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INVESTIGATION OF THE INFLUENCE OF THE BURNER DIAMETER-TO-EXIT VELOCITY RATIO ON COMBUSTION PARAMETERS IN THE SB-39 STEAM BOILER

Abstract. The article examines the design features and operating principles of the SB-39 steam boiler, designed for burning Ekibastuz coal with a calorific value of 17.5 MJ/kg. Special attention is given to the characteristics of the burners, gas flow parameters, combustion processes, and the impact of these factors on the boiler's efficiency. An analysis of the temperature profile and gas composition of the furnace gases is conducted, considering the specific properties of the coal fuel. The study addresses fuel burnout and improving combustion efficiency by optimizing boiler operating modes. The obtained results can be used for equipment modernization, enhancing the performance parameters of steam boilers, and reducing harmful emissions. Additionally, recommendations are provided for improving the design of burners and airflow distribution systems to achieve more complete fuel combustion and reduce slagging on furnace walls.

Keywords. Burner, expiration rate, burner diameter, Ekibastuz coal, fuel burnout, combustion efficiency.

Introduction.

Ekibastuz coals are widely used as an energy fuel at thermal power plants in Northern and Southern Kazakhstan. The use of coal as a fuel for energy production and, to some extent, as a technological raw material will continue for at least the coming decades, given the enormous volume of proven reserves. Currently, about 35% of the world's electricity is generated at coal-fired thermal power plants.

The attractiveness of coal as a primary energy source is due to several factors. The relatively low cost of thermal energy per unit and the well-developed technology for its combustion at thermal power plants make it an economically viable option. Another advantage of coal is the relative simplicity of storing it in large volumes. Additionally, coal consumption can be increased almost instantly, whereas for natural gas combustion, depending on the distance of its storage facility, the supply delay can take several hours, and in some countries, up to 10 hours.

However, coal combustion is also associated with several negative factors. The most significant drawbacks of coal as a fuel include its environmental impact, which involves the storage of ash and slag waste. The potential for slagging on furnace surfaces largely depends on the organization of the combustion process and typically occurs when operating parameters deviate from recommended values. Coal also requires pre-processing before combustion, including crushing and grinding. Furthermore, the presence of sulfur in the fuel leads to the formation of sulfur dioxide (SO_2) and sulfur trioxide (SO_3) during combustion, which, in the presence of moisture, can form sulfurous and sulfuric acids, causing corrosion in boiler metals, internal combustion engines, building structures, and other materials.

The SB-39 steam boiler was designed and built at the PMZ in 1961. It is designed to work on coals from the Ekibastuz field, the heat of combustion of which is 17.5 MJ/kg (4165 kcal/kg). Figure 1 shows the longitudinal section of a steam boiler**.**

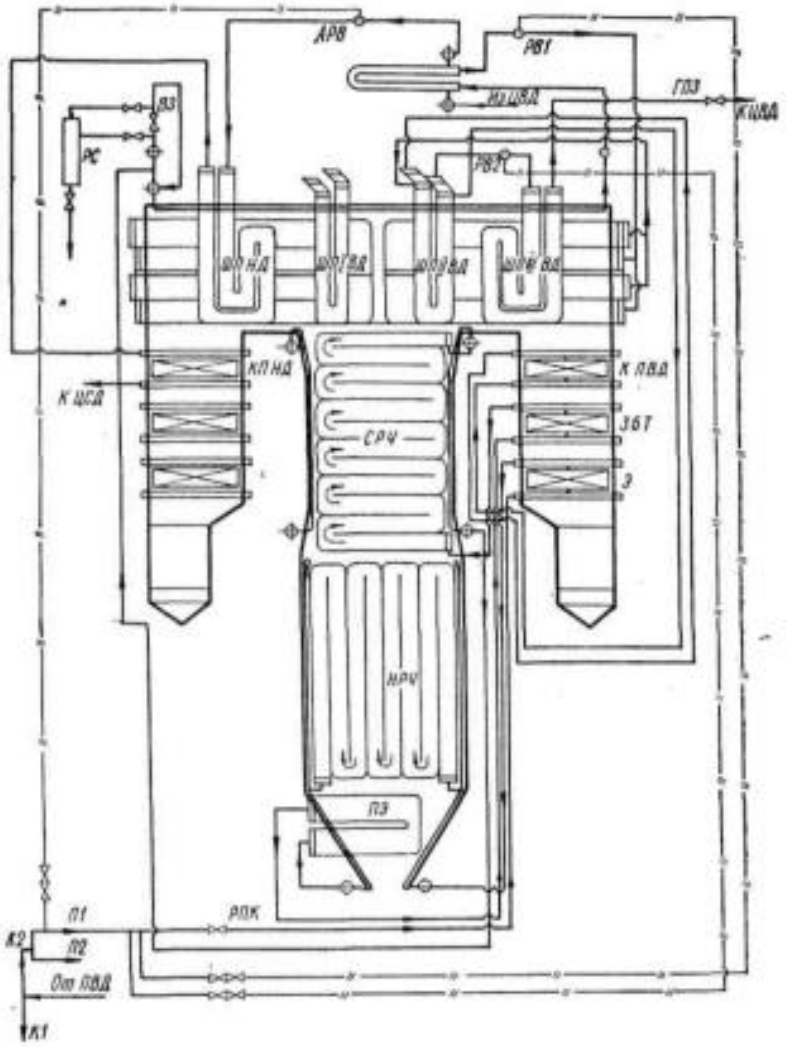

Figure 1 - Longitudinal section of the steam boiler SB-39 [1]

Outside the thermal power plant building, four air preheaters are installed, heating the air up to 350 °C. The boiler's steam-water circuit consists of four independently regulated flows, two in each housing. Water from the feedwater heater passes through the economizer and enters the vertical, single-pass, upward-flowing panels of the low-pressure evaporator, which are sequentially connected by unheated down comer tubes. The medium-pressure evaporator also consists of vertical single-pass panels with upward water flow. From the SPP, water is supplied to the intermediate platen superheaters, then passes through the primary steam reheater and enters the final platen superheaters, from where the steam moves to the high-pressure reheater, which consists of the ceiling screen and the turning chamber screens. The turning chamber is shielded with horizontal U-shaped panels.

The secondary steam reheating path consists of the and two sequentially connected packages of low-pressure convective reheaters. The regulation of the primary steam overheating temperature is carried out by maintaining a specific water-fuel ratio and two injection regulators, located before the inlet to the final platen superheaters and before the high-pressure convective reheater. The temperature of the secondary steam overheating is regulated by an external PPTO installed above the steam boiler. An emergency spray-type steam cooler is placed between the KPND panels. [1, p. 28]

Through swirl burners, the pulverized coal-air mixture and secondary air are supplied to the furnace in the form of swirling jets. Swirl burners are classified into three types:

a) Double-spiral burners with spiral swirlers for both the pulverized coal-air mixture and secondary air;

b) Spiral-blade burners with spiral swirlers for the pulverized coal-air mixture and an axial blade swirler for the secondary air;

c) Straight-flow spiral burners with a straight-flow channel for the pulverized coal-air mixture, featuring a diffuser at the outlet and a spiral swirler for the secondary air.

The structure of the pulverized coal-air mixture jets emerging from the swirl burner openings largely depends on the type and design of their swirling devices [2].

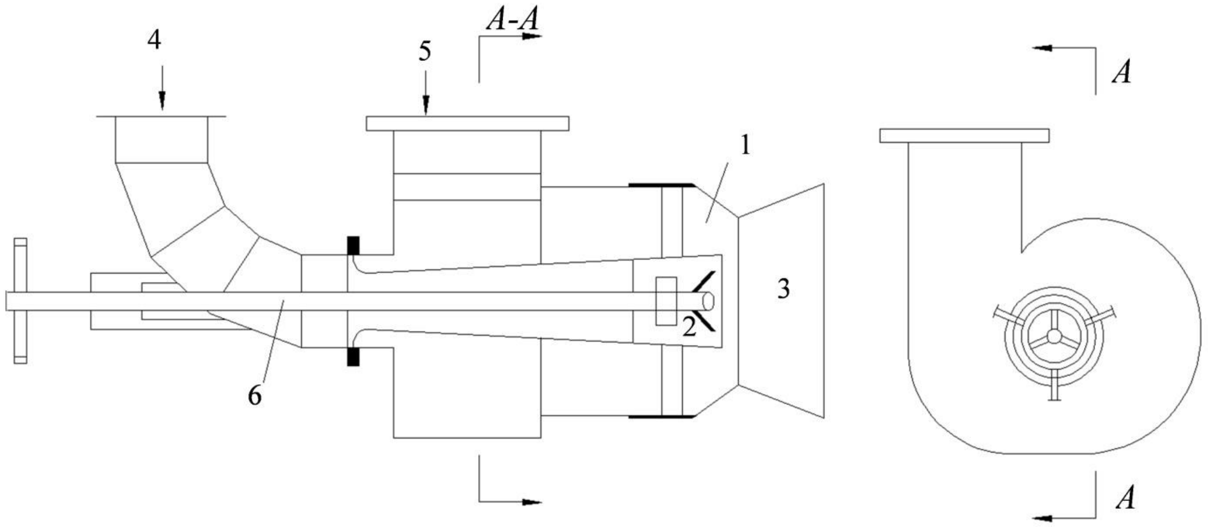

Figure 2 - Straight-flow spiral burner [2]

The study was conducted on the PK-39 boiler under various combustion modes and air-fuel flow ratios. Experimental studies on the influence of the burner diameter-to-exit velocity ratio were carried out using Ekibastuz coal with an ash content of Ar = 40-45%. The experimental parameters are presented in Table 1.

The first series of experiments was conducted using SB-39 burner models. To ensure identical thermal conditions during tests with a smaller-scale model, based on the Mw~1 methodology, a combustion chamber with an inner diameter of 0.9 m was installed in the furnace test stand (Fig. 2.). The chamber consists of two connected cylindrical water-cooled caissons with a total length of 1.2 m. The inner surface of the chamber is studded and coated with refractory mortar.

The second series of experiments was conducted using BKZ burner models. Temperature profiles, gas composition, and fuel burnout levels were recorded for burner models at various distances from the burner mouth. The experimental results showed that the temperature fields, gas composition, and fuel burnout levels had qualitatively similar distributions, characteristic of vortex-type pulverized coal burners.

Table 1 - Experimental Operating Parameters

№	Parameter Name	Boiler Burner	Model №1	Model №2	Model №3	Model №4
1.	2.	3.	4.	5.	6.	7.
Fuel Characteristics						
1.	Ash Content	40	44-45	44-45	40-41	39-41
2.	Moisture Content	6,6	1	1	1	1
3.	Fuel Calorific Value	$1{,}6\cdot10^4$	$1{,}6\cdot10^4$	$1{,}6\cdot10^4$	$1{,}8\cdot10^4$	$1{,}8\cdot10^4$
4.	Fineness of Grinding	15/2	15/0,2	15/0,2	15/0,2	15/0,2
5.	Theoretical Air Requirement	4,15	4,16	4,16	4,35	4,25
Operating Mode Characteristics						
	Fuel Flow Rate	20	0,075	0,08	0,04	0,068
	Thermal Intensity of Cross-section	$2{,}2\cdot10^6$	$6{,}1\cdot10^6$	$6{,}4\cdot10^6$	$11{,}3\cdot10^6$	$5{,}7\cdot10^6$
	Primary Air Velocity	20	6	20	21	7
	Secondary Air Velocity	25	8	26	25	7
	Air-Fuel Mixture Temperature	140	100	130	100	100
	Secondary Air Temperature	310	320	320	320	340
	Theoretical Combustion Temperature	1950	1970	1970	2060	2080
	Swirl Parameter of Air-Fuel Mixture	1,1	1,1	1,46	1,13	1,68
	Swirl Parameter of Secondary Air	1,8	1,8	1,88	1,7	1,86
	Burner Swirl Parameter	1,28	1,24	1,26	1,2	1,46
	Excess Air Ratio at Furnace Exit	1,2	1,2	1,15	1,25	1,2
Similarity Criteria						
1.	Reynolds Number for Gas Flow at Burner Exit	$5{,}87\cdot10^5$	$0{,}6\cdot10^5$	$1{,}2\cdot10^5$	$7{,}8\cdot10^5$	$5{,}8\cdot10^5$
2.	Stokes Criterion for Particles	6,8	6,4	37	58,2	11,3
3.	Ratio of Burner Diameter to Exit Velocity	0,06	0,06	0,012	0,007	0,036
4.	Arrhenius Criterion for Volatile Release from Particles	0,0108	0,0108	0,0108	0,0108	0,0108
5.	Fourier Diffusion Criterion for Volatile Release from Particles	1,3	1,3	0,24	0,15	0,78
6.	Fourier Diffusion Criterion for Particles	3800	3800	709	443	2279
7.	Arrhenius Criterion	$7{,}1\cdot10^{-5}$	$7{,}1\cdot10^{-5}$	$7{,}1\cdot10^{-5}$	$7{,}1\cdot10^{-5}$	$7{,}1\cdot10^{-5}$
8.	Biot Criterion for Particles	0,0016	0,0016	0,0016	0,0016	0,0016
9.	Primary Air Share	0,26	0,21	0,21	0,23	0,21
10.	Relative Dust Concentration	1	1	1	1	1
11.	Degree of Restriction	0,106	0,076	0,028	0,036	0,02

In the initial sections of the flame, larger gradients of temperature, gas composition, and fuel burnout degree are observed. In the main flow region, the temperature, CO_2 concentration, and fuel burnout degree have lower values, whereas in the peripheral and near-axis zones, these values are higher. As the distance from the burner outlet increases, the profiles of temperature, gas composition, and unburned fuel become more uniform, the temperature and CO_2 concentration rise, while the O_2 concentration and unburned fuel decrease. At a distance of x = 2–3 burner diameters, the profiles are mostly leveled, indicating the stabilization of the combustion process, and the flame temperature reaches its maximum. Further along the flame, the temperature gradually decreases.

It is of interest to compare the data on the flame of the full-scale PK-39 burner and its fire model. The average temperature in the flame cross-sections was calculated considering velocity fields obtained during isothermal purging. This introduces certain errors into the calculation results; however, for a qualitative characterization of the process, it is quite acceptable.

To track the dynamics of the combustion process development, we will construct the variation of the integral characteristics of the flame along the furnace length. Available experimental data obtained from full-scale boilers indicate that the velocity profiles in the swirling flame at a distance of x = 2–3 burner diameters from the burner outlet are mostly leveled. This simplifies the task of determining integral characteristics. Starting from these distances, the integral values of temperature and unburned fuel were determined using the following formula.

$$T = \frac{\sum T_i F_i}{\sum F_i} \tag{1}$$

$$q_{ун} = \frac{\sum \mu_i q_{унi} F_i}{\sum \mu_i F_i} \;, \tag{2}$$

where T_i is the temperature value, μ_i is the concentration and unburned fuel fraction for the i-th cross-sectional area of the furnace, and F_i is the area of the i-th section.

The concentration of coal dust was determined using the following formula:

$$\mu_i = \frac{\delta_i}{F_{отс} V_{отс} \tau_i} \;, \tag{3}$$

where δ_i is the sample weight (g), F_{ots} is the area of the probe intake opening (m^2), V_{ots} is the suction velocity (m/s), and τ_i is the sampling time (s).

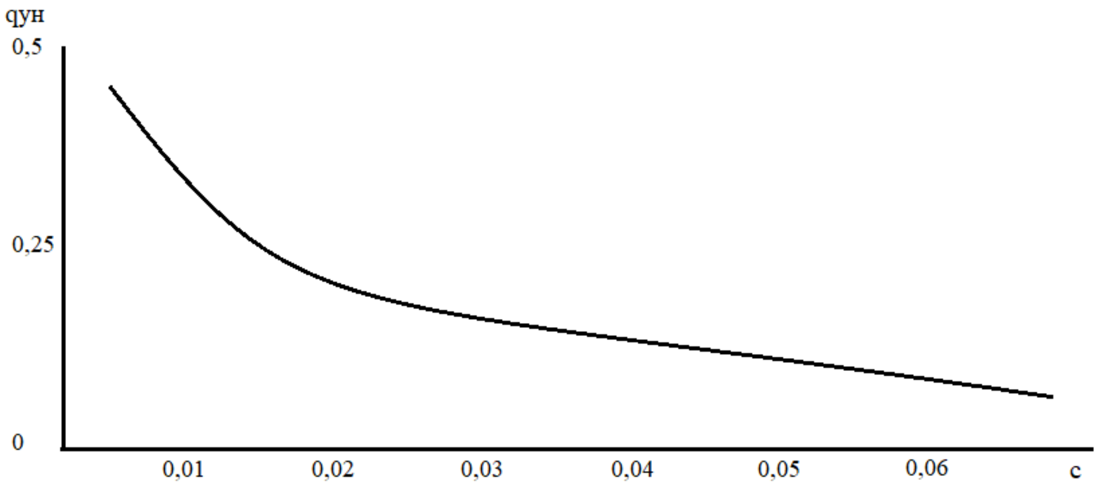

Figure 3 - Dependence of unburned fuel in the flame of burner models in the section x ≈ 3 on the ratio D_a/W_0

In Fig. 1, the integral values of unburned fuel at a distance of $x \approx 3$ calibers (the end of the horizontal section of the full-scale burner) are presented for various values of the D_a/W_0 ratio. As seen, there is a dependence between the degree of fuel burnout at $x \approx 3$ calibers and the value of D_a/W_0.

Thus, the degree of fuel burnout at the end of the initial section of the flame, measured in relative terms, is influenced by the difference in the residence time of coal particles in this section.

Because the ignition of a swirling pulverized coal flame does not depend on the D_a/W_0 ratio, the increase in unburned fuel at the end of the initial section with a decrease in D_a/W_0 can be explained as follows.

Assume that flame ignition occurs at a distance of $x \approx 0.5$ caliber. Then, the time required for the flame to travel the remaining 2.5 calibers will depend on the exit velocity and burner diameter.

a) Increasing the velocity while keeping the diameter constant will reduce residence time and increase unburned fuel.

b) Increasing the burner diameter while maintaining a constant velocity will increase residence time and reduce unburned fuel.

Starting from $D_a/W_0 > 0.03$ sec and beyond, the influence of this ratio on unburned fuel at the end of the initial section becomes insignificant within the investigated range for burner models.

The same Fig. 1 also presents data for full-scale burners. It is evident that the unburned fuel levels for the full-scale SB-39 boiler burner at $x \approx 3$ calibers are slightly higher than those of the burner models at identical D_a/W_0 values. This can be attributed to a slight delay in the ignition of the outermost burner. If ignition were more synchronized, the results would match more closely.

The proposed modeling methodology for studying swirling pulverized coal burners on combustion test stands considers:

1) The approximate similarity conditions of the initial flame section.

2) The specific operating conditions of the full-scale furnace where the burner is intended to be used.

This justifies the practical significance of such research.

The economic efficiency of applying this methodology, by reducing the volume and duration of full-scale burner testing in a 475 t/h boiler, is estimated as follows: Labor savings – 2,000 man-hours, Electricity savings – 45×10^6 kWh, Metal savings – 40 tons.

Results.

The study results demonstrated that changing the burner diameter-to-exit velocity ratio significantly influences the combustion process of Ekibastuz coal with an ash content of A_r = 40–45%.

Optimized parameters helped reduce NO_x emissions and minimize slagging on the furnace walls.

Experiments on the SB-39 boiler confirmed the efficiency of the selected operating modes, ensuring stable combustion under various loads.

Additionally, it was found that adjusting secondary airflows improves combustion characteristics and reduces unburned carbon in the ash.

List of Abbreviations

RVP – Regenerative Air Heater
RPK – Regulating Feed Valve

NRCh – Lower Radiant Section
SRCh – Middle Radiant Section
PPTO – Gas-Steam Heat Exchanger
KPND – Convective Low-Pressure Superheater
KPVD – Convective High-Pressure Superheater
BKZ - Block Boiler Factory

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ПК-39 БУ ҚАЗАНДЫҒЫНДА ЖАНУ ПАРАМЕТРЛЕРІНЕ ЖАНАРҒЫ ДИАМЕТРІНІҢ ШЫҒУ ЖЫЛДАМДЫҒЫНА ҚАТЫНАСЫНЫҢ ӘСЕРІН ЗЕРТТЕУ

Аңдатпа. Мақалада 17,5 МДж/кг жылу шығару қабілеті бар Екібастұз көмірін жағуға арналған ПК-39 бу қазандығының құрылымдық ерекшеліктері мен жұмыс істеу принциптері қарастырылады. Жағу сапасына әсер ететін негізгі факторлар – жанарғының сипаттамалары, газ ағынының параметрлері және жану процестері талданады. Отынның жану деңгейін, температуралық профильді және түтін газдарының құрамын зерттеу жүргізілді. Жану тиімділігін арттыру үшін қазандықтың жұмыс режимдерін оңтайландыру жолдары қарастырылды. Алынған нәтижелер жабдықты жаңғырту, бу қазандықтарының жұмыс параметрлерін жақсарту және зиянды шығарындыларды азайту үшін пайдаланылуы мүмкін. Сондай-ақ, отынның толық жануын қамтамасыз ету және пеш қабырғаларындағы шлактың түзілуін азайту үшін оттықтар мен ауа ағынын тарату жүйелерін жетілдіруге арналған ұсыныстар берілді.

Түйінді сөздер. Жанарғы, шығу жылдамдығы, жанарғы диаметрі, Екібастұз көмірі, отынның жануы, жану тиімділігі.

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ СООТНОШЕНИЯ ДИАМЕТРА ГОРЕЛКИ К СКОРОСТИ ИСТЕЧЕНИЯ НА ПАРАМЕТРЫ ГОРЕНИЯ В ПАРОВОМ КОТЛЕ ПК-39

Аннотация. В статье рассматриваются конструктивные особенности и принципы работы парового котла ПК-39, предназначенного для сжигания Экибастузского угля с теплотворной способностью 17,5 МДж/кг. Анализируются основные факторы, влияющие на качество сгорания, включая характеристики горелок, параметры газового потока и процессы горения. Проведено исследование уровня выгорания топлива, температурного профиля и состава дымовых газов. Рассмотрены пути оптимизации режимов работы котла для повышения эффективности сгорания. Полученные результаты могут быть использованы для модернизации оборудования, улучшения рабочих параметров паровых котлов и снижения вредных выбросов. Кроме того, даны рекомендации по совершенствованию конструкции горелок и системы распределения воздушных потоков с целью обеспечения более полного сгорания топлива и уменьшения ошлакования на стенках топки.

Ключевые слова. Горелка, скорость истечения, диаметр горелки, Экибастузский уголь, выгорание топлива, эффективность сгорания.

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