

Investigation of the Optimal Tightness of the Combustion Chamber of a Solid Fuel Boiler in Order to Increase its Environmental Friendliness

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ABSTRACT

The paper presents a model of a solid fuel boiler with the improvement of the locking mechanism to increase its efficiency, which in turn will increase the savings and ecological safety of such a boiler. The given calculation of the volume of dry gases, theoretical volume of nitrogen and the volume of water vapor, which makes it possible to determine the content of oxygen in the air and other elements in the fuel. Given a 3-D model of solid fuel boiler by means of FlowSimulation software. Based on the test results, the amount of combustion products leaving the chamber was shown. The research results show that, depending on the size of the boiler elements, there is no ventilation in the room where the boiler is located, and after an hour of operation, a long stay of a person may cause health problems. It has been shown that the excess air factor depends on the type of combustible fuel, the method of its combustion and the structure of the boiler combustion chamber. A construction of the closing mechanism of the combustion chamber of a solid fuel boiler is proposed. Based on experimental and computational research, a model of the boiler door handle was constructed, when automatic opening would be impossible. Such a design of the mechanism closing the combustion chamber of a solid fuel boiler allows to increase its efficiency as a result of the stability of the gas mixture composition and to reduce the risk of carbon monoxide falling into the room.

Keywords: heat supply, energy, combustion process, solid fuels, safety.

INTRODUCTION

The idea of socio-economic development of each country should assume such a development that will satisfy the needs of modern societies, without limiting the development possibilities of future generations. Sustainable development assumes parallel development of the economy, society and the environment [Kalda et al. 2020]. The current realities of the energy world show that the use of traditional energy sources, such as coal, natural gas or oil for the needs of industry,

public utilities and other sectors of the economy, should entail certain limitations. The use of fuel of appropriate quality, selected individually for each furnace, guarantees cheap and clean energy. Recognition of the combustion process, fuels of different quality in various types of furnaces, makes it possible to avoid negative phenomena, unfavorable from an economic and ecological point of view [Róg 2011, Purgał et al. 2008, Adanez et al. 2018, Rakopoulos et al. 2017, Guo et al. 2020]. Thanks to sustainable global energy, it is possible to reduce the burden on the

environment, and thus improve the ecological situation in the world, enable the use of alternative energy sources that will significantly reduce costs, and reduce the dependence of many countries in the world on those countries that are rich in traditional energy sources and they can use their resources to achieve a monopoly on the world market.

Ukraine's accession to the Energy Community offers great opportunities and the necessary tools for a consistent structural reform in the energy sector. The adoption and implementation of European norms and standards in the field of energy and environmental protection will allow to change and modernize the national legislation and enable Ukraine to restructure the economic sector, maintain the principles of sustainable development and, in the long term, membership in the European Union. Ukraine should become a country with a strong economy and breakthrough innovations. Among the priority reforms and programs in the decree of the President of Ukraine is the Energy Independence Program, the main task of which is, in particular, „ensuring energy security and the transition to energy-saving and energy-efficient use and consumption of energy resources through the introduction of innovative technologies”. In recent years, prices of fossil fuels, including natural gas, have increased all over the world, including Ukraine. Accordingly, when heating private houses, there is a transition to other heat sources, in particular, to solid fuel.

The use of bioenergy, especially solid fuels, is quite efficient in countries where large areas of land are used as agricultural land [Pronobis et al. 2020]. After harvesting, for example, sunflower or maize, there is a lot of vegetation that can be effectively used for heating private homes. Unfortunately, there are not enough bio-power plants in Ukraine. Currently, the number of power plants producing energy from biomass in Poland is 21 with a total capacity of 485.5 MW, and for biogas - 178 with a capacity of 111.8 MW. Therefore, the development and improvement of solid fuel boilers is a priority task for Ukraine today [Kalda and Wojciechowska 2015, Kalda and Borkowska 2013].

The main purpose of the work was to present the mechanism of blocking the closure of a solid fuel boiler, contributing to increasing its efficiency, savings and increasing the ecological and health safety of the boiler users.

RESEARCH METHODOLOGY

The calculation of solid fuel boilers consists in determining the cost of fuel, the calculation of the cost of electricity (i.e. the cost of electricity to drive fans, smoke exhausters, network pumps), the cost of emissions of pollutants into the atmosphere, as well as the cost of prevented environmental damage. After all, we understand that the solution of environmental problems in the energy sector is now on the same level as economic issues.

The environmental friendliness of solid fuel boilers lies in the fact that since fuel in the form of firewood, wood waste, straw, peat briquettes, which are not fossils, is suitable for this type of boiler, this type of heating is environmentally friendly. When using solid fuel boilers, a high efficiency is achieved. Pellets and straw are an environmentally friendly type of fuel, therefore, during combustion, it is not allowed to exceed the permissible emission standards for harmful substances. Pellets and straw are many times more environmentally friendly in terms of sulfur dioxide emissions than coal. Only due to proper combustion in boilers designed for this type of fuel, it is the most environmentally friendly energy resource.

The environmental friendliness of such fuel is as follows:

- when burning ecofuels, carbon dioxide emissions are 10–50 times lower;
- 10–20 times less ash is formed;
- sulfur is almost completely absent in emissions.

This makes it possible to reduce emissions of greenhouse gases and dust into the atmosphere.

On the other hand, using other types of solid fuels, it is known that carbon monoxide and other harmful substances are formed during the operation of the boiler. Emissions caused by incomplete combustion are mainly the result of insufficient mixing of combustion air and fuel in the combustion chamber, a general lack of oxygen available, too low a temperature, a short residence time and too high a concentration. As a result of incomplete combustion in boilers, the following components can enter the atmosphere: carbon monoxide, particulate matter, non-methane volatile organic compounds, ammonia and other chemical compounds.

A small amount of ammonia can be released as a result of the process of incomplete

Table 1. Emission levels from combustion of various types of fuel

Type of fuel	Emissions into the atmosphere without purification systems, tons per 1 thousand tons of natural fuel			
	CO ₂	NO ₂	SO ₂	Solid particles
Pellets	4.68	9.31	0.28	4.11
Sawdust	5.00	9.60	0.50	20.1
Tree bark	5.60	11.40	0.80	13.4
Peat briquettes	8.04	26.81	3.00	13.02
Coal	9.58	63.56	9.20	65.32

combustion of all nitrogen-containing solid fuels. This happens when the combustion temperature is very low and when there is not enough oxygen from outside. Table 1 presents some types of fuel and the level of emissions when they are burned.

In order for the process of fuel combustion in the boiler to be maximum, access to the optimal amount of oxygen is necessary. For oxygen access, a certain gap between the boiler body and the loading door is also required. Maximum tightness will not allow oxygen to get inside the boiler and then the combustion process will be less. Minimum tightness will cause a certain amount of carbon monoxide to escape to the outside, which is dangerous for people and undesirable for the environment. Therefore, the development and improvement of solid fuel boilers is an urgent problem. In this regard, we have researched and improved the locking mechanism of the solid fuel boiler to increase the efficiency of the boiler and improve environmental safety.

The first stage of the research was to determine the volume of combustion products weighing 1 kg of solid fuel with the composition: C = 51%; H = 6.1%; N = 0,6%; O = 42.3%. In order to carry out thermodynamic calculations of the combustion process, it was necessary to obtain initial, qualitative data needed, among others, to determine the total enthalpy of the fuel. It was assumed that with a stoichiometric ratio of fuel and oxidant (air), complete oxidation products, such as CO₂, H₂O, N₂, are formed.

Calculations were made of the theoretical volume of combustion products formed during the combustion of 1 kg of fuel for each element of the fuel. In order to perform the calculations, it was necessary to determine the volume of dry gases, the theoretical volume of nitrogen and the volume of water vapor.

The following chemical reactions of complete oxidation take place in the mixture:

- For coal $C + (O_2 + 3.76N_2) = CO_2 + 3.76N_2$.
 - molecular weight C = 12 kg/mol.
 - the volume of 1 kmole of any gaseous reaction product under normal conditions is 22.4 m³/kmol.

The volume of dry gases is determined by the formula [h]:

$$V_{CO_2} = \frac{M_{CO_2}}{\rho_{CO_2}^H} + \frac{M_{SO_2}}{\rho_{SO_2}^H} \quad (1)$$

A value was obtained from the performed calculations $V_{CO_2} = 1.87 \text{ m}^3$.

The theoretical volume of nitrogen was determined by the formula:

$$V_{N_2} = \left(\frac{V_B^O}{100} \cdot 79 \right) + \frac{N^P}{100 \cdot \rho_{N_2}} \quad (2)$$

Value obtained: $V_{N_2} = 7 \text{ m}^3$.

- For hydrogen $H + 0.25 \cdot (O_2 + 3.76 \cdot N_2)$.
 - molecular weight H = 1 kg/mol.

After performing the calculations, a value was obtained $V_{H_2O} = 11.2 \text{ m}^3$, $V_{N_2} = 21 \text{ m}^3$.

The composition of the combustible substance also includes nitrogen. The volume of 1 kg of nitrogen under normal conditions is $V_{N_2} = 0.8 \text{ m}^3$.

The combustible part of the flat contains oxygen. During the combustion process, oxygen is consumed as a result of the oxidation of combustible elements (hydrogen, carbon), so it can be concluded that less oxygen from the air in the combustion process is consumed by the amount of oxygen contained in the fuel.

Consequently, there will be less oxygen in the nitrogen combustion products when it was not contained in the fuel but was present in the air. There is a volume of nitrogen per 1 kg of oxygen in the air, equal to $V_{N_2} = 2.63 \text{ m}^3$.

The next step was to determine the volumetric composition of combustion products, knowing the mass fractions of elements in the analyzed fuel:

$$V_{\text{CO}_2} = 1.87 \cdot g_{\text{C}} = 1.87 \cdot 0.51 = 0.9537 \text{ m}^3$$

$$V_{\text{H}_2\text{O}} = 11.2 \cdot g_{\text{H}} = 11.2 \cdot 0.061 = 0.6832 \text{ m}^3$$

$$\begin{aligned} V_{\text{N}_2} &= 7 \cdot g_{\text{C}} + 21 \cdot g_{\text{H}} + 0.8 \cdot g_{\text{N}} - 2.63 \cdot g_{\text{O}} = \\ &= 7 \cdot 0.51 + 21 \cdot 0.061 + 0.8 \cdot 0.006 - \\ &\quad - 2.63 \cdot 0.423 = 3.74331 \text{ m}^3 \end{aligned}$$

The total volume of exhaust gases was determined by the formula:

$$V_{\text{tot}} = V_{\text{H}_2\text{O}}^{\text{O}} + V_{\text{CO}_2} + V_{\text{N}_2} + V_{\text{B}}^{\text{O}}(\alpha - 1) \quad (3)$$

Eventually received $V_{\text{tot}} = 5.38 \text{ m}^3$.

Theoretically, when burning 1 kg of solid fuel when $\alpha = 1$ (air excess factor that represents in how many times the quantity of air, which is actually comes into combustion chamber, differs from theoretically necessary quantity) 5.38 m^3 of combustion gases will leave through the flue.

For gas stream research in combustion chamber the boiler using FlowSimulation we have used simplified model of solid-fuel boiler of KORDI AOTV 16-20E production. Section of AOTB 16-20E boiler is shown on Figure 1.

Based on the results of the analysis, with the width of the gap between the door and the chamber $\delta = 0.1 \text{ mm}$, $\delta = 0.5 \text{ mm}$ and $\delta = 1 \text{ mm}$ the following results were obtained:

- in the first case, the amount of combustion products leaving the chamber through the slit was 0.3%;
- in the second case, this value has increased up to 0.7%;
- in third case – up to 0.9%.

For example, for boiler with 20 kW capacity you may need $30 \text{ m}^3/\text{hour}$ when burning wood with 20% moisture content. After multiplying volume by the present, received during simulation, we will receive volume of gas discharges in the premise of boiler room: in case of 0.1 mm – 0.09 m^3 , 0.5 mm – 0.21 m^3 , 1 mm – 0.27 m^3 .

If there is no efficient ventilation in the room where the boiler is located, then after one hour of operation of such a boiler and keeping the minimum width of the gap, a person staying in the boiler room is exposed to carbon monoxide poisoning.

The excess air factor depends on the type of combustible fuel, the type of its combustion process, and the design of the boiler combustion chamber. The value of the coefficient is adopted on the basis of experimental data [Adanez et al. 2018, Rakopoulos et al. 2017, Guo et al. 2020].

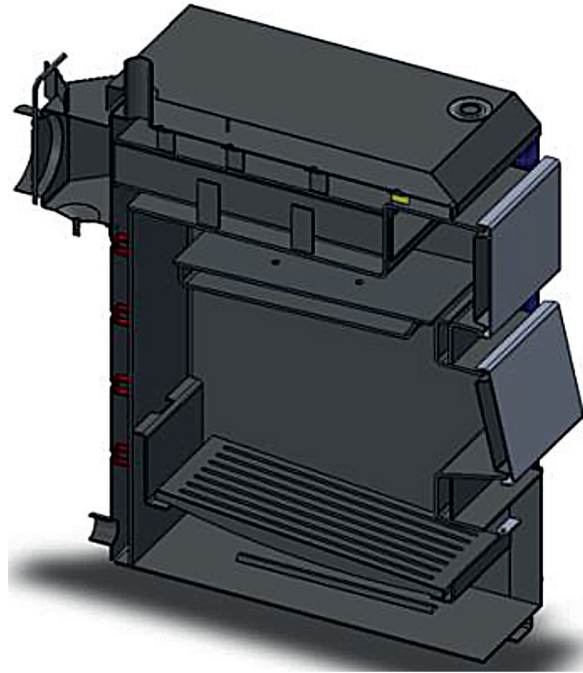


Figure 1. A 3-d cross-section of the AOTV 16-20E boiler model (own elaboration)

It is very important to correctly adjust air receipt in boiler's combustion chamber during fuel burning. If there will be not enough quantity of air, there won't be necessary amount of oxygen for full fuel burning, and part of combustion gases, originated in boiler's fire-chamber (for example, carbon oxide CO) and unburned particles of solid fuel will be removed along with combustion products in the flue. Incompleteness of fuel burning can be discovered by black smoke origin from the flue. It is obvious that such burning causes unnecessary fuel consumption.

For providing full fuel burning, in practice we need to feed fire-chamber with more air, than it is necessary according to calculation. But excessive quantity of air inside the boiler is inadmissible, since much heat is spent during this process for heating excess air, and a lot of heat leaves through flue.

Actual air quantity, necessary for full burning of 1 kg of fuel, must be theoretically a little bit bigger, inasmuch as during practical fuel burning not all quantity of theoretically necessary air is used for fuel burning, part of it doesn't participate in burning reaction as a result of insufficient intermixing of air and fuel, and also because air doesn't have enough time to enter clash with carbon of fuel and goes in boiler's flue in free state. Therefore relation between actual amount of air, fed into boiler's combustion chamber up to theoretically necessary quantity is called air excess factor:

$$\alpha_T = \frac{V_{A.F}}{V_A} \tag{4}$$

$$V_{A.F} = \alpha_T \cdot V_A \tag{5}$$

where: $V_{A.F}$ – actual air volume, fed into boiler’s combustion chamber for 1 kg of fuel;
 V_A – theoretical volume of air.

When burning fuel not all theoretically calculated amount of air enters into reaction. It is connected with insufficient blend of combustion product with oxygen. Oxygen that was not able to enter into reaction is removed through the flue in free state. As a matter of actual practice it was determined that actual amount of air must be 20–40% greater than theoretically calculated.

It is necessary to constantly keep an eye on effectiveness of burning processes according to control equipment during fire-chamber operation of all types. Significant influence on operation economy of the boiler has losses from chemically incomplete combustion of fuel. Value of losses mainly depends on the quantity of air, fed into fire-chamber.

It is commonly known that efficiency factor of the boiler with indirect heat-balance is equal to [Paraschiv et al. 2020]:

$$\eta = 100 - q_2 - q_3 - q_5 \tag{6}$$

where: q_2 – heat losses with originated gases, %;
 q_3 – heat losses from incomplete combustion, %;
 q_5 – heat losses into the environment, %.

In this formula we are interested only in q_2 , q_3 . Inasmuch as α doesn’t effect on q_5 . Incomplete combustion appears in case of lack of air. It is explained by origination of carbonic oxide – CO, soot, hydrogen H_2 in combustion products, and in some cases CH_4 . At that only part of combustion heat is exuded. Therefore we must always remember about incomplete combustion.

RESULTS

At that from our own experience, received on government enterprise that produces solid-fuel boilers it is known that when decreasing heat losses with combustion gases – q_2 , losses q_3 increase and according to the formula, efficiency factor will sharply decrease. Moreover, boiler operation in case of incomplete combustion even during short time will cause decrease of heat emission, and as a result boiler’s heat efficiency and its efficiency factor will significantly decrease.

In the case of excess air, the fuel is completely burned, but some heat is used to heat the excess air. Then the flue gas temperature drops, which equates to a decrease in the boiler efficiency and its efficiency. Hence, under the conditions of the optimal α value, the efficiency of the boiler will increase. The optimal value will work when the total heat losses are minimal.

Series of researches is represented in the Table 2. In order to select the optimal value of the excess air coefficient α , a number of tests were carried out with an identical load of 77% (the so-called approximate tests). A series of tests was carried out, while the obtained results are presented in Table 3. First, the value of α was higher than required, because then the incomplete combustion process will not occur. With a decrease in air pressure on the burner, parameters α and q_2 will gradually decrease. The operation of the boiler becomes more economical. If the air pressure drops further, incomplete combustion is achieved at some point. If the air pressure drops further, losses q_3 will increase very quickly. Approximately the point at which CO starts to rise will be the lowest point in the optimal zone.

Based on expert assessments and experience from conducted research, it was found that increasing the air supply to the combustion chamber by 0.1 reduces the amount of heat exchange by 4–5%. For example, for $\Delta\alpha = 0.1$ –0.2 it will

Table 2. Summary data of measurements (author’s experimental results)

Number of the research		1	2	3
Composition of exhaust gases	O ₂ , %	4.7	4.9	5.4
	CO, ppm	214	18	30
Composition of exhaust gases	O ₂ , %	4.8	5	5.5
	CO, ppm	202	40	57
Air excess factor according to the boiler		1.26	1.27	1.31
Air excess factor according to water economizer		1.27	1.28	1.32
Losses with exhaust gases, %		6.34	6.45	6.7

Table 3. Data used in calculations (author’s experimental results)

Parameter	Before	After
Temperature of exhaust gases	158.7	152
Air excess factor	1.34	1.28
Losses with combustion gases	7.02	6.41

increase the gas temperature by 4–8 °C. The air inflow to the boiler lowers the flue gas temperature in the inflow zone and reduces the amount of heat transferred through the heat exchange surfaces located at the inflow points.

By reducing the air supply to the combustion chamber, the efficiency can be reduced and increased. The data is when the load was 77% of the maximum value. Decrease of q_2 losses will be determined by formula:

$$q = \left(\frac{\alpha_1 - \alpha_2}{\alpha_1} \right) + \left(\frac{t_1 - t_2}{t_1} \right) \cdot q_2 \quad (7)$$

where: α_1 – air excess factor before decrease of air inflow;
 α_2 – air excess factor after decrease of air inflow;
 t_1 – temperature of exhaust gases according to energy losses before decrease of air inflow;
 t_2 – temperature of exhaust gases according to energy losses after decrease of air inflow.

As a result of air intake decreasing the efficiency factor of the boiler is improved for 0.61%.

Based on the author’s own research, a construction of the closing mechanism of the combustion chamber of a solid fuel boiler was proposed. The IZOPAK-57 thermal insulation cord with a 12×12 mm rectangular profile is used to ensure the tightness of the combustion chamber and the inspection chamber. According to the technical specification provided by the manufacturer, the tension necessary to ensure air-tightness when using the IZOPAK-57 thermal insulation cord is 0.3–0.4 MPa.

For calculation of necessary strain of doors closing it is necessary to determine contact area of heat insulating cord IZOPAK-57 and boiler’s frame. It is known from previous part that internal dimensions of boiler’s window is 250×390 mm, metal wall thickness is 6 mm. Contact area is determined by formula:

$$S_k = 2 \cdot ((l + 2t) \cdot t + h \cdot t) \quad (8)$$

Received $S_k = 7824 \text{ mm}^2$.

Biggest value is chosen for calculation for exact providing boiler’s hermeticity during operation. Also, loading will be increased for 25% to achieve reliability during calculation.

In order to check the opening of the handle, it is necessary to find the friction angle between the handle and the buckle. Since the handle

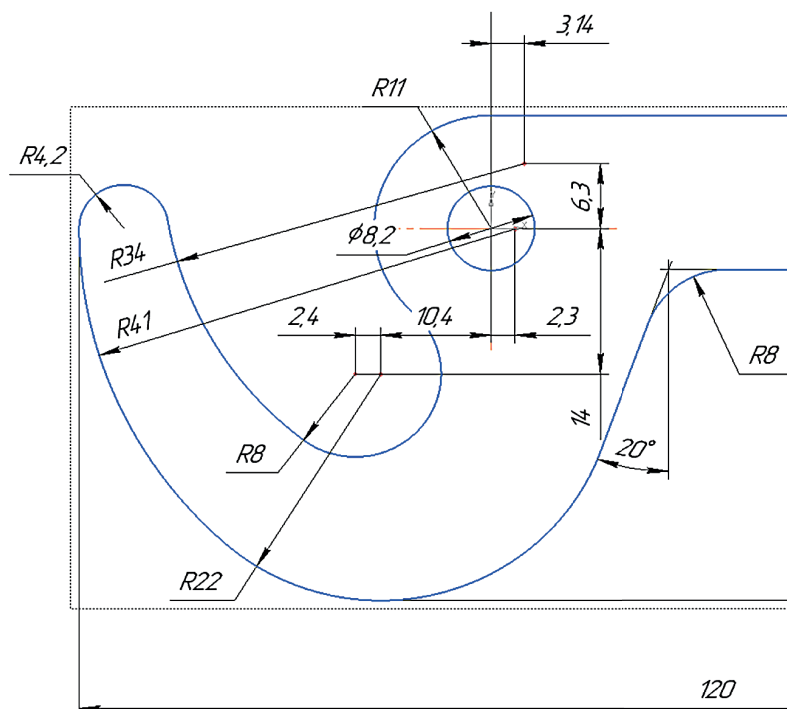


Figure 2. The geometry of gripping the handle (own study)

Table 4. Friction coefficients between material

Material	f under conditions of unlubricated friction	f under conditions of lubricated friction
Alumina - Steel	0.61	-
Copper - Steel	0.53	-
Steel - Steel	0.8	0.16
Steel - Polytetrafluoroethylene	0.04	0.04
Bronze - Steel	0.51	-
Steel - Wood	0.2–0.6	0.2

Table 5. Verification of the profile in terms for possibility of self-opening (results of author's calculations)

Angle α_0	Angle φ
22°	8.94°
24°	8.58°
30°	7.44°
35°	6.43°

geometry smoothly closes the door, it is necessary to find parts of the handle profile when self-opening is not possible. The handle geometry is presented in Figure 2. The diameter of the handle cross-section is 8 mm.

According to Table 4, static friction coefficient between metals in case of absence of greasing is 0.8, and in case of lubricating is 0.16. Inasmuch as during boiler's operation different substances are emitted during combustion process, and also when loading waste, greasing materials can get oneself on the boiler's handle – then we will choose 0.16 for calculation.

On the basis of the experimental research results, the angle between the friction force and the tangent line to the grip curvature cannot be greater than 9.1°.

Using Compas and SolidWorks software, we have determined an acceptable angle. Consequently, the angle α_0 21.1° is the minimum angle at which the handle does not open automatically. Simulation tests were carried out, the results of which are presented in Table 5.

Accordingly to received results, handle is suitable for use, insofar as when angle is 21.1° and more handle will provide safe closing of the boiler.

CONCLUSIONS

The paper presents the author's design of the mechanism closing the combustion chamber of a solid fuel boiler. The design allows to increase

the efficiency of the boiler operation as a result of the stability of the gas mixture composition and to reduce the risk of carbon monoxide entering the room. The designed structure of the closing mechanism has a flexible display and the possibility of adjusting the door window in three directions. Adjustment of the door inclination angle in relation to the horizon is performed by the deflection adjuster, and the door clamping forces are adjusted by moving the bolt nut along the external bolt thread. The crochet profile of the closing handle is designed in SolidWorks in such a way that the contact angle with the clamp is greater than the friction angle (9.1°), which ensures a reliable hooking and prevents it from opening automatically. The tests were carried out for the KORDI AOTV16-20E solid fuel boiler, manufactured by a leading boiler production company in Ukraine.

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