Improvement of pellet fuel bed combustion technology in low power boilers

I I Komarov¹, D M Rostova², A A Kaverin³, N M Bychkov¹

¹ Department of Innovation Activities, National Research University “Moscow Power Engineering Institute”, Krasnokazarmennaya 14, Moscow, 111250, Russia
² Department of Economics in Power Engineering and Industry, National Research University “Moscow Power Engineering Institute”, Krasnokazarmennaya 14, Moscow, 111250, Russia
³ Department of Thermal Power Plants, National Research University “Moscow Power Engineering Institute”, Krasnokazarmennaya 14, Moscow, 111250, Russia

E-mail: komarovii@mpei.ru

Abstract. This paper describes different ways of efficiency improvement in pellet fuel bed combustion and proposes methods of pellet fuel combustion, ensuring high environmental and energy performance. The constriction in the form of a convergent-divergent passage in the furnace chamber with simultaneous delivery of the secondary air at the point of maximum dispersal of the exhaust gases has reduced unburned combustible losses by 39%. At the same time, the constriction has reduced heat transfer surface area and residence time of hot gases in the furnace chamber, which increased the exhaust gases temperature at the combustion chamber outlet by 98°C. Ansys CFX software package was actively used for numerical simulation during the development of innovative furnace chamber design. To verify simulation results, the firing test bench was designed.

1. Introduction
The availability of an efficient and reliable energy supply system is the most important condition for a comfortable human life. In small and remote communities, the heat is supplied by individual low-power domestic boilers. The most simple and common way of individual heating is the use of natural gas fired hot water boilers. Due to the limited availability of a centralized gas transportation system, consumers have to seek for other fuels. The recent wide-spread alternative to natural gas is pellet fuels (or pellets) made from wood waste (mainly softwood dust). Pellet fuel has high energy performance: low humidity (5–10%), high reactivity, and high net calorific value (15–22 MJ/kg). Due to the combination of high combustion characteristics and reasonable price, wood pellets are one of the most common types of fuel for individual heating [1].

Due to constantly increasing number of pellet boilers used in individual heating systems, the issues related to improving their efficiency become more urgent. Most boilers with a capacity of 10–50 kW available in the market are fired on the principle of pellet fuel combustion in the dense bed zone, which is due to the compact design of the furnace, ease of use, and a wide range of the heat power control (10–100%).
2. Design development of furnace chambers for efficient combustion of biofuels

Still, fuel combustion in the dense bed zone has certain drawbacks, namely significant unburned combustible and carbon losses ($q_4$ may reach 10%). Generally, the efficiency of pellet boilers is 85–90%, which is lower than that for natural gas fired boilers (93–94%). Moreover, incomplete combustion may increase the specific emissions of nitrogen oxides and other harmful substances and cause substantial damage to the environment due to the widespread use of individual heat supply systems [2].

There are several major directions in the development of the pellet fuel bed combustion technology in order to increase the energy and environmental performance of low-power boilers:
- Ensuring a high degree of volatile fuel burn-up (reduction in unburned combustible losses);
- Reduction in carbon loss by applying the control methods of carbon in fly ash;
- Ensuring the completeness of the pellet fuel char gasification for efficient burning of producer gas in above-bed zone.

Presently, the research team of the Moscow Power Engineering Institute conducts research aimed at developing an efficient design of wood pellet boilers with the following performance targets: boiler thermal rating – 15 kW, minimum efficiency – 92%, and specific emissions of nitrogen oxides – not more than 320 μg/m$^3$.

One of the most important principles underlying the solution to this problem is the implementation of the stage-based process of solid fuel combustion, namely solid fuel gasification and post-combustion of volatiles in above-bed zone. A smaller part of the air is supplied under the grate ($\alpha_1 = 0.3–0.5$) to provide intense in-bed fuel gasification [3]. Char and gasification products are burned out in above-bed zone of the furnace chamber with a special secondary air supply system. The schematic diagram of the combustion process is shown in figure 1.

The secondary air supply system and the furnace geometry have a significant impact on the combustion process. Studies indicate that the furnace round section provides more uniform temperature distribution compared to rectangular or square section due to the absence of stagnant areas.

The secondary air supply system primarily determines the gas outflow pattern in the furnace, which influences the intensity of the secondary air mixing with gasification products, gas residence time in the furnace, and temperature level. In order to reduce the unburned combustible losses, the secondary air shall be intensively mixed with volatile components to provide better fuel burn-up. In general, the high efficiency of the boiler can be achieved, provided no significant increase in excess oxidant ratio. The objective of the present research was the development of the furnace chamber design in accordance with the specified conditions [4].

![Schematic diagram of the two-stage pellet fuel combustion process](image)

**Figure 1.** Schematic diagram of the two-stage pellet fuel combustion process.
To develop and test the effectiveness of design options providing low \( q_3 \) (unburned combustible losses) and \( q_4 \) (carbon losses), Ansys CFX software package was used for numerical simulation of aerodynamics in the furnace chamber, as well as combustion and heat transfer processes. Numerical simulation of solid fuel bed combustion is a quite challenging and time-consuming task due to the lack of mathematical models for accurate simulation of heterogeneous solid fuel bed combustion. However, a numerical study of the furnace chamber design efficiency can be limited to modeling the exceptional gas phase combustion in above-bed zone [5]. This approach assumes that all carbon and other combustible components are completely converted into gaseous fuels. Composition, quantity and calorific value of producer gas can be found in publications describing the results of experimental studies of pellet gasification and pyrolysis processes [6]. In order to obtain accurate results consistent with the actual process of stage-based combustion of biofuel, it is necessary to verify the accepted composition of gases in terms of compliance with the material and energy balance. The producer gas calorific value is usually 45–55% of the net calorific value of the pellets. To maintain the energy balance, it is necessary to increase the sensible heat of gases. As a result, the expression of the energy balance for determining the initial parameters of the producer gas can be written as (formula 1):

\[
\text{LHV}_{\text{pellet}} = (\text{LHV}_{\text{pg}} + Q_{\text{pg}}) \cdot V_{\text{pg}},
\]

where \( \text{LHV}_{\text{pellet}} \) is the pellet fuel calorific value, kJ/kg; \( \text{LHV}_{\text{pg}} \) is the chemically-bound producer gas calorific value, kJ/m\(^3\); \( Q_{\text{pg}} \) is the producer gas sensible heat, kJ/m\(^3\); and \( V_{\text{pg}} \) is the specific yield of producer gas, m\(^3\)/kg.

Within the scope of this research, three options for combustion of gasification products were developed. The 3D models of the considered design options of the furnace are presented in figure 2. The first option suggests the secondary air supply at a right angle to the gas flow with the offset of burners axes relative to each other (figure 2a); the second option differs from the first one by the inclination of the secondary air blast nozzles by 45° up the main stream (figure 2b); and the third design option features the constriction in the first third of the furnace length and subsequent expansion at a constant angle, while the secondary air is supplied in the narrowest point, ensuring intense mixing of the fuel with the oxidant (figure 2c).

![Figure 2. The 3D furnace models for numerical simulation.](image-url)
3. Simulation results

Numerical simulation was carried out to compare the effectiveness of the proposed design options. The simulation was performed using the k-ε turbulence model with a standard near-wall function. The rate of chemical reaction of combustion was simultaneously limited by both the turbulent mixing velocity of the components and the Arrhenius equation, using the combined Finit Rate Chemistry and Eddy Dissipation model. The radiation heat transfer was simulated using the Discrete Transfer model [7].

Initial simulation data are presented in table 1.

Table 1. Initial data for simulation of aerodynamics and combustion in the furnace chamber.

| Parameter                               | Value  |
|-----------------------------------------|--------|
| Gasification product contents, mass fractions, %: |        |
| CH₄                                     | 0.002  |
| CO                                      | 0.254  |
| H₂                                      | 0.201  |
| CO₂                                     | 0.019  |
| H₂O                                     | 0.052  |
| N₂                                      | 0.472  |
| Temperature of gasification products, °C | 650    |
| Flow rate of gasification products, kg/s | 0.00236|
| Secondary air flow rate, kg/s           | 0.00339|
| Excess oxidant ratio in the secondary combustion zone | 1.1    |
| Furnace wall temperature, °C            | 140    |

The mathematical simulation results are presented in table 2. The readings were taken at the outlet of the furnace cylindrical section.

Table 2. Numerical simulation results.

| Parameter                               | Design option 1 | Design option 2 | Design option 3 |
|-----------------------------------------|-----------------|-----------------|-----------------|
| Furnace exit temperature, °C            | 608             | 585             | 706             |
| Wall heat flux, kW                      | 11.46           | 10.34           | 10.71           |
| Unburned combustible loss,%             | 1               | 5.6             | 0.61            |
| NO, μg/m³                               | 93              | 129             | 851             |

The most substantial unburned combustible losses are peculiar to the design option 2 due to the worst conditions for mixing the producer gas and the oxidant, as can be clearly seen in figure 3b, where the current flow lines of the producer gas are shown in red and those of the secondary air are shown in blue. When supplying air at a right angle, a uniform mixture of gas and air is observed. The best mixing conditions are reached in design option 3 (figure 3c) with the constriction provided. However, in this case the furnace surface area is reduced, and thus, the heat flux decreases, and the gas exit temperature increases. It should be noted that the specific heat flux (W/m²) was the highest and reached 21 kW/m² due to the highest bulk temperature and higher gas velocity, which intensified convective heat transfer.
Figure 4 shows the bulk temperature patterns obtained from the simulation results for each type of the furnace chamber geometry considered. Figure 4b shows that when air is supplied at an angle of 45°, the combustion takes place in the near-wall region of the furnace, where the secondary air bypasses the opposing air flow supplied from the secondary air blast nozzles. Figure 4a shows the swirling flame caused by the counter-displaced arrangement of secondary air blast nozzles. There is no uniform flaming of the combustion space, however, the stable combustion propagation throughout the height of the furnace should be noted.

![Figure 4](image)

**Figure 4.** Bulk temperature distribution.

The results of the simulated combustion and heat transfer for the latter furnace design option show an intense fuel burn-up, and a uniform flaming of the furnace chamber without impingement on the furnace walls. The drawback of the furnace design option 3 is a large high-temperature area (about 1400 °C) which is a source of thermal nitrogen oxides (figure 4c).

The firing test bench shown in figure 5 was designed for verification of the results obtained and further development of the furnace chamber design.

The secondary air blast nozzles are arranged in such a way that their position and angle of inclination can be adjusted. Carrying out fire tests will confirm the data obtained by numerical simulation, namely gas temperature at the outlet of the furnace and above the fuel bed zone, concentration of carbon monoxide and nitrogen oxides, and will also allow us to get a qualitative insight about the combustion process.

The experimental data will serve the basis for checking the adequacy of the combustion and heat transfer models used, and also will allow us to refine the approach used for the simulation of fuel bed combustion.
Conclusion

The furnace chamber separation into the gasification zone and the combustion zone of the producer gas makes it possible to minimize unburned carbon losses and to arrange the efficient fuel combustion in a gas phase. The proposed furnace design options without increasing the excess oxidant ratio (which significantly affects the flue gas heat losses) ensured a high degree of fuel burn-up, which is confirmed by low unburned combustible losses – 0.61%. Extremely low emissions of nitrogen oxides (93 μg/m³) were observed for the first design option of the furnace chamber. The oxidant supply arrangement and the furnace chamber design have a significant effect on both the efficiency of combustion processes and heat transfer rate (convective and radiant), as well as the furnace exit gas temperature. The task for development of furnace chambers should be based on using the experimentally proven design methods. The research results presented in the paper allowed us to identify the further development path in the furnace chamber design, providing low unburned combustible and carbon losses, low emissions of nitrogen oxides and deep cooling of combustion products.

References

[1] Nunes L J R, Matias J C O and Catalao J P S 2016 Renew. Energ. 85 1011–16
[2] Bashkova M N, Kazimirov S A, Temlyantsev M V, Bagryantsev V I, Rybushkin A A and Slazhneva K S 2014 Bulletin of the Siberian State Industrial University 2(8)
[3] Buchmayr M, Gruber J, Hargassner M and Hochenauer C 2016 Biomass Bioenerg. 95 146–56
[4] Lambreg H, Sippula O, Tissari J and Jokiniemi J 2011 Energ. Fuel. 25(11) 4952–60
[5] Buczyński R, Weber R and Słęk A 2015 J. Energ. Inst. 88(1) 53–63
[6] Erlich C and Fransson T H 2011 Appl. Energ. 88(3) 899–908
[7] Komarov I I, Rostova D M and Vegera A N 2017 J. Phys.: Conf. Ser. 891(1) 012225