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Modern Combustion Technologies and Their Contribution to the Development of Industrial Energy

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Abstract: The article discusses the planned implementation of a new biomass boiler in an industrial enterprise, which represents an important step towards increasing the company's energy self-sufficiency and sustainable operation. The technology described is based on a high-pressure fluidized bed steam boiler with a connected backpressure turbine. This solution will enable more efficient electricity generation and rational use of available heat. As part of the assessment process, an analysis of capital investments, operational benefits, and environmental impacts was carried out.

Keywords: heat, fossil fuels, biomass, BFB and CFB boilers

1. Introduction

Boilers are used in power plants and industrial facilities, including chemical industries, petroleum refineries, wastewater treatment plants, and pulp and paper industry.

The common types of fuels utilized in industrial boilers include coal, liquid fuels, and natural gas. Although the use of fossil-derived fuels in industrial applications is common practice, they contribute to criteria and hazardous air pollutants that impact air quality and human health [1].

Energy transformation is a complex process that is currently one of the main priorities of European and national policies [2]. Its successful implementation depends on the introduction of innovative technologies capable of integrating economic efficiency with environmental sustainability. In this context, industrial enterprises are the dominant energy consumers, giving them a key role in reducing greenhouse gas emissions and strengthening energy security.

Recent studies have highlighted that replacing fossil fuels with biomass can substantially reduce emissions of CO_2, NOx, and particulate matter, contributing to improved air quality and climate mitigation efforts [3,4].

The main objective of the company described in the article is to build a new biomass boiler, which can be interpreted as a significant step towards decarbonisation measures in the industrial sector. In addition to reducing the carbon footprint, it also represents a significant step towards strengthening energy self-sufficiency, diversifying sources and reducing dependence on fossil fuels. From an economic point of view, there is a significant reduction in operating costs, which can be reflected in the company's economic performance in the long term. Modern combustion technology ensures a significant reduction in emissions of solid pollutants, nitrogen oxides, sulphur,

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and heavy metals, thereby contributing significantly to environmental benefits in the form of improved air quality, minimized negative impacts on human health, and the fulfilment of long-term sustainable development and climate and energy policy goals [5].

2. Modern Technologies for Energy Recovery from Biomass Combustion

Considering current technological trends in biomass combustion, two types of advanced combustion systems are most commonly used in industrial practice, which are analysed in detail in this article. These are bubbling fluidized bed (BFB) boilers and circulating fluidized bed (CFB) boilers. These technologies represent advanced solutions that enable high-energy efficiency while reducing pollutant emissions. A common feature of both systems is the use of the fluidization principle, while they differ in the combustion process mechanism. Their significant advantage is their versatility, as they allow the efficient use of a wide range of fuels, including low-quality and alternative fuels [6,7,8].

Table 1 compares BFB and CFB boiler technologies, which were evaluated when designing the replacement of an obsolete boiler with a new source using advanced fluid combustion technology in a given industrial plant.

Table 1: Comparison of BFB and CFB boilers [6,7,8].

Parameter	BFB	CFB
Operation	- lower energy consumption, - better operation at low load, - higher availability (fewer components, fewer refractory materials), - easy to operate,	- higher energy consumption, - higher efficiency (lower flue gas temperature at the outlet), - slightly lower availability (more components, more refractory materials), - easy to operate,
Fuel flexibility	- most suitable for fuels with low calorific value, moist and highly volatile fuels (biomass), - limited, especially for fuels with high calorific value and waste fuels, - full power (100%) for fuel oil or natural gas,	- most suitable for fuels with high calorific value, dry and low-volatile fuels, - more suitable for waste fuels (waste, SRF, RDF), - more flexible when burning many types of fuels, - limited capacity (40% / 60 – 70%) for fuel oil or natural gas,
Emissions	- good control of NO_x and CO (higher combustion temperature), - moderate self-reduction of SO_2 (30 – 50%),	- excellent NO_x and CO control (lower combustion temperature and strong turbulence/mixing), - lower ammonia/urea consumption, - better SO_2 self-reduction (65–85%), with limestone ($CaCO_3$) injection into the furnace up to 95%,
Chlorine	- conventional design < 0.05 wt.% dry matter, - design with co-combustion < 0.10 – 0.15 wt.% dry matter,	- conventional design < 0.10 wt.% dry matter, - design with co-combustion < 0.25 – 0.40 wt.% dry matter,
Corrosion	- higher risk of corrosion, - sensitive to furnace outlet temperature, - mitigated by high-alloy steels (superheater),	- lower risk of corrosion, - superheater in sand bed in loop seal,
Erosion	- negligible (low flue gas velocities and low solid particle circulation),	- increased risk due to high solid particle circulation velocities and higher flue gas velocities in the furnace,
Maintenance costs	- lower maintenance (fewer refractory materials, simpler design and no sand recirculation), - fewer components, - maintenance costs approx. 1.5% of boiler investment costs,	- slightly higher maintenance (risk of erosion), - more components, - maintenance costs approx. 2.5% of boiler investment costs,
Floor space	- smaller/lighter,	- larger/heavier (cyclone),
Installation costs	- lower (fewer components, fewer refractory materials),	- higher (more components (cyclone, superheater), more refractory materials),
Investment costs	- lower,	- approximately 10% higher,
Availability	- higher availability (fewer components, less refractory materials), - simpler design,	- slightly lower availability (more components, more refractory materials), - more complicated design,

Figure 1 shows the suitability of CFB and BFB technologies for different fuels according to their calorific value and volatile content.

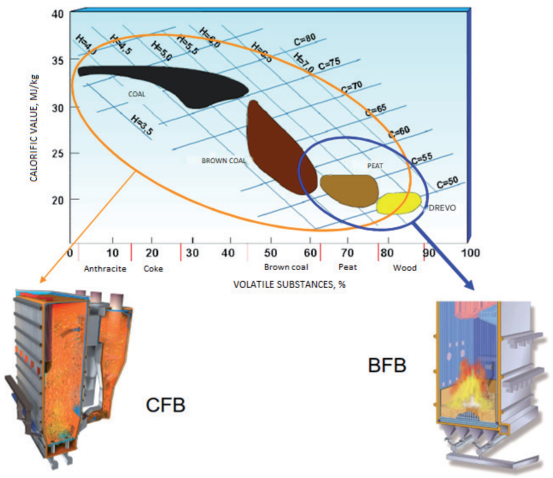

Figure 1: Suitability of CFB and BFB technologies for different fuels.

Figure 2 describes the suitability of fluidized combustion technology or grate - fired boilers depending on the fuel used, taking into account not only the calorific value but also the chemical composition or complexity of the fuel itself.

3. Proposal for New Technology in the Industrial Plant under Consideration

The energy infrastructure of the analysed industrial plant plays a key role in ensuring the continuous production of pulp, paper, and related products. With the technical obsolescence of existing equipment and growing environmental demands, it is essential to modernize energy sources. The implementation of a new circulating fluidized bed (CFB) boiler represents a modern technological solution that will enable the efficient combustion of a wide range of fuels while achieving high steam parameters.

The proposed biomass boiler with a nominal thermal output of 140 MW (corresponding to the production of approximately 167.4 $t{\cdot}h^{-1}$ of steam) is a high-pressure single-drum circulating fluidized bed (CFB) steam boiler with a membrane combustion chamber wall design. The fuel system ensures reliable and uniform transport of various biomass fuels. Transport is carried out by means of rotary screw and chain conveyors, dosing scales with screw feeders, and transport chutes equipped with rotary feeders. The bottom part of the chutes is air-cooled and the operation of the conveyors is regulated by frequency converters to increase

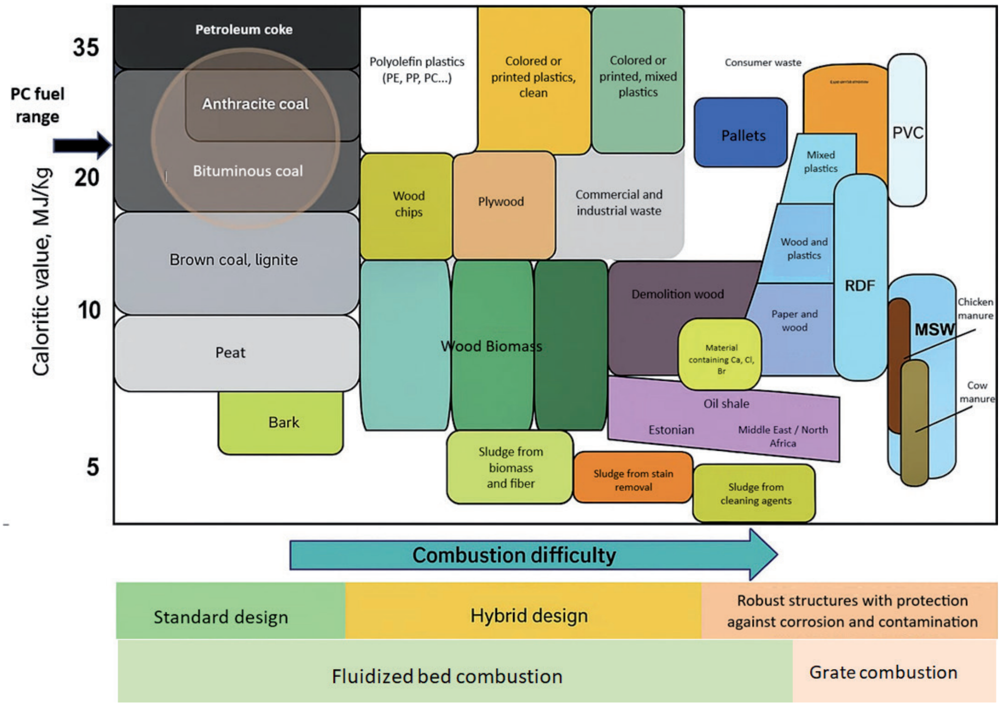

Figure 2: Suitability of fluid combustion technology.

reliability. The combustion chamber uses a system of burners ensuring flexible operation, with natural gas as the initial fuel. The combustion air is preheated and divided into primary, secondary, and tertiary for optimal mixing and emission control.

The boiler will be supplied with demineralized water from the existing water treatment plant and recycled condensates, which are vented in a degasser above the feed water tank. The feed water is preheated by an economizer, fed into a steam drum and steam generator, whose heat exchange surfaces form the walls of the combustion chamber and superheater. The resulting steam-liquid mixture is separated into steam and water in cyclone separators. The steam is further superheated, while the liquid phase is returned to circulation.

The flue gases are cleaned with a sorbent, activated carbon, and a fabric filter. Subsequently, the flue gases pass through a fan and are discharged through a new 150 m high chimney. The boiler will be equipped with an SNCR/SCR system to reduce NOx emissions. Up to 50% of the cleaned flue gas can be recirculated into the primary air stream, which helps to optimize the combustion process.

The steam produced at a pressure of approximately 111 bar will be fed into a new backpressure turbogenerator (TG10) with an installed electrical capacity of 27.9 MW. This is a backpressure turbine with regulated steam extraction, which allows the industrial plant's steam requirements for pulp and paper production and heat supply to external customers to be effectively met.

4. Results and Discussion

The proposed equipment is designed to produce thermal energy in the form of high-pressure steam, which is used both to cover the internal technological needs of the company and to supply heat to external customers and to produce electricity in a steam turbine. Compared to the existing boiler, operating at parameters of 402 °C and 43 bar, the new boiler will achieve significantly higher operating values – approximately 520 °C and 111 bar. The increase in the thermodynamic parameters of steam is directly reflected in the higher overall efficiency of the equipment and more efficient use of the fuel base. Fuel flexibility allows the combustion of various biomass and waste fuels, which significantly reduces the risk of dependence on a single source of raw material. Based on the above, the following energy inputs can be defined for the new biomass boiler: natural gas used primarily as a start-up and support fuel, biomass (purchased and own wood biomass – bark, wood chips and sawdust), primary sludge from wastewater treatment in pulp and paper production, waste from secondary raw material preparation (fibre rejects and sludge from mechanical separation), and biosludge from operations that exclusively process wastewater from paper production. Another energy source is biogas produced during technological processes. The use of methanol is also being considered. In addition to solid and liquid fuels, waste gases are also used in the process, with the biomass boiler functioning as a final oxidation device for their safe disposal.

Auxiliary substances (sand as the basic filling of the fluidized bed, urea, chemical reagents for feed water treatment, biofilter filling for biowaste processing, chemicals for cleaning the equipment) are important for the proper operation of the equipment, optimization of combustion, and compliance with emission requirements. After the installation of a new biomass boiler with a modern flue gas cleaning system, the list of these substances will be expanded to include sorbents designed to reduce emissions of acid gases, organic pollutants, and heavy metals, specifically calcium hydroxide, sodium bicarbonate, activated carbon and, in some cases, calcium carbonate. The use of granulated sulphur as an anti-corrosion additive is also being considered.

Based on the company's internal analyses and calculations, it can be concluded that the installation of the new boiler represents a fundamental change in the energy balance. The most significant shift was an increase in biomass consumption of 535,152 MWh, which was offset by a significant decrease in the purchase of electricity and natural gas. The increased consumption of biomass is reflected in an increase in heat production in the biomass boiler of 469,601 MWh. Overall, heat production increased by 828,640 MWh, indicating increased utilization of installed capacity. Electricity production increased by 301,591 MWh which should contribute to the energy self-sufficiency of the industrial enterprise.

The emission characteristics of the biomass boiler before and after modernization are shown in Table 2. The evaluated emission data were determined based on analytical calculations and

Table 2: Overview of emissions from the original and new boilers.

Emissions	Original state	After project implementation	Difference – emission savings	Difference
	$t \cdot year^{-1}$	$t \cdot year^{-1}$	$t \cdot year^{-1}$	%
TZL	58.06	27.12	30.94	53.3
SO_2	265.15	127.72	137.43	51.8
NO_x	586.83	355.02	231.80	39.5
CO	229.67	126.22	103.45	45.0
CO_2	**142,246**	**107,976**	**34,270**	**24.1**

represent a conservative, worst-case scenario. Since the new boiler with its modern design and flue gas cleaning meets the BAT (Best Available Techniques) requirements, it can be expected that actual emissions will be significantly lower. This is also confirmed by experience with the old boiler, where the actual values were often significantly lower than the considered limits, in some cases by an order of magnitude.

The emission results confirmed that even with a conservative assessment, the emission limits are not exceeded. The new boiler will contribute to reducing greenhouse gas emissions and other pollutants despite the planned increase in biomass consumption, through modern flue gas cleaning. The reduction in emissions will also be supported by lower consumption of natural gas and purchased electricity.

The economic assessment of the new boiler installation is based on the balance of energy savings, operating costs, and additional revenues. After the implementation of the new biomass boiler, annual savings of 68,922 MWh of natural gas and 134,894 MWh of electricity are expected, while biomass consumption will increase by 535,153 MWh. At current energy prices (€20.29/MWh for natural gas, €132.20/MWh for electricity, and €22.23/MWh for biomass), the net energy cost savings amount to approximately €7.33 million per year. The investment brings significant economic benefits, mainly through the sale of CO_2 emission allowances and revenues from ancillary services and guarantees of origin for renewable energy sources. Increased operating costs are associated with waste disposal, chemical consumption, and maintenance and repairs. After considering all items, the net annual change in costs represents a saving of €9.62 million, to which a €2.31 million increase in revenue per year can be added. With a total investment of €149.9 million, including the replacement of the boiler and related technologies, the simple payback period is 12.6 years, which is an acceptable value given the technical lifetime of the equipment (20 years) and confirms the economic efficiency of the investment. The real return on investment is set at 19.6 years, which is in line with the expected technical life of the equipment (20 years).

5. Conclusion

The evaluation of the new biomass boiler in an industrial enterprise has demonstrated significant technical, environmental, and economic benefits. The implementation of modern fluidized combustion in a high-pressure steam boiler with a backpressure turbine represents an integrated solution that optimizes heat and electricity production while enabling wider use of biomass and waste fuels. An environmental analysis confirmed that the implementation of the project would contribute to a significant reduction in emissions of particulate matter, sulphur oxides, nitrogen oxides, and greenhouse gases. The proposed solution fully meets the requirements of best available techniques and supports the Slovak Republic's goals in the area of decarbonisation and adaptation to climate change. The overall benefit is clearly positive and significantly outweighs the potential negative environmental impacts. From an energy security perspective, it strengthens the company's independence from external sources, particularly natural gas and electricity, and increases operational flexibility.

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