BIOMASS COMBUSTION IN BUBLLING FLUIDIZD BED BOILERS (BFB) - POTENTIAL PROBLEMS AND REMEDIES IDENTIFIED DURING LONG -TERM OPERATIONAL TESTS

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Abstract:
Generation of near CO_2-free energy in large scale can be achieved by substitution of fossil fuels with biomass commonly regarded as CO_2-neutral fuel. Versatile nature of biomass enables it to be utilized in virtually all parts of the world, but on the other this diversity makes it a complex and difficult fuel. Especially the high percentages of alkali and chlorine, together with high ash content in some sorts of biomass prove to be a major source of concern. Among different biomass combustion technologies, fluidized bed boiler are emerging as the best due to their flexibility and high efficiency. This paper presents the identification of major issues concerned with biomass combustion with special reference to the fluidized bed systems. Basing on the lab-scale experiments on BFB reactor, operational mechanisms have been identified and explained, leading to the indication of the solutions enabling the shut-down free boiler operation. Long term operational trial tests of BFB biomass boiler OFz-135 type fed with woody and agro-origin biomass have confirmed the proper solution achieved.

Keywords:
Biomass combustion, BFB boiler, fluidized bed boiler, alkali and chlorine.

1. Introduction

Combustion of biomass in the fluidized beds is currently practiced in many energy utilities, either equipped with bubbling bed or with circulation fluidization bed. The advantages of fluidized bed combustion such as high efficiency, the possibility of fast changes of the boiler load, relatively inexpensive desulphurization and energy easy conversion chemical energy of biomass and waste products. Although fluidized-bed combustion is ready a mature technique for use with coal, frequent operational problems have been encountered in its application to biomass combustion. One of these is the bed material agglomeration and agglomeration-induced defluidization. Under certain conditions as a result of the mechanical and the chemical reactions between the bed material particles, ash and flue gas can lead to the bed agglomeration. The causes and nature of the bed agglomeration and the effect of the combustion temperature, the fuel chemical composition has been the subject of broad process research. The compositions of biomass among fuel types are variable, especially with respect to inorganic constituents important to the critical problems of fouling and slagging. Alkali and alkaline earth metals, in combination with other fuel elements such as silica and sulfur, and facilitated by the presence of chlorine, are responsible for many undesirable reactions during the combustion. Elements including Si, K, Na, S, Cl, P, Ca, Mg, Fe are involved in reactions leading to ash fouling and slagging, and the principal mechanisms describing these phenomena in biomass combustors are now reasonably well understood [1]. During combustion, the mineral matter transforms into ash which may deposit on the heat transfer surfaces or other surfaces of the boiler interior. These phenomena are described as slagging if the deposit is in a molten or highly viscous state or fouling if the deposit is built up by species that have vaporized and subsequently condensed. Slagging is often found in zones directly exposed to flame radiation (in the hottest parts of the boiler), while fouling occurs in the cooler furnace regions (in the convection sections) [2]. Biomass ash relatively rich in alkali and alkaline earth metals, melts at relatively low temperatures. Fouling of the heat exchangers is an additional problem, which for the biomass combustion is becoming even more serious comparing to coal combustion [3]. Bed agglomeration process is influenced at most by the particle size of the bed material, the bed temperature, heating rate, the total mass of the layer, however, a chemical composition of ash has the largest. Bed agglomeration is mainly due to ash melting and its reaction with bed material. Ash rich in potassium and sodium compounds often has a low melting point which is close to normal temperature of combustion in fluidized bed (750-850 °C). The refractory material of the bed, such as silica sand or Aluminosilicate minerals reacts with the partially melted particles of ash resulting in a much lower temperatures than predicted for pure refractory material. The problem of agglomeration is basically related to the composition of the fuel ash, the operating temperature, and the type of bed material used. At elevated temperatures [4, 5] the presence of Na and K compounds in larger amounts can lead to rapid agglomeration of the fluidized bed. The higher the temperature, the greater the agglomeration tendency and the size of the agglomerates become [3]. The eutectic [K_2SO_4-$(KPO_3)_2$], which has a melting point as low as 718 °C, can also be found if the ash is rich in phosphorus [6]. In the case of biomass combustion on the bed particles revealed the presence of a thin film of melted ash [7], it is shown that the result of the reaction between potassium or calcium present in the fuel and the particles of the bed material. Similar observations were made during the combustion of coal [8]. In particular, for low-rank coals, the usually high levels of alkali elements present in these coals are responsible for these problems [9]. Combustion in CFB occurs in all parts of the riser and the cyclones, but during coal combustion most of the fuel combusts in bottom part of the furnace. Operating experiences from pilot- and full-scale boilers have shown that a significant fraction of the wood-based biomass fuels burns in the upper parts of the furnace and in the cyclone. This can be explained by the high moisture content of the fuels resulting in long drying and devolatilisation times, and low density of the fuel particles making them follow the gas flow to the top of the furnace. Consequently, the furnace top and cyclone temperatures even be 100-150° higher than the bed temperatures during biomass combustion [10]. This may have a negative effect in case of using biomass with low ash fusibility temperature. Heat exchange efficiency is reduced by the formed deposits and their associated corrosion causes damage to the superheater. The alkali metal salts included in the fly ash are especially troublesome, as they cause a reduction in ash melting point and increase of its viscosity, which in turn results in the intensification of the formation of deposits and agglomerates in the fluidized bed. When the bed agglomerates, fluidization decreases and may even be stopped. This can lead to failure and unplanned shut down needed for cleaning and replacement of bed material. Slagging hazard depends on the properties of ash, which can be (but only approximately) described by characteristic ash fusion temperatures: initial deformation temperature (IDT), softening temperature (ST), hemispherical temperature (HT) and flow temperature (FT). Over ST ashes can be strongly adhesive, which results in slagging [11]. For a more precise predicting of ash fusibility, various correlations between fusion temperatures and standardized (given in the form of oxides) chemical composition of ashes have been determined [1-2, 12]. The aim of the research described in the paper was to elaborate the recommendations for shut down free operation of biomass boiler combusting the mixture of chips wood (80%) and agro (20%) origin biomass. Since the very beginning of the boiler separation, shut-down periods were very frequent, very offer bed material had to be changed for the new one, due to the sintering. Lab scale test were recommended to elaborate the recommendations which later on have been verified at long time operational test of the boiler.

2. Description of the testing boiler

The subject boiler is a bubbling fluidized bed (BFB) combustion technology called HYBEX with maximum sustained performance of 135 t/h. The fluidized bed consists of sand and fuel ash which is supplied by the blend of biomass by means of two supply lines. The circulation of water in the boiler is natural and rises to the top in countercurrent to the flue gas. Boiler has one drum and three-stage steam feed heater and two section divide in two parts of steam coolers located between the degrees of the superheater. The air for fluidization is introduced into the combustion chamber from the air box below the furnace. Bottom ash from different parts of extension grate is removed with six hoppers. The flue gases from the boiler are removed by a centrifugal exhaust fan and then introduced to the electrostatic precipitator before leaving the chimney. Part of the flue gas due to gas recirculation is returned to the boiler so that it is possible to adjust the temperature of the bed by reducing the amount of oxygen in the combustion chamber.

Fuel combusted in the boiler consists of the woody biomass in the form of wood chips and agro biomass in the form of pellets from sunflower husk, rape, willow chips and bran cereal. The main component of the fuel are wood chips (80-100%) and the residual fuel is a agro biomass (0-20%).

3. Conducted analyzes and research tests

3.1. Analysis of the basic parameters of the boiler

A preliminary assessment of the causes of agglomeration of the bed, as well as obtaining a high exhaust gas temperature at the outlet of the boiler was done by analyzing the operation of the boiler with "as-usual" configuration (bed temperature, air distribution). On the basis of this performance evaluation the following conclusion can be drawn:

- To reduce the tendency to deposit sintering during the combustion of 20% mass shore of sunflower husk in accordance with the recommendation of the supplier of the boiler temperature is maintained at 750 °C.
- Maintaining the temperature in the bed causes the necessity of increased flue gas recirculation, which makes up 50% of the flow of the air-flue gas fed into the bed at rated load up to 85% of the stream mixes with the minimum load.
- With the above, the participation of the recirculated flue gases in a mixture of air and flue gas, in practice in a bed combustion takes place in an atmosphere low in oxygen (half reduction atmosphere), and only in the upper zone of the boiler combustion of small grains and separated combustible gases takes place. Confirmation of this condition is the temperature of the flue gas II ° superheater, which takes a value of more than 70K higher than the temperature in the bed. So it can be assumed that the temperature in the central zone of the furnace is close to or even higher than 900 °C. This is confirmed by the temperature of the metal II ° superheater which exceeds the permissible level.
- Properties of biomass ashes causes that the sintering temperature in a half reduction atmosphere are tens of degrees lower than the sintering temperature in an oxidizing atmosphere.
- Increased the flue gas recirculation streams to maintain a temperature of 750 ° C in a fluidized bed increase the total flue gas stream flowing through the boiler, resulting in an increased flow of the heat transferred in the second pass of the boiler.

3.2. Predicting bed agglomeration and fouling tendencies for the tested biomass fuels.

In this section, an assessment of the impact of the type of biomass and its mass share in fuel mix on slagging (S_R) and fouling (F_u) indexes was carried out. Analysis was carried out on the basis of chemical compositions (given in the form of oxides) of ashes from biomass: wood chips, sunflower husk, willow, pellets from rape straw, sunflower husk II and briquettes of wood chips.

Most of the slagging and fouling indicators has been developed for coal [11], but they were used also for the ashes of biomass [1, 13], sewage sludge [14], and obtained from the co-combustion of coal and biomass [15]. However, that they are not only the one parameter which characterizes the ashes, they can only help in the overall characteristics of ash. Results based on such calculations should not be seen as the only credible. A fuel sample cannot be assigned to the specific characteristics of ash melting, for the same fuel combusted in different conditions may give the ashes of different chemical composition, and therefore different characteristics fusibility. In general, iron compounds (sulfides, carbonates, oxides), calcium and magnesium, lower the melting point of ash, while the silicon and aluminum oxides – increase [16]. In the figures 3.1 and 3.2 alkali metal oxide content in the ash of the biomass taken for testing and selected for comparative analysis are presented.

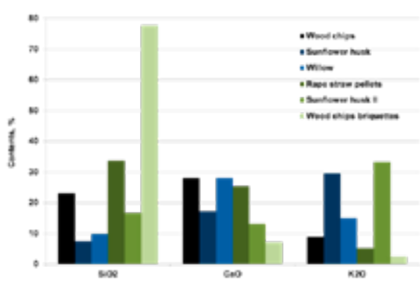

Figure 3.1. Alkali oxides composition for studied biomass.

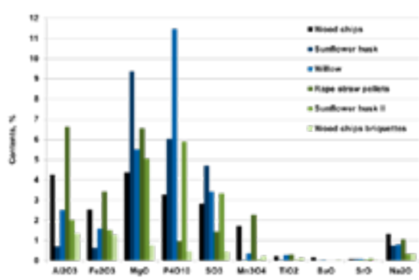

Figure 3.2. Alkali oxides composition for studied biomass.

Based on the chemical composition of the ashes the fouling *(F_U)* and slag viscosity index *(S_R)* indices were determined [2, 5, 11]:

$F_u = R_S \frac{Na_2O + K_2O}{S^d} = c_m \ (Na_2O + K_2O)$ (3.1)	$S_R = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} 100$ (3.2)
If: $F_u \le 0,6$ low fouling inclination $0,6 < F_u \le 40$ high $F_u > 40$ extremely high, tendency to sintering of deposits	If: $S_R > 72$ low slagging inclination $72 \ge S_R > 65$ medium $S_R \le 65$ high.

Calculated ratio Fu (Fouling Index) was calculated according to equation (3.1) basing on the composition of samples of biomass and selected for comparative analysis of biomass defines the tendency of fuel to fouling (then sintering) on heating surface. As it can be observed this index, aside from wood briquettes of wood shavings, has a value higher than 0.65 for all biomass. According to the literature [5, 11], when the ratio is higher than 0,65, the fuel has a strong tendency to fouling on heat exchange surfaces in boiler. Maximum value of this index takes the husks of sunflower. On the basis of the index value Fu can be seen that only briquettes of the wood chips should not exhibit a tendency to fouling. As dangerous the SR values be considered. Unfortunately for all analyzed biomass, the received value less than 65. It was alleged that ashes characterized by a index SR lessees than 65 have a very high tendency to slagging, through its large viscosity. In the case of briquettes of wood chips and pellets of bran cereal the coefficient SR was higher than 72, it indicates a very low tendency of these fuels to create slag.To determine the influence of the quantum of biomass in the type of mixture of two biomass for its tendency to slagging by the combustion process, simulated a mass share of the biomass in fuel stream. As was said earlier (wood chips, sunflower husk, willow), characterized by providing indicators on the average or very high tendency to fouling on boiler heating surfaces. Below in Figure 3.3 illustrated influence of the quantum of biomass in a mixture with other biomass to value ratios of „slagging index" SR and „Fouling index" Fu.

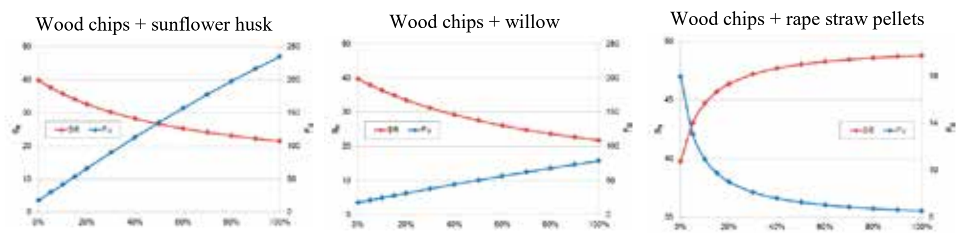

Figure 3.3. Changes in value of fouling and slagging indexes for a mixture of wood chips with different kinds of biomass with a variable mass share.

The analysis of the impact of adding different kinds of agro biomass to wood chips shows that a positive impact on reducing slagging and fouling have the pellets from rape straw. This result confirms the exception to the rule that the straw biomass negatively the affects sintering of ash.

3.3. Studies in BFB experimental installation

Research related to combustion of mixed biomass was carried out using experimental installation imitating combustion of solid fuel boiler with bubbling bed Fig. 3.4. The purpose of this step was to check whether the process parameters of biomass (grain size, flow speed in the combustion chamber) have any effect on the agglomeration of the bed and the experimental determination of the temperature distribution profile in the reactor according to these conditions. This distribution in the real affects the amount of heat transferred in the combustion chamber and carry-out of the heat with the flue gas to the convection part of the boiler. The study was conducted using a mixture of wood chips with two types of biomass: the husks of sunflower- currently burned in power plants and willow chips that could be an alternative biomass to ensure the appropriate share of non-woody biomass in the fuel flow.

Conditions to perform the tests on the experimental installation

To achieve visible and relatively fast effects of the impact of the type of the biomass, on the process of agglomeration of the bed in the tests used composed blend of biomass burned in power plants in the proportion of 50% wood chips and 50% sunflower husk. Additionally, tests were performed using willow chips mixture in proportion as in the case of sunflower husk. Tests mixture combustion of wood chips from sunflower husks were performed for two grain-size: 3,15-5mm and 0,2-3,15mm the two feed streams of primary air: 2,8 kg / h and 4 kg / h which when converted into thermal conditions in the fluid obtained gas velocity in the reactor at 0.7m / s and 1,05m / s.

Figure 3.4. General view of experimental installation

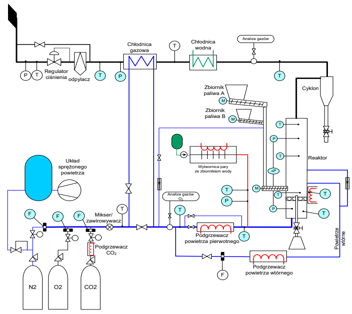

Figure 3.5. Flow diagram of experimental installation with BFB reactor

Due to that the information literature and the experience of implementers work showing the influence of the material used for the original deposit in the agglomeration during combustion, the mixture from sunflower husks as biomass increased to the sintering properties were studied in three types of bed material:

- The sand used in BFB boiler
- Low silicon Sand
- Bottom ash from the coal combustion (received from the coal fired utility plant).

During the research for the keeping the same process conditions the following conditions were maintained:

- The initial height of the sand bed: 75mm.
- The combustion air only was fed into the bed (primary air), and the two levels 170 mm and 280 mm above the screen distribution as the secondary air.
- Temperature of air fed to the combustion 130-150 ° C.
- Bed temperature: 840-850 ° C.
- Oxygen content at the outlet of 4-5%.

The temperature in the reactor was measured at four levels ie. 30mm, 130mm, 430mm, 950mm above the bottom (air distribution system). Each test was carried out on a clean, cleared from the previous test ash on the new portion of the bed material. The tests were carried out in the regime 4-5h of work on the set thermal conditions. In the absence of signs of a sinter with the selected test reactor on the second day the mixture was continued without changing the burning of the bed with new ones.

Summary of test results for experimental installation

The effects of the tests related to the impact assessment of the parameters of the process of combustion agglomeration deposits are presented in the Table 3.1

As results of the tests carried out in more adverse conditions, i.e. the bed temperature of 850 ° C, 50% of the biomass "agro" (husk sunflower or willow) compared with the actual conditions used in the boiler, only combustion a mixture of willow energy and combustion a mixture of sunflower husk in bottom ash from coal-fired boiler did not affect the formation of agglomerates.

Table 3.1. Summary of the tests and their result

Type of compound	Type of bed	The air flow into the bed [kg/h]	Results
Wood chips / Sunflower husk (50/50) grain size 3.15-5	Sand 0.2-0.315	1.05	After one hour rapid temperature increase was observed. Sinter
Wood chips / Sunflower husk (50/50) grain size 3.15-5	Ash 0.2-0.315	1.07	After 5 h operation no agglomeration observed.
Wood chips / Sunflower husk (50/50) grain size 3.15-5	Sand 0.2-0.315	1.06	After two days of operation per 4.5 h stable operation. Few agglomerates on the walls observed.
Wood chips / Sunflower husk (50/50) grain size 2-3.15	Sand 0.2-0.315	1.05	No sinter – in bed observed small balls resulting from ash sticking to sand.
Wood chips / Sunflower husk (50/50) grain size 2-3.15	Sand 0.2-0.315	1.05	After 4.5 h of common work agglomeration on walls and thermocouple was observed in areas witch temperature above 850°C
Wood chips / Sunflower husk (50/50) grain size 3.15-5	Sand 0.2-0.315	0.7	After 5 h operation small sinter and agglomeration on thermocouple was observed.
Wood chips / Sunflower husk (50/50) grain size 3.15-5	Low Silica Sand 0.2-0.315	0.7	After a few minutes operation, big amplitude of temperature in bed was observed -Sinter
Wood chips / Willow (50/50) grain size 3.15-5	Sand 0.2-0.315	1.06	After two days of operation per 4,5 h stable work. No sinter observed.
Wood chips / Willow (50/50) grain size 3.15-5	Sand 0.2-0.315	0.7	After 4.5 h stable operation. No sinter.

Produced during the test sinters and matted grain deposits are characterized by high brittleness, scatter in the fingers without the use of force. The figures 3.6 and 3.7 show pictures of sinter formed during one of the tests and conglomerated grain deposits.

Figure 3.6. View of the reactor interior and sinter of bed material

Figure 3.7. Bed material after combustion of fuel mix : sunflower husk and wood chips

The temperature distribution in the combustion chamber of the reactor

Due to the occurring high temperature of flue gas from the BFB boiler of the utility unit on the basis of the results of the tests on the experimental installation test the analysis of biomass combustion process in each zone of the furnace was carried out. Distribution of temperature of flue gas along the height of the reactor at different configurations of the process is shown in the figures: 3.8, 3.9 and 3.10.

Based on the results of tests on the experimental installation the following thesis can be raised:

- The temperature in the reactor along the height gradually decreases irrespective of the stream of gas. This is confirmed by the discuss of the test base that in real combustion is performed high over and above the bed, and thus high-temperature zone is formed.
- the mixture with sunflower husk, primarily combustion of the bottom part of the reactor where it gives slightly higher temperatures due to the fragmentation sunflower husk. Zone of higher temperature is more stretched along the height of the combustion chamber during combustion of willow.
- The time period followed by deposits agglomeration depends on:
  - the type of biomass, tests using willow at temperature of 850 °C and at the increased participation, show no tendency to sintering while the noticeable during tests of sunflower husk combustion;
  - flow rate of gases through the bed, which is destructive to the formed agglomerates through both, a fluidization intensity change as well as better mixing of the bed preventing the formation of locally reducing atmosphere;
  - grain size as the smaller particles have less tendency to stick together.the grain size, the smaller particles have less tendency to stick together.

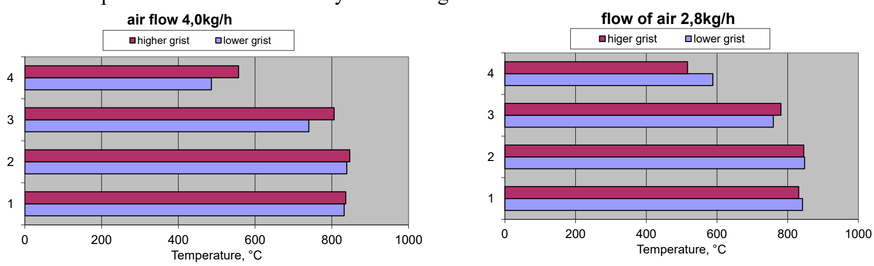

Figure 3.8. Temperature distribution along the height of the reactor, depending on the grain size

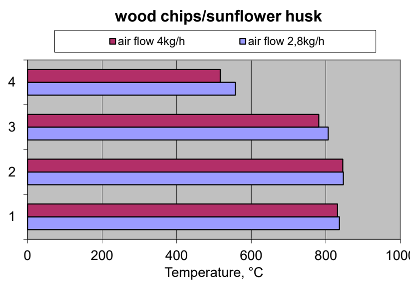

Figure 3.9. Temperature distribution along the height of the reactor during the combustion of the mixture with sunflower husk

Figure 3.10. Temperature distribution along the height of the reactor during the combustion of the mixture with willow

3.4. Optimization of the boiler on the basis of the results of work

The aim of the study was to perform tests to verify the optimal configuration of the boiler to achieve the lowest temperature of the flue gas. The basis for proposed the changes during testing verification were the results obtained from the analysis of the boiler during the base test, the analysis of indicators of biomass tendency to slagging and fouling of heating surfaces, and tests performed on experimental installation. When tested at two levels of temperature in the bed 765 ° C (tests from 1 to 4) and 770 ° C (tests from 5 to 8) made changes propagation of primary and secondary air with decreasing amount of flue gas recirculation. As the base configuration of the air distribution accepted test boiler, wherein the temperature in the bed was maintained at 750 ° C.

For all configurations settings of the boiler obtained temperature of flue gas achieved for the individual surfaces was lower than the base test (see fig. 3.11). Visible is the increase in temperature of flue gas with the passage of time from the surface treatment carried blowers ash. However, it is reduction temperature of the flue gas from the boiler.

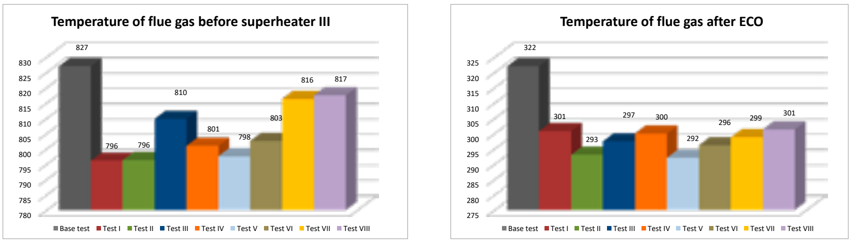

Figure 3.11. The flue gas temperature for different surfaces during the verification tests

The confirmation of the positive impact of the proposed configuration parameters of the boiler is getting lower temperature of metal superheater 2° mainly exposed to the effects of high temperature of the flue gas leaving the combustion chamber (Fig. 3.12)

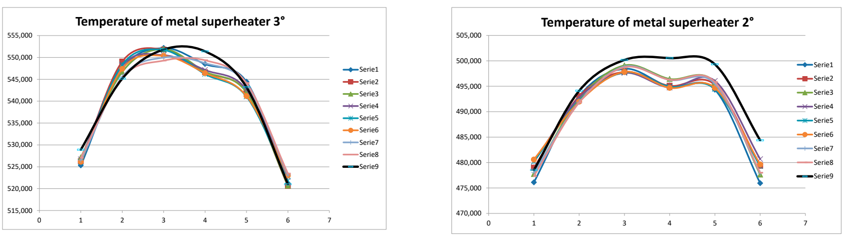

Figure 3.12. Distribution of temperature of superheater metal during testing

4. Conclusions

The ultimate and proximate analysis of biomass, the chemical composition of the ash as well as the tests carried out on with use of experimental installation led to the conclusion, that the agglomeration of the bed did not only depend on the sintering temperature, but also on other factors.

Factors influencing on the time period followed by deposits agglomeration depends on:

- flow rate of gases through the bed, which is destructive to the formed agglomerates through both, a fluidization intensity change as well as better mixing of the bed preventing the formation of locally reducing atmosphere;
- grain size as the smaller particles have less tendency to stick together.

Results gained during performed research allowed to convince the staff of the power plant to increase the temperature of the bed (imposed by the supplier of the boiler) from 750°C to 765°C, which resulted in:

- reduction of the amount of recirculated flue gas,
- decrease of temperature of the flue gas,
- increase of the efficiency of the boiler,
- at least double elongation of operational periods between boiler turns off related to the agglomeration of the bed,

The implementation of the obtained results to the plant operation gave the expected improvement of the boiler performance.

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