

FULL-SCALE TESTS ON THE CO-FIRING OF PEAT AND OIL SHALE IN AN OIL SHALE FIRED CIRCULATING FLUIDIZED BED BOILER

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Abstract. *The paper presents analysis of data obtained from tests of oil shale (OS) and peat co-combustion in a full-scale 250 MW_{th} (useful heat output) circulating fluidized bed (CFB) boiler. The tests were conducted at nominal boiler load, with peat thermal input up to 30%. During the experiments, gas analysis was performed and ash samples were collected. The specific consumption of the oil shale and peat blend per useful heat and gross electricity was calculated and other techno-economic characteristics were determined.*

It was found that the co-combustion of oil shale and wet peat increased the CO emission to the level of 60 mg/Nm³. The NO_x concentration increased from 120 to 165 mg/Nm³. The SO₂ and HCl emissions remained at a very low level – below 20 mg/Nm³. A significant ash reduction, approximately 4%, was measured in the case of a 30% peat content. Due to the high peat moisture, the flue gas volume increased 5–10%. As a result of addition of peat, the content of particulate matter (PM) 10/2.5 was also lower than that by conventional oil shale CFB firing. Oil shale and peat co-combustion can be considered as a viable option and near-term solution for reducing the environmental impact of oil shale power production.

Keywords: *oil shale, peat, biomass, co-combustion, particulate matter, ash composition, emissions.*

1. Introduction

In Estonia, 76% of electricity was produced from oil shale (OS) in 2015 [1, 2]. Two different combustion technologies – pulverized firing (PF) and

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circulating fluidized bed (CFB) – are used for power production from OS. The installed capacities are as follows: 1300 MW_{el} for PF and 430 MW_{el} for CFB. A 300 MW_{el} CFB unit is under commissioning. The new boiler is capable of burning 10% of OS retort gas, 50% of biomass and 20% of peat in OS blend, as designed.

The properties of Estonian OS definitely raise some challenges for boilers [3, 4]. High alkali and chlorine contents of OS ash have caused significant corrosion and fouling problems in PF units [5]. SO₂ and particulate matter (PM) emissions have been high. High ash content, > 50%, has been an environmental and technical challenge. Most of the ash is landfilled. Konist et al. [6] have found that the technology in use enables us to sequester up to 10% of emitted CO₂.

The CFB boiler design has resolved many of the oil shale combustion problems, no significant fouling or corrosion problems of convective heat exchangers have occurred in the CFB boilers during more than ten years of exploitation at the power plants of Enefit Energiatootmine AS. SO₂ emission has been reduced considerably due to the inherent lime content of oil shale ash, which favours sulphur capture in CFB conditions. The high SO₂ reduction efficiency is ensured by a high Ca/S molar ratio of Estonian OS – up to 10. The combustion process is so well controlled that no deSO_x facilities or additional lime inserted with fuel are needed. Because of the relatively low furnace temperatures and low organic nitrogen content in OS, deNO_x facilities are needed neither. The improved efficiency and decreased carbonate decomposition in CFB has decreased the CO₂ emission per produced power unit by nearly 24% [7].

The biomass/peat and OS co-combustion using CFB technology offers a possibility to further reduce the environmental impact of power production [2, 8–10]. The co-combustion of OS and biomass/peat blends saves precious unrenewable resource for later use. In addition, the cost of retrofitting the existing power plant to a co-combustion facility is considerably lower than building a new facility [11].

CFB combustion is considered a flexible technology that can burn fuels of widely varying quality. Recent studies point out that utilization of fuels like biomass and peat in CFB boilers may cause operational problems, such as agglomeration, deposit formation, and corrosion [12–16]. OS powered CFB units have been carefully designed to avoid such operational problems, OS and peat co-combustion in CFB seems a promising option for reducing the environmental impact of OS power production and more OS can be used for oil production.

Previous studies [8, 11] on coal and biomass co-combustion have indicated that 20% is the optimum share of co-fired fuel, which can be burnt in a CFB boiler without drawbacks. The emissions of NO_x and other flue gas components exceed the allowed limits set by environmental regulations and there have been noticed problems with heating surface fouling [16]. The current paper describes OS and peat co-combustion full-scale experiments in

the CFB boiler, performed with 30% of peat thermal contribution (25% by mass). Because of biomass storage and feeding system capacity, the 30% is maximum that can be achieved on peat firing.

2. Experimental

The OS and peat blends firing tests were carried out in the CFB double boiler energy unit. The capacity of the energy unit was 215 MW_e. The main parameters of the boiler were:

steam mass flow (primary/secondary), kg/s	95/76
primary/reheat steam pressure, MPa	12.7/2.4
primary/reheat steam temperature, °C	535/535

The energy unit was equipped with a biomass feeding system – two biomass burners per boiler located in the rear wall of the furnace between the solid separators.

The major goals of the tests were to carry out the analyses of ash and flue gas. The tests were conducted with the following fuel shares (as of thermal input): 70% of OS and 30% of peat. OS used in the tests was of class P3 (particle size 0–40 mm). The peat from different suppliers was used as the second component fuel of the blend. The main characteristics of fuels used are given in Table 1.

During the tests the analyses of fuel, ash and flue gas were carried out. The location of ports (1–8) for collecting ash samples is shown in Fig. 1.

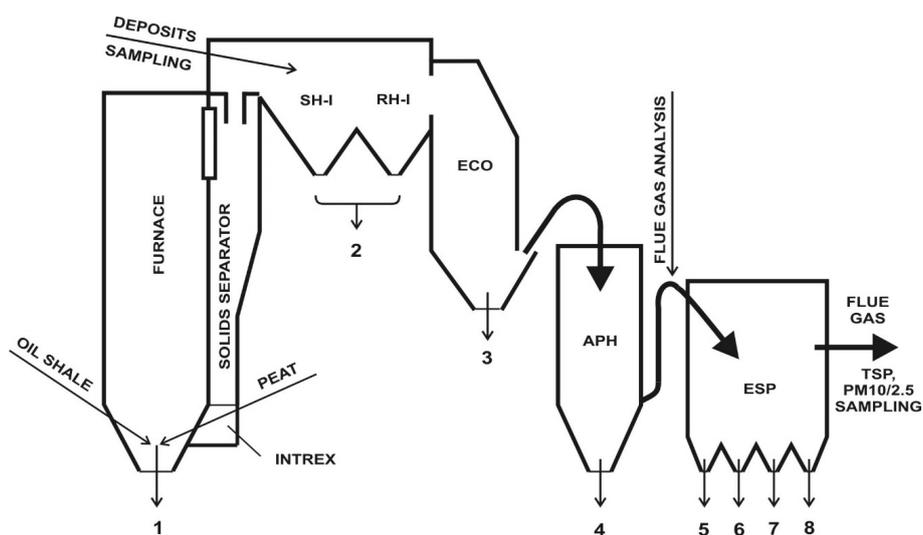


Fig. 1. CFB boiler sampling points.

Fuel samples were taken on an average daily basis. The ash samples were taken from several ports located in the furnace chamber, super-/reheater (SH, RH), economizer (ECO), air preheater (APH) and from all four fields of the electrostatic precipitator (ESP). Samples of fly ash for determining the mass division (PM 10/2.5) were taken after ESP. The samples were used for determining the detailed chemical composition of ash.

The results of sample analyses were averaged to reach a representative estimate. Also, during the tests the major process parameters of the boiler and energy unit were recorded using the plant's data acquisition system. The temperature and composition of flue gas were measured before ESP. The composition and moisture content of flue gas were determined applying an FTIR-type analyser for wet gas, at a temperature of 180 °C.

3. Results and discussion

3.1. Fuel – oil shale and peat

The oil shale and peat samples were analysed in the laboratory of the Department of Energy Technology of Tallinn University of Technology. The local laboratory of the power plant determined the average heating value and moisture content W_i^r of the used OS and peat daily. The University laboratory made the ultimate and proximate analyses of peat and OS. Table 1 presents the heating values determined in a calorimetric bomb (Q_b^d) and as received fuel (Q_i^r) calculated by general moisture content.

Table 2 contains the results of proximate analysis and Table 3 those of ultimate analysis of the fuels used.

Table 1. Fuel heating value, MJ/kg

Indicator	Peat	Oil shale
Q_b^d , dry fuel in calorimetric bomb	20.4	10.5
Q_i^r , as received fuel	10.5	8.5

Table 2. Proximate analysis, %

Indicator	Peat	Oil shale
W_i^r , moisture, as received fuel	37.8	11.2
A^d , ash content, as dry fuel	9.5	61.0*
V^d , volatile matter, as dry fuel	45.0	24.5**
Fixed carbon, dry matter	7.7	3.3

* Corrected ash content taking into account $(CO_2)_m^d$.

** Corresponds to 88% volatiles content in the organic part of OS (30.2%).

Table 3. Ultimate analysis, %

Indicator	Peat	Oil shale
Carbon	28.49	28.14*
Hydrogen	3.45	3.36
Nitrogen	1.31	0.10
Sulphur	0.19	1.38
Oxygen	19.19	3.60
Chlorine	0.06	0.29
Moisture	37.8	11.20
Ash	9.50	52.00

* Total carbon, sum of organic and inorganic carbon.

Carbon is present in both the organic matter and the mineral matter of oil shale. During OS combustion the mineral $(\text{CO}_2)_m$ is released as a result of decomposition of carbonate minerals. The extent of carbonate minerals decomposition is about 70% in case of the CFB mode. CO_2 is formed during the combustion of organic carbon and from minerals. When firing the OS and peat blend with the same thermal input, the share of CO_2 from minerals is reduced.

3.2. Bed, furnace and separator temperatures, deposits

Feeding peat into the fluidized bed caused a significant drop of the rear wall temperature as a result of its high moisture content (ca 40%). The temperature drop was approximately 30 °C (765–735 °C). Feeding more peat into the boiler increased the temperatures of the furnace dilute zone and the solid separator. The flue gas temperature after the convective pass remained similar with that of OS firing. Based on laboratory experiments, Lu et al. [17] predicted possible delayed ignition. The delayed ignition increased temperatures in solid separators and had an influence on flue gas composition, discussed later.

A short deposit measurement campaign was done during the tests. The deposits were collected by means of a water-cooled sampler. The sampling point was located in the flue gas pass between the solid separator and SH-1, where the flue gas temperature was about 700 °C. During this short campaign no bound deposits were found (Fig. 2). It is typical for OS firing in CFB.

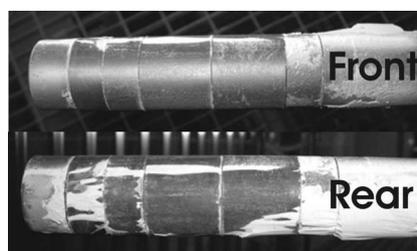


Fig. 2. Water-cooled deposit sampler after the experiments.

3.3. The chemical composition of ash samples

The samples were taken at nominal boiler load. The composition of ash is presented in Table 4 and shown in Figure 3. Nitrogen and hydrogen contents were below detection limit in all ash samples except in furnace ash whose hydrogen content was 0.13%.

The chemical composition of ash flows is comparable with that of ash flows from the pure OS firing [18, 19]: the calcium oxide content is high and that of sulphide sulphur low. The lower mineral carbon dioxide content in all ash flows is slightly exceptional. It is the effect of adding less limestone (as a constituent of OS) into the boiler. Higher chlorine content in all ash flows should also be noted and reminded that chlorine increases corrosion risk [20–22]. The organic carbon content is minimal in all ash flows. Low unburnt carbon content is typical in OS CFB firing because of high reactivity coke.

Table 4. Chemical composition of ash, %

Sampling point (Fig. 1)	CaO	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	MgO	K ₂ O	Na ₂ O	Cl	Free lime	CO ₂	SO ₃
Furnace (1)	50.2	12.4	3.8	1.9	3.1	0.7	0.2	0.3	18.3	13.5	15.8
SH (2)	32.8	29.4	4.5	6.3	7.5	2.9	0.3	0.3	15.6	4.8	11.8
ECO (3)	36.8	32.7	5.4	6.5	2.3	3.0	0.2	0.4	13.9	4.6	10.5
APH (4)	35.1	23.9	4.9	4.8	7.7	3.5	0.3	0.4	16.7	3.5	14.1
ESP1 (5)	36.1	34.1	2.6	9.9	3.6	3.8	0.3	0.7	14.6	4.1	4.9
ESP2 (6)	32.8	32.7	2.6	10.0	7.5	3.8	0.3	0.5	13.5	4.0	9.0
ESP3 (7)	30.9	34.7	2.9	11.7	5.1	3.8	0.3	1.2	10.5	3.5	8.8
ESP4 (8)	28.6	31.9	3.2	12.7	7.5	3.9	0.3	1.4	5.2	4.0	8.5
Total ash	40.9	25.0	3.3	6.4	4.2	2.5	0.2	0.5	15.9	7.8	10.4

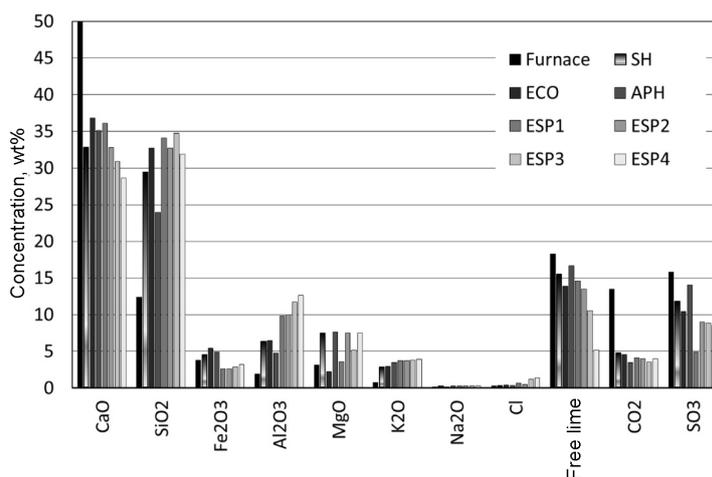


Fig. 3. Evolution of chemical composition of ash, %.

Table 5 gives the bulk densities determined for ashes from different sampling points: furnace, superheater, economizer, air preheater and ESP 1–4. For comparison, the table also presents previous results from the CFB firing test, during which the OS and biomass blend was combusted, the OS heating value being 8.5 MJ/kg [9, 18]. No significant changes were noticed, since most of the ash was formed from OS.

The boiler ash balance was calculated on the volume and ash bulk density bases. For comparison, the ash balance results from the previous OS firing test are added (Fig. 4 and Table 6) [18]. The fly ash/bottom ash split changed from 58/42 when firing pure OS of 8.5 MJ/kg to 61/39 when peat was added to OS. Despite the increased ESP ash load, a decrease of PM emissions was observed (Fig. 6).

Table 5. Bulk density of ash flows, g/cm³

Fuel	Furnace	SH-RH	ECO	APH	ESP1	ESP2	ESP3	ESP4
Oil shale + peat	1.474	0.794	0.726	0.841	0.652	0.658	0.570	0.424
Oil shale + biomass	1.503	0.908	0.791	0.919	0.698	0.681	0.543	0.412
Oil shale	1.483	0.787	0.668	0.841	0.652	0.666	0.564	0.431

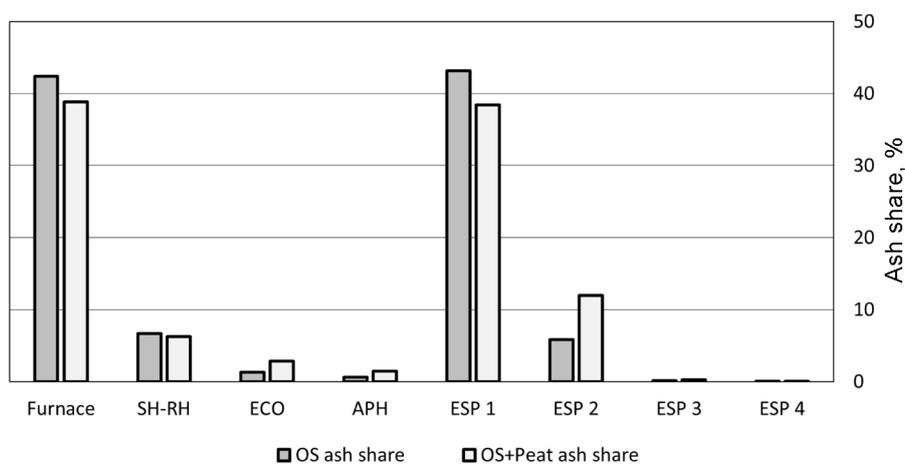


Fig. 4. Boiler ash balance upon firing oil shale [18] and co-firing oil shale and peat.

Table 6. Boiler ash balance

Fuel	Unit	Furnace	SH-RH	ECO	APH	ESP1	ESP2	ESP3	ESP4	Sum
Oil shale	kg/s	7.17	1.13	0.22	0.10	7.31	0.98	0.02	0.00	16.93
	%	42.35	6.66	1.30	0.58	43.16	5.81	0.12	0.01	100.00
Oil shale + peat	kg/s	6.28	1.01	0.47	0.23	6.21	1.94	0.04	0.00	16.19
	%	38.81	6.26	2.87	1.44	38.38	11.96	0.25	0.03	100.00

3.4. Flue gas and emissions

The composition of flue gas was determined before ESP. Figure 5 shows a fragment of the gas analysis. The NO_x concentration increases and CO becomes unstable immediately after the fuel blend reaches the furnace. The CO emission grows several times, varying on a relatively large scale. The CO concentration is at the level of 50–100 mg/Nm³ with peaks at 300 mg/Nm³. A possible reason might be the local bed temperature drop close to the biomass feeding points due to the high moisture content and delayed ignition [17, 23]. In this area a local reducing zone is formed that reduces the NO emission from peat nitrogen. Therefore, the NO_x content in flue gas is relatively low.

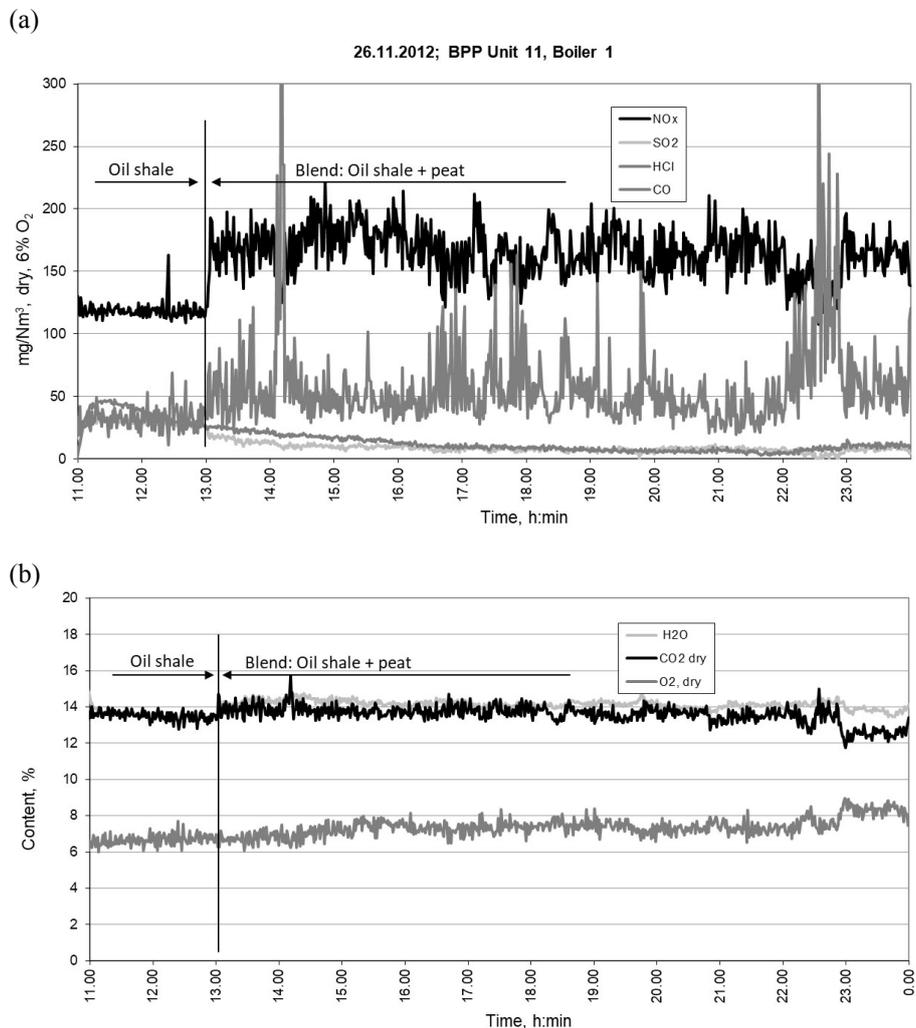


Fig. 5. Main components of flue gas.

The added peat causes the increase in the flue gas volume and speed, the flue gas moisture content increases by 2–3%, from 12 to 14%. In total, the flue gas volume increases 5–10%, due to which the loss with flue gases slightly increases.

The values of average concentrations of major emission gases are presented in Table 7. The results of OS and peat co-firing are compared with those from previous experiments with different oil shales and mixtures on CFB and PF.

Table 7. Average concentrations of main pollutants in flue gas (6% O₂), mg/Nm³

Fuel	CO	NO _x	SO ₂
Oil shale + peat	60	165	9
Oil shale + biomass [9]	20–30	140–200	< 5
Oil shale 8.5 [24]	35	120	15
PF oil shale [5]	30	220	3000*

* No deSO_x installed.

The finest particles content of fly ash together with its mass division (PM 10/2.5) after ESP is an important indicator of flue gas composition. Not all the fly ash can be caught by the final section (field) of ESP and, as a result, it is emitted into the surrounding atmosphere.

The mass division of fly ash after ESP was determined in tests with different blends (Fig. 6). During firing the OS blend with peat, the content of

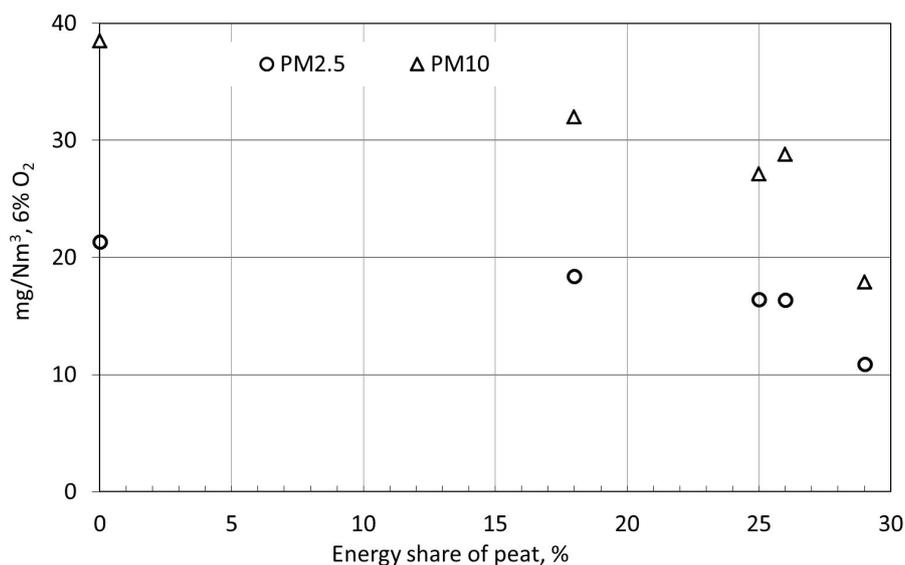


Fig. 6. Fly ash emission depending on the share of peat in OS.

the finest ash particles remained within the same limits as on firing pure OS [24]. In spite of the increase of flue gas volume and gas speed in ESP, the dust emissions slightly decrease. The reasons might be increasing water vapour content in flue gas, but also changed ash properties and decreased total ash load of the power unit. The exact cause remains yet unknown, but the OS and peat co-firing has a positive influence on PM emissions.

The emission of particulate matter decreases with an increase of the peat share caused by its lower ash content. The share of fine particles (PM 10/2.5) increases and content of particles larger than 10 μm is practically zero. The content of fine particles ($< 2.5 \mu\text{m}$) of ash after ESP remained within the same limits as reported by Parve et al. [24].

The CO_2 specific emission stays at the same level as in case of pure OS firing [25] (Table 8). The CO_2 emission is calculated on the basis of fuel composition. The CO emission is slightly higher than during pure OS firing. NO_x stays at the same level as during pure OS firing. The ash specific emission is lower because of the lower ash content of peat.

Table 8. Specific emission indicators per electricity (gross)

Pollutant	kg/MWh _e ^{br}
CO ₂	1 059
CO	0.111
NO _x	0.587
Ash emission	0.111

4. Conclusions

The data from experimental tests conducted on a CFB boiler indicate that the average concentrations of CO and NO_x emissions varied. The test with a peat thermal share of 30% showed that the specific emission of SO_2 , CO and NO_x increased slightly compared with the earlier findings by pure OS firing. The ash content decreased by 4%.

Based on the results obtained the following conclusions can be made:

1. The CO_2 emissions remain unchanged. Therefore, when firing the oil shale and peat blend with the same thermal input, the share of CO_2 from minerals is reduced.
2. The added peat causes the increase in the flue gas volume and speed, the flue gas moisture content increases by 2–3%, from 12 to 14%. Due to the high peat moisture, the flue gas amount increases 5–10%.
3. The CO emission grows several times, varying on a relatively large scale. The CO concentration is at the level of 50–100 mg/Nm^3 with peaks at 300 mg/Nm^3 (6% O_2) compared to stable 20 mg/Nm^3 (6% O_2) when firing pure oil shale.

4. Despite the higher nitrogen content of peat (ca 2%) compared to that of oil shale (ca 0.1%), the NO_x concentration increases only from 120 to 170 mg/Nm³.
5. Feeding peat into the fluidized bed causes a significant drop of the rear wall temperature as a result of the high moisture content (ca 40%) of peat. In this area a local reducing zone is formed that reduces the NO emission from peat nitrogen. Therefore, the NO_x content in flue gas is relatively low.
6. The SO₂ and HCl emissions remain at a very low level – below 30 mg/Nm³.
7. The emission of total suspended particles decreases with an increase of the share of peat caused by its lower ash content. The share of fine particulate matter (PM 10/2.5) increases and the content of particles larger than 10 µm is practically zero. The content of fine particles (< 2.5 µm) of ash after ESP remains within the same limits as in oil shale combustion.

The test results encourage the co-combustion of oil shale and peat in a circulating fluidized bed boiler using an installed biomass feeding system, which allows us to increase the biomass share up to 50% of thermal input.

Oil shale and peat co-combustion can be considered as a viable option and near-term solution for reducing the environmental impact of oil shale power production.

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