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EVOLUTION OF SOLID AND GAS FUEL REACTORS IN THE MUNICIPAL ECONOMY

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Purpose: The aim of this article is to show the evolution of reaction chambers for solid and gaseous fuels and to propose a new design solution that intensifies the heat exchange process and increases the efficiency of the heating device.

Design/methodology/approach: Previous designs of reaction chambers in boiler devices are mainly based on convective heat exchange. New solutions proposed in this work make the heat exchange process mainly through radiation more effective. These solutions have been patented in the Polish Patent Office.

Findings: New designs of combustion chambers, in which mainly radiative heat flow is realized, allow for increased power of the boiler device and low emission of pollutants. They eliminate the disadvantages of conventional solutions, which are often burdensome in operation.

Research limitations/implications: The new type of reaction chambers based on radiative heat flow will certainly be the subject of energy and emission research, as a result of which it will be possible to carry out a possible correction of the design parameters to optimize the energy conversion process, taking into account different types of fuel burned.

Practical implications: The article presents a practical solution for the construction of reaction chambers realizing radiative heat flow between the combustion zone and the heat exchanger walls. The increase in the power of heating devices with their relatively small dimensions and friendly use will stimulate their common use in the municipal economy.

Social implications: Correct implementation of the projects included in the article may contribute to the satisfaction of users with improved living conditions, generated savings and contact with modern construction solutions.

Originality/value: This paper presents new and patented designs of reaction chambers of boiler devices in which mainly radiative heat exchange is carried out.

Keywords: reaction chambers, combustion, gas boilers, coal boilers, heat exchange.

Category of the paper: Research paper.

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1. Introduction

Coal is the basic energy carrier on the basis of which the Polish energy system, municipal economy and scattered individual users operate. Figure 1 shows the balance of hard coal in the last decade. There is a decrease in coal consumption and extraction in Poland, while its import remains almost unchanged. This action has resulted in the occurrence of small reserves, which is a positive phenomenon compared to the large shortages in 2021.

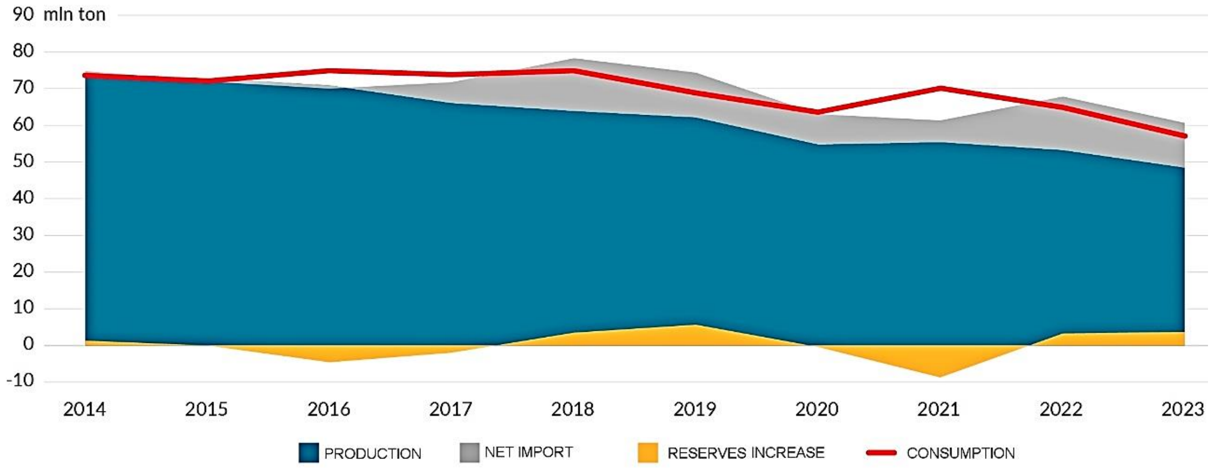

Figure 1. Hard coal balance in Poland.

Source: Dusiło, 2024.

Figure 2 shows the structure of coal consumption in the past decade. The largest amount of coal is consumed by professional power industry for the production of electricity (55.7%) and heating (20.4%). In third place are households (12.6%) using coal for heating and social and living needs. The high demand for coal among individual users results from its relatively low price, tradition of its use and ease of use of power equipment for converting chemical energy into useful energy.

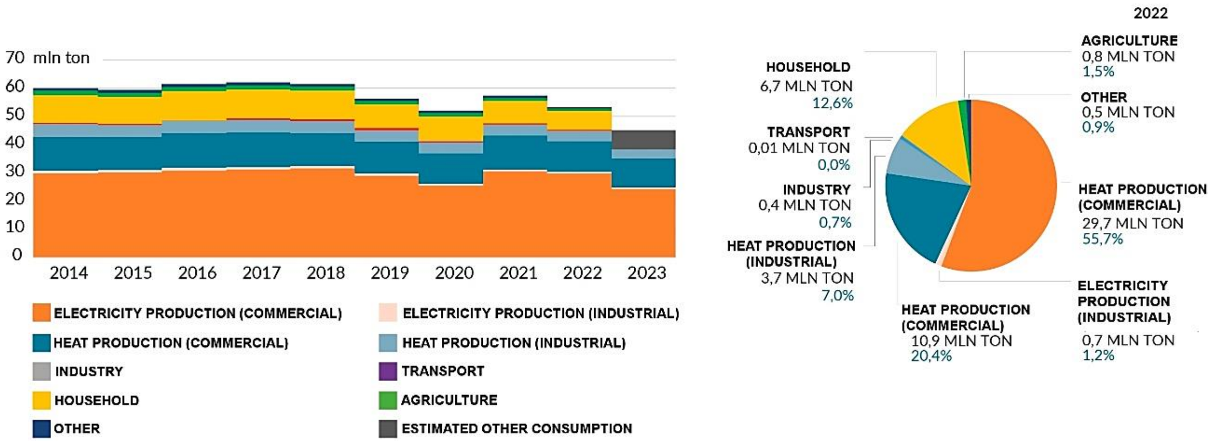

Figure 2. Structure of consumption of hard coal for energy purposes in Poland.

Source: Dusiło, 2024.

The natural gas balance is shown in Figure 3. The extraction of this raw material in Poland in 2023 decreased by 29% compared to 2014 (Dusiło, 2023). Unfortunately, the downward trend continues. Gas imports follow its consumption, which has increased by 13% over the last decade. A slight upward trend in gas consumption is observed.

The structure of natural gas consumption in the last decade is shown in Figure 4. The main recipient of gas is industry (33%), which, taking into account the production of electricity, heat and other branches of the economy, uses 67% of this raw material. In second place, right after industry, are households – about 29%.

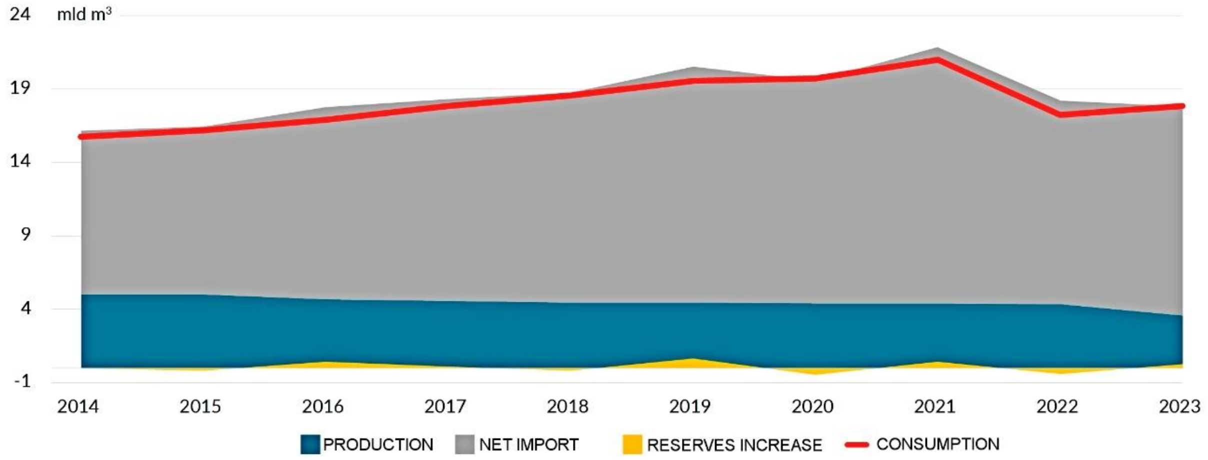

Figure 3. Natural gas balance in Poland.

Source: Dusiło, 2024.

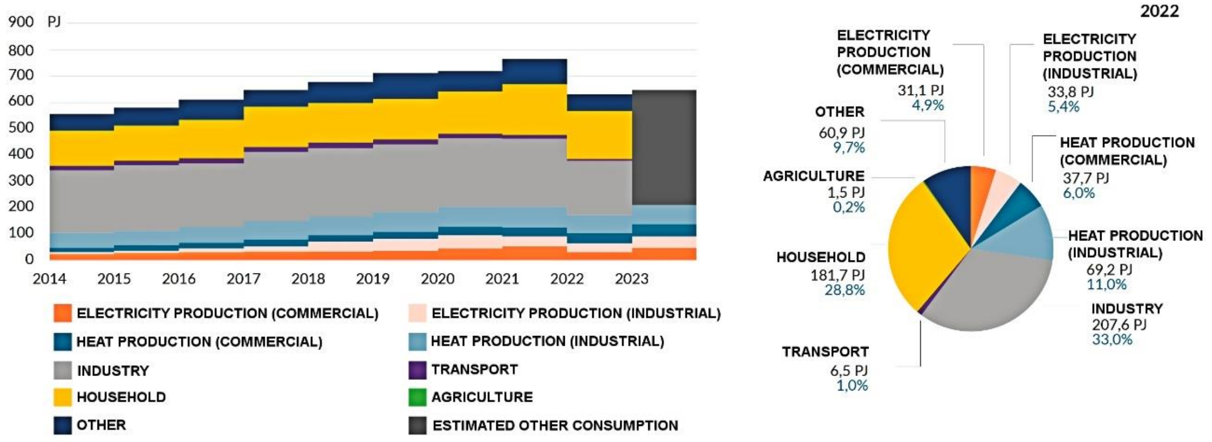

Figure 4. Structure of natural gas consumption in Poland.

Source: Dusiło, 2024.

The above data show that the municipal economy sector is a significant recipient of energy carriers, therefore their increasingly efficient use will reduce maintenance costs and contribute to anti-inflationary measures.

Figure 5 presents various heating techniques used in municipal economy. Although the data concerns 2018, it can still be considered reliable, because the period of operation of heating devices is relatively long and amounts to at least a dozen or so years. The share of energy from the heating network (40%) is comparable to the share of solid fuels (43%) used by individual users. The main component of solid fuels is hard coal. In small towns and rural areas, biomass (logs, round logs, wood chips, briquettes) is used for heating purposes in addition to coal.

The spectrum of design solutions for reaction chambers is wide for both gas and solid fuel reactors. This is due to the fact that these energy carriers have a long history of operation. Most of the older design solutions are widely known, so their detailed analysis of the design will be omitted in this work.

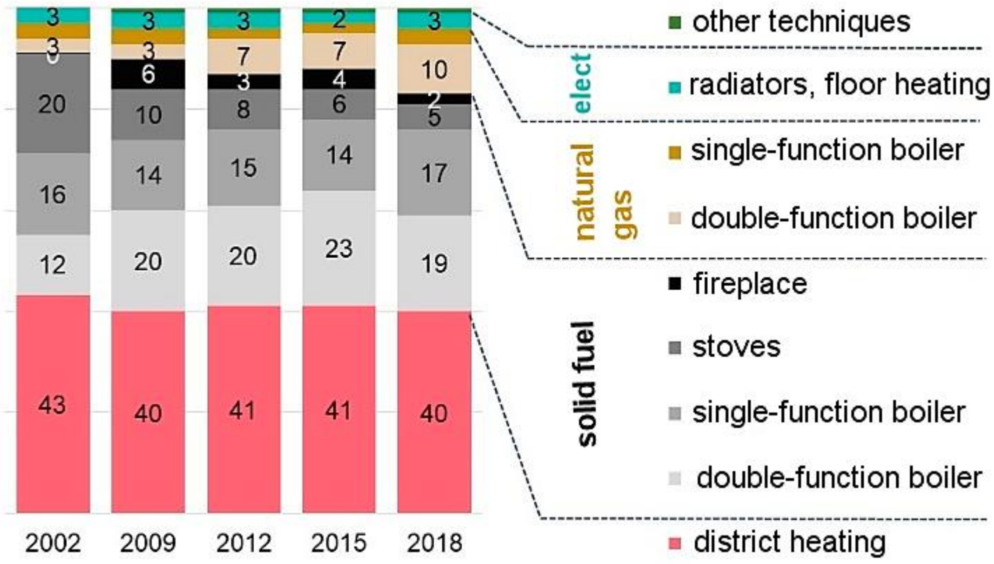

Figure 5. Structure of heating techniques used in domestic households.

Source: Dusiło, 2023.

2. Solid fuel reactors

Combustion of solid fuels will be referred to hard coal, because it has a dominant share in the energy economy. Due to the processes occurring in coal, the energy conversion process is complex. Pyrolysis reactions occur in the heated coal mass, the speed of which increases with temperature. The products of these reactions are, in addition to inert gases, flammable gases (hydrocarbons, carbon monoxide). The share of gaseous pyrolysis products in the coal mass is large and often amounts to about 30%. The dominant share in them is hydrocarbons with high calorific value, therefore, effective combustion of these gases, in addition to coke residue, affects the efficiency of conversion of chemical energy into thermal energy. This problem is easily illustrated on the example of stoker boilers. Figure 6 shows the principle of operation of a boiler with a solid stoker with bottom-up and top-down combustion (Wójcik, 2011a, pp. 105-110).

In the topsoil of a bottom-up combustion boiler (Figure 6a), four zones can be distinguished in the initial period of the combustion process:

1. Oxygen zone – located above the grate, under which the so-called primary air is supplied. All the heat energy in the boiler is generated in this zone.
2. Reduction zone – located directly above the oxygen zone. The oxygen content in this zone drops to zero, but due to the thermal effect of the oxygen zone, the temperature here is quite high. The CO2 flowing here from the oxygen zone is reduced to CO in contact with the hot surface of the char.
3. Degassing zone – located above the reduction zone. The temperature here is still relatively high, allowing for the degassing of the coal. The degassing products and the carbon monoxide flowing here move further, to the zone located higher.
4. Drying zone – located above the degassing zone. In this zone, surface moisture is removed from the coal and that which is in the pores near the surface. Through this zone flow: carbon monoxide – from the reduction zone and degassing products – from the degassing zone, which together with water vapour rise to the space above the bed.

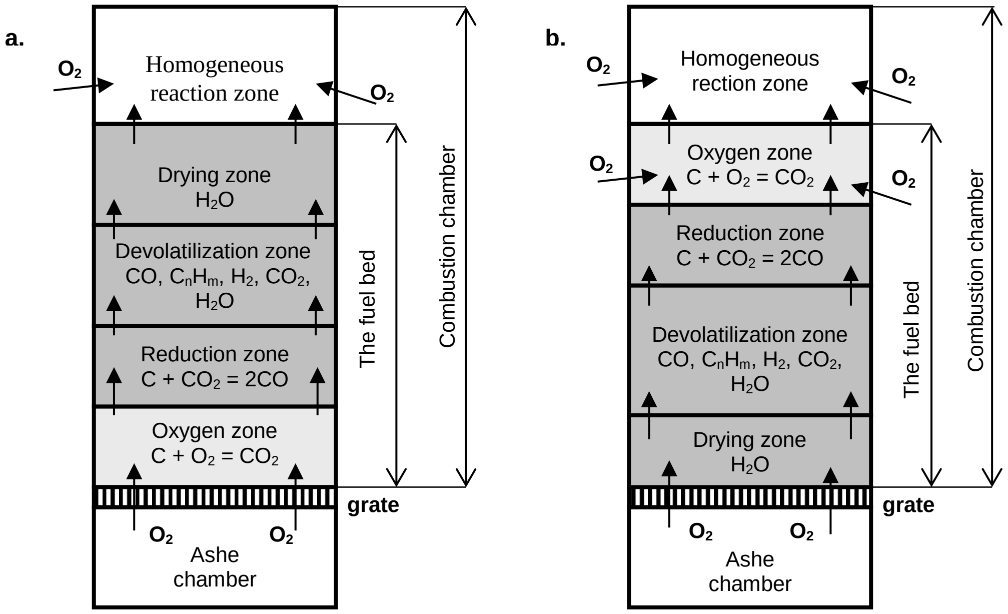

Figure 6. Burning stratum (fuel-bed) in the grade boiler: a.) with bottom-up burning; b.) with top-dawn burning.

Source: Wójcik, 2011a, pp. 105-110.

The area above the bed, the homogeneous reaction zone, is supplied with so-called secondary air in order to enable combustion of degassing products and CO. However, the temperature above the bed is too low to ensure proper combustion. In this type of grate furnaces, in the initial combustion period, significant emission of hydrocarbons into the atmosphere is observed. There are large energy losses.

In the top-down combustion boiler hopper (Figure 6b), the same zones are distinguished in the initial period of the combustion process as in bottom-up combustion, but they are located under the oxygen zone - the heterogeneous reaction zone.

The oxygen zone is located in the upper part of the combustion chamber, where the primary air is supplied. The amount of supplied air is greater than the demand of this zone by heterogeneous reactions, so its surplus is used to burn carbon monoxide and hydrocarbons in the homogeneous reaction zone.

The reduction zone is located below the oxygen zone. The carbon monoxide generated in the reduction zone flows through the hot heterogeneous reaction zone, where it has the greatest chance of burning. If this does not happen in the oxygen zone, the oxidation of CO will occur in the homogeneous combustion zone.

The degassing zone is located under the reduction zone, so the volatile parts rich in hydrocarbons will go through the reduction zone to the oxygen zone, where they will be burned. The part of the hydrocarbons that does not have time to burn in the oxygen zone will be burned in the homogeneous reaction zone. It must be remembered that the combustion of a certain amount of fuel does not occur immediately but lasts for a certain period of time.

The drying zone is located below the degassing zone. The steam passes through the subsequent zones to the homogeneous reaction area. It improves the CO combustion rate.

Below the drying zone there is a fixed grate through which secondary air is supplied to the boiler combustion chamber. This air forces the flow of gaseous components towards the oxygen zone, preventing them from flowing back and getting through the ash chamber door to the environment. Figure 7 shows a practical solution of a boiler with top-down combustion.

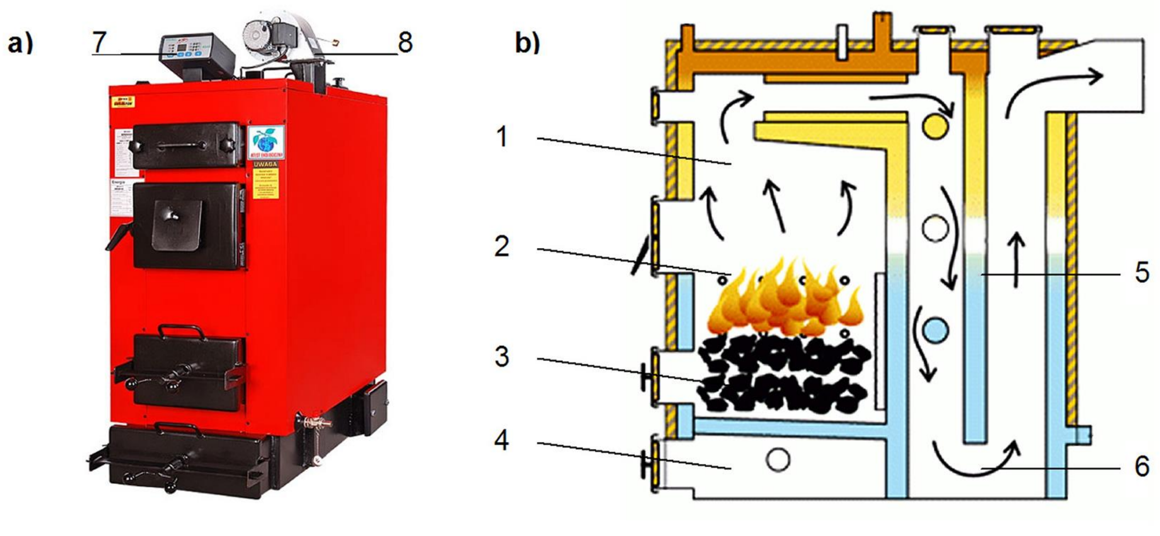

Figure 7. KWM-S 50 kW top-combustion grate boiler: a) general view; b) operation diagram. Explanations: 1 - fire chamber; 2 - secondary air nozzles; 3 - filling layer; 4 - ash chamber; 5 - heat exchanger, 6 - exhaust gases, 7 - control system; 8 - air supply system to the combustion zone.

Source: Wójcik, 2011a, pp. 105-110.

During the operation of a boiler with top-down combustion, the heterogeneous reaction zone moves towards the grate and above it there are combustion wastes, which hinder the course of homogeneous reactions due to the inaccurate mixing of the gas fuel with the oxidizer. This zone tends to channel, i.e. it does not move towards the grate evenly over the entire surface.

The boiler operates cyclically. After the end of one cycle, the chamber is refilled with fuel, it is ignited on the surface and another cycle begins. Such a furnace is relatively troublesome to operate. These disadvantages are not present in furnaces with a sliding mechanical grate, in which top-down combustion is also carried out. The sliding grate and a relatively thin layer of fuel cause good burning of the char and flammable gases above the grate surface. Furnaces with a mechanical grate are used in professional heating plants and their thermal power exceeds several dozen megawatts, so they are not suitable for individual users.

The modernization of the top-down combustion method is a reaction chamber with a retort – the so-called retort furnace. The principle of operation of such a furnace is shown in Figure 8.

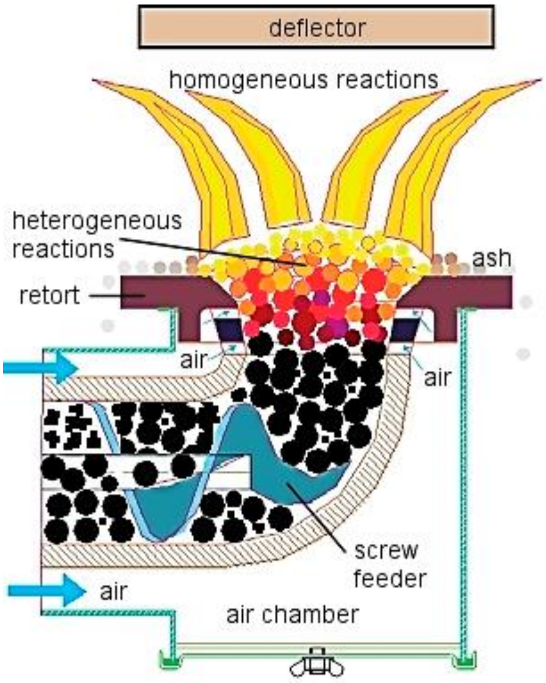

Figure 8. Construction of a typical retort furnace.

In the upper part of the retort there is a heterogeneous reaction zone and below it the next zones shown in Fig. 6b. Here all the zones are stationary due to the movement of the fuel, which is supplied by a screw feeder. Air is forced into the air box and from there to the nozzles located on the circumference of the retort in the heterogeneous reaction zone. Excess air flows into the homogeneous reaction zone, where the coal degassing products are burned. In the upper part of the homogeneous reactions there is a deflector - a steel plate on which the ash particles lose their kinetic energy and fall to the edge of the retort. From there they fall into the ash chamber located under the air box.

Figure 9 shows the operation of a reaction chamber with a retort furnace. This solution eliminates all the disadvantages of a furnace with a fixed grate, both with bottom-up and top-down combustion. Reaction chambers with retort furnaces are currently among the most modern, suitable for burning both coal and biomass. However, the fuel must be previously properly prepared, mainly in terms of granulation and sinterability. A detailed description of these furnaces can be found in (Wójcik, 2011b, pp. 515-525).

The heat exchange process in the retort reactor comes down to generating high-temperature exhaust gases that transfer heat energy to the circulating medium in the heat exchanger as a result of transferring heat from the exhaust gases to the exchanger wall in accordance with the equation

$$\dot{q} = \propto (T_g - T_w), \tag{1}$$

where:

$\dot{q}$ is the unit heat flux [J/m2s],

α – heat transfer coefficient from the gas to the exchanger walls [J/m2sK],

Tg – gas (exhaust gas) temperature [K],

Tw – temperature of the heat exchanger walls [K].

Figure 9. Operation of the retort furnace.

Source: Wójcik, 2011b, pp. 515-525.

The value of the unit heat flow is influenced by the temperature difference and the value of the heat transfer coefficient, which strongly depends on the local velocity of the exhaust gases relative to the heat exchanger walls. The higher the velocity, the higher α. By using appropriate exhaust gas swirlers, a turbulent flow is obtained in the exchanger and the value of the heat transfer coefficient increases significantly. The efficiency of the process increases.

The heat exchange process can be further intensified by generating a large flux of thermal radiation energy in the reaction chamber from the heterogeneous reaction area to the exchanger wall. Heat exchange by radiation between the surface of the embers and the exchanger wall proceeds according to the equation:

$$\dot{q}_r = \sigma\varepsilon(T_c^4 - T_w^4) \tag{2}$$

where:

σ = 5.67·10−8J/sm2K4 is the Stefan-Boltzmann constant,

Tc – the temperature of the glow,

ε is the emission capacity of the body (0 ≤ ε ≤ 1).

The value of the unit heat radiation flux is significant due to the temperature difference in the fourth powers.

Figure 10 shows a diagram of a boiler with a radiation combustion chamber for solid fuel. The solution is original and has been granted a patent in the Patent Office of the Republic of Poland (Wójcik, *Radiacyjna komora palenislowa na paliwo stałe*…).

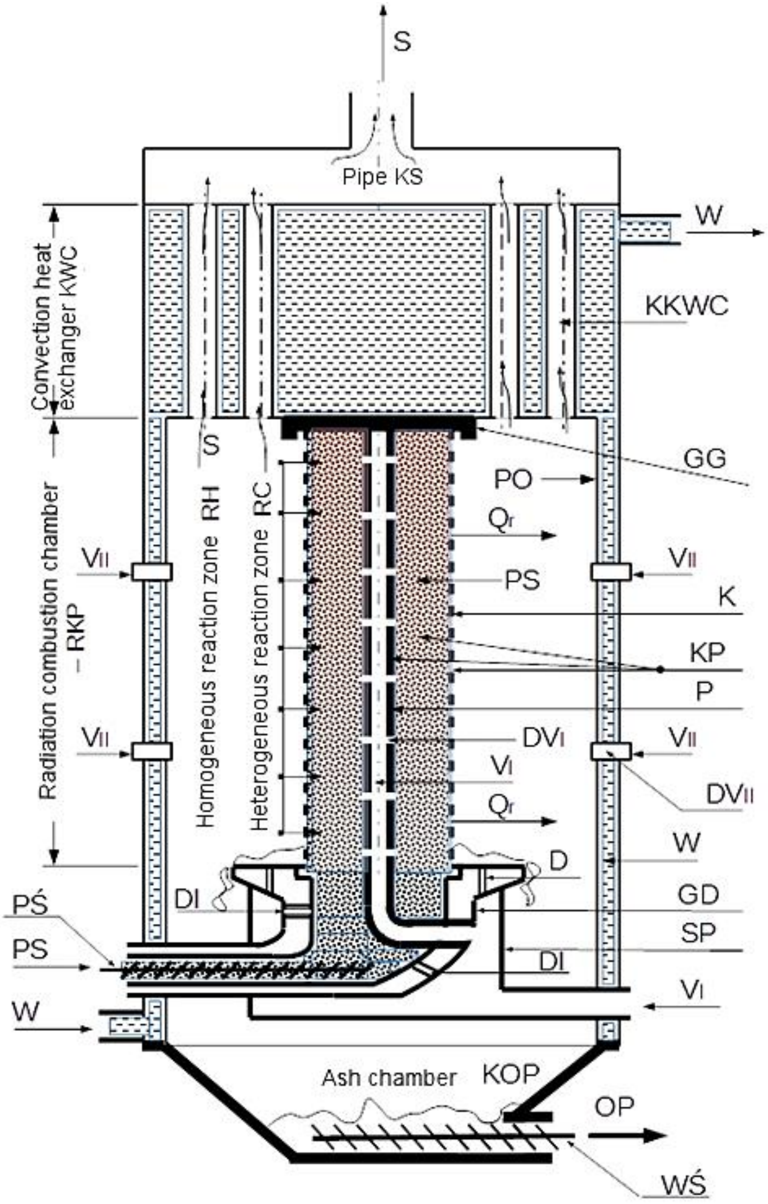

Figure 10. Boiler with a radiation combustion chamber (description in the text).

Source: Wójcik, *Radiacyjna komora paleniskowa na paliwo stałe…*

The solid fuel radiation reaction chamber is composed of a **KP** radiant column made of a heat-resistant basket **K**, inside which there is a combusted fuel **PS** and a centrally located air duct **P** with **DVI** nozzles supplying primary air $\mathbf{V_{I}}$ to the heterogeneous reaction zone **RC**. The design of the **KP** radiant basket depends on the type of combusted solid fuel, the size of the fraction and its sintering ability. The **KP** radiant column is thermally insulated from the top of the **KWC** convection heat exchanger by the upper socket **GG**, and in the lower part it is mounted in the lower socket **GD**, which is placed in the **SP** air box, to which the primary air $\mathbf{V_{I}}$ is **supplied.**

On the perimeter of the lower socket **GD** there are nozzles **D** supplying primary air $\mathbf{V_{I}}$ supporting the combustion of char, small amounts of which may be present in the combustion waste leaving the radiant column **KP**. In the lower part of the lower socket **GD** there are nozzles **DI** supplying air $\mathbf{V_{I}}$ to the fuel **PS** feeding the radiant column **KP**, in order to pneumatically isolate the combustion chamber from the environment. The solid fuel **PS** is supplied by the screw feeder **PŚ** to the lower socket **GD** from where it moves to the heat-resistant basket **K** of the radiant column **KP**, where it is dried, degassed and burned. In order to prevent the gases generated during coal pyrolysis from flowing back, primary air $\mathbf{V_{I}}$ is supplied through nozzles **DI**, which here acts as a pneumatic barrier isolating the radiant combustion chamber **RKP** from the environment. The **OP** combustion waste is automatically discharged from the **KP** radiant column and through the offset located on the circumference of the lower **GD** socket falls into the **KOP** ash chamber from where it is discharged outside by means of the **WŚ** screw selector. The unburned char contained in the **OP** combustion waste is post-burned on the offset of the lower **GD** socket, where primary air $\mathbf{V_{I}}$ necessary for burning the coke residue is supplied through nozzles **D**. High-energy heterogeneous reactions of combustion of solid fuel **PS** take place in the **KP** radiant column, the intensity of which depends on the amount of primary air $\mathbf{V_{I}}$ supplied through nozzles **DVI** located on the circumference of the air duct **P**. The amount of fuel **PS** burned must be synchronized with the speed of its supply by the **PŚ** screw feeder. The released thermal energy $\mathbf{Q_{r}}$ in the heterogeneous reaction zone **RC** of the combustion of char formed from solid fuel **PS** is radiated towards the wall **PO**, behind which there is a circulating medium **W**. Combustible products of degassing of solid fuel **PS** containing hydrocarbons and unburned carbon monoxide from heterogeneous reactions are combusted in the homogeneous reaction zone **RH**, in the vicinity of the radiant column **KP**, and the products of these reactions leave the radiant combustion chamber **RK**P in the form of exhaust gases **S**. Secondary air $\mathbf{V_{II}}$ is fed to the homogeneous reaction zone **RH** through $\mathbf{DV_{II}}$ nozzles in order to efficiently conduct these reactions and obtain high energy of exhaust gases **S**. Hot exhaust gases **S** leave the radiant combustion chamber **RKP** and move through the **KKWC** channels in the **KW**C convective heat exchanger, releasing thermal energy to the circulating medium **W**, which was previously preheated by the heat $\mathbf{Q_{r}}$ radiated from the radiant column **KP**. The exhaust gases **S** cooled in the convection heat exchanger **KWC** move to the exhaust gas chamber **KS** and are then removed outside.

The aim of the new solution is to increase the total heat energy flux generated in the reaction chamber as a result of radiation energy from the heterogeneous reaction zone and the energy contained in hot exhaust gases moving to the heat exchanger.

3. Gas fueled reactors

Like solid fuel reactors, gas fuel reactors have a long tradition of use, hence the large variety of technical solutions. Leaving aside the historical outline, the paper will present solutions that are currently commonly used. These are structures that operate classically, but they use new materials and manufacturing technologies. The basic element in a gas fuel reaction chamber is a gas burner. Basically, gas burners are divided into atmospheric and fan burners. Figure 11 shows an atmospheric injector burner.

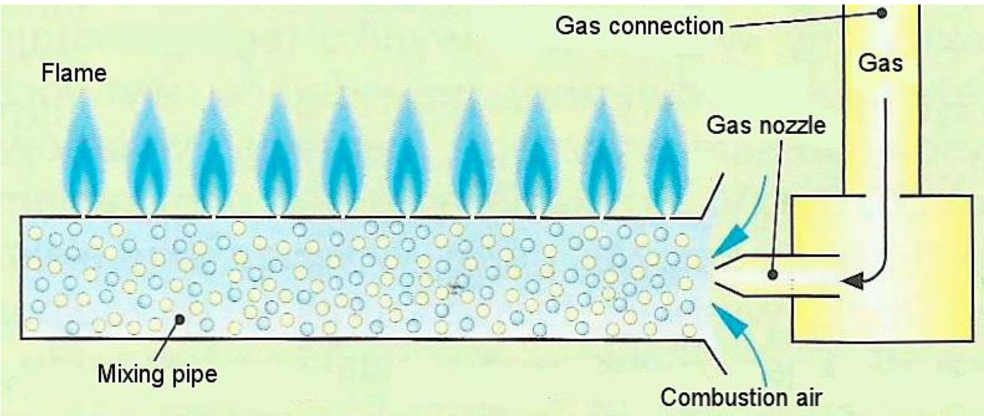

Figure 11. Principle of operation of an atmospheric injector burner.

Source: Vissmann sp. z o.o.

The gas flowing out of the nozzle creates a static vacuum due to the suction action of the jet. As a result, atmospheric air is sucked into the pipe, where it mixes with the gas fuel to create a combustible mixture. These burners are characterized by simple construction and quiet operation. Their efficiency is lower than that of blower (fan) burners. Figure 12 shows an example of the use of an injector burner in gas boilers with a power of up to several kW.

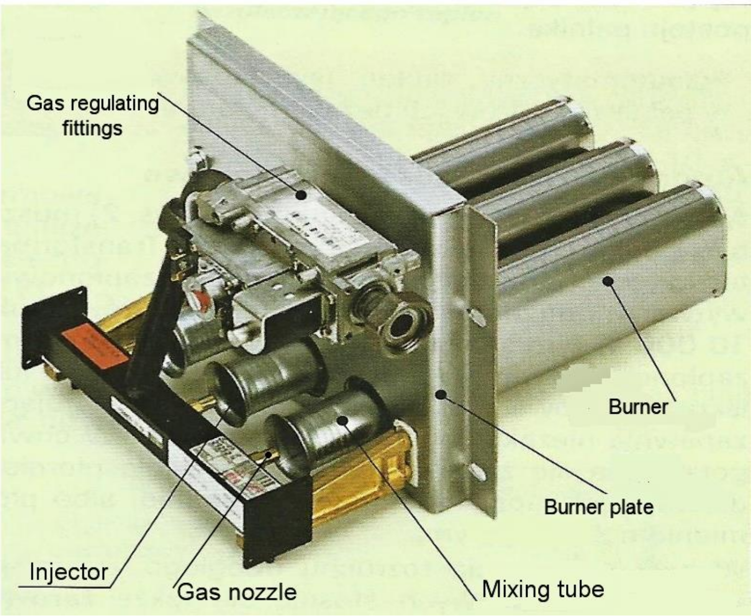

Figure 12. Atmospheric (injector) Gas Burner.

Source: Vissmann sp. z o.o.

Currently, the most modern gas burners include structures that generate a swirl flame. Figure 13 shows the principle of operation of such a burner. The oxidizer and fuel streams flowing out of the burner are introduced into a swirling motion, thanks to which the fuel and oxidizer are well mixed. This is a necessary condition for rapid combustion. Gas particles have two velocity components - axial v_x and radial v_r. Circumferential velocity v causes the particle to move in a spiral. As a result of the radial velocity, the flame thickness increases and a negative pressure is created inside it. Hot exhaust gases from the flame front are sucked into its interior and heat the fuel-air mixture - as a result, the combustion rate increases.

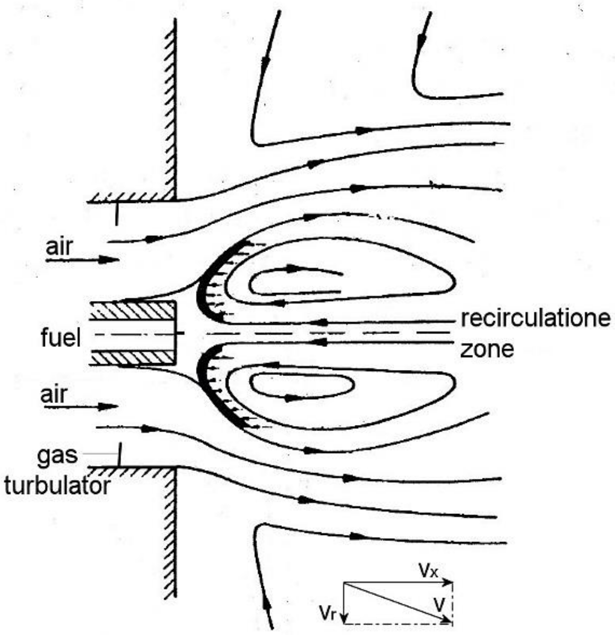

Figure 13. Swirled flame with exhaust gas recirculation.

Depending on the degree of swirling, the shape of the flame can be formed by adapting it to the size of the reaction chamber. The issues related to this are described in (Wójcik, 2011b, pp. 515-525; Wójcik, 2021, pp. 103-122). Figure 14 and Figure 15 show reaction chambers for gas fuel with burners generating a swirled flame. The degree of swirling is different, so in Figure 14 the flame is elongated, in Figure 15 - circular.

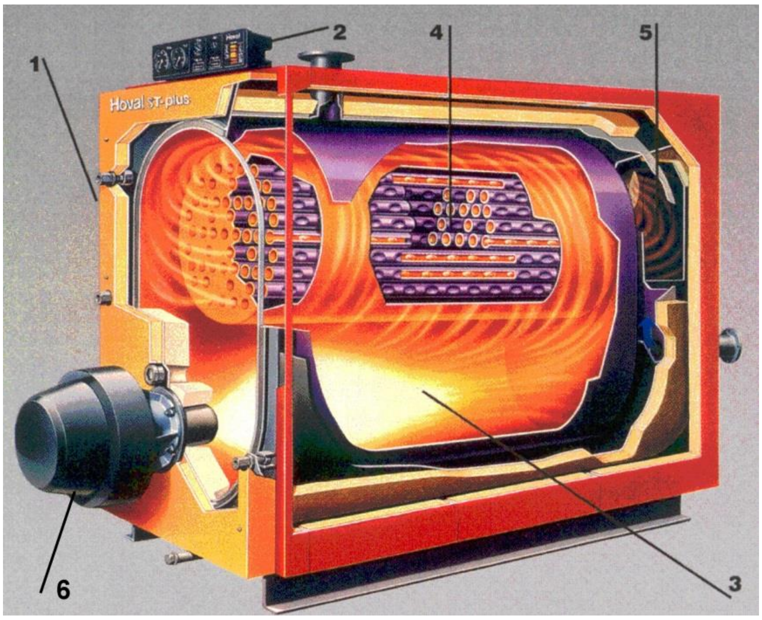

Figure 14. Gas boiler: 1 - body, 2 - control panel, 3 - swirl flame, 4 - flame heat exchanger, 5 - exhaust gas outlet, 6 - gas burner.

Source: Hoval sp. z o.o., 2012.

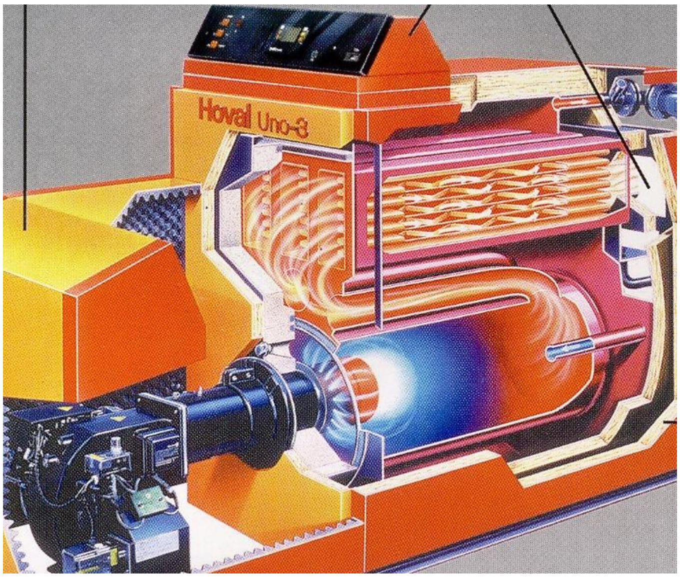

Figure 15. Gas boiler: 1 - body, 2 - control panel, 3 - swirl flame, 4 - heat exchanger.

Source: Hoval sp. z o.o., 2012.

As in solid fuel reactors, these reactors also have a problem with heat exchange efficiency. Gas radiation is negligible and practically negligible. Therefore, the entire energy flow is transferred through hot exhaust gases to the heat exchanger according to equation (1).

Generating an additional stream of energy emitted by radiation can significantly increase the efficiency of heat exchange in the reaction chamber of the boiler. Design changes are necessary, consisting in introducing a radiator into the reaction chamber, which can be a porous ceramic mass. Figure 16 shows a diagram of a boiler with a radiation combustion chamber for gas fuel. The solution is original and has been granted a patent in the Patent Office of the Republic of Poland (Wójcik, *Radiacyjna komora palenislowa na paliwo gazowe…*).

The gas fuel radiation combustion chamber consists of a **KP** radiant column located in a reaction chamber limited by the internal walls of the boiler. Gas fuel **G** is supplied to the **KM** mixing chamber via the **PG** pipe. At the end of the **PG** pipe there is a swirler **Z**, the task of which is to create turbulence in the gas fuel. At the same time, air flows through the **PP** pipe to the **KM** mixing chamber, previously also introduced into a swirling motion by the **Z** swirlers. The combustible gas **G** and air **P** mix in the **KM** mixing chamber and a fuel-air mixture **PG** is created, which moves to the channel **K**, located centrally in the **KP** radiant column built of a ceramic porous mass **MP** and then moves through the pores in the ceramic porous mass towards its external surface **MPA**, where the homogeneous combustion zone **SH** is located. The surface layer of the ceramic porous mass is heated by the heat generated in the homogeneous combustion zone and, as a result, its temperature increases. The heated external surface **MPA** of the ceramic porous mass **MP** sends thermal radiation energy $\mathbf{Q_r}$ towards the internal surface **PO** of the radiant combustion chamber **RKP**, heating the circulating medium **W**. The hot exhaust gases **S** generated in the homogeneous combustion zone **SH** move towards the channels **KKWC** of the convective heat exchanger **KWC** where they transfer thermal energy to the circulating medium. The cooled exhaust gases accumulate in the combustion chamber **KS** from where they are discharged outside. On the external surface **MPA** of the ceramic porous mass **MP** of the radiant column **KP** there is a heat-resistant steel mesh **SS**, the task of which is to protect the radiant column **KP** against damage in the event of high thermal stresses in the ceramic porous mass **MP**. Such a situation can occur when the radiation atmosphere of the combustion chamber suddenly cools down, e.g. when it is opened and cold air is let into its interior. The **KP** radiant column is fixed in the radiation combustion chamber by means of the lower socket **GD** and the upper socket **GG** thermally insulating it from the convection heat exchanger **KWC**. The holes in the porous mass on its external surface act as miniaturized burners, to which the combustible gas mixture flows through channels inside the ceramic porous mass. The porous mass heated by the miniature flames emits thermal radiation $\mathbf{Q_r}$ causing heating of the circulating medium **W**. Due to the lack of a long flame of combustion of the gas fuel, the volume of the combustion chamber decreases, which increases the amount of energy generated in the unit of the radiation volume of the combustion chamber.

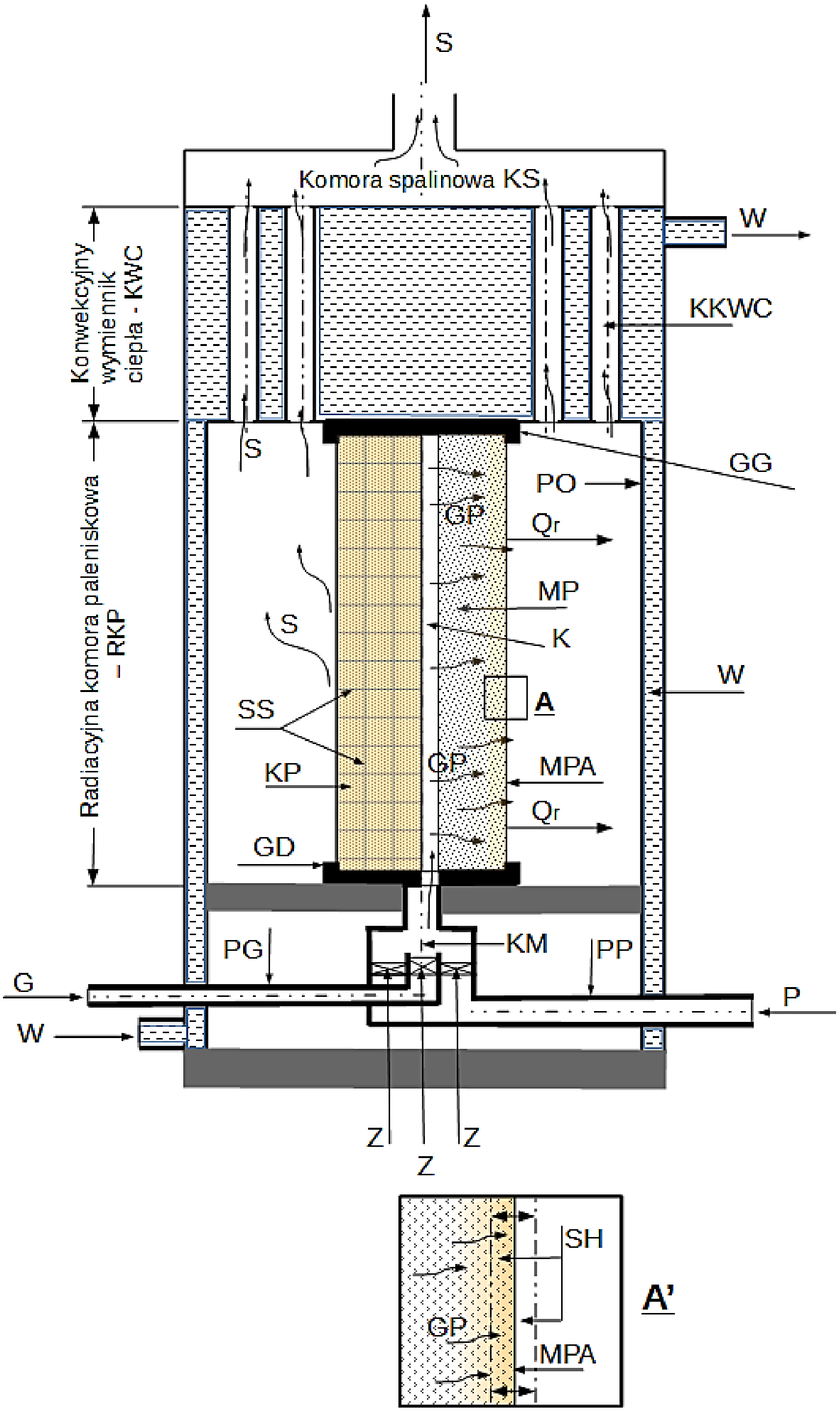

Figure 16. Gas boiler with radiation reaction chamber (description in the text).

Source: Wójcik, *Radiacyjna komora paleniskowa na paliwo gazowe*…

The quality of combustion of the gas fuel increases and the noise that occurs during the operation of the gas burner is eliminated. These improvements are unheard of in conventional solutions. The boiler is designed to operate in automatic mode, maintaining all the rigors regarding the combustion of gas fuels. Flame control and the reliability of the ignition system are particularly important.

The advantage of the proposed solution is the large amount of energy generated in the unit of the radiation volume of the reaction chamber. Kinetic combustion of gas ensures high temperature and purity of exhaust gases. The operation of the device is environmentally friendly - there is no noise, as is the case with gas burners with strong turbulence. The described design is unheard of in previous solutions. The method of operation of the boiler predisposes it to work with advanced automation taking into account the current demand for thermal energy, control of the combustion process in order to determine the composition of the fuel-air mixture, switching the device on and off, controlling and safety elements. Controlling the operation of energy devices is a broad topic and goes beyond the scope of the work.

4. Summary

Solid and gas fuels are the main source of meeting the energy needs of municipalities and individual users. Although fuel prices are constantly rising, the share of these carriers is still dominant. This results not only from the tradition of energy economy based on coal and gas, but mainly from operating costs, which consist of relatively low prices of energy devices. Requirements for fuel combustion efficiency require the use of modern structures with high energy efficiency. It seemed that the previous design solutions of solid and gas fuel reactors are such that it is not possible to significantly improve them. Yes, the control of these devices is constantly being improved, which is the result of the use on an increasingly large scale of industrial processors and detectors with high sensitivity and resistance to temperature, dust, etc.; The new proposed solutions are the next step in the evolution of the design of solid and gas fuel boilers for municipal economy. The emphasis here is on heat exchange by radiation to the surfaces absorbing heat in the reactor. The higher the emitter temperature, the greater the flow of energy radiated to the surfaces radiated in the reactor. This is due to the temperature difference in the fourth powers between the emitter and the exchanger walls. The increase in the prices of energy carriers forces their rational management.

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