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By Using Burners For Pulse Combustion To Greater Efficiency And Reduce Emissions Of Solid Fuel Boilers

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ABSTRACT: *Decarbonization of the thermal energy and industrial sector is a necessary, current and demanding process. In addition to the requirement for a continuous reduction in the use of fossil fuels by the substitution of renewable and alternative fuels, this process is simultaneously accompanied by requirements for improving the efficiency of the conversion of primary energy from fuel, but also by corresponding limitations and unknowns. These unknowns are particularly expressed in many different cases where the burning of low-value solid fuels is a fundamental process in this conversion - a very similar remark is also valid in cases of fuel burning with a marked change in quality in a short time. It is imperative in all cases, even in the mentioned cases, to establish a stable, highly efficient and low-waste combustion. The possibility of establishing such an energetically, economically and environmentally acceptable combustion process is a function of a number of variables, of which the collective properties of the fuel, including the ash from that fuel, are dominant in this sense. A positive contribution to all of this is also possible through the development and application of existing and/or new combustion techniques. With the motive of a scientific contribution to the energy transition, improving the efficiency of the combustion process, and thus the overall plant, as reflected in the reduction of flue gas emissions into the environment, a set of laboratory studies of the characteristics of pulse combustion of gaseous fuel in a modular burner with aerodynamic valves and cooled by water was carried out. In particular, a simple and robust burner without moving parts has been developed, which can be used in energy and industrial furnaces, i.e. boilers. The obtained results and findings suggest that the burner in question can be used as an auxiliary burner in the combustion chamber of the mentioned boilers with the aim of additional turbulization of the combustion atmosphere and thus increasing the degree of efficiency of conversion of chemical energy from fuel to thermal energy. In addition, the burner can also be used as a device for generating high-frequency pressure waves and significant sound energy in the zones of the combustion chamber or convective channels of flue gases with the aim of preventing the formation or removal of already formed ash deposits from the heating surfaces in the boiler. Each of these possible applications of the burner would result in more intense heat transfer in the boiler, reduction of basic fuel consumption, increase in operational and time availability of the plant, and reduction of environmental load with undesirable and polluting substances, especially* CO_2 *and* NO_x*. This paper presents an extract from the results obtained during extensive laboratory research on the dependence of the process performance on the geometry and operating conditions of the burner. The analysis and suggestions for the possible application of the subject burner as an auxiliary in the combustion chamber and/or as a tool for cleaning heating surfaces was performed on the basis of the results obtained by applying the burner to the boiler model.*

KEYWORDS: *boilers, combustor, furnace, pulse combustion, pulsating pressure*

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I. INTRODUCTION

The conversion of primary energy from fossil fuels, in the majority of cases even today, begins with the combustion process. These combustion processes, apart from being accompanied by a series of problems of a technical-technological nature, are inevitably and very significant producers of undesirable and polluting substances: CO_2, CO, NO_x and SO_2. This is especially pronounced in the case of combustion fuels, which are dirty, low heating value and poor reactivity fuels, primarily coal. Therefore, in the current era, decarbonization and improving the efficiency of the energy and industrial sectors are a constant and necessary imperative. In this sense, there are increasingly strict requirements that are placed on the mentioned sectors of the economy, which lead to at least partial substitution of fossil fuels with renewable and/or alternative fuels. Therefore, this need is particularly pronounced in the field of thermal energy and industry, which is based on the use of low heating value and poor reactivity coal as a carrier of primary energy, but also in cases of burning other solid fuels, e.g. during the co-firing of these coals with biomass or fuel derived from municipal waste with a marked change in quality. Due to the pronounced complexity of the implementation, primarily due to the accompanying unknowns in the unfolding of the overall process, complex and demanding technical and economic operations on existing energy plants, this energy transition from fossil to renewable sources is happening gradually, [1-8]. Namely, it is primarily necessary to ensure the stability and independence of the energy or industrial system at every moment of operation. According to the dynamics with which it was projected, the transition process will continue for some time, especially in countries that have yet to enter the process on a larger scale, roughly two to three decades. In order for fossil fuels to be replaced in the foreseeable future and the transition of the energy and industrial sectors to be carried out in a sustainable manner, the focus of research is on environmentally acceptable fuels with further improvement of the efficiency of primary energy use.

The possibility of establishing such an energetically, economically and environmentally acceptable combustion process is a function of a number of variables, of which the collective properties of the fuel, including the properties of the ash from that fuel, are dominant in that sense, [9-12]. A positive contribution to all this is also possible through the development and application of existing and/or completely new combustion techniques. The development of such combustion technologies belongs to the new so-called clean coal technologies, thus providing a global scientific contribution aimed at mitigating climate change, [13-14], including local and national level contributions to a cleaner environment, as defined by the goals of the United Nations Agenda for Sustainable Development 2030, [15] , and the Green Agenda of the EU and the Balkans, [16]. And the goals of the European Union (EU) are clear and defined by the European Green Deal initiative, [17], which is a commitment to complete climate neutrality by 2050, which was also confirmed in the report of the International Energy Agency for last year, [18-20]. At the same time, due to competition and increasingly strict requirements regarding the overall reduction of the negative impact on the environment, the coal-based energy and industrial sector are forced to follow and adopt new technologies. Therefore, in addition to a higher degree of utilization, these plants should also be classified as plants with a significantly lower burden on the environment based on undesirable and polluting components in the flue gases. At the same time, on a smaller scale, this prolongs the use of fossil fuels for a certain period of time in which a further alternative or replacement for fossil fuels with other sources of energy should be found. New technologies, "clean coal technologies" (CCT), also include technologies with additional renewable and/or alternative fuel, e.g. co-firing with waste woody and agricultural biomass (residues from felling and wood processing, small branches, sawdust, straw, stalks of agricultural crops after harvesting and harvesting, etc.), fuel originating from municipal and industrial waste (fuels labeled RDF - Refuse Derived Fuel and SRF - Solid Recovered Fuel and sewage sludge and the like). In the developed countries of the world, in addition to the use of biomass, the burning of waste for the purpose of obtaining electrical and/or thermal energy with minimal negative impact on the environment is widely used [21-22]. Namely, the partial use of biomass replaces a certain amount of coal in the production of electricity and heat, reduces the amount of undesirable and harmful gases, primarily CO_2, because about 98% of the total CO_2 emission at the world level originates from the burning of fossil fuels, and 30% to 40 % of that CO_2 emission is caused by burning coal, [1-2]. Recently, each year, burning coal produces more than 14 billion tons of carbon dioxide (CO_2), which is released into the atmosphere, of which this CO_2 is mostly generated during the production of electricity, [4], [23]. In the paper [24], it is stated that the negative greenhouse effect is mainly contributed by CO_2 with a share of about 55%. In this regard, research into the characteristics of the combustion of solid fuels, including coal, is currently being carried out all over the world, and it is aimed both at the possibility of improving efficiency and reducing the level of emissions of flue gas components and trace elements, as well as at further knowledge of the behavior of ash from the fuel (or fuel mix) in a given process - evaluation of the tendency of ash in a given process to soiling, filling and slagging and the possibility of corrosion of the heating surfaces in the combustion chamber, i.e. the boiler during the thus established combustion process of the given fuel mix. These facts continuously give a strong impetus to the research of combustion technologies of different fuels with a more favorable effect on the environment, and especially with the aim of achieving higher energy efficiency compared to the conventional technologies. In addition to the mentioned technical aspects of energy plants, they are equally important economically, because the future operation of these plants depends on each of them, and thus their impact on the environment.

For all the reasons mentioned, it is necessary to develop both new and improve already existing or insufficiently researched methods of high-efficiency and low-waste combustion, especially in cases, as already stated, of using low-value solid fuels, [25]. Significant opportunities in this regard are provided by the pulse combustion procedure, which, according to its performance, is classified in the group of low-waste and highly efficient procedures for the energy conversion of chemical energy contained in the fuel. In addition, the phenomenon of pulse combustion can be usefully applied as an auxiliary tool on existing energy and other boilers of medium and high power, as a device for preventing the formation and cleaning the outside of already dirty heating surfaces. In addition, also in the combustion furnace of boilers, the mixing of reagents and the turbulence of the combustion atmosphere can be used for additional improvement with the aim of increasing the combustion efficiency, [26-27]. The main reasons for the still insufficiently widespread application of the process are the intense noise, which is almost inevitably generated during pulse combustion. With the motive of a scientific contribution to the energy transition and especially to improve the efficiency of the combustion process, and thus the overall plant, as reflected in the reduction of flue gas emissions into the environment, the design development of a modular burner for pulse combustion with aerodynamic valves and cooled by water was first carried out. Then, for the burner established in this way, a set of laboratory studies of the characteristics of the burner and pulse combustion of gaseous fuel (LPG - Liquified Petroleum Gas) was performed. Part of those research results is given in the continuation of the paper, with an emphasis on the geometric forms of the burner with the best performance in terms of the proposed application of the burner, [28], [29-35].

II. PRINCIPLE OF OPERATION, EXPERIMENTAL LINE AND MEASURING EQUIPMENT

Principle of operation: Basically, a pulse combustion burner consists of a cylindrical combustion chamber (C), tubular air inlets (AI) and a resonance pipe (RP). During burner operation, an asymmetric flow of working media (reactants, fuel/gas and air) along the combustion chamber is established thanks primarily to mechanical or, in this particular case, aerodynamic valves (AV, 4 of them) placed on the air intake side. Namely, during the expansion of the generated flue gases, during and after combustion, which is as a rule interrupted - intermittently, the flue gases dominantly expand through the resonance tube further through the elements of the system or directly into the environment, Fig. 1-left, [28, 35]. Analogously, in the same picture, on the right, the theoretical working cycle of a burner for pulse combustion is shown in the p-v diagram.

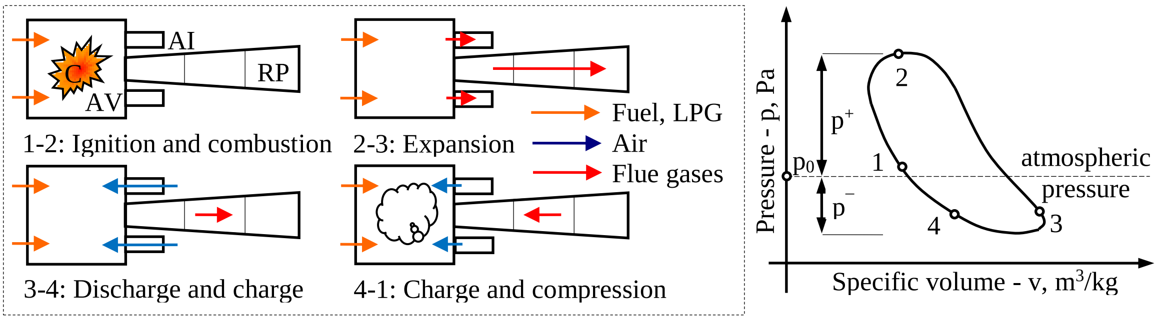

Figure 1. Schematic representation of the characteristic phases of burner operation with media flows on (left), Theoretical operating cycle of a burner for pulse combustion in the p-v diagram (right), [28], [35], [36]

The dominant expansion of flue gases through the resonant pipe, in the case of the application of aerodynamic valves for air intake, is the result of a significantly higher resistance to the flow from the chamber compared to the resistance to the flow in the opposite direction - the flow of fresh air into the combustion chamber. As a result, a negative pressure is generated in the combustion chamber during the expansion of flue gases, thanks to which the chamber is filled with a new fresh portion of combustion air through the air inlets. All this time, fuel/gas is continuously introduced into the chamber in a certain way - in this way, the next portion of a fresh mixture of reagents is formed. In addition to starting the burner, there is a spontaneous ignition of the newly formed fresh mixture of reagents and a cyclical repetition of the process. Therefore, any ignition of the newly formed reagent mixture occurs due to the return flow of part of the hot flue gases from the resonant tube into the combustion chamber and/or due to the contact of the newly formed reagent mixture with the hot walls of the combustion chamber. Therefore, no external process support is required in this case, except when the burner is put into operation. Thus, there is no need for a pressure fan for supplying fresh air to the combustion chamber and for a suction fan for dispatching flue gases from the burner, because the generation of force required for both air intake and flue gas suppression is ensured by the very nature of the process, [28], [37-39].

Compared to conventional combustion at constant pressure in the combustion chamber/furnace, pulse combustion is characterized by a qualitative breakthrough in the following::

- *More efficient combustion* which is a consequence of intense mixing of reactants caused by pulsations. In this way, a more complete conversion of chemical energy from fuel to heat is achieved even in a very compact combustion chamber/furnace. This advantage comes to the fore when there is a greater change in heat load and working conditions, and all of this contributes to an increase in the plant's energy efficiency.

- *The suction and pressure effect established by pulsations* which is achieved by the appropriate construction of burner elements that ensure a directed flow of flue gases. In these conditions of operation of the burner, there is no need for suction and discharge fans, which significantly saves on the own consumption of the system or plant.
- *Reducing the emission of nitrogen oxides*, because the constant pulsation of flue gases achieves an effect similar to the recirculation of flue gases in the furnace, which is known to be a suitable, recognized and effective method for lowering the temperature in the combustion zone. This directly reduces NO_x emissions - the process is intermittent and high-frequency, so the retention time of reagents and products in high and higher temperature zones is very short (a few milliseconds), Fig. 2, [28], [35], [36].

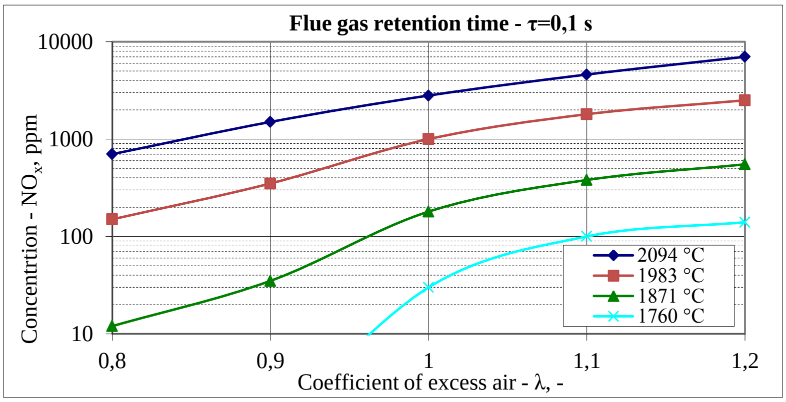

Figure 2. NOx emission during the combustion of natural gas, [28]

- *More flexible operation* because due to intensive mixing of reagents, it is possible to change the thermal load of the burner in a wider range.
- *More efficient heat transfer* as a result of the pulse flow of flue gases, i.e. a better heat transfer coefficient on the side of the heat transmitter, which results in the need for a smaller heating surface and a lower investment, and additionally enables the use of at least part of the latent heat of moisture from the flue gases, i.e. the energy from the fuel that is in this way, it approaches the use of the upper thermal power of the fuel. More efficient heat transfer also means the possibility of installing cheaper exchangers due to their compactness.
- *Self-cleaning of the heating surfaces* from the side of the flue gases occurs as a consequence of the high-frequency and oscillatory flow of flue gases around the heating surfaces, but at the same time as a result of the inevitable generation of a significant level of sound energy. This clearly further intensifies the transfer of heat to the receiver, which also achieves savings in primary fuel, improves the energy and time availability of the plant, and reduces the load on the environment with undesirable and polluting components, [28], [35], [40-44].

Experimental line: A schematic representation of the laboratory line of a burner for pulse combustion of gaseous fuel with aerodynamic valves on the side of the intake of combustion air and cooled by water is given in Fig. 3. The key elements are marked in the Fig. 3 as well as the corresponding measuring points, [28], [35].

The water-cooled pulse combustion burner is a constructive modification of the air-cooled burner that was previously designed and researched at the University of Sarajevo - Faculty of Mechanical Engineering, [36], [45-46].
This burner, cooled by water, with mounted measuring equipment and connected to a pipe for exhausting flue gases into the environment, in which a tubular heat exchanger is also incorporated, is shown in Fig. 4-left, while Fig. 4-right shows a burner applied to a boiler model, from the side in the area of the boiler furnace.

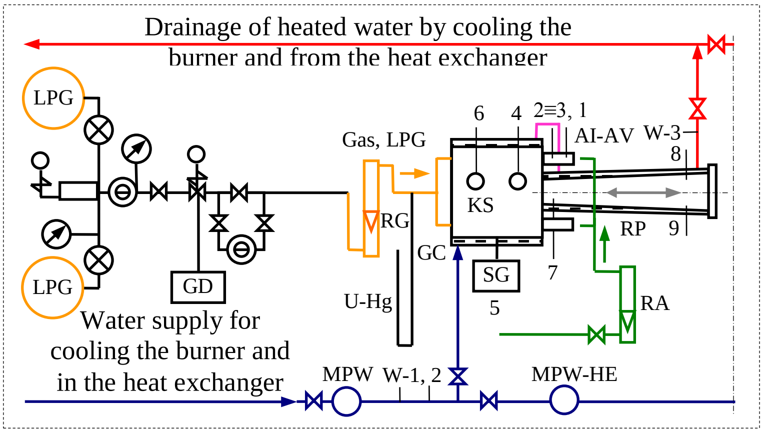

Figure 3. Scheme of a laboratory line of a burner for pulse combustion of gaseous fuel with aerodynamic valves on the side of the intake of combustion air and cooled by water in the zone of the furnace and basic resonance tubes: LPG - Liquified Petroleum Gas, RG - Rotameter for gas flow measurement, Hg - "U" pressure gauge with mercury, SG - Electric spark generator, RA - Rotameter for air flow measurement, MPW - Total water flow meter, MP-HE - Water flow meter through the heat exchanger, 1÷9 - Measuring points for temperature, pressure and composition analysis of flue gases on the burner, W-1÷W-3 - Measuring points on the water line for cooling the burner, GC - Gas supply collector, GD - Gas leakage detector, [25], [35].

Figure 4. A burner for pulse combustion cooled by water with mounted measuring equipment and connected to the pipe for exhausting flue gases into the environment - left, i.e. applied to the side of the boiler model in the combustion zone - right; Pulse Combustion Laboratory, University of Sarajevo - Faculty of Mechanical Engineering, [28], [35].

One of the set goals of the research was to obtain results on the basis of which the possibility of applying burners for pulse combustion on high power boilers can be assessed. In this regard, this paper also presents the results of research related to two possibilities of application of this burner on high power boilers in terms of:

a) Applications of burners as auxiliary, the commissioning of which would, occasionally and if necessary, intensify the mixing of reactants by additional turbulence of the combustion atmosphere, and thus improve the combustion of base fuel in the furnace - especially in the combustion of low heating value and poor reactive fuels, and
b) Applications of burners as devices for preventing the formation and cleaning of already formed deposits on the outside of boiler heating surfaces, especially in the convective part, in which coal is burned whose mineral part is prone to slagging/fouling of boilers surface.

In terms of researching previous possibilities of burner application on high power boilers, the subject burner is mounted on a laboratory model of the boiler that allows research from both desired aspects of burner application (connection I, side), Fig. 5, [28], [35]:

a) application of burners in the furnace zone - the pipe bundle is then in the upper position,
b) application of burners in the convective part of the boiler - the pipe bundle is then in the lower position.

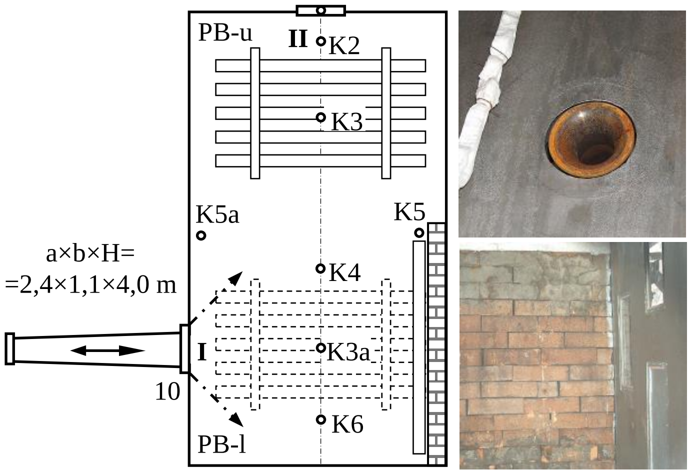

Figure 5. Scheme of application of burners for pulse combustion with indication of measuring points, PB - pipe bundle, u - upper, l - lower. The upper picture with the diagram shows the output of the resonant tube of the burner in the plane of the side of the boiler model, and the lower one a classic brick wall, [28], [35].

For different geometric shapes of burners and different thermal loads or burner power, appropriate process parameters such as propagation, deformation and intensity of pressure pulsations in the free space of the boiler model and inside the pipe register and the influence of pulse flue gas flow were monitored, Fig. 5.

The continuation of the scheme of the experimental line of the burner for pulse combustion from Fig. 3, in the variant when the burner is connected to the flue gas exhaust pipe in which the heat exchanger is installed, is shown in Fig. 6-left. Such a setup of the line enables research and analysis of heat transfer in the pulse flow of flue gases. At the same time, the design of the heat exchanger is with a tube bundle, one passage of working media through the exchanger and with the possibility of choosing the flow of these working fluids: co-current or counter-current flow. The actual appearance of the tube heat exchanger with measuring equipment for detecting changes in dynamic pressure and temperature of pulse flue gases is given in Fig. 6-right.

A total of 96 burners of different geometric shapes were tested during these investigations, which are basically obtained by simple assembly/combination of basic elements of burners of different dimensions, e.g. three volumes of the furnace (2.12÷4.24 dm^3), two lengths and two diameters of the combustion air inlets (150 and 300 mm) and three lengths of resonance tube extensions (1085÷1600 mm).

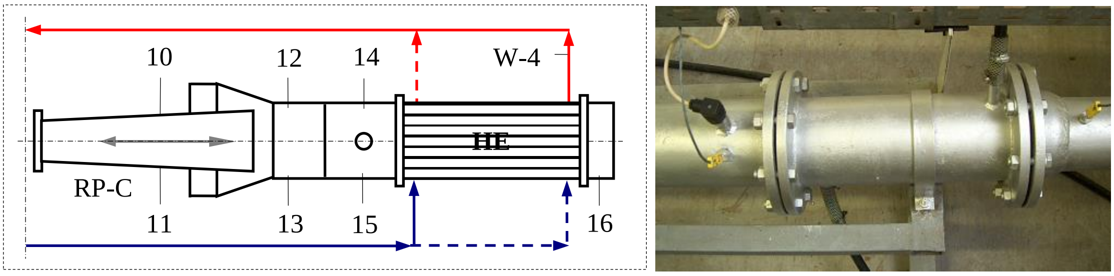

Figure 6. Segment of the laboratory line with measuring points that enables the investigation of heat transfer in the pulse flow of flue gases, RP-C - resonance tube, HE - heat exchanger (left), A heat exchanger mounted in a pipe for the discharge of pulse flue gases - the choice of the flow of working fluids is enabled; Pulse Combustion Laboratory, University of Sarajevo - Faculty of Mechanical Engineering (right), [28], [35].

During the research, it turned out that, in relation to the total number of burner forms investigated, a significant number of those forms do not allow the establishment of an automatic (*self-pumping*) mode - operation without any external support, Fig. 7.

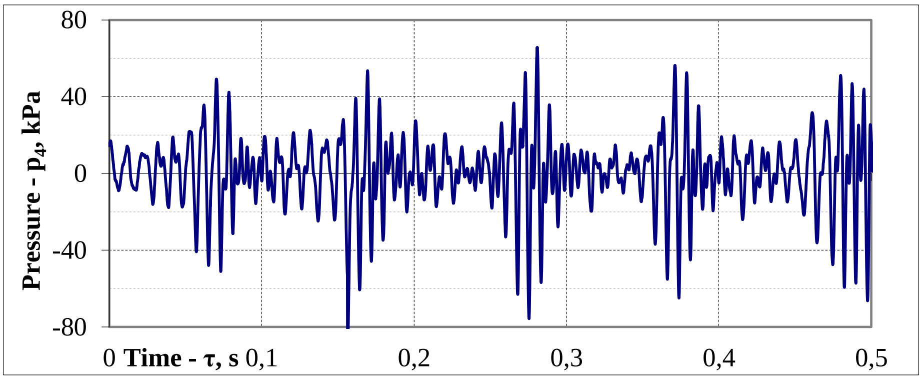

Figure 7. An example of unstable operation of the burner as a result of mismatched geometry: pressure change in the furnace, [28], [35].

Therefore, the research results are given here only for those geometric forms that enable this - an example of such a self-pumping mode of operation of the burner, Fig. 8. Such stable operation of the burner implies operation without any external support to the process: self-ignition of the new reactant mixture is established, there is no forced the supply of air to the combustion chamber nor the forced delivery of the resulting flue gases.

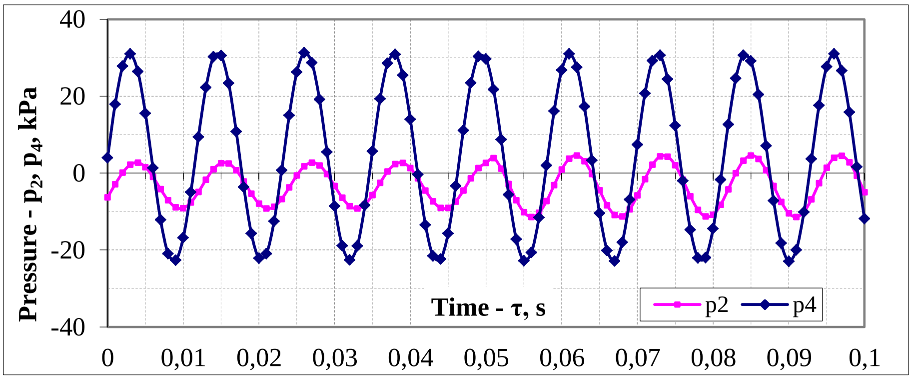

Figure 8. An example of stable, self-pumping burner operation: pressure change in the air inlets and in the furnace, [28], [35].

Measuring equipment: Kistler pressure sensors were used to measure flue gas pressure pulsations: type 601 A and SEN-8700, Crystal CERA-LINE-S, type SEN-8700. Thermocouples of type K (NiCr-Ni) and type J (Cu-CuNi) were used to measure the flue gas temperature, while a flow meter type: ams, (Qn1.5 AH-B) was used to measure the water flow, and gas rotameter Novodirekt, type: C72979, Aalborg, VMRP - 010083, S/N 115-218-1, 0-250 ℓ/min of reference fluid. During the measurement, the acquisition of DEWE-BOOK data, ie DEWESoft software - the software is licensed. The Testo 350XL device was used to analyze the composition of flue gases, [28].

III. RESULTS AND DISCUSSION

An example of the performance of a freely placed burner: As an example of the performance of a burner for pulse combustion, the diagrams in Fig. 9 and 10 are given. These research results always refer to the middle combustion furnace on which short or long air inlets (SAI, LAI) are mounted, i.e. the basic, short, medium or long resonant tube (B, S, M, L). It can be seen that the average temperature in the furnace is always less than 1200 °C, which is one of the essential prerequisites for low NO_x emissions, Fig. 9.

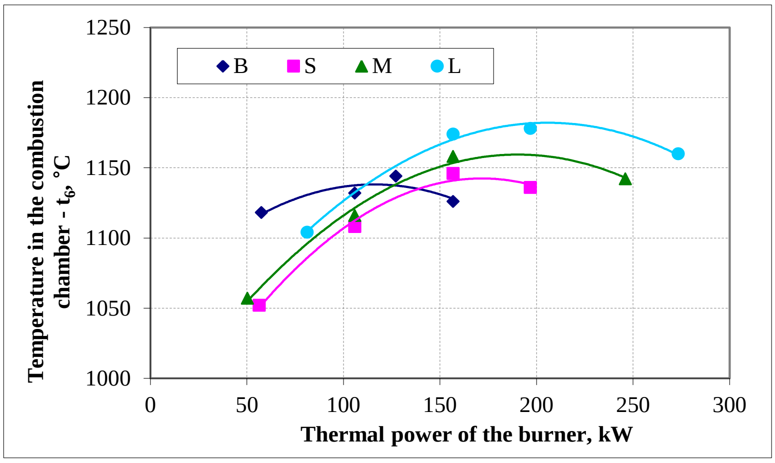

Figure 9. Mean temperature in the combustion furnace as a function of the geometry of the modular burner, [28], [35].

The total pressure deflection and the frequency of the process depend on the length of the combustion air inlet - both shown dependences were obtained at a burner power of about 150 kW and a cooling water flow of 0.4 kg/s, Fig. 10. The maximum flue gas pressure deviation is 80 kPa (long air inlets LAI and long resonant tube L). The process frequency range is quite wide, in this case from 90 to 142 Hz - otherwise, the process frequency, depending on the geometrical configuration of the burners can even go over 180 Hz.

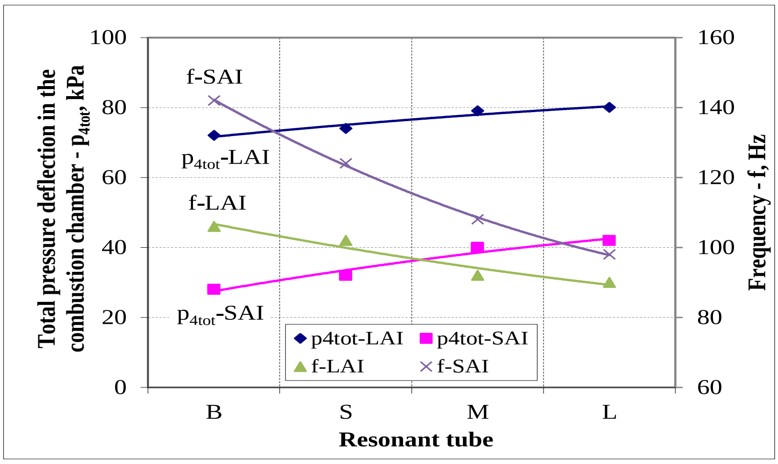

Figure 10. Total pressure deflection in the combustion furnace as a function of modular burner geometry

The pressure pulsations in the combustion chamber of geometric shapes of burners with mounted long air inlets are, in the general case and for the same combustion chamber, generally higher in relation to burners with short air inlets. An example of the structure of pulsating pressure in the furnace (p_4) and the change in oscillation intensity with changing the thermal load of the burner, one of such burners with long air inlets and a cooling water flow of 0.4 kg/s is given in Fig. 11. The geometry of this burner is denoted by code 43 (middle combustion chamber MC, long air inlets for combustion LAI and middle resonant tube M, i.e. form of mark MC-LAI-L), and whose extending-uishing limits or possible operating range are: 50÷246 kW. Additionally, the same figure also shows the total pressure deflection during more intensive cooling of the burner with water (0.60 kg/s compared to 0.40 kg/s), Fig. 11.

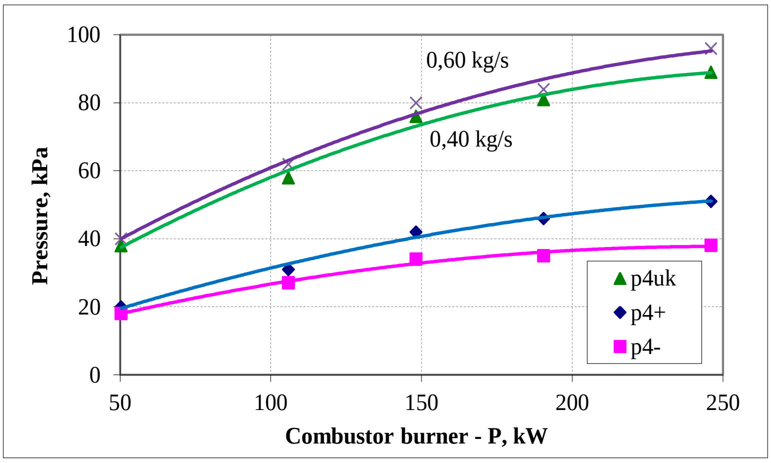

Figure 11. Structure of pulsating pressure in the combustion chamber and change of oscillation intensity with change of burner load; geometry: code 43, cooling water flow: 0.40 and 0.60 kg/s, [28].

Flue gas pressure pulsations when applying a burner to a boiler model: The aim of this set of research was to reach results based on which the possibility of applying a water-cooled pulse combustion burner in power and industrial boilers can be assessed, in terms of the application of burners as auxiliary devices with the role of intensifying the mixing of reagents by additional turbulisation of the combustion atmosphere and thus improving the combustion of the basic fuel in the furnace - especially when burning low-value and weakly reactive solid fuels, or as a device for preventing the formation and cleaning of already formed deposits from the outside of the heating surfaces of those boilers, especially in convective part. In this sense, a burner was mounted on the laboratory model of the boiler via two differently adapted and directed connections: I - side, application of the burner in the combustion chamber zone, and II - upper: application of the burner in the convective part with transverse flow of pulse flue gases on the pipe bundle. At the same time, when applying different geometric forms of the burner and heat load, the intensity of pressure pulsations in the free space of the boiler model and inside the pipe register, as well as the influence of the pulse flow of flue gases and accompanying sound energy on the wall of the boiler model, were monitored and measured - see Fig. 5. Attenuation of pulsations flue gas pressure in the boiler model on the experimental line designed in this way is presented in Fig. 12. The results refer to the geometric shape of the code 43 burner, the thermal power of the burner of 150 and 245 kW, and two different positions of the tube bundle, upper and lower. In addition to the deformation of pressure pulsations inside the boiler model caused by the multiple reflection of waves from a solid surface, a significant reduction in the intensity of those pressure pulsations in the space observed in relation to the values measured at the corresponding measuring points of the burner is also noticeable, Fig. 12.

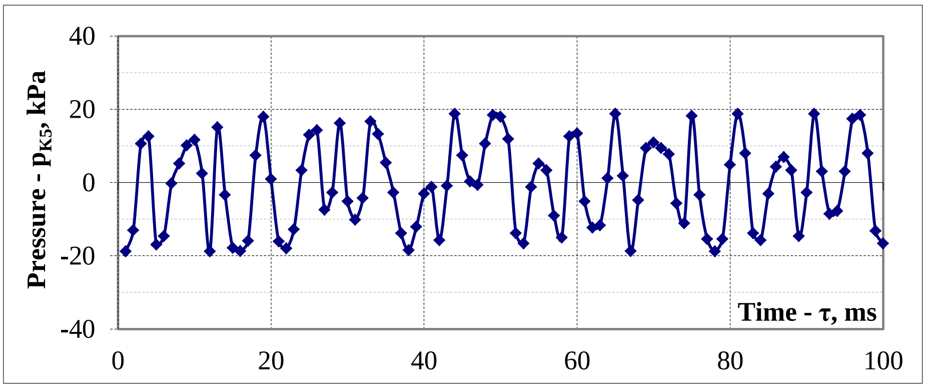

Figure 12. An example of deformation and reduction in the intensity of pressure pulsations in the space of the boiler model, measuring point K5, [28].

It is also evident that pressure pulsations decrease during the propagation of pulsations through the tube bundle in the boiler model - see the values for measuring points K3, K3a and K2 in Fig. 13. In the case of lowering the tube bundle to the lower position (into the combustion chamber of the model, PB-l) it is possible to investigate the change of parameters, primarily the change of pressure, in the case of the longitudinal flow of pulsating flue gases on the pipes of boiler elements and in this way investigate the possibilities of using the burner as a device to prevent the formation and cleaning of already formed deposits on the boiler heating surfaces - [28], [35].

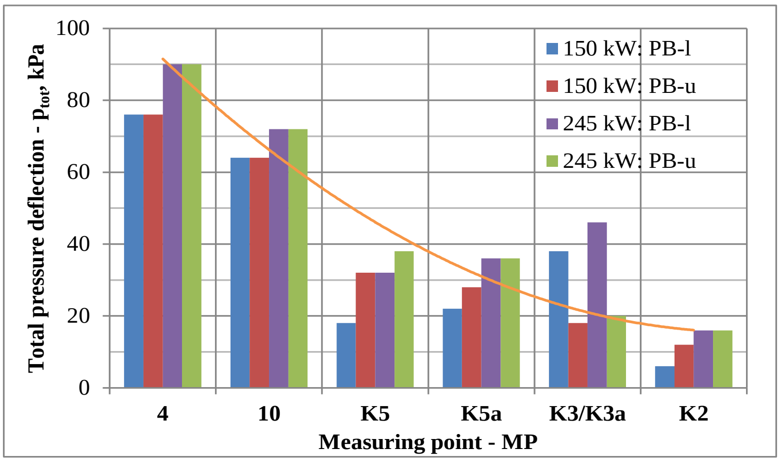

Figure 13. Intensity of pressure pulsations in measuring points in the boiler model at the thermal power of the burner of 150 and 245 kW and the application of the burner from the side of the boiler model (I), tube bundle in the upper (PB-u) and lower position (PB-l) - see also Figure 5.

In Fig. 13, two characteristics of the presented results stand out in particular: smaller values of the total pressure deflection at the measuring points K5, K5a and K2 compared to the values, at the same measuring points, when the tube bundle is in the upper position - this can be explained by a significant weakening of the intensity of pulsations inside the tube bundle - the highest values of the total pressure deflection in the boiler model occur in the middle of the tube bundle, measuring point K3a - here it should be emphasized that the sensor at this measuring point is in the axis of the resonant tube of the burner and about 1.2 m away from its end. Relatively high values of the total pressure pulsation deflection inside the pipe registers of the boiler elements is precisely the desired result considering the intention of using the burner for pulsating combustion cooled by water as a device for cleaning the heating surfaces of the boiler - [28], [35].

The intensity of accompanying noise, of a wide spectrum of wavelengths, generated during the operation of these burners reaches over 130 dB. This significant sound energy can be usefully used. The sound energy emitted from the outlet opening of the resonant tube and introduced into the furnace and/or the convective part of the boiler will additionally contribute both to the effect of intensifying the turbulence of the furnace atmosphere and to the effect of preventing soiling or cleaning already soiled heating surfaces. In this way, the performance of boiler operation would be raised to a higher level, while at the same time reducing the negative impact of boiler operation on the environment.

Application of burners on the boiler in real operation: Inspired by the previous long-term successful experience of applying the detonation-impulse technique for cleaning already dirty heating surfaces on boilers 5 and 6 at the Kakanj Thermal Power Plant, Bosnia and Herzegovina, [42], [45], and bearing in mind the results of laboratory research on the performance of burners for pulse combustion of cooled water, there is a proposal and a need to apply and test the operation and efficiency of the burner in real operation. Namely, the presented results obtained during laboratory research indicate that significant beneficial effects could be achieved by using the burners as auxiliary burners in boilers and furnaces that burn low heating value and poor reactivity solid fuels. In such an application, these burners would either be constantly in operation or would be switched on periodically as needed - burners PCB1 and PCB2 in Fig. 14, [28].

Due to the generation of pulsating pressure of high frequency and significant amplitude, as well as high-level and wide-spectrum sound energy, it is advisable to expect that such pulsating jets are able to establish such an atmosphere in the boiler that is able to have a destructive effect on the deposit or ash deposits that have already formed on boiler heating surfaces, and/or prevent their formation, especially the initial formation of those deposits, which represents the key phase of that process - burners PCB3 and PCB4 in Fig. 14, [28].

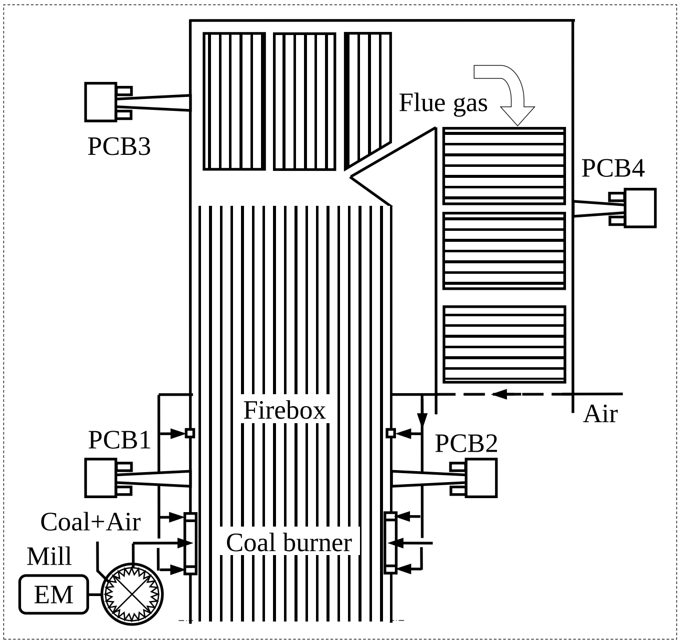

Figure 14. The concept of possible application of one or more pulsed combustion burners (PCB) in the furnace and/or convective tract of the boiler - permanent operation or as needed

Heat transfer in the pulse flow of flue gases: A purpose-built tubular heat exchanger with a single passage of media/fluid (flue gases - water) is mounted in a flue gas discharge channel to the environment, [28]. Pulse flue gases flow through a pipe bundle of 19 copper pipes, and water dominates longitudinally around those pipes. By choosing the location of the water inlet and outlet from the exchanger, it is possible to establish a direct or counter-directional flow of fluids through the exchanger - here are the results of research with a direct flow of fluids. Dependence of heat transfer intensity, i.e. heat transfer coefficient, determined by measuring fuel consumption, temperature and composition of flue gases at measuring points 15 and 16, intensity and character of pressure pulsations immediately before entering the exchanger (measuring point 14), flow water through the exchanger and water temperatures at the inlet and outlet of the exchanger. A characteristic example of the deformed form of pressure pulsations, primarily expressed in the area of overpressure, directly at the entrance to the pipe register of the exchanger, is given in Fig. 15. The deformation of the pulsations can be related to the geometry of the pipe space through which the gases flow and whose flow cross-section is also suddenly changes - the flue gases flow directly from the flue pipe to the pipe bundle of the exchanger, [28], [35].

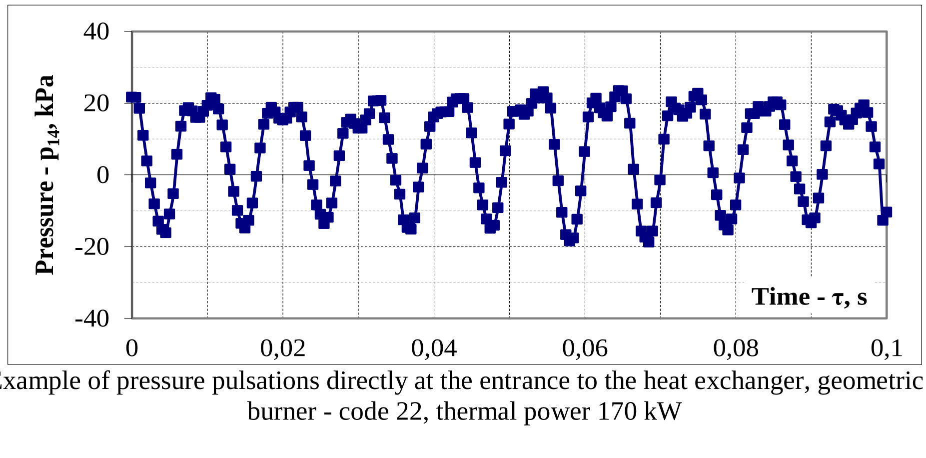

Figure 15. Example of pressure pulsations directly at the entrance to the heat exchanger, geometric shape of the burner - code 22, thermal power 170 kW

The dependence of the heat transfer coefficient is directly related to the total flue gas pressure deviation for the observed geometry (burner code 22, 41 and 43) and the heat load of the burner - compare figures 16 and 17.

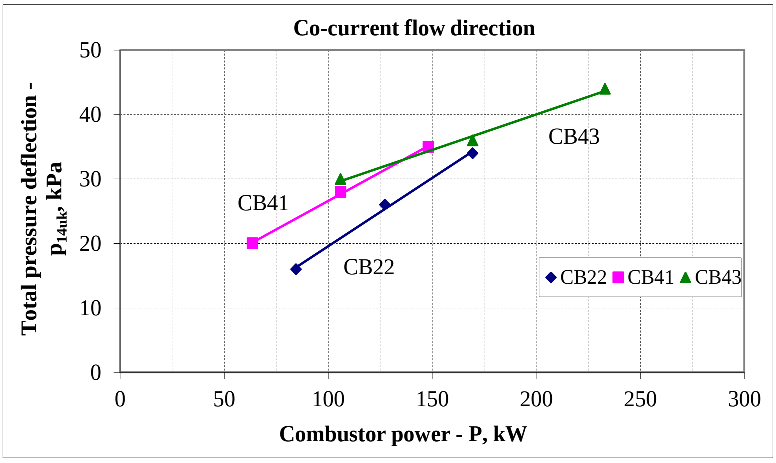

Figure 16. Total flue gas pressure deflection in front of the heat exchanger for different power and geometric shapes of burners, measuring point 14

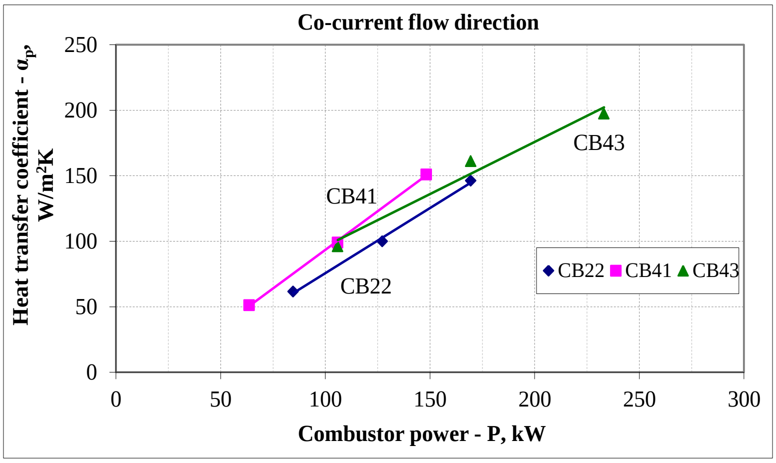

Figure 17. Coefficient of heat transfer on the side of pulse flue gases for different power and geometric shapes of burners, [28].

It turns out that the measured coefficient of heat transfer during a pulse flow of flue gases, compared with the calculated values of the coefficient of heat transfer during a developed turbulent flow without pulsations for the same medium (flue gases of the same composition), is higher, Fig. 18. In particular, it was shown that the coefficient of heat transfer in the conditions of flue gas pressure pulsation on average by 2 times or by 100%.

Fig. 18 shows that the heat transfer coefficient increases when the thermal load of the burner increases. However, in addition to increasing with the increase in the thermal load of the burner because the mass and velocity of the flue gases through the exchanger increases, at the same time the heat transfer coefficient additionally increases due to the increase in the total deflection of the pressure of the flue gases when the thermal load of the burner increases. Namely, the ratio of the relevant heat transfer coefficients (α_p/α) at the thermal power of the burner of 106 kW is 1.92, while this ratio at the power of the burner of 233 kW is 2.11.

Very similar results, related to the values and ratio of heat transfer coefficients in the flow with and without flue gas pressure pulsations, were also obtained when investigating the phenomenon of heat transfer during the counter-flow of working media through the heat exchanger, [28], [35] - see also [44].

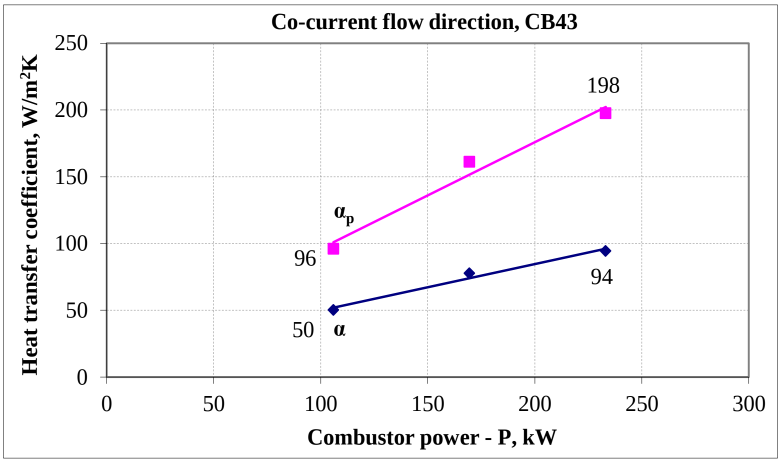

Figure 18. Comparative presentation of heat transfer coefficients in the flow with (α_p) and without (α) flue gas pressure pulsations, [28].

IV. CONCLUSION

From the presented results of laboratory research on the performance of pulse combustion of gaseous fuel generated in the burner of modular form with aerodynamic valves for air intake and cooled by water, the following conclusions arise:

- a robust and compact burner without moving parts, in a modular version, was designed and developed,
- the burner works in "self-pumping" mode, except at the very start, i.e. the process automatically generates air intake for combustion and transport of flue gases, so pressure and exhaust fans are not required,
- process parameters depend on the geometric form, cooling intensity and thermal load of the burner,
- the burner is flexible in operation - the ratio of maximum and minimum power is 5:1,
- the intensity of cooling of the burner does not significantly affect the operational flexibility of the burner,
- the mean temperature of the process is generally relatively low and, depending on the geometric form of the burner and the heat load, is always below 1200 °C,
- the combustion process is highly efficient and with low NO_x emissions,
- the cooling intensity of the chamber and the basic resonant tube affects the process parameters - with the increase in cooling intensity, the frequency of pressure pulsations decreases, while the amplitude of pressure pulsations increases: the frequency value is in the range from about 90 to over 140 Hz and the total pressure deflection generated in the combustion chamber up to almost 100 kPa,
- the intensity of the sound, as an inevitable side effect of the burner operation, is over 130 dB, and the sound spectrum of that sound is quite wide,
- due to significant pressure pulsations and their propagation within a free and especially closed space, the conclusion is imposed that it is highly advisable to test in practice the effects of placing burners as auxiliary in the furnace of industrial boilers, especially boilers that burn LHV and poor reactive solid fuels,
- the goal of using these burners in combustion plants is to achieve, by constantly or intermittently operating the burners, intensification of turbulence in the combustion chamber and thus better mixing of reactants, more efficient combustion of the base fuel, greater energy efficiency of the plant and less environmental load with undesirable and polluting substances - flue gases , slag and ash,
- the values of high-frequency pressure pulsations in the environment of the boiler elements in the boiler model, but also within them, are significant - bearing this in mind, together with the simultaneous and multiple reflection of the flow pulsations and the significant level of generated sound energy, it is recommended to perform operational testing of the burner and as a device for preventing the formation and/or cleaning of already formed ash deposits, primarily in the convective channels of industrial boilers, especially those in which fuels with a more pronounced tendency to dirty the heating surfaces in the boiler are burned,
- high-frequency pressure pulsations in the flow of flue gases significantly affect heat transfer - the coefficient of heat transfer in a pulse flow of flue gases is more than 2 times higher than the corresponding coefficient of heat transfer in a developed turbulent flow without pulsations,
- operational testing and application of the burners in furnaces and boilers when burning low heating value and poor reactivity solid fuels is recommended, as well as in the case of furnaces and boilers where the problems of backfilling, slagging and fouling with ash are pronounced, and all in the direction of improving

efficiency, operational and time availability and reduced negative impacts of the operation of those facilities on the environment.

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