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NUMERICAL SIMULATION OF FUEL COMBUSTION PROCESSES TO REDUCE HARMFUL DUST AND GAS EMISSIONS USING OVER FIRE AIR

Currently, air pollution is a huge environmental problem. The participation of energy companies in environmental pollution by fuel combustion products and solid waste is significant. Above all, power plants operating on solid fuel are one of the main sources of air, water and soil pollution. Until recently, during coal combustion process the most part of attention has been paid to protecting the environment from solid pollutants, such as ash. Very little attention has been paid to the gas products of combustion reactions, especially to NO_x и SO_2.

Mainly NO and NO_2 of nitrogen oxides are found in the atmosphere. NO is an unstable component that oxidizes to NO_2 during 0.5-3 to 100 hours. The toxicity of NO_2 is 7 times higher than the toxicity of NO. Nitrogen oxides are most dangerous as an active ingredient in the formation of photochemical smog. Currently nitrogen oxides are recognized as the most toxic atmospheric pollutants, and their maximum permissible concentration is 6 times less than for sulfur dioxide. It is believed that emissions of nitrogen oxides generated during combustion contribute to the oxidation of precipitation, photochemical air pollution and depletion of the ozone layer.

In this regard, many studies are aimed at the development of technologies for environmentally friendly combustion, which provide harmful dust and gas emissions at the level of international standards.

One of the ways to reduce the concentration of nitrogen oxides NO_x is the stepwise combustion of a powdered coal mixture, in particular the "Over Fire Air" technology. The idea of this method is based on the fact that the main volume of air is supplied to powdered coal burners, and the rest of the air is supplied further along the height of the torch through special nozzles.

The article presents the study results of the Over Fire Air technology influence on the aerodynamic characteristics of the combustion chamber of the BKZ-160 boiler.

Key words*:* energy, combustion, nitrogen oxide, injector, combustion chamber, aerodynamics.

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Over Fire Air-ды қолданып зиянды шаңгазды тозаңды қалдықтарды азайту үшін отынды жағу процестерін сандық модельдеу

Қазіргі уақытта атмосфералық ауаның ластануы күн тәртібіндегі өзекті экологиялық мәселе болып отыр. Энергетикалық кәсіпорындардың қоршаған ортаны отынның жану өнімдерімен, қатты қалдықтармен ластануына қатысуы айтарлықтай дәрежеге жеткен және мұндай нысандарға ең алдымен қатты отынмен жұмыс жасайтын, әрі ауа, су және топырақты ластаушы негізгі көздердің бірі болып саналатын электр станциялары жатады. Соңғы кездері көмірді жағу барысында қоршаған ортаны қатты ластауыштардан, мысалы, күлден қорғауға баса назар аударылып келді, алайда, жану реакциясының газды өнімдері, әсіресе NO_x пен SO_2 қатысты мәселелер қиындық тудырып тұр.

Атмосферада азот тотықтарының ішінде негізінен NO және NO_2 кездеседі. NO 0,5-3-тен 100 сағ ішінде NO_2 дейін тотығатын орнықсыз компонент болып табылады. NO_2 улылығы NO улылығынан 7 есе жоғары. Азот тотықтары фотохимиялық тұмшаның түзілуі кезіндегі белсенді компонент ретінде қауіптілік тудырады. Қазіргі уақытта азот тотықтары атмосфераның ең ірі улы ластаушылары болып танылған, ал олардың шекті рұқсат етілген концентрациясы күкіртті газбен салыстырғанда 6 есе аз. Жану барысында қалыптасатын азот тотықтарының қалдықтары атмосфералық ылғалдың тотығуына, ауаның фотохимиялық ластануына және озон қабатының азғындалуына әкеліп соқтырады. Осы тұрғыда көптеген зерттеулер зиянды шаңгаздық тозаңды қалдықтары халықаралық стандарттар деңгейінде шығуын қадағалайтын таза жағу технологияларын жасауға бағытталған.

Азот тотықтарының NO_x концентрацияларын кемітудің осындай тәсілдеріне шаңкөмірлі қоспаны сатылай жағуды айтуға болады, оның ішінде нақтырақ айтсақ, «Over Fire Air» технологиясы. Аталған әдістің мәні ауаның негізгі көлемі шаңкөмірлі жанарғыларға, ал қалған ауа алаудың биіктігі бойымен арнайы соплолар арқылы берілетіндігіне негізделеді.

Мақалада Over Fire Air технологиясының БКЗ-160 қазандығының жану камерасының аэродинамикалық сипаттамаларына әсерін зерттеу нәтижелері келтірілген.

Түйін сөздер: энергия, жану, азот оксиді, инжектор, жану камерасы, аэродинамика.

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Численное моделирование процессов сжигания топлива для снижения вредных пылегазовых выбросов с применением Over Fire Air

В настоящее время острой экологической проблемой является загрязнение атмосферного воздуха. Участие энергопредприятий в загрязнении окружающей среды продуктами сгорания топлива, твердыми отходами значительно, и это, прежде всего, электростанции, работающие на твердом топливе и являющиеся одним из основных источников загрязнения воздуха, воды и почвы. До последнего времени при сжигании угля внимание уделялось защите окружающей среды от твердых загрязнителей, например золы, значительно сложнее обстоит дело с газовыми продуктами реакций горения, и особенно с NO_x и SO_2.

В атмосфере из оксидов азота встречаются в основном NO и NO_2. NO является неустойчивым компонентом, который в течение от 0,5 – 3 до 100 ч окисляется до NO_2. Токсичность NO_2 в 7 раз выше токсичности NO. Наибольшую опасность оксиды азота представляют как активный компонент при образовании фотохимического смога. Окислы азота признаны в настоящее время наиболее токсичными загрязнителями атмосферы, а их предельно допустимая концентрация в 6 раз меньше, чем для сернистого газа. Считается, что выбросы оксидов азота, образующихся при горении, способствуют окислению атмосферных осадков, фотохимическому загрязнению воздуха и истощению озонового слоя.

В этой связи многие исследования направлены на разработку технологий экологически чистого сжигания, обеспечивающих вредные пылегазовые выбросы на уровне требований международных стандартов.

Одним из способов снижения концентрации оксидов азота NO_x является ступенчатое сжигание пылеугольной смеси, в частности технология «Over Fire Air». Суть данного метода заключается в том, что основной объем воздуха подается в пылеугольные горелки, а остальной воздух – далее по высоте факела через специальные сопла.

В статье представлены результаты исследования влияния технологии Over Fire Air на аэродинамические характеристики топочной камеры котла БКЗ-160.

Ключевые слова: энергия, горение, оксид азота, инжектор, топочная камера, аэродинамика.

Introduction

Energy is one of the leading industries of many industrialized countries. These countries have switched to the innovative development of this industry, they have changed the system of view on its role and place in the modern and future society radically. The new system of view is reflected in the Smart Gird concept – the smart energy system, which should be the basis of the national energy and innovation development policy of any country and should be taken into account in the development of the domestic energy.

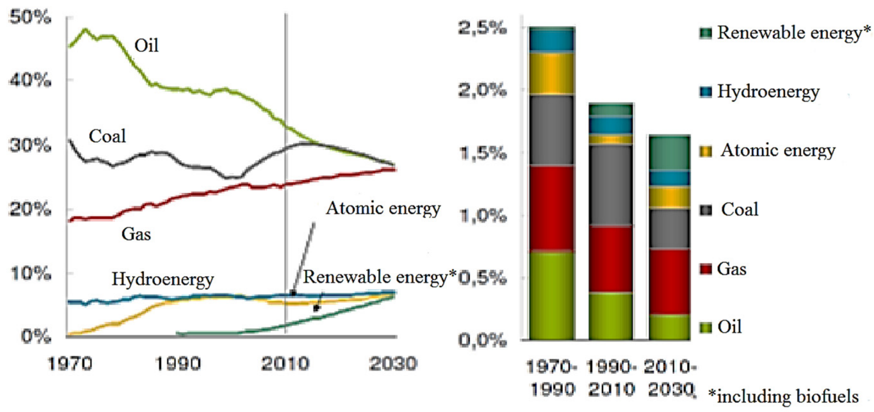
Efficient energy use is a prerequisite for economic and social development, as well as improving the ecology.

In the "Kazakhstan-2050 Strategy" N.A. Nazarbayev noted that: "Kazakhstan is one of the key elements of global energy security...".

Worldwide, the use of renewable energy resources (the share of solar and wind energy in the total energy consumption of the Republic of Kazakhstan is about 0.02%) is an integral part of measures to solve environmental problems. However, solar and wind energy production is relatively expensive compared to traditional sources.

The country's coal power plants generate more than 80% of energy. Therefore, "in the future, coal will have been playing a significant role in the country's energy sector" [1-4].

Energy is one of the leading industries in many industrialized countries, including Kazakhstan. It should be noted that more than 80% of all energy produced in the world is produced by combustion organic fuel (Figure 1) [5]. In Kazakhstan, about 70% of electricity is generated from coal, 14.6% from hydro resources, 10.6% from gas and 4.9% from oil.



a) b)

Figure 1 – The share of energy sources in the period from 1970 to 2030

The main part of electricity in Kazakhstan is generated by 37 thermal power plants operating on coal from Ekibastuz, Maikubinsk, Turgai and Karaganda basins.

Production of electricity by burning solid fuel (coal) for our country is the traditional and most developed way due to the presence of hard coal huge reserves. Therefore, in spite of the beginning of the search process for Kazakhstan of alternative, more environmentally friendly ways of obtaining energy, for a long time the power plants operating on solid fuels will have been being the basis of energy production and energy security of the country. The quality and quantity of gas emissions and waste of thermal power plants is greatly influenced by the type of used fuel [6-9].

The coal of Kazakhstan is cheap energy fuel, the reserves of which will be enough for many hundreds of years. At the same time, its low sulfur content and low nitrogen content (not more than one percent) should be noted. However, at the same time, the coal of Kazakhstan, being a good energy fuel in its reactivity, has one big drawback – high ash content. The ash content of coal supplied from individual Kazakhstani fields to thermal power plants sometimes exceeds 70%. In compliance with the law in the UK it is – 22%, in the USA – 9%, in Germany – 8%.

The presence of ash in the fuel affects on its quality negatively, since ash reduces the amount of heat per unit mass of fuel. The smallest solid particles of ash are captured by the flow of flue gases and are carried away from the burner, forming fly ash, which pollutes and sometimes floods the convective heating surface.

During combustion of all types of fossil fuels, one of the most harmful products of combustion are NO_x oxides, which damage both the environment and human health.

Thus, one of the actual tasks in the development of new and operation of existing combustion devices is to reduce the concentration of carbon and nitrogen oxides during the combustion products.

Reducing NO_x emissions from fuel combustion at TPPs plays an important role in reducing the total level of nitrogen oxides NO_x emitted into the atmosphere. When using methods to reduce NO_x in calculating the amount of NO_2, it should not be used the traditional percentage of NO_2 of the total amount of NO_x (10%), as this leads to very significant errors in the calculations.

One of the ways to reduce the concentration of nitrogen oxides NO_x is the stepwise combustion of a powdered coal mixture, in particular the "Over Fire Air" technology. The idea of this method is based on the fact that the main volume of air is supplied to powdered coal burners, and the rest of the air is supplied further along the height of the torch through special nozzles [10-15].

Mathematical model describing the process of heat and mass transfer during combustion of coal dust in the combustion chamber of the boiler BKZ-160 on Almaty thermal power plant

Many experimental and analytical studies are conducted under simplified conditions that differ from the actual conditions of the combustion process. For example, many of them are conducted under the conditions of burning large particles when they are burned in a large excess of air. Some researchers assumed that the temperature of the medium during the combustion process would not change, and the combustion would proceed in one of the extreme regimes: kinetic or diffuse. Such simplification of the combustion process misrepresents its essence and does not allow to determine the aerodynamics and heat transfer occurring in a real combustion chamber.

During the combustion of solid fuel in a powdered state, turbulent processes of heat and mass transfer of reacting components and products of their interaction occur in the combustion chamber. Equations based on the laws of mass and momentum conservation describe such processes. For reacting streams in which heat transfer processes and chemical reactions occur, it is necessary to solve the energy conservation equation and add the mixture components conservation equation or the mixture fractions conservation equation and their changes additionally. Turbulence is described by transport equations for turbulent characteristics.

The system of basic equations of the mathematical model used in this project to describe the processes of turbulent heat and mass transfer during the combustion of solid fuel in a powdered state (powdered coal flame) [15-20]:

a) The mass conservation equation, or the continuity equation:

$$\frac{\partial \rho}{\partial \tau} = -\frac{\partial}{\partial x_i}(\rho u_i)\,, \qquad (1)$$

b) The law of conservation of momentum:

$$\frac{\partial}{\partial \tau}(\rho u_i) = -\frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial}{\partial x_j}(\tau_{ij}) - \frac{\partial p}{\partial x_j} + \rho f_i\,, \qquad (2)$$

Here f_i is bulk forces, τ_{ij} is viscous stress tensor.

Turbulent flows are characterized by velocity pulsations that contribute to the mixing of transported characteristics, such as impulse, energy, and component concentration, and also cause fluctuations in these characteristics. Since the pulsations can be small in scale, but have a high frequency, directly calculating them is a very difficult task in practical technical calculations. Instead, the instantaneous (exact) determining equations can be averaged by the time, represented as an average over an ensemble, which leads to modified systems of equations that need less costs to solve.

However, the modified equations contain additional unknown variables. Therefore, additional turbulence models are necessary for their determination.

Many turbulence models used in computational practice are based on the concept of vortex (turbulent) viscosity. In contrast to molecular viscosity ν, turbulent viscosity ν_t is determined by the state of turbulence and does not relate to the properties of the fluid. Turbulent viscosity can vary greatly from point to point in space depending on the type of flow. Sometimes, when calculating turbulent flows, ν_t is assumed to be constant. However, such a rough description of turbulence is permissible in those cases where the value of turbulent transfer is not significant or the use of more complex structures seems to be unjustified.

In this project, the standard k-ε model of turbulence is used to describe turbulence.

c) Energy equation:

$$\frac{\partial}{\partial t}(\rho h) = -\frac{\partial}{\partial x_i}(\rho u_i h) - \frac{\partial q_i^{res}}{\partial x_j} + \frac{\partial p}{\partial t} + u_i\frac{\partial p}{\partial x_i} + \tau_{ij}\frac{\partial u_j}{\partial x_i} + S_q, \quad (3)$$

here h is enthalpy; q_i^{res} is energy flow density due to molecular heat transfer, S_q is energy source.

The source term S_q takes into account:

- heat flow due to convective exchange between particles and the gas phase – $S_{h,p}$;
- the combustion heat, which takes into account the presence of solid particles of powdered coal fuel in the total flow of the mixture – S_{abr};
- heat due to radiation – S_{str}, the contribution of which, in the flame zone, is about 90% or more to the full heat transfer.

Therefore, we have: $S_h = S_{str} + S_{abr} + S_{h,p}$

Heat exchange through radiation, as mentioned above, makes the maximum contribution during powdered coal fuel combustion in the combustion chambers of industrial boilers. In this regard, the simulation of radiant heat transfer in the study of heat and mass transfer in the combustion chambers is an important step in the calculation of heat exchange processes with physics and chemical transformations.

d) Conservation law for a substance component:

The concentrations of the mixture components in the element's volume are recorded through the corresponding balance ratio, which takes into account the physics and chemical processes that influence on the concentration change of these substances.

In the element's volume, the total mass is determined by the sum of the masses of all components involved in the chemical reaction of the coal particle combustion:

$$m = \sum_n m_n. \quad (4)$$

In general form the equation describing the concentration of the mixture components is written as follows:

$$\frac{\partial}{\partial t}(\rho c_n) + \frac{\partial}{\partial x_i}(\rho u_i c_n) = = \frac{\partial}{\partial x_i}\left[\frac{\mu_{eff}}{\sigma_{c_{n,eff}}}\frac{\partial c_n}{\partial x_i}\right] + S_{c_n}, \quad (5)$$

where S_{c_n} is source term, taking into account the contribution of chemical reactions to changes in the components concentration.

For multicomponent mixture, the source term is determined by the relation:

$$S_{c_n} = \sum \omega_{n,r}, \quad (6)$$

where $\omega_{n,r}$ is the speed of the chemical reaction, which is written as follows:

$$\omega_{n,r} = \frac{dc_{AB}}{dt} = k(T)c_A c_B.$$

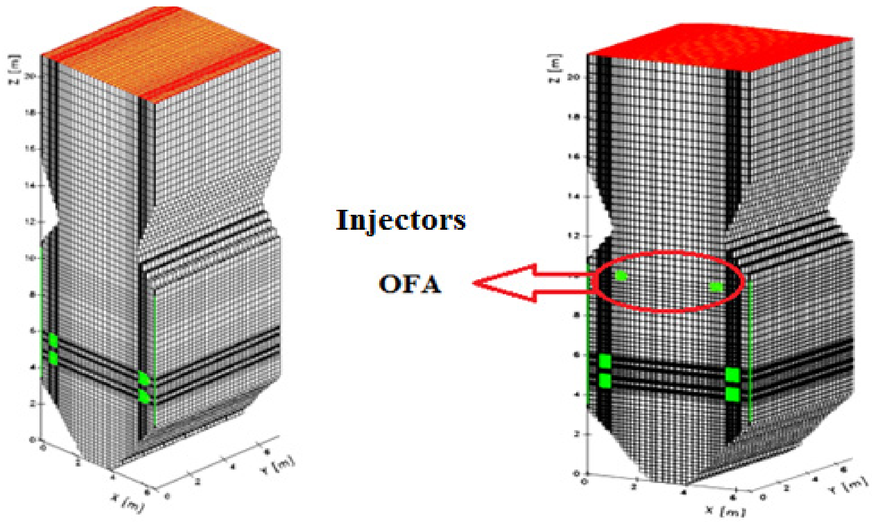
The speed of the reaction depends on the temperature and concentrations of the substances A and B involved in the reaction (starting, intermediate, final products). The speed constant of the reaction k(T) is written as an exponential temperature dependence in the form of the Arrhenius law:

$$k(T) = k_0 e^{-E/RT}, \quad (7)$$

where: k_0 is the constant, in the first approximation, is not dependent on temperature, E [kcal / mol] is activation energy, R=1.986 [kcal/mol·K] is universal gas constant.

Results of modeling the coal combustion process, using «Over Fire Air» technology

The combustion chamber of the BKZ-160 boiler (Figure 2a) has a design steam capacity of 160 t/h, at a pressure of 9.8 MPa and a superheat temperature of 540 °C. Thermal power of the combustion chamber is 124.4 MW. On the sides of the combustion chamber there are 4 blocks of straight-through slot burners, directed tangentially to the central conventional circle. To study the influence of OFA, 3 modes were selected: 0%, 10% and 20% of the total air volume supplied through injectors in the upper part of the combustion chamber (Figure 2b) [21-26].

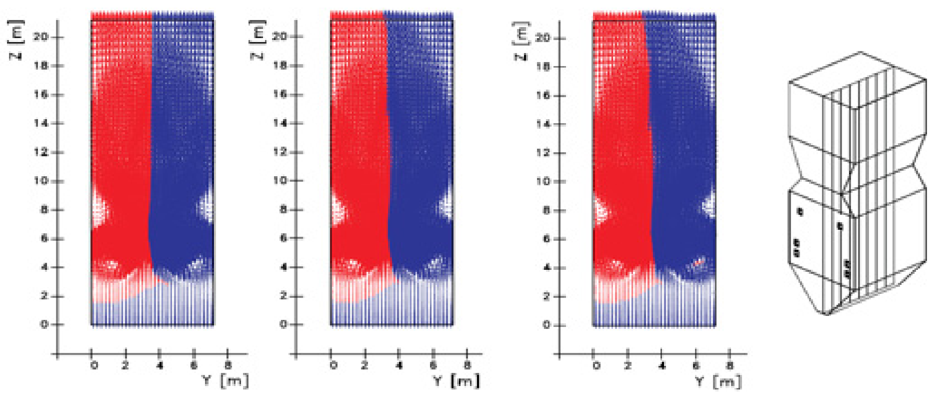


a) Traditional combustion mode b) Combustion using OFA Injectors

Figure 2 – General view of the combustion chamber of the BKZ-160 boiler and its divisionon control volumes

The location of the injectors applied to the "Over Fire Air" technology and the determination of the level where the secondary injected air mixes thoroughly (Figure 2b) are very important to create the conditions for the efficient combustion of coal powder.

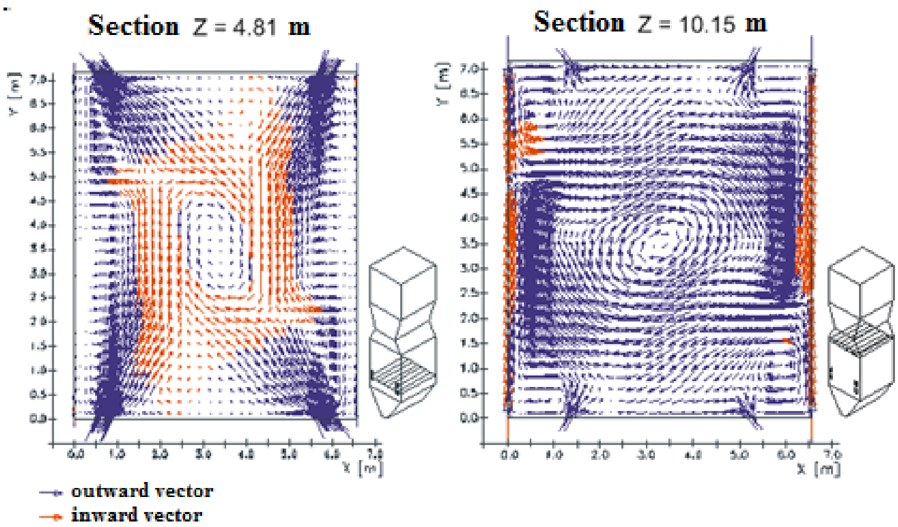
Figures 3 and 4 show the results of computational experiments on the effect of OFA technology on the aerodynamics of flows in the combustion chamber of the BKZ-160 boiler. There is also comparison with the basic combustion mode of solid fuel, when there is no additional air supply (OFA = 0%).



а) OFA-0% б) OFA-10% в) OFA-20%

Figure 3 – The distribution of velocity vectors in the longitudinal section of the combustion chamber of the BKZ-160 boiler

Analysis of the figures shows that the use of OFA-injectors in the area above the combustion devices does not have a significant effect on the aerodynamic picture in longitudinal sections along the height of the combustion chamber (Figure 3), i.e. it does not violate the general combustion mode of powdered coal and removal of combustion products from the combustion chamber.



a) Burner cross section б) OFA-injector section

Figure 4 – The velocity vector field in the cross sections of the combustion chamber of the boiler BKZ-160

However, if we look at Figure 4, which shows the distribution of the velocity vector in the cross section of the installation of burners (Figure 4a) and in the cross section of the installation of OFA-injectors (Figure 4b), here we see that the supplying of an additional air amount through the OFA-injectors supports the vortex process of combustion. This affects favorably on the intensive mixing of the fuel and oxidizer, and, consequently, on the complete combustion of coal particles, which lead to a reduction in mechanical incombustion and in harmful dust and gas emissions, such as NO_x.

Conclusion

The study conducted a comprehensive study on the creation of energy-saving and environmentally friendly technologies (Over Fire Air technology) in order to increase the efficiency of thermal power plants and minimize harmful dust-gas emissions into the atmosphere when high-ash Ekibastuz coal is burned in the combustion chambers of the BKZ-160 power boilers.

The “Over Fire Air” technology has been described and applied to optimize the combustion of coal dust in combustion chambers. The methods for its implementation in power boilers of thermal power plants have been developed. The experience of foreign experts in reducing harmful emissions into the atmosphere have been studied.

The analysis of the "Over Fire Air" technology and the methods of Kazakhstan's energy fuel combustion were carried out taking into account its peculiarities, as well as the design features of the combustion chambers of operating TPPs industrial boilers. The existing technology “Over Fire Air” has been adapted and supplemented to a specific low-grade Kazakhstan fuel having an ash content of ~ 40-50%.

Various systems of staged air supply were investigated: the systems of separate (SOFA) and dual “sharp” blast (CCOFA). The aerodynamics of the flue space was obtained (the aerodynamic picture of introducing additional air streams into the chamber according to the Over Fire Air method and the velocity distribution in the combustion chamber).

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