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Stimulated Surface Combustion in Infrared Burners

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***Abstract*—A permeable matrix is placed in the flow of the combustible gas mixture in infrared (IR) burners for the organization and stabilization of the surface combustion regime. A stable regime of surface combustion occurs on the surface of the permeable matrix. Until the combustion rate of the gas mixture near the surface exceeds the velocity of the gas mixture, the surface combustion process is stable. If the combustion rate becomes less than the velocity of the gas mixture, the combustion zone is separated from the surface and combustion passes into the flare mode. In our previous works it is shown that the introduction of recuperative elements into the design of the IR burner allows to increase the heat flow from the combustion products to the surface of the permeable matrix and to increase the maximum value of the specific combustion power for the surface combustion mode to values of more than 100 W/cm^2. However, at such high values of the specific power of surface combustion, the surface temperature of the permeable matrix increases to the values at which the surface of the permeable matrix is destroyed. Application to the surface of the permeable matrix of metal foam or wire ceramic material has increased the specific combustion power to values of more than 120 W/cm^2. A further increase in the specific combustion power led to the destruction of the surface of the permeable metal matrix with a ceramic coating. Studies conducted, the results of which are presented in this paper, showed that it is possible to implement the surface combustion mode in the IR burner with specific power values of more than 200 W/cm^2, if you use the design of the IR burner without a permeable matrix. To do this, it is necessary to organize the regime of stimulated surface combustion (StSC) on the surface of the recuperative elements. Mode (StSC) in the IR burner may sustained combustion of gas mixtures not capable of self-combustion, or when the velocities of the gas mixtures exceed the rate of combustion. In our experiments on laboratory models of the IR burner, the stimulated surface combustion mode with a specific combustion power of more than 290 W/cm^2 was implemented. Plates 1 mm thick were used as recuperative elements. The material of the plates is made of high-temperature resistant iron-based alloy (chromium 25%, aluminium 6%,) strengthened by yttrium oxide. Environmental characteristics of IR burners operating in the mode of stimulated surface combustion with a specific power of 170-290 W/cm^2 do not differ from the values typical for conventional IR burners operating at a specific power of 20-30 W/cm^2. The proposed design of the IR burner allows you to get away from the problems associated with the destruction of permeable matrices.**

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***Keywords*— gas mixture, surface combustion, infrared burner**

I. Introduction

Currently, the process of natural gas with air mixtures burning is the main source of energy in many countries. Humans created a huge number of devices to implement this process. Nevertheless, work continues for improving burner devices. Within many years the combustion laboratory of the Institute of Chemical Physics of the Russian Academy of Sciences has been focused on the various studies to control and improve the combustion process in IR burners [1]. The main positive characteristics of IR burners are high energy efficiency and, which is especially important for environmental protection, low content of toxic gases in combustion products [2]. For realizing the combustion of gas mixtures on the surface of the permeable matrix of IR burner preheating of the gas mixture occurs when it moves through channels or pores of a permeable matrix. To date, construction of the IR burners includes a permeable matrix, as required. Until the combustion rate of the gas mixture near the outlet surface of matrix exceeds the velocity of the gas mixture, the surface combustion process is stable.

Fig. 1. A photo of the infrared burner operating without a permeable matrix in the mode of stimulated surface combustion near the surface of the recuperative elements. Combustion intensity 290 W/cm^2, air ratio is equal 1.4.

If the combustion rate becomes less than the velocity of the gas mixture, the combustion zone is separated from the surface and combustion passes into the flare mode. Surface burning of gases (SBG) on a permeable matrix allows to reduce emissions of nitrogen oxides during the combustion of a gas mixture and to increase the radiation energy flux density, which is of interest for the creation of environmentally friendly, compact heat generators and powerful sources of infrared radiation. This fact is explained by the fact that the combustion of the gas mixture occurs at the surface of the matrix. Due to the intensive heat transfer between the combustion products and the surface of the matrix in the SBG mode, the matrix surface is heated to high temperatures. The temperature of the combustion products in the combustion zone decreases, which leads to a decrease in the concentration of nitrogen oxides in the combustion products. In our previous work [3] it is shown that the introduction of recuperative elements into the design of the IR burner allows to increase the heat flow from the combustion products to the surface of the permeable matrix and to increase the maximum value of the specific combustion power for the surface combustion mode to values of more than 100 W/cm^2. However, at such high values of the specific power of surface combustion, the surface temperature of the permeable matrix increases to the values at which the surface of the permeable matrix is destroyed. Application to the surface of the permeable matrix of metal foam or wire ceramic material has increased the specific combustion power to values of more than 120 W/cm^2 [4, 5]. A further increase in the specific combustion power led to the destruction of the surface of the permeable metal matrix with a ceramic coating. Studies conducted in 2018, the results of which are presented in this paper, showed that it is possible to implement the surface combustion mode in the IR burner with specific power values of more than 200 W/cm^2, if you use the design of the IR burner without a permeable matrix. To do this, it is necessary to organize the regime of stimulated surface combustion (StSC) on the surface of the recuperative elements. A photo of the infrared burner operating without a permeable matrix in the mode of stimulated surface combustion near the surface of the recuperative elements is shown in Fig.1. The experiments were carried out on mixtures of natural gas and air.

II. Experimental procedure

Experimental studies of the surface combustion of natural gas–air mixtures were carried out on a model burner device without permeable matrix. The scheme of the experimental setup is shown in Fig.2. On a metal disc with a hole of 60 mm in diameter, a plate of thick ceramic paper 6 mm thick with a hole was horizontally fixed. The hole in the ceramic paper was located coaxially with the hole in the metal disc. The edges of the ceramic paper plate were crimped with stainless steel plates so that the air-gas mixture could pass through the plate only through the hole in the plate. The hole diameter was changed from 50 mm to 60 mm. From the lower side ceramic plate is supported by a grid with large cells 4x4 mm of the silica threads. Inside the body of the burner device was a perforated disk, which provides a uniform distribution of the gas flow. The ceramic paper is coated by a mesh of stainless steel. The recuperative elements system of the 1 mm-thick plates is located on the stainless-steel mesh. Material of plates is heat-resistant iron-based alloy (chromium content of 25%, the aluminum content of 6%) [6]. The operating temperature of this material is 1400ºC. The thickness of the layer of recuperative elements in the experiments varied from 8mm to 40 mm. A mixture of natural gas from the city network and air were used in the experiments. The gas mixture was formed in the mixer and fed to the lower part of the burner housing. Gas flow rate was measured using a gas meter brand BK-G2,5 LLC "ELSTER gas Electronics". The air flow rate was measured using a gas meter brand BK-G6 ELSTER Instromet GmbH. At first, after initiation of combustion above the upper surface of the system of recuperative elements, combustion occurred above the upper surface of the system of recuperative elements in the form of a blue flame torch. In this flare combustion mode, the combustion products contained nitrogen oxides in an amount of more than 60 ppm and carbon monoxide in an amount of more than 300 ppm. As the recuperative elements heat the flames were absorbed into the system of recuperative elements. The recuperative elements were heated to a temperature of red glow. After that, combustion occurred only in the zone between the recuperative elements.

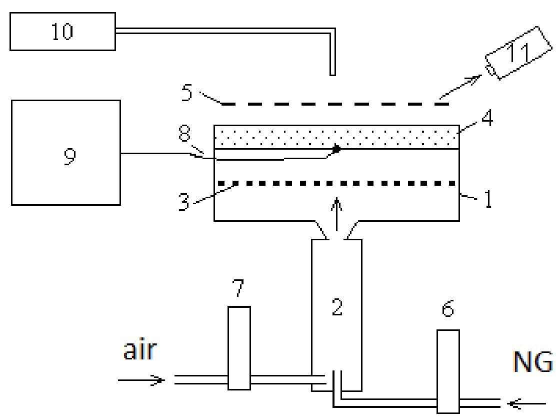

Fig.2. 1 - housing burner, 2 – mixer, 3 – gas mixture flow distributor, 4 - 5-recuperative elements system, 6 - gas flow meter, 7 - air flow meter, 8 – thermocouple, 9 - convertor, 10 - gas analyzer, 11 – IR pyrometer.

The temperature of the recuperative elements of the lowest layer, in the zone where combustion begins, was measured using a thermocouple. The temperature of the upper layer of the recuperative elements, in the area where combustion is completed, was measured using an infrared thermometer AR882, analyzing the radiation in the region of 8-14 microns or using a standard chromel - aluminum thermocouple with a thickness of 1 mm. The temperature of the lower layer of the recuperative elements system was measured by a similar thermocouple. Concentrations of nitrogen oxides, carbon monoxide and oxygen in the combustion products above the surface of the recuperative elements were determined by the gas analyzer TESTO 335. Based on the results of air and gas flow measurements, the value of the air ratio in the initial mixture was calculated. The probe of the gas analyzer with a diameter of 4 mm was placed above the surface of the recuperative elements in the central part of the system at distance of 5 mm from the surface of the recuperative elements system.

III. Experimental results

Experiments have shown that in some variants of the design of the proposed IR burner device, a stable surface combustion mode with a high value of the specific combustion power w (the ratio of the combustion power to the working area) is realized. A photo of the process of stimulated surface combustion is shown in Fig.1 at a record value of the specific power of surface combustion w = 290 W/cm^2 (combustion power 5.8 kW, air ratio of 1.4). Stable surface combustion on the burner model used in the experiments exists in the range of specific combustion power values from 170 W/cm^2 to 290 W/m^2.

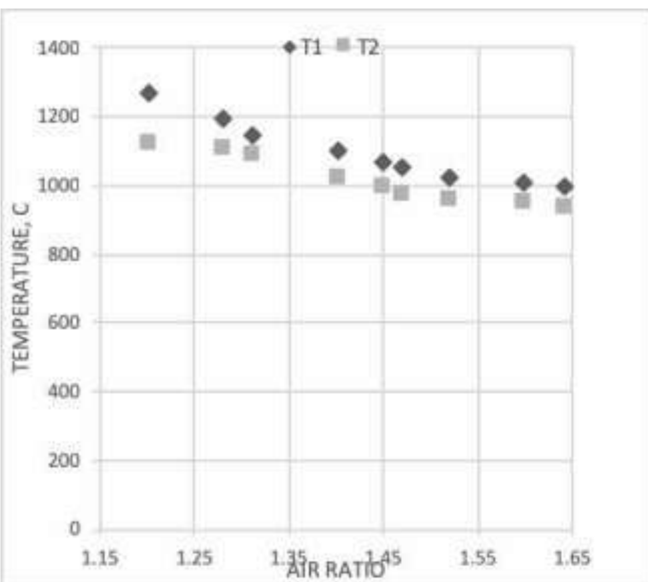

Fig.3. Temperatures of recuperative elements for different values of air ratio. T1 is the temperature of the lower part of the recuperative elements located at the inlet of the gas mixture to the combustion zone, T2 is the temperature of the upper part of the recuperative elements. The specific power of burning is equal 175W/cm^2.

For comparison, we indicate that in a burner with a matrix of metal foam with ceramic coating and recuperative elements combustion intensity changes in region of 15W/cm^2 to 120 W/cm^2 [4]. The displacement of the region of stable surface combustion mode in the range of specific power values is explained by the absence of heat removal from the combustion zone to the matrix and stabilization of the combustion zone of high-speed flow in the spaces between the hot recuperative elements. The results of measurements of the temperature of the plates at the inlet and outlet of the gas mixture in the combustion zone for the specific combustion power of 175 W/cm^2 and 275W/cm^2 are shown in Fig.3 and Fig.4, respectively. The air ratio was changed in such a range that the temperature of the recuperative elements located at the entrance to the combustion zone did not exceed 1250°C. At a specific combustion power of 175 W/cm^2, the air ratio was changed in the range of 1.2 to 1.65. At a specific combustion power of 275 W/cm2, the air ratio was changed in the range from 1.4 to 1.65. In the whole investigated range of values of specific power at values of air ratio coefficient more than 1,65 there was a failure of the mode of the stimulated surface burning and transition to the mode of flare burning. The temperature of the upper surface of the recuperative elements is about 50 - 100°C less than the surface temperature of the recuperative elements near the entrance to the combustion zone. Note that at high specific combustion power there is no separation of the flame from the system of recuperative elements even though the flow rates of the gas mixture are realized that exceed the values of the normal combustion rate in the initial gas-air mixture.

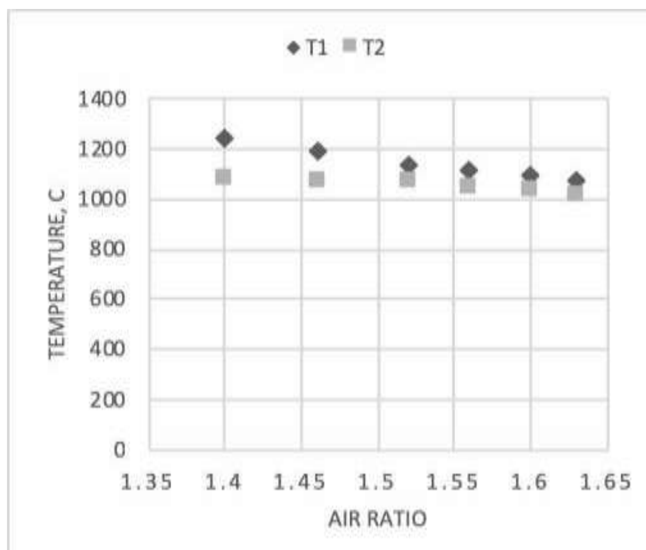

Fig.4. Temperatures of recuperative elements for different values of air ratio. T1 is the temperature of the lower part of the recuperative elements located at the inlet of the gas mixture to the combustion zone, T2 is the temperature of the upper part of the recuperative elements. The specific power of burning is equal 275W/cm^2.

It turned out that for the air ratio less than 1.65 combustion occurs on the surface of heat-conducting heat-resistant recuperative elements, and not in torches and not in micro-torches, i.e. in the surface layers of the gas-air mixture flowing around the heated recuperative elements, and in the radiation field of recuperative elements. Thus, a new stable regime of surface combustion is realized. Intensive heat transfer between the combustion products and the plates of the recuperative elements forming the radiating cavities leads to an increase in the radiation efficiency of the burner device, since the temperature of the exhaust products of combustion decreases.

The results of measurements of the concentrations of nitrogen oxides and carbon monoxide in the combustion products of the burner model for the values of the specific combustion power of 175 W/cm^2 and 275 W/cm^2 are shown in Fig.5 and Fig.6, respectively. The concentration of nitrogen oxides at equal values of the specific combustion power is approximately the same as for burners with metal foam matrices with recuperative elements and less than one and a half times than in combustion products in conventional matrices of metal foam. The decrease in the concentration of nitrogen oxides in the combustion products of gas mixtures for IR burners with recuperative elements, compared with conventional IR burners, is associated with an increase in the share of energy released in the form of radiation. In this case, the amount of energy carried away by the combustion products, and, consequently, the temperature of the combustion products decreases, which leads to a decrease in the concentration of nitrogen oxides in the combustion products.

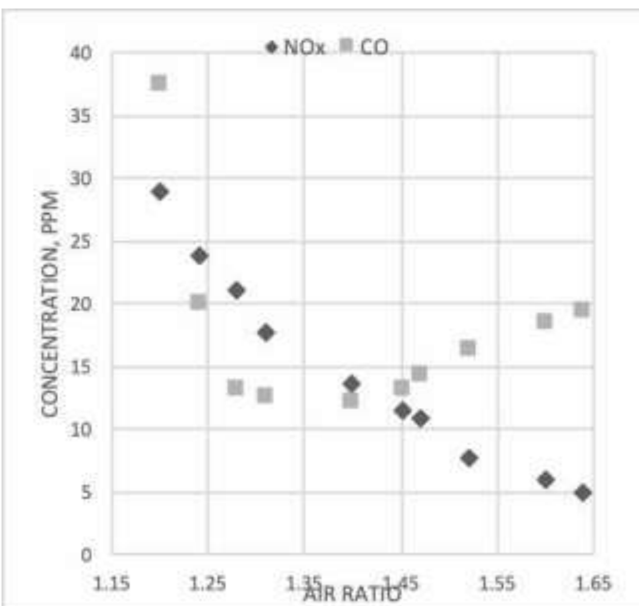

Fig. 5. Concentrations of nitrogen oxides and carbon monoxide for different air ratio. NOx is the concentration of nitrogen oxides; CO is the concentration of carbon monoxide. The specific power of burning is equal 175W/cm^2.

A more significant effect of the design of the studied IR burner device has on the concentration of carbon monoxide. The content of carbon monoxide in combustion products at the same values of the specific combustion power is less than for permeable matrices with recuperative elements [4]. This is due to the burn-up of carbon monoxide to CO_2 in the area between the plates of the system of recuperative elements.

IV. Conclusions

The design of IR burners without permeable matrix, using the mode of stimulated surface combustion on the surface of heat-resistant recuperative elements made of heat resistant iron-based alloy (25%Cr,6%Al) provides the possibility of stable operation of the burner in the mode of surface combustion at specific combustion power values of more than 250W/cm^2 without destroying the burner. The record values of the specific power of stable surface combustion (290W/cm^2) were achieved. An increase in the power of the burner devices is obtained while maintaining the environmental characteristics of the IR burner device. The proposed design of the IR burner allows you to get away from the problems associated with the destruction of permeable matrices arising from the intense modes of operation of IR burners, extend the life of the burners without replacing the elements. The design of the IR burner without a permeable matrix expands the possibilities for creating burners of different shapes, expands the range of fuels used for combustion in the mode of surface combustion in IR burners.

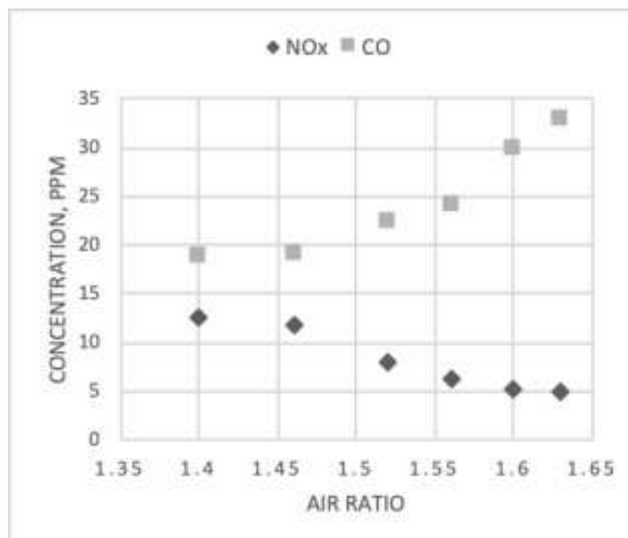

Fig. 6. Concentrations of nitrogen oxides and carbon monoxide for different air ratio. NOx is the concentration of nitrogen oxides; CO is the concentration of carbon monoxide. The specific power of burning is equal 275W/cm^2.

This design allows the burner to burn in the surface combustion mode with good environmental performance two-phase fuel mixture and reduce the hydraulic resistance of the combustion chamber when using the surface combustion mode, which is important for the operation of gas turbine plants.

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