Influence of burner form and pellet type on domestic pellet boiler performance

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Abstract. The study presents combustion and emission results obtained using two serial pellet boilers of the same heating capacity 40 kW. These boilers have been designed by producers for domestic conditions of exploitation. The principal difference between boilers was the type of the burner. The study concerns the efficiency and ecological performance difference between burners of circular and rectangular forms. The features of the combustion process in both types of burners were studied when boiler operated with different sorts of pellets. The results suggest that the burner of circular form excels the rectangular form burner. However, there is some difference of NOx emission between circular and rectangular burners.

1. Introduction

At present day many economical, technical, ecological, as well as political reasons motivate firms and homeowners to use their own autonomous, independent of central heating pipeline and gas pipeline heat energy sources. The causes of such choice usually are striving for independence of the heat supplying organization pricing policy, avoidance of bureaucratic apparatus cooperation with (in questions of tariff agreement, the correspondence heating pipeline and gas pipeline connection standards, payment for extra project documentation necessary for central pipeline connection), unwillingness to bear expenses for the heat energy losses in a long and, sometimes, not of perfect quality heating pipeline from a relatively distant central heating source. A diesel fuel boiler, a wood boiler, a coal boiler, a heat pump may be used as independent heat energy source, when it is technically possible. A boiler with biomass and a boiler with granules can also be used. The use of boilers with fuel manual load with relatively big heat power is complicated by the need of heavy manual work. Diesel fuel heating is appreciably more expensive that all others named above and causes serious air pollution. The heat pump for relatively big heat power requires sufficiently big electrical power; a pellet or ground biomass boiler is the most suitable option for such decision.

In the last 15–20 years pellet boilers have gained serious popularity in Russia and the EU countries and the number of sold pellet boilers keeps growing. The high prevalence of such heat energy sources is reached thanks to several certain factors: easiness of automatization of the fuel feeding process owing to the standardized size of pellets; easy ash removal that can be automatic or manual, because the pellets ash content seldom exceeds 4 %. The exception is pellets made of straw with the ash content from 7 to 10 percent; compactness of all equipment as compared with unstandardized solid fuel boilers; accessibility of pellets in the market, reasonable price for domestic use. In all pellet boilers the fuel-bed firing technology is used. However, prevailing burner and feeding systems in the EU countries and Russia are different.
1.1. Examples of different pellet burners

A typical boiler consists of a steel body with a fully insulated cladding. Wood pellets are loaded manually, by screw auger or pneumatically into a hopper and feed by screw auger into the top feed burner. The burner automatically ignites when the control system signals a heat demand. Subsequent to the purging mechanism, ignition starts (induced by thermal resistance) and the pellet auger switches on and refills the burner pot. The burner pot is made of high temperature resistant stainless steel and is supplied with primary and secondary combustion air by a speed controlled vacuum fan. As soon as flame presence is detected by a flame supervision sensor, the boiler enters the flame stabilization phase followed by the control mode (modulation mode) and keeps the boiler water at the specified boiler temperature set point (between 60° C and 75° C). All types of modern boilers can modulate their heat output between 30% and 100% of the nominal power and therefore they are suitable to be operated without buffer storage. The boiler enters the burnout mode if the output drops below the minimum nominal thermal output. The fan continues operation until the burner pot has cooled down [1]. Dynamic modeling of such pellet boilers has been reported in literature [2, 3]. The heat exchanger is equipped with an automatic cleaning mechanism and an automatic ash removal. The hot combustion gases are directed through a vertical heat exchanger where the combustion heat is transferred to water. The control concept of the combustion process is based on the flue gas temperature, which is measured directly at the exit of the combustion chamber. In the boiler on fig. 1 the burner horizontal section has the shape of a circle. The type of boiler shown above is widespread in the EU countries; the features of such construction and assembling type are a high extent of automatization and mechanization of feeding, burner cleaning and ash evacuation operations. The monoblock boiler construction despite its advantages is not the only, the main weakness of such type is heating capacity restrictions. The boilers of such construction usually have the heating capacity not more than 70-80 kW. Pellet boilers (heat power more than 100 – 150 kW) often use another type of the burner. The burner has a rectangular shape and different principle of feeding mechanism and ash evacuation. The burner built-in basement is shown in fig.1. The concept of feeding, fuel combustion and ash evacuation in the rectangular burner is schematically illustrated in fig. 3. Pellets are fed to lower part of the burner and moves towards the upper part driven by the screw feeder. The ash is forced out the burner by the fresh fuel. The principle of combustion process control is the same as the principle of round upperfeeding burner exploitation. The input parameters of the system are temperature of the water inside and the temperature of exhaust. The system turns on the burner by the signal from the water temperature sensor when heat is required. First, the ignitor (induced by thermal resistance) starts, the fan with the valve system supplies the burner with primary and secondary air. Some boilers have two fans. One of fans is for supplying the primary air; the second is for supplying the secondary air. When the needed temperature is achieved the control system turns off the burner.

Figure 1. The rectangular shape pellet burner

Figure 2. The pellet burner with lower feeding

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2. Materials and methods

Increases in the price of fossil fuels, growing environmental concerns regarding their use and impact (including climate change) and considerations regarding the security of energy supply have motivated the rising use of renewable energy sources worldwide [3]. Use of biomass for energy production comprises the advantages such as reduced CO₂ emissions from combustion of fossil fuels, reduced SO₂ formation through a decrease in fuel bound sulphur and reduced NOₓ formation through a reduction in fuel bound nitrogen. In the EU countries and Russia, biomass boilers have some differences [4]. Emissions and efficiency of biomass heat energy systems vary as a function of quality of fuel, combustion technology used and operational conditions. The physic-chemical and thermal properties of biomass fuel such as bulk and energy density, heating value, chemical composition, moisture, ash and fine contents are important for their use in residential devices. The higher the moisture content, the lower the energy density and consequently the more space will be needed to store the pellet fuel. The sulphur and nitrogen contents of biomass fuels are directly related to the SOₓ and NOₓ emissions from small combustion systems [5].

At present day the number of pellets producers on Russian market is sustainably growing, they offer quite a big variety of wood and agro pellets. Wood pellet are usually produced directly in wood working shops as a by-product. The pellets made by such manufacturers notable for their high quality, energy density, heating value and low ash content. Pellets are produced of different sorts of wood in different Russian regions. The high usage wood species for pellets production are pine, birch, larch. The most popular sort of wood pellets in Russian market is pine pellets; they perform the best value for customer money. Agro pellets in Russia are mostly produced of buckwheat husk and sunflower husk. The agro pellets price is significantly lower, but the qualitative characteristics such as energy density, heating value and ash content and others are appreciably worse than wood.

2.1. Experiment data

All experiments investigation was founded on the basis of authors [6-13]. Two pellet boilers of different manufacturers of the same heating power (40 kW), equipped with a horizontally feed burners were used to perform the measurements in the present study. The heating power declared by the producer of the both boiler the same. The principle difference is the type of the burner. The first boiler is equipped with the burner of circular form (fig. 3) and the second is equipped with the rectangular burner (fig. 4), both are underfeeding by auger type. A vertical heat exchanger is used in both types of boilers.

An ideal reversible cycle based on the two temperatures of the system in Figure 1 can be drawn on a temperature–entropy basis. In this cycle a unit mass of fluid is subjected to four processes after which it returns to its original state. The compression and expansion processes, shown as vertical lines, take place at constant entropy. A constant entropy (isentropic) process is a reversible or an ideal process. The criterion of perfection is that no entropy is generated during the process, i.e. the quantity (s) remains constant.

![Figure 3. Circle burner](image3.png)

![Figure 4. Rectangular burner](image4.png)
The experiments are based on their availability and prevalence on the Russian market. Three sorts of pellets were selected: pine wood pellets, buckwheat husk pellets and sunflower husk pellets. All the pellets are exported to the EU and DIN+ certified. The pellets were purchased in Russia. The pellets characteristics are presented in table 1.

| Parameter                          | Pine wood | Buckwheat husk | Sunflower husk |
|------------------------------------|-----------|----------------|----------------|
| Diameter (mm)                      | 8.00      | 8.00           | 8.00           |
| Humidity (wt%)                     | 7.21      | 10.11          | 11.81          |
| Mechanical durability (wt%)        | 98.53     | 94.50          | 90.31          |
| Bulk density (kg·m⁻³)              | 695.29    | 609.57         | 531.15         |
| Fine contents (wt%)                | 0.29      | 1.56           | 11.25          |
| Ach (wt%)                          | 0.66      | 2.03           | 2.81           |
| Gross calorific value (MJ·kg⁻¹)    | 20.29     | 20.22          | 20.28          |
| Net calorific value (MJ·kg⁻¹)      | 17.37     | 16.32          | 16.31          |
| C (wt%)                            | 49.91     | 49.89          | 49.89          |
| H (wt%)                            | 6.32      | 9.19           | 6.21           |
| O (wt%)                            | 43.51     | 42.89          | 42.90          |
| N (wt%)                            | 0.40      | 0.98           | 1.10           |
| S (mg/kg dry fuel)                 | 109.00    | 1290.00        | 1380.00        |
| Cl (mg/kg dry fuel)                | <10       | <10            | <10            |
| Ni (mg/kg dry fuel)                | <10       | <10            | <10            |
| Cd (mg/kg dry fuel)                | <0.5      | <0.5           | <0.5           |
| Cr (mg/kg dry fuel)                | <10       | <10            | <10            |
| Cu (mg/kg dry fuel)                | <10       | <10            | <10            |
| Pb (mg/kg dry fuel)                | <10       | <10            | <10            |
| Zn (mg/kg dry fuel)                | <100      | <100           | <100           |
| Na (mg/kg dry fuel)                | 17        | 12             | 13             |
| Si (mg/kg dry fuel)                | 78        | 81             | 81             |

2.2. The experimental setup

Two pellet boilers, equipped with different type burners were used one after another to perform laboratory measurements in the present study. Both boilers were equipped with a vertical heat exchanger with 16 passes for the hot flue gas (water in tube type). The heat exchanger cleaning is manual. The boilers have a pellet hopper to store pellets. The pellets were manually loaded into the hopper and were fed into the combustion chamber through an impulse controlled, horizontal screw feeder. The pellets were fed at the center of the combustion chamber under the pellets bed. Ignition occurred manually. The laboratory measurements were performed by equipment: «Testo instruments» TESTO-340. The concept of the experimental setup was borrowed from [5].

2.3. The emissions of gas measurements

As soon as the boiler operation was stabilized, the emissions of gas were measured using the instruments «Testo-340» and «Testo 454» in real life conditions. The measurement principles of the gas analyzers were galvanic oxygen analyzer (O₂), non-dispersive infra-red (CO, CO₂), chemiluminescence for (NOₓ). Each gas analyzer was calibrated with appropriate gas at zero and span points, before and after the measurements. Flue gas and ambient temperature were measured using thermocouple probes (±0.5% accuracy).
3. Results of measurements

Table 2 illustrates CO emissions during the combustion of several sorts of pellets in the boiler equipped with different burners.

| Parameter           | CO Emissions mg/m³ |
|---------------------|---------------------|
| Pine Wood           | Buckwheat husk      | Sunflower husk |
| Circular burner     | 200                 | 1500           | 1740          |
| Rectangular burner  | 290                 | 2250           | 2364          |

Table 3 illustrates NO<sub>x</sub> emissions during the combustion of several sorts of pellets in the boiler equipped with different burners:

| Parameter           | NO<sub>x</sub> Emissions mg/m³ |
|---------------------|--------------------------------|
| Pine Wood           | Buckwheat husk | Sunflower husk |
| Circular burner     | 140             | 160           | 164          |
| Rectangular burner  | 141             | 159           | 166          |

Table 4 illustrates the boiler efficiency during the combustion of several sorts of pellets in the boiler equipped with different burners:

| Parameter           | Boiler efficiency, % |
|---------------------|----------------------|
| Pine Wood           | Buckwheat husk | Sunflower husk |
| Circular burner     | 91.4            | 89.9          | 89.2         |
| Rectangular burner  | 91.1            | 89.2          | 88.6         |

The results of experimental investigation can be shown in diagrams.

4. Conclusion

Both types of burners have shown the highest efficiency of firing wood pellets, such result was expectable because wood pellets are characterized by highest physic-chemical and thermal properties such as bulk and energy density, heating value, chemical composition, moisture, ash and fine contents. The higher emissions of CO in rectangular burner can be explain by poor combustion which might result from low combustion temperature, insufficient oxygen, poor mixing of fuel with combustion air and a too short residence time of the combustion gases in the combustion zone [14].

In the small burner and combustion space, the temperature of the gas exceeds 1300 °C leading to the thermal oxidation of atmospheric nitrogen to form NO<sub>x</sub> [15,16]. Therefore, NO<sub>x</sub> emissions should be directly related to the nitrogen bound in fuel, but due to relatively high ash contents of agro-pellets (not wood), the catalytic effects of ash surface on NO<sub>x</sub> formation must be taken into account. The NO<sub>x</sub> emissions do not vary significantly depending on the type of burner.

The circular shape burner has shown high efficiency. The reasons of such result can be better mixing of fuel with combustion air than the same process in the rectangular burner and the longer residence time of the combustion gases in the combustion zone [17,18,19].

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