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ENVIRONMENTAL EFFICIENCY OF MANAGING THE COMBUSTION PROCESS IN BOILERS WITH CIRCULATING FLUIDIZED BED

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Abstract

The article is devoted to the actual problem of the technogenic load reducing on the environment from heat and power enterprises by introducing an environmentally friendly technology for solid fuel burning in circulating fluidized bed boilers (CFB). The purpose of the work is to increase the efficiency of ensuring the environmental safety of combustion processes in circulating fluidized bed power units, which allows minimizing emissions of man-made components into the atmosphere. The state and prospects of coal fuel burning in a circulating fluidized bed in thermal power plants with a focus on assessing the environmental efficiency of the process was considered. The latest trends in the development of CFB technology are summarized and a look at the future regarding the problems and opportunities of this technology was presented. The factors that determine the level of air pollution by emissions from combined heat and power plants was analyzed, their impact on the environment was considered and the dynamics of pollutants' emissions in Ukraine was shown. The main methods of reducing the negative impact of CFB boilers on the environment was considered. It has been established that the reduction of nitrogen oxide emissions can be reduced by controlling the temperature field of fuel combustion. The principle of operation and features of circulating fluidized bed boilers, their environmental efficiency compared with the flare method of fuel burning was considered. The ecological efficiency of the combustion process control in the CFB boilers was estimated using the real object's example. It has been determined that the provided technical solutions and environmental protection measures will reduce the gross emissions of pollutants into the atmosphere by 6370.9 tons, which will significantly reduce the load on the air basin and improve the environmental situation in the zone of its influence.

Keywords: thermal power plant; coal burning; air pollution; circulating fluidized bed.

1. Problem statement and analysis of the recent researches and publications.

Nowadays, combined heat and power plants (CHPP) are the most common electricity producers. They also belong to objects with increased environmental hazards. Large amount of oxides of sulfur and nitrogen, fine solid particles of ash, slag, and completely unburned fuel is emitted from the pipes of CHPP into the atmosphere.

Radioactive contamination of the earth's surface and atmosphere is caused by the burning of coal and waste rock, which contains radioactive elements. In this case, radioactive contamination can far exceed the possible radioactive contamination during the operation of nuclear power plants [1–4]. The isotopes of the uranium-radium and thorium families, which are contained in the starting coal, remain almost completely in the ash and fly ash after burning.

The uses of cleaning devices [5–8] significantly reduce the level of environmental pollution. However, this approach does not completely solve the problem. The functioning of the cleaning devices is accompanied by additional waste formation [9].

Clean coal technologies are a particularly important option for reducing emissions of harmful fossil fuels. Such an approach is a cost-effective option in developing countries where coal is readily available [10–11].

In some countries with large coal reserves, for example in Kazakhstan, Turkey, India [12–14], there is a need to move to a new technological level with the introduction of new energy technologies of coal burning. Ukraine also has large reserves of this fossil fuel and needs to introduce new environmentally friendly technologies for its combustion. Thus, in Ukraine the Energy Strategy for the period up to 2035 «Safety, energy efficiency, competitiveness» was developed and approved in 2017.

Conventional combustion of fuel at power plants causes the gases release which contains liquid droplets and solid particles. This mixture is removed from power plants in a controlled way through chimneys. The main pollutants emitted from the chimneys of CHPP are:

– sulfur dioxide (SO_2): coal power plants are responsible for health population. They contribute to the small particles formation that can penetrate in the human lungs and be absorbed by the bloodstream. SO_2 causes acid rain, which oxidizes lakes and rivers, and also damages crops, forests and soils [15];

– nitrogen oxides (NO_X): cause ozone or smog on the ground level, which can burn lung tissue, aggravate asthma and make people more susceptible to chronic respiratory diseases [15, 16];

– solid particles: soot or fly ash can cause chronic bronchitis, aggravated asthma, and even lead to fatal consequences;

– mercury: toxic heavy metal causes brain damage and heart problems;

– other harmful pollutants: lead, cadmium and other toxic heavy metals, hydrocarbons, volatile organic compounds, arsenic and also carbon monoxide, which causes headaches and creates additional stress for people with heart disease [17, 18].

Various amounts of pollutants are released into the atmosphere by burning different types of fossil fuels. The impact of CHPP on the environment depends on the type of fuel [19]. Table 1 shows the temperature characteristics of coals and table 2 shows the average emissions from coal combustion.

Table 1 – Thermal characteristics of coals [20]

Coal type	Ignition temperature	Volatile initial release temperature
Lignite	250 – 450	130 – 170
Bituminous coal	400 – 500	200 – 300
Anthracite	700 – 800	380 – 400

Table 2 – Average emissions from coal combustion, g/GJ [20]

Pollutant	Anthracite	Lignite
CO_2	94,600	101,000
SO_2	765	1,361
NO_X	292	183
CO	89.1	89.1
Particular matter	1,203	3,254

Figures 1 and 2 show the dynamics of major pollutants' emission in Ukraine by stationary sources.

Air pollution level is determined by the impurities concentration in the air surface layer and depends on technological factors: gas-air mixture flow rate and its temperature; impurities concentration in the emissions; sources height; pipe mouth cross section, etc.

Meteorological factors include: emission source location; prevailing winds direction and their speed, temperature and atmospheric air humidity; presence of inversion, fog, precipitation and etc.

The coal-fired power plants influence on the microclimate formation is determined by:

– air basin and water bodies thermal pollution;

– atmosphere chemical pollution (flue gas emissions).

The air basin chemical and thermal pollution is caused by a change in the microclimate in zone of Sumy CHPP influence. Such a microclimate change is due to the energy production specifics, accompanied by powerful and active flue gases emissions into the atmosphere.

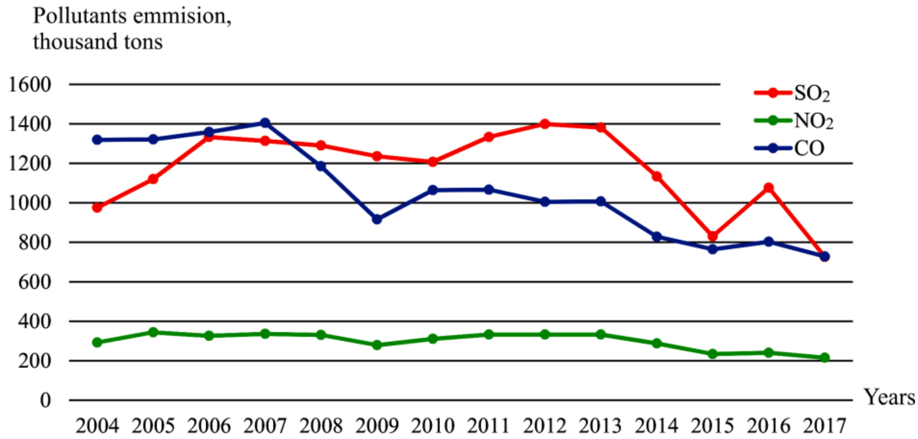

Figure 1 – Pollutants emission by stationary sources [21]

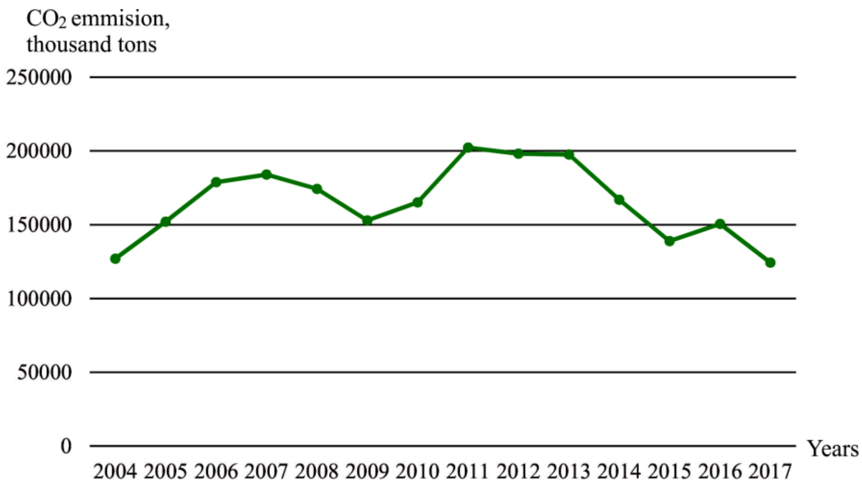

Figure 2 – CO_2 emission by stationary sources [21]

Oxides of sulfur, nitrogen, carbon, and solid particles (ash shale) are the priority atmospheric air pollutants, which are contained in the combustion products of organic solid fuel (anthracite) on Sumy CHPP.

The high temperature in the flame core, which is necessary for burning coal with liquid slag removal, causes a high concentration of NO_X emissions. The high sulfur content in the fuel causes high SO_2 concentrations in the emissions. Environmental problems in cleaning the air from oxides of sulfur and nitrogen remain unresolved. Wet flue gas cleaning allows capturing only up to 2.5 % sulfur dioxide from the total content.

Sumy CHPP has prepared a feasibility study for the reconstruction with the installation of a new power unit with a capacity of 60 MW. The increase in power capacity is determined by the energy deficit in the region, which is covered by only 60 – 70 %. The increase in power entails an increase in the load on the atmosphere during the combustion of solid fuels. However, the installation of the CFB boiler will provide high environmental performance on emissions into the atmosphere without installing additional equipment for cleaning flue gases.

The total expected reduction of pollutants emissions into the atmosphere will be 6370.9 tons/year. This emissions reduction should be considered as a positive factor in terms of the impact on the microclimate in the area of the CHPP.

Mandatory conditions for the admissibility of the reconstruction of process equipment and operation of the Sumy CHPP:

– compliance with atmospheric air environmental safety standards, which exclude a negative impact on the environment;

– compliance with standards for pollutants maximum permissible emissions.

The maximum permissible concentration (MPC) of pollutants in atmospheric air are the main criteria for assessing atmospheric air quality in determining the level of direct negative emissions impact. The main condition that must be met for each pollutant emitted into the atmosphere:

$$\frac{C_m}{MPC} \le 1, \qquad (1)$$

where C_m – the maximum calculated surface pollutant concentration in the air, mg/m^3; MPC – the one-time maximum permissible concentration, mg/m^3.

In accordance with the promising areas of the Energy Strategy, environmentally friendly coal generation should be developed through the introduction of such parameters:

– power units with supercritical steam parameters with an efficiency of 46 – 55 %, when burning high-quality and high-calorific coal by the flare method;

– power units with supercritical steam parameters, equipped with circulating fluidized bed boilers (CFB).

Four main ways to reduce emissions have been proposed for CHPP: fuel replacement or its enrichment; coal washing; burning coal in a fluidized bed; use of scrubbers, filters [22].

Fuel replacement must be carried out taking into account the fact that there are grades of coal with low sulfur content. However, the transition to them depends on economic factors. Some types of low-sulfur coal have a lower heat value. Switching to this coal type may not bring a significant reduction in emissions. Sulfur dioxide emissions can be reduced not only by using expensive low-sulfur coal but with cleaning coal from sulfur before burning. The action of gas-cleaning units of different design is based on the dioxide chemical reactions. Chemical reaction products can either be discarded as waste or used as a product. Today, the use of scrubbers is a common technology.

2. Statement of the problem and its solution.

The research aim is to study the environmental efficiency of combustion control in circulating fluidized bed boilers.

Applying any methods to emissions clean up is a solution of the problem, but not a preventive method. A promising option to prevent pollution is coal burning in circulating fluidized bed boilers [9].

2.1. Materials and methods.

Computer simulation of the turbulent combustion process in the CFB makes it possible to fully calculate the temperature field and ensures the elimination of technogenic components' emissions into the atmosphere.

The considered chemical processes occurring in the combustion zone are described by a system of nonlinear differential equations. An effective method of theoretical research is numerical simulation with a computational experiment.

The computational experiment was performed with the ANSYS Fluent application package using the example of a real energy model.

To describe the movement of the fuel component in the combustion zone, a system of differential equations was used, including the law of conservation of mass, momentum, energy and the law of conservation of the substances' components:

$$\frac{\partial \rho}{\partial t} = \frac{\partial(\rho u_j)}{\partial x_j}, \qquad (2)$$

$$\frac{\partial(\rho u_i)}{\partial t} = \frac{\partial(\rho u_i u_i)}{\partial x_j} + \frac{\partial t_{i,j}}{\partial x_j} + \frac{\partial p}{\partial x_i} + \rho f_i, \qquad (3)$$

$$\frac{\partial}{\partial \tau}(\rho h) = -\frac{\partial}{\partial x_i}(\rho u, h)\frac{\partial Q_i}{\partial x_j} + \frac{\partial \rho}{\partial \tau} + + u_i \frac{\partial \rho}{\partial x_i} + \tau_{ij}\frac{\partial u_j}{\partial x_i} + S_q, \qquad (4)$$

$$\frac{\partial}{\partial t}(\rho C_\beta) = -\frac{\partial}{\partial x_i}(\rho C_\beta u_i) - \frac{\partial j_i}{\partial x_i} + R_\beta, \qquad (5)$$

where ρ – density; t – time; $u_{i,j}$ – velocity; p – pressure; τ – stress tensor; f_i – bulk forces; $x_{i,j}$ – coordinate; C_β – mass concentration; h – enthalpy; j_i – diffusion flow; R_β – source of substance.

The fields of concentrations of combustion products (CO, CO_2, NO, NO_2, SO_2) during the combustion of a monodisperse coal mass were obtained based on the solution of the system of equations by a numerical method.

2.2. Results and discussion.

2.2.1. The operation principle of boilers with CFB and their effectiveness evaluation. Unlike the fixed bed, the presence of fine particulates matter in the fuel is not critical to the organization of the combustion process in a fluidized bed, they do not significantly reduce its effectiveness. The fact is that fine particulates matter (less than 0.5 mm in size) removed from a layer are not returned. Since the temperature in the overlayer space is lower than in the main layer, the combustion of fine particulates matter stops. Trapping fine particulates matter and returning them to afterburning in the layer are ineffective because the efficiency of trapping cyclones for dust particles does not exceed 70 %. A qualitative leap occurred when the fuel began to be crushed to a size of 0 – 3 mm and below, and the gas velocity to the living section of the firebox was increased to 5 – 7 m/s. It turned out that under conditions when a powerful stream of particles of 0.1 – 1 mm in size is removed from the layer, the overall efficiency of the cyclone rises to 99 % or more due to the fact that well-caught particles of the specified size carry along smaller ones. So a circulating fluidized bed furnace were created (figure 3).

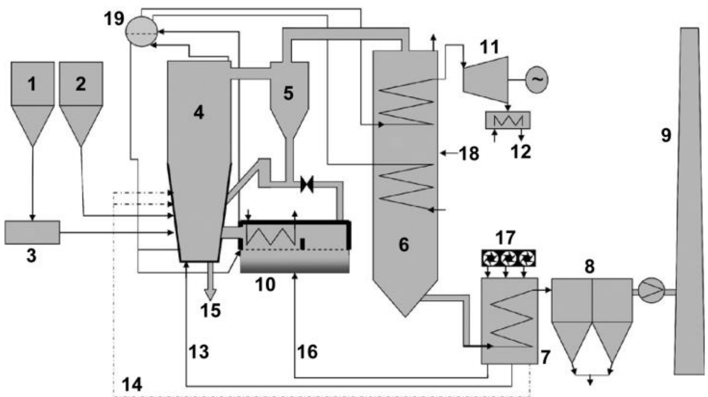

Figure 3 – Schematic representation of a coal-fired CFB plant [23]:
1 – coal bunker; 2 – limestone bunker; 3 – coal crusher; 4 – CFB combustor; 5 – cyclone; 6 – convective pass; 7 – air pre-heater; 8 – electrostatic filter; 9 – chimney; 10 – fluid bed heat exchanger; 11 – turbo-generator; 12 – district heating; 13 – primary air; 14 – secondary air; 15 – bottom ash; 16 – fluid bed heat exchanger air; 17 – blowers; 18 – feed water; 19 – drum

The principal difference is that a cyclone is installed behind the furnace, in which all unburned particles are captured and returned to the furnace. Thus, the particles are «locked» in the closed system «furnace – cyclone – furnace» until they are completely burned out. Such boilers are almost as efficient as chamber furnaces, while retaining all the environmental advantages.

Circulating fluidized bed furnaces have a higher degree of fuel burnout (approximately 98 – 99 % versus 90 – 95 % for stationary fluidized bed boilers) and can be operated with a lower air excess factor.

Serious research with the purpose of applied use of CFB technology originates from the beginning to the middle of the 1970s, and the first energy CFB boiler was built in Finland in 1979. Currently, the main developers of combustion technologies in the boilers with CFB are Foster Wheeler, Babcock & Wilcox and others.

The requirements for the fuel quality at the CFB are no more stringent than that of the fluidized bed, and the efficiency of fuel burning, including those containing small particles, is much higher. Environmental indicators are also better: in terms of sulfur binding – due to a longer retention of limestone in the furnace, and on nitrogen oxides emissions – due to the organization of a reduction zone between the primary and secondary air inlets.

In addition, CFB furnaces have much smaller scale limitations, therefore they can be used not only in small steam and hot water boilers, as furnaces with a fixed and fluidized bed, but also in boilers of large power plants' units with an electrical capacity of 300 MW and more. It should be noted that, in terms of ash content, sludge wastes with ash content up to 60 %, which are currently accumulated up to 150 million tons or about 70 million tons of fuel equivalent, are suitable for burning in boilers with CFB. Their utilization would not only expand the fuel base of thermal energy without significant capital investment, but also solve a lot of environmental problems associated with the recultivation of areas occupied by sludge-storages. A necessary condition for the incineration of high-ash sludge in the CFB is its agglomeration, which is provided during drying due to the natural clay component.

Circulating fluidized bed combustion provides low emissions. One of his main advantages is the ability to effectively capture sulfur dioxide (SO_2) by feeding limestone into the layer.

$$CaCO_2 + SO_2 \rightarrow CaSO_4 + CO_2;$$
$$CaO + SO_2 \rightarrow CaSO_3;$$
$$2CaSO_3 + O_2 \rightarrow 2CaSO_4.$$

Calcium sulfide is poorly soluble in water (0.136 g/L). It quickly supersaturates solution and falls in the form of small crystals during the cleaning process.

The conditions in the fluidized bed furnace are very suitable for the absorption process organization. Therefore, sulfur is captured much more efficiently in a fluidized bed than when lime is injected into a furnace with pulverized coal. The combustion of fuels using this technology does not cause the formation of «thermal» NO_X from air nitrogen (i.e. it is practically absent). In addition, the NO_X level is reduced by a stepwise supply of air. Moreover, the formation of nitrogen oxides does not occur in the CFB, because fuel burns in a temperature mode of 850 – 900 °C.

Thus, the main advantages of the CFB technology are:

– the possibility of efficient combustion of low-calorie, high-ash fuels, which is determined by a stable temperature in the furnace, low carbon content in the layer and a long residence time of the coke-ash residue in the reaction zone;

– the ability to effectively bind sulfur by a relatively cheap method of feeding limestone;

– low emissions of nitrogen oxides (less than 200 – 300 mg/m^3) without the use of special means of nitrogen treatment;

– the possibility of burning fuels of different quality in the same boiler, a simplified scheme of fuel preparation, good dynamic characteristics, quick start from the «hot» state;

– compactness of the boiler plant due to the lack of means of sulfur and nitrogen treatment, which allows to place the boiler with the CFB in the existing boiler cells.

2.2.2. Evaluation of the technology's environmental efficiency. Evaluation of the CHPP impact after the introduction of the CFB technology. In connection with the implementation of new design solutions, a significant reduction of pollutants emissions into the atmosphere (table 3) is expected due to the replacement of existing boilers by boilers with environmentally friendly technology of burning solid fuel in a circulating fluidized bed with the ability to control the temperature field and installing high-performance electrostatic precipitators.

Table 3 – Expected reduction of pollutant emissions after the CHPP reconstruction

Pollutant	Pollutants gross emissions, tons/year			
	the status quo	after reconstruc-tion	emission reduction	emission increase
Nitrogen oxides, NO_X	528.7	259.2	269.5	–
Sulphur dioxide, SO_2	3830.4	1174.9	2655.5	–
Carbon monoxide, CO	71.3	358.3	–	287.0
Particullar matter	4591.1	858.2	3732.9	–
Total:	9021.5	2650.6	6657.9	287.0

The concentration of carbon monoxide in circulating fluidized bed boilers is higher than with the flare method of burning solid fuels, by maintaining the optimum excess air at 1.25. This leads to an increase of carbon monoxide emissions after the reconstruction of CHPP and the necessity to apply an additional method of cleaning.

The provided technical solutions and environmental protection measures will reduce the total emissions of pollutants into the atmosphere generally by 6370.9 tons, which is 70.6 %. This will improve the environmental situation in the zone of influence of Sumy CHPP.

Conclusion.

The use of any methods for emissions cleaning up at power plants is a problem solution, but not a preventive method. A promising option to prevent pollution is coal burning in circulating fluidized bed boilers.

As a result of the research, the ecological efficiency of combustion control in boilers with CFB was established, it will allow to reduce the technogenic load on the air basin in the zone of influence of the Sumy CHPP. This is due to the following advantages of the CFB: compatible with fuels wide range; low level of pollution with sulfur oxides (due to its binding with limestone) and nitrogen (due to the boiler operation at lower temperatures – in the range of 850 – 900 °C, when NO_X is not formed); high combustion efficiency; ease of maintenance.

Construction of a new boiler with an environmentally friendly technology of burning solid fuel in a circulating fluidized bed with a controlled temperature field will significantly reduce air pollution in the zone of influence of CHPP, compared with the existing situation, and ensure compliance with sanitary standards for atmospheric air quality. The calculation has showed that the new technical solutions will reduce the emissions to the atmosphere of the Sumy CHPP by 6370.9 tons per year, which is 70.6 % less than the current emissions.

The maximum surface concentrations of pollutants will not exceed the maximum allowable concentrations for all ingredients and possible summing effects.

Thus, in Ukraine and other countries circulating fluidized bed technology can play an important role in the effective use of the enormous potential of available coal reserves, including lignite, for the production of relatively clean energy.

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Conflicts of Interest.

The authors declare no conflict of interest in preparing this article.

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ЕКОЛОГІЧНА ЕФЕКТИВНІСТЬ УПРАВЛІННЯ ПРОЦЕСОМ ГОРІННЯ В КОТЛАХ ІЗ ЦИРКУЛЮЮЧИМ КИПЛЯЧИМ ШАРОМ

Стаття присвячена актуальній проблемі зменшення техногенного навантаження на навколишнє середовище від теплоенергетичних підприємств шляхом впровадження екологічно чистої технології спалювання твердого палива в котлах із циркулюючим киплячим шаром (ЦКШ). Метою дослідження є підвищення ефективності забезпечення екологічної безпеки процесів горіння в енергетичних агрегатах із циркулюючим киплячим шаром, який дозволяє мінімізувати викиди техногенних компонентів в атмосферу. Розглянуто стан і перспективи спалювання вугільного палива в циркулюючому киплячому шарі (ЦКШ) на теплових електростанціях з акцентом на оцінку екологічної ефективності процесу. Коротко викладені останні тенденції розвитку технології ЦКШ і подано погляд на майбутнє щодо проблем і можливостей даної технології. Проаналізовано фактори, що визначають рівень забруднення атмосфери викидами ТЕЦ, розглянуто їх вплив на навколишнє природне середовище та показана динаміка викидів забруднюючих речовин в Україні. Розглянуто основні методи зменшення негативного впливу ТЕЦ на навколишнє природне середовище. Встановлено, що зменшення викидів оксидів азоту можна зменшити шляхом управління температурним полем горіння палива. Розглянуто принцип роботи та особливості котлів з циркулюючим киплячим шаром, їх екологічна ефективність, у порівнянні з факельним способом спалювання палива. Проведено оцінювання екологічної ефективності управління процесом горіння в котлах ЦКШ на прикладі реального об'єкта. Встановлено, що передбачені технічні рішення та природоохоронні заходи дозволять скоротити валові викиди забруднюючих речовин у атмосферу на 6370,9 т, що значно знизить навантаження на повітряний басейн і поліпшить екологічну ситуацію в зоні її впливу.

Ключові слова: теплові електростанції; горіння вугілля; забруднення повітря; циркулюючий киплячий шар.

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ЭКОЛОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ УПРАВЛЕНИЯ ПРОЦЕССОМ ГОРЕНИЯ В КОТЛАХ С ЦИРКУЛИРУЮЩИМ КИПЯЩИМ СЛОЕМ

Статья посвящена актуальной проблеме уменьшения техногенной нагрузки на окружающую среду от теплоэнергетических предприятий путем внедрения экологически чистой технологии сжигания твердого топлива в котлах с циркулирующим кипящим слоем (ЦКС). Целью исследования является повышение эффективности обеспечения экологической безопасности процессов горения в энергетических агрегатах с циркулирующим кипящим слоем, который позволяет минимизировать выбросы техногенных компонентов в атмосферу. Рассмотрено существующее состояние и перспективы сжигания угольного топлива в циркулирующем кипящем слое на тепловых электростанциях с акцентом на оценку экологической эффективности процесса. Кратко изложены последние тенденции развития технологии ЦКС и дан взгляд на будущее в отношении проблем и возможностей данной технологии. Проанализированы факторы, определяющие уровень загрязнения атмосферы выбросами ТЭЦ, рассмотрено их влияние на окружающую среду и показана динамика выбросов загрязняющих веществ в Украине. Рассмотрены основные методы снижения негативного воздействия предприятий теплоэнергетики на окружающую природную среду. Установлено, что уменьшение выбросов оксидов азота можно уменьшить путем управления температурным полем горения топлива. Рассмотрен принцип работы и особенности энергетических агрегатов с циркулирующим кипящим слоем, их экологическая эффективность, по сравнению с факельным способом сжигания топлива. Оценена экологическая эффективность управления процессом горения в котлах ЦКС на примере реального объекта. Установлено, что предусмотренные технические решения и природоохранные мероприятия позволят сократить валовые выбросы загрязняющих веществ в атмосферу на 6370,9 т, что значительно снизит нагрузку на воздушный бассейн и улучшит экологическую ситуацию в зоне ее влияния.

Ключевые слова: тепловые электростанции; горение угля; загрязнение воздуха; циркулирующий кипящий слой.