

Boilers slagging when burning wood pellets

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Abstract. A promising trend for upgrading wastes from timber cutting, processing and treatment is their granulation. It allows to increase their specific heats of combustion by 2.5–3.5 times and their portability characteristics by 3–4 times, to reduce transportation costs by 6–10 times and to improve all the operations stages. The construction and commissioning of boiler facilities operating on refined biofuel made it possible to form a stable domestic market for wood pellets. However, 0.5 – 1.5 MW nominal capacity hot water boilers equipped with furnaces and profiled burners at the bottom, in cold seasons had fast accumulation of focal residues deposits in the burners and on the furnace chambers lining. The process was complicated by these deposits hardening due to their melting and sintering. These circumstances cause a decrease in the energy and environmental performance of heat-generating installations and their reliability, and also leads to the unplanned shutdowns to clean the boiler furnaces. To find out the reasons for these negative phenomena and to develop recommendations for their elimination, a set of research operations was carried out with wood pellets shipped by the manufacturer and supplied to the burners of the boilers under the analyses; with focal residues accumulated in the burners and on the lining of the furnace chambers; as well as an analysis of the heat generating facilities operation modes. The studies carried out made it possible to identify the main factors that caused these negative phenomena and to develop the recommendations for their elimination.

1. Introduction

Energy supply problems are vitally important for any country in the world. As civilization develops, the specific energy consumption is constantly increasing. However, the traditional energy reserves are very limited, and they are constantly becoming more expensive. Meanwhile, peoples' activity is accompanied by large amount of wastes accumulation: wood, agricultural, solid household, sewage sludge, etc., the volumes of which are growing rapidly and pose a serious threat to the modern world.

Timber wastes accumulated from cutting, processing and treatment are classified as difficult to burn fuels due to their high moisture content, low energy density and extremely heterogeneous particle size. A promising approach for such wastes upgrading is their granulation [1]. Since the beginning of the XXI century, this industry has been intensively developing in Russia. The country bioenergy potential, as well as fossil hydrocarbons one, surpasses those of any region in the world [1-5].

Considering the fact that towns energy and environmental problems are closely interconnected and have to be addressed in a comprehensive manner, simultaneously and by utilizing the resource-saving technologies, a program was developed in the Arkhangelsk region to replace imported fuels with

biofuels [6], to upgrade the existing energy facilities and to build the new ones: modular, fully automated, operating on refined environmentally friendly biofuel - granules. So, since 2010, more than 100 regional energy facilities have been commissioned, upgraded and transferred to the use of solid biofuels.

As an example, the total installed capacity of six new fully automated boiler houses of LLC "Arkhbioenergo" operating on wood pellets amounted to 46 MW, and the achieved gross efficiency of hot water boilers is more than 90.0%. At the same time, carbon monoxide emissions, soot particles and nitrogen oxides were minimal [7]. The achieved gross efficiency of biofuel boilers corresponds to the efficiency of fuel oil boilers in good technical condition. The construction and commissioning of boiler houses operating on refined biofuel made it possible to form a stable domestic market for wood pellets. This circumstance provided additional internal guarantees for the dynamic work of pelleted fuel regional producers.

However, 0.5 – 1.5 MW nominal capacity hot water boilers equipped with furnaces and profiled burners at the bottom had (in cold seasons) fast accumulation of focal residues deposits in the burners and on the furnace chambers lining. The process was complicated by these deposits hardening due to their melting and sintering. These circumstances caused a decrease in the energy and environmental performance of heat-generating installations and their reliability, and also led to the unplanned shutdowns to clean the boiler furnaces.

The focal residues processes at high temperatures (softening, melting, fluidity of the resulting melt) present one of the most important technological characteristics of energy fuel. These characteristics significantly affect the boiler design, its reliability, as well as the operating costs [8-9].

Granular fuel in such hot water boilers is fed by auger feeders to the burners, the primary air passes through the gaps of the grates made of refractory cast iron with chromium addition and penetrates the fuel layer. To ensure the afterburning of the fuel combustible components, secondary air is supplied to the above-layer zone of the burner through nozzles located oppositely on the side walls.

To clarify the reasons for the above listed negative phenomena and to develop the recommendations for their elimination, the research work was carried out with wood pellets entering the burners, with focal residues formed in the burners and on the furnace chambers lining, as well as an analysis was performed for the energy facilities operating modes.

2. Objects, materials and methods of research

The determination of the elements composition of wood pellets and raw materials used for their production, as well as of focal residues, was carried out using an automated Euro EA-3000 analyzer according to the CHNS analysis standard (carbon, hydrogen, nitrogen and sulfur). In addition, an EDX-8000 X-ray fluorescence spectrometer was used to determine the elements composition of the materials under study. The device allows simultaneously detect, measure and record the radiation intensity of various elements. The studies were carried out at the Scientific Equipment Center of the Scientific Association "Arctic" in the Northern (Arctic) Federal University (NArFU) named after M.V. Lomonosov in Arkhangelsk city.

Thermal analyzes of wood fuels and focal residues were carried out using an IKA C 2000 basic Version 2 calorimeter with a LOIP FT-216-25 liquid cryothermostat and with the units of the complex thermal analysis laboratory of the Educational and Scientific Center for Energy Innovation of NArFU. Investigations of the granulometric composition of the fuel and focal residues were carried out by the sieve method using the Retzsch AS 200 Control and "029" analyzers. The portable NHP 100 tester from the German company Holmen was used to study the mechanical strength and abrasion of the granules. minimum hot water boilers heating capacity is 20% of the nominal.

The units under the research were the automated power sources equipped by Hekotek with 0.5–1.5 MW nominal capacity hot water boilers. The vertical cylinder tanks were mounted next to the boiler houses to provide the granular fuel stock for operations,. The working pressure of hot water at the outlet of these heat-generating installations should not exceed 0.4 MPa, and the temperature should not exceed 115 ° C. Hot water boilers have two circuits, with chemically purified deaerated water

circulating in the first one. 110/90 ° C is the calculated temperature mode for the primary circuit working conditions. Combustion products provide heating of the primary circuit boiler water by making three strokes in the boiler smoke tubes, then they are cleaned in a multicyclone. Heating of the secondary circuit water (70/90 ° C) is carried out using a plate heat exchanger. Each boiler is equipped with an individual heat exchanger and the smoke pipe. To ensure smooth adjustments of the heat-generating installations performance, the drive of smoke exhausters, augers, fans of primary and secondary air has frequency control. The minimum hot water boilers heating capacity is 20% of the nominal.

The surveyed substances were sampled in accordance with the current requirements [10].

3. Results

Based on the analysis of the experience of burning granular fuel in the Russian Federation and abroad [1, 5, 7, 11-18] the following preliminary conclusions were made:

1. The process of sintering and the agglomerates formation occurs when pellets contain small granules less than 3.15 mm in size and a large amount of dust particles. Such a finely dispersed mass has an increased bulk density and, upon entering the combustion zone, forms fuel agglomerates that are poorly blown by air flows; in these places, a crust begins to form, gradually increasing in size. During a long stay in the burner device, the combustible substances are almost completely oxidized. One of such ash and slag agglomerates, extracted from 1.5 MW nominal power hot water boiler, is shown in Fig. 1. There are several causes for such "small parts" formation in wood pellets:

- Low-quality pellets from the supplier, as a result of the plant's equipment failure or pellets abrasion and destruction during transportation and reloading.
- Improper storage of pellets, namely: placing "big bags" on the ground without a stand (mat) that blocks wetting the pellets from the ground; or high humidity in the storage room, leading to crushing of the pellets in the lower third of the bag and literally turning them into dust.
- Incorrectly designed wood pellets storage area and boilers burners fuel supply system resulting in the pellets significant part been shredded.

2. Different impurities present in the wood granules, such as bark and sand, give another cause of sintering parts. Sand softens and melts in the high temperature zone, especially in a reducing atmosphere, which can also lead to slagging.

3. Boilers operations with significant deviations from optimal modes. This contributes to the creation of conditions for the initial formation of fuel and ash and slag agglomerates and the adhesion of molten mineral particles to the surface of the grate and to the boilers lining.

4. Boiler burners design without continuous stable withdrawal and tedding of focal residues formed in pellets burning process.



Figure 1. Sintered ash and slag agglomerate.

CJSC "Sawmill № 25" is the largest producer of pelleted fuel in the Arkhangelsk region. Pellets for the power facilities under analyses are supplied from its "Tsiglomensky" site, where the wood pellet preparation shop No.2 is located. An extended analysis of the granular fuel produced in the shop No.2 showed that the granular fuel sample meets the requirements of Russian and European standards in terms of all heat engineering and strength parameters, as well as in bulk density [19]. The main indicators of wood pellets are presented in Table 1.

Table 1. The main performance of the boiler.

Indicator, units of measurement	Working weight	Dry weight	Combustible mass
Moisture, %	5.74		
Ash content, %	0.52	0.55	
Combustion heat lowest, MJ / kg	17.615		18.943
Combustion heat, highest, MJ / kg			20.422
Sulfur, %	0	0	0
Hydrogen, %	6.12	6.49	6.53
Nitrogen, %	0.19	0.20	0.20
Chlorine, %	-	-	
Lead, %	-	-	
Vanadium, %	-	-	
Molybdenum, %	-	-	
Volatiles, %	78.78	83.58	84.04
Mechanical strength, %	98.45		
Average diameter, mm	8.06		
Average apparent density, g / cm ³	1.18		
Bulk density, g / cm ³	0.695		
Coke residue	Powdery		

4. Results

The study of the wood pellets particle size distribution showed: the weight content of chips (particles with a size of 3.15 mm or less) is much less than 1.0% (Fig. 2); granules with a length of 40 mm or more are absent, which meets Russian and European standards [19]. The performed analyzes also showed: granules of 12 to 25 mm length dominate in the fuel under study; their mass fraction was 83.52% (polydispersity coefficient $n = 5.618$, and the coefficient characterizing the composition size $b = 1.15 \cdot 10^{-24}$).

Based on the above, there are no claims to the quality indicators of the wood pellets manufacturer.

The study of the particle size distribution, strength and abrasion of wood pellets taken from the auger feeder in front of the boiler with 1.5 MW rated power showed that the pellets have a much less homogeneous and finer composition ($n = 2.369$; $b = 1.619 \cdot 10^{-10}$). At the same time, granules with 8 to 20 mm length dominated in the fuel under study, their mass fraction was 75.19% (Fig. 2), and the chips content was about 6%. The wood pellets mechanical strength ($DU = 98.43\%$) was slightly lower than the sample taken from the manufacturer's wood pellet preparation shop No.2 ($DU = 98.45\%$).

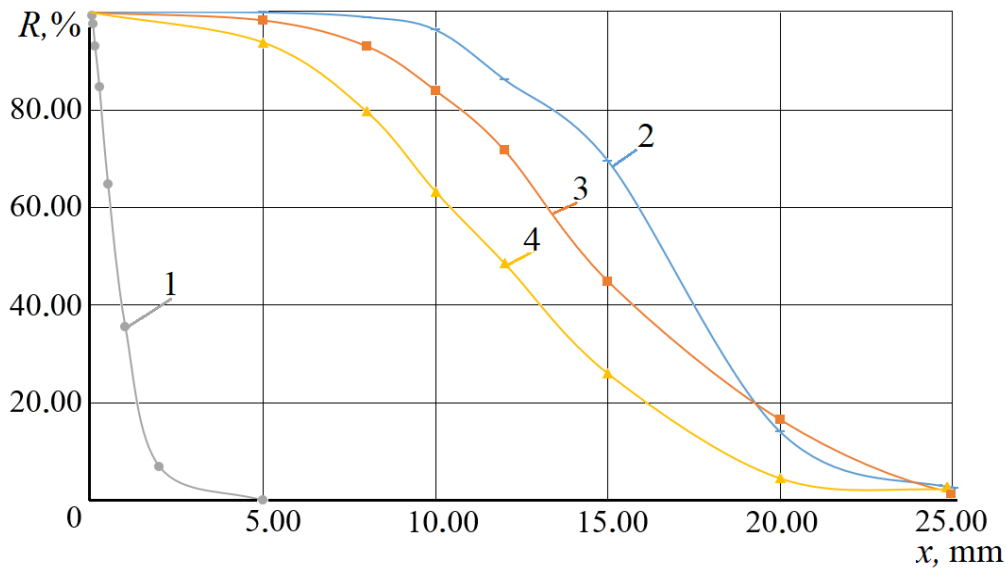


Figure 2. Wood material particle size distribution before the pellet press (1) and pellets shipped by the manufacturer (2), and before the burners of boilers with a rated power of 0.74 MW (3) and 1.5 MW (4).

The study of the particle size distribution, strength and abrasion of wood pellets taken from the auger feeder in front of the boiler with 0.74 MW nominal power showed that the pellets have a less homogeneous and finer composition ($n = 3.105$; $b = 7.863 \times 10^{-14}$) than the pellets in Shop No.2. In this case, the studied fuel is dominated by granules with a length of 10 to 25 mm, their mass fraction was 82.51% (Fig. 2), and the crumb content was about 1.6%. The mechanical strength of wood pellets ($DU = 98.40\%$) was slightly lower than in sample taken from the manufacturer in Shop No.2.

The obtained results allow us to conclude that the pellets strength characteristics do not significantly decrease in the systems of wood pellets storage and fuel supply in boiler units equipped with Hekotek boilers rated for 0.74 and 1.5 MW capacity. Moreover, they fully comply with Russian and European standards set for granules of all classes [19]. Earlier, a similar conclusion was made for hot water boilers KBT 4000T, installed in the settlement of “Katunino”. However, it is necessary to note the increased content of fines in the samples, especially in the granular fuel for boilers with 1.5 MW nominal power.

The issue of various impurities in wood pellets possible presence, such as bark and sand. As per thermal analyses results, the ash content in dry weight is 0.55% in Shop # 2 granules; thus, the present parameter meets the requirements of Russian and European standards for the highest quality class A1 pellets [19]. This result would be impossible in case of sand in the wood material. The analyses of the Shop # 2 granules structure and color indicates the minimum bark presence in wood material, which is confirmed by thermal analysis results. These facts make it possible to exclude the option of various impurities, such as bark and sand, presence in wood granules and the associated slagging.

Let us mention the issue of boilers operating with significant deviations from the optimal modes. Boiler operators log books review led us to the following conclusions: rarefaction in the boiler furnaces had values close to optimal; flue gas temperatures had unacceptably high values (235–248 °C), while the boilers power was less than 0.61 of the nominal rates. The temperatures were about 120 °C higher than in modes with clean heating surfaces [20]. It should be kept in mind that the temperature of flue gases in front of the smoke exhauster should not exceed 220–250 °C according to the condition of its reliable operation. Thus, boilers were operated under the conditions that are critical for smoke exhausters for a long period.

In response to the question when should the boiler unit be cleaned? It is impossible to give a definite answer, because a lot depends on the conditions for power generation and on the availability

of the standby units to switch to if required in winter. Therefore, the time for cleaning the heating surfaces is selected depending on the circumstances. The main rule is: if the flue gases temperature at the same boiler load increased by more than 40–50 ° compared to the one recorded immediately after the soot and ash particles removal, it is time to repeat the cleaning procedure [1].

Based on the foregoing, the operation of hot water boilers with extremely contaminated heating surfaces causes a decrease in their gross efficiency by almost 10%, which accordingly requires an increase in fuel consumption of ~ 10% to ensure the required heating capacity. The increased fuel consumption increases the level of the solid phase in the boiler burners to a value at which the nozzle openings for the secondary air supply are blocked. In boilers with 1.5 MW nominal power, the secondary air nozzles inner diameter is 20 mm, they are 115 mm spaced and their total number is $n = 13 + 10 = 23$ pcs. In the slag with vitreous formations, removed from the side wall, a ~ 20 mm diameter hole can be seen (Fig. 3)/ It was obviously "pierced" in the slag melt by the secondary air flow. This vitreous formation in the solidified state is stronger than steel. When the secondary air nozzles are blocked, the boiler automation increases the primary air flow rate to ensure the specified oxygen concentration, that increases the temperature in the burner to a level of fast slagging.

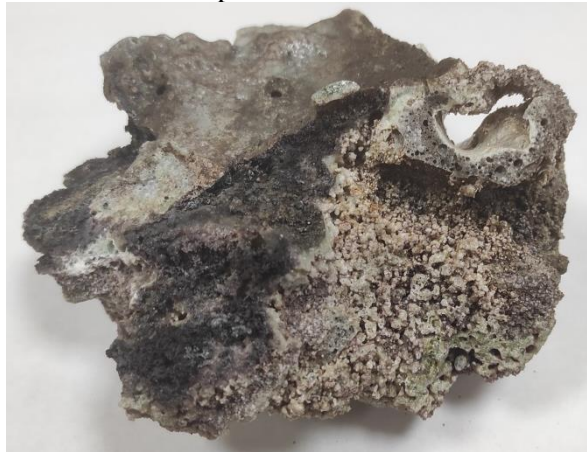


Figure 3. Slag build-up with vitreous formations and a hole.

These circumstances let us conclude that the boilers at the inspected power facilities were operated with the significant deviations from the optimal modes.

Wood pellets from Shop # 2 are delivered to boiler houses by trucks and are loaded into the fuel bunkers. The loading augers move the pellets to elevators and then feed to silos. Visual inspection of the bunkers discovered that a large number of partially and completely destroyed granules accumulated near their walls. It is highly probable that all these fines and dust fall into the silo when the new pellets batch arrive.

Visual examination of the status and color of ash and slag agglomerates removed from the burners showed that their segments differ in color significantly. Based on this finding, the samples were taken from areas with: - black (sample code 09-P), - gray-white (10-P), - violet (12-P) color.

The elements analysis showed a very low combustible substances presence in the samples (Table 2).

The sample taken from the black zone had an increased content of copper oxide ($\text{CuO} = 0.031\%$). The sample taken from the violet zone had an increased content of copper and chromium oxides ($\text{CuO} = 0.028\%$; $\text{Cr}_2\text{O}_3 = 0.188\%$). The sample taken from the gray-white zone had an increased content of zinc oxide.

Slag sampling from the zone with vitreous formations (sample code 11-P) for elements composition analyses was very hard, since its harder than steel. The very high strength of this slag zone can be associated with an increased content of vanadium and molybdenum oxides.

Summarizing the above, it should be noted that slagging physical and chemical processes are extremely complex. This is due to the multiphase structure of deposits, consisting of a liquid phase and a number of crystalline phases. Slag deposits differ in composition even layer by layer, which was confirmed by the performed experiments (Table 2). In most cases, the deposits are the result of adhesion of the glassy and partially crystalline phase of ash when it interacts with the grates or lining surface.

Table 2. Element's composition of focal residues in dry weight, %.

	09-P	10-P	11-P	12-P
SrO	0.297	0.120	0.187	0.157
ZnO	0.009	0.136	0.005	0.002
CuO	0.031	0.019	0.012	0.028
NiO	0.018	0.029	0.015	0.019
Fe ₂ O ₃	15.00	13.70	12.70	12.90
MnO	4.49	1.45	2.06	2.08
Cr ₂ O ₃	0.034	0.086	0.124	0.188
CaO	38.00	14.10	24.70	18.20
K ₂ O	5.31	5.32	4.29	13.80
SO ₃	0.733	0.568	0.160	4.41
P ₂ O ₅	2.00	0.868	1.16	0.960
SiO ₂	27.20	58.80	49.30	42.50
Al ₂ O ₃	1.49	1.83	1.56	1.49
MgO	3.91	1.39	2.28	1.77
Na ₂ O	0.229	0.571	0.248	0.441
V ₂ O ₅	-	0.002	0.011	-
TiO ₂	0.072	0.086	0.068	0.102
BaO	0.515	0.173	0.301	0.256
MoO ₃	-	-	0.042	-
Rb ₂ O	0.011	0.021	0.014	0.060
N	0.091	0.267	0.220	0.175
C	0.309	0.423	0.529	0.396

In some cases, the formation of the very first layers is affected by the sublimation and subsequent condensation of vapors of low-melting components of the mineral part of the fuel, which, first of all, include oxides of alkali (K₂O, Na₂O) and alkaline earth metals (MgO, CaO). The studies performed have shown the presence of a significant amount of these oxides. In addition, the formation of the very first layers of deposits can also simply cause aggregation of particles due to the surface energy of highly dispersed fractions.

Due to the primary layer stickiness, a loose secondary layer of ash particles grows on its surface. Due to ash low thermal conductivity, the outer temperature of the secondary layer rapidly increases with an increase in its thickness and can exceed the temperature of the liquid phase formation start corresponding to the temperature of the onset of deformation of the ash sample (t_A). The deposits melting leads to an increase in their density and strength, while the surface stickiness increases and the growth of the layer thickness is accelerated. In some cases, the secondary layer hardening is also possible at temperatures below t_A due to processes leading to particle sintering. These processes are mass transfer between particles by the mechanism of molecular diffusion and topochemical reactions. The temperature of the onset of ash deformation characterizes the boundary beyond which intensive slagging of the boiler elements is possible.

Thus, boiler slagging is a progressive accumulation of focal residues in the furnace, in the burner and in the gas ducts, accompanied by the hardening of these deposits due to their melting and sintering. Slagging speed depends on the one hand, on the boiler unit design and operating mode and,

on the other hand, on the composition and specific properties of the mineral part of the combusted fuel.

Focal residues, being multicomponent systems, do not have one strictly defined melting temperature. Their transition from solid to liquid state and back occurs in a certain temperature range [8, 9]. The lower boundary of this interval - the solidus temperature corresponds to the appearance of the first drops of liquid melt; a further increase in temperature is accompanied by a decrease in the amount of the solid phase and an increase in the liquid phase. At the liquidus temperature, the last crystals of the solid phase disappear.

Almost all the components of ash and slag are quite refractory. For example, the melting temperature of SiO₂ is 1728, Al₂O₃ is 2050, Fe₂O₃ is 1652, CaO is 2585, MgO is 2800 ° C. However, for two- and multicomponent systems, due to the formation of eutectic alloys in them, the emergence of a liquid phase is observed at temperatures significantly below the melting temperatures of pure components

5. Conclusions

Based on the results of the laboratory studies and the analysis of the operating modes of hot water boilers, the following conclusions were made:

1. The main cause of hard ash and slag deposits is the operation of boilers with significant deviations from their optimal modes.

2. The design of some hot water boilers burners does not provide continuous stable withdrawal and tending of the focal residues accumulated in case the boilers operating modes deviate from the optimal ones; that contributes to fast accumulation of focal residues in the burner and on the combustion chamber lining, accompanied by deposits hardening due to their melting and sintering. These problems were identified for 0.5 to 1.5 MW nominal power Hekotek hot water boilers fueled with high quality wood pellets.

3. All cases of dust cloud occurred during granules loading into the incoming fuel bunkers at the boiler facilities should be recorded and investigated. Regular sampling and monitoring of the incoming biofuel quality should be carried out.

4. It is necessary to maintain the boilers optimal parameters in all operating ranges of load variation in accordance with the Operating Charts. Do not allow to fill the burner and the combustion chamber with wood pellets to the secondary air nozzles level.

5. To provide hot water boilers better and regular cleaning. Temperature of the flue gases leaving the boilers is the most important criteria for the necessity to clean the boilers. To include into the boiler maintenance checklist the steps for cleaning the fuel storage systems and fuel supply conveyors from wood dust, sawdust and "fines" for the purpose: to reduce their share in the burned fuel; to reduce sintering; to reduce their deposition on the lining and on heat exchange surfaces; to exclude their incomplete burning in the boilers increased heat output.

6. When designing boiler facilities for Russian Federation Arctic zone, preference should be given to boilers equipped with combustion chambers, so that they do not depend on the possible slag accumulation because of granular fuel bad quality.

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