MODERN APPLICATION OF INERT OPEN-CELL POROUS CERAMIC MATERIALS FOR DESIGNING NON-CONVENTIONAL SELF-ASPIRANTING BURNERS

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ABSTRACT: The paper refers to the application of inert porous ceramic materials with large open pores in the construction of porous burners, capable of contributing to increasing the combustion stability, increasing the combustion speed, and reducing nitrogen oxide emissions (NO and NO_2). Two categories of porous ceramic materials were considered adequate for this purpose. A glass foam obtained by expansion of the glass waste and coal fly ash used the capacity of SiC as an expansion product to produce the suitable permeable body for the burning area of fuel-air mix. The method for making this porous piece had a special character of originality, the sintering/expanding heating being obtained through an own unconventional microwave heating technique, preponderantly direct and partially indirect. The porous ceramic piece for the combustion zone was procured from Germany. Testing the burner equipped with the two ceramic pieces confirmed the viability of the innovative solution.
KEYWORDS: porous burner, open-cell, SiC, nitrogen oxide emissions, radiant.

1. INTRODUCTION

Several advances of burning in porous ceramic structures compared to the conventional processes were found and researched since the first decades of the 20th century. These advantages are low pollutant emissions into the atmosphere, high radiant emissions as well as small burner dimensions. Despite the burning peculiarities in porous medium an important step in the field of these burner types was only achieved at the beginning of the new millennium. Obviously, a major role in developing the new combustion processes was played by the advances obtained in the manufacture of porous ceramic materials with open or semi-open pores [1].

By comparison with the traditional burning processes, the combustion technique in porous medium is characterized by higher burning rates, higher stability of the flame, much higher flame thermal radiation, lower emissions of nitrogen oxides (NO and NO_2) [1].

The operating principle of porous burners is based on the recirculation of hot waste gases in a porous ceramic piece that preheats the combustion air and also possibly the gaseous fuel [2]. As a result, the combustion speed becomes higher than that of a conventional flame, the operating stability improves and the emission of gaseous pollutants decreases. In general, the new type of burner consists of a pre-warming area of the energetic fluids prepared of a ceramic mater with low open cells and low heat conductance, playing the role of a flame barrier as well as a burning area produced of a ceramic mater with large open cells. If a stoichiometric fuel-air mixture is preheated, then at the boundary separating the two mentioned zones the fuel ignition occurs.

The main challenge of the permeable burner is to find the optimal solution for the manufacture of the permeable ceramic product in its burning area. A suitable variant was proposed in [3], consisting in the use of a ceramic froth (SiSiC) built on SiC with Si infiltrations. Alumina ceramic fiber was proposed for the preheating zone material.

According to [4], combustion in porous medium favours heat recirculation, which contributes to the local temperature increase and thus the process reactions take place at increased heat levels. The burning speed also grows by comparison with traditional burning processes. Due to heat reconditioned into permeable medium, the lower ignition limit can be improved facilitating the burning of reduced calorific value fuels [5]. Experimental determinations of operating with methane-air mix into SiSiC-permeable medium confirmed the results presented in the work [3].

In the work [6], authors designed and tested a burner operating in porous environment intended for household use for food preparation. The permeable ceramic product embedded in the burner body allowed pre-warming the self-aspirated combustion air by heat recovering in the area provided with small open cells. The heat recirculation from the burning area with large open cells offered the possibility of valorizing fuels with lower calorific value, thus increasing the energy effectiveness of the heating equipment application in the domestic sector [7].

The article [8] presented the realization of a burner operating with gaseous fuel and self-aspirated air preheated in a porous media. This type of burner was designed for use in heating processes in small and medium-sized companies, having as the objective increasing the energy efficiency of these processes. The preheating area was made of a layer of alumina spheres, while the combustion zone was constituted by a porous ceramic piece. The burner flame was submerged, the heat resulting from the strong thermal radiation of the superior surface of the ceramic body. The thermal power of the burner set was within the limits of 23-61 kW, carbon monoxide emissions being relatively low (below 200 ppm, i.e. 229 $mg\cdot m^{-3}$) and NO_x emissions being under 98 ppm, i.e. 240 $mg\cdot m^{-3}$.

The comparison performed in the paper [9] between performances of the preheating area of porous burner consisting of a 12-15 mm layer of alumina spheres and of the ceramic block with porosity of 40 % and thickness of 10 mm allowed the conclusion of the superior efficiency of the permeable body. The burner burning area produced of SiC-froth with thickness of 20 mm and high porousness (80-90 %) seems to be adequate. Froths with porousness of 90 % allow NO_x proportions in the range of 0-0.75 $mg\cdot m^{-3}$ and CO proportions within the limits of 12-124 $mg\cdot m^{-3}$. Compared to emissions of a burner based on liquefied petroleum gas, NO_x is in proportions in the range of 4-7 $mg\cdot m^{-3}$ and CO within the limits of 240-655 $mg\cdot m^{-3}$ [10].

A porous radiant burner applied in the household for food preparation is presented in the paper [11]. Experimental burners with inert medium porosities between 80-90 % were tried for different thermal powers. The highest thermal efficiency of the burner reached 75 %, being with 10 % higher compared to efficiency of conventional cooking stoves used in households operating with liquid petroleum gas (butane and propane). The measured CO emissions were between 10-160 $mg\cdot m^{-3}$ and those of NO_x were below 0.9 $mg\cdot m^{-3}$, for burner thermal powers between 1.3-1.7 kW.

Another work in the literature [12] confirms by own experimental results superior energy efficiency of burners intended for households and small-scale food industry, which use the heat recirculation of the exhausted hot gases due to the application of the porous media technique. According to the paper's authors, the energy efficiency of common household burners with open flame is very low (below 30 %). The utilization of permeable medium allowed the energy recycling for part of the waste gases heat for the purpose of advanced preheating of the combustion air up to 300 °C. A technical solution for further increasing the combustion efficiency is proposed in this paper, consisting in the simultaneous application of the swirling flame combustion (already known for several decades) [13, 14], which could increase the efficiency, in the authors' version, up to about 60 %.

A very recent work [15] has extended the applicability area of the use of porous inert media in case of an oxy-fuel burner, where the fuel is methane. Open-pore expanded ceramic materials were placed in the path of energy fluids having either variable cross-section or straight cylindrical structures. According to the experimental results, the cross-section structure proved its viability for extending the stability interval by more than four times. By growing loss of the heat at the exit due to the increased cross-section, its temperature is reduced under the temperature value of the straight cylindrical structure, so that the flame temperature in the case of adopting the variable cross-section will be lower compared to that corresponding to the use of the burner construction with straight cylindrical structures, provided that the walls are insulated. On the other hand, the efficiency of the thermal cycle in the case of the variable cross-section decreases by about 2 % compared to that specific to the application of the straight cylindrical structure. Regarding pollutant emissions, the variable cross structure favours a slight increase in CO emissions corresponding to low thermal powers, but it is lower than that characterizes the cylindrical structure at high thermal power. Heat loss through the burner walls is reduced by using the variable cross-section structure. Also, this type of structure ensures uniformity of the burner temperature in the exit area when the thermal power is high and at the same time, ensures the reduction of pollutant emissions. Therefore, at high thermal powers, adopting the structure with variable cross-sections is more efficient and leads to reduced pollutant emissions.

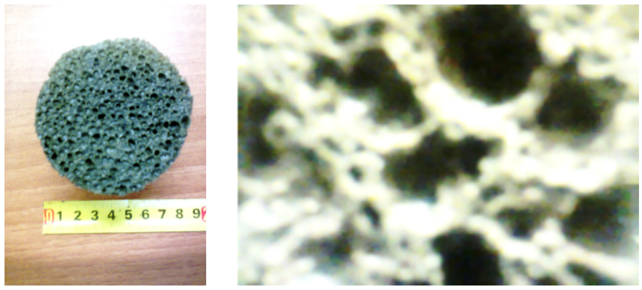
Current paper's authors conducted research in 2021 on the experimentation of a new 20 kW self-aspiration burning equipment operating with natural gas in inert permeable medium [10]. Two permeable bodies were performed in the Daily Sourcing & Research company (Romania) by expanding processes in an adapted microwave oven. The techniques chosen for the production of the two ceramic pieces have provided to reach sintering/expanding temperatures of 960 °C (required for making the piece designed for the preheating zone) and 1600 °C (required for producing the piece for the combustion zone). The manufacturing recipe for the first ceramic piece included 87 % glass waste, 10 % fly ash, and 3 % SiC, while the recipe used for production of the burning area body included 65 % SiC, 23 % rezidual clay, as well as 12 % fly ash, under the conditions of direct microwave heating [16]. The permeable product utilized for pre-warming area was a glass froth obtained by expanding with SiC at 960 °C. Pore size of the froth was under 1.2 mm, its structure including partly open cells (in proportion of about 50 %). Ceramic material features representing the burning area were: porousness of 36.8 %, heat conductance of 6.85 $W \cdot m^{-1} \cdot K^{-1}$, compression resistance of 58 MPa, thermal resistance at about 1400 °C, and pore dimension in the range of 2-5 mm, containing partly open cells (in proportion of approx. 60 %).

The objective of research presented in this paper was to improve the burner performance operating in inert porous medium. For this purpose, it was decided to adopt a SiC-reticulated foam with open pores of approximately 5 mm [17] purchased from Germany to be used as the burner combustion zone. The ceramic material of the preheating zone was made through the method used by authors in the previous work [9] for producing a glass foam from recycled residual glass, coal fly ash, and SiC as an expanding agent.

2. PROCEDURES AND MATERS

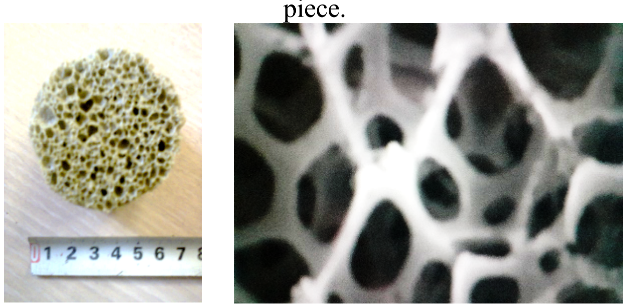
2.1 Procedures

In principle, the burner that is the subject of this research is a burner operating by self-aspiration of combustion air due to the high pressure of the central jet of gaseous fuel (natural gas in this case). This burner type is well-known in the thermal energy field. The novelty of the research is related to the way of transmitting thermal energy through the burner frontal area. The traditional self-aspirating burner develops a flame resulting from the ignition of the gas-air mixture, formed in the divergent area of the burner body. The stability of the burning procedure is usually ensured by a perforated metal piece (possibly a sieve). The new type of burner is provided with two ceramic pieces with open cells in contact, one in succession to the other. The first of them with fairly small pores (Figure 1) plays the role of preheating the mixture, while the second piece with large pores (Figure 2) constitutes the flame propagation area, ignited at the boundary between the two ceramic pieces. Obviously, in this combustion zone high temperatures develop (1100-1300 °C), that are transmitted by thermal conductivity to the preheating zone and the effect is increasing the temperature of the gas mixture with major implications on the efficiency of the combustion process, as well as the possibility of using fuels with lower thermal power. To obtain the maximum radiant effect it is advisable that the flames propagated through the channels of the cellular structure of the burning area finish their circulation at the superior face of the inorganic, heat-resistant piece (Figure 3). In this way, almost all of the available thermal energy is transferred to the hot heat-resistant body, which will radiate heat at maximum intensity. Thus, the application field of the porous burner will be focused on radiation drying processes (including industrial processes) and hot food preparing in the household.



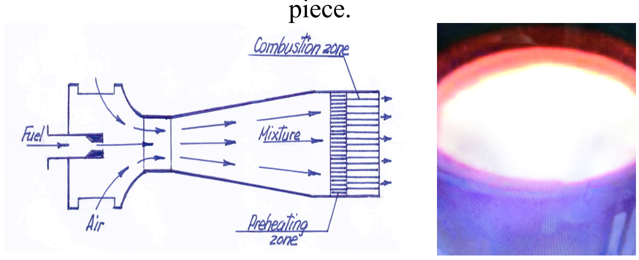
a b |-----| **1 mm**

Figure 1. Images of preheating zone
a – porous ceramic piece; b – microstructural aspect of the piece.



a b |------------| **4 mm**

Figure 2. Images of the combustion zone
a – porous ceramic piece; b – microstructural aspect of the piece.



a b

Figure 3. Images of the porous inert medium burner
a – burner scheme; b – thermal radiation.

The porous burner was tried in the open air, the area above its radiant surface being preserved with a heat-resistant hood. The operational frameworks were identified as follows: the natural gas flow rate with a natural gas flowmeter, the gas pressure with an Einstal manometer for gas pressure between 0-300 mbar, residual gas composition (CO_2, CO, O_2, NO, and NO_x representing NO_2) using a portable AFRISO MAXILYZER analyzer, and the radiant surface temperature of the burner with a Pyrovar-radiation pyrometer.

2.2 Materials

The burner was constructed from common metal components based on carbon steel, except for the cylindrical part of the burner head made of refractory steel containing nickel, chromium, and silicon. This cylindrical metal part will contain the two types of porous ceramic pieces in its interior space.

The inorganic, heat-resistant body representing the pre-warming area of the new burning equipment has been produced using an advanced unconventional microwave heating technique to foam the mixture composed of recycled residual glass, ash, and silicon carbide as an expanding product. The technique adopted by authors of the paper had own particularity by using a microwave-susceptible ceramic tube, positioned between the wave propagating source and the mater mixture to avoid too intense direct contact between microwaves and the glass [10].

The other heat-resistant body intended for the burning area was purchased from Germany as a SiC-reticulated froth with large open cells [15] (Figure 2).

3. OUTCOMES AND DELIBERATION

3.1 Outcomes

By designing, the following burner operational and constructive characteristics were chosen, being shown in Table 1.

Table 1. Operational and constructive features

Feature	Unit	Value
Nominal thermal power	kW	20
Fuel nature	--	natural gas
Nominal fuel flow rate	$m^3N\cdot h^{-1}$	2.0
Nominal fuel pressure	mbar	243
Fuel speed in the nozzle	$m\cdot s^{-1}$	120
Fuel nozzle inner diameter size	mm	2.5
Critical section size	mm	5.5
Angle of the burner divergent piece	degree	12
Stainless steel box size for ceramic porous pieces - inner diameter -length	 mm mm	 80 38

Testing the burner with nominal thermal power of 20 kW operating with natural gas and self-aspirated air, the combustion process taking place in an inert permeable medium, led to the following outcomes shown in Table 2.

Table 2. Testing outcomes

Natural gas		**Radiant surface temperature**	**Oxide composition of residual gas**				
Hourly flow rate ($m^3N\cdot h^{-1}$)	Pressure (mbar)	**(°C)**	CO_2 (vol. %)	O_2 (vol. %)	CO ($mg\cdot m^3N^{-1}$)	NO ($mg\cdot m^3N^{-1}$)	NO_2 ($mg\cdot m^3N^{-1}$)
2.2	260	1445	11.58	0.25	115	0.98	1.05
2.0	243	1440	11.54	0.28	114	0.94	1.05
1.8	168	1410	11.36	0.41	116	0.83	0.90
1.4	111	1354	11.21	0.56	119	0.79	0.73
1.1	79	1305	10.96	0.89	124	0.66	0.70

According to the data in Table 1, the experimental burner operational in inert porous medium has operated under very good stability conditions in the range of natural gas flow rates 1.1-2.2 $m^3N\cdot h^{-1}$ corresponding to fuel supply pressures within the limits of 79-260 mbar. In terms of energy, in the data range of 1.8-2.2 $m^3N\cdot h^{-1}$, the radiant surface temperature of ceramic piece representing burner combustion zone has exceeded 1400 °C, reaching to 1445 °C at the maximum thermal regime and 1440 °C at the nominal regime (2.0 $m^3N\cdot h^{-1}$). The oxide composition of waste gases captured from the burner head area allowed the evaluation of the performance of combustion process with self-aspirated air. Percentage volumes of CO_2, at least in the case of maximum and nominal regimes (11.58 and respectively, 11.54 vol. %) analyzed together the oxygen volumes in waste gases for the same thermal regimes (0.25 and respectively, 0.28 vol. %) indicate an excellent combustion efficiency for the burner type with air auto-aspiration. It can also be mentioned that the burner operates at a natural gas flow rate of 1.8 $m^3N\cdot h^{-1}$, for which 11.36 CO_2 and 0.41 % O_2 show very good combustion conditions. According to Table 1, the lowest value of CO emissions (114 $mg\cdot m^3N^{-1}$) corresponds to the nominal regime (2.0 $m^3N\cdot h^{-1}$), but also the neighbouring regimes (2.2 and 1.8 $m^3N\cdot h^{-1}$) record low CO values (115 and 116 $mg\cdot m^3N^{-1}$). Despite the high combustion temperature of over 1400 °C that favours nitrogen oxide emissions, the amounts of NO and NO_2 measured in waste gases are low (between 0.83-0.98 mg·m^{3}N^{-1} in the case of NO and between 0.90-1.05 mg·m^{3}N^{-1} in the case of NO_2). As is normal, the amounts of NO and NO_2 emitted at lower thermal regimes show a tendency to decrease their values.

3.2 Deliberation

The use in the household sector of self-aspirating air burners running with liquid crude oil gas (mixture of C_4H_{10} and C_3H_8) has significantly reduced pollutant emissions (CO, NO_x) compared to the old cooking equipment, but the energy efficiency of the burning process has remained below 35 % for common thermal powers between 10-70 kW of burners. Regulations in European Union countries require the use of thermal equipment with a minimum thermal yield of 52 % [7].

For this reason, recently, burning the gaseous fuel with heat recirculation through the use of permeable heat-resistant environment has become a concern and at the same time, a challenge for specialists in this field of thermal energy.

The materials designated to act as permeable heat-resistant materials for pre-warming area and respectively, for burning area of the burner have special characteristics. The material for pre-warming area was designed and made in the Daily Sourcing & Research Society (Romania) by expanding in the microwave oven, constituting one of originality elements of the work. The basic raw material was represented by recycled residual glass (87 %), including also coal fly ash (10 %), while fine SiC powder (3 %) constituted the expanding agent for creating the porous structure of the material.

Physio-mechanical and heat characteristics of the permeable product made for pre-warming area were: apparent denseness of 0.29 g·cm^{-3}, porousness of 85.2 %, thermal conductance of 0.069 W·m^{-1}·K^{-1}, compression resistance of 1.9 MPa, as well as pore size within the limits of 0.2-1.2 mm.

The other permeable body used to constitute burning area of this heating equipment was processed from a sample of SiC-reticulated froth procured from Germany, with dimensions of 100 x 100 x 12 mm and large open cells in the range of 2-5 mm. The porousness of this material exceeded 90 %, while the compression resistance was around 1 MPa.

4. CONCLUSION

The research has sought to achieve in Romania one of the first types of self-aspirating burner based on the use of porous ceramic materials with predominantly open cells. In this work, the authors' concern was focused on the permeable heat-resistant body constituting pre-warming area of the heating equipment. Made from recycled residual bottle and recycled industrial coal ash as feedstocks as well as SiC as an expanding product, the permeable body was sintered and foamed at 960 C through an own technique of preponderantly direct and partly indirect microwave heat treatment. This permeable piece had the following physical, thermal, and mechanical characteristics: denseness of 0.29 g·cm^{-3}, porousness of 85.2 %, heat conductance of 0.069 W·m^{-1}·K^{-1}, compression resistance of 1.9 MPa, and cell dimensions within the limits of 0.2-1.2 mm. The permeable material chosen for the combustion zone of the burner was purchased from Germany and was a SiC-reticulated foam with large open pores between 2-5 mm. The porousness of this material was very high of over 90 %. Trying the burner equipped with the two ceramic permeable pieces confirmed the viability of the innovative solution.

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