Thermotechnical tests of the low power solid fuel heating boilers while incinerating briquetted RDF

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Abstract. Objective of this paper is an analysis of briquetted waste combustion in the low power boilers. Research was conducted for the 100 kW pyrolysis heating boiler and 200 kW heating boiler with grate stoker. Briquettes were made by compacting milled and crushed materials into cylinders 50 mm in diameter, with a length of 100-200 mm, density of 800 kg/m3. It was established that process of combustion in low power boilers has low thermal efficiency, value of which fluctuated within 60...74% for wood combustion and 50...70% for RDF briquettes combustion. Burning process was stable and characteristics of the RDF combustion were similar to the wood combustion. Incineration of the fuel briquettes had better efficiency than burning of solid wood. During RDF briquettes combustion high СО content (up to 0.2% or 2000 ppm) in flue gas was observed, which is an indication of insufficient burning time. It may be concluded that waste incineration in low-duty plants is viable, but to secure complete combustion and desired temperatures process of combustion and heat extraction should be separate in terms of design.

1. Introduction

Arranging for recycling of municipal solid waste (MSW) is a challenging technical problem, which consist of logistics management, environmental issues, energy and economics aspects [1]. In the paper [2] has been noted that MSW recycling is not just commercial investment project but also a need for society survival that cannot be overlooked.

Landfill is a main way of recycling of municipal solid waste (MSW) for most of the countries [3]. Ecological requirements, possibility of ground water contamination in particular, and landfill gas recycling [4] increases cost of waste disposal [5]. One of the most efficient ways of waste recycling is a thermal utilization with energy generation [5, 6], that allows to reduce costs for waste recycling when marketable energy is being produced in the process [7]. Table 1 presents comparison of the popular MSW recycling methods with energy production. Additional advantage of the recuperation of energy from waste by incinerating is a fact that for energy production can be used MSW with wide range of quality [8].
Table 1. Comparison of MSW recycling methods [9].

| MSW recycling method | Anaerobic fermentation | Gasification | Incineration |
|----------------------|------------------------|--------------|-------------|
| Energy production per ton of waste | 314 kWh of electricity | 456 litre of synthetic gas (equivalent of 2676 kWh) | 58.4 kWh of electricity |
| Type of waste | Food waste, green biomass | Wood, green biomass | All waste except metal, stone and glass particles |
| Necessity for separation | Yes | Yes | Needs removal of non-combustible inclusions |

Competitive advantage of electricity-producing waste treatment is determined by the following factors [2]:

- high cost of waste recycling on landfills;
- high cost of electricity in the region;
- low cost for collection and separation of waste;
- high effectiveness of waste incinerating plants.

From the economic point of view, in most cases, thermal utilization is more efficient in comparison to the other types of MSW recycling, which is stated in the paper [10]. Comparison of waste “life cycle” which includes economic and environmental aspects, that was carried out in the paper [11], has shown that biological way of recycling is more preferable from the environmental point of view, while incineration and gasification from the economical point of view. The paper [12] has stated that use of shredded RDF in conventional co-generating plants gives positive ecological and thermotechnical results.

Papers [5, 13] suggested criteria to conduct initial estimates for such projects. Decision for simultaneous production of electricity and heat is justified only if there is a large consumer of heat power available [14]. In the paper [15] analysis of RDF incineration at the power plant was performed using second law of thermodynamics. This analysis led to the conclusion that effectiveness of the system is very low and steam generation creates most of the energy losses. Similar conclusions were drawn in the paper [16], where energy analysis of a steam boiler incinerating waste presented. According to the analysis report, exergy efficiency of boiler units is a direct function of heated water and steam temperature in it. The paper [17] presents analysis of the other types of waste thermal utilization (gasification, pyrolysis, plasma technology, combinations), that suggests matching process and waste type, which makes those methods not versatile. Temperature of waste incineration in the heat-exchange unit entrance, not more than 950°C, guaranty that ash deposits, contaminating heating surfaces, will be non-coherent and can be easily cleaned out [7]. The highest efficiency of the plants for waste incineration is no more than 65-70% [7].

Use of alternative fuel has similar impact on the environment in comparison to traditional fuel in the power plants [6]. Partial presence of RDF in the fuel mixes decreased amount of SO₂ in the emissions and didn’t change amount of NOₓ [18]. Test of simultaneous burning of RDF and coal indicated that presence of RDF has no influence on SO₂ emissions, NO, HCl, N₂O emissions slightly increased, and amount of dioxin in ash and slag increased in sync with RDF content in the fuel [19]. Results in the paper [20] has shown that blending of solid municipal waste with biotype fuel improves its energy characteristics.

Waste recycling plants in USA produce electricity or work in co-generating mode, 5% of plants make steam for process purposes [21]. In addition, in spite of large number potential use of all waste corresponds to electricity generating output of more than 2800 MW, which is only 0.33% of the whole US generating market [22]. In Europe waste utilization structure differs from country to country [3]. In some countries (Greece, Hungary, Iceland, Ireland, Great Britain) most of waste goes to landfills; in Danmark, Switzerland, Luxemburg, Netherlands half of waste is being incinerated for energy production.
Waste incineration without preliminary treatment is being characterized by sufficient degree of reliability that is comparable to other types of heat energy and electricity production [7]. But as of now, incineration technologies developed for large scale production with waste utilization of 100 thousand tons per year [23, 24]. Some of the papers studied effectiveness of waste combustion for small towns. For example, based on analyses of cities with population of 100,000 to 1 million people the paper [25] has shown increase of effectiveness of electricity production from waste instead of landfill utilization if city size increases. The paper [26] analyzed data for industrial combustion technologies and gasification for medium-sized municipals and indicated that the best economic results can be achieved by using unsorted municipal waste.

Existing situation overview suggests following conclusion that incineration is effective way of utilization if thermotechnical and ecological requirements are respected. But as of now industrial combustion technologies for MSW incineration has being developed only for utilization of 100 thousand tons per year (10 t per hour).

2. Materials and Methods
The paper objective was:

- analysis of briquettes combustion in the pyrolysis water heating boiler in comparison to solid wood, that by design supposed to be used in the boiler (Fuel 1 and Fuel 2);
- analysis of combustion of different composition briquettes in the water heating boiler with grate stoker (Fuel 3 and Fuel 4);
- analysis of flue gas content for different types of fuel combustion.

The paper examined three types of units that was used for waste incineration:

- 100 kW pyrolysis water heating boiler;
- 200 kW water heating boiler with grate stoker.

Boilers have been installed at the industrial site in Belgorod city (Russia) and designated to yield hot water for heating of two, 600 and 1900 m², administrative buildings. Thermal loads, taken from the building thermal design, are 32 and 86 kW respectively, that exceeds standard by approximately twofold (standard thermal loads for the mentioned above buildings are 13 and 41 kW). Heating system, in this example, is closed dependent type.

2.1. 100 kW pyrolysis boiler
Boiler “KO-100”, made by “Boiler equipment factory in Kostroma city” (trademark “F.B.R.G.”) (figure 1), is an all welded steel design that consists of two combustion chambers. At the lower chamber, which is a gasification chamber, where air flow is limited and temperature is high, fuel separates into solids and volatile fraction. Upper chamber is designed for afterburning of the released gas. Lower part of the gasification chamber has a nonadjustable window for an air intake and window with door to adjust oxygen intake, latter, according to the manual, should stay open only during boiler ignition. Smoke exhaust duct has damper.

![Figure 1. Pyrolysis boiler KO-100](image-url)
Pyrolysis boiler allows single loading of fuel to burn much longer and use as fuel large un-milled pieces of waste. According to the manual, boiler has following characteristics:

- Heat power: 100 kW;
- Heated space area: 900 m²;
- Efficiency: 80-90%;
- Operating temperature: 90 °C;
- Operating pressure: 2-3 bar;
- Furnace volume: 0.65 m³;
- Flue gas duct diameter: 250 mm;
- Weight of the boiler: 950 kg;
- Fuel consumption: 0.36 m³/day.

2.2. 200 kW water heating boiler with grate stoker

Solid fuel boiler made by OOO “TK Ecotrans” (figure 2) is an all welded steel design. Size: 1230 mm (width) x 1600 mm (depth) x 2170 mm (height). Fuel combustion is on the grate, air flow can be natural as well as by forced-flow fan. Boiler walls are insulated by the mineral wool Izovol CT-40.

![Figure 2. Solid fuel water heating boiler](image)

2.3. Description of the incinerated samples

Solid wood and railway sleepers as well as cylindrical briquettes were used for measurements. Cylinder diameter is 50 mm, length 100-200 mm, density 800 kg/m³, made by compacting grounded and crumbled wood. Materials were incinerated during tests and results presented in the Table 2.

| Boiler type               | Fuel number | Composition         | Form                        |
|--------------------------|-------------|---------------------|-----------------------------|
| Pyrolysis boiler         | 1           | Wood (pine tree)    | Large ungrounded fragments  |
|                          | 2           | Wood granules       | Cylindrical briquettes      |
| Boler with grate stoker  | 3           | Wood 70%, plastic 30% | Cylindrical briquettes      |
|                          | 4           | Wood 50%, plastic 50% | Cylindrical briquettes      |

For Fuel 3 and Fuel 4 humidity was measured by using method of drying out quantity of substance in the muffle furnace. Bulk humidity as follows: Fuel 3 - 13.6%, Fuel 4 - 13.5%.

2.4. Test schedule and instruments

Boilers has been tested between 2013 and 2016. Test schedule and measured parameters presented in the table 3. Table 4 presents instruments used for measurement.
Table 3. Measurements schedule.

| Type of the boiler | Date of test   | Time of test | Fuel number | Measurement of flue gas | Measurement of heat transfer agent characteristics | Measurement of temperature inside furnace |
|--------------------|---------------|--------------|-------------|-------------------------|-----------------------------------------------|-----------------------------------------|
| Pyrolysis          | 03.12.2013    | 13:00–14:00 | 1           | X                       | –                                             | –                                       |
|                    | 04.12.2013    | 13:40–15:50 | 2           | X                       | X                                             | –                                       |
| With grate stoker  | 22.03.2016    | 10:48–11:56 | 3           | X                       | X                                             | X                                       |
|                    | 29.03.2016    | 12:48–13:58 | 3           | X                       | X                                             | X                                       |
|                    | 04.04.2016    | 11:20–13:10 | 4           | X                       | X                                             | X                                       |

Table 4. Instruments used for measurement.

| Name                                | Measured parameters                                                                 |
|-------------------------------------|-------------------------------------------------------------------------------------|
| Gas analyzer Testo 330-1 LL         | Gas temperature                                                                    |
|                                     | O2, CO content                                                                      |
| Gas analyzer GANC-4                 | Mass concentration of hazardous substances (substance list is determined by availability of the cassettes) |
| Ultrasonic flowmeter “PanametricsPT878” | Volume flow rate of heat transfer agent                                                |
| Infrared pyrometer Testo-845       | Fuel surface layer temperature, temperature of pipe outer surface                   |

2.5. **Testing methods for boilers**

Testing methods description:

1. Fuel load and setting boiler to the nominal operating mode.
2. Measurement of water temperature in supply and return pipelines and water flow in return pipeline with ultrasonic flowmeter Panametrics PT878 and pyrometer/contact thermometer Testo-845 (3 min interval).
3. Temperature and flue gas content (O2, CO) measurement with gas analyzer “Testo 330-1 LL” (1 min interval).
4. Measurement of emissions in exhaust duct after the boiler (CO, NO2, NH3, mercaptans R-SH, H2S, phenol) with portable gas analyzer GANC-4.
5. Measurement of fuel combustion temperature in the furnace with pyrometer Testo-845 (15-20 min interval).

Using obtained during tests data amount of produced heat energy, heat losses and boiler unit efficiency (by indirect heat balance method using simplified thermocentral calculation technique) were calculated.

3. **Results and Discussion**

3.1. **Effectiveness evaluation of waste incineration in pyrolysis boiler**

It was established that during firewood combustion process of burning in the boiler is stable and disrupted only when firewood is being loaded. Closed flue damper doesn’t interrupt combustion mode (no increase of CO or O2 content), but flue gas temperature after the boiler decreases significantly. Efficiency of the boiler in stable operational mode is 67-74%, which is lower than numbers from the manual.
Two series of tests were conducted. First one evaluated operation of the boiler with closed door in order to stop air flow, during second test the door was partially opened in order to let air in. Test results presented in the figures 3, 4. Briquettes loading happened at 13:42; 13:58 и 15:13.

### Figure 3. Measured results of wood incineration (fuel 1), 03.12.2013

### Figure 4. Measured results of wood briquettes incineration (fuel 2), 04.12.2013

3.2. Evaluation of boiler heat power

Since boiler operates in unstable mode, its capacity changes in the course of time. The following graph presents capacity that was received by calculation using measured temperature and flow rate of the heat transfer agent.

Capacity was determined by utilizing measured data of heat transfer agent flow rate $V$, m$^3$/sec, being heated in the boiler (measured with ultrasonic clamp-on flowmeter) and temperature of supply $t_{sup}$ and return $t_{ret}$ water, °C, measured with fixed temperature sensors, installed in supply and return water pipelines.

Boiler thermal output:

$$Q = 4.186 \cdot (t_{sup} - t_{ret})V \rho, \text{ k}W,$$

where $t_{sup}, t_{ret}$ – supply and return water temperature, °C; $V$ – volume flow rate, m$^3$/sec; $\rho$ – water density, kg/m$^3$.

Heat generated from fuel incineration:

$$Q_f = Q / \eta,$$

where $\eta$ – boiler efficiency, determined by data from gas analysis and indirect heat balance calculation utilizing simplified thermotechnical method.

Calculated capacity presented in figure 5.
Conclusions after completed boiler thermotechnical tests for combustion of wood and briquettes (Fuel 1 and Fuel 2)

Combustion process in the boiler is stable and gets interrupted only at fuel loading.

Boiler mean hourly capacity for wood briquettes combustion is 95.6 kW, that is 5.6% more than boiler mean hourly capacity for firewood combustion.

Boiler efficiency doesn’t exceed 74%, mean efficiency at stable operation mode – 60-74%, which is lower than indicated in the manual (84%). Fuel in the boiler burns out completely, indication of which is low CO content in flue gas.

3.3. Evaluation of effectiveness of briquetted waste incineration in the boiler with grate stoker

For measurements briquettes were incinerated. Briquettes had form of a cylinder with 50 mm in diameter, 100-200 mm in length, 800 kg/m³ in density, made of compacted grated and crushed wood. Briquettes content: Fuel 3 (wood 70%, plastic 30%); Fuel 4 (wood 50%, plastic 50%). Tests continued for 3 days.

Table 5 presents average measured data from tests.

| Date and time of measurement | Type of fuel | Flue gas temperature tfg, ºC | Content of CO, ppm | Excess air coefficient |
|------------------------------|-------------|-------------------------------|-------------------|-----------------------|
| 22.03.16 10:48-11:56         | Fuel 3      | 263                           | 917               | 5,7                   |
| 29.03.16 12:48-12:57         |             | 322                           | 1012              | 4,3                   |
| 29.03.16 13:03-13:13         |             | 291                           | 1390              | 4,9                   |
| 29.03.16 13:42-13:52         |             | 270                           | 1823              | 5,4                   |
| 29.03.16 14:53-15:03         | Fuel 4      | 260                           | 1668              | 4,9                   |
| 29.03.16 15:31-15:43         |             | 279                           | 1438              | 3,7                   |
| 04.04.16 12:25-12:33         |             | 212                           | 1832              | 10,6                  |
| 04.04.16 12:37-12:47         |             | 235                           | 1961              | 9,3                   |
| 04.04.16 12:01-12:11         |             | 277                           | 1305              | 5,1                   |
| 04.04.16 11:41-11:51         |             | 283                           | 1170              | 4,8                   |

Figure 6 presents change in parameters of the boiler in the process of tests.
Figure 6. Results of the measurement of flue gas temperature $t_{fg}$, combustion temperature $t_c$, excess air coefficient $\alpha$, CO content and thermal efficiency.

Analysis of dependencies between parameters (figure 7) has shown that there is a dependence between flue gas temperature $t_{fg}$ and excess air coefficient $\alpha$, correlation coefficient $-0.75$. There is no dependency between flue gas temperature $t_{fg}$ and CO content (correlation coefficient $-0.39$) as well as between CO content and excess air coefficient $\alpha$ (correlation coefficient $-0.29$). This suggests that burning time is not sufficient and heat extraction from gas decreases waste incineration effectiveness.

Figure 7. Dependence between parameters of combustion
Combustion temperature, measured on the third day of the test, was at 600...785°C, which is lower than theoretical values [27] and requirements in the Directive of the European Parliament and of the Council 2000/76/EC “On the incineration of waste”. According to this document, plant can meet environmental requirements only if flue gas stays in it no less than 2 sec at a temperature of 850°C.

One can draw a conclusion that low combustion temperature is due to high excess air coefficient and process optimization of the incineration will help to meet the environmental requirements.

Figure 8 presents calculation data of the boiler heat power.

**Figure 8.** Boiler rated power

**Conclusions for RDF briquettes incineration in the boiler with grate stoker**

Combustion process in the boiler is stable and has direct dependence on burn-out time of fuel.

Mean hourly capacity for wood briquettes combustion is 50...110 kW, which is similar to the parameters for firewood and wood briquettes combustion.

Boiler efficiency doesn’t exceed 70%, mean efficiency in stable mode operation – 50-60%, which is lower than certified data (84%). High CO content (up to 0.2% or 2000 ppm) in flue gas, when excess air coefficient is high, suggests that burn-out time is insufficient.

**4. Conclusion**

Combustion process in the low power boilers is characterized by low thermal efficiency, value of which varies within 60...70% for pyrolysis boiler and 50...70% for RDF briquettes combustion. Characteristics of RDF combustion matches up characteristics of wood and wood briquettes combustion. Combustion process was stable and plant thermotechnical parameters were in direct dependence on
degree of fuel combustion. Fuel briquettes incineration had higher effectiveness in comparison with solid wood.

Flue gas, during tests, were examined for hazardous chemicals content (this paper doesn’t mention about it). Findings have shown that for all tested materials estimated ground level concentration of hazardous chemicals didn’t exceed maximum allowable concentration, and in most of the cases was significantly lower.

RDF briquettes incineration analysis have shown high content of CO (up to 0.2% or 2000 ppm) in flue gas at high value of excess air coefficient, which is the evidence of insufficient burn-out time.

In summary, waste incineration in the low-duty plants is feasible, but to secure complete combustion and necessary temperatures combustion process and heat extraction should be separated in terms of design.

Acknowledgments
The article was prepared within development program of the Flagship Regional University on the basis of Belgorod State Technological University named after V.G. Shukhov.

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