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Impact of boiler plants on soot particles pollution

Victor Lyubov, Evgeniya Popova, Anatoly Popov

Northern (Arctic) Federal University, Arkhangelsk, 163002, Russia
v.lubov@narfu.ru

Abstract

Quantity of soot particles in the flue gases of energy facilitiesis a criterion of effectiveness for organization of the burning process. Several heat producing units do not provide the required energy and environmental efficiency, which results in irrational use of energy resources and acute pollution of environment. The paper summarizes the results of experimental study of solid particles emission from wide range of capacity boilers burning different fossil fuels; lists emissions of fine soot particles (PM 2.5); structure, composition and dimensions of entrained particles with the use of electronic scanning microscope Zeiss SIGMA VP were also studied. The results reveal an impact of several factors on soot particles emission.

Keywords: Boiler; Fuel; Coefficient of effectiveness; Harmful substances; Soot particles emissions; Heat losses

1. Introduction

Quantity of soot particles in the flue gases of energy facilities is a criterion of effectiveness for organization of the burning process. Many of the existing furnace and burner devices do not provide the required energy and environmental efficiency, which results in irrational use of energy resources and acute pollution of environment. This in particular affects environment of the Arctic territories. Soot is the most refractory and light-absorbing component of carbonaceous combustion particles (Petzold et al., 2013). Emission of soot particles can lead to big losses of fuel. Soot is a powerful carcinogen classified as a class 2 hazardous substance with maximum permissible concentration limit 0.15 mg/m^3, and can be dispersed by the wind as a dust for thousands of kilometers. The negative impact of soot is much (680 times) higher than for carbon dioxide. Small size of soot particles and the global atmospheric circulation contribute to its transport for thousands of kilometers. Therefore, more strict environmental and economical requirements to the energy facilities

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shall be applied for protection of the Arctic and subarctic ecosystems from degradation and global climate change.

2. Study of energy facilities emissions

Survey of boiler units (320-380MW) of large power plants operating on natural gas (the proportion of 98% methane) revealed (Lyubov et al., 2015) that the experimental measurements carried out by the method (Malygin et al., 2005) provide results within the method's permissible tolerance.

These boiler units operating on grade 100 residual fuel oil provide PM 2.5 emission factor of 0.104-0.110 g/GJ.

The results of the test measurements performed at boiler units (128-160 MW) equipped with tangential burners and wet scrubbers revealed that PM 2.5 emission factor during burning of high reactivity black coal was 0.25-1.05 g/GJ.

For the small power boilers with high physical depreciation operating at black coal PM 2.5 emission factor values is within a very wide range 2.0-26 g/GJ. In accordance with the investigations (Lyubov et al., 2015) the level of soot particles emissions depends on the fuel quality, burner unit design, combustion method and settings of the automation system, gas cleaning installation type, technical state and maintenance factor of the heat producing units.

Increase of the bioenergetics share in the energy balance of many European countries and forest regions of Russia is an upcoming trend to reduce technological environmental impact of the power industry facilities. It is particularly important to involve by-products of timber industry for energy production.

In the cycle of plywood production formed a large amount of by-products, which from economic and environmental points of view should be used as energy fuel. In 2015 ZAO «Arkhangelsk plywood factory" was installed and put into operation boiler PRD 22000 Austrian company «Polytechnik Luft- und Feuerungstechnik GmbH». This boiler produces saturated steam at a temperature of 192 °C, its nominal capacity 22MW. Fuel for boiler is the mixture consists of chip plywood, pitch bark, veneer, wood sanding dust, sawdust of the plywood processing. The components of the fuel mixture significantly differ in thermotechnical characteristics and technological parameters, but especially in size composition (Lyubov & Romanov, 2006). Particle dimensions in the fuel mixture differ by more than a thousand times which makes it «unique» and very difficult to ensure the effective and non-explosive use of energy. Wood sanding dust and sawdust from line of cutting of plywood are small fraction material and relate to IV group of explosion. Criterion of explosive (K_f) for them has great values (K_f^{WSD}=10.85; K_f^{saw}=9.66). Thus, the composition of the burnt wood fuel complicates operating conditions of the boiler PRD 22000. However, the boiler design and automation system provided cost-effective energy use of the fuel mixture with high environmental performance. Gross efficiency in the nominal capacity range 89-96% is 89.4-90.26%; NO_x emissions are 62-67; carbon monoxide emissions are 11-12; soot particles emission factor are 9.02-9.93 g/GJ. The PM 2.5 emission factor was 1.62-1.79 g/GJ, which is a good result.

Boilers PRD 9500 Austrian company «Polytechnik Luft- und Feuerungstechnik GmbH» was installed in the CHP-2 of ZAO «Sawmill 25» and produce superheated steam at a pressure of 2.4 MPa and a temperature of 425 °C. Nominal capacity of each boiler is 9.5 MW. During energy tests the boilers burned bark wastes at a moister content W_t^r=57.2-59.8%. Gross efficiency in the capacity range 7.82-9.14 MW is 86.96-87.86%; NO_x emissions are 57-71; carbon monoxide emissions are 4-144 g/GJ (Lyubov et al., 2015).

Two sampling methods were used to determine the particles content and the efficiency of the ash collectors: internal and external filtration. Sampling was carried out at the dust-laden flow isokinetic conditions; in this case, data from preliminary calibrations was used.

The study allowed to determine soot particles emission factor which amounted in 52.72-58.61 g/GJ. Wherein PM 2.5 emission factor varies between 8.61 and 10.03 g/GJ. Study of selected particles with use of electronic scanning microscope Zeiss SIGMA VP (Carl Zeiss) allowed to determine the structure, dimensions of particles and qualitative composition of constituent elements. PM 2.5 emission factor were 1.21-1.4 g/GJ. The size of soot particles were in the range of 0.1-10 μm (Lyubov et al., 2015).

The results of the experiments revealed that the inertial ash collectors (RGE 9500) do not allow effective purification of flue gas from soot particles due to their small dimensions and lower density in comparison with mineral particles. This is evidenced by the increased content of soot particles in the solid phase: before ash collector 4.6-5.5%, after - 16.3-17.1%. The values of the total purification degree of flue gas from the solids in the gas cleaning facilities of boilers accounted for 85.3-90.0%, and the degree of purification of soot particles was 63.1-67.0%.

Automated boilers (Arimax Bio Energu) with capacity of 0.7-1.5 MW and equipped with inertial ash collectors (HEKMC-3×3) are used at small power facilities operating on pellets in the Arkhangelsk region. Two-step scheme of combustion is utilized at the boilers furnaces. Additional configuration of the boilers automation system has allowed to provide high completeness of fuel combustion and stable low values of soot particles emissions (Lyubov & Popov, 2011). PM 2.5 emission factor was 0.521-0.966 g/GJ. Maximum achieved gross efficiency of boilers with capacity 0.7MW was 91.0% and 1.5 MW - 92.0%; which corresponds to the efficiency of oil-fired boilers in a good technical condition. To ensure stable high economic and environmental performance of these boilers it is necessary to conduct monitoring of the pellets quality indicators including the content of dust particles. In addition, cleaning of each boiler element must be carried out promptly.

An effective direction of comprehensive solution of energy and environmental problems in providing heating loads of the household sector consumers is the use of modern boilers for solid biofuels and peat. The scientific platform for research became boiler Firematic 60 manufactured by Austrian company «Herz Energietechnik GmbH». The boiler is design to work on pellets and splint no larger than 50 mm with relative moisture less than 35%.

The study was carried out in several stages. During the first stage, experiments were carried out with feeding boiler furnace by 8 mm in diameter pellets with uniform particle size distribution. At the second stage the boiler worked with pine bark which thermotechnical characteristics had the following values: moisture W_t^r=13.72%; ash content A^r=2.52%; received fuel mass inferior calorific value Q_i^r=17.98 MJ/kg.

Results showed the boiler operating on biofuels provides high environmental and economic performance and should be used for the heating low-rise buildings, especially in the Arctic region conditions (Lyubov & Popov, 2011). Gross efficiency of the boiler operating on pellets was 92.86-95.20%; NO_x emissions 51-54; carbon monoxide emissions 12-21 g/GJ. For the boiler operating on pine bark which has less uniform particle size distribution, the environment and economic performance had the following values: gross efficiency 92.7-93.2%; NO_x emissions 57-100; carbon monoxide emissions 85-323 g/GJ.

During the third stage, experiments were carried out with applying non-project fuels: peat granules with a diameter of 10mm and sod peat characterized by a nonuniform particle size distribution. Thermotechnical characteristics of peat granules had the following values: W_t^r=16.50%; A^r=9.95%; S_t^r=0.22%; Q_i^r=14.88 MJ/kg. Sod peat had the following characteristics: W_t^r=8,2%; A^r=11,76%; S_t^r=0,19%; Q_t^r=15.47 MJ/kg (Lyubov et al., 2011).

When the boiler operates on the peat granules which ash content significantly larger in comparison with pine, the heat loss with mechanically incomplete combustion increased to 2.17% and gross efficiency reduced to 91.24-91.37%. Emissions of harmful substances were: NO_x 169-177; CO 7-23; $SO_2$331-338 g/GJ.

Conversion to burning the sod peat with high content of fine particles led to a sharp increase of heat loss with mechanical incomplete combustion to 13.00%. Gross efficiency of the boiler decrease to 81.01-81.22%. Fractional fly ash analysis revealed that the greatest amount of combustibles contained in particles of 0.5mm or more. Analysis of the experimental data, with taking into account the mass content of different fractions, revealed that removal of unburned peat particles with a size of $0.25<\delta<2$ mm has significant role in the mechanical incomplete combustion heat loss.

This boiler for burning sod peat is not recommended to use without significant changes in the collection and removal of the combustion residues due to the high ash content and high heterogeneity of particle size distribution of sod peat in comparison with biofuels (pellets and wood chips). Conversion from the peat granules to burning sod peat caused approximately three-time increase of the solid particles concentration in the flue gases.

In the experiments, particulate sampling from the gas flue before chimney was carried out using the method of external filtering. The captured particles were studied by the electronic scanning microscope. Device parameters used to capture images were: InLens and SE2 detectors, the accelerating voltage of the electron gun 5 to 20 kV.

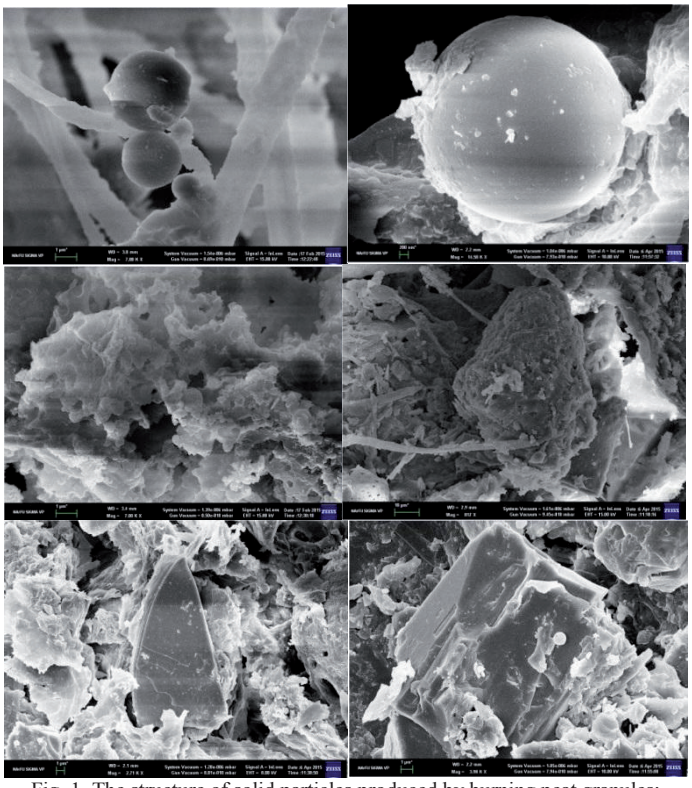

Fig. 1. The structure of solid particles produced by burning peat granules:
a - spherical; b - amorphous; c – crystalline

Results of the study of soot particles emissions during the combustion of pellets revealed that the average soot particles emission factor was 5.594 g/GJ and PM 2.5 emission factor was 0.834 g/GJ. During the pine bark combustion the soot particles emission factor grew up to 9.324 g/GJ and PM 2.5 emission factor up to 1.305 g/GJ.

For the boiler operating on peat granules the average soot particles emission factor was 2.477 g/GJ and PM 2.5 emission factor - 0.347 g/GJ. The conversion to burning sod peat was followed by the sharp increase of soot particles emission factor to 17.254 g/GJ and PM 2.5 emission factor to 2.416 g/GJ.

Three main types of particles in selected samples have been identified: spherical shape, with an amorphous structure and solid crystal particles (Fig. 1,2). The origin of spherical particles is probably due to the decomposition of plant organic matter. Influenced by heat, the sugar decompose and take on the properties of a fluid. This fluid forms spherical particles during solidification. We can assume that the particles are composed of hydroxymethylfurfurol.

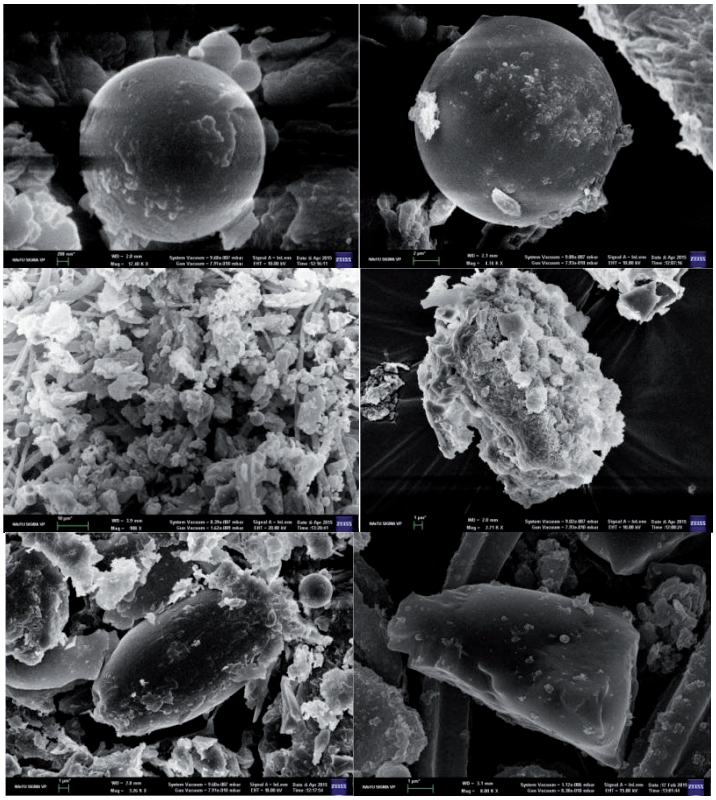

Fig. 2. The structure of solid particles produced by burning sod peat: a - spherical; b - amorphous; c - crystalline

Crystalline particles in the sample taken after peat granules combustion are likely unburned plant residues that are part of peat. The part of crystalline particles contained in the sample taken after sod peat combustion with determined amounts of silicon can be particles of sand and clay. Another part of crystalline particles is unburnt plant residues that are part of peat.

With given elemental composition data (Table 1), particles with amorphous structure are fragments of the peat-forming components. The average content of the basic elements on the dry weight of solids in various shapes is expressed as weight equivalent and shown in Table 1.

Table 1. Elemental analysis of solid particles removed in chimney during combustion of the peat granules and sod peat

Element	Soot particles with spheric shape, %	Soot particles with amorphous structure, %	Crystalline soot particles, %
C	30.0/33.47*	31.44/41.98	30.02/39,9
O	27.85/30.21	33.56/17.98	25.77/23.19
Ca	5.59/0.15	3.72/0.55	4.99/0.24
Si	8.16/9.75	2.32/3.87	0.33/14.52
Fe	2.79/6.69	0.74/6.20	0.35/4.09
Al	2.83/3.87	0.42/2.10	0.35/4.31

*The denominator contains data obtained by burning of sod peat

Simultaneously with the study of soot particles shapes, their dimensions were determined (Table 2). Small size of soot particles and the global atmospheric circulation contribute to its transfer for thousands of kilometers. Therefore, more strict requirements on ecological and economical performance for energy facilities at Arctic areas have to be developed to protect fragile Arctic ecosystems and global climate change from degradation and destruction.

Table 2. Soot particles dimensions

Name of particles	During peat granules combustion, min/max, micron	During sod peat combustion, min/max, micron
Spherical shape	0.7 / 11	0.2 / 15
With amorphous structure	0.1 / 15	0.1 / 25
Crystalline particles	0.1 / 20	0.1 / 30

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