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DEVELOPMENT OF THERMAL JET TOOL FOR PREPARATION AND COMBUSTION OF PULVERIZED COAL FUEL

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Abstract. The article discusses key aspects of preparing fuel components for efficient combustion in boiler units. The main challenge lies in ensuring complete and stable combustion of pulverized fuels while minimizing ignition energy costs and reducing risks of incomplete combustion, which can cause tube slagging and lower overall efficiency. The topic is highly relevant due to the need to improve the performance of thermal power plants and adapt to fuels with varying characteristics. The study analyzes coal dust mixture preparation, focusing on mixing processes, dispersion, and the influence of aerosol concentration and primary air temperature on fuel burnout rates. Theoretical methods were employed to evaluate combustion dynamics, including particle burnout time estimated with Nusselt and Blinov formulas, which incorporate diffusion effects, flame aerodynamics, and reaction kinetics. Key factors such as grinding fineness, excess air ratio, and furnace temperature were investigated. A core hypothesis is that a compact rocket burner generating a supersonic, high-temperature flame significantly improves ignition stability and combustion efficiency of pulverized coal. Results indicate that optimal conditions are achieved at an excess air ratio of α = 1.2-1.25 and with a properly dispersed mixture. The developed thermal tool ensures reliable ignition with minimal specific energy consumption, enhances combustion stability, and increases the efficiency of boiler units. The results obtained can be used in practice to modernize pulverized coal combustion systems at thermal power plants, as well as in the design of new boiler plants that require stable and economical fuel combustion.

Keywords: combustion, thermal tool, shock waves, fuel components, boiler unit

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ШАҢ-КӨМІР ОТЫНЫН ДАЙЫНДАУҒА ЖӘНЕ ЖАҒУҒА АРНАЛҒАН ТЕРМОАҒЫНДЫ ҚҰРАЛДЫ ӘЗІРЛЕУ

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Аннотация. Мақалада қазандық агрегаттарында отынды тиімді жағу үшін отын компоненттерін дайындаудың негізгі аспектілері қарастырылады. Негізгі міндет – ұнтақталған отынды тұтас және тұрақты жағуды қамтамасыз ету, тұтануға кететін энергия шығынын барынша азайту және толық жанбау қаупін төмендету, бұл құбырлардың қождануына және жалпы пайдалы әсер коэффициентінің төмендеуіне әкелуі мүмкін. Бұл тақырып жылу электр станцияларының өнімділігін арттыру және әртүрлі сипаттағы отын түрлеріне бейімделу қажеттілігіне байланысты өзекті болып отыр. Зерттеуде көмір ұнтағынан қоспа дайындау талданады, әсіресе араластыру процестері, дисперстілік және аэросмесь концентрациясы мен бастапқы ауаның температурасының жану жылдамдығына әсері қарастырылады. Жану динамикасын бағалау үшін теориялық әдістер қолданылды, соның ішінде бөлшектердің жану уақытын диффузия әсерін, жалын аэродинамикасын және реакция кинетикасын ескеретін Нуссельт пен Блинов формулалары бойынша есептеу. Ұнтақталу дәрежесі, артық ауа коэффициенті және топтық камера температурасы сияқты негізгі факторлар зерттелді. Негізгі гипотеза

– аса жоғары температуралы дыбыстан жылдам жалын түзетін ықшамды зымырандық оттық көмір ұнтағының тұтану тұрақтылығын және жану тиімділігін айтарлықтай арттырады. Нәтижелер көрсеткендей, оңтайлы шарттар артық ауа коэффициенті α = 1,2-1,25 кезінде және қоспаның дұрыс дисперсті бөлінуінде қамтамасыз етіледі. Әзірленген термоқұрал сенімді тұтануды минималды меншікті энергия шығынымен қамтамасыз етіп, жану тұрақтылығын жақсартады және қазандық агрегаттарының пайдалы әсер коэффициентін арттырады. Алынған нәтижелер жылу электр станцияларында шаң көмірімен жағу жүйелерін жаңғырту үшін, сондай-ақ отынның тұрақты және үнемді жануын талап ететін жаңа қазандық қондырғыларын жобалау кезінде практикада пайдаланылуы мүмкін.

Түйін сөздер: жану, термо құрал, соққылы толқын, отын компоненттері, қазандық агрегат

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РАЗРАБОТКА ТЕРМОСТРУЙНОГО ИНСТРУМЕНТА ДЛЯ ПОДГОТОВКИ И СЖИГАНИЯ ПЫЛЕУГОЛЬНОГО ТОПЛИВА

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Аннотация. В статье рассматриваются ключевые аспекты подготовки топливных компонентов для эффективного сжигания в котельных агрегатах. Основная задача заключается в обеспечении полного и стабильного сжигания пылевидных топлив при минимизации затрат энергии на воспламенение и снижении риска неполного сгорания, которое может привести к зашлакованию труб и снижению общего коэффициента полезного действия. Эта тема весьма актуальна в связи с необходимостью повышения производительности тепловых электростанций и адаптации к топливу с различными характеристиками. В исследовании анализируется приготовление пылеугольной смеси с уделением особого внимания процессам смешивания, дисперсности и влиянию концентрации аэросмеси и температуры первичного воздуха на скорость выгорания топлива. Для оценки динамики горения использованы теоретические методы, в том числе расчёт времени выгорания частиц по формулам Нуссельта и Блинова, которые учитывают эффекты диффузии, аэродинамику пламени и кинетику реакции. Исследованы такие ключевые факторы, как тонкость помола, коэффициент избытка воздуха и температура топочной камеры. Основная гипотеза заключается в том, что компактная ракетная горелка, генерирующая сверхзвуковое высокотемпературное пламя, значительно повышает стабильность воспламенения и эффективность сгорания угольной пыли. Результаты показывают, что оптимальные условия достигаются при коэффициенте избытка воздуха α = 1,2-1,25 и при надлежащем распределении смеси по дисперсности. Разработанный термоинструмент обеспечивает надёжное воспламенение при минимальных удельных энергозатратах, повышает стабильность горения и увеличивает коэффициент полезного действия котельных агрегатов. Полученные результаты могут быть использованы на практике для модернизации систем пылеугольного сжигания на тепловых электростанциях, а также при проектировании новых котельных установок, требующих устойчивого и экономичного горения топлива.

Ключевые слова: горение, термоинструмент, ударные волны, топливные компоненты, котлеагрегат

Introduction. Combustion is a chemical process of interaction between a substance and an oxidising agent, accompanied by intense heat release. A characteristic feature of the combustion process is the rapidity of the reaction. This distinguishes combustion from other oxidising processes with slow heat release. The role of oxidising agent in boiler plants is played by atmospheric air oxygen (Reznyakov et al., 1968; Babii et al., 1986: 54; Ustimenko et al., 1982: 30).

In order for each fuel particle fed into the furnace to meet a sufficient amount of oxidant for combustion, it is necessary to prepare a mixture of fuel and air (Boiko, 2005: 76; Leithner et al., 2003: 84).

There are two principles of mixture formation: kinetic (Figure 1, a), diffusion (Figure 1, b).

Figure 1 – The scheme of the formation

Under the same principle, the mixture of fuel and air is homogeneous in the mixture of water and water. After that, the mixture is fed into the furnace, where it ignites and burns. With this principle of combustion, the combustion rate is determined mainly by the rate of reaction and does not depend on the rate of supply of oxidizer (Leithner, 2006: 25).

With the diffuse combustion principle, fuel and air are fed into the furnace separately. In this case, the rate of combustion is greater than the rate of combustion is no longer determined by the rate of reaction, but by the rate of supply of oxidizer. When using the kinetic principle of combustion, the main factor is the rate of expansion of the flame, i.e. the speed at which the ignition front is moving in the flow. In contrast to the layer-by-layer process, the process is not characterized by a sudden movement of the fuel cells together with the gas-air flow, which transports them through the furnace chamber in a suspended state. In order to ensure complete combustion of the fuel in the suspended state, the time limits for their combustion are limited (1-2 seconds), the fuel particles are changed to a dusty state. The speeds of these specks of dust are very small, and the impact of the flax is enormous. For example, coal dust at a diameter of 30 microns has a specific gravity of 500 m^2/kg and a wind velocity of $3.5*10^{-5}$ m/s. Due to the low velocity of the wind, the dust flows with the flow of the gas at a speed equal to the speed of the gas. Consequently, in the facial processes, the rate of dust particle rotation is almost zero (Bejarano et al., 2008: 270).

In order to give the torch sufficient stability in the sense of the absence of phenomena of coarse separation and evaporation of large particles on the surface, of the order of tens and hundreds of microns, different grinding is recommended for different fuels. That is, the windage of the ships is extremely developed (Khatami et al., 2012: 1254).

The high rate of dust particle rotation leads to a deterioration in the conditions of turbulent exchange due to the behavior of coal dust particles. But this is not the case in any computer: there is a significant increase in molecular diffusion (the diffusion coefficient for fine dust is higher); there is a significant decrease in the amount of fuel in each speck of dust; there is a significant decrease in the amount of particles of non-natural shape, which is due to the dust particles pulsate and turn on the line (depending on the position in the flow) (Hunt et al., 1995: 118).

Materials and methods of research. The flare process is characterized by a negligible amount of fuel in the furnace (unlike the layered one). This leads to inertia-free process, and therefore to extreme sensitivity to adjustment and various disturbances (operation of the feeder, etc.).

During dust combustion, each particle of fuel goes through the same sequential stages as with the layered combustion method, namely:

1) heating of a mixture of air and dust to the ignition temperature (heating, drying, gasification);

2) the actual combustion process of volatiles and coke.

The first way to reduce the flame length is to reduce the I part. The following methods can be used to accelerate the preparation process:

1) reducing the amount of primary air;

2) increase in its temperature;
3) reduction of dust humidity;
4) increase of temperature in the furnace.

The required air heating temperature depends on the quantity and quality of volatiles contained in the fuel. Studies have shown that at an air temperature of 900^{0}C, ignition for all fuels is almost instantaneous. The faster the ignition occurs, the better the volume of the furnace will be used, the better the coal particles will be burnt out, the less will be the loss of q_4. This is especially important when burning fuels with low volatile yield. Therefore, when burning anthracite and lean coal, high air heating (400-450^{0}C) is used to shorten the ignition path. At the same time, the amount of primary air is reduced to 15-17 % of the total amount (Doroshchuk et al., 1979: 138).

In modern boilers the furnace chambers are covered with screens. The screens, absorbing heat, reduce the flame temperature and slow down the combustion process. Therefore, when burning fuels such as anthracite and lean coal, the furnace chamber walls (screens) are covered with incendiary belts at some distance. This increases the temperature in the furnace at the place of dust-air mixture exit and intensifies the preparatory processes. When the boiler load is reduced, the temperature in the furnace chamber drops. Practice has shown that there is a minimum boiler load, below which combustion becomes unstable due to low combustion temperatures. For anthracite, for example, the minimum load based on combustion stability is 50 - 60 % of the nominal load (Kuang et al., 2013: 5520).

The dust burnout rate depends on:
1) the fineness of grinding;
2) the aerodynamics of the furnace;
3) temperature in the furnace.

Since the relative velocity of dust particles in the flare is small (0.5-0.7 m/s), the combustion of dust in the flare is almost similar to combustion in a stationary medium.

Assuming that the combustion of a dust particle occurs in a relatively stationary medium, Nusselt proposed a formula for the theoretical time, s, of combustion of a dust particle:

$$\tau = 144\frac{\gamma r_0^2 v_0}{D_0 T_{av}} \tag{1}$$

where r_0 - the partial radius of the particle;
γ – specific carbon weight;
v_0 – is the thermal volume of air required for complete combustion of 1 kg of fuel, nm^3/kg;
D_0 – diffusion coefficient, m^2/h;
T_{av} – the average temperature of the medium in K,

$$T_{av} = \frac{T_1 - T_2}{ln\frac{T_1}{T_0}} \tag{2}$$

where T_1 – temperature of the external surface of the burning powder;

T_0 - temperature of the surrounding air.

The formula shows that the time of complete combustion is proportional to the square of the particle size and inversely proportional to the temperature.

The actual combustion time can be obtained from the Nusselt combustion time by correcting for the excess air factor:

$$\tau_\alpha = \tau_0 f(\alpha) \tag{3}$$

The actual time of complete combustion decreases with increasing α. Nusselt's formula is not quite accurate due to a number of simplifications (dust is spherical, the law of heat transfer for a stationary medium is applied, etc.). Nusselt's formula is theoretical, not verified by experience. Nusselt considered the process of combustion of a single particle and took into account only diffusion without taking into account the kinetics of the process. He assumed that combustion occurs only on the surface of the particle. Blinov proved that combustion takes place also in the pores of the fuel.

In addition, Nusselt assumed that combustion occurs by a complete reaction in CO_2. Here there is diffusive combustion, in which, as it is known, CO formation takes place (Leithner, 2005: 137).

Another formula was proposed by Blinov:

$$\tau_0 = A r_0^{1.6} - B r_0 \tag{4}$$

$$A = \frac{\beta\gamma}{C_0}\frac{1}{1.07\, W_0^{0.4} D_0^{0.6}};\ B = \frac{\beta\gamma}{C_0 k}$$

where β is the amount of oxygen consumed per unit weight of carbon;

r_0 - initial radius of the particle;

γ - specific weight of carbon in g/cm^3;

C_0 - initial concentration of oxygen in gases in kg/m^3;

W_0 - gas velocity in cm/s;

D_0 - diffusion coefficient in m^2/h;

k_1 - reaction rate constant, strongly increasing with increasing temperature.

It is determined by the Arrhenius formula:

$$k_1 = k_0 e^{-\frac{\varepsilon}{RT}}, \tag{5}$$

where e = 2.7183 is the base of the natural logarithm;

ε - activation energy kcal/g*mol;

T is the absolute temperature in K;

R is the universal gas constant in kcal/g*mol.

The Blinov formula takes into account the velocity of gases. In addition to the diffusion coefficient, the reaction rate constant is also taken into account.

Blinov's formula is verified experimentally and does not have the simplifications made in Nusselt's formula.

In deriving the formula, Blinov assumed that combustion occurs simultaneously in CO_2 and CO, i.e., he used the complex theory of combustion.

The dust combustion rate depends on the excess air ratio and the grinding fineness. The operating experience has shown that the best results are obtained at α = 1.2 - 1.25.

The combustion rate of coal dust in the furnace chamber is not constant, because at the beginning of the combustion of small fractions this rate is maximum, and after that the combustion process slows down. Thus, at coarse grinding the combustion process is slow and the flame is stretched. This leads to an increase in the temperature of the first rows of tubes, which causes their slagging. Figure 2 shows a graph of coal dust burnout of different grinding fineness by time.

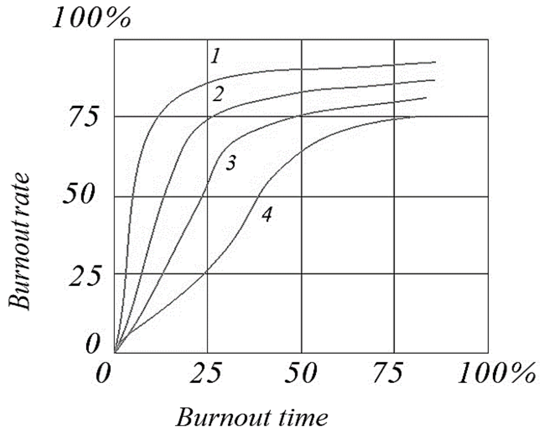

Figure 2 - Variation of particle burn-up fraction
curve 1 – R_{88} = 5 %, curve 2 – R_{88} = 15 %, curve 3 – R_{88} = 25 %, curve 4 – R_{88} = 35 %

The graph shows that most of the particles burn out quickly. The remaining small part of larger particles burns out during the rest of the time.

Consequently, in order to ensure good combustion of not a large number of the largest particles, it is necessary to increase the length of the flame, for example, by increasing the volume of the furnace or by adopting a smaller volume of the furnace, deliberately go to incomplete combustion of large particles, i.e. increase the loss q_4.

Depending on the boiler load, the values of fuel particle burnout are characterised by the curves in the graph Figure 3. The character of the curves shows that the percentage of burnout at the first metres of the flame length grows faster than at the last metres. The percentage of dust burnout at high boiler loads is less than at low loads. This is explained by the increase in gas velocities with increasing load, and, consequently, by the decrease in the residence time of dust particles in the furnace.

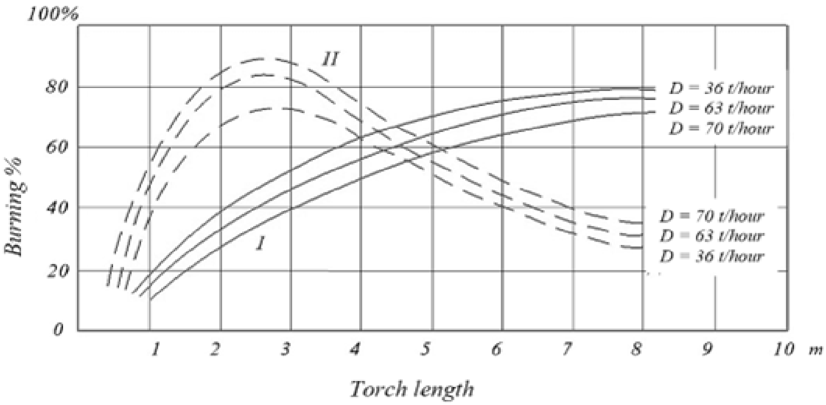

Figure 3 - Graph of fuel particle burnout along the flare length
I – particle burn-up curves along the flame length, II – temperature variation along the length of the plume

The temperature in the furnace increases with increasing boiler load. The increase of gas temperature at the first metres of the flame length is due to the fact that the heat input due to fuel combustion is greater than its consumption.

The process of dust combustion can be characterised not only by the particle burning rate and temperature change curves, but also by the change of gas composition along the length of the flame (Figure 4). The curve of oxygen content along the length of the flame decreases all the time. Only at the end of the furnace the curve goes almost horizontally and even rises a little due to air suction.

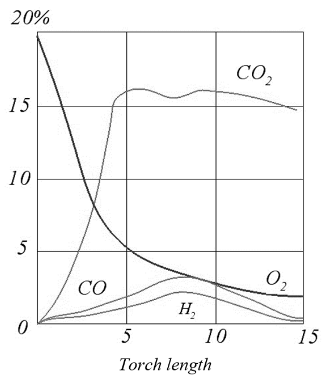

Figure 4 - Variation of gas composition along the length of the flare

The curve of CO_2 content at the beginning sharply increases, and at the end it also begins to decrease due to air suction. In the middle part of the curve there is a saddle in the active combustion zone. Lack of oxygen causes a partial conversion of CO_2 to CO. The saddle of the CO_2 curve corresponds to the maximum of the CO and H_2 curve.

In modern powerful boilers, the combustion process is designed in such a way that the CO and H_2 content at the furnace outlet is zero.

At modern thermal power plants, solid fuel is preliminarily crushed and blown into the furnace chamber in the form of dust mixed with air, where it burns in a suspended state in the gas flow. To transform large pieces of wet fuel into dry coal dust suitable for combustion, solid fuel is subjected to the preparation process in the dust preparation system, which consists in preliminary coarse crushing into pieces of several tens of millimetres, drying and further grinding to dust-like state with particle size of several tens or hundreds of micrometres.

By converting lump fuel into coal dust, a multiple increase in the response surface is achieved. Thus, if a piece of coal with a diameter of 15 mm is crushed into particles of 50 microns, the total surface area of the obtained particles will be 300 times larger than that of the original particle. The increase in the response surface significantly improves combustion conditions, since fuel combustion is a heterogeneous process (fuel and oxidant are in different aggregate states - solid and gaseous, respectively) occurring on the surface of fuel particles (Smorodin, et al, 2018: 112).

The main advantages of combustion of solid fuels in the pulverised state are the following:

− possibility of combustion with sufficiently high efficiency of any fuel, including low-reactive anthracites, as well as high-moisture and high-ash coals and coal preparation waste;

− practically unrestricted by the conditions of fuel combustion unit output of the boiler;

− full mechanisation of the furnace process, ease of regulation, possibility of full automation of the furnace process;

− absence of moving parts in the furnace, which increases the operational reliability of the unit.

The disadvantages of combustion of fuels in a pulverised state are:

− complexity, cumbersomeness and in most cases high cost of dust preparation equipment;

− significant power consumption for dust preparation, for example, for anthracite it is 25...30 kWh/t;

− low (0.1...0.3 MW/m^3) volumetric densities of heat release in the furnace at solid fuel flaring, which is explained by low mass concentration of fuel in the unit volume of the furnace (20...30 g/m^3), as well as by unfavourable conditions of oxidant supply to the reaction surface and removal of combustion products due to low relative velocity of burning particles in the gas-air flow.

Results. On the basis of the analysis of the process of combustion of fuel components in boiler units, for combustion of pulverised fuels (coals) a small-sized unit, made in the form of a thermo-instrument, allowing to create a high-speed and high-temperature flame of combustion, has been developed (Povetkin, et al, 2022: 4). The task of the development is to create a device that allows igniting the air mixture with minimum specific energy consumption. This increases the reliability of pulverised coal fuel ignition and stability of its subsequent combustion due to the use of increasing the power of the burner flame and full utilization of its energy characteristics.

As an actuating device for ignition of fuel aerosmixture a small-size rocket burner built into a resonance chamber with supersonic gas stream of high speed and temperature is used. In this case, the combustion process of fuel components (air-hydrocarbon fuel) is carried out in the formed, in the supersonic flow of the gas jet of the thermal tool (Bukayeva et al., 2020: 45). The solution of the problem is achieved by the fact that excite compaction jumps along the formed jet of the burner torch after its introduction into a special nozzle, the inner diameter of the nozzle hole is slightly larger than the diameter of the critical cross-section of the Laval nozzle of the burner, and made perforated for atmospheric air ejection.

Implementation of this method is conditioned by the use of a new design device consisting of a flame-jet burner with a Laval nozzle and a cylindrical nozzle coaxial to the nozzle with two rows of ejection windows at its outlet. The ejection windows of the first row are designed to excite a powerful stationary compaction jump (shock wave) at the beginning of the main section of the main supersonic jet of the burner, in which the fuel is afterburning, supplied in excess from the combustion chamber 7 through the Laval nozzle 8. This makes it possible to increase the flare power using high-speed combustion in the stationary jump of the nozzle compaction, i.e. increase the energy characteristics of the flare. Such introduction of the new flare to the operating mode allows to obtain a high-power flare with a more complete utilisation of its energy characteristics without using bulky compressor equipment and large-sized burners. The second perforation cascade is designed to create an underlying layer of ejected atmospheric air for cooling the nozzle outlet nozzle.

The technical result of the useful model is the increase of burner torch power due to more complete combustion of fuel components in compaction jumps (shock waves) and, as a consequence, the increase of fuel mixture ignition efficiency due to high temperature of the burner torch and its high acoustic power of the gas flow in the formed acoustic field, allowing to intensify the combustion processes of fuel aero mixture. There are no solutions identified in the prior art having features coinciding with the distinctive features of the utility model. Therefore, it can be stated that the proposed technical solution fulfils the condition of inventive step.

Figure 5 shows a longitudinal section of a supersonic pulverised fuel ignition device.

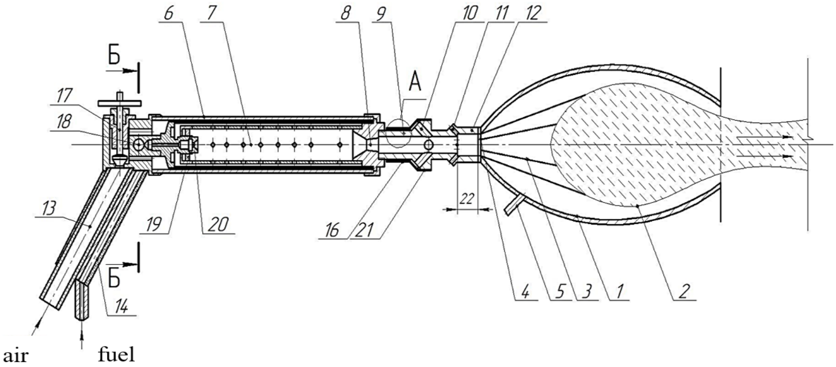

Figure 5 - Supersonic device for pulverised coal fuel ignition

The proposed supersonic device for ignition of pulverised coal fuel contains a body 1, a cylindrical resonance chamber 2, a zone of combustion of fuel components 3, an entrance to the resonance chamber 4 and a fuel line 5, a supersonic thermoinjector 6 having a combustion chamber 7 with a Laval nozzle 8, behind the Laval nozzle an elongated cylindrical nozzle 9 is made, located coaxially with the Laval nozzle 8, in which ejection windows 10 are made, at an angle to the axis of the nozzle.

The end of the nozzle 9 is made with a slightly larger diameter and has ejection windows 11 for sucking in the ejected outside air going to cool the outlet nozzle 12.

The burner device 6 is equipped with lines for supplying fuel components - air 13, fuel 14, control valves 17, 18 and swirler 19 for supplying swirled air flow into the combustion chamber 7, nozzle 20 for supplying fuel and its atomisation.

Also for cooling the surface of the nozzle 9, in the area of development of the centre of combustion of fuel components, the latter is provided with a removable protective casing 21 and formed between the outer surface of the nozzle 9 and the casing 21 gap 15, annular channel 16, through which the ejected external air is sucked, the oxygen of which goes to maintain combustion in the jump seal, and the gap 15 is made larger than the total area of the ejected windows, providing, due to the speed of the incoming cooling air through the guaranteed gap 15 and cooling of the surface of the nozzle 9.

The combustion chamber 7, Laval nozzle 8 and nozzle 9 are made of heat-resistant steel, supersonic device for ignition of pulverised coal fuel 5 is made parallel to the longitudinal axis of the resonance chamber 2, the fuel line 5 is introduced into the latter, the longitudinal axis of which is directed at an angle to the longitudinal axis of the resonance chamber 2.

The operation of the supersonic thermal tool device for ignition of pulverised coal fuel is carried out as follows. Prepared pulverised coal fuel is fed into the resonance chamber 2 through the fuel pipeline 5 to the combustion zone 3, simultaneously, fuel components (air, solar oil) are fed into the combustion chamber 7 of the thermal tool 6 through the pipeline 12,13, and further, through the swirler 19, nozzles 20, their mixing and ignition from the electric candle (not shown in the figure) takes place, and their combustion takes place on the whole space in the combustion chamber 7 of the thermal tool 6. Then the flame of the combustible mixture from the combustion chamber 7 moves through the Laval nozzle 8 and nozzle 9 into the resonance chamber 2, into the combustion region of the fuel components.

The torch from a supersonic burner - thermo-tool has high aerodynamic and thermal properties, the velocity of the torch flow is of the order of 2 km/s, and its temperature and acoustic parameters, respectively, are - 2000^{0}C and more than 120 dB of sound pressure or power level.

As a result, intensive mixing of fuel particles takes place in the resonance chamber, and this is facilitated by a powerful acoustic field in which fuel particles interact during their combustion, i.e. due to the rotation of elementary fuel particles and exposure of their new free surfaces, there is an intensification of their combustion, with the release of the maximum amount of heat into the boiler space. Superimposition of a powerful acoustic field generated by the nozzle apparatus 8 of the thermal tools 6 on the combustion zone of the fuel components coming from the fuel line 5, makes it possible to additionally increase the parameters of the combustion process and, in general, to increase the productivity of the boiler unit process.

The process of formation of the torch of the thermal tool 6 and its feeding through the Laval nozzle 8 into the combustion zone 3 occurs through a complex design of the nozzle apparatus, in which the heat flow of glowing gases formed in the combustion chamber 7, supersonic thermal tool 6, from the combustion of the incoming fuel components of the fuel and oxidant (air) through the lines 13,14 and nozzle apparatus 20 for fine atomisation of the fuel and air swirler 19, enters the combustion chamber 7.

The high-speed gas flow from the combustion chamber 7, transformed in the nozzle apparatus - Laval nozzle 8 into a supersonic flow, speed (about 2 km/s) and temperature more than 2000^{0}C, enters a special design of the nozzle 9, having a passage diameter slightly larger than the output diameter of the Laval nozzle, as well as ejection windows 10, 11 of the nozzle for feeding cold atmospheric air into the supersonic gas flow and formation of a standing detonation shock wave initiated by roughness of the inner surface of the nozzle aperture formed by drilling of ejection windows 10,11 in which the unburned fuel components are afterburning with high - more than 100 m/s combustion velocity, acquiring higher gas velocity flows of 2.5 km/s and temperatures of more than 2000^{0}C. In this case, the high-speed, high-temperature torch of the burner 6 interacts with the pulverised coal air mixture, ignites it, and the acoustic field intensifies this combustion process.

As a result of combustion of a part of coal the whole aero mixture is ignited, release of combustible elements from coal and partial gasification of coke sludge take place. At the outlet from the resonance chamber 1 a fuel mixture with temperature over 700°C and content of combustible substances in the gas phase up to 40% is obtained. Such a mixture burns steadily, which allows its use for various technological processes, for example, for ignition of pulverised coal aero mixture when creating a more powerful pulverised coal flame (Vockrodt et al., 1999: 95). Application of the proposed utility model allows to ignite pulverised coal fuel with minimum specific energy consumption. It increases reliability of pulverised coal fuel ignition and stability of its subsequent combustion.

At development of boilers of large capacity, it is possible to increase the flow characteristics of supersonic thermal tool, with a slight change of design parameters of thermal tool (diameter of combustion chamber, Laval nozzle and nozzle passage diameter).

Discussion. The results of the study show that the use of supersonic thermal tools provides more efficient ignition of pulverized coal aerosol mixture compared to traditional burner devices. Analysis of the thermotechnical parameters showed that the high flare temperature (about 2000 ° C) and supersonic flow rate (up to 2-2.5 km/s) contribute to the intensification of heat and mass exchange processes. This allows us to achieve a reduction in the time for complete burnup of coal particles by 20-30% while maintaining the stability of the process.

A comparative analysis of specific energy costs shows that the proposed design reduces energy consumption for fuel ignition by 15-20% due to the optimal distribution of heat flux and acoustic activation of the mixture. The use of a resonance chamber and ejection windows ensures uniform mixing of dust with the oxidizer, which reduces the likelihood of formation of incomplete combustion zones and reduces the risk of slagging of pipes by 10-12%.

An important advantage is the scalability of the thermal tool: changing the diameter of the combustion chamber and Laval nozzle allows you to adapt the design for boilers of different capacities without a significant increase in operating costs. This makes the technology applicable in modern thermal power plants and industrial boilers of high productivity.

Thus, the analysis confirms that the introduction of supersonic thermal tools increases the efficiency of boiler units, increasing the overall efficiency by 2-3% due to more complete combustion of fuel and reduced heat loss.

Conclusion. The processes of mixing of fuel components are considered. At the diffuse combustion principle fuel and air are fed into the furnace separately. The flare combustion process is characterised by continuous movement of fuel particles together with the gas-air flow.

It is established that at air temperature of 900^0C ignition for all fuels is almost immediate.

It is established that in powerful boilers the combustion process is characterised by the fact that the CO and H_2 content at the furnace outlet is zero.

A device for ignition of fuel aerosmash, made in the form of a small-sized rocket burner, which allows, with minimum specific energy consumption, to ignite aerosmash, is developed. Due to the use of increased power of the burner torch and full utilisation of its energy characteristics, the reliability of pulverised coal fuel ignition and stability of its subsequent combustion are increased.

Superimposition of a powerful acoustic field generated by the nozzle apparatus of the thermal tools on the combustion zone of fuel components makes it possible to increase the parameters of the combustion process of boiler units.

References

Babii V.I., Kuvaev Yu.F., Kuvaev Yu.F. (1986) Gorenie ugol'noi pyli i raschet pyleugol'nogo fakela [Coal dust burning and pulverized coal flare calculation]. Moscow: Energoatomizdat. — P. 208. (in Russian).

Bejarano P.A., & Levendis Y. (2008) Single-coal-particle combustion in O_2/N_2 and O_2/CO_2 environments. *Combustion and Flame. — 153* (1-2). — P. 270-287. https://doi.org/10.1016/j.combustflame.2007.10.022 (in English).

Boiko E.A. (2005) Kotel'nye ustanovki i parogeneratory (uchebnoe posobie) [Boiler plants and steam generators (training manual)]. Krasnoyarsk. 292 p. (in Russian).

Bukayeva A.Z., Povetkin V.V., Bektibay B., Nurymov Ye.K., Yermekov D.K. (2020) Intensification of combustion fuel mixture in petrolair thermal tools with ejector nozzle. NEWS of the National Academy of Sciences of the Republic of Kazakhstan Series of geology and technical sciences. — Vol. 3. Number 441. — P. 40-47. https://doi.org/10.32014/2020.2518-170X.52 (in English).

Smorodin S.N., Ivanov A.N., Belousov V.N. (2018) Kotel'nye ustanovki i parogeneratory (uchebnoe posobie) [Boiler plants and steam generators (training manual)]. Saint Petersburg. — P. 185. (in Russian).

Doroshchuk V.E., Ruban V.B. (1979) Kotel'nye i turbinnye ustanovki energoblokov moshchnost'yu 500 i 800 MVt. Sozdanie i osvoenie [Boiler and turbine units of power units with a capacity of 500 and 800 MW. Creation and development]. Moscow: Energiya. — P. 680. (in Russian).

Hunt T., Muzio L., Smith R., Hanley T.J. (1995) Integrating low-NOx burners, overfire air, and selective non-catalytic reduction on a utility coal-fired boiler. Environmental Progress. — Vol. 14, No. 2. — P. 115-120 (in English).

Khatami R., Stivers C., Joshi K., Levendis Y., & Sarofim A. F. (2012). Combustion behavior of single particles from three different coal ranks and from sugar cane bagasse in O_2/N_2 and O_2/CO_2 atmospheres. Combustion and Flame. — 159(3). — P. 1253-1271. https://doi.org/10.1016/j.combustflame.2011.09.009 (in English).

Kuang M., Li Zh., Jing X., Zeng X. et al. (2013) Characterization of combustion and NOx emissions with respect to overfire air damper opening in a down-fired pulverized-coal furnace. Energy Fuels. — Vol. 27, No. 9. — P. 5518-5526 (in English).

Leithner R., Müller H. (2003) CFD studies for boilers. Second M.I.T. Conf. on Computational Fluid and Solid Mechanics. Cambridge. — P. 172. (in English).

Leithner R. (2006) Numerical simulation. Computational fluid dynamics CFD: Course of lecture. Braunschweig. — P. 52 (in English).

Leithner R. (2005) Energy conversion processes with intrinsic CO_2 separation. Transactions of the Society for Mining, Metallurgy and Exploration. — Vol. 18. — P. 135-145 (in English).

Povetkin V.V., Bukaeva A.Z. Patent na poleznuyu model' RK №7640. Sverkhzvukovoe ustroistvo dlya vosplameneniya pyleugol'nogo topliva [Supersonic device for ignition of pulverized coal fuel]. Opubl. 02.12.2022. byul. №48. — P. 6. (in Russian).

Reznyakov A.B., Basina I.P., Bukhman S.V., Vdovenko M.I. i dr. (1968) Gorenie natural'nogo tverdogo topliva [Combustion of natural solid fuels]. Alma-Ata: Nauka. — P. 410. (in Russian).

Ustimenko B.P., Aliyarov B.K., Abubakirov E.K. (1982) Ognevoe modelirovanie pyleugol'nykh topok [Fire modeling of pulverized coal furnaces]. Alma-Ata: Nauka. — P. 212. (in Russian).

Vockrodt S., Leithner R., Schiller A., et al. (1999) Firing technique measures for increased efficiency and minimization of toxic emissions in Kasakh coal firing. 19th German Conf. on Flames, Germany. — Vol. 1492. — P. 93-97 (in English).

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