Technology of Thermal Preparation of Coal for Ecologically Pure Combustion of Fuel in Small Boilers

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Abstract. The problems of ecologically clean coal combustion are connected with the need to reduce the formation of pollutants to the environment during thermal transformation of fuel. Currently, about 180-190 million tons of coal are burned in Russia to produce heat and electricity, with more than 60% in the eastern regions of the country. Most of the coal (about 80%) is consumed by large thermal stations, which are equipped with pollutant trapping systems. The remaining part is burned in numerous boiler houses that operate in both urban and rural areas to provide heat to social facilities and the population. The analysis shows that the role of boiler houses increases significantly in the territories with a low population or in remote and decentralized areas. In this regard, the coal pretreatment technology before burning including the thermal preparation of coal is important. The use of thermally prepared fuel (semi-coke) will significantly reduce emissions of NOx and SOx, as well as improve the "culture" of thermal energy production at small boilers by switching to fully automated technologies, as well as significantly reducing the financial burden of utilities by reducing the wage fund and emission fees.

1. Introduction

A distinctive feature of the eastern regions of Russia from the subjects of the central and European parts of the country is the use of coal in boiler houses of various capacities for the needs of heat supply to the population. As a rule, coal from local deposits is used to ensure its availability and relative low cost for consumers of small settlements.

It should be noted that the burning of coal, from an environmental point of view, is more connected with the emission of pollutants into the atmosphere. It is known that when burning fossil fuels, including coal, in various power plants, oxides of sulfur and nitrogen are typical harmful impurities.

The main types of heat sources in small settlements in the eastern part of Russia are boiler houses with boilers of small capacity (up to 1 Gcal/h) with layer burning of solid fuel and manual loading. These boiler houses, as a rule, provide heat to separate public and administrative buildings or to a small group of such consumers. The efficiency of small heat sources on coal is usually very low and amounts to about 40-50%. Flue gas purification is not performed or is unsatisfactory. Even in the presence of cyclones in the boiler houses, they are in bad condition and lack repairs due to chronic unprofitability of such heat sources.

Environmentally friendly combustion of coal in small-capacity boilers, and, accordingly, reducing or eliminating the emission of pollutants into the elements of the environment, primarily include the preparation of fuel for its combustion. The preparation of fuel before burning needs appropriate
storage of fuels, loading/unloading, protection against wind erosion and waterlogging, as well as energy and resource saving measures, taking into account the conditions of application. Such an approach is the most acceptable for small capacity boiler houses. As a rule, the measures mentioned above allow reducing fuel consumption in boiler houses by up to 20% and, accordingly, decrease emissions. Sorting fuel can increase fuel combustion efficiency by 5-12%. At the same time, the reduction of fuel consumption by up to 24% will entail a decrease of emissions into the atmosphere and ash and slag waste formation [1].

Another technology for the preparation of fuels before burning is an energy-technological processing of coal, the so-called purification of solid fuels. Such technologies of cleaning fuel with producing secondary products have become widespread in the coal mining, oil refining and coking industries. In the case of small boiler houses, the improvement of fuel quality due to the production of refined coal-based fuels becomes especially topical. In essence, this is the process of semi-cooking or thermal preparation of coal. Thermal preparation technologies of coal before burning allows reducing moisture, ash content, and sulfur content with increasing calorific value of fuels. Extraction or reduction of these components in the fuel, in turn, will allow reducing the emission of pollutants to the environment.

In general, the amount of emissions of harmful substances depends on the qualitative composition of the fuel, its quantity, and the combustion conditions in the boiler houses as well as on the work of purification equipment. However, first of all, the emission of pollutants into the elements of the environment during coal combustion essentially depends on the qualitative composition of fuels [2].

2. The dependence of the pollutant emissions into the atmosphere on the quality of coal

To identify the dependence of pollutants emissions on the qualitative composition of coal, a number of calculations were carried out. They were based on the methodological recommendations for determining the amount of pollutants entering the air basin when burning fuel in boiler houses with a capacity of less than 30 tons of steam per hour or less than 20 GCal per hour [3, 4].

For example, formula (1) is used to calculate the amount of particulate matter emissions ($M_{PM}$):

$$M_{PM} = 0.01 \times B \times (A_f \times A_r + q_4 \times (q_r^{d})^{32680}) \times (1 - \frac{\eta}{100}),\text{ tonn per year (g/s)}$$  \hspace{1cm} (1)

Here: $B$ is the fuel consumption, tonn per year (g/s), $A_r$ is the ash content of fuel, $\%$, $a_{fa}$ is the ash fraction in ablation, $q_4$ is the heat loss with mechanical underburning of fuel, $\%$, $Q_r$ is the calorific value of the fuel, and $kJ/kg$, $\eta$ is the percentage of particulate matter captured in the ash collector, $\%$.

As can see from formula (1), the amount of particulate matter emissions directly depends on fuel consumption, ash content, combustion conditions and operation of purification equipment.

As an example, the amount of particulate matter emissions of different coals were calculated under the same fuel consumption (88 kg c.e./h [5]), the conditions of combustion and purification of flue gases. The quality characteristics of coals are presented in table 1.

**Table 1.** The main quality characteristics of various coals.

| Coal          | $W$, $\%$ | $A$, $\%$ | $S$, $\%$ | $Q$, $MJ/kg$ |
|---------------|-----------|-----------|-----------|--------------|
| Mugunsky      | 21.6      | 5.6       | 0.6       | 16.6         |
| Azeisky       | 12.2      | 7.6       | 0.1       | 30.2         |
| Tarasovsky    | 12.8      | 10.3      | 0.4       | 24.2         |
| Cheremkhovsy  | 3.3       | 16.8      | 1.0       | 26.9         |
| Kharanutsky   | 2.7       | 26.5      | 1.1       | 34.3         |

Note: $W$ – moisture content, $A$ – ash content, $Q$ – calorific value of fuel, $r$ – as received, $d$ – dry, $daf$ – dry ash free fuel mass.

When ranking coals according to the degree of ash content increase in the fuel, the emission of particulate matters is seen to increase proportionally, figure 1.
Figure 1. Dependence of particulate matters emissions on ash content in coals.

However, the influence of fuel quality characteristics is not so unambiguous [2]. For example, ash content has a direct relationship to the amount of particulate matters emissions, as is the sulfur content in the initial fuel which is proportional to the amount of sulfur oxide emissions. However, the emission of nitrogen oxides is only partially dependent on nitrogen content in the coal, since in the fuel combustion, the so-called “air” nitrogen oxides are formed, the amount of which depends on the combustion conditions.

The calorific value of fuels directly depends on the amount of emissions of nitrogen oxides; and numerous calculations (ceteris paribus) have shown that in the case of emissions of particulate matters, emission decreases by an average of 0.15 - 0.18% per each percent of rise of calorific value of coal, i.e. slightly.

In general, the change in the quality of the fuel before it is burned in boiler houses can significantly change the end result, i.e. the emission of pollutants into the atmosphere. It is possible to achieve such a change using the technology of thermal preparation of coal.

3. Technology of thermal preparation of coal

Recently, the greatest interest has been shown to technologies of preparation of coal for burning in boiler rooms. One of such technologies is coal sorting, which allows increasing the efficiency of coal combustion by reducing mechanical and chemical underburning. Another technology is the thermal preparation of coal resulting in the production of semi-coke that improves reactionary and environmental characteristics (the absence or significant reduction of nitrogen and sulphur in fuel compounds). Thermal preparation process is a pyrolysis of coal at a given temperature. Studies of coal pyrolysis, conducted using thermal analysis and mass spectrometry, show that nitrogen and sulfur oxides are formed during the release of volatiles [6]. In this context, a stand for thermal preparation of coal was designed and put into operation at ISEM SB RAS.

The stand layout is presented in figure 2. The height of the reactor is 340 mm, the diameter of the reactor is 159 mm, the length of the gas vent is 300 mm, and the diameter of the gas vent is 32 mm. The reactor vessel has thermal insulation. The gas vent has no insulation. The lack of thermal insulation contributes to the fact that the tar formed as a result of pyrolysis condenses in the cold zone and flows back into the reactor. The grate is placed inside the reactor, under which inert gas (Ar) is supplied. Inert gas allows quickly displacing oxygen from the volume of the reactor. The reactor is
heated by electric heaters. During the pyrolysis, the temperature in the bed and above the bed of coal in the reactor is controlled, and the temperature of the outgoing gas is recorded as well.

Figure 2. Layout of the reactor for thermal preparation of coal: 1. Hull, 2, 3. Gas vent, 4. Gas extraction, 5. Heat insulation, T1-T4 – Thermocouples.

Using this stand, experiments out on the thermal preparation of Mugunsky coal were carried. Mugunsky coal was chosen as a test coal because of its widespread use in low-capacity boiler houses with bed boilers in the Irkutsk region. In addition, this coal is non-caking. The technical characteristics of the Mugunsky coal are given in table 2. The temperature of the intensive yield of volatiles was chosen as that of thermal preparation of coal.

Figure 3 shows the dependences of temperature changes in the layer and above the layer of coal and the outgoing gas.

Figure 3. The dependence of temperature change in the layer and above the layer of coal, as well as the temperature of the outgoing gas on the time of the experiment.

Analysis of figure 3 shows that upon reaching 566 ° C, the stationary mode of coal pyrolysis is established. The curve of the flue gas temperature serves to conclude that the formation of volatiles
occurs in two stages. It has been established that the release of volatiles, in which the main amount of SOx and NOx is formed, takes place in two stages. At the first stage, weak polar bonds are broken with the formation of predominantly hydrogen-containing compounds and low molecular weight tar. At the second stage, stronger bonds are “broken” and the main formation of sulfur oxides occurs. Such a development of thermal preparation (pyrolysis) of coal is consistent with the data previously obtained with the methods of thermal analysis and mass spectrometry.

Table 2 shows technical characteristics and elemental composition of coal and semi-coke. These characteristics were determined using the methods of thermal analysis and mass spectrometry. The method for determining these values is detailed in [7].

| Coal        | W<sub>r</sub>, % | A<sub>d</sub>, % | V<sub>daf</sub>, % | C<sub>daf</sub>, % | H<sub>daf</sub>, % | O<sub>daf</sub>, % | S<sub>daf</sub>, % | Q<sub>daf</sub>, MJ/kg |
|-------------|-----------------|-----------------|-------------------|------------------|------------------|------------------|------------------|---------------------|
| coal        | 21.6            | 5.6             | 33.7              | 61.1             | 5.6              | 32.7             | 0.6              | 16.6                |
| semi-coke   | 1.4             | 17.2            | 12.2              | 76.3             | 1.9              | 21.8             | 0                | 20.7                |

Analysis of table 1 shows that as a result of the experiment, sulfur-containing compounds are completely removed from the organic mass of coal. At the same time, despite the increase in the ash content of the semi-coke, its calorific value increases significantly.

4. Discussion of research results

Based on the quality data of coal, including char, a calculation of pollutants emissions into the atmosphere under equal combustion conditions and a given fuel consumption of 88 kg c.e./hour was made, table 3.

The total calculated emissions from coal combustion are 1.11 times (or about 11%) lower than from semi-coke one. At semi-coke combustion, there is no emission of sulfur dioxides, but emissions of nitrogen oxides and carbon monoxide are about the same as from coal combustion.

| Fuel     | Recalculati on of fuel consumptio n in g/s | Emissions, g/s | Total  |
|----------|-------------------------------------------|----------------|--------|
|          | Particulate matters | Sulfur oxides | Nitrogen oxides | Carbon monoxide |
| Mugunsky coal | 43.15 | 1.89 | 0.34 | 0.57 | 1.33 | 4.14 |
| Mugunsky semi-coke | 34.60 | 2.65 | 0 | 0.60 | 1.33 | 4.58 |

The structure of the calculated emission for both coal and semi-coke is characterized by the predominance of particulate matters, figures 4 and 5.
A comparative analysis of the results of calculating the emissions of two types of fuels shows that the ash content, which is 3.1 times higher in semi-coke, plays a significant role. The 1.25 times increase in coke calorific value did not play a great role in reducing fuel consumption, which was the same, when converting from conditional to natural: reduction in consumption when burning semi-coke was 1.25 times (from 43.15 to 34.6 g/s).

5. Conclusion

It has been revealed that a change in one of the qualitative characteristics of fuels (ash content, sulfur and nitrogen content, calorific value) under the same combustion conditions and purification equipments may affect the final result – the amount of emissions. So, there is a direct dependence of emissions on the amount of fuel burnt and an inverse one on the quality characteristics of fuels (the better the fuel, the lower the emission).

To reduce the amount of emissions, different measures are taken, including the thermal preparation of fuels before burning, which allows producing semi-coke with improved reactionary and environmental characteristics.

It should be noted that the main environmental problem of small capacity boiler houses in the Siberian and Far Eastern regions is the emission of particulate matters into the atmosphere. Accordingly, to reduce the formation of particulate matters during the combustion of coal in existing boiler houses, the most effective is reducing the ash content of the original fuel and improving the combustion process.

One of the most important results of this study is that thermal preparation of coal before burning allows completely eliminating sulfur and significantly reducing the nitrogen content in the original fuel. This, in turn, will lead to a reduction in emissions of sulfur and nitrogen oxides. However, the increase of ash content in the fuel after thermal preparation contributes to a significant rise in particulate matters emission, which is very important for small capacity boilers. It is known that in coal-fired boiler of small capacity (up to 1 Gcal/h) ash-collecting equipment either is absent or works satisfactorily. Accordingly, thermal preparation will not solve the problem of particulate matters emission in small capacity boiler houses.

In this regard, it is most appropriate to use fuel after thermal preparation at large energy facilities that are equipped with rather powerful ash collecting devices. In addition, the use of fuel after thermal preparation will eliminate the emission of sulfur oxides. This adds competitiveness compared to desulfurization plants, which even on the scale of thermal power plants are bulky, expensive, and uncommon.

Thus, the use of coal thermal preparation technology for ecologically pure combustion of fuel is the most relevant for large energy facilities.
Acknowledgments
The research was supported by the RFBR and the Government of the Irkutsk Oblast, Project No. 17-48-380009 with using the equipment of the High-Temperature Circuit Multi-Access Research Center of ESI SB RAS.

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