

PRIMARY METHOD FOR REDUCTION OF SO₂ EMISSION AND ITS IMPACT ON CO₂ IN PULVERIZED OIL SHALE-FIRED BOILERS AT NARVA POWER PLANT

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Primary method if used in pulverized oil shale-firing boilers in operation enables to achieve the target value of SO₂ specific emission 400 mg/nm³. It will also be possible to meet the SO₂ specific emission limit value (200 mg/nm³) set by the European Union for the new-installed solid-fuel boilers by further optimization of technological parameters of pulverized oil shale firing and construction of oil shale boilers on the basis of primary methods. Optimization would make it possible to design a pulverized oil shale-fired boiler for supercritical and ultracritical steam parameters and to enhance the efficient and environmental-friendly use of oil shale to a considerable extent.

Introduction

Reduction of the sulphur dioxide (SO₂) emission produced as a result of firing pulverized oil shale is one of the most important and complicated problems in the whole complex of ecological problems at Narva Power Plants. Treaty of Accession of Estonia to the EU sets out a requirement to limit the amount of SO₂ emissions to 25,000 tonnes per year starting from 2012, bringing about restriction of electricity production in Estonia.

The LCP directive (Large Combustion Plant Directive) lays down a requirement to considerably reduce the discharged amount of specific emissions, *i.e.* SO₂, NO_x and fly ash, starting from 2016 [1]. This will considerably restrict electricity production in Estonia.

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To fulfil the EU requirements, several different flue gas cleaning methods targeted at the reduction of SO₂ emission (dry, semi-dry, wet, and plasma, photochemical) have been studied and tested [2].

However, the experience gained thanks to these tests shows that the specific nature of the mineral structure of oil shale has not been fully taken into account yet. The possibility to use these methods and the relevant efficiency guarantee are also questionable [3].

Improvement of the capture effect of SO₂ in the pulverized oil shale-fired boilers by applying primary methods shall offer a large reserve for the reduction of SO₂ emission. In the case of oil shale, nature itself has offered a solution for this problem as oil shale kerogen is furnished with the mineral ballast which contains up to 10 times more of the components capable of capturing SO₂ (CaO, MgO, K₂O, etc.) than necessary from the stoichiometric point of view. However, capturing of SO₂ in the pulverized oil shale-fired (PF) boiler varies to a large extent in the case of the currently applied PF methods: 70–80%. The specific emission of SO₂ in the leaving flue gases 1,800–2,700 mg/nm³ [4] shows that the number changes considerably during the period of boiler operation due to changes in modes and technological parameters. It proves that there exist large reserves for capturing SO₂ in the PF boiler when primary methods are applied, and these reserves are not yet fully made use of. The main difficulty in making use of these reserves for capturing SO₂ lies in the fact that there is no global experience related to combustion of a fuel of similar composition and capturing SO₂ by applying primary methods.

Primary method discussed here deals with the use of oil shale, air and water components. In the PF boiler, which simultaneously functions as a desulphurisation reactor, there takes place a natural desulphurisation process in the course of which the amount of SO₂ emissions is reduced up to four times (the SO₂ capture coefficient of a boiler at Eesti Power Plant is ~75%, and the specific emission of SO₂ is ~2,200 mg/nm³) [4].

Analysis of the results gained from the research and tests carried out in the pulverized oil shale-fired boiler have revealed that:

- quantity of the SO₂ capture sorbent (components such as CaO, MgO, K₂O, etc.) in oil shale is large, the stoichiometric ratio Ca/S is ~10;
- quality of the SO₂ capture sorbent is low (the content of active components capturing SO₂ in ash is small ~25%);
- efficiency of the SO₂ capture sorbent is low ~8% ($(0.75/10) \times 100\% = 7.5\%$).

The low efficiency of sorbent is related to large losses of sorbent which occur (Fig. 1):

- at large-fraction crushing of oil shale accompanied by a loss of ash (sorbent) – mechanical losses ~50%;
- at high flame temperature, which brings about agglomeration – losses caused by high temperature ~50%;

- at chemical destruction of mechanical and chemical additives contained in fly ash – chemical losses ~50%;
- due to the clogging of fly ash pores with sulphates accompanied by physical destruction – physical losses ~34%.

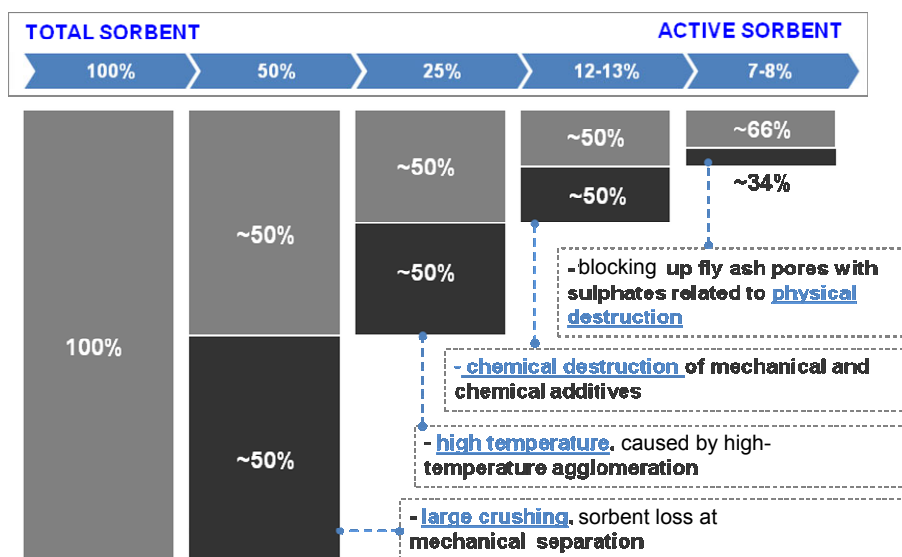


Fig. 1. Sorbent loss in pulverized oil shale boiler.

Calculations of the sorbent loss percentages have been based on the fly ash-focused research carried out in the PF boiler by the team from Universities of Technology in Tallinn and St. Petersburg [5-7].

The SO₂ capturing processes in the PF boiler and in the gas cleaning equipment operating on the basis of dry method are similar [8-11]. Basing on the results gained from the research on adsorption and chemisorption [12], and from the industrial tests focused on the dry sorbent-injection (SI) methods [13, 14], the following conclusions were reached:

- capturing of SO₂ with limestone at the stoichiometric ratio Ca/S ~3 results in ~50% of SO₂ being captured;
- efficiency of the SO₂ capture sorbent is ~16% $((0.50/3) \times 100\% = 16.7\%)$;
- efficiency of sorbent is two times higher $(16/8 = 2)$ when the SI method is applied.

A higher efficiency of sorbent is achieved due to:

- selection of the best sorbent (calcite content up to 95% and porosity up to 50%) which reduces chemical destruction;
- preparation of the best sorbent (particle size of crushed sorbent dust up to 30 μm) which reduces chemical separation;

- use of the best sorbent (sorbent is injected into the cooling section of the furnace) which reduces high-temperature agglomeration.

On the basis of the above-listed conclusions, the primary method for capturing SO₂ in the PF boiler was worked out.

Primary method consists of three optimisation levels: mode-related level, technological level and optimal construction level.

The mode-related level involves optimisation of the boiler's operational mode (quantitative modifications) and is related to the impacts that the quantities of oil shale, air and water injected into the boiler have on SO₂ emission.

The technological level involves optimisation of the boiler's technological parameters (qualitative modifications) and is related to a finer particle size of crushed oil shale dust, circulation of flue gases and to the impact of water injection on the SO₂ emission.

The optimal construction level involves optimisation of the boiler's design and is related to new constructional and technological solutions of boiler furnace, flue gas channels, heating surfaces and auxiliary equipment.

The analyses carried out led to the following conclusions:

- the quality of oil shale sorbent (porosity of limestone and its content in the mineral structure of oil shale) is predetermined by nature being intrinsic;
- it is possible to increase the SO₂ capture coefficient and enhance the efficiency of sorbent in the PF boiler, in case:
 - flame temperature is lowered, which will reduce high-temperature agglomeration;
 - oil shale is crushed to a finer particle size, which will reduce mechanical separation.

Results of experimental implementation of primary method

Mode-related level

More than 100 modes were tested during the research carried out on the Eesti Power Plant boiler walls 4-B and 1-B and on boiler No. 8 of the Balti Power Plant with the aim to study the impact of different modes on the SO₂, NO_x and RO_x emissions.

The technical possibilities and economic purposefulness of primary methods were studied with the aim of reducing the SO₂, NO_x and RO_x emissions.

Marking of *modes* and the mode parameters:

- 0-mode: max. load ($N = 0.9 N_{nom}$).
- L-mode: 0-mode + sliding excess-air coefficient (full opening of the fan control apparatus at secondary speed). $\Delta\alpha = 0.18$.

- LW-mode: L-mode + injection of water (clarified water from the ash disposal area) into the flame (via 4 nozzles into the upper-level burners). $\Delta W = 10$ t/h.
- B-load: optimal load ($N = 0.7 N_{nom}$). $\Delta N = 0.2$.
- BL-mode: B-mode + sliding excess-air coefficient (full opening of the fan control apparatus at primary speed). $\Delta \alpha = 0.20$.
- BLW-mode: BL-mode + water injection into the flame. $\Delta W = 10$ t/h.
- b-mode: min. load ($N = 0.4 N_{nom}$). $\Delta N = 0.5$.
- bL-mode: b-mode + sliding excess-air coefficient (full opening of the fan control apparatus at primary speed). $\Delta \alpha = 0.70$.
- bW-mode: b-mode + water injection into the flame. $\Delta W = 10$ t/h.

Analysis of the modes is presented in Table.

Results of the mode tests (0, LW, B, BLW) are presented in Fig. 2.

Table. Investment values calculated by authors basing on mathematical algorithm

C _b	10	€/t	t	6000	h	C _{bcond}	35	€/t
C _{CO₂}	20	€/t	z	10	a			
C _{NO_x}	8	M€	N _{max}	180	MW	e _{max}	0.08	
C _{RO_x}	8	M€	N _{min}	80	MW	e _{min}	0.1	
C _w	2	M€	N _{opt}	140	MW	e _{opt}	0.09	

Operation mode	C _{SO₂} mg/nm ³	η _{SO₂} %	η _E %	b _B g/kWh	q _{SO₂} g/kWh	q _{CO₂} g/kWh	Δb _B g/kWh	Δq _{SO₂} g/kWh	Δq _{CO₂} g/kWh	C _b €/t _{SO₂}	C _{CO₂} €/t _{SO₂}	C _{var} €/t _{SO₂}	C _{const} €/t _{SO₂}	C _Σ €/t _{SO₂}	β _{SO₂} %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
0	2200	75.6	30.1	409	10.49	1287	0.0	0.0	0	0	0	0	0	0	0.0
2 L	1600	82.2	29.4	418	7.81	1318	9.7	2.7	31	127	229	356	0	356	25.5
3 LW	1000	88.9	28.3	435	5.07	1369	26.0	5.4	82	168	302	470	0	470	51.6
4 B	1400	84.4	29.5	417	6.81	1313	8.3	3.7	26	79	142	221	0	221	35.0
5 BL	1100	87.8	28.4	433	5.56	1364	24.5	4.9	77	174	313	486	0	486	47.0
6 BLW	800	91.1	27.3	451	4.21	1419	41.9	6.3	132	233	420	654	0	654	59.8
7 b	1100	87.8	27.2	452	5.80	1424	43.6	4.7	137	325	586	911	0	911	44.6
8 bL	700	92.2	24.8	496	4.05	1562	87.3	6.4	275	475	855	1329	0	1329	61.3
9 bW	600	93.3	25.1	490	3.43	1544	81.4	7.1	256	404	727	1130	0	1130	67.2

Operation mode	C _{SO₂} mg/nm ³	η _{SO₂} %	η _E %	b _B g/kWh	q _{SO₂} g/kWh	q _{CO₂} g/kWh	Δb _B g/kWh	Δq _{SO₂} g/kWh	Δq _{CO₂} g/kWh	C _b €/t _{SO₂}	C _{CO₂} €/t _{SO₂}	C _{var} €/t _{SO₂}	C _{const} €/t _{SO₂}	C _Σ €/t _{SO₂}	β _{SO₂} %
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
10 LW/ROX	500	94.4	27.1	454	2.65	1430	45.2	7.8	142	202	363	565	103	668	74.7
11 BLW/ROX	400	95.6	26	473	2.21	1490	64.4	8.3	203	272	490	763	126	889	78.9
12 bLW/ROX	50	99.4	23.5	523	0.31	1649	114.8	10.2	362	394	710	1104	182	1286	97.0
13 NO _x	1000	88.9	29.8	413	4.82	1300	4.1	5.7	13	25	46	71	142	213	54.0
14 B/NO _x	800	91.1	28.7	429	4.00	1350	19.9	6.5	63	108	194	301	161	462	61.8
15 b/NO _x	600	93.3	26.5	464	3.25	1462	55.5	7.2	175	268	483	751	256	1007	68.9
16 RO _x /NO _x	500	94.4	28.5	432	2.52	1359	22.9	8.0	72	101	181	282	202	484	75.9
17 B/RO _x /NO _x	400	95.6	27.4	449	2.09	1414	40.3	8.4	127	168	302	470	249	720	79.9
18 b/RO _x /NO _x	50	99.4	24.8	496	0.29	1562	87.3	10.2	275	300	539	839	363	1202	97.1
19 RO _x /No _x /W	400	95.6	28.6	430	2.01	1355	21.4	8.5	68	88	159	248	214	461	80.8
20 B/RO _x /No _x /W	320	96.4	26.7	461	1.72	1451	52.0	8.8	164	208	374	582	269	850	83.5
21 b/RO _x /No _x /W	40	99.6	24.2	508	0.24	1601	99.6	10.3	314	340	612	952	406	1359	97.6

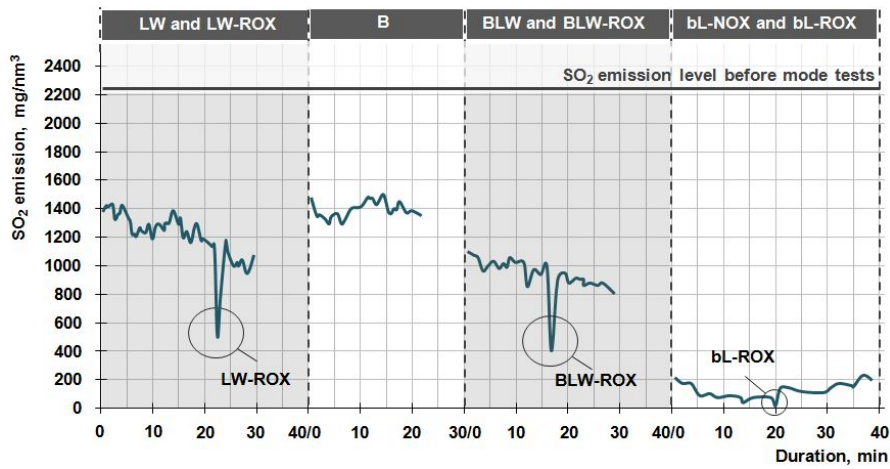


Fig. 2. Results of mode tests of primary method.

Source data subjected to changes:

- C_b – price of oil shale, €/t
- CCO_2 – price for CO₂ emission, €/t
- CNO_x – investment in flue gas circulation, million €
- CRO_x – investment in finer crushing of oil shale dust, million €
- CW – investment in water injection, million €
- t – number of operational hours of the energy block per year, h
- z – payback period, y
- $Cb\ cond$ – price of standard fuel, €/t

Source data on energy block:

- N_{max} – max. load of energy block, MW
- N_{min} – min. load of energy block, MW
- N_{opt} – optimal load of energy block, MW
- e_{max} – auxiliary power of energy block at max. load
- e_{min} – auxiliary power of energy block at min. load
- e_{opt} – auxiliary power of energy block at optimal load

Columns of the Table:

- Mode: code of mode
- CSO_2 : the rounded average specific emission of SO₂ per mode, mg/nm³
- $\Delta\eta\ SO_2$: the average SO₂ capture coefficient per mode, %
- $\eta\ E$: average efficiency of the energy block per mode, % η
- bB : average specific fuel consumption of standard fuel per mode, g/kWh
- qSO_2 : average discharge of SO₂ specific emissions per mode, g/kWh

- q_{CO_2} : average discharge of CO₂ specific emissions *per* mode, g/kWh
- Δb_B : average increase in the specific fuel consumption of standard fuel, g/kWh
- Δq_{SO_2} : average decrease in the SO₂ specific emissions *per* mode, g/kWh
- Δq_{CO_2} : average increase in the CO₂ specific emissions *per* mode, g/kWh
- C_b : cost for surplus consumption of fuel per reduction of 1 t of SO₂ emission, €/t of SO₂
- CCO_2 : cost for the increased CO₂ emission when the SO₂ emission is reduced, €/t of SO₂
- C_{var} : variable costs per reduction of 1 t of SO₂, €/t SO₂
- C_{const} : investment cost per reduction of 1 t of SO₂ emission, €/t SO₂
- C_{Σ} : costs per reduction of 1 t of SO₂ emission, €/t SO₂
- β_{SO_2} : relative decrease in the SO₂ emission, %

Analysis of the advantages and drawbacks of primary method modes:

Advantages

1. no investments needed (desulphurization takes place in the boiler);
2. no sorbents needed (air and water are injected);
3. no further processing, transportation or storage of the produced solid emissions (sulphates) is needed (removed together with ash);
4. satisfactory level of the SO₂ specific emission ~800 mg/nm³;
5. satisfactory level of costs related to capturing SO₂ ~654 €/t SO₂ (price of oil shale – 10 €/t and price of CO₂ – 20 €/t) Proposed values are indicative and can be changed according to actual circumstances;
6. in 2012, it will be possible that the existing energy blocks of Narva Power Plants will generate ~6 TWh of electricity per year (taking into account the prescribed quota of SO₂ – 25 thousand t/4.21 thousand t of SO₂/TWh = 5.9 TWh).

Drawbacks

1. inadequate level of the discharge of SO₂ specific emissions (the level required starting from the year 2016 is 400 mg/nm³);
2. high energy intensity $b_B = 450.6$ g/kWh (increase in the consumption of oil shale by 10.4%);
3. high level of the CO₂ specific emission $q_{CO_2} = 1419.4$ g/kWh (increase in the amount of CO₂ emissions by 10.4%);
4. remarkable wearing (erosion) of heating surfaces (an up to 40% increase in the wearing of heating surfaces, since the flue gas velocity increases by up to 14%). In case the SO₂ emission is reduced by 1 t, the increase in the costs related to erosion remains below 1% of total costs;

5. in 2016, it will be possible that the existing energy blocks will generate ~1.5 TWh of electricity (with the permitted level of SO₂ specific emission being 400 mg/nm³). The specified amount will be produced in co-operation of the Eesti Power Plant energy blocks Nos. 7 and 8 with the Balti Power Plant energy blocks Nos. 11 and 12.

Discussion

Tests of primary method modes indicated that optimisation of the boiler modes induces a decrease in the flame temperature from ~1,450 °C (0-mode) down to ~1,150 °C (BLW mode), causing the reduction of SO₂ specific emission by up to 60%.

A switch-over to primary method modes requires performance of check tests (during ~240 hours) in order to specify the impact of modes on the efficiency, operating reliability and ecology.

Reaching the SO₂ specific emission level ~800 mg/nm³ is an incomplete solution, since (starting from 2016) the level required is 400 mg/nm³.

Please note the following principle of dialectics: winning involves losing.

A simple solution (primary method modes), which requires no investments and sorbents, no cleaning, transportation and storage of emissions, involves an increase in the costs for oil shale, CO₂ and wearing of heating surfaces.

In order to meet the SO₂ specific emission limit value (400 mg/nm³) [1] set as a target for 2016 by the European Union, it is advisable to apply flue gas circulation, finer crushing of oil shale dust and water injection first to one of the pulverized oil shale-fired boilers for the purpose of studying the impacts of these factors on the SO₂ emission.

Flue gas circulation is used to lower the flame temperature, which in turn reduces high-temperature agglomeration.

A smaller particle size of oil shale dust achieved due to finer crushing facilitates the reduction of mechanical losses and enlarges chemisorption surface of fly ash.

For a long time, both primary measures have been widely and successfully applied at coal-firing power plants for the reduction of NO_x emissions [15–20].

Application of the referred primary methods to pulverized oil shale firing shall reduce the emissions of NO_x as well as of SO₂. The results of the tests carried out on the walls of a boiler at the Eesti Power Plant prove the decrease in SO₂ emissions. The tests imitated those carried out earlier on a boiler at the Balti Power Plant where application of finer oil shale and water injection after superheater resulted in an enlarged chemisorption surface of fly ash.

Water injection after superheater activates fly ash. The water injection method is a simplified high-temperature method developed on the basis of

the LIFAC gas cleaning method. For a long time, the LIFAC gas cleaning method has been successfully and widely applied at coal-firing power plants for the reduction of SO₂ emissions [21, 22].

The advantage of primary methods lies in considerably smaller investments and operation costs compared to those related to the gas cleaning equipment – *i.e.* SO₂ scrubbers and catalytic reactors for NO_x [23–27].

Earlier, investments to be made in the application of primary methods to pulverized oil shale firing were estimated at one boiler of the Eesti Power Plant (two boiler walls) as follows:

- 8 million € – investment in finer crushing of oil shale dust;
- 8 million € – investment in flue gas circulation;
- 2 million € – investment in water injection.

Values proposed for the above-mentioned investments are indicative and can be changed according to actual circumstances.

Payback period, with physical depreciation of energy blocks taken into account, is estimated to be 10 years.

In Table and in Fig. 3 the source data on investments and operation can be modified, and the relevant impacts, resulting from such modifications, on the cost of the reduction of 1 ton of SO₂ emission can be estimated.

Marking of the technological modes and the technological parameters of modes:

- LW/RO_x-mode imitates finer crushing of oil shale dust: max. load, sliding excess-air coefficient, water injection into the flame and increased concentration of the fly ash. MRS operation (three-minute shaking of the primary and secondary screens of the downstream flue gas channels).
- BLW/RO_x-mode imitates finer crushing of oil shale dust: optimal load, sliding excess-air coefficient, water injection into the flame and increased concentration of the fly ash.
- bL/RO_x-mode imitates finer crushing of oil shale dust: min load, sliding excess-air coefficient, water injection into the flame and increased concentration of the fly ash.
- NO_x flue gas circulation mode, analogous to the LW-mode at capturing SO₂: max. load.
- B/NO_x flue gas circulation mode, analogous to the LW-mode at capturing SO₂: optimal load.
- b/NO_x flue gas circulation mode, analogous to the bL-mode at capturing SO₂: min. load.
- RO_x/NO_x mode involves finer crushing of oil shale dust and flue gas circulation, analogous to the LW/RO_x-mode at capturing SO₂: max. load.
- B/RO_x/NO_x mode involves finer crushing of oil shale dust and flue gas circulation, analogous to the LW/RO_x-mode at capturing SO₂: optimal load.

- b/RO_x/NO_x mode involves finer crushing of oil shale dust and flue gas circulation, analogous to the bL/RO_x-mode at capturing SO₂: min. load.
- RO_x/NO_x/W: RO_x/NO_x-mode + the water injection mode which reduces the SO₂ specific emission by 20% compared to the RO_x/NO_x-mode: max. load.
- B/RO_x/NO_x/W: B/RO_x/NO_x-mode + the water injection mode which reduces the SO₂ specific emission by 20% compared to the B/RO_x/NO_x -mode: optimal load.
- b/RO_x/NO_x/W: b/RO_x/NO_x-mode + the water injection mode which reduces the SO₂ specific emission by 20% compared to the b/RO_x/NO_x-mode: min. load.

Results gained from the tests of the primary method modes LW/RO_x, BLW/RO_x, bL/RO_x are presented in Fig. 2 and Table.

Analysis of the advantages and drawbacks of the primary method:

Advantages

1. satisfactory level of the SO₂ specific emission – 400 mg/nm³;
2. satisfactory energy intensity bB = 430.0 g/kWh (consumption of oil shale increases by 5.4%);
3. satisfactory level of the CO₂ emission – qCO₂=1,355 g/kWh (the amount of CO₂ emissions increases by 5.4%);
4. satisfactory level of the wearing (erosion) of heating surfaces (the wearing of heating surfaces decreases from 40% in the BLW mode to 20% in the B/NO_x-mode, since the circulation of flue gases reduces flue gas velocity, and finer crushing of oil shale dust makes the particles of the oil shale fly ash smaller, thus reducing the kinetic energy and wearing of heating surfaces);
5. satisfactory level of costs related to capturing SO₂ – 461 €/t of SO₂ (optimal ratio of investment costs 214 €/t SO₂, and operation costs 248 €/t SO₂);
6. a technology in no need of sorbent;
7. the produced solid particles are removed together with ash;
8. the SO₂ specific emission target level set for 2016 will not restrict the generation of electricity on the basis of existing energy blocks at Narva Power Plants.

Drawbacks

– Data not available.

Conclusions basing on the imaginary tests of primary method are as follows:

The tests of the imaginary modes of primary method indicated that the SO₂ specific emission limit value (400 mg/nm³) set by the European Union

for 2016 can be achieved through optimising technological parameters of boiler by applying primary methods.

A switch-over to the primary method modes requires actual tests to be conducted in order to specify the impact of technological changes on efficiency, operation reliability and ecology.

For this purpose, the following matters should be clarified:

- possibilities of existing mills for finer crushing of oil shale;
- flue gas circulation possibilities for lowering flame temperature [20];
- water injection possibilities for activating fly ash.

Energy intensity and the amount of CO₂ emission can be reduced by optimising the BLW mode.

For this purpose, the following matters should be clarified:

- possibilities for multiple-stage crushing of oil shale (enrichment of oil shale with kerogen in the first stage and with calcite in the final stage). This should reduce the energy consumption needed for crushing, since only calcite is crushed to finer particles;
- possibilities for multiple-stage combustion (changing the excess-air coefficient in burners). This shall improve the capture of SO₂ and reduce the circulation of flue gases;
- possibilities for multiple-stage injection of water (into superheater, after the economizer and the air pre-heater). This shall improve the capture of SO₂ and reduce the amount of water to be injected.

Conclusions

The application of primary method enables to achieve the target value of SO₂ specific emission 400 mg/nm³ at firing pulverized oil shale in the existing boilers. It will also be possible to meet the SO₂ specific emission limit value (200 mg/nm³) set by the European Union for the new installed solid-fuel boilers by further optimising the PF-technology parameters and construction of oil shale boiler on the basis of primary methods. This would make it possible to design a PF boiler for supercritical and ultracritical steam parameters and to enhance the efficient and environmental-friendly use of oil shale to a considerable extent.

The following fact should be taken into account at optimization of boiler construction (*i.e.* improvement of SO₂ capture): the efficiency of desulphurisation depends on two physical-chemical processes – lime burning and lime sulphurization.

Lime burning (dissociation of calcite) occurs in the flame and in the cooling section of the furnace. The efficiency of lime burning depends on the quality of limestone and on technological parameters of the burning process – *i.e.* on temperature and time. The higher the quality of limestone (cleaner, more porous and finer) and the closer the combustion temperature of lime-

stone to the lime agglomeration temperature, the higher the quality of lime and the more efficient the following SO₂ adsorption.

Lime sulphurisation (chemisorption of SO₂) occurs in the boiler; the process starts when flue gases exit the furnace and continues in the boiler's flue gas channels. The efficiency of lime sulphurization depends on the quantity and quality of lime, on concentration of flue gas components and on technological parameters of the lime sulphurization process *i.e.* on temperature and time. The larger the quantity of lime (Ca/S), the higher its quality (cleaner, more porous and finer) and the higher the concentrations of SO₂, O₂ and H₂O in flue gases – the more effective the chemisorption of SO₂.

The closer the lime sulphurization temperature to the lime agglomeration temperature and the longer the period of lime sulphurization – the more effective the chemisorption of SO₂.

Improvement of the capture of SO₂ by optimising boiler construction is a topic which requires further research, construction-related solutions and tests.

In order to achieve the SO₂ limit value (400 mg/nm³) set by the European Union for 2016 and work out a commercial solution of the BLW technology, flue gas circulation with oil shale dust crushed to a finer particle size should first be applied and tested on one of the boilers. Flue gas circulation lowers flame temperature and the oil shale dust of a finer particle size enlarges the fly ash adsorption surface. Both measures have for a long time been successfully and widely applied in coal-firing power plants for the reduction of NO_x emissions (at oil shale firing, both NO_x and SO₂ emissions would decrease). Considerably smaller investments and operation costs compared with those needed for gas cleaning equipment, *i.e.* the SO₂ scrubbers and the NO_x catalytic reactors, can be pointed out as advantages of these measures.

The future of oil shale power industry will depend on how successful we are in fulfilling the ecology-related requirements set by the European Union. If we are able to implement them cheaper than in case of coal-fired power plants, we will definitely ensure the sustainability of oil shale power industry in Estonia. However, copying of the ecological technologies used at coal-firing power plants will require 1.5 times larger investments and increase the risk by 30%.

Note that the capture properties of oil shale ash are similar to those of cement. Carburizing of ash is an obstacle to the use of semi-dry and wet technologies for capturing SO₂.

Consequently, the primary method of SO₂ capture is a “lifebuoy” to guarantee the continuing development of oil shale power industry in Estonia after the year 2012 (Fig. 3).

Note that in case the application of primary method does not enable to achieve the SO₂ specific emission target value 400 mg/nm³ in the PF boilers in operation, which is of little probability the additive method (addition of high-quality conditioners, sorbents and convertors into the boiler or electric filter) must be applied.

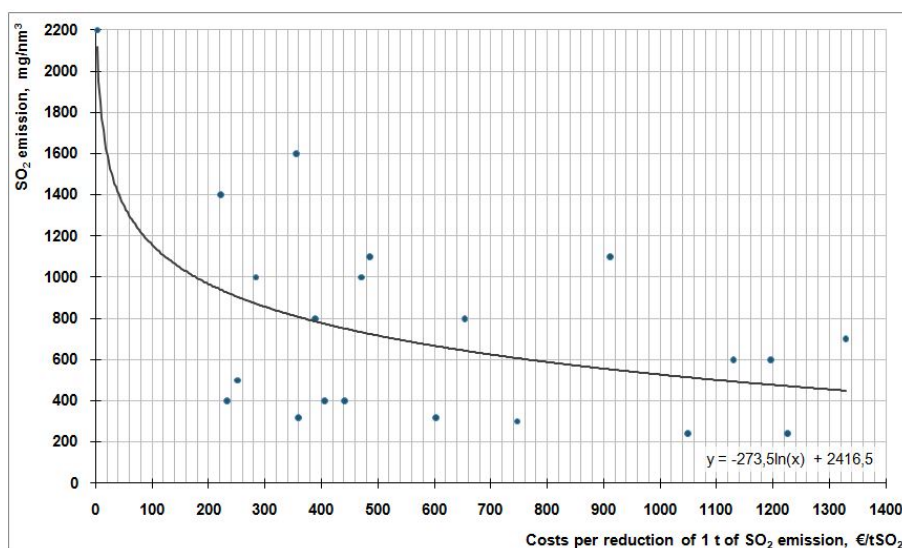


Fig. 3. Costs per reduction of 1 ton of SO₂ emission.

In order not to allow the SO₂ emission level to exceed in 2012 the SO₂ emission quota (25 thousand tons) established by the European Union, a long-term (during ~240 hours) check test on one boiler must be followed by a switch-over to BLW modes, which will make it possible for Narva Power Plants to achieve the output of up to 6 TWh of electricity on the basis of existing energy blocks.

Figure 4 describes how the cost of carbon dioxide influences the cost of one ton of bound SO₂ when using the specific method of SO₂ binding. Vertical axis shows the cost of one bound SO₂ ton in €, and horizontal axis shows the change in the cost of CO₂ ton with CO₂ basic price being 20 €/ton (0% value on horizontal axis).

The smallest effect is revealed by the methods in the case of which a smaller fall in power efficiency and bigger SO₂-binding degree were projected. The initial data displayed in the Table serve as a basis for the analysis of SO₂ effect sensitivity.

Figure 5 characterises how the projected investments, necessary for integrating the specific methods of SO₂ binding into operation, influence the cost of one ton of bound SO₂. Vertical axis shows the cost of one ton of bound SO₂ in € and horizontal axis shows the change in investments expressed in percentages. Basic values of investments have been separately set out in the Table.

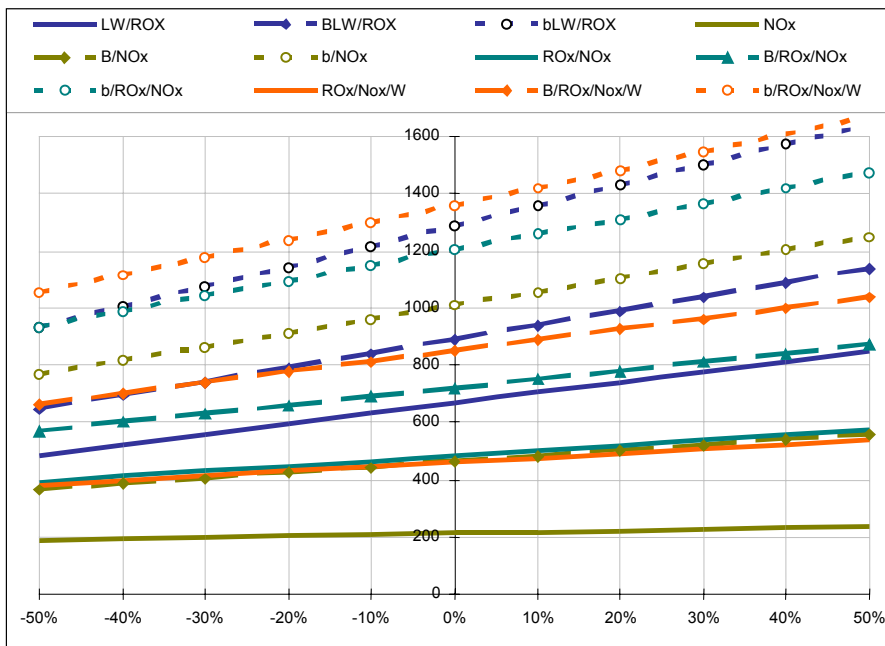


Fig. 4. Cost for 1 ton of CO₂.

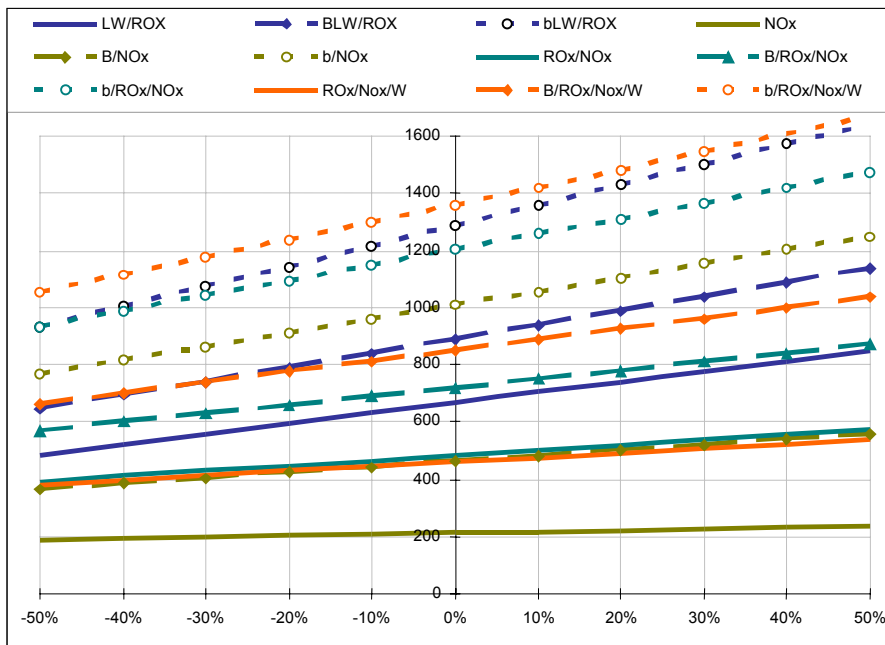


Fig. 5. Projected investments.

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