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Oleksandr Povazhnyi, Volodymyr Kukhar, Oleksiy Koyfman,
Khrystyna Malii, Volodymyr Pashynskyi

CHAPTER 5

IMPROVING CONDITION MONITORING AND MAINTENANCE FRAMEWORK FOR REFRACTORY LININGS IN INDUCTION MELTING FURNACES THROUGH CONTINUOUS IMPROVEMENT METHODS

ABSTRACT

The aim of the work is to develop a technology for co-firing of coal and biomass, which will allow to reduce emissions of CO_2, SO_2, NO_x, dust, as well as to diversify fuel sources for CHPs within the framework of ensuring compliance with standards for reducing pollutant emissions and solving problems with coal supply to power plants, and improving coal ignition conditions in furnaces.

The article reviews biomass combustion and gasification technologies and their application for co-firing of pulverized coal with biomass, and the possibility of using them in TPP boilers in Ukraine. The co-firing of pulverized bituminous coal and varied biomass was experimentally investigated. A zone-by-zone thermal calculation of the boiler unit was performed when feeding biomass with coal. Using ANSYS FLUENT, the co-firing of coal with biomass was calculated for the selected solution of the biomass feeding system to the boiler furnace. Recommendations are provided for the application of co-firing of bituminous coal and varied biomass at TPPs in Ukraine.

KEYWORDS

TPP, coal, biofuels, biomass, co-firing.

Co-firing of biomass with coal began in Europe and North America in the late 1990s. It has been proven to be a relatively rapid and cost-effective way to partially decarbonize coal-fired electricity generation in the short to medium term. Co-firing in coal-fired power plants can contribute to the achievement of the UN Sustainable Development Goals in Ukraine, such as Goal 7 "Affordable and Clean Energy" (by 2030, substantially increase the share of renewable energy in the global energy mix, strengthen international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil fuel technologies), and Goal 13 "Climate Change" (integrate climate change measures into national policies, strategies and planning) [1]. Co-firing with biomass also helps extend the life of coal-fired power plants during the transition to other low-carbon types of generation. Although most of Western Europe is gradually abandoning coal-fired power generation, which will reduce the opportunities for co-firing of biomass, coal remains an important fuel for electricity generation in Asia and Eastern Europe [2]. Co-firing activity is growing in these regions, so work on developing co-firing technologies is ongoing.

During the period of martial law, the earliest possible resumption of coal-fired TPPs became particularly important to ensure energy independence, supply heat and electricity to the population and, if possible, with simultaneous low-cost modernization with improved economic and environmental performance and given their small capacity compared to TPPs.

The authors fully support the global goal of the "green transition", enshrined in the legislation of Ukraine and the world by numerous legislative acts. But it should be noted that, as is already understood in most countries of the world and noted in reviews by the most authoritative global energy organization, the IEA [2], the world energy sector still faces a fairly long transition period of 20–30 years, when heat and electricity will be produced from both fossil and renewable fuels [3].

Despite the fact that many countries are abandoning fossil fuels, in 2023 global coal consumption reached a staggering 164 exajoules (EJ) of energy, which is a record for any year. Coal provides 26% of global energy in 2023, more than all non-fossil fuel sources combined. The only energy source that made a greater contribution to the global energy balance was oil.

Here is how this consumption is distributed by region (**Table 5.1**).

Table 5.1 Coal consumption in different regions of the world (2023)

Region	Consumption (EJ)	Part, %
China	91.9	56.1
Asia Pacific (excluding China)	43.8	26.7
Americas	10.0	6.1
Europe	8.4	5.1
CIS	5.5	3.4
Africa	4.1	2.5
Middle East	0.4	0.2
Total	164.0	100

Source: [3]

Coal consumption has declined in many regions. For example, both North America and Europe reduced their coal energy consumption by 16% in 2023. However, the heavy reliance on coal in the Asia-Pacific region has meant that global coal consumption has remained largely unchanged over the past 10 years. In 2023, China increased its coal consumption from 88 EJ to almost 92 EJ, accounting for 56% of global coal consumption. This has largely contributed to Asia-Pacific becoming the global leader with a staggering 83% of global coal consumption.

Easy access to existing infrastructure and reasonable prices has not only supported global coal consumption over the past 10 years, but has also paved the way for potential growth. Many developing countries are currently expanding their coal consumption.

For example, according to the Statistical Review of World Energy 2024, Bangladesh and Colombia experienced double-digit percentage increases in coal consumption from 2022 to 2023, compared to the previous year: 41% and 53%, respectively.

Coal continues to play a major role in the global energy mix, especially in developing countries, where its availability makes it the preferred energy source for them at present.

Coal-biomass co-firing technologies have been actively developing for over two decades as a partial replacement for fossil fuels in line with global trends. At the beginning of the 21st century, this technology was widely used in both Europe and North America [4]. For example, in 2015, the Netherlands built a showcase power plant for energy conservation and deep reduction of CO_2 emissions, as well as CO_2 capture, consisting of a 1,100 MW supercritical unit + biomass combustion + closed water supply installation. The biomass utilization rate is 30%, and the plant efficiency is over 47%. Compared to the Netherlands, Finland built the world's largest circulating fluidized bed boiler with a capacity of 550 MW. Biomass, such as coal, sludge, wood, forest waste, etc., can be burned in any ratio in circulating fluidized bed boilers. As an example, the United Kingdom is the country with the largest use of biomass combustion technology, with an installed biomass combustion capacity of 25.336 GW by 2018 [5].

Today, due to the energy policy of these regions of complete abandonment of fossil fuels, co-firing of biomass with coal (CFBC) is undergoing a replacement stage at existing TPPs burning biomass or waste (DRAX TPP – Great Britain [6], AMAGER TPP – Denmark [7]), but has found its second life in the countries of the Asia-Pacific region.

Thus, China is a large agricultural country with large biomass resources and great potential for the development and utilization of biomass energy, for which CFBC is a promising choice [8]. Utilization of agricultural waste in existing coal-fired power plants is an attractive option to reduce environmental pollution and reduce the overexploitation of fossil fuels [9]. Thanks to domestic measures to encourage and support the development of renewable energy, investment in biomass power generation is rapidly increasing, and the construction of various projects for power generation from agricultural and forestry waste has already begun. China's biomass power generation technology industry shows an overall trend of accelerated development [10]. In the first three quarters of 2019, biomass power generation in China added 3.35 million kW of installed capacity, and the total installed capacity was 21.16 million kW, an increase of 15.4% over the previous year. The installed capacity of biomass power generation was 80.4 billion kWh, an increase of 19.4% over the previous year [11]. By 2020, the installed capacity of coal-fired power plants in China will reach 1.1 billion kW. If 50% of biomass can be used for power generation in coal-fired power plants, the total capacity of coal-biomass power units can reach 550 million kW. Based on an average blending rate of 10%, the installed capacity of biomass power plants can reach 5.5 MW. If 50% of biomass is used for power generation in China every year, the amount of electricity that can be generated is about 720 billion kWh, which translates into an installed capacity of about 180 million kW, accounting for 12% of the national electricity generation in 2016 [12]. Large-capacity coal-fired power plants and high-efficiency coal-fired power plants are switching to co-firing of coal and biomass, which is expected to be the main carbon reduction measure at this stage in China.

Co-firing technology and efficiency are constantly developing in Indonesia to reduce coal consumption. Researchers in this technology focus on the behavior of biomass as the most complex fuel in the coal-biomass pair [13]. The type of biomass and the composition of the mixture used determine the efficiency of the boiler. The conditions of pre-mixing of biomass and coal are critical factors [14]. Biomass with high moisture content, low calorific value and poor grindability must be considered [15]. As a result, optimizing the quality of biomass is crucial to achieve high combustion efficiency.

As an example, the Indonesian PLN energy campaign. Co-firing was introduced as one of the strategic initiatives under the Green Booster program to accelerate the achievement of the 23% renewable energy target by 2025 by using existing power plant infrastructure and waste management solutions. The total capacity of PLN Group's co-firing steam power plants is 18.9 GW [13]. Co-firing activities have been carried out at several PLN Group CFPP facilities since 2020 using various boiler types, namely: PC, CCS, etc. The types of biomass used include sawdust (30.8%), palm shell (21.2%), wood chips (15.4%), wood pellets (11.5%), rice husk (7.7%), coconut shell, OPEFB, solid renewable fuel (SRF) pellets, water hyacinth and corn cobs (3.8%).

It is recommended to improve fuel quality by hydrothermal treatment (HTT) to reduce the impact of biomass ash on such characteristics as alkalinity, high water content, and low calorific value. According to studies by Praevia and Widayat, the HTT process can increase the calorific value of biomass from 7.86 MJ/kg to 22.22 MJ/kg, which is comparable to the calorific value of coal (22.34 MJ/kg) [16].

The first studies on the influence of the chemical composition of biomass on slagging and corrosion of heating surfaces of existing boilers during the CFBC of domestic biomass and coal from Ukrainian deposits were initiated in Ukraine by the Thermal Energy Technology Institute of the National Academy of Sciences of Ukraine (TETI NASU) [17–19]. Therefore, the use of foreign experience in CFBC and the introduction of this technology into the energy sector of Ukraine, especially in the war and post-war period, seems to the authors to be quite appropriate and economically justified.

Coal-fired TPPs in Ukraine are usually located either within or near settlements. Therefore, they are always subject to stricter emission requirements. Given the wear and tear of TPP equipment and the service life, as well as the significant costs of installing gas cleaning systems, it is not possible to expect their widespread installation of cleaning plants in the near future.

In addition, given the updated Energy Strategy of Ukraine for the period until 2050 [20], one of the urgent tasks of the Ukrainian energy sector is the need to increase the production of heat and electricity from renewable energy sources and reduce emissions of harmful substances and greenhouse gases from large combustion plants in accordance with Ukraine's commitment within the framework of the European Energy Community. Since biomass is CO_2-neutral and contains almost no sulfur and ash, it is an ideal fuel for generating energy without polluting the environment. In addition, replacing part of the coal with biomass leads to a significant reduction in the sulfur dioxide emission fee. Today, the emission of one ton of SO_2 costs about 58,5 USD. Adding, for example, 10% of biomass (in terms of heat) for a 300 MW power unit will reduce the sulfur dioxide emission fee by more than 93,600 USD per year.

5.1 COAL AND SOLID BIOFUEL CO-FIRING TECHNOLOGIES

5.1.1 EXISTING BIOMASS AND COAL CO-FIRING TECHNOLOGIES

Currently, there are three main technological schemes for co-firing of biomass and coal: direct, indirect and parallel combustion. The choice of the scheme depends on the design features of the boiler units, the ash composition [21] and the ratio of biomass in co-firing [22, 23].

For these schemes, **Fig. 5.1** shows the methods of co-firing of biomass at coal-fired TPPs and summarizes the main technical options for these configurations.

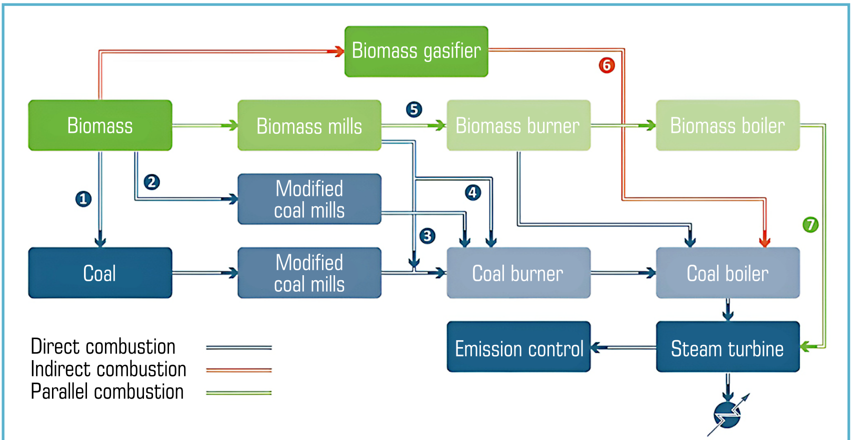


Fig. 5.1 Variants of biomass co-firing at power plants: direct, indirect and parallel combustion
Source: [24]

In direct combustion, coal and biomass are combusted in the same boiler. The biomass is premixed with the coal in the existing coal handling and transportation system, at moderate co-firing ratios (typically less than 10% biomass in terms of energy), then co-combusted and combusted in the existing coal combustion system (Option 1 in **Fig. 5.1**). This is the most popular approach to co-firing, as it can be implemented relatively quickly with minimal capital investment and minimal modifications. The main investment is the biomass storage and handling system. In Option 2, the biomass is comminuted in a separate, modified existing coal mill and combusted with the coal in the existing coal combustion system. The biomass can be comminuted in a new dedicated mill to increase the co-firing ratio; up to 50% in terms of energy can be achieved.

There are then several ways to co-combust biomass. In Option 3, biomass is injected into a pipe that feeds coal to the burner. In Option 4, biomass is injected into modified coal burners. In Option 5, biomass is injected into a new dedicated biomass burner. These options involve much higher capital investment levels than Options 1 and 2. In indirect co-firing (Option 6), biomass is gasified in a separate gasifier, and the fuel gas is combusted with coal in the same coal fired boiler. Parallel (Option 7) combustion has separate boilers for coal and biomass, which are powered by a single turbine. This scheme allows the largest ratio of biomass to be used, and biomass types with high alkali and chlorine content can be burned [25].

Both indirect and parallel combustion allow for compositions with high biomass content and have greater fuel flexibility [24].

In the paper [26], co-firing technologies were summarized depending on the fuel: grate furnaces, fluidized bed furnaces (combustion in a fluidized bed or in boilers with a bubbling fluidized bed, or in boilers with a circulating fluidized bed) and pulverized coal combustion furnaces (**Table 5.2**).

Co-firing, depending on the technology (furnace type), has its advantages and disadvantages.

Table 5.2 Co-firing technologies in the corresponding furnaces. Advantages and disadvantages

Furnace Type	Advantages	Disadvantages
1	**2**	**3**
Grates	– low investment costs for plants <20 MW and low operating costs; – almost any wood can be used; – suitable for biomass fuels with high moisture content (10–60%wt); – suitable for fuels with high ash content and different particle sizes (with a limitation on the number of fine particles)	– mixtures of wood fuels can be used, but combinations of fuels with different combustion characteristics and ash melting points (e.g. mixtures of wood and straw) are sometimes difficult to operate; – increased temperatures can cause ash melting and corrosion
Fluidized bed modifications	– wide range of fuels in terms of calorific value, moisture content and ash content, which allows fuel diversification and increasing the number of fuel types in existing power plants; – low combustion temperature in the bed, resulting in low NOx emissions; – provides the possibility of direct injection of limestone for sulfur removal, which is cost-effective (instead of flue gas desulfurization equipment);	– despite the wide range of fuels, it is not always possible to use the existing biomass supply system by fuel pre-mixing (the cheapest option); – where the characteristics of the co-fired fuel differ too much from those of the primary fuel, a separate feeder must be installed; – slag formation and deposits on boiler walls and tubes when burning fuels with a high alkali content;

Continuation of Table 5.2

1	2	3
	– maximum combustion efficiency even with low-grade fuels; – environmental performance of FB plants with low CO, NOx emissions and high boiler efficiency (approx. 90%); – fluidized bed technologies allow fuel conversion from coal to biomass/coal co-firing with relatively low investment	– agglomeration of the bed when burning fuels with a high alkali content; – Cl-corrosion on heat exchange surfaces (e.g. superheater tubes); – high investment costs; – low flexibility in particle size selection, high dust level in flue gases, loss of bed material with ash
Pulverized combustion	– increased efficiency due to low excess oxygen, high NOx reduction possible when using appropriate burners	– biomass particle size limited to $<$10–20 mm; – low moisture content required for pneumatic feeding and reduced efficiency for fuels with high moisture content

5.1.2 CURRENT BIOMASS RESEARCH

Recent research and development [27] focuses mainly on pretreatment technologies used to improve the physicochemical properties of biomass and its energy density.

The most common pretreatment technologies include washing and leaching, liquefaction, steam explosion, and densification and pelletization. Typically, pretreatment technologies are interconnected, and the final product, biomass pellets, often undergoes several processing stages. Special attention is paid to the treatment of agricultural waste. China began co-firing these materials in 2017 to reduce air pollution from unregulated waste burning. India is also interested in co-firing agricultural waste for the same reason. Thus, much of the current research is focused on the co-firing of agricultural waste, especially straw.

Research on the pre-treatment of biomass for co-firing is beyond the scope of this article, so let's limit ourselves to a brief comment.

Torrefaction and pelletization are commercialized, and these processes are often combined in production. Pellets from peat biomass are widely available worldwide. While open air weathering of biomass is common practice, leaching treatment is only done on a pilot scale. The steam explosion biomass preparation technology is currently in the industrial demonstration stage (April 2020) with the support of the EU Horizon 2020 program [28]. Wet torrefaction is still in the laboratory research stage.

When choosing a biomass pretreatment method, the most important aspect to consider is the overall energy efficiency. Although the higher energy density of pretreated biomass means lower storage and transportation costs, energy is also consumed during processing (in particular, during grinding, loosening and compaction). However, pretreatment is necessary to overcome the problems inherent in biomass combustion.

The high costs of pelletization can be justified by the improved operability of the fuel (treatment, transportation, storage and feeding), which leads to improved boiler operation and combustion efficiency. Processed biomass has a higher energy density than raw biomass, making it suitable for long-distance transportation. While pretreatment and upgrading of biomass makes it easier to handle and improves combustion efficiency, the energy density of biomass remains lower than that of coal. In the future, research should be conducted on the evaluation of the entire process from an economic point of view, as this will invariably affect the practical implementation of biomass pretreatment on an industrial scale.

A brief summary of the experience [29], accumulated worldwide as a result of the commercial operation of co-firing at TPPs, allows to draw the following conclusions:

1) co-firing of biomass with coal, brown coal and peat in traditional steam boilers provides a unique opportunity, combining the utilization of renewable energy sources and fossil fuels, to obtain the greatest benefit from both types of fuel;

2) adding biomass to the fuel balance allows to significantly reduce carbon dioxide emissions, reduce emissions of other pollutants into the soil and air. When co-firing biomass in pulverized-coal fired boilers, up to 10% of the coal burned in the boiler can be easily replaced with minor equipment changes, which is extremely important, given Ukraine's limited ability to invest in equipment modernization;

3) in fluidized bed plants, significantly higher biomass share can usually be achieved with co-firing, along with extremely mild requirements for coal quality and crushed biomass size.

The issue of using biomass as a second fuel for Ukraine, especially now, is becoming very relevant. Replacing at least part of the coal with biomass during the period of urgent restoration of damaged generating capacities of coal-fired TPPs is one of the ways to solve the problem of shortage of fuel and energy resources, the possibility of using existing equipment of TPPs to improve the environmental performance of combustion, the involvement of renewable sources in the energy balance of the country, given the economic indicators of the implementation of direct co-firing technology in fuel boilers of various capacities can be considered the most acceptable.

TETI NASU has been developing technologies for co-firing of biomass and anthracite since 2007, when, during cooperation with the Pittsburgh Coal Energy Technology Center (PETC) of the US Department of Energy (within the framework of the NATO Science for Peace and Security program, its foundation was laid). In the course of work to calculate the combustion process, the optimal operating parameters, synergistic effects of the mutual influence of two different solid fuels and their kinetic characteristics were determined [30, 31].

From the beginning, the goal of these studies was to determine the optimal ratio between biomass and anthracite for more complete combustion of both types of fuel during a certain time of residence in the fuel of an anthracite fired boiler unit; rational mode parameters of such combustion; characteristics of a wide range of domestic biomass (pine sawdust, pulp, wheat straw pellets, rapeseed, etc.) for calculating the process of co-firing of biomass and coal. The influence of biomass impurities on the efficiency of coal combustion was studied [24] and calculation methods [32, 33] and combustion of the mixture.

In 2008, the institute conducted experiments on a pilot plant, which simulated the processes occurring in the lower radiation part of the fuel boiler and at the outlet of the burner embrasure, in order to confirm the possibility of replacing the supporting gas with biomass with a high content of volatile substances, which ensures the stability of the torch in the process of burning high-ash, low-reactivity anthracite, as well as to identify the mode and cost features of the process of co-burning anthracite and biomass (sawdust and pine chips – waste from woodworking production). Further, these works were developed, with the removal, for known reasons, of anthracite from the fuel base of TPP, with the involvement of bituminous coal and various types of domestic biomass in the research.

5.2 EXPERIMENTAL STUDY OF JOINT PULVERIZED COMBUSTION OF BITUMINOUS COAL AND BIOMASS

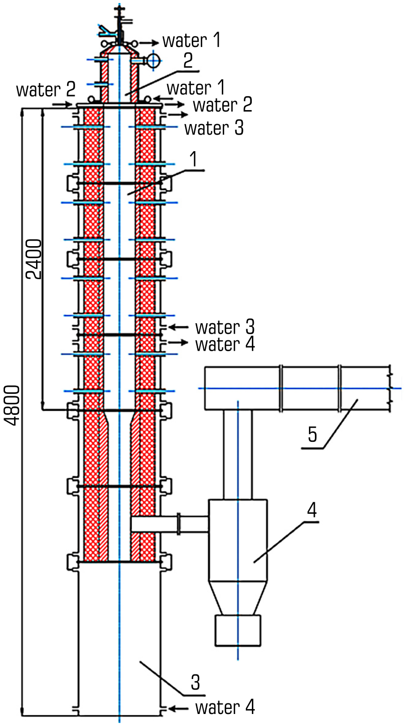
To select the optimal biomass/coal ratio for heat, it is necessary to carry out joint combustion of coal and biomass under conditions close to those in fuel boilers. The installation of the TETI NASU allows for the combustion of two solid fuels simultaneously with a flow rate of up to 30 kg/h. The temperature level in the installation can reach 1700°C, while the flow rates of components, temperatures along the length and the composition of gases at the outlet of the installation are controlled.

The schematic diagram of a pilot installation with heat power in the coal combustion mode in unenriched air up to 100 kW [34] is presented in **Fig. 5.2**. It includes a vertical downflow reactor 1, a burner device 2, a slag collector 3, a rotary section with a cyclone 4, a cooling and afterburning chamber 5. The total length of the reactor is 4.8 m, the reactor section before turning into a cyclone is 3.2 m. The length of the diagnostic section from the output section of the burner device is 2.4 m.

The diagnostic section consists of 4 sections 0.6 m long, internal diameter 0.28 m. The water-cooled reactor walls are covered from the inside with a three-layer lining: the fire layer is zirconium dioxide, the heat-insulating layer is chamotte, the thermal compensation layer is asbestos fabric.

The burner device is a vertical water-cooled lined cylinder with an internal diameter of 0.2 m, a length of 0.5 m, installed through a water-cooled transition flange on the upper section of the reactor, equipped with two burners and operational and diagnostic windows. The main gas burner is installed at its end, designed for burning natural gas. In addition to air and natural gas, coal dust is supplied to it from the feeder. A natural gas channel is coaxially located, which ends with a short section with perforation for gas outlet. Coaxially with the gas is a channel for supplying air or a mixture of air and coal, which ends with a blade swirler to intensify the mixing of air with gas, and coal with gas combustion products.

The unit provides for the supply of natural gas, air (to the main and auxiliary burners, transporting air with coal and biomass, secondary air), biomass and coal dust.



1 – diagnostic section of the reactor;
2 – burner device;
3 – slag collector;
4 – cyclone;
5 – afterburning and cooling chamber

Fig. 5.2 Experimental unit

At a flow temperature of 1200–1250°C, the residence time of fuel particles was 0.75–0.8 s, which is close to the residence time of particles in the lower radiation part of pulverized-coal fired boilers. Previous studies [35] show that during this residence time, when burning high-ash anthracite dust, a degree of carbon conversion of X_c=0.6–0.8 is achieved, which also corresponds to the characteristics of pulverized-coal fired boilers [36].

In view of the conversion of TPP-210A boilers to bituminous coal, previously designed for burning anthracite, a series of experiments were conducted on the joint flare combustion of coal dust of the gas group with three types of solid biomass – pine pellets, wheat agropellets and sunflower husk pellets [32].

Pulverized-coal of standard TPP's grinding was chosen for combustion. Biomass was selected from 3 types in the form of pellets, which were previously crushed to an average size of 1.6 mm. The results of sieving samples of the biomass that was burned are given in **Table 5.3**.

Table 5.3 Sieving of biomass prepared for combustion

Fraction, mm	Pine, %	Sunflower husk pellets, %	Agropellets, %
>1.6	0.40	0.27	0.34
1–1.6	14.58	9.84	10.38
0.63–1	21.29	20.68	18.15
0.4–0.63	24.75	28.79	22.69
0.2–0.4	23.08	24.09	25.05
0.09–0.2	10.67	12.73	15.35
<0.09	5.22	3.59	8.02

As can be seen, the particle sizes of biomass of different types are approximately the same, and the main part of the particles have a size of <1.6 mm. Technical and elemental analysis of the studied fuels are given, respectively, in **Tables 5.4** and **5.5**.

Table 5.4 Proximate analysis of fuel samples

Sample name	Total moisture content on the working state of the fuel, W_t^r, %	Ash content on the dry state of the fuel A^d, %	Total sulfur on the dry state of the fuel S_t^d, %	Volatile substances yield V^{daf}, %	Ash fusibility, °C			Lower calorific value, Q_i^r	
					t_A	t_B	t_C	MJ/kg	kcal/kg
Wheat pellets	9.0	12.4	0.12	84.2	1130	1180	1350	14.4	3442
Pine pellets	6.8	0.8	–	86.1	1180	1200	1215	18.1	4318
Sunflower husk pellets	10.7	5.8	0.24	80.7	>1400	>1400	>1400	16.9	4054
Bituminous coal	1.3	23.5	2.44	43.1	1300	1321	1360	21.47	5124

A comparison of the obtained technical characteristics of biofuels with bituminous coal showed that:

1) the ash content of biofuels is significantly lower than the ash content of coal;

2) the sulfur content in biomass is 5–10 times lower than in coal, which significantly reduces the formation and emissions of SO_2, respectively, environmental pollution and emission fees for TPP are reduced;

3) the content of combustible volatile substances in biomass is approximately 2 times higher than in bituminous coal (V^{daf} > 80%), this helps the ignition of coal, but may require special measures at the preparation and transportation site;

4) the melting point of ash can vary in a wide range, which must be taken into account for each new batch of biofuel.

The experiments were conducted in three series, with each type of biomass, at different biomass/coal ratio. The compressor capabilities and the rarefaction in the installation determined fuel feeding. For comparison, only data from one experimental day were selected due to the maximum similarity of feeding parameters.

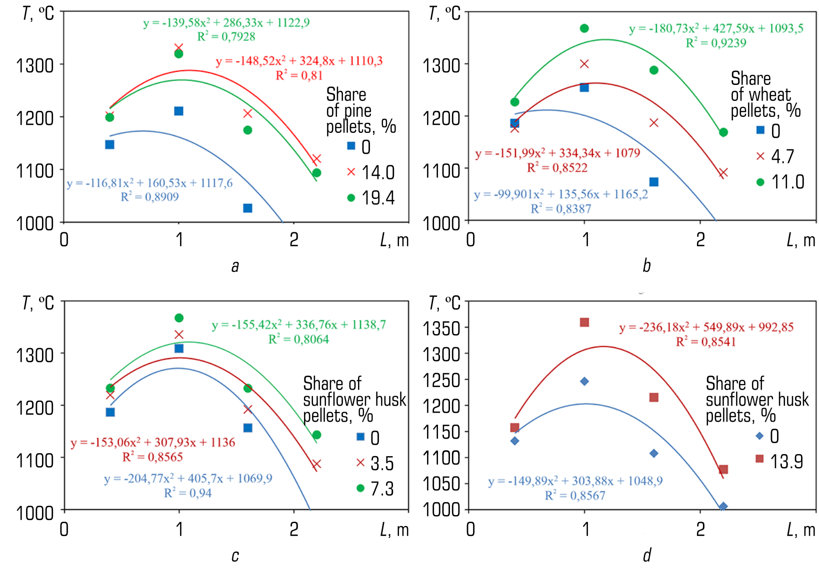
Table 5.5 Ultimate analysis of fuel samples of the combustible mass and chlorine content of fuel samples

Sample name	Chlorine on dry fuel, Cl^d, %	Elemental composition, %				
		C^{daf}	H^{daf}	O^{daf}	N^{daf}	S^{daf}
Wheat pellets	0.39	49.6	6.55	41.56	2.15	0.14
Pine pellets	0.10	52.93	6.64	37.67	2.76	–
Sunflower husk pellets	0.53	53.77	6.38	38.10	1.49	0.26
Bituminous coal	0.61	86.99	5.00	5.31	1.44	1.26

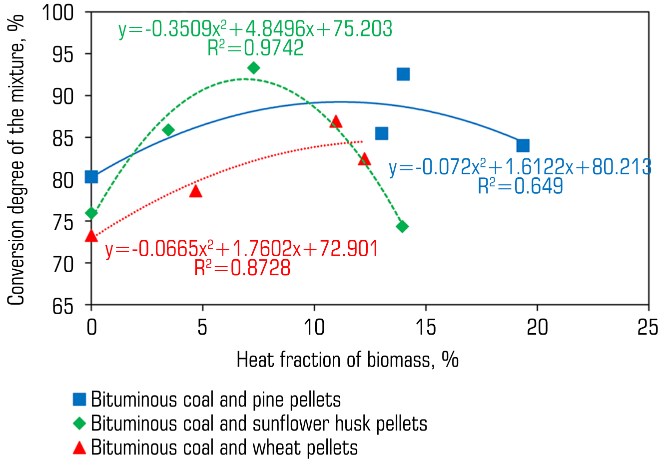
Bituminous coal contains more than 40% volatile substances, which ensures its stable combustion without the use of gas. At the same time, the addition of biomass, which has a lower calorific value, leads to an increase in the temperature in the reactor by 100–200°C, which indicates an intensification of ignition even of highly reactive coal. Temperature profiles along the length of the reactor depending on the biomass share are shown in **Fig. 5.3**.

After testing the mode on bituminous coal, a certain share of crushed pine pellets was fed into the plant, which has the highest calorific value of the studied biomass samples. The reaction of the reactor to the addition of biomass was almost the same – there was a temperature increase of 120°C in the 2nd section and a slightly larger increase in other sections (**Fig. 5.3, *a***). The maximum temperature is observed in the range of the biomass share in terms of heat from 7–8% to 14–15%.

During the testing of the above experimental modes, the degree of fuel burnout in general was monitored – an important indicator of the combustion process necessary to determine the optimal ratio of biomass in the mixture with coal. It was impossible to determine the degree of combustion of biomass and coal separately, although with different reactivity, the rate of combustion of coal and biomass is different. Therefore, the degree of fuel combustion characterized the combustion process as a whole. For this, the probe at the outlet of the installation sucked off the flue gases, from which solid particles were filtered. The average degree of conversion for the two fuels was calculated based on the ash content of the sample taken. The dependence of the degree of conversion of mixtures on the biomass content in the mixture with bituminous coal is shown in **Fig. 5.4**.



⬡ **Fig. 5.3** Temperatures in the reactor in the modes of co-firing of bituminous coal dust and crushed pellets: *a* – pine; *b* – wheat straw; *c* – sunflower husk; *d* – sunflower husk of the 2nd series



⬡ **Fig. 5.4** Conversion degree of a mixture of bituminous coal and different types of biomass depending on the share of biomass in the mixture

Calculations of the conversion degree demonstrate an improvement in the completeness of the mixture burnout when adding the smallest share of biomass (about 5%). With an increase in the share of biomass in the mixture, the burnout improved even more and reached a maximum value in the range of 8–14%. The presence of an extremum can be explained by a change in the balance of multidirectional effects. On the one hand, adding a small amount of a more highly reactive fuel that burns faster than coal improves the ignition conditions of the latter. At the same time, oxygen is consumed for the combustion of additional volatile biomass substances, which occurs at the root of the torch, which leads to a decrease in the concentration of the oxidant in its core. When adding only 5% of biomass, such a slight decrease does not slow down the burnout of coal particles. With an increase in the biomass share above 8–14%, the effect of oxygen deficiency begins to prevail over the positive effect of early ignition of coal, which causes a decrease in the degree of conversion of the mixture relative to the maximum value. Also, the decrease in the positive effect when adding biomass above 8–14% is affected by a decrease in the calorific value of the mixture. Due to the significantly lower calorific value of biomass, its further addition does not lead to an increase in the temperature in the torch core (**Fig. 5.3**).

The resulting effect of adding biomass on the formation of NO as a result of co-firing with coal was also assessed. An increase in the temperature in the core should lead to an increase in thermal nitrogen oxide emissions, and the low nitrogen content in biomass should reduce fuel nitrogen oxide emissions during co-firing. NO concentrations were recorded using gas analysis. The concentration of nitrogen oxide at the outlet of the installation depending on the biomass share is shown in **Fig. 5.5**.

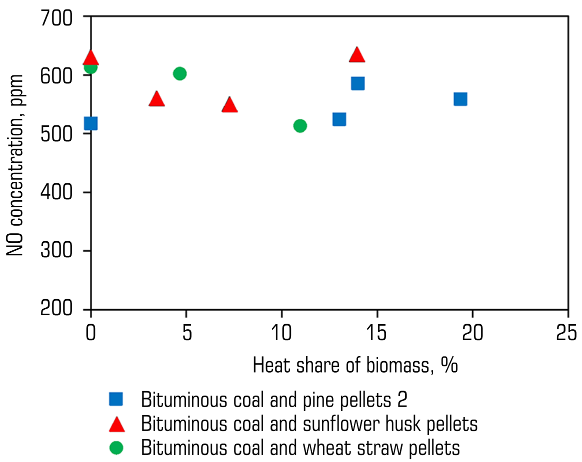


Fig. 5.5 Concentration of nitrogen oxide at the outlet depending on the biomass share

From the above, it can be assumed that the increase in the formation of thermal nitrogen oxides as a result of a local increase in temperature is compensated by a decrease in the output of fuel nitrogen oxides, which allows to assume a decrease in the total concentration of nitrogen oxides in the boiler unit exhaust gases.

BRIEF CONCLUSIONS

1. As a result of the conducted experimental studies, it was established that the addition of different types of biomass to bituminous coal leads to an increase in the temperature in the torch core by 100–200°C. As well as to the stabilization of the torch combustion, its shift towards the burner device, which in turn indicates an improvement in the conditions for coal ignition.

2. The obtained dependences of the completeness of the burnout of a mixture of different types of biomass with bituminous coal on the ratio of the two fuels demonstrate an improvement in the completeness of the burnout of the mixture with an increase in the share of biomass. The dependence has an extremum when adding 7–14% biomass in terms of heat.

3. It is shown that the increase in the formation of thermal nitrogen oxides as a result of a local increase in temperature is compensated by a decrease in the yield of fuel nitrogen oxides, which suggests a decrease in the total concentration of nitrogen oxides in the boiler unit exhaust gases.

5.3 VERIFICATION OF THE OBTAINED RESULTS BY PERFORMING ENGINEERING CALCULATIONS USING THE NORMATIVE METHOD

According to the practical focus of the development, it is necessary to verify the impact of co-firing of coal and biomass by means of verification calculations of the existing boiler unit on which it is proposed for implementation. The initial concept envisaged the implementation of co-firing on anthracite fired boiler units, where it is possible to obtain maximum synergy from co-firing. However, given the shortage of anthracite in Ukraine caused by hostilities, and in addition, the conversion of most anthracite fired boilers to burning bituminous coal, experimental and computational studies were extended to coal of a different degree of metamorphism, which is currently mined in Ukraine or imported from abroad.

Co-firing calculations were performed using the example of TP-87 boiler units of Kalush CHP (fuel – bituminous coal) according to the Normative method of thermal calculation of boiler units [37].

The conditions for the calculation are determined by the operation of the boiler on a mixture of 2 fuels. The ratio is made up by thermal load: 90% – bituminous coal, and 10% crushed wood pellets from pine, or pellets from straw, or pellets from sunflower husks.

TP-87 boilers with natural circulation are made in the traditional design. A distinctive feature of the boilers of its series is the absence of a two-light screen in the furnace, which divides the furnace in half, the presence of a constriction in the lower part of the furnace and the equipment of vortex-type burners.

The main parameters of the boiler are given in **Table 5.6**.

The furnace, unlike conventional prismatic chambers, has a constriction in the lower part, formed by the fuel pipes of the front and rear screens bent inward. Some of these pipes, approximately 50%, are curved according to the profile of the protrusion without forks, and the other part has forks in the lower and upper parts of the protrusions.

The depth of the constriction protrusions is 1890 mm on each side. The lower part of the furnace is a pre-furnace. The afterburning chamber is located above the constriction. Screen pipes ∅60 × 6, st. 20 with a constriction of 64 mm completely cover the front, rear and side walls of the furnace and, converging at the bottom, form a furnace with two inlets for removing liquid slag. The design and thermal parameters of the combustion chamber are presented in **Table 5.7**.

Table 5.6 Main parameters of the boiler operation

No.	Characteristics	Unit	Value
1	Nominal steam output	t/h	420
2	Working pressure in the steam separation chamber	MPa	14.0
3	Working pressure in the boiler drum	MPa	15.5
4	Temperature of superheated steam	°C	560
5	Feed water temperature	°C	230
6	Flue gas temperature	°C	120 (gas) 137(coal)
7	Hot air temperature	°C	400
8	Efficiency of the boiler unit at nominal load on the calculated fuel	%	92.6 (coal) 94.6 (gas)

Table 5.7 Furnace characteristics

No.	Characteristics	Unit	Whole furnace	Pre-furnace
1	Fuel dimensions in plan	mm	7552×14080	7552×14080
2	Calculated volume of the fuel chamber	m^3	2180	580
3	Temperature of gases at the fuel outlet	°C	1234	1785
4	Radiation heating surface	m^2	1235	411
5	Volumic heat flux	kW/m^3	149	578

Thermal calculations of boilers and zone-by-zone calculations of fuel chambers of TP-87 boiler units of Kalush CHP are performed in 4 variants:

– variant 1 – nominal boiler operation mode;
– variant 2 – operation with the addition of wood pellets;
– variant 3 – operation with the addition of sunflower husk pellets;
– variant 4 – operation with the addition of grain straw pellets.

The share of biomass addition – according to the results of the experiments presented in paragraph 2 – 10% of the total heat load of the boiler.

The task of the verification calculation of the combustion chamber is to determine the temperature of the gases at the outlet of the combustion chamber at the specified design dimensions. Also, within the framework of the calculation, it is necessary to confirm the conditions for the exit of liquid slag (characteristics of the burners and fuel chamber) and the absence of slagging of the screens.

A sketch of the combustion chamber is shown in **Fig. 5.6**.

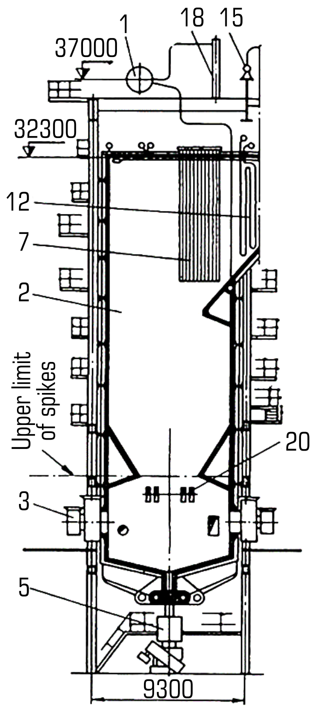


Fig. 5.6 Sketch of the furnace of the TP-87 boiler

The results obtained characterize the operating mode of the TP-87 boiler furnace when operating on bituminous coal and on a mixture of bituminous coal with the addition of 10% of pellets in the variants of using pine pellets (var. 2), sunflower husks (var. 3) and straw (var. 4). The temperature at the fuel outlet at the nominal load ensures reliable operation of the boiler. In the case of burning coal that is slagging, it is necessary to reduce the load and conduct an additional calculation to determine the boiler operating load, which will ensure a decrease in the temperature at the outlet of the furnace below 1100 °C.

In the conditions of the Kalush CHP, the boilers operate at 70–80% of the nominal load, which ensures a decrease in the temperature at the outlet of the furnace and, as a result, guarantees long-term operation of the CHP boilers without the risk of slagging of screens and superheaters.

To determine the detailed thermal characteristics of the furnace, let's perform its zone-by-zone calculation.

Fig. 5.7 shows the diagram of the TP-87 boiler furnace.

Table 5.8 presents the results of the zone-by-zone calculation of the boiler.

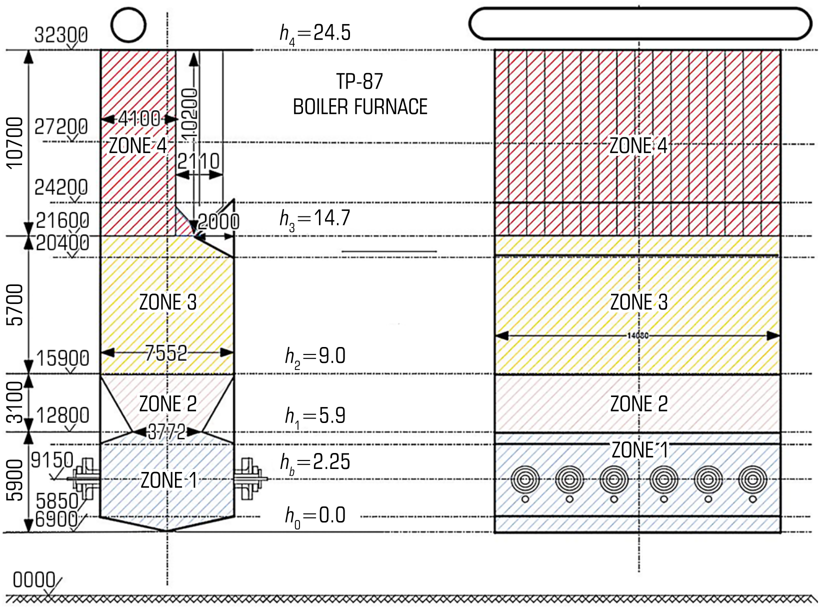


Fig. 5.7 Furnace diagram with zones

Table 5.8 Zone-by-zone calculation of the furnace

Value: Name	Value: Designation	Units of measurement	Variants: 1	2	3	4
Zone 1						
Zone relative height	$h_1/H_{furnace}$	–	0.323	0.323	0.323	0.323
Fuel burn-up rate at zone exit	β_{burn1}	–	0.955	0.955	0.955	0.955
Gas temperature at zone exit	ϑ_m''	°C	1609.95	1611.15	1606.08	1611.28
Average specific heat load of the radiation-receiving surface of the zone	q_{rrs}	kW/m^2	116.95	116.37	115.74	116.70
Zone 2						
Zone relative height	$h_2/H_{furnace}$	–	0.470	0.470	0.470	0.470
Fuel burn-up rate at zone exit	β_{burn2}	–	0.995	0.955	0.955	0.955
Gas temperature at zone exit	ϑ_m''	°C	1505.7	1508.5	1504.2	1501.4
Average specific heat load of the radiation-receiving surface of the zone	q_{rrs}	kW/m^2	250.16	245.15	244.53	242.13
Zone 3						
Zone relative height	$h_3/H_{furnace}$	–	0.7377	0.7377	0.7377	0.7377
Fuel burn-up rate at zone exit	β_{burn3}	–	0.995	0.995	0.995	0.995
Gas temperature at zone exit	ϑ_m''	°C	1277.4	1281.8	1278.7	1278.14
Average specific heat load of the radiation-receiving surface of the zone	q_{rrs}	kW/m^2	126.61	126.21	126.62	125.73
Zone 4						
Zone relative height	$h_4/H_{furnace}$	–	1	1	1	1
Fuel burn-up rate at zone exit	β_{burn4}	–	0.995	0.995	0.995	0.995
Gas temperature at zone exit	ϑ_m''	°C	1064	1075	1072	1073
Average specific heat load of the radiation-receiving surface of the zone	q_{rrs}	kW/m^2	61.62	62.51	62.90	62.54

It has been calculated that when the boiler is operating on a mixture of bituminous coal and solid biofuel:

– conditions for reliable operation of the furnace with a stable liquid slag mode without the risk of slagging of the screens are ensured;

– the temperature at the outlet of the furnace in all modes does not reach the level of the beginning of deformation of ash particles (t_A=1270–1300°C).

Based on the results of the calculations, the decision of the technical council of the Kalush CHP was approved, and it was recommended to use the obtained results for further implementation of the project.

5.4 CALCULATION OF CO-FIRING OF COAL WITH BIOMASS FOR SELECTED SCHEMATIC SOLUTIONS OF THE BIOMASS FEED SYSTEM TO THE BOILER FURNACE

To verify the process of co-firing of coal and biomass, three-dimensional calculations were performed using the example of the TP-87 boiler (Kalush TTP, Kalush, Ukraine).

5.4.1 INITIAL CONDITIONS FOR MODELING CO-FIRING

The modeling of the flow, heat exchange and combustion processes in the TP-87 boiler fuel tank was carried out using the generally accepted ANSYS Fluent program. For this purpose, the geometry of the calculation area shown in **Fig. 5.8** was constructed in the Gambit program, and a calculation grid was created on its basis.

Half of a fuel boiler with 6 burners was modeled, the plane bordering the discarded part was defined in the calculations as the plane of symmetry. The calculations took into account suction, it was assumed that dust is transported to the burners by air.

When setting the boundary conditions – wall surface temperatures (pollution) T_w and their degrees of blackness ε, as well as the flow rates and temperatures of the introduced components, let's rely on the results of the zone-by-zone calculation of fuel according to the normative method. The parameters used in the simulation are given in **Tables 5.9** and **5.10**.

Table 5.9 Boundary conditions on the walls of the zones

Zone No.	T_w, **K**	ε
1	1790	0.68
2	1243	0.75
3	1071	0.74
4	894	0.74

In **Table 5.10**, the parameters are given as follows – firstly, the tangential components of the velocity are indicated on the scale of the axial components, equal to unity. Secondly, the value of the coal feeding is taken directly from the boiler calculation by the normative method in the nominal mode, and the air feeding is found from the characteristics and coal feeding using the recommendations of S. Shagalova and I. Schnitser [38] for vortex scroll-blade burners ($\alpha_b = 1.05$, $\alpha_1 = 0.26$). The suction intake at a temperature of 313 K is taken based on the value $\alpha_f = 1.2$ ($\alpha_{1st\ zone} = 0.09$, $\alpha_{2nd\ zone} = 0.06$).

In modes with a co-feeding of coal and pellets, the thermal power of the mixed fuel remained the same as when only coal was fed, and the feeding was found based on the ratio of the thermal powers of coal and pellets as 0.9:0.1.

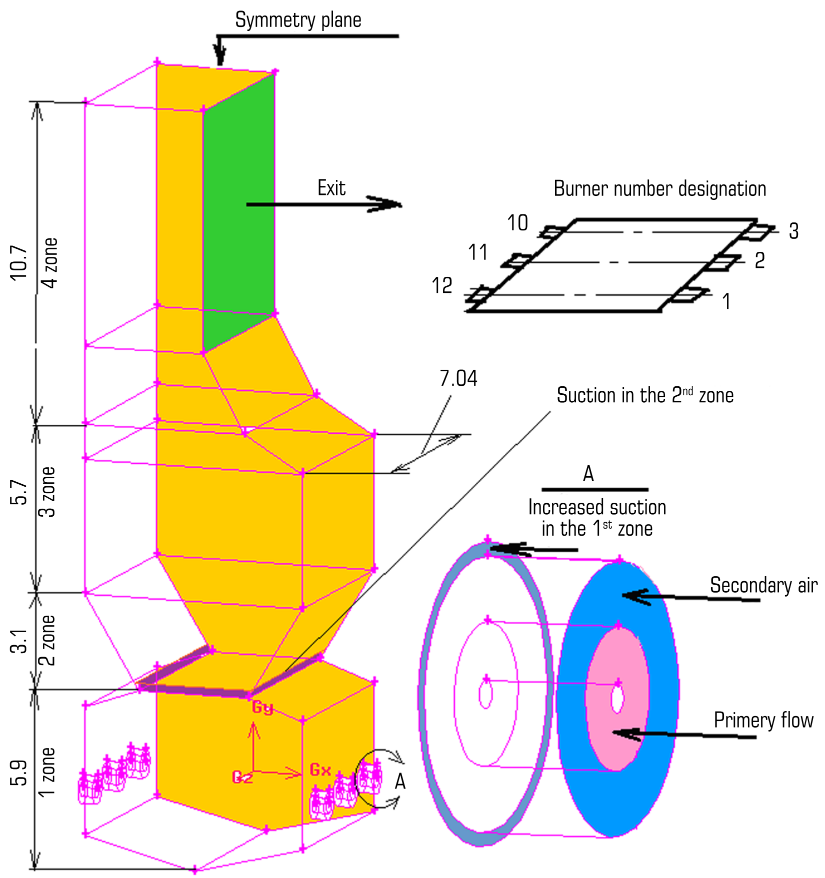


Fig. 5.8 Geometry of the calculation area – TP-87 fuel boilers

Table 5.10 Input component parameters assigned to one burner

Component	Air			Coal
	Flow rate	Temperature	Tangential component	Feeding
	kg/s	K	–	kg/s
Primery flow	1.739	363	2.53	1.136
Secondary flow	6.955	643	2.63	0
Suctions of the 1st zone	0.745	313	0	0
Suctions of the 2nd zone	0.397	313	0	0

The parameters of bituminous coal and pine pellets are given in the following **Table 5.11**.

Here (taking into account the recommendations of the ANSYS Fluent program) the sulfur content is conditionally added to nitrogen. The coal particle sizes were specified according to the Rosin-Ramler distribution in the range from 5 to 200 μm with an average size of 60 μm, the distribution parameter was taken equal to 1. The pellet particles were specified as monodisperse with a variable size. The particle shape in all variants was assumed to be spherical.

Table 5.11 Characteristics of bituminous coal and pine pellets

Type	W^r, %	A^r, %	V^r, %	C^{daf}, %	H^{daf}, %	O^{daf}, %	N^{daf}, %	Q^r_i, MJ/kg
Bituminous coal	11	19.58	25.55	80.27	5.10	12.01	2.62	22.766
Pine pellets	8.70	0.37	78.43	51.87	6.33	41.63	0.17	17.632

5.4.2 MAIN RESULTS OF MODELING IN THE MODE WITHOUT PELLET INPUT

The following figures illustrate the main results of modeling processes in the furnace in the mode without pellet input. The temperature fields in different furnace cross-sections (**Fig. 5.9**) and the fields of coke burnout and volatiles release in the furnace cross-section for burners 3–10 (**Fig. 5.10**) are shown. **Fig. 5.11–5.13** compare the results of numerical modeling with the data of zone calculations using the normative method in terms of temperature distributions along the furnace height (**Fig. 5.11**), heat flux densities in the walls (**Fig. 5.12**) and coke burnout intensity (**Fig. 5.13**). It can be noted that there is a fairly satisfactory correspondence in the temperature distribution (the difference is mainly within 100 °C) with a slightly worse agreement in terms of heat flux densities and burnout intensities.

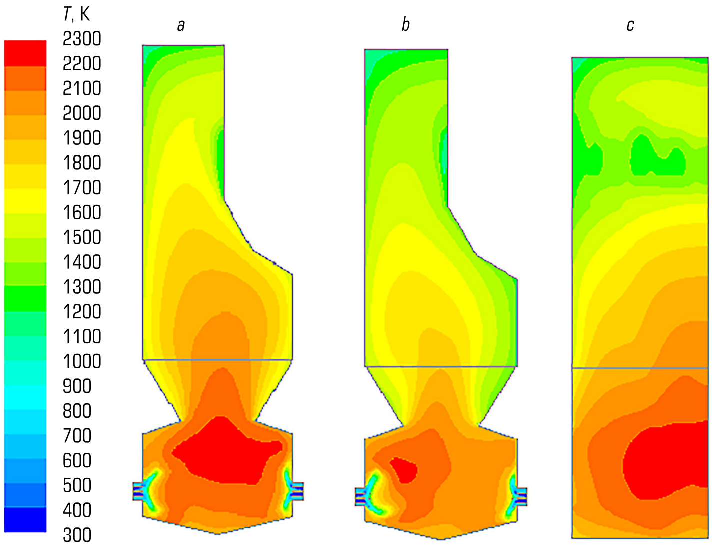


Fig. 5.9 Temperature fields in sections along burners 3–10 (*a*), along burners 1–12 (*b*) and along the z axis (*c*)

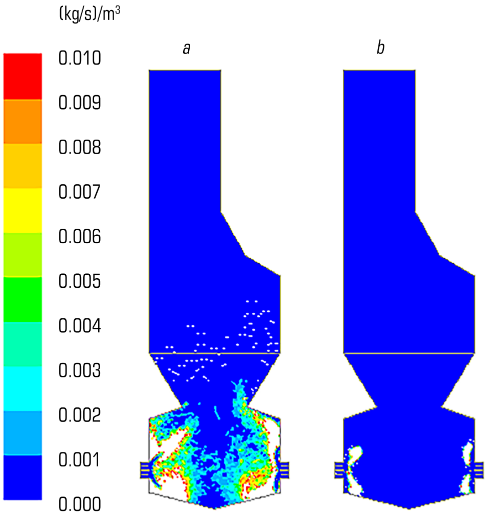


Fig. 5.10 Coke burnout intensities (*a*) and devolitalization (*b*) in the section along burners 3–10. White field – exceeding the upper limit of the scale

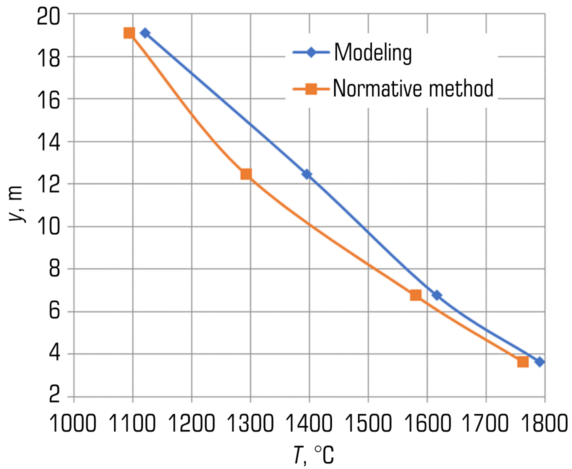


Fig. 5.11 Comparison of mass-average temperatures at the zone outlet based on the results of numerical modeling with the data of the zone-by-zone calculation using the normative method

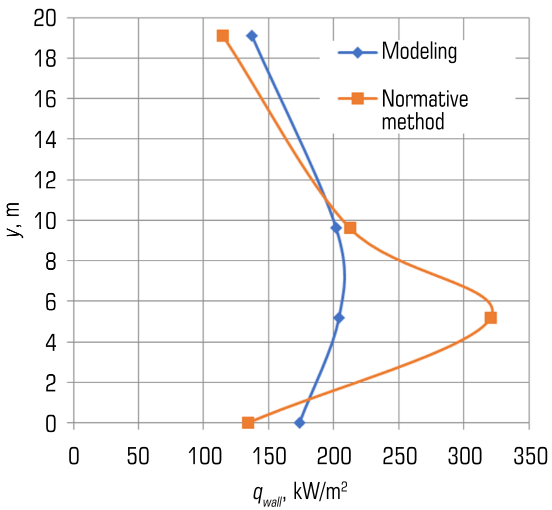


Fig. 5.12 Comparison of heat flux densities in the walls of zones according to the results of numerical modeling with the data of zone-by-zone calculations using the normative method

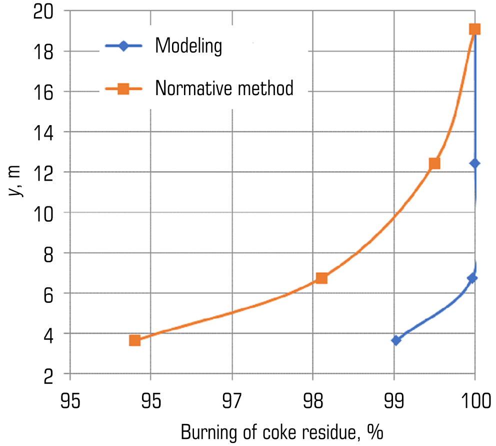


Fig. 5.13 Distribution of coke burnout intensity by fuel height according to the results of numerical modeling and according to the data of the zone calculation by the normative method

5.4.3 MAIN RESULTS OF MODELING IN THE MODE WITH THE FEEDING OF PELLETS

The results of numerical modeling lead to the conclusion that the effect of the feeding of pine pellets in the amount of 10% by heat on the processes in the furnace significantly depends on the fineness of the pellet grinding. Therefore, let's first consider this effect at the minimum of the considered pellet sizes – 60 microns.

From a comparison of these results (**Fig. 5.14**) with the data without the feeding of pellets (**Fig. 5.9**), it can be seen that the temperature level in the furnace decreased with the introduction of pellets, although the difference is small and will not affect the operation of the boiler mode and the liquid slag removal mode. This is more clearly illustrated by the values of the gas phase temperatures at the exit of the zones (**Fig. 5.15**).

A comparison of the distributions of coke coal combustion intensities in the fuel (**Fig. 5.16**) with similar results without pellet feeding (**Fig. 5.10**) shows that pellet introduction stretches the coke coal combustion zone.

As already noted, a significant impact on the combustion processes in the fuel is exerted by the size of the particles fed, namely, with an increase in this size, the burnout intensity in the furnace of both coal fuel and the pellets themselves decreases significantly (**Fig. 5.17**).

These results should be taken into account when choosing a biomass preparation technology for use as an additive to coal fuel. However, it is necessary to take into account that the size of the pellets in the simulation does not directly correspond to the size of the real biomass particles fed for combustion. These are conditionally spherical particles of the coke residue. While the size of biomass particles changes significantly during the process of rapid heating and pyrolysis with the release of more than 80% of volatile substances.

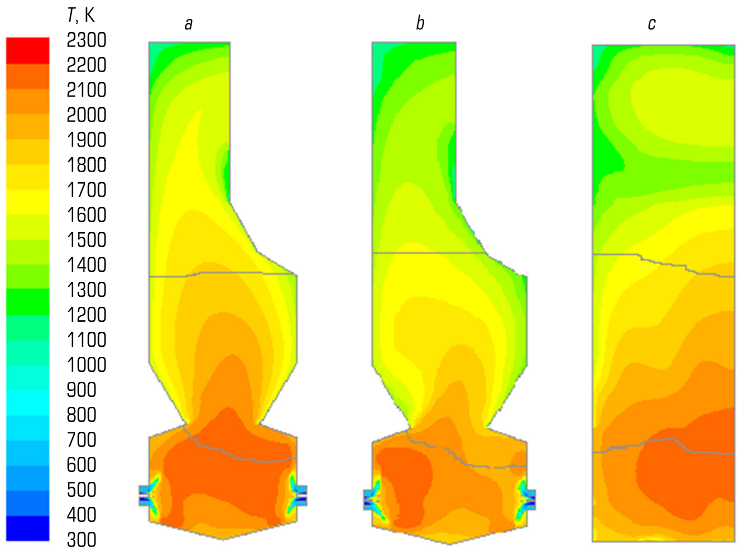


Fig. 5.14 Temperature fields in the mode with the feeding of 10% pine pellets in sections along the burners, 3 – 10 (*a*), 1 – 12 (*b*) and along the z axis (*c*)

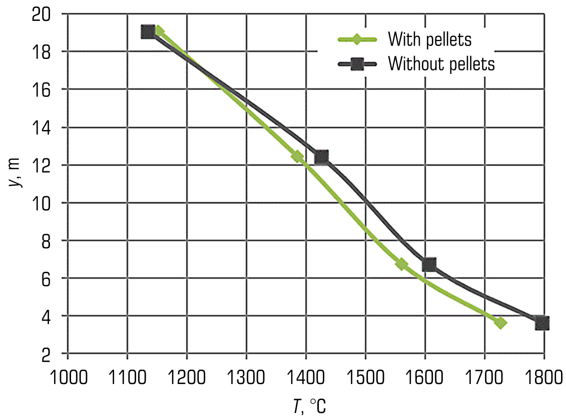


Fig. 5.15 Effect of pellet introduction on mass average temperatures at the zones outlet

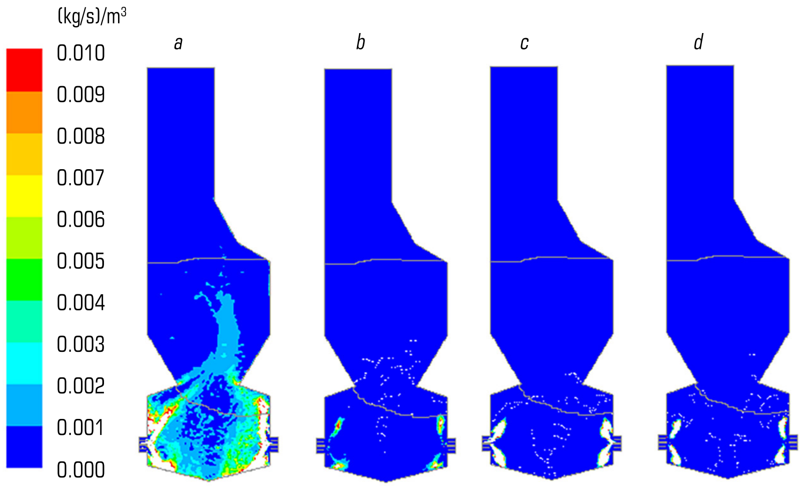


Fig. 5.16 Coke burnout intensities of coal (*a*) and pellets (*b*), as well as the devolatilization intensities of coal (*c*) and pellets (d) in the cross section of burners 3 – 10.
White field – exceeding the upper limit of the scale

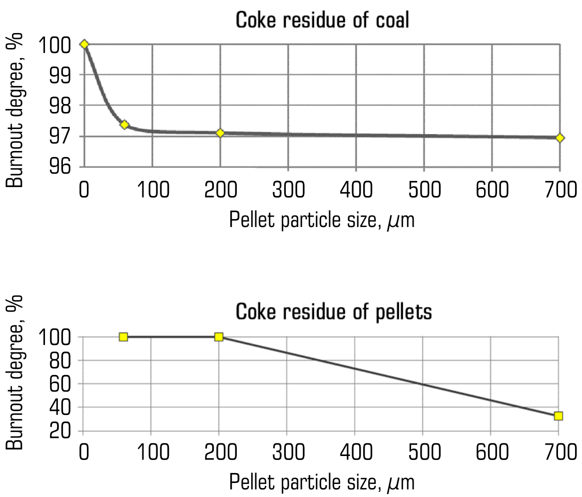


Fig. 5.17 The effect of pellet particle size on the efficiency of coal and pellet coke burnout

BRIEF CONCLUSIONS

As a result of modeling the co-firing of gas coal and pine biomass in the fuel of the TP-87 boiler, the following conclusions can be drawn:

1) ignition of both fuels occurs without delay;

2) addition of biomass does not worsen the conditions of liquid slag removal and the temperature conditions of slagging of the screen superheater (but the characteristics of biomass ash must be taken into account);

3) the average temperature level in the furnace decreases by 10–40°C, which can reduce the maximum steam power of the boiler by 5%;

4) increase in the size of biomass particles can lead to an increase in underburning (the maximum size requires verification on a real boiler).

5.5 RECOMMENDATIONS FOR THE USE OF CO-FIRING OF COAL AND BIOMASS AT UKRAINIAN TPPS

Based on the world experience of co-firing and the calculations and experiments conducted on the combustion of coal and biomass of Ukrainian origin, the following recommendations can be made for co-firing at TPPs:

1) at the moment, the optimal co-firing scheme is direct combustion of coal and biomass in one existing boiler, since such a scheme, compared to others, allows for maximum use of existing equipment and does not require much additional space;

2) to ensure reliable operation of the fuel preparation and feeding system (maintaining the regulatory degree of coal grinding, as well as the temperature of the air mixture), let's recommend using a separate fuel storage, grinding and feeding system for biofuel, which will ensure minimal impact of biomass on the reliability of the coal preparation system. This will also allow the use of not only wood pellets, but also sunflower husk pellets, due to the use of a mill specially designed for biomass;

3) the recommended form of biomass use at stations is pellets, which allows to reduce the costs of transporting biofuel, and also significantly increases the heat of its combustion;

4) the verification calculation of the furnace shows that with co-firing, reliable boiler operation is maintained with a stable output of liquid slag, the possibility of screens slagging requires practical study;

5) the experimentally shown stable co-firing of biomass of all three studied species (pine pellets, sunflower husk pellets, straw agropellets) for a long time (more than an hour for each of the modes);

6) the optimal share of biomass that improves coal combustion, but does not require significant reconstruction of the power plant is 8–12% by heat. When using CFBC on boilers that burn gas coal, a gradual expansion of the share of biomass can be considered with conducting of balance tests;

7) the optimal degree of grinding of different types of biomass corresponds to the maximum size of 1.6 mm, which allows it to ignite quickly, but does not require large grinding costs;

8) it is recommended to store pellets in closed silos that provide a 15-day fuel feeding. Silos should be equipped with a temperature control system, it is recommended to maintain the temperature no higher than 45°C. This will protect the biomass from getting wet (it has increased moisture absorption compared to coal) and spontaneous combustion;

9) when choosing biomass, it is necessary to pay attention to the characteristics of the fusibility of its ash. The melting points of ash are often lower than those of coal, which is positive when using liquid slag removal. But at the same time t_A should not be lower than the temperature of the combustion products in front of the screen superheaters +50°C;

10) the recommended biomass feed zone is the central channel of the vortex burner. This allows to reduce the costs of boiler reconstruction and, if necessary, quickly and easily return to 100% coal combustion.

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