Environmental and radiative characteristics of cylindrical Ni-Al burners for LPG combustion

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Abstract. This paper presents experimentally studied environmental and radiation parameters of hollow cylindrical burners during operation with LPG-air fuel mixture. Two combustion modes have been examined – an external combustion mode where the flame anchored near the outer surface of the burner, and an internal combustion mode when the combustion takes place in the inner cavity of the burner. The dependences of CO/NO\textsubscript{x} emissions and radiation efficiency on a firing rate in the range of 160-420 kW/m\textsuperscript{2}, air-fuel equivalence ratio in the range of 1.0-1.4, as well as the porous structure of a burner have been analyzed. An influence of a flow deflector installed in front of the burner inlet in order to distribute the flow over the inner cavity of the cylindrical burner on environmental characteristics of the burner is discussed. The necessary condition that ensures CO emission below 50 ppm, NO\textsubscript{x} emission below 20 ppm and radiation efficiency in the range of 45-55 \% is described in the paper.

1. Introduction
There are two types of gas burners used for generation of infrared fluxes: (1) gas fired radiant tube heaters [EN 416-1: 2009] and (2) gas fired luminous radiant heaters [EN 419-1:2009]. Their operation principle is similar – there is a solid body, emitter, which participates in heat transfer with high temperature gaseous combustion products, thus and so heated up and emits the infrared flux in accordance with Stephan-Boltzmann law. In burners of the first type, the emitter is usually a long metal pipe along which flue gases are blown through. Generally, a firing rate of such a burner does not exceed 50 kW/m\textsuperscript{2}, and the temperature of a pipe emitter is lower than 900 K. Under this condition, the temperature color is dark brown. Low intensity radiant tube heaters are extensively used for space heating, for example in warmhouses. In gas fired luminous radiant heaters (also known as gas-fired radiant burners, infrared or porous plug burners) the emitter is a gas permeable material and combustion of gas mixture occurs above or slightly under its outer surface. In contrast to radiant tube heaters, the combustion of gases takes place throughout the porous emitter surface. Generally, a firing rate of such burners is between 100-1000 kW/m\textsuperscript{2} and the temperature of the emitter surface is up to 1600 K [1,2]. Radiant burners were developed in the first half of the XX century and successfully used for heating and drying, as well as any other thermal processing of substances [3,4].

Nowadays the researchers are working on increasing the burner efficiency doubly along with minimization of its environmental impact as well as developing simple design of a burner and providing low cost [5-7]. Under the burner efficiency, further referred to as ‘radiation efficiency’, it is meant a power fraction transferred into the infrared flux from the surface of the emitter [8]. The radiation efficiency of the burner significantly depends on the configuration of the porous emitter and
the way in which the combustion is realized. If the combustion occurs above the radiative surface of the emitter (external or surface stabilized combustion mode), the radiation efficiency is limited, approximately less than 30% [9,10]. This is because of poor heat-exchange between combustion products and the emitter. Maximal radiation efficiency is achieved under the condition of the emitter temperature equality with the flue gases temperature near the outer surface of the emitter. This condition is realized when combustion occurs under the radiative surface (internal or submerged combustion mode) [2,6]. As for this study, it has been motivated by the experimental research findings about temperature and radiative characteristics of hollow cylindrical Ni-Al alloy burners able to operate in the internal combustion mode [11,12]. Under this conditions, the combustion takes place in the inner cavity of the hollow cylindrical emitter that reveals a significant improvement in the radiation efficiency – up to 60%. For cylindrical burners, it is needed to employ materials that can provide advanced thermal stability and high temperature oxidation resistance. Commonly used materials for radiative burners, such as oxide or carbide ceramics as well as FeCr or NiCr steels, are practically unsuitable for cylindrical burners. Ceramics are prone to brittle failure and cannot resist to nonuniform thermo-mechanical deformations, stainless steels are not sufficiently resistant to oxidation at the temperatures above 1000 °C. The promising materials for axisymmetric burners are ordered aluminides [13-15]. Due to the combination of advanced characteristics, Ni-Al intermetallics with 13.3 - 31.5 wt.% of aluminium are promising for use as porous permeable materials that are capable of operating under conditions of variable mechanical loads at high temperatures and oxidizing environment [16-18]. Such conditions are basic for radiant burners of a cylindrical shape and metal supported solid oxide fuel cells [19].

A cylindrical design of the burner provides natural stabilization of the combustion front inside the burner because the feed rate of a fresh mixture is much higher than burning velocity. In this regard, a destructive flashback mode, when the flame skips into the mixing chamber or manifold, is impossible. The only option for a hollow cylindrical burner is the realization of internal combustion mode instead of external one. It should be noted that for flat burners the size of gas permeable channels is chosen in order to provide flame quenching with preventing the flashback, generally less than 1 mm. For cylindrical burners, emitters might have channels of any size therefore the porous structure can be optimized for low CO/NOX emissions and high radiation efficiency. The objective of this study is to experimentally study the effects of emitter pores structure on environmental and radiative characteristics of cylindrical radiative burners for LPG combustion.

2. Experimental methods
The cylindrical burners with equal overall porosity of 55% but different structure parameters have been studied: the average size of the frame elements is \(D_E = 600, 1000\) and \(1350\) μm respectively. The burners are made by a combustion synthesis technique [20,21] in the form of hollow cylinders with a hemispherical head, the diameter of 48 mm, total length of 76 mm, and the wall thickness of 8.5 mm (figure 1).

![Diagram of a radiation burner](image)

**Figure 1.** Diagram of a radiation burner.
1 – manifold ending with burner housing;
2 – flow deflector;
3 – hollow cylindrical burner.

The LPG of the following composition has been used as a fuel: propane 61.66 vol.%, ethane 13.82 vol.%, methane 10.67 vol.%, the rest (carbon dioxide, butane, pentane) – 13.83 vol.%; the low heat value is \(H_l = 80.60\) kJ/nl. Three firing rates have been analyzed \(F_R = 160, 260\) and \(420\) kW/m².

An air compressor and high-pressure cylinder respectively provided air and LPG supply. The power of the burner was maintained by a mass flow controller RRG-12, accuracy of ± 0,03 nlm/min.
(Eltochpribor, Russia). The composition of a fuel-air mixture was controlled by flow meters Mass-View MV-304 and MV-306, accuracy of ± 2 % (Bronkhorst, Netherlands). After the mass flow control, the gases were supplied into a gas mixing chamber and then into a 10 mm manifold equipped with a burner housing at the end. The burner housing had a conical shape with a possibility to install a flow deflector therein. The external combustion mode was established by matching the lighting of the flame from the outer surface of the cylindrical burner. In order to realize the internal combustion mode, an electric spark plug mounted in the burner housing was used.

The Polar gas analyzer equipped with a BOP-1 dehydration unit (Promekopribor, Russia) was used to measure the concentration of CO/NOX in flue gases. In order to avoid a premix of air to the combustion products, the burner was placed inside a quartz tube with a diameter of 90 mm and a length of 500 mm. Measured concentrations of CO/NOX (NOX as sum of NO and NO2) were reduced to concentrations of combustion products undiluted with excess air under standard conditions i.e. for flue gases of a gas mixture with an equivalence ratio 1.0.

The radiation efficiency was measured in accordance with the scheme presented in [12] using a 12A P/N 7Z02638 power sensor (Ophir, Israel): spectral range of 0.19 - 20 µm, specific power measurement range of 10² - 60 kW/m², and measurement accuracy of ± 3%.

3. Experimental results and discussion

It has been found that a steady state external combustion mode can be realized only for burners with an average size of the frame elements \( D_e = 600 \, \mu m \). The flashback into the cylindrical burner cavity is spontaneously realized during 15-30 seconds after the external lightning for burners with \( D_e = 1000 \, \mu m \) and \( D_e = 1350 \, \mu m \). For these burners, only the internal combustion mode might exist.

It has been also revealed that in the external combustion mode the higher is a firing rate and lower is the equivalence ratio, the higher CO/NOX concentrations are in the flue gases (figure 2). It has been also established that using a flow deflector is beneficial for decreasing the CO emission. NOx emission is the same no matter if the flow deflector has been installed or not. It has been found that the porous structure of a burner significantly determines CO emission in the internal combustion mode: the larger are the structural elements of the material, the lower is CO concentration in the flue gases (figure 3, a-c). It has been also established that with an increase of the firing rate, the CO emission decreases. Thus, at air-fuel equivalence ratio \( \alpha = 1.2 \), the CO concentration decreases from 50-100 ppm at 160 kW/m² to 5-10 ppm at 420 kW/m². It has been established that in external combustion mode there is no dependence of CO emission on a flow deflector.

It has been found that with a decrease in the equivalence ratio, the NOX concentration in the combustion products significantly reduces, while the NOX emission is practically independent on the firing rate and porous structure of the burner. As shown in fig. 3 d, for the case of installed flow deflector at \( \alpha = 1.1 \), the NOX concentration of about 40 ppm, at \( \alpha > 1.3 \) NOX < 20 ppm is provided. Without the flow deflector, the NOx emission is higher, and it might be attributed to the existence of non-uniform temperature field along the burner. It is believed that in a hotter region, the NOx emissions is higher [22].

It has been established that with a decrease in the equivalence ratio and the firing rate, the radiation efficiency slightly reduces (figure 4). In accordance with established conception of heat transfer between a fluid flow and porous media, the higher is the specific surface of the media, the more intense are heat transfer processes if other things are equal. From this point of view, the smaller is the porous channels, the higher is the temperature of the porous burner and, consequently, the higher radiation efficiency should be. Indeed, higher radiation efficiency was observed for the burner with the fine structure \( D_e = 600 \, \mu m \). However, the lower efficiency is not attributed to a burner with a coarse structure \( D_e = 1350 \, \mu m \). A burner with a coarse structure at 160 kW/m² shows practically the same efficiency as a burner with a fine structure and even higher at \( \alpha > 1.3 \). This tendency is neglected with an increase in a firing rate, and the efficiency for burners with \( D_e = 1000 \, \mu m \) and \( D_e = 1350 \, \mu m \) is practically the same at 420 kW/m². This interesting result is required to be investigated in depth, which is out of the scope of the current work.
Figure 2. Experimental dependences of CO (parts a-c) and NOX (part d) concentration on an air-fuel equivalence ratio for the external combustion mode and burner with average size of the frame elements 600 μm. Abbreviation FD stands for ‘flow deflector’.

Figure 3. Experimental dependences of CO (parts a, b) and NOX (part c) concentrations on an air-fuel equivalence ratio for the internal combustion mode. Abbreviation FD stands for ‘flow deflector’.

Figure 4. Experimental dependences of radiation efficiency on an air-fuel equivalence ratio for following firing rates: 160 kW/m² (part a), 260 kW/m² (part b), 420 kW/m² (part c). For the case when the flow deflector is installed.
4. Concluding remarks
The experimental findings have suggested that:
1). An internal combustion mode for burners with an average size of the frame elements $D_e > 1000 \mu m$ can be realized by means of external lightning. This feature is beneficial for the development of autonomous appliances with low-pressure injection fuel-air supply capable to work without electricity and spark plugs;
2). Environmental characteristics are strongly influenced by uniform distribution of an inlet flow of the fuel-air mixture over the inner cavity of the cylindrical burner. Therefore, to decrease the environmental impact of a certain burner, an appropriate flow deflector design should be considered;
3). Porous burners with an average size of the frame elements $D_e = 1350 \mu m$ are superior to the other ones. This porous structure provides the minimal CO emission and high radiation efficiency for the burner. The main factor in reducing CO/NOX emissions is the control of the equivalence ratio. So with the equivalence ratio of about 1.3, CO emissions are below 50 ppm, NOx emissions are below 20 ppm.

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References
[1] Arrieta C E, Garcia A M and Amell A A 2017 Int. J. Hydrogen Energy 42(17) 12669–80
[2] Janvekar A A, Miskam M A, Abas A, Ahmad Z A, Juntakan T and Abdullah M Z 2017 Energy 122 103–10
[3] Wood S and Harris A T 2008 Prog. Energy Combust. Sci. 34(5) 667–84
[4] Liu Z and Qiu K A 2017 Energy 141 892–7
[5] Wu H, Kim Y J, Vandadi V, Park C, Kaviany M and Kwon O C 2015 Appl. Energy 156 390–7
[6] Vasilik N Y and Shmelev V M 2016 Russ. J. Phys. Chem. B 10(5) 774–9
[7] Qiu K and Hayden A C S. 2009 Appl. Energy 86(3) 349–54
[8] Zhdanok S A, Dobrego K V and Futko S I 2000 Int. J. Heat Mass Transf. 43(18) 3469–80
[9] Hashemi S A, Nikfar M and Motaghedifard R 2015 Therm. Sci. 19(1) 11–20
[10] Shmelev V M 2014 Combust. Sci. Technol. 186(7) 943–52
[11] Fursenko R, Maznoy A, Odintsov E, Kirdyashkin A, Minaev S and Sudarshan K 2016 Int. J. Heat Mass Transf. 98 277-284
[12] Maznoy A, Kirdyashkin A, Minaev S, Markov A, Pichugin N and Yakovlev E 2018 Energy 160 399-409
[13] Deevi S C and Sikka V K 1996 Intermetallics 4(5) 357–75
[14] David S A and Deevi S C 2017 Sci. Technol. Weld. Join. 22(8) 681–705
[15] Grabke H J 1999 Intermetallics 7(10) 1153–8
[16] Kim S H, Oh M H, Kishida K, Hirano T and Wee D M 2005 Intermetallics 13(2) 129–36
[17] Czeppe T and Wierzbinski S 2000 Int. J. Mech. Sci. 42(8) 1499–518
[18] Maznoy A, Kirdyashkin A, Kitler V and Solovyev A 2017 J. Alloys Compd. 697 114–23
[19] Solovyev A A, Rabotkin S V, Shipilova A V, Kirdyashkin A I, Ionov I V, Kovalchuk A N, Maznoy A S, Kitler V D and Borduleva A O 2015 Int. J. Hydrogen Energy 40(40) 14077-84
[20] Levashov E A, Mukasyan A S, Rogachev A S and Shtansky D V 2017 Int. Mater. Rev. 62(4) 203–39
[21] Maznoy A S and Kirdyashkin A I 2014 Combust. Explo. Shock Waves. 50(1) 60–7
[22] Hill S C and Smoot L D 2000 Prog. Energy Combust. Sci. 26(4–6) 417–58