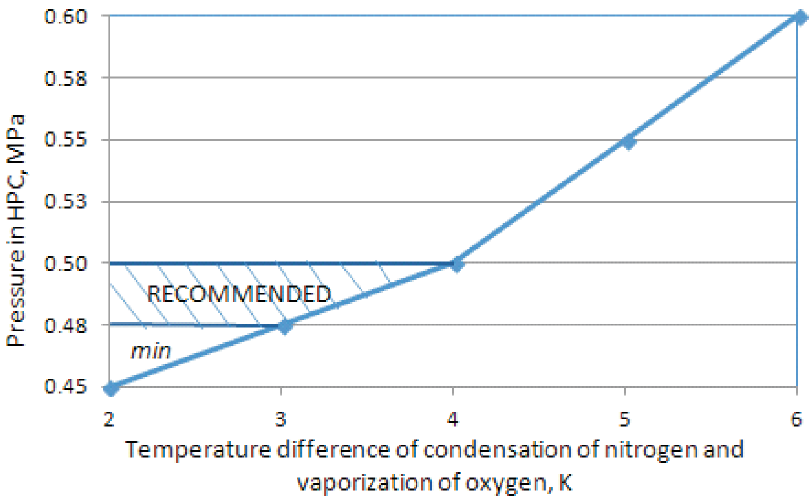

Figure 8: Effect of difference in temperatures of saturation in the evaporator-condenser on energy consumption during oxygen production.

2.4 Analysis of the effects of heat recovery from the compressed air coolers

In order to examine the effect of heat recovery from the compressed air coolers the variant with the intermediate agent was considered, namely, with water cooling the compressed air and next initially heating the condensate of the energy power unit. Due to such applying of the cooling intermediate fluid, the compressor driving power calculated previously will remain unchanged, however the heat taken away by the fluid serving as intermediate agent will be partly introduced into the coal fired power unit system after the main condenser, what increases the power of the coal fired power unit when the fuel use is unchanged. Below there is presented a scheme of the air cooling system (Fig. 9). In further calculations, as before, a temperature of the air from the surroundings has been assumed at the level of 283.15 K and cooling water also at the level of 283.15 K. This water, which is an intermediate agent, after cooling the air, transferres some part of taken heat, as mentioned earlier, to the condensate (Fig. 10). Applying an intermediate agent is not advantageous from a thermodynamic point of view, however it is necessary because of exploitation reasons, as it is not practically possible to direct the condensate immediately to the air coolers.

After including an additional balance equations for the supplementary

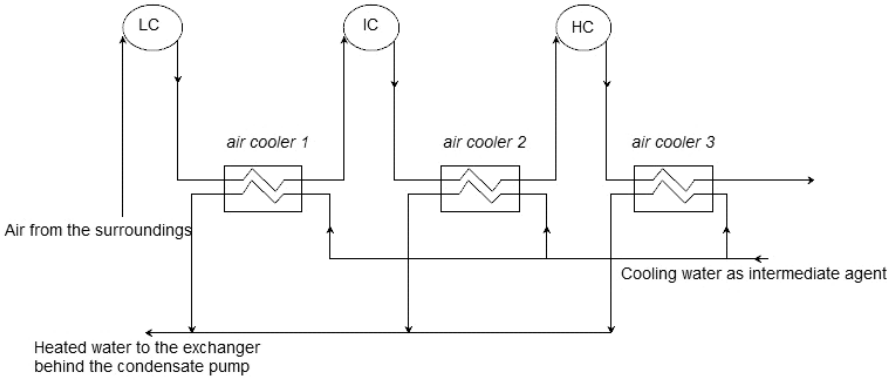

Figure 9: Flow chart of absorption of heat through cooling water in the air coolers: LC, IC, HC – low, intermediate, and high pressure compressor section, respectively.

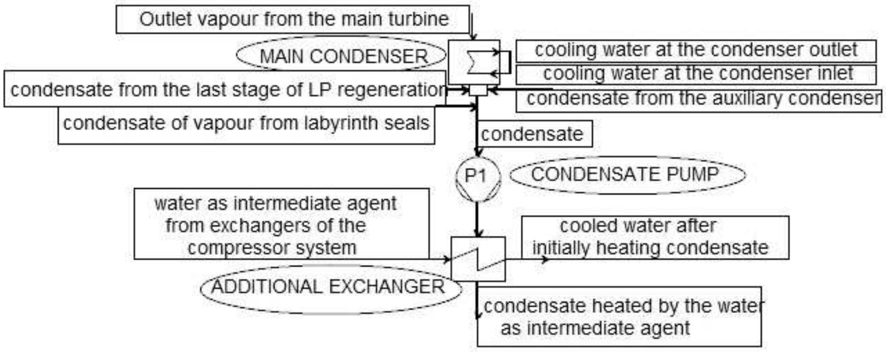

Figure 10: Plan of location of an additional water heater behind the condensate pump.

heat exchanger to the set of equations for the power plant unit, the additional calculations demostrate an increase in electric power of the power plant 1.6 MW and an increase of its efficiency by 0.1%.

2.5 Influence of the oxygen excess ratio during combustion process

The oxygen excess ratio for combustion in the boiler, λ, should have a minimum value ensuring entire and full combustion. In practice somewhat higher values are applied to this ratio, causing a corresponding increase of driving power of the compressor in the oxygen unit with a slight increase in the power recovered in the expander. The effect of this fact has been presented in the graph in Fig. 11. The oxygen excess ratio is the ratio of the actual amount of oxygen to the theoretical amount of oxygen necessary for ideal fuel combustion. The oxygen excess ratio under examination is of a justified volume for the overall boiler under examination and is calculated using the classic method. The actual value of the oxygen excess ratio in the boiler combustion chamber is somewhat higher due to the recirculation of some part of the combustion gases containing additive of oxygen.

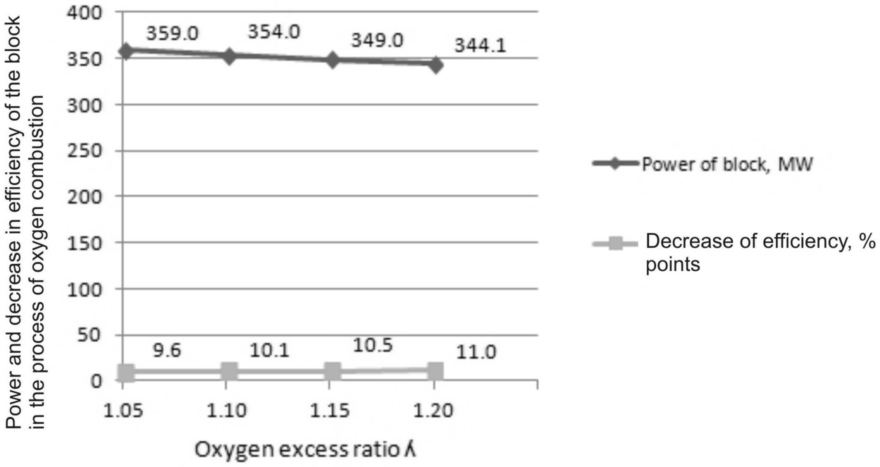

Figure 11: Effect of the oxygen excess ratio λ on the power and efficiency of the power plant integrated with the oxygen unit.

3 Final comments, conclusions

The biggest changes in the way in which the coal fired power unit operates, after incorporating the system enabling oxygen combustion, are caused by large consumption of energy by the system producing oxygen having the required parameters. The conditions relating to stream and purity of oxygen produced for the purposes of oxygen combustion are satisfied currently solely by the cryogenic method, which, as indicated, is consuming a large amount of energy. The analysis of recovery of a part of the energy from the turbo expander of the cryogenic oxygen unit and additional heat from the coolers of the compressed air have shown that the energy recovered in this way is insignificant and does not have an important effect on the parameters of operation of the block. As was demonstrated, selection of optimal pressures in subsequent stages of compresor is rather essential. The value of the difference in pressure in the evaporator-condenser heat exchanger in the oxygen unit is important as well as the final pressure of technical oxygen leaving the oxygen unit and subsequently supplied to the boiler of the power plant. The effect of the value of the oxygen excess ratio was also examined and the results show that for the increase of this ratio the driving power of the oxygen unit clearly increases, although this system may at the same time recover somewhat more energy from the turbo expander, namely up to 2.2% of power used to compress air in the oxygen unit. The effect of the share of oxygen in the technical oxygen is negligible, an important part is played by the participation of oxygen in waste nitrogen on the required stream of compressed air as together with its increase by 3% the driving power of the compressor increases by around 9%. There was also analyzed the effect of the difference in temperatures in the evaporator-condenser which revealed that reducing the temperature difference in that heat exchanger, i.e., the difference of the condensation temperature of nitrogen and vaporization temperature of oxygen, the required pressure in the high pressure column visibly falls. Thereby the energy consumption during oxygen production is reduced. The minimum difference in temperatures required for correct operation of the criogenic system is however around 3 K.

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