Article

Selected Aspects of Combustion Optimization of Coal in Power Plants

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Abstract: Growing ecological standards force the implementation of solutions that will contribute to reducing greenhouse gas (GHG) emissions to the atmosphere. This is particularly important in Poland, whose energy system is almost 80% based on coal. In the interest of low carbon development it is worth considering the optimization of existing old coal-based power plants. The main goal of the research was to present the benefits of modernization of existing boiler equipment and to analyze the combustion process of various types of coal sorts that have a significant impact on the optimization of the production processes of energy media. An analysis of the processes occurring in boiler devices during the combustion of fuel was carried out, which had a significant impact on the quality of generated heat and electricity. The conducted research defined technological solutions for boiler structures that have a significant impact on improving the efficiency of the technological process in heating plants and the characteristics of coal as energy fuel. Practical technical and modernization solutions have been proposed that contribute to the optimization of coal combustion processes, resulting in increased energy efficiency of the heating plant.

Keywords: combustion; coal; economy; optimization; power plant; Poland

1. Introduction

In the heating industry, a boiler device is referred to as a whole set of devices that are used to convert chemical energy contained in solid fuel, which is coal, into thermal energy in the form of water or steam, which is used for technological processes when driving steam turbines or hot water supply [1,2].

Interpreting the phrase steam boiler, we define a boiler device in which the process of changing the liquid, which is water, in the so-called saturated steam. Depending on the method of fuel combustion, boilers are divided into granular dust, fired with hard coal or lignite, whose use is mainly in power plants, due to their dimensions and media production capacity. The second most popular type of energy devices are the so-called grate boilers, in which coal is burned on various types of grates, used mainly for heating purposes and steam generation in various types of energy lines. The study analyses the issue of optimizing coal combustion with regard to grate heating boilers [3].

A large number of heating power plants in Poland were installed over 30 years ago and their lifetime will end soon [4]. Obsolete boilers often require immediate modernization or replacement.

Continued use of these units is often associated with deterioration of their operating parameters such as energy efficiency and reliability. Exploitation of the outdated machinery park is also related to huge financial outlays needed to maintain equipment in working order. Frequent unplanned repairs of the devices cause long downtime during the heating season and thus huge financial losses. In such cases, the best solution is most often the complete modernization of the machine park so that the operated boiler begins to meet stringent energy efficiency standards as well as exhaust emissions' standards [5]. The modernization of the devices is aimed at reducing operating costs as well as reducing the financial outlays of the combined heat and power CHP plant [6]. These activities require removal of any structural defects and adaptation of functioning boilers to new operating conditions (e.g., other than design fuel characteristics or new requirements regarding emission limits for harmful substances), as well as other than during the construction of fuel prices, construction materials and energy. Energy efficiency of power plant affects the economy of the whole country. The price of energy is included in every good and service. Too high energy prices in a given country may contribute to the deterioration of its competitiveness in relation to other countries.

Modernization issues in the heating industry are comprehensive and each action is focused on improving the main process parameters [7]. Usually, complicated optimization changes occur, the solution of which allows the selection of the most advantageous modernization and optimization variant. The issue of optimizing coal combustion is most often associated with renovation activities that allow increasing the energy efficiency of existing power units [8]. This type of work significantly extends the service life of heating devices. Of course, any interference in the structure of existing power lines, such as pipelines, drums, steam gate valves and boiler piping is associated with shutdowns of up to several months for one boiler [9]. However, properly conducted optimization of the combustion system and the steam system mean that the planned investments in a very short time result in a return on investment [10–13].

Growing ecological standards force the implementation of solutions that will contribute to reducing greenhouse gas (GHG) emissions to the atmosphere [14–18]. This is particularly important in Poland, whose energy system is almost 80% based on coal [19].

The main goal of the research was to present the benefits of modernization of existing boiler equipment and to analyze the combustion process of various types of coal sorts that have a significant impact on the optimization of the production processes of energy media [20]. The proposed organizational and modernization solutions are aimed at significantly improving the functioning of existing thermal power plants. The purpose of the research was also to present an analysis of optimization methods in relation to ecological issues, which in modern heating plants cannot in any way be ignored [21]. The scope of conducted research included, among others: Analysis of basic terminology in the field of thermal energy, characteristics of grate-fired boilers (Figure 1) and their parameters, analysis of thermal issues, analysis of hard coal properties, its storage, transport and combustion, calculations of fuel calorific values, analysis of the impact of burning various types of coal on the operation of boiler equipment, analysis of the principles of design and modernization of boilers, the concept of optimizing the coal combustion process, principles of energy balancing of heating equipment and environmental aspects in the energy industry [22].

Figure 1. Grate furnace of steam boiler [21,23]. 1. coal bunker, 2. left side of the boiler, 3. front wall of the boiler, 4. air space, 5. main path, 6. support, 7. drive shaft, 8. gate shaft, 9. and 10. air dampers, 11. dump grate, 12. wall, 13. blockages and 14. drive.

2. Analysis of Grate Boilers Construction

The boiler most often used in most combined heat and power plants in Poland and Central and Eastern Europe is the device with the operating symbol OR-32 or OR-50, where OR stands for a grate-irradiated boiler. The number indicates the maximum amount of steam generated under full boiler load Mg/h. The boiler is fired with fine coal and is equipped with two independent movable scale grates 2.5 m wide each [24]. Parallel technological auxiliary devices cooperate with the OR boiler: Primary and secondary air fan, slag screw conveyors, cyclone dust collectors, extractor fan, coal bunkers and carburizing devices [25].

Depending on the operating pressure used, the steam boilers use:

- Low pressure boilers with an operating pressure of less than 4 MPa;
- Medium pressure with an operating pressure of up to 8 MPa;
- Diesel with an operating pressure above 8 MPa;
- Boilers for so-called supercritical pressure where the steam has a pressure of about 22 MPa.

The OR-32 boiler device is an example of an advanced grate device designed together with a dedusting and desulfurization installation to minimize the emission of harmful compounds into the atmosphere [26]. The boiler is fired with fine coal with an energy value of not less than 19 MJ/kg and an ash content of not more than 25%, while the fuel moisture content cannot be greater than 15%. As a result of the analysis, it should be stated that below these parameters the constructor of the device did not predict the optimal environment for the production of the energy carrier [27]. The most important components of steam boilers, which are mainly used in combined heat and power plants, include:

1. Furnace firebox, in which fuel is burned and the energy needed to circulate water is produced. After this process, exhaust gases are expelled outside the boiler thanks to the exhaust fans. Combustion products escape into the atmosphere and go there through the chimney flues to the chimney.
2. An evaporator, in which water is heated and brought to a boil. The water and steam medium are separated from each other by a water surface, which is the limit of phase change. Combustion products escape into the atmosphere and go there through the chimney flues to the chimney. In classic water boilers, thick-walled pipes are evaporator, while in the steam boiler this element is a steam drum, which is an integral part of the boiler.
3. The feed heater preheats the water to a temperature of about 120 °C, which is used for the boiler's own needs. This element is a heat exchanger.

4. The plate-type air heater heats the saturated steam, replacing it with the so-called supersaturated steam at a temperature of about 480 °C. The energy carrier prepared in this way is used as a medium for steam turbines.

Depending on the specifics of the power plant, different types of water circuits are used. The most popular thermal device used on a large scale in domestic thermal energy is the OR-32 boiler, which is equipped with a forced water circuit, in which the movement of the energy carrier is controlled by a feed pump.

Basic technical data of the OR-32 steam boiler:

- Maximum performance—8 kg/s
- Working pressure in the steam drum—4 MPa;
- Steam outlet temperature—485 °C;
- Feed water temperature—110 °C;
- Boiler heated surface—245m²;
- Heating surface of the plate-type air heater—228 m²;
- Boiler energy efficiency around—76%.

The OR-32 steam boiler is a unit commonly used for thermal energy. Due to its technical qualities and expandability, it is a device that served as the basis for modernization (Figure 2).

Figure 2. Steam boiler OR-32 [21,23]. 1. steam drum, 2. combustion chamber, 3. burners, 4. downpipes, 5. steam superheater, 6. water superheater, 7. air preheater and 8. air fan.

The basic parameters for boilers determining their energy values are:

- The maximum amount of steam generated in Mg/h;
- Working pressure calculated in Pa;
- Feed water temperature in °C;
- Maximum boiler power calculated in MW.

3. Optimization of Coal Combustion in Relation to Design and Modernization Aspects of Boiler Equipment

3.1. The Legitimacy of Introducing Modernization and Optimization Works in Power Plants

In recent years, more and more power plants in Poland have encountered the problem of optimizing power lines. This is largely dictated by changes in regulations regarding environmental

protection requirements. Existing power blocks in the national power industry are usually systems designed and built over 30 years ago, at a time when the problem of efficiency and energy saving was not paid much attention to. Soon, there will be a moment when the management of heating plants will face a choice: Investment in the purchase of new boiler equipment, whose average price in Poland ranges per 1 kW of energy in the range of 400–500 euros; or to modernize and optimize existing power units. Examples of successful modernization of power plants in Poland that have been analyzed in scientific articles can be Rybnik Power Plant and Turów Power Plant [7,28].

The choice of the second option becomes justified, as the cost of modernizing 1 kW of energy usually does not exceed 50 euros. Changing energy regulations and strong competition in the free market economy caused the need to modernize existing heating devices to meet modern requirements.

In recent years, drastic increases in solid fuels have become the reason for the commencement of enormous changes in the energy economy. Performing modernization measures brings the company very measurable benefits in the form of a quick return on investment costs and a large time saving in relation to the construction of new boilers. Designing and building a new power line from scratch takes about three years, while the modernization of the existing energy system takes no more than nine months [29].

Optimization works bring significant economic benefits related to boiler production processes. From the technical side, this type of investment is most often associated with renovation works, which are connected with subsequent [30]:

- Optimization of energy efficiency;
- Reducing emissions of harmful gases and dust into the atmosphere [31,32];
- Adapting the device to work with selected coal grades [33];
- Reduction of thermal elements failures; increasing the surfaces heated by the flame; increasing performance;
- Optimization of the device operation at higher energy carrier pressure;
- Reduction of coal combustion, while increasing efficiency [34,35].

Optimization works are also aimed at eliminating structural errors that occurred during the operation of the device. Issues in the field of modernization and optimization of energy processes bring measurable benefits to media producers and their recipients [11,36].

Designers whose task is to adapt boilers to new operating conditions avoid the so-called renovation works consisting only in the reconstruction of existing elements. Obviously, such treatments lead to an extension of the life of the renovated elements, but they do not increase the production capacity of the devices, and thus do not eliminate the issue of structural errors resulting in reduced energy efficiency, which were revealed during operation.

As a result of the use of optimization and renovation processes carried out on functioning devices, a unit may be created which, by its parameters, meets all requirements for modern thermal devices. Modernized boilers are very flexible, adapted to burn various types of coal sorts. Operation of modified boiler equipment becomes less complicated and friendlier for less experienced employees [37].

Emissions of dusts and fumes return to levels accepted by modern energy law, so that power plants are not obliged to pay fines for too high harmful emissions [38,39]. The design and modernization principles provide for maintaining the original dimensions of the device, making intervention in the building structure of the power plant unnecessary [33,40].

3.2. Increasing the Working Capacity of the Boiler Steam Device as a Function of Optimizing the Production Process of Energy Utilities

All boiler devices in terms of design and construction are adapted to achieve the rated parameters of the carrier medium, which is steam as well as to the operating conditions in which the nominal efficiency of the device is achieved ($X_Q = 100\%$). The main requirements for steam units are [2]:

- Achieving the desired parameters of fresh steam in the range of $X_Q = 60\%–100\%$;

- Achieving the desired dry steam parameters in the range of $X_Q = 65\%–100\%$.

Often, power plants need a small increase in energy efficiency, which is very often possible to implement on existing devices without the need for modernization work. During frequent boundary overloading of the steam system it is necessary to start modernization activities of the technological line. This type of treatment is dictated mainly by the safety of people operating the heating plant. Continuous overloading of the boiler to the value of more than 10% of the rated power can lead to uncontrolled delamination of the thick-walled pipes of the device, especially to the outlet of the drop steam drum, which mainly runs outside the boiler and, as a result, releases a large amount of carrier medium in the form of steam, whose temperature often exceeds 500 °C [41]. This type of event almost always leads to irreparable damage to the boiler and its auxiliary devices [11,42].

In any case, before undertaking any works related to the modernization of the power line, it is absolutely necessary to analyze the technical condition of the main components of the system and its auxiliary devices. It should be determined what coal sorts are planned to be burned and whether the devices cooperating with the boiler, such as: feeding and circulating water pumps, coal container, primary and secondary forced-draught fans have a surplus of processing capacity, because properly carried out modernization and optimization is associated with an increased water, air and fuel flow as well as limitation of chimney loss, which significantly affects the efficiency of the power plant [31,43–45].

3.3. Modernization of the Boiler Device to Reduce Heat Loss through the Chimney

In the energy sector in Poland, many outdated devices operate, which in the course of the production of energy utilities generate huge production losses. One of the more damaging losses in economic terms is the so-called chimney loss [46]. It is a process in which the device loses large amounts of unprocessed heat energy escaping through chimney flues along with flue gas. Often, the temperature of the exhaust gas exceeds 200 °C, where the optimum value is 140 °C. In order to reduce the temperature of exhaust gases and reduce chimney loss, the following modernization works should be carried out [11,36]:

- Rebuilding pressure-convection elements;
- Reconstruction of the air preheater;
- Using steam soot blowers, cleaning the inside of the furnace;
- Designing an external water exchanger for the utility needs of the plant.

As a result of the conducted analyses, it was found that while limiting the chimney loss, the most important elements for the reconstruction are the final elements of the thermal system. Water and air heater, which are located next to the exhaust outlet to the chimney flue. Modification and enlargement of these elements causes that escaping flues are retained longer in the boiler, while cooling them [47].

By optimizing the end elements of the boiler, it is possible to increase the heated area. Renovation work should be preceded by a detailed analysis of the distribution of additional piping surface, technical condition of the modernized device. The designer very often has limited options for extending existing elements of water and air heater, therefore it is appropriate to completely replace them with new elements. Figure 3 shows the classic solution of the water heater tube bundles used so far, where the flow of exhaust gas can be observed, which does not encounter any resistance. In this case, it is possible to see typical structural errors that should be eliminated by using, for example, denser piping and reducing stack losses [45].

Figure 3. Diagram of an old type of ribbing system for water and air heaters [10]. S_1 and S_2 —distances between tubular-type air heaters. W_s —direction of transmission of burnt gases.

The applied solution presented in Figure 3 caused the creation of chimney loss and contributed to the reduction of the boiler's energy efficiency. This type of distribution is presented in the figures below. Such a solution regarding the placement of the boiler's heating surfaces pipes reduces the temperature of the gases escaping to the chimney flues [10].

By modernizing the air preheater and water heater, the process of fuel combustion in the furnace firebox is also optimized, because the water feeding the boiler is heated more intensively. The primary air has a higher temperature, so that the coal is preheated and dried [11].

To reduce the chimney loss, a denser distribution of the bundles of piping of the end elements of the boiler is used (Figure 4). Such a solution regarding the placement of the boiler's heating surfaces pipes reduces the temperature of the gases escaping to the chimney flues.

Figure 4. Diagram of a new type of ribbing system for water and air heaters [10]. S_1 and S_2 —distances between tubular-type air heaters. W_s —transmission direction burnt gases.

Thanks to the expansion of the water heater and the use of denser fins, the exhaust gases coming out meet the resistance caused by additional structural elements. In this way, the temperature of flue gas escaping to the chimney flues is limited.

The reduction of exhaust gas temperature should be explained by the formation of turbulent flows subject to fast-changing fluctuations. In the turbulent flow of flue gas, the heat transfer is intensified and the level of this transfer is obtained by choosing the flow conditions to achieve the developed turbulent flow (i.e., $Re \geq 10,000$). Then a quite large heat transfer coefficient α is obtained, and in

addition, increasing the Reynolds number (by increasing the speed) gives a relatively rapid increase in the heat transfer coefficient α .

Intensification of heat transfer is obtained by using transverse flow around the cylinder-round tube bundles. In this case, the first series of pipes (Figure 5) is washed like a single cylinder so that the heat transfer on them is more intense, but the others are already in the swirl tracks of the first pipes. Heat transfer stabilizes from the third row [12].

The variety of solutions used in older boilers regarding the arrangement and shape of the coils of the boiler elements, forces modern designers to adapt the size of heated elements to the boiler structure.

Optimization work is closely related to increasing boiler efficiency. Often, the intention to modernize is to switch to better coal grades, the combustion temperature of which is much higher than previously used types of fuel. Thanks to the achievements of the modern metallurgical industry, it is possible to use new, more resistant to high stress and high temperature steel. Newly manufactured boiler components are often lighter and always more efficient than previously used. The impact of new metallurgical technologies is particularly noticeable when modernizing water heaters, which are relatively easy to replace by repair teams [20,43].

A simple method to reduce the exhaust gas temperature is to replace the air preheater. Structurally, these elements are relatively simple to use in modernized boilers [32]. Structures existing on the market are distinguished by their construction and performance:

- Plate (Figure 5a);
- Tubular (Figure 5b);
- From thick-walled pipes (Figure 5c);
- Regenerative and rotational (Figure 6).

Figure 5. Cont.

Figure 5. Diagram of air heaters used in steam boilers [37]. (a) Plate air heater. (b) Tubular air heater. (c) Air heater made of thick-walled pipes.

Figure 6. Diagram of the innovative regenerative heater constructed by ALSTOM POWER company [35]. 1. heating elements, 2. finger-shaped rim, 3. supporting construction, 4. perimeter seal, 5 and 6 radial seal, 7. main drive, 8. emergency and manual drive, 9. housing, 10. connector for air duct, 11. radial wall of the rotor, 12. upper bearing, 13. fire detector, 14. nozzles of the extinguishing system, 15. fire water supply, 16. monitoring device, 17. soot blower, 18. rotary blower arm, 19. and 20. steam and compressed air valve and 21. supply of steam and compressed air.

Heating plants, in which, due to limited space, it is not possible to extend the end elements of the boiler, can use regenerative air heaters. It is a structure that is mounted directly behind the rear combustion firebox (Figure 6).

In old boiler constructions, the large air heater is very extensive and not very effective, due to the materials used during their construction. A good solution is to replace the old heated element with a new, more effective one. Made of better heat-conducting materials and more technologically effective. The use of one of the above air heaters by the designers depends on the specificity of the modernized thermal power plant.

3.4. The Importance of Installing Devices that Clean the Boiler Heated Surfaces to Increase its Efficiency

In the heat power plants there are problems of a temporary decrease in boiler efficiency and production capacity, which is caused by the deposition on the internal coils of deposits resulting from the combustion of fuel. The intensity of this process depends on many factors. The quality of coal burned is crucial in ongoing processes [48,49].

Fuel contaminated with a large amount of volatile substances causes a very rapid increase of deposits, which accumulate on heated surfaces and thus causes worse heat exchange of the device. There is then a rapid decrease in efficiency and an increase in fuel consumption [13,50].

There is a need to manually clean the coil screens. It is a time-consuming process that requires the use of special high-pressure washers. Moreover, this is an operation that can only be carried out when the machine is cold.

These types of cleansing treatments can last up to two weeks, provided that the process is carried out by a specialized company. If there is a need to clean the boiler, the device cannot generate energy utilities (i.e., it generates losses for the power plant from an economic point of view). Each of the boilers must undergo mandatory cleaning at least once every four months (i.e., more than a month in a year the device is not profitable) [10].

The application of the so-called steam ash blowers becomes justified. The optimization process using soot blowers is expensive. However, over a longer period of use, it can bring measurable benefits in the form of increased time intervals between pressure cleaning of a boiler, which even after using steam soot blowers cannot be abandoned [51].

As a result of tests, it was found that when using soot blowers it is enough to use the device only once a year for manual cleaning.

Various types of ash blowers are used. They are produced by many specialist companies. The use of these devices makes it possible to clean the heating surfaces of boilers without the need for forced shutdown.

The most important advantages of installing soot blowers include:

- Increasing the boiler efficiency by reducing the flue gas temperature;
- Increasing the efficiency of the energy draft, by increasing the steam temperature;
- Increasing the efficiency of the dust collection system;
- Reduction of energy consumption due to better air flow through the boiler; reduction of carbon oxides and nitrogen oxides' emissions.

For the optimization of coal combustion processes, the process of cleaning the boiler's heating surface is also very important, because the deposits formed on the convective parts of the boiler do not have heat conduction properties. The effect of this phenomenon is a difficult heat exchange of heated parts, which causes an increase in the cost of producing an energy factor, which is hot water and supersaturated steam [38,48].

Long-term operation of a boiler contaminated with deposits resulting from the combustion of fuel leads to operational anomalies in the form of sudden decreases in the device's efficiency, which is a very undesirable phenomenon in winter periods, when the consumption of water factor by the recipients is peak.

The greatest threat to the security of the power plant due to the ash-contaminated device is an uncontrolled decrease in the temperature of the steam used to drive the turbine. In this case, when the dry steam temperature (around 485 °C) falls below 400 °C, it turns into wet steam.

The consequence of this phenomenon may be the explosion of the turbo team, causing human casualties and millions of destruction.

Figure 7 shows a diagram of a soot blower, whose installation to an existing boiler structure causes the boiler walls to be cleaned of impurities arising from fuel combustion. Figure 8 shows an insufflator nozzle. This is the element that is in the boiler. High pressure steam is blown into the device to clean the heating surface.

Figure 7. Diagram of a steam blower used to clean screen tubes from contaminants generated during solid fuel combustion [10].

Figure 8. Scheme of nozzle insufflator, the movable element [10]. 1. corpus, 2. mandrel, 3. bottom of the insufflator, 4. support, 5. ring, 6. washer, 7. hexagon nut.

Soot blowers are devices made of high temperature steel. The scope of their work is even 1150 °C. They work on the principle of washing the convection pipes of the device with a steam jet. Typical parameters of their work are:

- Vapor pressure around 1.4–6 MPa;
- Blow-out temperature 500 °C;
- Ash blowing frequency, every 30 min.

Ash blowers are modernization elements relatively briefly used in thermal energy. Preliminary tests performed by specialized laboratory plants show that the use of steam ash blowers effectively clean the working surface of the boiler. A negative impact of high pressure from blowers on the surface of pipes has also been proven. The top surface of the screen bundles is damaged more quickly [52–56].

It should be emphasized that in the long term the production of electricity and heat in old coal-fired power plants will be associated with incurring charges for GHG emissions. This problem applies not only to Poland, but also to other countries of the Visegrad Group [57–61]. Price drop for CO₂ emissions at the end of the first quarter of 2020 is associated with the economic slowdown due to the coronavirus epidemic.

4. Conclusions

The Polish energy sector is facing a great challenge, which is to move away from coal. However, this process will be spread over decades. During this time, the activities indicated in the article are necessary due to the growing ecological requirements. Non-compliance with current standards in the field of emissions of harmful substances into the air, such as, for example, benzo(a)pyrene, will result in the imposition of multi-million penalties on those enterprises that will not meet current ecological requirements. Excessive GHG emissions and rising prices of CO₂ emission allowances are also a serious problem for the Polish energy sector. Without upgrading existing installations, these fees will be even higher due to the lower efficiency of the energy generating equipment.

The paper presents the principles of functioning of a modern thermal power plant, together with its components. Since the existing generating units in the energy system are outdated and about 35% of them were built over 30 years ago, it is necessary to technically optimize them to meet applicable standards on the efficiency and emissions of harmful substances. Obsolete installations for environmental, economic and legal reasons must be replaced or modernized.

The paper presents only some possible modernization and optimization variants of existing power lines. The criterion for choosing such a solution was the criterion of lower financial outlays. The design and construction of a new boiler device would require much greater financial outlays. A very important element in improving energy efficiency is the analysis of the possibilities to increase the energy efficiency of steam boilers and their auxiliary devices. Detailed technical analysis of energy fuels, their internal transport in the thermal plant allowed choosing ways to optimize the combustion process in order to increase the boiler's peak power.

The measurable result of the conducted research was indicating the possibility of renovation modernization of heating lines by expanding the final heating elements of the water heater and the air preheater, which significantly optimizes the combustion process. Optimization of the combustion process has contributed to a much better coal burn and increase the nominal power of steam boilers. Modernization works significantly reduced the chimney loss, thanks to which greater efficiency of energy devices was achieved, and consequently allowed for a significant increase in the efficiency of modernized power lines by about 15%–20%, which translated into lower fuel consumption and, above all, lower emission of harmful emissions. In the future, most thermal power plants will be forced to modernize their equipment to meet changing energy generation requirements as well as exhaust emissions standards.

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