AGGLOMERATION OF BED MATERIAL: INFLUENCE ON EFFICIENCY OF BIOFUEL FLUIDIZED BED BOILER

by

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The successful design and operation of a fluidized bed combustor requires the ability to control and mitigate ash-related problems. The main ash-related problem of biomass firing boiler is agglomeration. The fluidized bed boiler with steam capacity of 66 t/h (4 MPa, 440 °C) was started up at the Arkhangelsk Paper-Pulp-Plant in 2001. This boiler was manufactured by the Russian companies "Energosofin" and "Belenergomash" and installed instead of the existing boiler with mechanical grate. Some constructional elements and steam drum of existing boiler remained unchanged. The primary air fan was installed past the common air fan, which supply part of the air into 24 secondary air ports.

First operating period shows that the bed material is expanded and then operator should increase the primary air rate, and the boiler efficiency dramatically decreases. This paper presents some results of our investigations of fuel, bed and fly ash chemical compositions and other characteristics. Special experiments were carried out to optimize the bed drain flow rate. The influence of secondary air supply improvement on mixing with the main flow and boiler efficiency are given.

Key words: biomass combustion, bubbling fluidized bed, agglomeration, boiler efficiency

Introduction

In 2000, the "Energosofin" supplied the fluidized-bed boiler manufactured by the "Belenergomash" to the pulp-and-paper processing plant of the Arkhangelsk TPP-3. All items of the boiler auxiliaries had been produced in Russia.The specific features of the design required the utmost use of the load-bearing structures while keeping the boiler drum and boiler bay dimensions unchanged. All this demanded the minimum height of the boiler furnace (fig. 1).

The 66 t/h, 4 MPa, 440 °C boiler was designed to fire the bark and wood waste of 57% moisture content. The air is fed by the common air fan and part of it is removed past the lower banks of the tubular air heater to the primary air fan under the grate. The

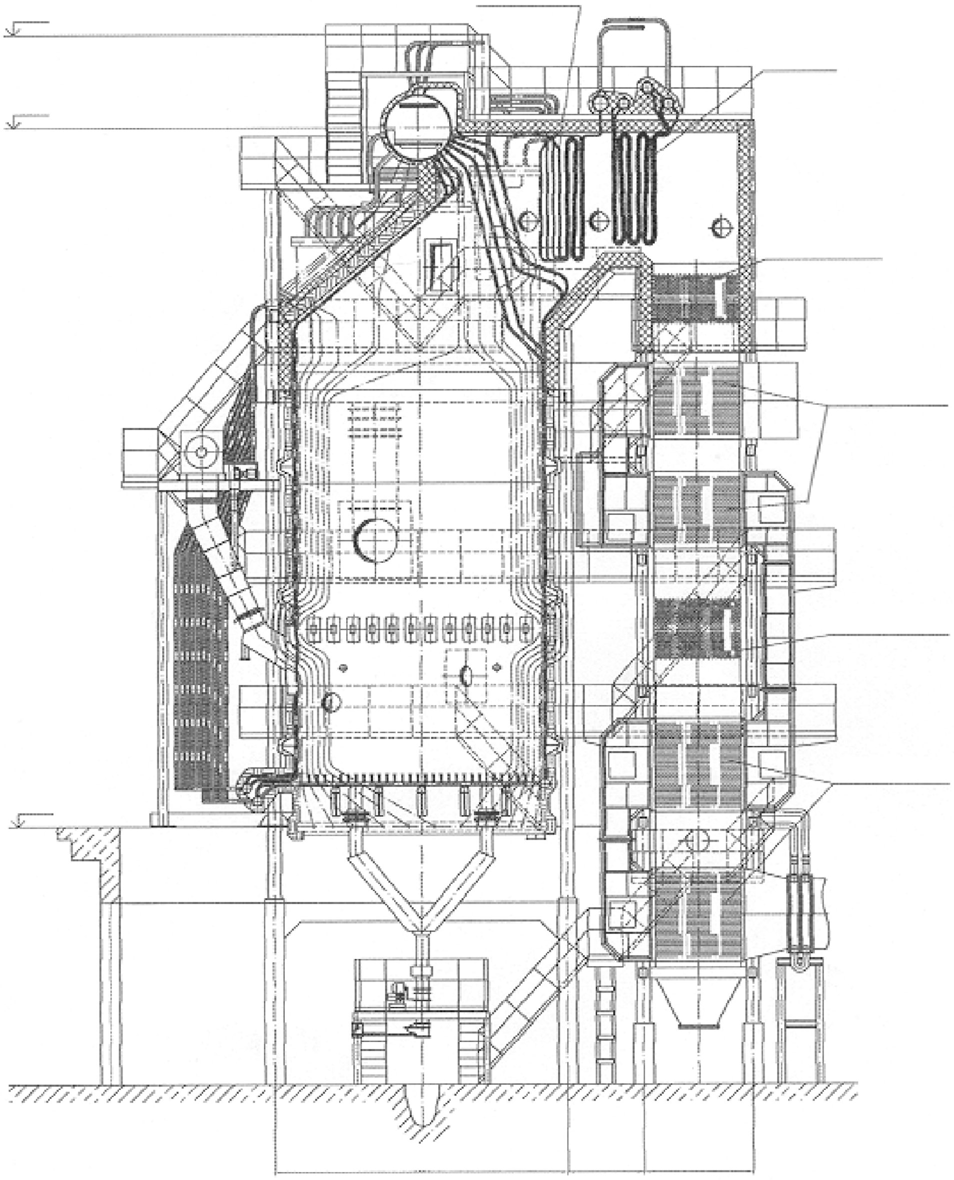


Figure 1. FM boiler KM-75-40 M

secondary air past the upper air heater bank is directed to the nozzles located at the furnace side walls. The fuel is fed via the inclined chutes from the boiler front. The cap no-riddling grate is provided with six ports for the removal of the bed ash pairwise interconnected with the ash removal lines via the ducts.

Investigatons of fuel, bed ash, and sand characteristics

Generally, sand of a specified grain size is used as bed material. It is a common knowledge that some wood waste ash components cause the bed particle size to increase. This was found at TPP-3 boiler. Table 1 illustrates the size composition of the initial sand, bed ash removed from the boiler after one-week and 1.5-month operation, and the entrained fly ash.

Table 1. Particle size distribution

Screen size m	Initial sand Over-size %	Bed ash (one-week operation) Over-size %	Bed ash (1.5-month operation) Over-size %	Fly ash Over-size %
2500	–	1.00	10.09	–
1600	0.06	1.24	45.66	0.15
1000	12.15	11.41	85.09	0.38
630	76.89	80.71	96.77	6.37
400	97.4	92.95	98.53	25.01
200	99.41	97.12	98.99	52.79
90	99.78	99.31	99.17	86.93
63	99.88	99.69	99.25	93.59
<50	100.00	100.00	100.00	100.00

Figure 2 presents the data of tab. 1 as a dependence of undersize (*R* %) *vs.* screen size (*d* mm). The average size of the sand over the bed surface was about 0.7 mm. After the one-week operation, the bed ash size was about as that of the initial sand. However, large sand fractions (over 1.6 mm of 1.24%) appeared and the fine size sand (<0.5 mm), was found to increase from 8 to 11%. It is an evidence of the two processes occurring simultaneously, particle attrition and agglomeration. The bulk density of the bed ash (1.437 kg/m^3) is close to the density of the initial (1.437 kg/m^3) sand. The ash discharged after 1.5-month operation mostly consists of agglomerated particles of the average size of 1.3 mm. In this case, the share of large fractions above 1.6 mm in size had become at 45%, and that of the fine particles (<0.5 mm) was only 2%. The bulk density of the bed ash was 950 kg/m^3. Thus, during long operation, agglomeration becomes more pronounced as compared to attrition. The bed drain flow rate was 1 to 1.5 t/d in that period of operation.

A complex of physical and chemical analyses was carried out of the initial (as-fired) fuel. Table 2 presents the basic fuel proximate analysis. The fuel ash chemical composition is illustrated in tab. 3.

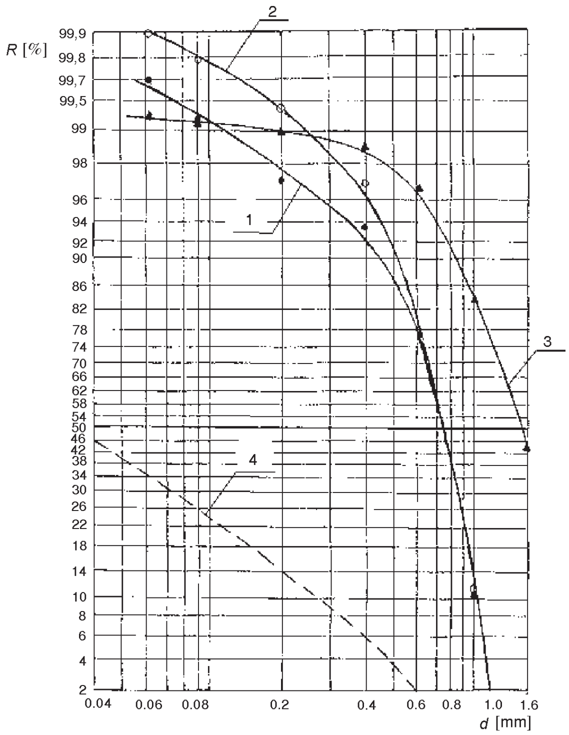


Figure 2. Saving analysis of bed materials and fly ash
1 – Sand, 2 – Bed ash one-week operation,
3 – Bed ash 1.5-months operation, 4 – Fly ash

Table 2. Fuel proximate analysis

Name	Content
Moisture %	47.2
Ash %	1.4
Carbon %	29.85
Hydrogen %	1.90
Sulfur %	0.05
Nitrogen %	0.32
Oxygen %	9.28
LHV kJ/kg	8730

Table 3. Fuel ash chemical composition

Compound	Content
SiO_2	26.6
TiO_2	0.7
Al_2O_3	4.7
Fe_2O_3	4.0
CaO	45.0
MgO	6.1
SO_3	0.14
$Na_2O + K_2O$	<12.8

The semi-quantitative elementary analysis of the bed ash and the sand was carried out using the VRA-30 X-ray fluorescent method. The results obtained are given in tab. 4. The softing characteristics were determined using the “heating” microscope in a semi-reducing medium. The results obtained are given in tab. 5.

Table 4. Sample quantitative elementary analysis

Sample	Compounds %								
	SiO_2	TiO_2	Fe_2O_3	Al_2O_3	CaO	MgO	K_2O	Na_2O	SO
Fly ash	63.8	–	6.7	<1.0	20.2	<0.5	6.6	–	0.4
Bed ash (1.5-month operation)	68.2	–	9.6	<1.0	12.9	<0.5	1.0	–	0.5
Bed ash (one-week operation)	92.4	–	0.3	<1.0	5.1	0.7	1.1	–	0.9
Initial sand	100	–	–	–	–	–	–	–	–

Table 5. Bed ash softing characteristics

Name	Temperature °C		
	t_A	t_B	t_C
Bed ash agglomerates	1010-1020	1140-1155	1190-1200
Bed ash (one-week operation)	1115	>1310	–

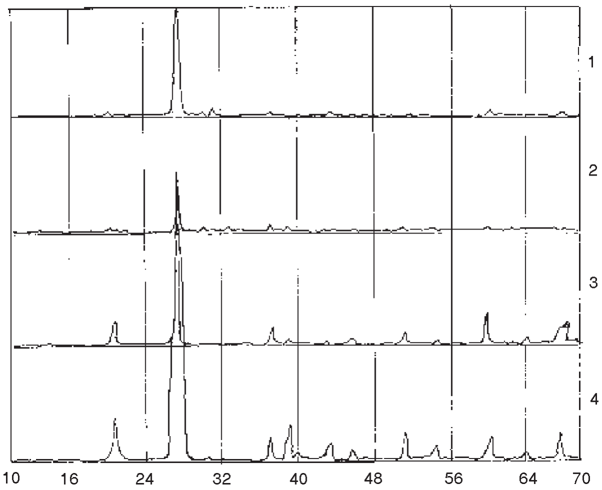


Figure 3. Results of X-ray analysis
1 – Bed ash 1.5-month operation, 2 – Agglomerate, 3 – Bed-ash one-week operation, 4 – Sand

Based on the data presented above, one may conclude that the bed agglomerated material considerably differs from the initial sand and fuel ash in both in the composition and characteristics. The X-ray phase analysis of the bed material showed that the bed ash agglomerates are in fact amorphous vitreous substance comprising a little bit of the crystalline structure made up by quartz and calcium silicate formed at a temperature of about 1000 °C. The X-ray photographs of the samples are illustrated in fig. 3.

The sand structure was also examined with a microscope using the digital camera (figs. 4-7). After a week operation, the bed material sample contained fine sand and of up to 20% of grey and black agglomerated particles (fig. 5). The bed ash particles after 1.5-month operation had a rounded-off shape and were of dark-grey color with white embedment (fig. 6). When being crushed, one can see that such particle (fig. 7) is non uniform in its inner structure.

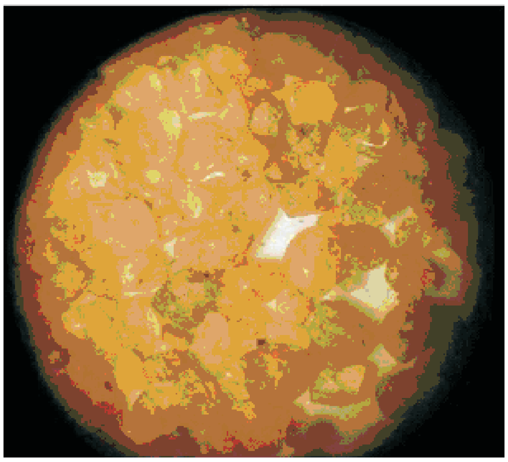
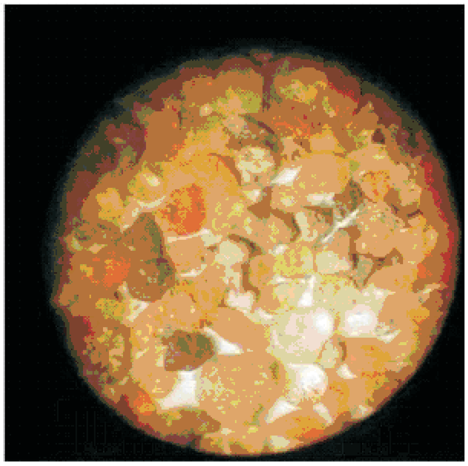


Figure 4.



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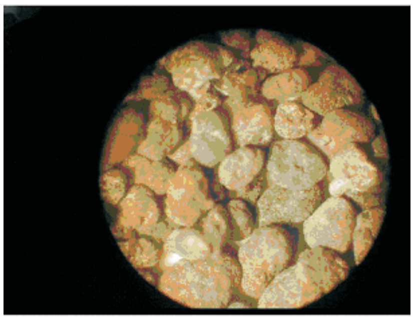

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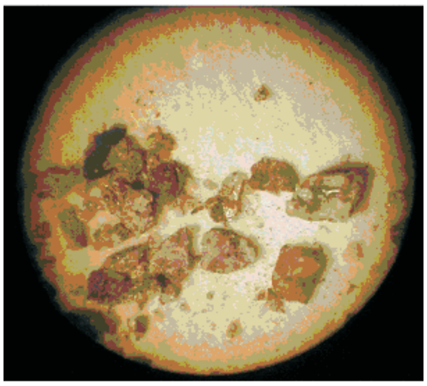

Figure 7.

Analyses

The problems with bed agglomeration have yet not been studied well. It is known that the rate of formation of agglomerates is influenced by ash Ca and Na content, bed temperature and fluidizing velocity. No one can exclude the formation of eutectics at a softing temperature in the ternary system SiO_2-CaO-FeO. It is noted in 1 , that at a temperature below 750 °C, the agglomeration processes are decelerated. The increased fluidizing velocity also decreases the rate of agglomeration. In this case, sand as bed material is the worst out of the investigated materials 1 as regards the bed particle agglomeration.

The interaction of the ash components with the quartz sand causes the formation of readily softening eutectics. Here, according to 2, 3 , the most probable reactions to occur are as follows:

$$2SiO_2 \quad Na_2CO_3 \quad\quad Na_2O\ 2SiO_2 \quad CO_2 \tag{1}$$

$$4SiO_2 \quad K_2CO_3 \quad\quad K_2O\ 4SiO_2 \quad CO_2 \tag{2}$$

In this case, the softing temperature of the reaction products (1) and (2) is 874 and 764 °C, respectively. This is significantly lower as compared to individual components. The readily fusible eutectics have even lower softing temperature.

The picture in the softing of the following investigated systems is as follows:

$$(1)\ Na_2O\ 2SiO_2 \quad SiO_2 \quad T_s \quad 790\ ^\circ C\ (Na_2O \quad 26\%, SiO_2 \quad 74\%),\ \text{and}$$

$$(2)\ K_2O\ 2SiO_2 \quad K_2O\ 4SiO_2 \quad T_s \quad 760\ ^\circ C\ (K_2O \quad 33\%, SiO_2 \quad 67\%)$$

The data of 3 give the evidence that the ash ferric compounds also react with alkalines:

$$Fe_2O_3 \quad Na_2CO_3 \quad\quad Na_2Fe_2O_4 \quad CO_2 \tag{3}$$

$$Fe_2O_3 \quad K_2CO_3 \quad\quad K_2Fe_2O_4 \quad CO_2 \tag{4}$$

However, the softing temperature of the reaction (3) products reaches 1135 °C. Nevertheless, in the presence of large amount of ash Fe_2O_3, the alkalines will primarily react with Fe_2O_3, forming no readily softening eutectics. The coal ash features rather higher molar ferric to alkalines ratio as compared to biomass ash.

It is of importance to know the share of K, Na, and Fe compounds remained in the bed. The data of 2 give the experimental results obtained on 150 kW test facility when corn cob with high K_2O content was fired. The sand of the average granulation size of 760 mm (350 mm bed height) was used as bed material. Two runs were conducted. First, bed temperature of 820 °C, excess air 1.72, fluidizing velocity of 1.58 m/s. In the second run, the respective figures were 750 °C, 1.87 and 1.32 m/s. Figure 8 2 illustrates the time variations of Na+K and Fe compounds in the bed along with the predictive mass balance data. It was founds that 43% and 39% (runs I and II) of Na and K

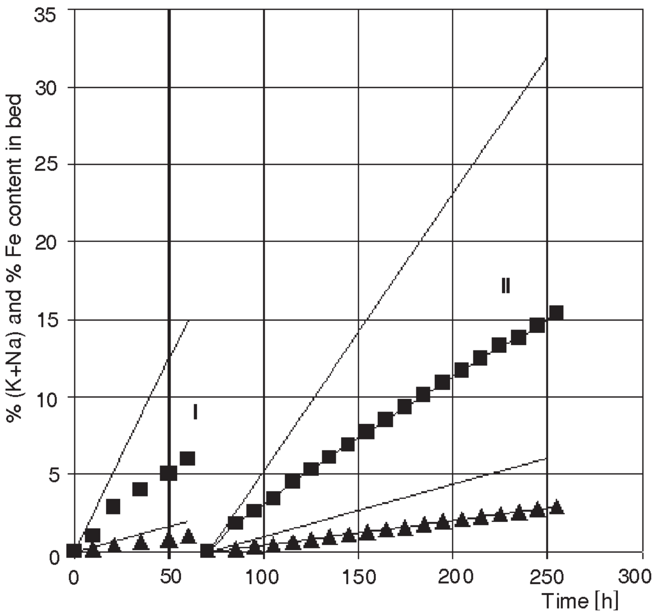

Figure 8. Build-up of alkalines in bed due to combustion of corn cob 2
■ – measured (K+Na),
—— mass balance line (K+Na)
▲ – measured (Fe),
—— mass balance line (Fe)

compounds contained in the ash, remained in the bed. The comparative data for Fe compounds were 56 and 49%.

Our data on the bed material structure are in good agreement with those of (B. G. Grubor *et al.*, 1995 2). Reduction of the bed temperature to 700 °C in industrial boilers increases the period when agglomeration occurs by 2 to 3 times. However, this approach results in impermissible CO emission rise.

The traditional way to reduce the negative effects of bed agglomeration lies in increasing the bed drain with the addition of the fresh inert material. There are known cases were the 7-20 t/d sand was added at some industrial boilers. Here, the bottom ash was regenerated by screening and recirculation on the required fractions in the bed. Practically, it is important to evaluate the necessary flow rate to prevent agglomeration. To this end, the material balance and Na and K components balance equations are as follows:

$$G_d + G_e = G_a + G_s \tag{5}$$

$$G_d S_d + G_e S_e = G_a S_a + G_s S_s \tag{6}$$

where

G_d, G_e, G_a, G_s – bed drain, entrainment solids, fuel ash and fresh sand flow rates, kg/h ,
S_d, S_e, S_a, S_s – (Na + K) concentration in the bed, entrainment solids, fuel ash and fresh sand, % .

If we assume that the added sand is free of Na and K, and the entrainment share is 0.95 (boiler design), then the ratio of the added sand and the fuel ash will be:

$$\frac{G_s}{G_a} \quad 0.05\,\frac{S_a \quad S_e}{S_d} \tag{7}$$

Accordingly, at the critical in-bed concentrations of Na + K of 1% (tab. 5), the relative added flow rate sand for TPP-3 boiler will be 0.31 of the ash gone to the bed, *i. e.* about 2.6 t/h and the bed drain of about 3 t/h. Probably, these predictions are underestimated due to the neglect of the sand entrainment and Na + K compounds in the fresh sand.

Another approach lies in increasing the gas velocity in the bed. Bellow, one can see the results of the analysis of bed hydrodynamics. We had determined the fluidizing coefficients, time of complete mixing, primary air flow rate required to prevent the stagnation zones, as well as bed material entrainment for the initial sand and the agglomerates.

The fluidizing coefficient (K) is in fact the ratio of the air velocity at the bed temperature and minimum fluidizing velocity. For the initial sand with the average size of 0.7 mm and under nominal load and with the share of the primary air of 50%, said coefficient eq. (7), and for agglomerates under the same conditions it is 3.

The time of complete mixing is both in reverse proportion to the diffusion coefficient and to the square of the furnace width. Said time shall be lower than that required for bed material phenomena, and is found to increase with increasing bed height and temperature. It is the acceptable value, considering burn-up of the fuel of granulation size of 50 mm, and is reached for initial sand bed height of over 600 mm at temperatures above 800 °C.

The absence of the stagnation zones was assessed using the two methods obtaining almost identical results for sand size of 0.5-0.8 mm. No stagnation zones were observed in the case of the initial sand at air velocity in the holes of at least 50 m/s. This value for agglomerates was found to be over 60 m/s. In this case, for sand the primary air flow rates are somewhat and for agglomerates substantially higher as compared to the nominal values.

Inadequate in-bed mixing leads to increased bed temperature difference. In some regimes with bed agglomeration, said difference exceeded 100 °C. Besides, during the initial operation at velocities in the bubbling grate nozzles of about 50 m/s, the 6-point measurement difference was 40 °C max.

With increasing primary air velocity, the share of the fuel fired in the bed and the sand particle entrainment from the bed increased. Figure 9 illustrates the calculation data using the dependence of particle entrainment *vs.* in-bed gas velocity. To this end, use was made of the entrainment constants and the dancing velocity of the in-bed fines obtained experimentally. The entrainment increases sharply with increased gas velocity, share of fines in the initial sand and bed height. With the normal primary air flow rate, it is about 10-50 kg/h, whereas at a higher flow rate (in the presence of agglomerates) it was found to exceed 2000 kg/h. The latter value is above the ash fed to the bed with resultant depletion thereof.

The above-stated necessity of maintaining the sufficient secondary air flow rate had been well proved by the boiler operational experience. At the flow rate of 0.5 of the total value, firing and heat liberation in the furnace are enhanced. The reduction of the secondary air share causes delayed firing as it is well illustrated in fig. 10. There, one can see the air jet trajectories determined by the techniques jointly developed by the Moscow Power Institute and the All-Russian Thermal Engineering Institute 4 . The fact of a significant amount of air fed for cooling the load-carrying and lighting-up burners was considered.

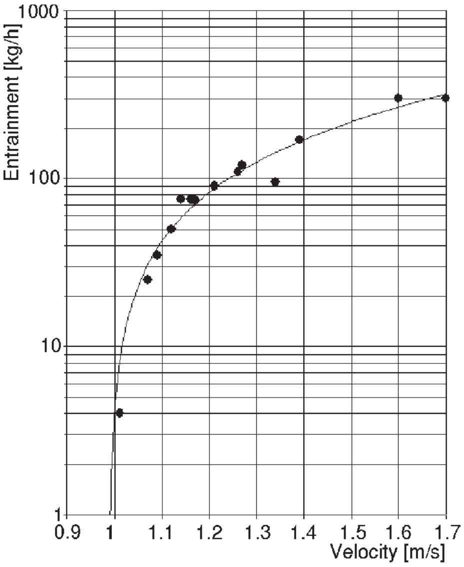

Figure 9. Particles entrainment from the bed

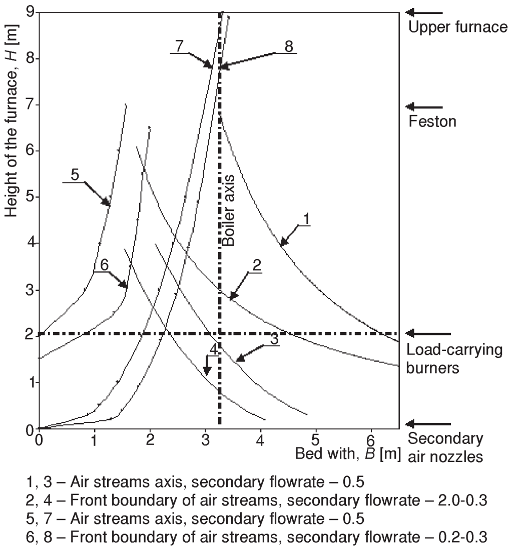

Figure 10. The secondary air jet trajectories

Conclusions

The economical operating of FB boilers requires correct, advance knowledge of biofuels, to optimize the combustion. The successful design and operation of a fluidized bed combustor require the ability to control and mitigate ash-related problems. The main ash-related problem of biomass firing boiler is agglomeration.

The problems with bed agglomeration have not been studied well yet. This paper presents some results of the investigations of fuel, bed and fly ash chemical compositions and other characteristics. The interaction of the ash components with the quartz sand causes the formation with low melting point eutectics.

The traditional way to reduce the negative effects of bed agglomeration lies in increasing the bed drain with the addition of the fresh inert material. Practically, it is important to evaluate the necessary flow rate to prevent agglomeration. The equations to estimate of bed drain flow rate were presented in the paper .

Another approach lies in increasing the gas velocity in the bed. We had determined the fluidizing coefficients, time of complete mixing, primary air flow rate required to prevent the stagnation zones, as well as bed material entrainment for the initial sand and the agglomerates. Inadequate in-bed mixing leads to increased bed temperature difference. In some regimes with bed agglomeration, said difference exceeded 100 °C.

The necessity of maintaining the sufficient secondary air flow rate had been clearly proved by the boiler operational experience. The fact of a significant amount of air for cooling the load-carrying and lighting-up burners was considered. The influence of secondary air layout improving on mixing between air and gas main flow and boiler efficiency are also presented in the paper.

Data have not been completed for detail calculation and optimization of the FB boiler design and operation. The chemical and physical characteristics of bed materials must be interpreted to a suitable form for the boiler operation. The research in this area should be emphasized.

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