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Original Research Article

POSSIBILITY OF IMPROVING AIR DISTRIBUTION AND HEAT FLOW CONDITIONS IN MECHANICAL GRATE FURNACES

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Abstract

One group of plants commonly used for solids combustion are grate furnaces. These furnaces come in numerous design solutions, dedicated to fuels with different properties and plants with different capacities. The use of grate furnaces presents the as-yet unresolved challenge of how to ensure the most favourable air distribution along the length of the grate. The paper proposes a design solution to ensure proper air distribution along the length of the grate. An additional advantage of the proposed solution is the intensification of heat exchange in the furnace, enabling the boiler's circulating medium to be heated more efficiently. Both of the advantages allow an increase in the energy efficiency of the plant and therefore contribute to a reduction in the amount of fuel burned and CO_2 emissions.

Keywords: combustion, mechanical grates, furnace adjustment, furnace retrofit, low-emission combustion, combustion efficiency, air distribution along the grate length

1. GRATE FURNACES

Most highly developed countries are now moving away from fossil fuel combustion and even moving away from biomass combustion. In fact, the only

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solid fuel combustion processes in this group of countries will be those burning waste or, more commonly, waste-based fuels most commonly referred to as RDF (Refuse Derived Fuel). Although, due to the environmental policies implemented in these countries (e.g., implementation of the circular economy in the EU), the importance of these processes will also decline, they will still be an important element of waste management systems for decades to come. An argument in favour of this can be seen in the fact that between 2008 and 2018, around 60 municipal waste-to-energy plants went on-line in European countries and in 2018 there were almost five hundred [1, 2]. It is also worth noting that in Poland, more than a hundred proposals for the construction of this type of plant have been submitted in recent years [1].

Because of its relatively high availability, biomass is still an important source of energy [3, 4]. Approximately 85% of biomass is solid biomass, which is used in more than 95% of combustion processes [5], much of it in grate furnaces [6]. The impact of biomass combustion on the greenhouse effect is considered to be neutral or at least close to neutral. In 2019, biomass was the third largest renewable source of electricity (after hydropower and wind power) [7]. In 2020, 1.93 bcm of firewood was produced globally [7].

Hard coal will also continue to be an important component of the fuel balance in a number of countries for a long time to come. This is evidenced by the fact that there is a significant increase in consumption of this fuel in China and India in 2021 and 2022 [8, 9, 10, 11]. Also, this fuel can be burned in grate furnaces.

Therefore, it can be concluded that solid fuel combustion processes will continue to be a source of heat and electricity for the foreseeable future.

In plants for the thermal recovery of municipal waste, grate furnaces predominate. In individual countries as well as throughout regions of the world, grate furnaces account for approximately 70% of the total number of combustion plant constructions for the thermal utilisation of municipal waste (e.g., in the USA and Canada over the figure is 75%, and in the EU almost 90%) [12, 13]. The waste incineration plants not of this type are equipped with fluidised and rotary furnaces.

In the case of the energetic use of coals (coal and lignite), in large power plants and CHPs, the combustion processes are carried out in pulverised or fluidised bed furnaces [4, 14, 15]. In the case of small and medium-sized facilities (e.g., smaller combined heat and power plants, district and company heating plants, boiler houses), coals are usually burned in grate furnaces [5, 16]. Biomass can also be burned in grate furnaces [4, 5, 6, 17].

There are a large number of grate and grate furnace designs. The differences in designs are mainly due to the fact that the grates and furnace are adapted to the properties of the fuel being burned, the capacity of the furnace and its function (e.g., boiler furnaces, furnace in a water or steam boiler) [3, 6, 13, 15, 17].

The main advantages of grate furnaces include flexibility in terms of the properties of the fuels burned, ease of operation and high reliability. Thus, the various furnace designs usually enable fuels with very different grain sizes and calorific values to be burned. Substances burned in grate furnaces require considerably less preparation than, for example, fluidised furnaces. This is an important consideration for waste incineration and the use of coals of different grades and sorts (e.g., the cheapest on the market) [5, 12]. Even in the absence of developed control and measurement systems and/or a less well-trained crew, there is a relatively limited risk of damage to the plant. Most often, these factors reduce the energy efficiency of the plant. The high reliability of grate furnaces is mainly due to the fact that there is more than two centuries of experience in their design and construction and that a large number of such plants have been put in operation.

The energetic and environmental effects of combustion in hearths of boilers and furnaces depend on a number of factors. Fundamental ones, in addition to structural ones, include:

- parameters of the fuel burned;
- primary air parameters;
- secondary air parameters;
- thickness of the combustible layer;
- speed of grate travel (fuel burning time).

Some of the factors mentioned above are characterised by a number of further parameters. In the case of primary air, these include its total demand, the distribution of the flow along the length of the grate, the temperature of the air, as well as its composition (the air may, for example, be mixed with the flue gases in the process of flue gas recirculation).

These primary air parameters, for the most part, do not pose any major measurement or control problems. The problem, however, is selecting the correct air distribution along the length of the grate [18, 19].

2. BURNING IN GRATE FURNACES

During the combustion of fuels on the mechanical grates, the following sub-processes take place along the length of the grate: drying, combustion of degassing products and gasification, and afterburning of biochar. It should be noted that there is often an overlap between these processes (different processes take place in a given longitudinal cross-section of grate and fuel, at different heights of the fuel layer and above it). This results in a change in fuel quantity and quality along the length of the grate. Each of the processes mentioned also has different, often highly variable air requirements. The highest airflow is required for the combustion of the degassing and gasification products, while a much lower airflow is required for the afterburning of biochar. With normal, continuous operation of the furnace chamber, all processes run simultaneously. Each of these sub-processes requires, among other things, a different amount of primary air [6, 13, 15]. The optimum amount of air required to supply each sub-process is further influenced by the thickness of the fuel layer and its properties. In addition, as the rate of grate travel (or fuel travel on the grate – depending on the type of grate) changes, the locations of the individual processes, shift along the length of the grate [16, 18].

In addition, different flame lengths and different flue gas temperatures and compositions are obtained in the various sub-processes. The greatest flame length and flue gas temperature occurs in the sub-process of combustion of degassing and gasification products. The shortest flames occur in the afterburning of biochar. These conditions together with the shape of the furnace determine the temperature of the flue gases and the heat transfer by radiation and convection between the inner surface of the walls bounding the furnace chamber and the surface of the fuel burned on the grate.

In order to be able to control the amount of primary air along the length of the mechanical grate, a zonal regulation of the air supply is carried out. Depending on the design, the space under the grate is divided into several or over a dozen zones. The design of the grate and the combustion chamber allow different primary airflows to be supplied to the individual zones. This is most often done by means of sector air boxes.

The main problem with regulating the amount of air supplied to the different zones arises from not knowing the curve describing the most favourable air distribution along the length of the grate for a given fuel and furnace and its output. In the literature, only qualitative information on the variation of air demand along the length of the grate can be found, without a description to enable a more detailed characterisation [16, 19].

Another problem arises from the difficulty of assessing whether the amount of air supplied to a zone is optimal or close to it. Most often, with boilers and industrial furnaces, the measurement of flue gas composition (or only the measurement of O_2 and/or CO_2 concentrations) is carried out at a very limited number of points, and often only at one. This point, in turn, is not infrequently located at the outlet of the flue gas from the furnace or indeed the entire plant. In such a case, the measurement results only allow an assessment of the correctness of the overall process and do not provide information on the possibility of rapid improvement. Such improvement is only possible by changing the settings of the control parameters by a process of trial and error. Taking into account the fact that the performance of the plant and the properties of the fuel being burned change, this results in the need to frequently change the control parameters and to operate the furnace for long periods of time under conditions that differ significantly from reasonable parameters. The exception to this is furnaces built into municipal waste incineration facilities. In their case, the number of measuring points measuring the most important (for reasons of combustion regulation) components of the flue gas (i.e., CO, CO_2 and/or O_2) and temperature is relatively large. However, even for these plants, due to the turbulent nature of the process and the often considerable size of the combustion chamber, regulation is difficult.

Attempts to solve this problem have been presented in numerous publications [12, 14, 17, 19] and patent applications [20, 21, 22, 23].

Figure 1 shows one possible grate furnace arrangement, with the design features given above. It is a furnace fitted with a mechanical band (flat) grate. This type of furnace is one of the relatively widespread mechanical grate furnace designs. Furnaces of this type are still the most common mechanical furnace designs found in Poland. However, it is important to note that currently, due to environmental policies and the associated restrictions on coal burning, the number of these furnaces is being reduced. In the remainder of the text, the figures given in brackets correspond to the designations given in Figures 1 and 2.

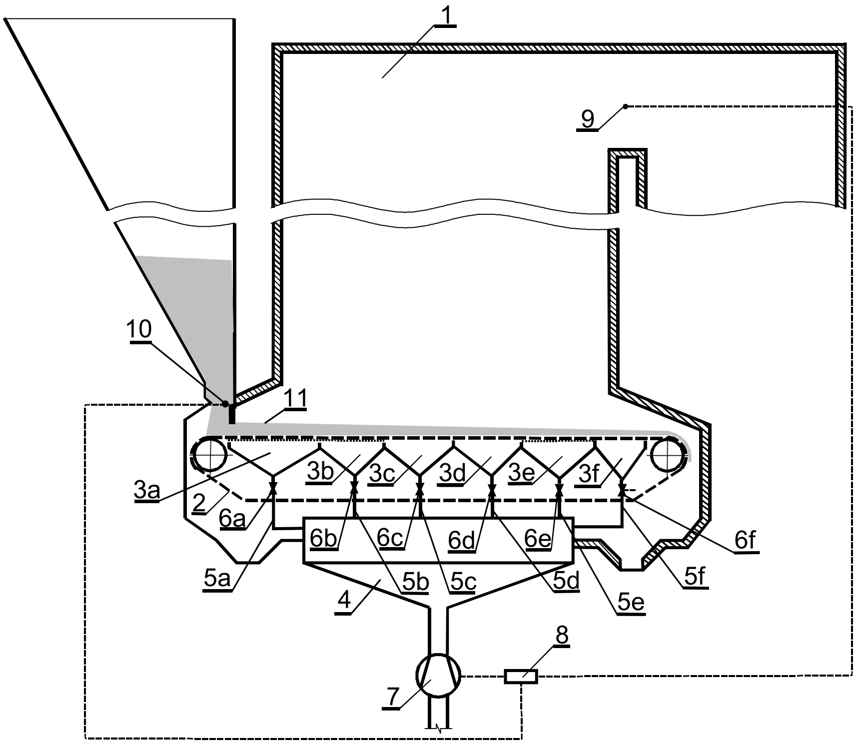

Fig. 1. Diagram of a longitudinal cross-section of a furnace with a mechanical belt grate: 1 – furnace chamber; 2 – grate; 3a, 3b, 3c, 3d, 3e, 3f – sector air boxes; 4 – manifold air box; 5a, 5b, 5c, 5d, 5e, 5f – pipelines; 6a, 6b, 6c, 6d, 6e, 6f – regulation valves; 7 – fan; 8 – regulator; 9 – central sensor; 10 – fuel feed quantity regulator; 11 – fuel

Figure 1 shows schematically a longitudinal cross-section of a furnace chamber (1) equipped with a mechanical flat grate (2) and one flue gas composition measurement system (9). The flue gas composition measurement system is located at the exhaust outlet of the combustion chamber. In addition, the figure shows a manifold air box (4) which is connected by pipelines (5a, 5b, 5c, 5d, 5e, 5f) fitted with control valves (6a, 6b, 6c, 6d, 6e, 6f) to the sector air boxes (3a, 3b, 3c, 3d, 3e, 3f). In addition, the manifold air box is connected to the fan. The signals from the flue gas measurement system, after processing, are used to regulate the fan performance. Fan performance is also influenced by signals from the system measuring the amount of fuel fed.

Due to problems in identifying and properly regulating the distribution of the primary airflow fed along the grate length, a new solution was proposed. This solution is discussed in the next chapter.

3. PROPOSAL FOR A SOLUTION TO IMPROVE THE REGULATION OF THE AIR VOLUME ALONG THE LENGTH OF THE GRATE AND TO INTENSIFY THE HEAT EXCHANGE

The furnace shown in Figure 1, due to its relatively uncomplicated design, allows a simple way to present the proposed solution for retrofitting grate furnaces. Therefore, the essence of the proposed solution is discussed using an example of this type of construction. It should be noted that the proposed solution can also be applied to a number of furnaces equipped with other types of mechanical grates.

The idea behind the proposed solution is shown in Figure 2. In terms of construction, the solution consists of fitting baffles (12a, 12b, 12c, 12d) to the side walls of the furnace chamber in the furnace (e.g. as shown in Fig. 1), at the height of the theoretically highest fuel layer thickness in a given location (11). The baffles are located transverse to the grate. Thus, the width of the baffles is at least equal to the width of the furnace chamber. The baffles form channels to allow the flue gases to flow away from part of the surface of the fuel layer. The layout of the baffles corresponds to the subdivision of the space under the grate formed by the sector air boxes (3a, 3b, 3c, 3d). The height of the baffles should be at least equal to the average flame length obtained when burning the fuel in the duct. At the exit of the flue gas from each duct, at least one sensor is placed to measure the component or components of the flue gas (15a, 15b, 15c, 15d). Once processed, the signals from this sensor control the settings of the valves regulating the air supply to the individual sector air boxes (6a, 6b, 6c, 6d).

In Figure 2, the baffle heights decrease in the direction of fuel movement on the grate, but an equal-height version is also acceptable. Baffles may also be formed, in whole or in part, by membrane walls that form part of a fluid heating system (e.g., water, steam, air), or the superheating of steam.

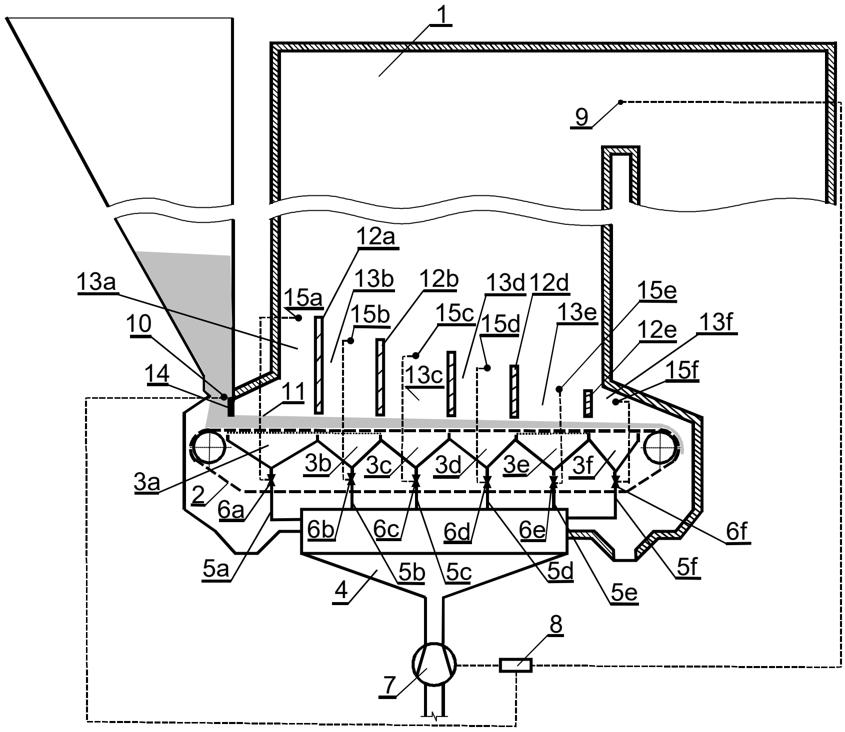

Fig. 2. Diagram of a longitudinal cross-section of a furnace with a mechanical belt grate with an integrated system to improve air distribution along the length of the grate: 1 – furnace chamber; 2 – grate; 3a, 3b, 3c, 3d – sector air boxes; 4 – manifold air box; 5a, 5b, 5c, 5d, 5e, 5f – pipelines; 6a, 6b, 6c, 6d, 6e, 6f – regulation valves; 7 – fan; 8 – regulator; 9 – central sensor; 10 – fuel feed quantity regulator; 11 – fuel; 12a, 12b, 12c, 12d, 12e – baffles; 13a, 13b, 13c, 13d, 13e, 13f – channels; 14 – front chamber wall; 15a, 15b, 15c, 15d – sensors to measure the component or components of the gas.

The proposed solution allows the most favourable air distribution along the length of the grate to be determined and implemented. For optimum separation, the determination of optimum values for excess air ratios is additionally required. This volume is a function of the fuel composition and combustion conditions. As a result of the installation of the baffles (12a, 12b, 12c, 12d, 12e) and the regulation system used (consisting, among other things, of sensors: 15a, 15b, 15c, 15d, 15e, 15f and control valves 6a, 6b, 6c, 6d, 6e, 6f), it is possible to supply the correct amount of air to each zone. This in turn allows the correct value of the total excess air ratio (for the overall combustion process) to be achieved. This value should be lower than that possible when operating a boiler without this system. This, in turn, should translate into an increase in the energy efficiency of the plant (e.g., the boiler) and enable easier and auto-thermal combustion of some of the low-calorific fuels.

It is important to note that the controller 8 should be equipped with or work in conjunction with a programmable central unit to automate the control of the furnace regulation settings. This is due to the fact that a relatively large number of measured parameters are included in the regulation. Otherwise, it will require constant supervision of the plant operator. This can result in: slower responses to changes in the combustion process taking place, as well as differing regulation efficiency (due to differences in staff skills).

An important feature of the proposed solution is that, in order to ensure proper air distribution, it is not necessary to know the composition of the fuel being burned.

The baffle configuration shown allows temperature segregation of the flue gases and promotes the intensification of radiative heat transfer between the fuel surface, the inner walls of the baffles bounding the individual channels and the flue gases flowing through them. An increase in flue gas temperature significantly increases the radiative heat transfer coefficient, which is approximately proportional to the absolute flue gas temperature raised to the third power [24]. The use of air distribution regulation with simultaneous temperature segregation of the flue gases results in:

- an increase in the partial pressure of the radiating gases in the individual ducts as a result of a reduction in excess air volumes, which increases the emissivity and absorptivity of the flue gases,
- promoting lower emissivity and absorption due to a reduction in the thickness of the flue gas layer.

The realisation of the combustion process is generally favoured by the increase in the temperature of the top layer of the fuel resulting from temperature segregation of the flue gas.. In addition, an improvement in the heat transfer conditions in the grate furnace is achieved by replacing the almost flat surface of the fuel on the grate with a surface having a concavity formed by the flue gas ducts, a phenomenon known as the Eckert-Surinov effect [24].

The baffles do not need to be installed over each edge of the sector air boxes. In particular, this applies to the initial length of the grate. The larger volume of the first zone, which includes, in addition to the drying sub-process, the degassing and combustion sub-process of the process gases, enables better heating of the fuel in the drying zone.

As already stated, the installation of baffles allows for better regulation of air distribution, resulting in complete and total combustion of the fuel, thus reducing emissions such as CO, benzopyrene and soot. The proposed solution also makes it possible to improve the regulation of the combustion process due to the achievement of other specific technological objectives, e.g., the reduction of NO_x

emissions (as a result of the better control of the proportion of oxygen in the atmosphere of the reacting gases).

The disadvantages of the solution presented include the need to carry out extensive retrofitting work, as well as the proper construction of baffles. This is because the baffles are exposed to relatively high temperatures and an aggressive environment (so the baffles will be expensive to make). At the same time, the effect of the installed baffles will diminish, if the furnace is operated frequently, with settings for the thickness of the burning fuel layer significantly thinner than its maximum thickness. Significant pressure differences between the individual ducts will also contribute to the deterioration of the system's performance (there will be sucking up of air between the individual ducts, and turbulence of the flue gases in the upper part of the ducts).

As a result of the proposed solution, it will become more complicated to operate the furnace as a result of the need to programme the system or algorithmise the actions taken by the operator. This process will require a series of combustion tests to gather an appropriate set of data to form the basis for algorithm development and control system programming. The complexity of the furnace design will also result in an increase in the time and cost of carrying out maintenance work.

The proposed solution is the subject of patent application No. P.432320 [WIPO ST 10/C PL432320] of the University of Zielona Góra and the Silesian University of Technology [25].

4. CONCLUSIONS

Solid fuels will continue to be responsible for meeting a significant proportion of humanity's energy needs for decades to come. This applies to coals as well as biomass and waste. The role of coals in highly developed countries is being reduced, but at the same time their consumption continues to increase in poorer countries. Solid biomass combustion is still considered environmentally friendly and climate-neutral in many parts of the world [3, 4]. In the case of waste management, zero landfill management still requires thermal treatment of a few tens of percent of the mass of municipal waste.

One of the basic designs for burning solid fuels are furnaces with mechanical grates. These furnaces dominate municipal waste incineration facilities. They are also among the most frequently chosen designs for burning coal and biomass in medium-capacity plants (most often in boiler plants and small and medium heat and power plants).

One of the main regulation-related issues for mechanical grate furnaces is ensuring proper air distribution along the grate length.

The paper proposes a design solution to solve the above problem.

The proposed solution of installing baffles and a control and measurement system with a regulation system contributes to, among other things:

- limitation of the total excess air ratio;
- improved heat exchange conditions in the combustion chamber;
- improved energy efficiency of the process and reduction in fuel consumption and CO_2 emissions as a result;
- improved fuel combustion conditions, enabling auto-thermal combustion of parts of fuels where this was not previously possible;
- achieving complete and total combustion, thereby contributing to a reduction in pollutant emissions (e.g.: CO, aromatic hydrocarbons, soot) and better fuel burn-up (e.g., in waste incineration plants this is important not only because of the impact on process efficiency, but also because of the burn-up rate, which determines the acceptability of the process).

In addition, the proposed solution allows the furnace operation to be regulated, due to the achievement of other specific technological objectives, such as the reduction of NO_x emissions.

An important feature of the proposed solution is that, in order to ensure proper air distribution along the grate length, it is not necessary to know the composition of the fuel being burned.

The main disadvantages of the proposed solution include the need for significant intervention in the furnace structure and the cost of doing so. At the same time, the benefits of implementing the proposed solution will be limited, in the case of certain furnace operating conditions (e.g., a fuel layer that is too thin in relation to the installation height of the baffles above the grate, or a pressure difference between the individual channels that is too high). As a result of the proposed solution, the operation of the furnace will also become more complicated due to the need to control the system and to carry out maintenance work. At the same time, it should be noted that the control of the system requires the installation of a programmable central unit and/or places increased demands on the operation of the furnace.

The authors did not have any information on the operational effects of the proposed technical solution. This is the main reason for the lack of detailed economic analysis. It should be noted that the hardware outlays largely do not depend on the performance of the device (the cost of the central unit, software and control and measurement equipment). Therefore, the presented proposal is dedicated to high-performance grate furnaces.

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