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Environmental Aspects of The High Ash Content Biofuel Pellets Combustion in The Experimental Burner.

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ABSTRACT

The environmental aspects of the developed energy-efficient heating system (EHS) operation intended for the thermal energy generation from wood waste and high ash content agricultural raw materials are considered in the paper. The burner which operates with any granular biofuel type is the basic component of the EHS. From the environmental point of view, the biofuel combustion is related to CO, NO_x and other gases discharge in the air. The oxygen supply in the burner has the most significant impact on combustion process and air emissions. The continuous control of the oxygen supply during combustion will allow for emissions reduction up to the threshold limit values. The developed high efficiency combustion unit will permit to reduce the ecological environmental impact of the energy-efficient heating system to a great extent. The energy-efficient heating system operation analysis was performed in the paper to determine the air emissions volume during combustion of the granular biofuel from wood waste and high ash content agricultural raw materials.

Keywords: Granular biofuel, burner, environmental performance, oxygen supply, ash content, combustion, thermotechnical characteristics.

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INTRODUCTION

The biofuel pellets along with the pipeline natural gas are the worthy alternative to conventional fuels such as diesel fuel, coal and firewood in Russia. The fuel pellets are called the “improved” fuel. As opposed to conventional firewood, the pellets have the far lesser moisture of 8-12 %. Due to the moisture level along with the rather high density up to 1400 kg/m^3, the calorific efficiency of 14-23 MJ/kg can be achieved, which is more than the calorific efficiency of the lignite coal and the peat briquettes [1-2].

The pellets have become popular for domestic use, as far as the heat from the firewood is perceived as more comfortable than the heat generated from the light fuel oil or natural gas. Moreover, there are the municipal boiler stations and the small-scale enterprises operating on pellets in Europe [1-2].

In recent years, the biomass combustion in the low power boilers (<300 kW, according to EN 303-5) in domestic and public buildings becomes more and more popular. The environmental problem of the heating systems operating on wood waste and high ash content agricultural raw materials has become crucial. However, due to depletion of conventional fuels, used at large CHP plants, the small heating systems are used more than ever. The small boilers for pellets combustion got the widespread use. The performance coefficient of such boilers reaches 95 % [3-4].

For the existing techniques of thermal energy generation in small boiler plants and households, the use of high quality fuel is required. Consequently, the expensive imported fuel is used. Its quality is reduced during the long-term transportation, which leads to the increase in its cost and the thermal energy generation costs, as well as the decrease in the boiler reliability and efficiency. The boiler equipment thermal insulation control and quantitative assessment of the heat radiated by the boiler into the ambient medium will allow for more efficient use of the thermal energy generation methods for all kinds of boilers [5].

Even if the biomass combustion is often considered as ecologically clean as compared to coal and oil, this is not always the case. The biomass combustion is a complex process, which requires fine control for achievement of maximum efficiency and low emissions of gaseous pollutant substances.

There are the standards for the biomass combustion in the low power boilers with power less than 250 kW in Europe. Nevertheless, the European standard EN 303-5 does not completely ensure the ecological safety of emissions for the boilers which have recently entered the market in large quantities [4]. The modern boilers meet the requirements of the standard mentioned above, but in case of unstable mode the CO and hydrocarbons emissions can be increased while the efficiency is significantly reduced [6]. The present problem has become significant due to the large number of the boilers being installed. Starting from 2002, the total annual sales of the small boilers operating on biomass are approximately several dozens of thousands per year [7]. In this case, in the context of inappropriate biomass combustion there can be a significant negative impact on the air quality. The paper is concerned with the environmental problem solving by means of the EHS with multivariable control which permits to achieve the preset heat power values and provide the optimal combustion conditions for maximum efficiency and minimum emissions achievement.

EXISTING METHOD OF THE BIOFUEL PELLETS COMBUSTION

The fuel pellets combustion can be illustrated by a strong example of combustion on the grate, where a part of processes occurs in the fuel bed and another part in the combustion space. There are several combustion stages which differ by the temperature. During combustion, the fuel is charged on the distribution grate and blown out by the air. Herewith the fuel is heated up to the temperature of 100-105 °C, when evaporation begins. The heat released in the chamber quickly warms up the fuel cell to the higher temperatures of 220-250 °C, when emission of the volatile substances generated during heating begins (H_2, CO, CH_4, etc.). The volatile substances above the fuel bed in the combustion space are quickly ignited and also the small particles removed from the bed by the air flow are burnt out [8]. During the volatile substances combustion, the fuel cell temperature reaches a maximum and the carbon combustion occurs. The maximum temperature level depends on the fuel properties and the excess air ratio. During the fuel combustion, the precautionary measures should be taken for incomplete burning reduction which results in the loss of the boiler efficiency. At first the fuel is injected in the combustion chamber. Generally, the more fuel is injected in a moment, the more heat is required for evaporation of the fuel moisture. Herewith, continuous fuel supply, that is, the fewer input fuel during the longer-term period, is problematic in the existing furnaces. The quickly generated volatile substances are required to be mixed with the air. In case of the lack of the air, the volatile substances are not completely burnt out, but they are emitted with the flue gases in the form of carbon oxide and hydrocarbons. Consequently, the fuel injection above the fuel bed can become the reasonable solution of the present problem [8-9].

The zone with practically complete consumption of the air oxygen supplied under the fuel bed is called the oxygen-rich zone. If the fuel bed height exceeds the oxygen-rich zone, the reducing zone is developed after the oxygen-rich zone where the CO_2 and H_2O reactions proceed on the surface of the carbon (char) particles:

$$CO_2 + C = 2CO \quad (1)$$

$$H_2O + C = CO + H_2 \quad (2)$$

In this case, the flue gases contain combustion gases CO and H_2 in addition to CO_2, H_2O and N_2. The combustion gases mentioned above were generated not only during the volatile substances emission but also as a result of CO_2 and H_2O, reducing reactions, wherein their concentration is increased with the reducing zone height increase [9].

The supplementary air supply for combustion above the fuel bed is required for adequate mixing of oxygen with the released volatile substances. But there still remains the solid carbon on the grate. Therefore, during combustion the air is split into two streams. The first air stream passes through the grate for the required carbon combustion. The second air stream is injected above the grate level for the volatile substances combustion. The directional control of the primary and the secondary air streams is the major problem, which cannot be always solved in the modern boilers. In the most advanced boilers, there is a possibility of the manual setting of the primary and secondary air ratio, but the ratio control is a rather complex problem [9-10].

The excess air ratio α_f in the furnace depends on the following factors:

- the fuel type;
- the combustion method;
- the furnace structure;
- the way of combustible mixture production (the burner structure), etc.

Minimum total losses related to the released gases q_2, incomplete combustion q_3 and unburned carbon loss q_4 [9] are the governing factors during selection of the optimal excess air ratio value.

The increase in the excess air leads to the increase in the heat losses associated with the released gases (q_2), and the decrease in the excess air leads to the increase in the incomplete combustion and unburned carbon losses (q_3 and q_4). The optimal value of the excess air ratio will correspond to the minimum value of the total loss $q_2 + q_3 + q_4$ [9].

The boiler efficiency and CO, CO_2 and NO_x emission rate depend on the excess air ratio. The latter indicates the amount of excess air for combustion, associated with stoichiometric conditions, and is determined by the following equation [10]:

$$\alpha = \frac{V_{act}}{V_0} \quad (3)$$

where V_0 is the stoichiometric air volume for combustion, m^3/kg or m^3/m^3; V_{act} is the actual air volume for combustion, m^3/kg.

The concentration of practically all combustion products should be measured for the excess air ratio determination, that is: oxygen, nitrogen, carbon oxide, hydrogen and methane concentrations.

Two simplified methods of the excess air ratio determination are used in practice: by the oxygen concentration and by concentration of the dry triatomic gases in the combustion products. The direct determination of the oxygen concentration is the basic method [10]:

$$\alpha = \frac{21}{21-[O_{excess}]} \quad (4)$$

$$[O_{excess}] = [O_2] - 0.5[CO] - 0.5[H_2] - 2[CH_4]$$

where $[O_2]$, $[CO]$, $[H_2]$, $[CH_4]$ are the concentrations of the corresponding gases (%) obtained on the basis of the combustion products gas analysis.

The temperature field measurements throughout the combustion chamber should be performed along with measurement of the oxygen, carbon monoxide and hydrocarbons concentrations in the flue gas for verification of the calculated excess air ratio correctness.

The uniform temperature-height distribution and low concentration of CO indicate that the air ratio is correct. Any temperature imbalances are the indicators of the air ratio incorrectness. For instance, too low temperature in the complete combustion zone along with too high oxygen content in the flue gas mean that there is too much secondary air [11].

The full-fledged time-dependent thermal model of the enclosure, which can be used for integral assessment of thermal protection in different time for different initial data, can be developed by means of conduction of the experiments set where the temperature and time parameters are fixed. For instance, the heating boiler can be installed not indoors but outdoors. In this case, the complementary error can be caused by the environmental conditions, but being adequately considered, this factor will have insignificant impact on the measurements results [12].

The adequacy of data obtained from the basic sensors, which are used for the boiler control, is the major problem in the context of the boiler operation ecological safety. In this case, the temperature sensor and the oxygen sensor are of special interest. Temperature and oxygen concentration, measured by means of the lambda probe, were continuously controlled in the experimental burner.

INVESTIGATIONS PROCEDURE

The study of different thermotechnical, thermophysical and processing characteristics of combustion of the different waste types produced by the wood and the high ash content agricultural raw materials was performed. The EHS which contains the burner operating with any granular biofuel type was developed and verified with the purpose of the system efficiency optimization and air emissions minimization. The rated output power of the EHS is 25 kW. The following samples were collected for study: sunflower pellets, wood pellets and straw pellets (Table 1).

Table 1. Characteristics of the samples.

Characteristics	Sunflower pellets	Wood pellets (1 grade)	Straw pellets
Diameter, mm	6-8	6-8	6-8
Length, mm	10-50	10-30	10-50
Moisture, %	7.7	7.3	6.8
Ash content, %	5.4	2	5.7
Density, t/m^3	1.1	0.6	0.65
Combustion value, MJ/kg	18.46	16.9	16.0

In the developed EHS with the burner being the basic component of the system, the bed combustion technique is used. The fuel is supplied from the fuel hopper by the screw conveyor and then to the furnace. The pellets are burnt in the air flow, produced by the burner blower. The air for combustion is delivered by special nozzles through the gaps between the grate elements. For combustion intensity increase in the combustion cavity, the supplementary air is delivered in the form of the “overfire air” streams through the nozzles installed on the rear wall. The pellets entering the combustion zone are quickly transformed to the live coal and are burnt out with the flame sweep creation, the temperature of which reaches 1200 °C. The hot gases flow directed to the convection section to the flue tubes gives up its heat to the system heat carrier medium and then goes away through the exhaust duct. The wood pellets ash falls from the combustion zone into the ash pan and then, as in case of the large burner, is removed by the automated device (by means of electrically actuated screw) to the ash storage tank. The EHS is equipped by the control unit which permits to control the process (Figures 1, 2). The control unit is connected to standard PC, which make it possible to preset all the experiments on the computer.

The bench for the EHS experimental prototype testing is presented in Figure 1. The burner which operates with any granular biofuel type is the basic component of the EHS (Figure 2).

Figure 1. The bench for the EHS experimental prototype testing.

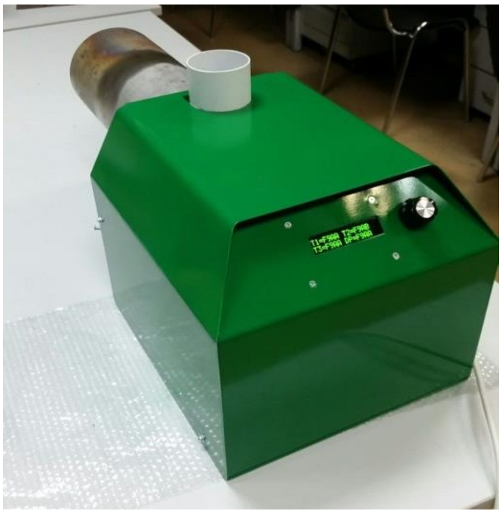

Figure 2. The prototype of the experimental burner with hardware-software complex of control automation for investigation tests conduction.

For validation of the EHS application for the combustion of pellets from wood waste and high ash content agricultural raw materials, the following commonly used research techniques were used:

- determination of the pollutant emissions as per GOST ISO 9096-2006, European standard EN 13284-1 and Finnish standard SFS 3866;
- during the tests conduction, only the measuring means which passed the metrological calibration test are used according to GOST 8.513-84. The measurement errors during the tests conduction should not exceed the values, specified in GOST 20440-75.

The results evaluation was performed according to the known procedures with the use of computer programs.

Biofuel pellets combustion on the EHS experimental prototype.

During the pellets combustion on the EHS experimental prototype, the emissions formation significantly depends on the fuel type, which is burnt out in the heat source. The fuels have different properties and chemical composition, which finally influences the combustion process, the amount of the actual emissions and the ash content. During experimental measurements, the equal combustion conditions were provided, that is, the uniform supply of the primary and the secondary air, equal pressure in the flue tube (12 Pa) and maximum fuel charge of 1.5 kg.

Among other things, the EHS operation depends heavily on the fuel bed stroking on the grate. The carbon combustion reaction is the basic exothermal reaction on the grate [8]:

$$C + O_2 = CO_2 + 405.8 \text{ kJ}$$

For some time, the fuel is accumulated on the grate resulting in the bed formation. The bed top comprises the fresh fuel and the bed bottom comprises slowly burning coke. In this case, the coke is poorly mixed with the air for combustion. In case of contact of the carbon dioxide generated from this reaction with the hot coke in zones with low oxygen content, a part of oxygen can be escaped inducing the bed cooling [8]:

$$C + CO_2 = 2CO - 160.7 \text{ kJ}$$

With the grate purification, the bottom bed is displaced forward and the fresh fuel mixed with coal induces the flame suppression during the definite time period until the establishment of equilibrium. The grate purification periods can be controlled. The period is related to the temperature increase and CO concentration decrease. This problem can be solved by the change of the grate purification period. The period reduction from 9.5 minutes to 1.5 minutes results in the temperature stabilization and CO emissions reduction, which is seen from the diagrams presented in Figures 3 and 4.

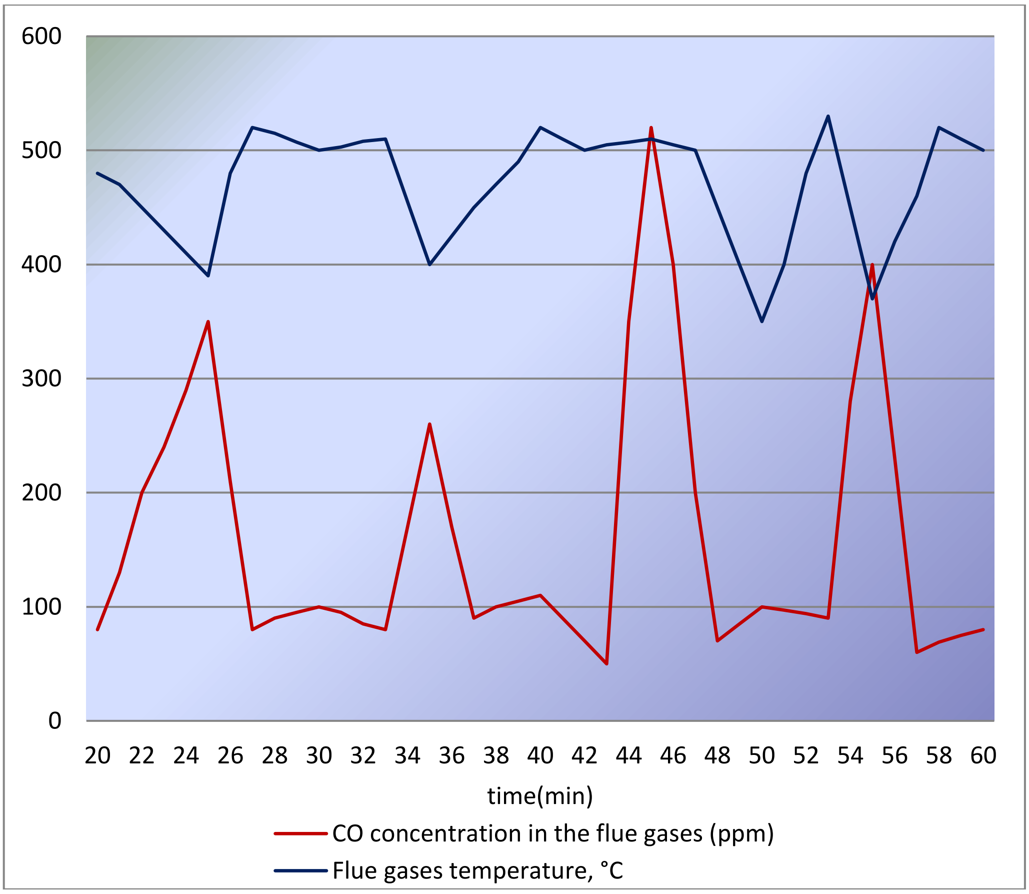

Figure 3. The flue gases temperature during the grate purification with a period of 10 minutes.

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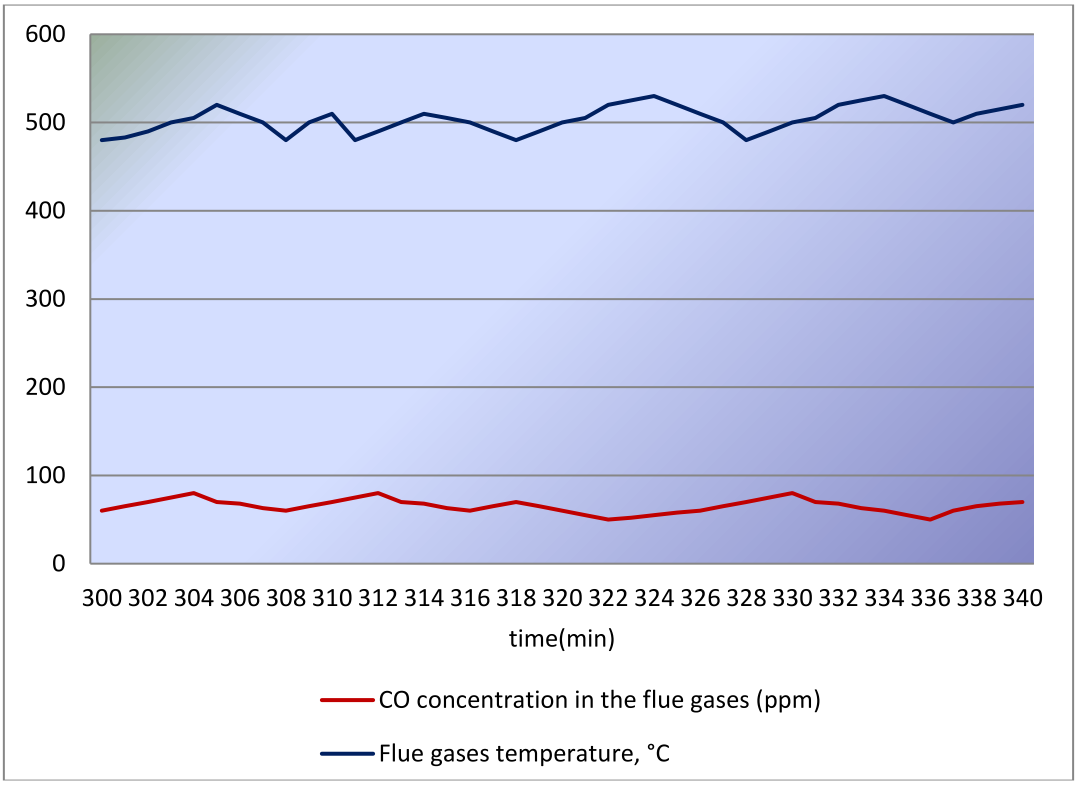

Figure 4. The flue gases temperature during the grate purification with a period of 10 minutes.

From the environmental point of view, attention should be paid to the following two sensors: temperature and oxygen sensors. During the biofuel combustion in the EHS, temperature and oxygen concentration were continuously controlled by the lambda probe. The CO emissions are very sensitive to the oxygen concentration changes; therefore, the oxygen concentration is the most important factor [11]. In case of the lack of oxygen, the incomplete fuel combustion occurs. The test data concerning the oxygen concentration changes is presented in Tables 2 and 3.

The tests were performed with three pellet types (sunflower pellets, wood pellets and straw pellets) with the use of different air supply methods. The air supply performed by special nozzles through the gaps between the grates elements is the primary supply. The supplementary air supply in the form of the "overfire air" streams is the secondary supply. The sunflower pellets are called pellets 1, the wood pellets (of the first grade) are called pellets 2 and the straw pellets are called pellets 3.

Test 1 – means the combustion of pellets 1 and only primary air supply.
Test 2 – means the combustion of pellets 2 and only primary air supply.
Test 3 – means the combustion of pellets 3 and only primary air supply.
Test 4 – means the combustion of pellets 1 as well as primary and secondary air supply.
Test 5 – means the combustion of pellets 2 as well as primary and secondary air supply.
Test 6 – means the combustion of pellets 3 as well as primary and secondary air supply.

The tests were performed in accordance with GOST R 55682.15-2013\EN 12952-15. The time of each test was limited by 30 minutes. The results in the form of the averaged values of sensors readings and calculations are presented in Table 2.

Table 2. Operating conditions.

	Heat power, kW	Air distribution (primary/secondary)	O_2, %
Test 1	42.5	100:0	6.05
Test 2	44.0	100:0	6.07
Test 3	27.0	100:0	5.01
Test 4	41.0	50:50	5.89
Test 5	42.7	50:50	5.92
Test 6	43.1	25:75	5.54

The CO and particulate matters (PM) emissions for each test are presented in Table 3. All the values were recalculated with consideration of the oxygen and flue gases concentrations.

Table 3. Amount of ash and emissions.

	CO, mg $(nm^3)^{-1}$ in case of O_2 content of 10 %	PM, mg $(nm^3)^{-1}$ in case of O_2 content of 10 %	Ash amount, mg	Content of combustible substances in the ash, %
Test 1	2.154	52.8	5.25	87.2 %
Test 2	2.256	52.6	5.15	83.1 %
Test 3	4.325	195.3	3.18	51.2 %
Test 4	339	39.1	3.54	58.3 %
Test 5	343	39.7	3,.49	51.1 %
Test 6	706	125.8	7.07	81.5 %

The CO emissions are very sensitive to the oxygen concentration. It is seen from Table 3, where the supplied oxygen dependence on the released CO was shown with the use of the new EHS control system. In case of the oxygen concentration change, the CO concentration, which is one of the direct indicators of the incomplete combustion can be also changed, which can result in the less effective fuel combustion.

During the lambda probe operation, the incorrect readings of the oxygen concentration are possible. If the present errors do not result in the complete failure of the sensor, it is difficult to determine if the sensor readings are incorrect, as far as in the context of the external control of combustion everything seems to operate in standard mode. However, as it is seen from Tables 2 and 3, even the slight change of the oxygen concentration induces the change in CO concentration and consequently the change in the system operation efficiency. The lambda probe failure induces the definite unsteadiness during the measurements conduction. Let us assume that the sensor readings are less than the actual oxygen concentration. The underestimated value of O_2 concentration results in changes in the oxygen control sensors, which will add the air in the heating system. Consequently, the temperature, being under the control of another sensor, will be decreased. In order to provide the required temperature level the present sensor will add the definite fuel amount. Actually, the air amount remained the same, but the α value will leave the optimal operating range. It can lead to the increase in the undesirable CO emissions amount and consequently the system degradation. The lambda probe failure can be avoided by means of the additional sensor installation or software installation in the system. The additional sensor installation will lead to the increase in the heating system cost; therefore, the EHS is equipped by the control unit, which allows for the on-line combustion control.

CONCLUSIONS

At the present time, the environmental impact associated with the use of local energy resources in small heating systems is a crucial problem. The biofuel pellets combustion with the air staging causes the higher amount of CO emission and higher ash content. It has been established that by means of the air supply control the biofuel pellets combustion process can be optimized and the emissions amount can be reduced.

The existing control systems modification for the heating system performance improvement and cost optimization is suggested. For this purpose, the energy-efficient heating system (EHS) intended for the thermal energy generation from wood waste and high ash content agricultural raw materials was developed. The burner, being the basic component of the EHS, operates with any granular biofuel type and is equipped by the control unit for the on-line combustion control.

It was demonstrated that from the environmental point of view attention should be paid to the following two sensors: temperature and oxygen sensors. In the heating system, the sensors operation is managed by the EHS control unit with the multivariable control which makes possible the preset heat power values achievement and providing the optimal combustion conditions for maximum efficiency and minimum emissions achievement.

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REFERENCES

[1] Bulatkin, G.A. (2010). Proizvodstvo biotopliva vtorogo pokoleniya iz rastitel'nogo syr'ya [Manufacturing of Second Generation Biofuels from plant material]. Vestnik Rossiyskoy Akademii nauk, 80(5-6), 522-532.

[2] Orsik, L.S., Sorokin, N.T., & Fedorenko, V.F. (2008). Bioenergetika: mirovoy opyt i prognozy razvitiya [Bioenergy: Global Experience and Development Forecasts]. Moscow: Rosinformagroteh.

[3] Lackner, M., Winter, F., & Agarwal, A.K. (Eds.). (2010). Handbook of Combustion (Vol. 4). Wiley-VCH Verlag.

[4] EN 303-5: Heating Boilers. (2000).

[5] Yakushkin, I.P., Larchikov, A.V., & Rygalyn, D.B. (2015). Study of Thermal Processes in Envelope Structures of Heating Boiling Operating on biofuel Using Methods of Infrared Diagnostics. Research Journal of Pharmaceutical, Biological and Chemical Sciences, 6(3), 1914-1924.

[6] Kaltschmitt, M., Hartmann, H., & Hofbauer, H. (2009). Energies aus Biomass. Berlin, Heidelberg: Springer Verlag.

[7] COMMISSION STAFF WORKING DOCUMENT State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU. Brussels, 28.7.2014 SWD(2014) 259 final.

a. https://ec.europa.eu/energy/en/topics/renewable-energy/biomass

[8] Vares, V., Kask, Yu., Muiste, P., Pihu, T., & Soosaar, S. (2005). Spravochnik potrebitelya biotopliva [Reference Guide of the Biofuel Consumer] (pp. 73-75). Tallinn: Tallinn Technical University.

[9] Belousov, V.N., Smorodin, S.N., & Smirnova, O.S. (2011). Toplivo i teoriya goreniya. Chast' II: Teoriya goreniya [The Fuel and the Combustion Theory. Part II: The Combustion Theory] (pp. 17-25). Saint Petersburg.

[10] Piteľ, J., Boržíková, J., & Mižák, J. (2010). Biomass Combustion Process Control Using Artificial Intelligence Techniques, In Proceedings of XXXV Seminar ASR'2009 “Instruments and Control” (pp. 317-321). Ostrava: VŠB-TU Ostrava.

[11] Janvijitsakul, K., & Kuprianov, V.I. (2011). Least-Cost NO_x Emissions Control in a Fluidized-Bed Combustor Fired with Rice Husk. https://www.researchgate.net/publication/239280615_Least-cost_NOx_Emissions_Control_in_a_Fluidized-bed_Combustor_Fired_with_Rice_Husk

[12] Yakushkin, I.P., Larchikov, A.V., & Rygalyn, D.B. (2015). Methodology of Calculation of Heat Losses by Envelope Structures on an Example of a Heating Boiler Using Biofuel. Research Journal of Pharmaceutical, Biological and Chemical Sciences, 6(3), 1925-1935.