Infrared Burner with Increased Firing Rate and High Surface Temperature

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Abstract—**Experiments and computations were conducted on infrared radiant burner operated on natural gas/air mixtures. The burner had not porous media and consisted of plates (recuperative elements) of heat-resistant metal alloy (Fe base, Cr 25%, Al 6%) with high thermal conductivity. The height of the recuperative elements system varied from 18 mm to 70 mm. The Al_2O_3 coatings were tested and found effective for covering the surface of the recuperative elements in burners. The operating surface temperature of recuperative elements coated with aluminum oxide reached values of 1450°C. Stable combustion mode is implemented in the range of specific burning power (firing rate) values from 2.8 MW/m^2 to 5.3 MW/m^2 per unit area of the gas stream cross-section. The maximum power of the burner is 16 kW with a flow cross-section of 30 cm^2. The concentration of nitrogen oxides in the combustion products is up to 14ppm, the concentration of carbon monoxide is up to 20 ppm with an excess air coefficient (air ratio) of 1.4. The combustion process of fuel mixtures with an oxidizer in an infrared burner, which allows to work at increased values of firing rate and maintain the values of concentrations of toxic components in the combustion products characteristic of traditional infrared burners, consists of two stages. The first stage is the ignition of the mixture by a heated surface. The second stage is the combustion of the mixture inside the channel between recuperative elements in the conditions of heat exchange with the walls with the correct intensity. Sustained operation of the infrared burner is ensured by: high thermal conductivity and heat resistance of the recuperative elements material, the conditions for stable ignition of the gas mixture by heated recuperative elements surface, geometrical parameters of the recuperative elements system, the value of flow velocity and the composition of the mixture.**

Keywords—**infrared burner, natural gas, recuperative element, coating, surface combustion, firing rate, surface temperature, emissons**

I. Introduction

Last year we reported [1] about the discovery in the combustion laboratory of Institute chemical physics of RAS of a new combustion mode in the IR (infrared) burners. It is a combustion mode in the gaps between heat-resistant, recuperative elements with high thermal conductivity. The new combustion mode was implemented in IR burners after a revolutionary change in the design of the IR burner.

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The fine-pored permeable matrix that provides a stable surface combustion mode in conventional infrared burners has been removed from the burner design, and the system of recuperative elements has been strengthened. The design changes and the new combustion mode allowed to increase the firing rate in an IR burner operating on mixtures of natural gas and air to 2.9 MW/m^2, while maintaining good environmental characteristics [1]. Over the past year we have progressed in understanding the new combustion regime and reached values of firing rate at 5.3 MW/m^2 (Fig.1), approaching the values of the firing rate, made in burners, using combustion in a free jet. For comparison, it can be indicated that the highest value of the firing rate in IR burners, obtained experimentally in the works of other authors [2], is equal to 2.0 MW/m^2 on mixtures of methane with air and 2.6 MW/m^2 on mixtures of propane with air.

Figure 1. Photo of a laboratory layout of an IR burner operating without a fine-pored matrix. Power 16 kW, flow cross-section area 30 cm^2. The concentration of nitrogen oxides in the combustion products is 14 ppm, the concentration of carbon monoxide is 20 ppm with a value of air ratio 1.4. The maximum surface temperature of the recuperative elements is 1450°C.

II. Experimental Apparatus

The experimental apparatus is shown Figure 2. The burner in this study consisted of plates of a heat-resistant metal alloy (Fe base, Cr 25%, Al 6%) strengthened by yttrium oxide. The material developed and manufactured at the Institute of powder metallurgy [3].
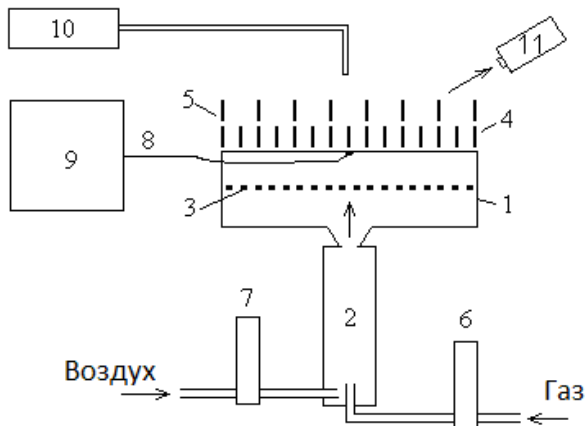

Figure 2. Diagram of the experimental apparatus. 1 - housing burner, 2 – mixer, 3 – gas mixture flow distributor, 4 - 5-recuperative elements system, 6 - gas flow meter, 7 - air flow meter, 8 – thermocouple, 9 - convertor, 10 -gas analyzer, 11 – IR pyrometer.

Recuperative elements in the form of plates with parameters: thickness 1mm, width from 8mm to 60 mm, length 80mm, could be installed on a metal disk in several layers. Sealing and thermal insulation of the recuperative elements system on the surface of the metal disk was carried out using a heat resistant fibrous ceramic material. The height of the recuperative elements system varied from 18 to 70 mm. The experiments used a mixture of natural gas from the Moscow city network and air. The gas mixture was formed in the mixing device and fed to the lower part of the burner housing. The consumption of natural network gas was measured using a Bronkhorst flow meter. The air flow was measured with an AGAT G25 gas meter. The fuel and the air were filtered for oil, water, and particulates. Temperature measurements during experimentation were taken using a combination of thermocouples and IR pyrometer. Emissions measurements in this research were taken using a gas analyzer TESTO 335. Based on the concentration of residual oxygen, the gas analyzer calculated the value of the air ratio α in the initial mixture. The value of the air ratio in the mixture, calculated from the results of gas and air flow measurements, at values of the α less than 1.55, coincided with the value of the air ratio calculated by the gas analyzer from the concentration of residual oxygen with high accuracy. This indicates that the combustion of hydrocarbons is complete in combustion modes at α <1.55 and that there are no gas leaks in the supply system.

III. Results of Experiments

The flow of a mixture of natural gas and air was ignited over the upper edge of the recuperative element system. While the system remained cold, the combustion of the mixture occurred in the mode of a torch above the surface of the system. As the system of elements warmed up, the combustion zone was partially or completely immersed in the system, depending on the height of the system and the value of gas mixture consumption. The height of the system of recuperative elements along the stream varied in the range from 18 to 70 mm. Natural gas consumption was varied from 14 normal liters per minute to 26.2 normal liters per minute. The air ratio α was changed in the range from 1.38 to 1.65. The diameter of the hole through which the gas-air mixture entered the system of recuperative elements is 50 mm. The temperature of the gas-air mixture at the entrance to the system is 20-25℃. The velocity of the gas mixture at the inlet to the system, averaged over the cross section of the gas flow, in the considered range of gas and air flow rates varied from 1.85 m / s to 4.15 m/s. The Reynolds number Re varied from 500 to 1100 at the entrance to the channel between the recuperative elements. When the gas mixture moves inside the system, the size of the gas mixture flow across the plates remained equal to 50 mm, along the plates, the gas flow was able to expand to a size of 60 mm. The cross-sectional area of the flow inside the system of recuperative elements is 30 cm^2. Experiments have shown that in contact with the surface of heated recuperative elements, the gas mixture is ignited, while the flame front inside the channel is strongly stretched along the surface of the elements (Fig.3). Maximum laminar flame speed of gas mixtures with air [4] is less than the minimum speed of the gas mixture at the entrance to the system in our experiments. There were no cases of flame escaping from the system of recuperative elements into the zone of mixture entry in experiments, despite the absence of a fine-pored matrix in the design of the IR burner. The absence of a fine-pored matrix with a high hydraulic resistance makes it possible to have a high velocity of movement of the fuel mixture in the burner. Firing rate is a function of both fuel mixture composition and fuel mixture velocity. The high speed of the fuel mixture movement allowed to obtain a record value of the firing rate in the IR burner of the new design. When calculating the combustion power, the value of the lowest calorific value of natural gas was used 35.62 ± 1.07 MJ/m^3 (under standard conditions at T = 288.16 K, P = 101325 Pa). The calculated combustion power varied from 8,500 W to 16,000 W. The maximum value of the firing rate reached 5.3 MW/m^2, the minimum firing rate on the IR burner was 2.8 MW/m^2. Experiments with changing the height of the system of recuperative elements from 18 mm to 70 mm showed that the main part of the gas for firing rate up to 3.6 MW/m^2 at air ratio of 1.4 burns at a distance of 30 mm from the input edge of the system.

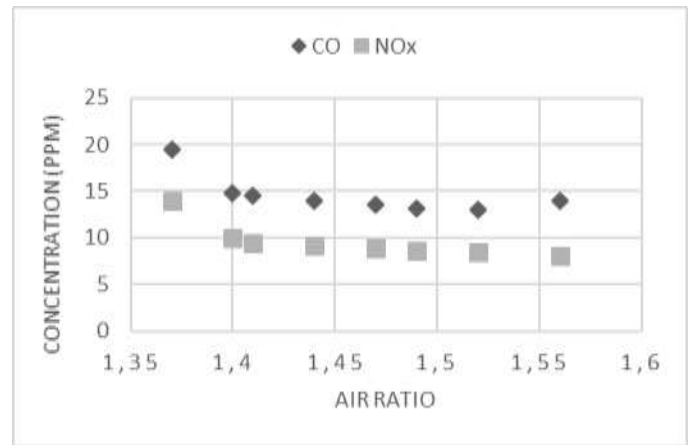Figure 3. Photo of the flame front in the channel between the plates.

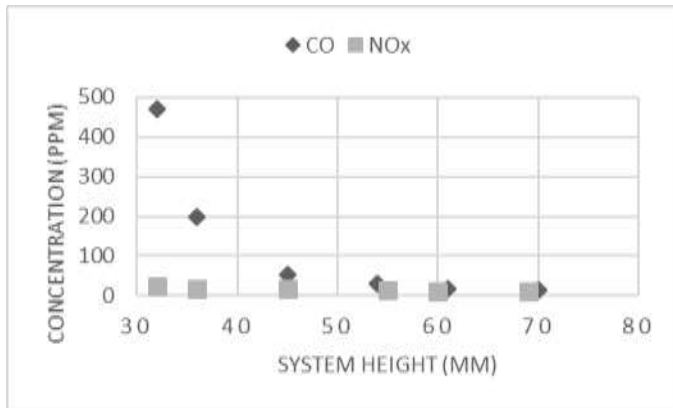Figure 5. Effect of changing air ratio on emissions levels. The system height is 70 mm.

Figure 4. Concentrations of carbon monoxide and nitrogen oxides in the combustion products at the exit from the system of recuperative elements for different values of the system height. The air ratio is 1.4.

The concentration of one of the main combustion products - carbon dioxide in the combustion products when changing the height of the system from 32 mm to 70 mm changes slightly from 8.13% to 8.16 %. However, at a distance of 30 mm from the lower edge of the recuperative element system, the concentration of carbon monoxide in the combustion products is still high (400-1000 ppm). Concentrations of carbon monoxide and nitrogen oxides in the combustion products of a mixture of natural gas and air with air ratio of 1.4 at the outlet of the system recuperative elements, depending on the system height at the firing rate 3,6 MW/m^2 is shown in Fig. 4. In the range of height values from 30 mm to 60 mm, the concentration of carbon monoxide, the value of which characterizes the completeness of the combustion of the gas-air mixture, changes tenfold. The concentration of nitrogen oxides in this range of values of the system height changes approximately twice.

When the air ratio increases, the concentration of nitrogen oxides in the combustion products monotonously decreases, and the concentration of carbon monoxide passes through a minimum. The concentrations of carbon monoxide and nitrogen oxides in the combustion products at the outlet of the recuperative element system for various values of the air ratio at the system height of 70 mm are shown in Fig. 5. The maximum temperature of combustion products for mixtures of natural gas with air at air ratio of 1.4 is equal to 1570 ° C. The maximum temperature of the lower layer of the plates of the recuperative elements, depending on the air ratio and the value of the firing rate, varied from 1200 ° C to 1450 ° C. Note that the operating temperature of the used heat-resistant alloy is equal to 1400ºC [3]. The plates of the recuperative element system worked steadily at a temperature of 1400 ° C without coating. Working at a temperature of 1450 ° C, the plates received edge destruction. Coatings on the plates of the system of recuperative elements made of aluminum oxide with a thickness of 50 - 100 microns, applied using a multi-chamber detonation unit [5], allowed for a long time to work at plate temperatures of 1450 ° C without changing the properties of the plate surface. Resistance of coatings of aluminum oxide on the surface heat-resistant alloy due to the fact that the coefficients of thermal expansion of aluminum oxide and heat-resistant alloy (11 μm/m/K at 20 ° C, to 15.5 μm/m/K at 1300 ° C) in the temperature range below 1000 ° C have similar values [6] . At temperatures above 1000 ° C, when the coefficient of alloy thermal expansion becomes 1.5 times greater than aluminum oxide, coating acquire plasticity. In addition, aluminum oxide coatings applied using a multi-chamber detonation system are highly resistant to cracking [7]. Earlier in our work, it was shown that the aluminum oxide coating stabilizes the combustion process in IR burners on the surface of porous matrices at a surface temperature of up to 1100ºC [8]. In this study, the coatings are tested to surface temperatures of 1450ºC. Results of the measurements of the plates upper edge temperature in the center of the flow at different values of the air ratio for two values of the system

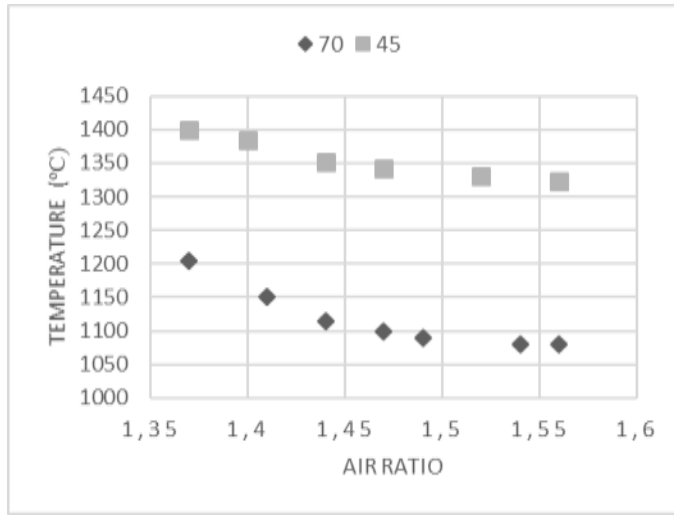height of 45mm and 70mm at a firing rate of 3.6 MW/m^2 are shown Figure 6.

Figure 6. Effect of changing air ratio on temperature of the plates upper edge in center of flow.

IV. Results of Computations and Discussion

The computation results were obtained using the Ansys Fluent software package. We used a two-dimensional approach that includes the effects of solid- and gas-phase conduction, solid surface-gas heat exchange, species diffusion, and chemical reactions. When performing calculations in the flow of a mixture of natural gas and air, chemical reactions and the values of chemical reaction rates recommended in [9] were taken into account. First, calculations were made of the parameters of the air flow when moving in a gap with heated walls made of a metal alloy. This allows you to understand how the gas-air mixture moves and heats up in the gaps between the elements of the IR burner until the moment of ignition. Figure 7 shows the velocity profiles in the air when moving through a gap with Kanthal walls with a temperature of 1200°C at various distances from the entrance to the gap. The flow rate of air entering the channel of 2m/s across the width of the slit, the air temperature at the entrance of the channel 20°C, the distance between the walls is 4 mm, slit length 100mm, air pressure at the output of 100000 Pa. The parameters of the air flow correspond to the parameters of the gas mixture flow in the conditions of our experiments. The Reynolds number for all calculated modes is less than 1000, and the flow is laminar. A viscous gas-dynamic boundary layer and a thermal boundary layer are formed near the walls of the gap. In these boundary layers near the walls, the gas flow is slowed down due to viscosity, and due to thermal conductivity, the air flow is heated and the central part of the flow is accelerated Fig. 7. On the abscissa axis in this figure,

the distance from the wall in meters is shown, on the ordinate axis - values of the air flow velocity. The curves show the flow velocity values in sections perpendicular to the flow axis at distances of 2 mm; 5 mm; 10 mm; 50 mm and 100 mm (exit from the channel) from the channel entrance. When the core of the flow is heated, it accelerates to a speed higher than the maximum normal combustion speed of a mixture of natural gas and air.
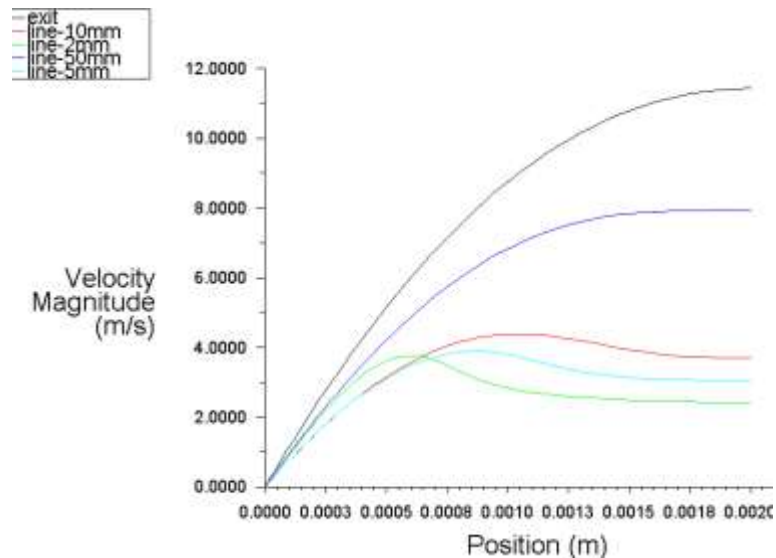

Fig. 7. Values of the gas mixture velocity at different distances from the entrance to the gap and from the gap wall.

At this ratio the rate of combustion and the speed of the central part of stream the combustion occurs from the walls to the center of the flow, as seen in the pictures Fig. 3 and confirmed by the results of calculations of mass concentration of methane in the flow of a stoichiometric mixture of methane with air, taking into account the chemical reactions Fig. 8. The lower border of figure 8 corresponds to the wall, the upper border-the axis of symmetry, located at a distance of 2 mm from the wall. The results of the mathematical modeling performed under these conditions qualitatively coincide with the results of the experiment. The original mix is shown in red. The front of the heat release zone (shown in yellow in figure 8) is extended along the wall. In experiments, the channel wall was warmed up to 1300°C - 1450°C, what is higher than the calculated wall temperature of 1200°C, and the mixture burned out faster.

In system with a height of 70 mm, after the system was warmed up, the entire combustion zone was permanently located inside the system channels under all the gas and air supply modes used. Thus, and experiment, and mathematical modeling allow us to conclude that when the velocity of the combustible mixture is greater than the maximum possible speed of combustion, in the gaps of the IR burner may not exist a stationary regime of combustion with a combustion front across the flow that takes place, for example, in a multi-channel system made of quartz plates at flow rates of 20 cm/s to 70 cm/s [10]. The new combustion mode implemented in IR

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burners, which is stable at higher speeds of the medium than in burners with fine-pored matrices and in a multi-channel system [10], and allows the IR burner to work with good environmental characteristics, includes two stages. The first stage is the ignition of the mixture by a heated surface. The second stage is the combustion of the mixture inside the channel in the conditions of heat exchange with the walls with the correct intensity. Sustained operation of the IR burner is ensured by: high thermal conductivity and heat resistance of the material of the recuperative elements, the conditions for stable ignition of the gas mixture by heated surface, geometrical parameters of the system and the composition of the mixture. These conditions help on the one hand to ensure full combustion, and, on the other hand, to prevent intense oxidation of nitrogen by oxygen. The conditions for the stable implementation of the process of a gas mixture ignition by the incandescent surface are discussed in detail in [11,12]. Conditions for the implementation of the second stage of the new combustion mode in IR burners were selected empirically during experiments. Both stages of the new combustion mode occur in the interaction of the flow with the surface. In this sense, the new mode is a surface combustion mode. Combustion mode, which takes place in our experiments, differs from the mode of surface combustion in conventional IR burners. Between the front of flame and the surface of the matrix is nothing but the combustible gas mixture for the infrared burners of traditional design. In our IR burner, the combustible gas mixture contacts the surface of the recuperative element system only at the ignition stage. At the main part of combustion process the front of flame is separated from the surface by a layer of combustion products (see Fig. 8). Moreover, in the IR burner, our design, there is a forced ignition. Forced ignition in textbook «Physics of combustion and explosion» [4] is understood as a case of ignition, when the main part of the flammable medium remains cold at the time of ignition, and heating to ignition is only performed in a small volume of the flammable medium, for example, when the flammable medium contacts a heated body. The case is realized in our IR burner. The new mode of operation of the IR burner was implemented in the laboratory of combustion of the Semenov Federal center of chemical physics of RAS. We suggest to call the new mode of combustion with high values of firing rate and low emissions levels forced surface combustion (FSC).

The experimental study have shown that it is possible to increase the firing rate for IR burners operating on a system of recuperative elements without permeable matrices with small pores to the values of 5.3 MW/m^2 typical for flare burners and to maintain the environmental characteristics of these burners at the level typical for the best IR burners of traditional design. Aluminum oxide coatings with a thickness of 50 to 100 microns applied to the plates of the recuperative element system using a multi-chamber detonation unit [5] allowed long-term operation at plate temperatures of 1450 ° C without changing the properties of the plate surface.
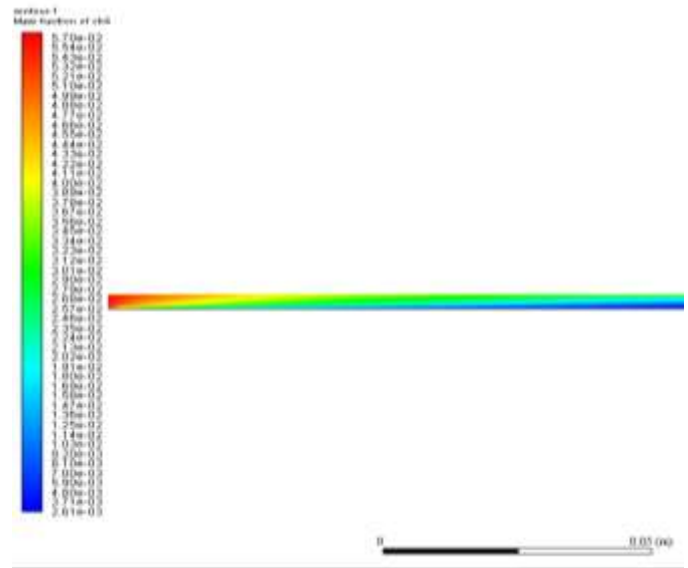

Figure 8. Values of mass concentrations of methane in the flow of a stoichiometric mixture of methane with air, when moving in a channel with walls heated to 1200 °C.

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