COMBUSTION OF ESTONIAN OIL SHALE IN FLUIDIZED BED BOILERS, HEATING VALUE OF FUEL, BOILER EFFICIENCY AND CO$_2$ EMISSIONS

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The paper gives an overview of changes in heating value of Estonian oil shale, when it is burned in fluidized bed (FB) boilers, and of the accompanying phenomena – increase in boiler efficiency, fuel flow, and decrease in harmful atmospheric emissions. In the context of boiler efficiency, the paper also tackles the issue of the extent of the actual increase in efficiency and the importance of partial decomposition of carbonate in the mineral part of oil shale, and almost complete sulphur binding in FB boilers.

Compilation of boiler heat balance and determination of boiler efficiency is based on heating value of the burned fuel. As a rule, lower heating value of the fuel as received is used, re-calculating the value measured experimentally in the calorimetric bomb [1, 2]. In practice, for some types of fuel we have to take into account several other factors that can affect the heating value. Estonian oil shale is just such a fuel. Decomposition of carbonate present in the mineral part of oil shale and binding of sulphur by ash are the factors affecting heating value in this particular case.

As for the heat effect caused by carbonate decomposition and sulphur binding in the case of Estonian oil shale, the presence of magnesium and calcium carbonates (MgCO$_3$ and CaCO$_3$) in its carbonate part should be taken into account. Both carbonates exhibit negative dissociation heat (i.e. their dissociation requires heat). As magnesium carbonate dissociates at lower temperatures than calcium carbonate, magnesium carbonate indeed dissociates before calcium carbonate when fuel is burned. A part of calcium carbonate is present in dolomite, but most of it is nevertheless present in the form of calcite (CaCO$_3$).

Proceeding from the data about the average composition of the carbonate part of oil shale published in [3, 4], MgCO$_3$ comprises 13.80% of the carbonate part while the percentage of CaCO$_3$ is 85.85%. The remaining

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0.35% is $FeCO_3$, and its influence is usually not included in calculations due to its small amount. The heat effect caused by decomposition of carbonates, if carbonates dissociate completely, is 3.882 MJ for kg released CO_2. If carbonates dissociate partially, the component remaining intact is calcite, and calculations of the heat effect at lack of carbonate decomposition should be based on dissociation heat of calcite, that is 4.1232 MJ for kg released CO_2. The heat effect of sulphur binding by ash is positive (i.e. it releases heat) and is 15.616 MJ for kg of bound sulphur.

When determining heating value of the fuel as received in calorimetric bomb [1], the presumption is made that, if heating value of oil shale exceeds 5.540 MJ/kg, carbonates dissociate completely and the extent of sulphur binding is so small that its heat effect should not be taken into account. That is why lower heating value (Q^r_i), calculated on the basis of the data obtained, corresponds to the conditions when the extent of carbonate decomposition $k_{CO_2} = 1$ and sulphur binding extent $k_S \approx 0$.

Since the extent of carbonate decomposition in pulverized-firing (PF) boilers is high, 0.97–0.98 on average, and the heat effect caused by sulphur binding, despite binding extent 0.75–0.80 is not very high, boiler calculations have often been based on lower heating value of oil shale. In order to demonstrate how substantial an error this can cause, the results of calculations made mostly on the basis of the data about oil shale currently used at power plants are presented below.

Table 1. **Correction of Lower Heating Value of Oil Shale Fired in PF Boilers**

Indices	Value			
Heating value of fuel as received Q^r_i, MJ/kg	8.400			
Total sulphur content in fuel as received S^r_t, %	1.5			
Carbonate CO_2 content in fuel as received $(CO_2)^r_M$, %	17.74			
Extent of carbonate decomposition k_{CO_2}	0.97	0.98	0.97	0.98
Extent of sulphur binding k_S	0.75	0.75	0.80	0.80
Correction factor for heating value due to incomplete decomposition of carbonates $\Delta Q^r_{i\,carb}$, MJ/kg	0.022	0.015	0.022	0.015
Correction factor for heating value due to sulphur binding $\Delta Q^r_{i\,sulph}$, MJ/kg	0.079	0.079	0.091	0.091
Corrected heating value of fuel as received fuel $Q^r_{i\,correc}$, MJ/kg	8.501	8.494	8.513	8.505
Ratio of heating values $Q^r_{i\,correc}/Q^r_i$	1.012	1.011	1.013	1.013

As the calculation results indicate, the increase in heating value due to non-dissociation of carbonates and sulphur binding makes 1.1–1.3% of oil-shale lower heating value and can thus, if extreme precision is not required, not be taken into account.

The situation is somewhat different in the case of FB boilers. As demonstrated at testing of the new FB boiler installed at the Eesti Power Plant, the extent of carbonate decomposition in this boiler is only 70–75% (sometimes even less) due to a low temperature in the furnace (~800 °C) and sulphur is practically completely bound by ash in the boiler. As a result of all

this, the increase in heating value of oil shale in FB boilers is higher than that in PF boilers. The data on the increase in heating value for the carbonate decomposition range $k_{CO_2} = 0.70$–0.75 are presented in Table 2. The calculation is based on oil shale characteristics given in Table 1 (but the extent of sulphur binding at FB is 0.999).

As demonstrated by the data in Table 2, heating value of oil shale in FB boilers is, on average, over 3% higher than that in PF boilers (see Table 1) due to a substantially lower extent of carbonate decomposition and almost complete binding of sulphur. (Compared to lower heating value determined in calorimetric bomb – even ~4%).

It is clear that the higher heating value of oil shale the less of it is needed to produce the same amount of heat.

As the amount of oil shale feed depends on oil shale heating value, it depends also on the composition of the carbonate mineral. To characterize this dependence, Fig. 1 illustrates the data about the decrease in consumption of oil shale of different heating values depending on the extent of carbonate decomposition. Heating values of tested oil shales 8.200 and 8.600 MJ/kg cover the main range of heating value of oil shale used in power plants. The calculations are based on average characteristics of oil shale determined in accordance with the methods described in [3].

As for calculating the efficiency of FB boilers, it is clear that when calculations are based on lower heating value determined in calorimetric bomb, the results are higher than the actual ones because in this boiler the extent of carbonate decomposition is less and the extent of sulphur binding higher, owing to what an additional amount of heat is produced that is not considered in fuel specification. Thus, the boiler efficiency calculated is ostensible and includes both the actual value and an additional effect caused by the increase in heating value.

The increase in heating value due to decomposition of carbonates, as the data in Table 2 show, is approximately 4% and can be easily calculated when the extent of carbonate decomposition is known. It should be noted here that the data in Figs 1 and 2, the latter concerning fuel flow and decrease in CO_2 emission, were calculated only on the basis of the additional heat effect caused by non-decomposition of carbonates and sulphur binding. The actual efficiency of the FB boiler improved heat utilization in the boiler was not included in the calculation.

Table 2. **Increase in Oil Shale Heating Value Depending on the Extent of Carbonate Decomposition**

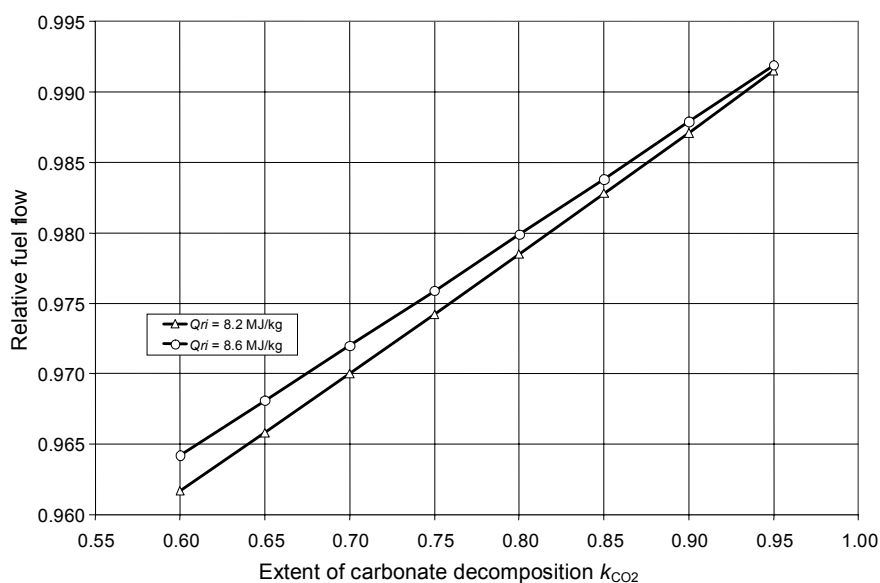| Extent of carbonate decomposition k_{CO_2}	Corrected heating value of fuel as received $Q^r_{i\ correc,}$ MJ/kg	Ratio of heating values $Q^r_{i\ correc}/Q^r_i$
0.70	8.755	1.042
0.71	8.748	1.041
0.72	8.741	1.041
0.73	8.733	1.040
0.74	8.726	1.039
0.75	8.719	1.038

Fig. 1. Relative fuel flow depending on the extent of carbonate decomposition

As demonstrated at testing of FB boilers at the Eesti Power Plant, their efficiency, when operating at nominal load, was 93.29–94.90% that is substantially more than the efficiency of PF boilers (in 2002 the average efficiency of the TP-101 boilers was 82.28% [5]). As the calculated efficiency of FB boilers was based on heating value in calorimetric bomb, this efficiency did not account the heat released by sulphur binding and the heat added by non-decomposition of carbonates. The calculation corrected by accounting these heat effects gave approximately 4% lower value for boiler efficiency, compared to the value calculated basing on heating value in calorimetric bomb. The numerical values of efficiencies are between 89.03–90.86%. These values might be somewhat higher compared to long-term operation numbers because during the tests boilers operated in a well-tuned mode.

Another positive characteristic for FB boilers is the decrease in the amount of CO_2 emitted into the air. PF boilers are still plagued by a large amount of atmospheric emissions of CO_2 caused by the fact that the amount of CO_2 formed at combustion of the organic part of the fuel is coupled by the amount of CO_2 from the dissociation of carbonates in the mineral part. The amount of CO_2 released into the air from FB boilers is much less owing to two reasons.

Firstly, the amount of CO_2 is decreased due to smaller extent of carbonate decomposition in these boilers on account of lower temperatures in the furnace. Secondly, a smaller extent of carbonate decomposition and a larger one of sulphur binding both cause an increase in the amount of heat released from the fuel fed into the boiler. It means that less fuel is needed to produce

the same amount of steam. The new energy block equipped with FB boilers produces the same amount of energy combusting less fuel at higher efficiency. The reconstructed steam turbine of higher efficiency has also contributed to higher efficiencies of boiler operation.

As for the extent of carbonate decomposition of Estonian oil shale, it is easy to determine basing on ash analysis only if no great precision is needed. In fact, 99.2%, on average, of CaO present in oil shale, and 96.7%, on average, of MgO belong to the composition of carbonate minerals. As CaO and MgO do not evaporate in the firing process but are completely transferred into ash, their content in ash allows for easy calculation of the amount of carbonate CO_2 in the fuel as received. Knowing the amount of carbonate CO_2 in ash, it is easy, on the basis of this data, to establish the extent of carbonate decomposition.

Figure 2 gives the data on CO_2 emissions and fuel consumption in the FB boiler depending on the extent of carbonate decomposition calculated as percentage from the corresponding data for the PF boiler. For both boiler types, lower heating value of oil shale determined in calorimetric bomb was used – 8,400 MJ/kg. The extent of carbonate decomposition and that of sulphur binding in the PF boiler being compared were taken constant, $k_{CO_2} = 0.98$ and $k_S = 0.80$, respectively. The extent of carbonate decomposition in the FB boiler varied in the range of 0.60–0.95, the extent of sulphur binding was 0.999.
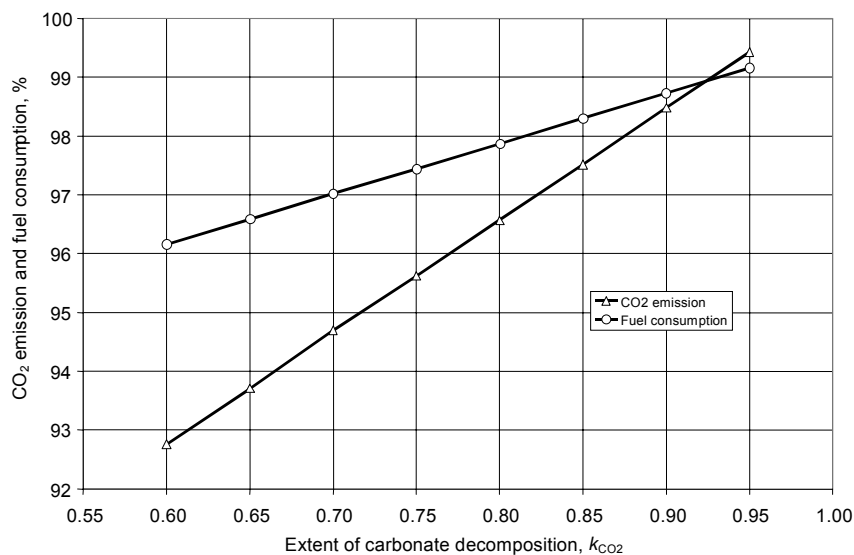

Fig. 2. Changes in fuel consumption and the amount of CO_2 depending on the extent of carbonate decomposition

Actually, the differences between the data on FB boilers and PF boilers considering fuel consumption and CO_2 emissions are considerably larger than those given in Fig. 2 because fuel economy owing to higher efficiency of FB boilers compared to TP-67 and TP-101 ones is not taken into account.

To get comparable data about the decrease in the amount of CO_2 emissions in energy units equipped with FB boilers an approximate calculation was carried out. CO_2 amounts emitted from the new CFB energy block No. 8 (2004) and from PF energy block with TP-101-type boilers (average over the year 2002) were compared [5]. The results of calculations are presented in Table 3.

Table 3. **CO_2 Discharge from PF and FB Energy Units**

Item	PF unit	CFB unit
Electric output of energy unit (mean), MW	147	186,7
Specific fuel rate of conventional fuel (29.308 MJ/kg), g/kWh	400.5	346.0
Specific heat rate:		
as kJ/kWh	11,737.9	10,140.6
as kWh/kWh	3.260	2.817
Heating value of as received fuel, kJ/kg	8420	8410
Specific fuel rate of as received fuel, kg/kWh	1.394	1.206
Carbonate decomposition extent, k_{CO_2}	0.97	0.70
CO_2 discharge (calculated per fuel kg), Nm^3/kg	0.468	0.4492
Density of CO_2, kg/Nm^3	1.964	1.964
CO_2 discharge per kg, kg/kg	0.9192	0.8822
CO_2 discharge per kWh, kg/kWh	1.2813	1.0636
CO_2 discharge of CFB units related to the PF units, %		83.0

Basing on investigation published in [6] the extent of carbonate decomposition for PF boilers k_{CO_2} is 0.97. It has to be mentioned that at testing the FB boiler the amount of CO_2 was even approximately 77% of the data given in Table 3.

To sum up, it must be noted that the re-equipment of an oil shale power plant replacing PF boilers by FB boilers is accompanied by several changes, vital and useful for environment protection.

The main changes are:

1. Boiler efficiency increases from 81–82% to ~90–94%[*], thus also decreasing fuel consumption.
2. The emission of SO_2 into the atmosphere stops almost completely.
3. Emission of CO_2 from FB energy units decreases by up to 20% compared to PF energy units.

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[*] Efficiency characteristics of boiler and energy unit of PF and CFB processes are difficult to compare because of different methods used at estimation (Editor's comment).

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