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APPLICATION OF CIRCULATING FLUIDIZED BED BOILERS IN THE FUEL COMBUSTION PROCESS

ZASTOSOWANIE KOTŁÓW Z CYRKULACYJNĄ WARSTWĄ FLUIDALNĄ W PROCESIE SPALANIA PALIW

Abstract

The combustion of fuels plays an important role in the field of industry and power engineering. Nowadays, a lot is being done to reduce the industry's interference in the environment, due to ecological considerations. Not only is the fluid technology environmentally friendly, but also it is a convenient method of energy production from wide range of fuels. The article presents a summary of the most significant events in the history of fluidized bed boilers, there is also a description of construction and operation of a circulating fluidized bed boiler and its comparison with technologically similar bubbling fluidized bed boiler. The usage of diverse types of fuels is discussed and compared. Special emphasis is placed on the application of fluidized bed boilers in Polish industry.

Keywords: fluidized bed, combustion, circulating fluidized bed boiler, CFB boiler

Streszczenie

Spalanie paliw odgrywa ważną rolę w dziedzinach przemysłu i inżynierii energetycznej. Obecnie, dokonuje się wielu starań, mających na celu zmniejszenie wpływu przemysłu na środowisko, ze względu na względy ekologiczne. Technologia fluidalna jest nie tylko przyjazna środowisku, ale także jest dogodną metodą produkcji energii z szerokiej gamy paliw. Artykuł przedstawia kilka najważniejszych wydarzeń historycznych, które przyczyniły się do rozwoju technologii fluidalnej. Umieszczono w nim opis konstrukcji i działania kotła z cyrkulacyjną warstwą fluidalną, a także jego porównanie z podobnym pod względem technologicznym kotłem z bąbelkową warstwą fluidalną. Opisane i porównane jest użycie różnych typów paliw. Szczególny nacisk położony jest na użycie kotłów fluidyzacyjnych w polskim przemyśle.

Słowa kluczowe: złoża fluidalne, warstwa fluidalna, spalanie, kocioł z cyrkulacyjną warstwą fluidalną, kocioł CFB

1. Introduction

Along with the development of technology, many innovative fuel combustion methods have been developed in power boilers. An important role is played by fluidized bed boilers, which due to the structure of the fluidized bed can be divided into bubbling fluidized bed boilers (BFB) and circulating fluidized bed boilers (CFB).

Fluidized bed boilers are devices for direct conversion of chemical energy contained in fuel for thermal energy. Indirectly from the generated hot steam electricity can be generated. These boilers do not have a complicated construction. The basic construction element is the sieve bottom, under which a fluidizing agent, e.g. air, is fed. Apart from fuel, the bed can also be built from inert material (eg quartz sand or chamotte), which allows maintenance favorable process conditions, such as, for example, increasing the combustion surface, isothermality of the bed, good mixing of fuel and oxidant [1].

The use of fluid combustion technology brings many benefits. First of all, the emission of dinitrogen oxide to the atmosphere is significantly reduced due to the low temperature in a fluidized bed chamber (about 860°C) [2]. Moreover, thanks to the addition to the fluidized bed sorbent binding sulphur from fuel, one can note a reduction emitted to the atmosphere sulphur oxides. The sorbent is usually ground limestone. In fluidized bed combustion, the fuel particles are intensely mixed with the oxidant, which makes it possible reducing the size of the combustion chamber itself. This technology also allows for the combustion of low-quality fuels with a simplified carburizing system [3].

For the first time, the fluidization process was observed in 1921, when German chemist Fritz Winkler introduced gas combustion products into the bottom of the crucible in which the coke particles were found. He observed then an intense process of lifting particles through a flowing gas that resembled boiling water liquid. The year 1939 brought another discovery - two scientists from the Massachusetts Institute of Technology then tried to find the right contacting process for the solid phase and gas to perform catalytic cracking. That's how the new discovery came about phenomenon – fluidization in the circulating layer. Since then, this technique has begun to develop dynamically in the petrochemical industry. In the sixties fluidized combustion in the bubbling layer was investigated [2]. Currently, a huge share of fluidized bed boilers are used on the Asian continent.

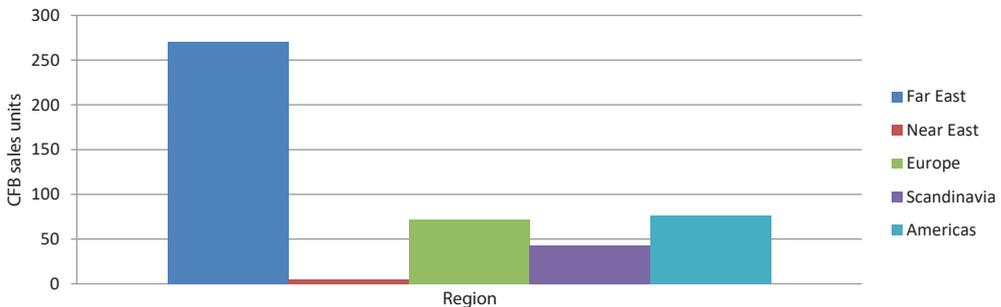


Fig. 1. Sales of CFB boilers by Amec Foster Wheeler until 2015 [4]

The growing interest in CFB technology resulted in the 60s discovery that it is suitable for carrying out operations with powdered solids and at high speeds. The method was developed for calcination of aluminium, which soon came into common use. The first CFB boiler designed to generate steam and heat was built in 1982. It was a revolutionary event in the field of energy, and this technology still exists and is dynamically developing [2]. Compared to CFB technology, BFB technology is currently much less common, as evidenced by the list of installed by Finnish heating companies in the form of CFB and BFB boilers (Fig. 2).

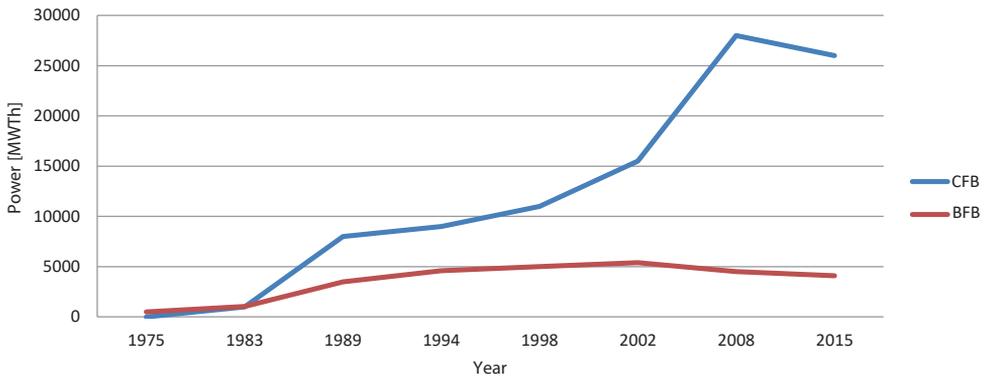


Fig. 2. Installed thermal power of CFB and BFB boilers in the years 1975–2015 [5]

Analysis and broadening of knowledge in the field of fuel combustion in fluidized bed boilers, and especially in boilers with a circulating fluidized bed, can reduce costs combustion and improve the quality of the atmosphere. Air on earth at the turn of recent years it is becoming worse and worse quality, among others due to exceeding the content toxic dusts and chemical compounds emitted, among others from a combined heat and power plant, traditional coal stoves, or factories. It is observed in the United States significant reduction of harmful gas emissions as a result of pro-ecological implementation solutions in the energy sector (Fig. 3).

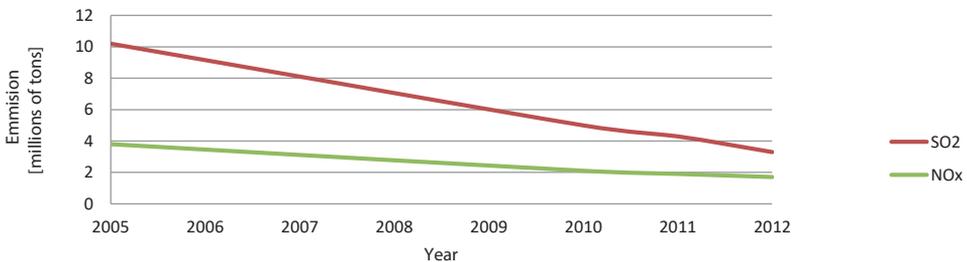


Fig. 3. Emission of sulphur dioxide and nitrogen oxides in the electricity sector in the USA [5]

2. Fluid combustion

2.1. Circulating fluidized bed (CFB)

An example diagram of an installation for burning solid fuels using CFB technology is shown in Figure 4. The fluidized bed combustion process starts with transporting the fuel with a screw conveyor (1) to CFB reactor (2). In the lower part of the reactor for the under-sieve chamber (3), a continuous air stream is fed (4) to ensure adequate turbulence and circulation of the bed in the camera. The fluidizing agent is preheated in a heat recuperator (5) to temperatures around 350°C by waste gases. In addition, when starting up the reactor or if the process requires it, the air can be additionally heated in the pre-heater (6) before introduction to the chamber. Secondary air (7) is fed after the cyclone. The off-gas after leaving the reactor is transported to the cyclone (8), where its purification with solid particles (ash, fluidized bed material) takes place. The gas then goes to the wet cleaning chamber (9) and the heat exchanger (5). In the last phase of the process, the exhaust gases are tested for the content of such gases chemical components, such as heavy metals or dioxins. Depending on the results of the quantitative and qualitative analysis of the flue gas can be directed to the installation purification or be introduced directly into the atmosphere [6].

Furnace ash, so-called ashes from the bed are removed from the bottom reactor connection (10). In this ash, there are no sinters or fused silica (glass), however, there are gypsum, calcium oxide and other amorphous ingredients [7].

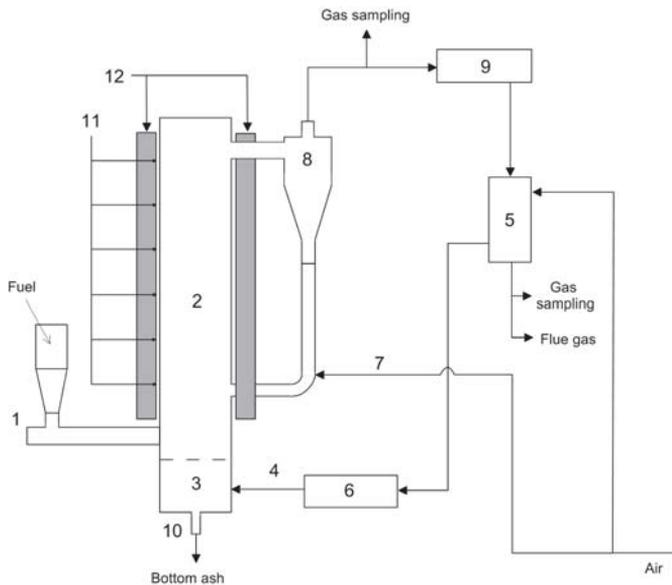


Fig. 4. Installation diagram using a circulating fluidized bed (CFB) [6]

- 1 – screw feeder, 2 – CFB reactor, 3 – sieve chamber, 4 – stream of air, 5 – heat exchanger, 6 – heater, 7 – secondary air, 8 – cyclone, 9 – wet chamber flue gas cleaning, 10 – spigot, 11 – thermocouples, 12 – electrically heated modules

The reactor contains thermocouples (11) that are used for measurement inside the reactor, at different heights. For temperature control ignition and start-up of the reactor, before it reaches its nominal operating parameters, there are electric heating modules installed (12) [7].

The main carrier of dioxins, heavy metals and other undesirable chemical compounds generated by fluidized bed combustion are fly ash contained in waste gases leaving the CFB reactor. These contaminants follow the pattern later they get to the exhaust gas, where their number is calculated as given below pattern [9]:

$$c_{1,i} = \frac{Ash}{2V_{fg}} c_{0,i}$$

where:

$c_{1,i}$ – dioxins/heavy metals content in exhaust gas [mg/Nm³]

Ash – ash content in solid fuel

V_{fg} – volume of fumes per kilogram of solid fuel [Nm³/kg]

$c_{0,i}$ – initial content of dioxins/heavy metals in solid fuel [mg/kg]

2.2. Comparison of a circulating fluidized bed with a bubbling fluidized bed

The first used fluidized bed boilers were bubbling fluidized bed boilers (BFB). Their action is based on the fact that under the influence of air flowing through the fuel layer, gas bubbles appear in the bed particles of fuel, ash or sorbent. The deposit in this case will not circulate in the boiler space, as is the case in CFB boilers [9]. Both of these fluidized bed combustion techniques differ in min. thermal load, the amount of sorbent used, additional equipment (Tab. 1). In CFB boilers it is necessary to use larger fluidizing velocity compared to a stationary bed. CFB technology allows for the construction of power boilers with much higher powers than in the case of BFB.

A limitation in increasing the energy efficiency of CFB boilers remains the strength of construction materials for process conditions.

Table 1. Comparison of CFB and BFB combustion techniques [3, 7]

Parameter CFB		Boiler type	
		CFB	BFB
Thermal load	q_A [MV/m ²] ¹	1.8–2.5	1.2–1.5
	q_V [MV/m ³] ²	0.2–0.4	0.1–0.2
Average size of fuel particles [mm]		3-30	< 25
Power [MW _{th}]		>50	<50
Air speed [m/s]		5–9	1–3
Burning temperature [°C]		850–900	850
The surface of the deposit		unspecified	strictly defined
Ca/S		1.5	2.5–3.5
The influence of the bed height on binding of SO ₂		no	yes

¹ thermal load related to the surface,

² thermal load related to the volume.

2.3. Costs of fluidized bed combustion

Fluidized bed combustion has many benefits, but it is worth knowing whether investing in such processes also brings financial benefits. Demand for capital for the construction of a fluidized-bed plant at power 200,000 t/a is about 54,500,000 €. These costs include, for example: land development, equipment costs, boiler, steam generator, turbogenerator and other construction costs and capital costs. These amounts, however, are located in the same range as in the case of grate combustion.

The use of fluid combustion is known for the fact that there is no need to instal equipment for removing nitrogen oxides from flue gases. However, the risk increases corrosion and related costs of equipment renovation and repairs [13].

3. Combustion of fuels in CFB boilers

3.1. Petroleum coke

The main task of the petrochemical industry is oil refining to petroleum coke. In recent years the production of this substance has increased significantly, which is a clear threat to the environment, due to the high sulphur content in this product. The use of petroleum coke as a raw material for the metallurgical industry is not advisable, a much better method is use of coke as fuel.

Combustion of coke in pulverized boilers, however, may cause excessive sulphur oxide emissions to the atmosphere. However, the use of a circulating fluidized bed boiler ensures reduction of pollutant emissions by binding sulphur in the bed. A deposit containing limestone then binds the sulphur, the product of which is calcium sulphate [2].

In the case of burning of petroleum coke, the most important thing is to adopt appropriate operating parameters. Pilot studies on emissions of sulphur dioxide to the atmosphere showed that its concentration in the flue gas decreases almost linearly with an increase in the excess air ratio and the calcium to sulphur ratio (Ca/S). In addition, the temperature of approx. 850°C

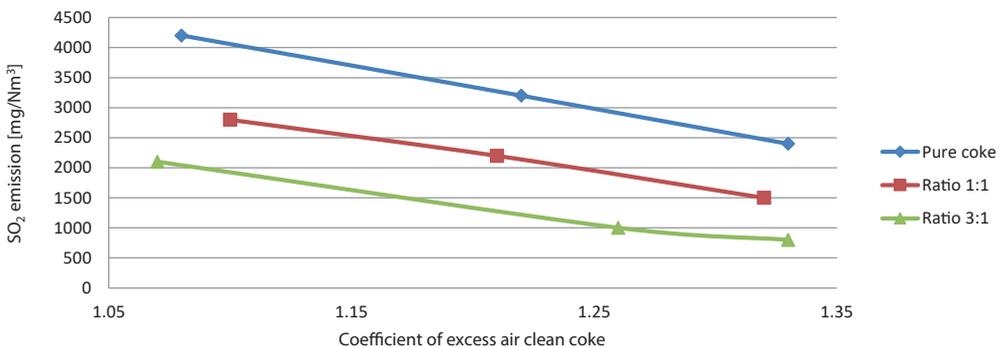


Fig. 5. SO₂ emission to the atmosphere as a function of the excess air ratio [10]

is the optimum temperature for sulphur retention. The values slightly differ from each other, depending on the ratio of carbon to coke (Fig. 5).

In a circulating fluidized bed, the main technical problem is heavy metal oil coke escaping into the melting ash. Despite the fact that coke has relatively low ash content, elements such as vanadium or nickel penetrating there form molten ash compounds that cause problems with agglomeration in the combustion chamber or in the circulating fluidized bed. Agglomeration takes place under the effect of fluidized bed temperature, fluidization velocity, material concentrations in the exhaust gases and the temperature of the walls of the heating surfaces. A relatively high fluidization velocity and material concentration will be conducive to the prevention of agglomeration [10].

There are two main types of erosion caused by different substances. The first of these is high-temperature erosion with strong links to agglomeration, as it is caused by heavy metals. In high temperature conditions ($> 590^{\circ}\text{C}$) molten ash compounds are formed that can react with sulphur to form complexes with a low melting point and contributing to erosion. The second type of erosion is erosion caused by SO_2 , which occurs if no limestone is added to the boiler. In the temperature range $850\text{--}950^{\circ}\text{C}$ and with the addition of sorbent, you can easily reduce this phenomenon. Temperature control in the boiler allows the impact of agglomeration and erosion to be limited [10].

3.2. Coal and granules made of rice straw

In addition to conventional methods of obtaining energy, consisting of burning fossil fuels, such as coal, oil or natural gas, waste incineration is also used (including industrial, municipal, agricultural). These methods are gaining increasing popularity, due to the usually low costs of obtaining raw materials energy. An example of an installation using both conventional and agricultural fuels, as well as innovative, is a boiler with a circulating fluidized bed, used for combustion a mixture of coal and granules from rice straw, where sand is used as a bed silica [11].

The use of rice straw as a fuel is strictly determined by areas the presence of this plant. The most profitable is for countries where this plant is common - these are Asian countries, such as China, Thailand, Vietnam, India or Japan. If the above-mentioned installation is used, it occurs to lower the average temperature of the deposit due to the presence of rice straw in the fuel. A lower bed temperature, the effect of reducing emissions of nitrogen oxides NO_x and dioxide SO_2 sulphur, however, carbon monoxide CO emissions are increased.

The combustion efficiency after adding the granulate to the coal decreases slightly by adding 25% of the mass granules, the yield is reduced by less than 0.5%. At the presence of 50% by mass of straw granules, this efficiency drops by about 1%, whereby in each case, it is not less than 98.5% of pure combustion efficiency coal.

Conducting the above-described process is economically justified and in many countries, allows you to get rid of agricultural waste, contributes to the reduction of oxides nitrogen and sulphur oxide. The only disadvantages appear to be a slightly higher emission of carbon monoxide and minimal decrease in combustion efficiency.

3.3. Coal combustion in fluidized bed boilers

Although the fluidization phenomenon will soon be celebrating its 100th anniversary discoveries, in the professional power engineering the first boilers with fluidization furnaces appeared in the 1960s. Dynamic growth in this type of solutions may be observed over the last twenty-five years, when the block energy with fluidization furnaces began to achieve thermal efficiency comparable to other systems (Tab. 2) and developed in societies' larger environmental awareness. For the users of this type of solution, it turned out to be valuable potential to reduce emissions of SO₂ and NO_x, but also the opportunity to use fuel solid and liquid of low quality [15].

Combustion of fossil fuels in fluidized bed boilers brings many benefits, such as reducing harmful emissions or increasing combustion efficiency [11]. This feature is particularly important in the case of coal combustion, which is usually a heavily contaminated material (Tab. 3). Coal occurring in the USA contains on average from 0.5% to 5% of sulphur in its composition [12]. Because of its presence, sulphur compounds, mainly sulphur dioxide, get into the atmosphere from burnt coal is the main cause of the formation of acid rain (due to the formation of acid sulphate after dissolving this oxide in water). In addition to sulphur dioxide, to the atmosphere small amounts of sulphur dioxide are also emitted, which forms with water sulphuric acid [13]. These compounds have a negative impact on the environment, and often on industrial equipment due to the potential for the formation of acidic substances. This often brings with it the need to use more expensive materials, such as permanently resistant to corrosion.

It is common practice in the combustion of fuels to use clean for this purpose oxygen instead of air. This technology has many advantages, such as reducing the quantity impurities entering the boiler, reduction of emissions of sulphur oxides, carbon and nitrogen, or also the leveling of unburnt carbon in fly ash [14].

Table 2. Comparison of thermal efficiency and investment outlays of energy blocks [15]

Energy blocks	Capital expenditures, EUR90/MW			Thermal efficiency in %		
	1995	2010	2020	1995	2010	2020
Combined circuit with gas turbine (GTCC)	559	550	528	55	60	62
Steam-gas system with gassing (IGCC)	1661	1552	1333	46	49	50
Fluidized bed furnaces	1249	1179	1040	44	45	47
Supercritical	1336	1262	1114	44	48	51
Fuel cells	1828	1128	820	61	66	71

Table 3. The content of some elements in selected samples of solid fuels [14]

Raw	% by weight				
	C	H	O	N	S
American coal	67.42	4.14	7.98	1.04	3.05
Chinese coal	65.00	3.85	9.95	0.76	0.50
Chinese petroleum coke	88.56	3.53	0.14	1.06	4.31

Table 4. Emission of harmful substances for the CFB boiler at EC Katowice [15]

Compound	Guaranteed emission [mg/Nm ³]	Measurement [mg/Nm ³]
SO ₂	540	417
NO _x	460	155
CO	200	52
Dust	50	8.3

The combination of several pro-ecological solutions in the field of fuel combustion gives measurable benefits. Particular emphasis on the implementation of these solutions should put countries having large natural carbon deposits and deriving energy to a large extent from it, in particular, USA, Russia, Australia and China. It is not without reason that the dynamic development of CFB technology is observed in China, where coal resources are very large, and the population in this country is over 1.3 billion.

3.3.1. The use of fluidized bed boilers in the Polish power industry

In Poland, the first fluidized bed boiler was put into service in 1997 in Bielsko-Biala Heat and Power Plant and since then you can observe a regular replacement of boilers in power plants in various regions of the country. In 2000, a new fluidized bed boiler was commissioned at EC Katowice CFB construction, which in addition to the combustion of the basic fuel in the form of carbon. It is also intended to incinerate waste in the form of post-flotation silt coal. The boiler used is a single-boiler boiler with a furnace atmospheric and natural water circulation. Fluidized bed combustion takes place at a temperature of 850-900°C. The circulating bed material is formed of ash resulting from the combustion of fuel, sand and limestone, which is used for capturing the sulphur released in the combustion process. Sand is used only during the boiler start-up to create a preliminary bed layer to allow start burning solid fuel. Low combustion temperature in the boiler with circulating fluidized bed is the optimal temperature for dry flue gas desulphurization using limestone. The combustion technology in the circulating fluidized bed ensures very low emissions of harmful substances without additional construction external installations (Tab. 4) [16].

One of the most spectacular examples on a global scale is the use of fluidized bed boiler in power industry is putting into use in 2009 a block power plant with 460 MW power at the Łagisza power plant in Będzin. This is the first on the world's energy block which is completely based on fluid technology and simultaneously having supercritical parameters, and at the same time it is the largest fluidized bed boiler. The fuel used is hard coal and coal-derived waste, mainly coal sludge. The block replaced five retired small units (3 x 120 MW and 2 x 50 MW) significantly increasing the efficiency of production and reducing global dust and gas emissions. As a result, the burden of environmental pollution has been reduced and economic efficiency increased. The efficiency of existing blocks at the Łagisza power plant was around 35–36 percent, and the new block achieved 45 percent. This significant difference is primarily due to the supercritical parameters and better efficiency of the whole circulation [17].

Supercritical parameters mean that there is such a high pressure that it minimises the difference in density between steam and water. Above the critical point of balance thermodynamic is the phase that does not determine whether it is steam or water at temperature 560°C and a pressure of 275 bar. These are the parameters above which the water only occurs in the gas state. After the pressure increase, you cannot condense steam. Fluidized bed boilers are a better solution for supercritical parameters, because thermal loads in the combustion chamber on the fuel side they are smaller than in dust boilers, working conditions and stress risk are also more favourable. Emission requirements for Łagisza comply with the European Union Directive for Large Combustion Installations (Large Combustion Plants). The emission of sulphur dioxide is controlled by adding limestone to the furnace. The emission of nitric oxide is controlled by the process gradual combustion and its relatively low temperature, while dust emission it is controlled by an electrostatic precipitator. The boiler is also equipped with installations supporting devices such as the ammonia water injection system (SNCR) [10,22].

3.4. Waste incineration in fluidized bed boilers

In 2015, a total of 142 million tonnes of waste was generated in Poland, of which 8% (11 million tonnes) were municipal waste, and 92%, or 131 million tonnes, other than utility waste. The main source of the latter, as in previous years is mining and extraction, which constitutes approx. 53% of total waste. The yearly amount of municipal waste produced by enterprises and households increases by around 5% per annum and in 2015 one inhabitant of Poland accounted for about 280 kilos of rubbish production per year.

In Poland, the basic method of waste management is storage, from the data presented in the 2016 GUS report, it appears that in this way 44% of their total quantity was neutralized and 26% recycled. Only 13% municipal waste generated in Poland has been disposed of in trash incinerators, which makes the result more than twice lower than the European average (Fig. 6) [19].

Separated energy fractions from municipal waste (biomass, plastics) are a source of alternative fuel (RDF) production and clean thermal energy. Secondary segregation allows,

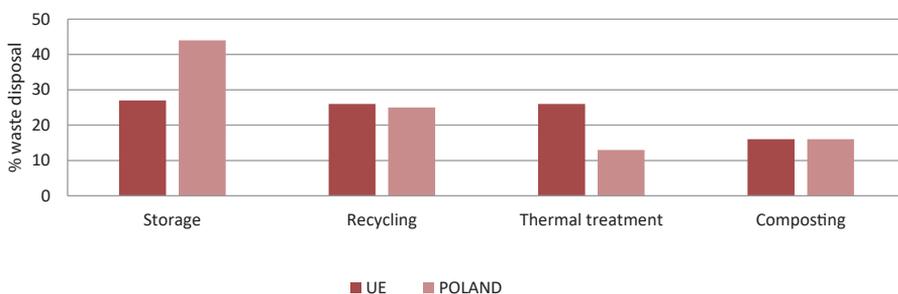


Fig. 6. Methods of disposal of municipal waste in the EU and Poland in 2015 [19]

on the one hand, recovery of recyclable materials and recycling for production. On the other hand, mixed materials can be used to obtain materials producing alternative fuel in the form of briquettes and pellets. In this regard, significant progress has been made on the candles, including fluidized bed incinerators where alternative fuels are burnt are becoming more and more popular.

There are over 470 municipal waste incineration plants in Europe. In Poland at present, there are 6 municipal waste incineration plants, and another 4 are planned or are under construction. In the domestic thermal processing of waste none of the incinerators use CFB boilers, but this technology is being successfully used in Europe and worldwide. One of the newest alternative fuel fired power plants is in Lomellina (Italy), processing 200 thousand Mg/year of municipal waste. The cost of its construction amounted to EUR 130 million, and 17 MWe power has been obtained. The plant has three technological lines separating municipal waste into fractions depending on the size of the fuel particles and their enriching substances. Alternative fuel obtained in the amount of 60% of recycled municipal waste, has a calorific value of 10.5 to 17 MJ/kg. In the combustion process RDF produces 7% ash, with organic parts below 1% unburnt organic content and boiler thermal efficiency of 86%. Low combustion temperature (850°C), application of a dry flue-gas cleaning method with lime and activated carbon and also fabric filters guarantee meeting strict emission requirements (Tab. 5) [20].

Table 5. Emission of harmful substances for the CFB boiler at the Lomellina LE1 incineration plant (dry exhaust, 11% volume O₂, average for 8h) [20]

Compound	Average values [mg/Nm ³]	
	Guaranteed value	Measurement
SO ₂	100	0.4
NO _x	200	152.2
CO	50	9.2
Dust	10	1.2

Municipal waste is, however, a small percentage of all waste in Poland, the rest is mining waste, of which 26% are wastes related to the extraction of hard coal. Almost 60 million tons of such waste in various forms (Fig. 7) is disposed of in various ways. The main direction their use are leveling and construction robots as well as aggregate production. About 30% this waste is used in domestic energy, partly in low-power heat-generating plants, but also in large combined heat and power plants equipped with fluidized bed furnaces [21].

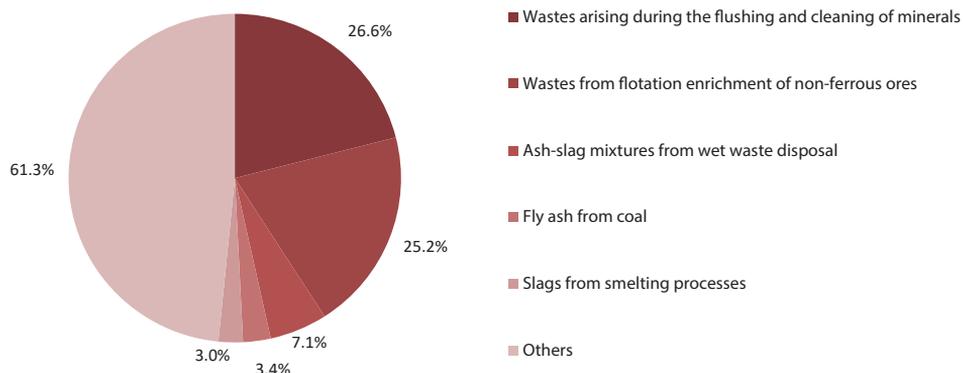


Fig. 7. Structure of mining waste generated in Poland in 2015 [21]

Coal sludge is used as a fuel for fluidized bed furnaces. Most often, however, it is used as a fuel additive. In this respect, it is important to highlight the great achievements of some of the national power plants with fluidized bed boilers. In most solutions, sludge is fed into the deposit in the form of silt-water pulp. Solutions are also known, mainly abroad, where sludge is the basic fuel for fluidized bed furnaces (Tab. 6) [20, 21].

Table 6. Selected coal-fired power plants and combined heat and power plants [20]

Location	Type of fluidizing hearth	Power, MW _e	Carbon fuel	Emission guaranteed, mg/Nm ³			
				SO ₂	NO _x	CO	Dust
EC Katowice	CFB, cyclone cooled by steam	120	+ sludge	540	460	200	50
El. Jaworzno II	CFB kompakt x 2	2x70	+ sludge	560	470	310	50
EC Siersza	CFB, hot cyclone	2x336	+ sludge + biomass	250	300	200	50
El. Łagisza	CFB on supercritical parameters	460	+ sludge + biomass	200	200	200	30

4. Summary

Fluidized bed boilers have undergone significant metamorphosis since their invention. As time passed, new ways of using them began to be implemented. CFB technology now seems to dominate BFB technology and this will probably be continuous. Its important advantages are the ability to build high-power units and the use of low quality fuels. Technical environment for the combustion process allows emissions to be reduced at source, which is less expensive than flue gas cleaning in external installations.

CFB boilers are very widely used in combined heat and power plants, steel mills, or garbage incinerators. To a large extent, their success is based on the fact that they are environmentally friendly due to low emission of pollutants. It can therefore be expected that the use of these boilers will continue to grow because ecological matters are playing an increasingly important role in global politics.

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