 ©2021 Romanian Association of Nonconventional Technologies

NONCONVENTIONAL TECHNIQUE OF FUEL COMBUSTION IN POROUS INERT MEDIA

Lucian Paunescu[1,2] and Sorin Mircea Axinte[3,4]
[1] Bilmetal Industries SRL Popesti Leordeni-Ilfov, Romania, lucianpaunescu16@gmail.com
[2] Daily Sourcing & Research SRL Bucharest, Romania, lucianpaunescu16@gmail.com
[3] Daily Sourcing & Research SRL Bucharest, Romania, sorinaxinte@yahoo.com
[4] Department of Applied Chemistry and Materials Science, University POLITEHNICA of Bucharest, Romania, sorinaxinte@yahoo,com

ABSTRACT: The first achieving in Romania of a self-aspirating burner using the nonconventional technique of burning in a porous inert media is presented in the paper. The originality of the work is the way of manufacturing the porous ceramic piece in the combustion zone of the burner by using the nonconventional method of producing a SiC ceramic foam by direct microwave heating. The main characteristics of the ceramic piece are: porosity of 36.8%, compressive strength of 58 MPa and operating temperature of 1430 ºC. The burner was made for operation with natural gas with a nominal thermal power of 20 kW. The concentration of pollutants emitted into the atmosphere is low: CO below 120 mg/m^{3}N and NO_x below 1.03 mg/m^{3}N.
KEYWORDS: self-aspirating burner, porous inert media, natural gas, SiC ceramic foam, pollutant, microwave.

1. INTRODUCTION

The combustion technology in a porous media is based on the stabilization of combustion reactions in an inert ceramic structure with open cells. Significant advantages result from burning in porous structures compared to conventional free flame burners including low pollutant emissions, high efficiency of radiant emissions, small burner size. Although the process of burning in a porous media began to be researched in the first decades of the last century, only recently (after 2000) important results were obtained. In general, the porous ceramic materials used in burners are exposed to severe thermal and mechanical stresses due to the combustion processes developed in their area. Porous structures must have high mechanical and thermal resistance, low pressure loss and long life [1].

The new technology is characterized by higher combustion rates, higher flame stability, higher radiation, lower combustion zone temperatures and, implicitly, lower NO_x emissions [1].

According to [2], the porous burners run on the principle of recirculating the heat of the hot waste gases in the ceramic porous piece to the reactants that supply the burner (fuel and combustion air). Consequently, the burning rates are higher compared to those of a free flame. Also, pollutant emissions are lower and the functional stability is better over a wide range of fuel flows and concentrations. In principle, the porous burner has a preheating zone of the gaseous mixture of fuel and air made of a ceramic material with small open pores and low thermal conductivity acting as a flame barrier and a combustion zone made of a ceramic material with large open pores. At the separation limit between the two areas, the mixture ignites.

One of the main problems of making a porous burner is the suitable type of ceramic material. The paper [3] considers that the combustion area in the burner with an applicability limit of 1400 ºC should be a ceramic foam based on silicon infiltrated silicon carbide (SiSiC). The flame trap is usually made of alumina ceramic fiber with an artificial bore pattern.

According to [4], the combustion in porous inert media contributes to intensify the heat transfer and the mixing of reactants. Major different characteristics of this combustion type compared to the free combustion are exhibited like the reduction of pollutant emissions (NO_x and CO), the increase of the thermal emissivity and the flame stability range as well as the reduction of the thermo-acoustic instabilities. By combustion in porous media, burning low-heating value gaseous fuels becomes possible. The combustion in a porous media favors the heat recirculation. By cross-mixing, the hydrodynamic dispersion can occur by improving the heat propagation. Its recirculation increases locally the gas temperature and chemical reactions occur at a higher temperature. Consequently, the burning rate increases compared to the free burning. Due to the recirculation of heat in the porous media, the low flammability limit may increase allowing the combustion of fuels with low energy content. The results of the experiments described in the work confirmed the increase of combustion rates and flame thickness compared to the laminar free combustion mode. Measurements were performed for a methane-air mixture in a SiSiC porous media. The flame being stabilized at the porous surface, part of the heat released by the combustion reactions is transferred to the porous solid body. Its temperature rises so that the burner adopts a functional radiant mode.

The research presented in the paper [5] was focused on the development of a type of burner with porous media operation for use in the household in food preparation. The authors considered that in the European Union countries the household sector consumes 25% of the total thermal energy and that 25% of the CO_2 emissions belong to this sector [6]. According to [5], the thermal energy released by combustion of fuel with air heats the solid porous body by convection, which then transmits the heat by radiation and convection causing upward heating. Thus, the cold fluids (fuel and air) that enter into the burner body are preheated in the porous preheating area with small pore size. This recirculation of the heat from the combustion zone to the preheating zone leads to the burner ability to use fuels with lower calorific value or lean fuel mixtures.

A type of burner operating in a porous media with self-aspirating, the porous combustion area being a bed of 15 mm-alumina spheres, was achieved [7] for higher thermal powers (between 23-61 kW). Operating with liquefied petroleum gas (LPG) containing butane and propane (around 46 MJ/kg), the burner had an output radiation efficiency of 23% and a turn-down ratio of 2.65. The CO emission was less of 200 ppm and NO_x emission was below 98 ppm.

A comparative analysis [8] of the construction of some burners using as a porous media in the preheating area a bed of alumina balls with a layer height of 12-15 mm and respectively, a ceramic block with a thickness of 10 mm and a porosity of 40% led to the conclusion that the porous media made of ceramic block is more efficient. For the combustion zone of the burner, a SiC-ceramic foam with a thickness of 20 mm and a porosity between 80-90% is indicated. In the case of SiC foam with a porosity of 90%, NO_x emissions ranged between 0-0.75 mg/m^3 and CO emissions ranged between 12-124 mg/m^3. By comparison, the conventional LPG hobs have NO_x emissions between 4-7 mg/m^3 and CO emissions in the range of 250-650.7 mg/m^3.

An important problem of making a porous burner is the preparation of the ceramic material intended for burning in a porous media. The use of this material as a component part of the burner requires resistance to high temperature and thermal shock as well as mechanical strength. An American patent [9] proposes an open cell silicon carbide ceramic foam, resistant to high temperatures and thermal shocks. The manufacturing process involves mixing a SiC powder with clay and aluminum oxide. Sintering occurs at temperatures between 1100-1400 ºC. Thus, the SiC granules are coated with vitreous or semicrystalline aluminosilicate compounds.

A team of researchers from the Romanian company Daily Sourcing & Research, including authors of the current paper, experimentally manufactured on a small scale [10] various SiC ceramic foams with partially open pores. The applied technique was nonconventional using the direct microwave heating, a pressed powder mixture composed of SiC powder (between 40-75 wt.%), recycled red clay waste (between 15-40 wt.%) and coal fly ash (between 10-20 wt.%) being sintered and foamed at temperatures between 1560-1610 ºC. The manufactured ceramic material had the apparent density between 1.05-1.38 g/cm^3, porosity between 37.1-51.4%, thermal conductivity in the range of 2.34-6.85 W/mK and compressive strength between 28.3-58.0 MPa, being suitable for use as a porous inert media in the combustion zone of the porous burner.

2. ADOPTING THE TECHNICAL SOLUTION

The type of burner presented in this paper is a self-aspirating air burner running on natural gas. The fuel is fed through an axial pipe with a nozzle that distributes the gas jet at high rate (over 100 m/s) capable of aspirating the atmospheric air due to the depression created by side slits in the premix chamber. The burner has the shape of an ejector (convergent-divergent), the fuel and air being mixed in the diffuser (divergent piece). The front area of the burner contains a ceramic piece with small open pores, which is the preheating zone of the mixture and a SiC-based ceramic piece with larger open pores, which is the combustion zone. The porous ceramic pieces in the frontal area constitute the components of the burner in which the combustion takes place in a porous media with the recirculation of the residual gases and respectively, the preheating of the mixture of energetic fluids by taking over the heat of the recirculated gases. The fuel mixture ignites on the separation surface between the preheating zone and the combustion zone. A constructive and functional scheme of the porous burned designed for testing is shown in Figure 1.

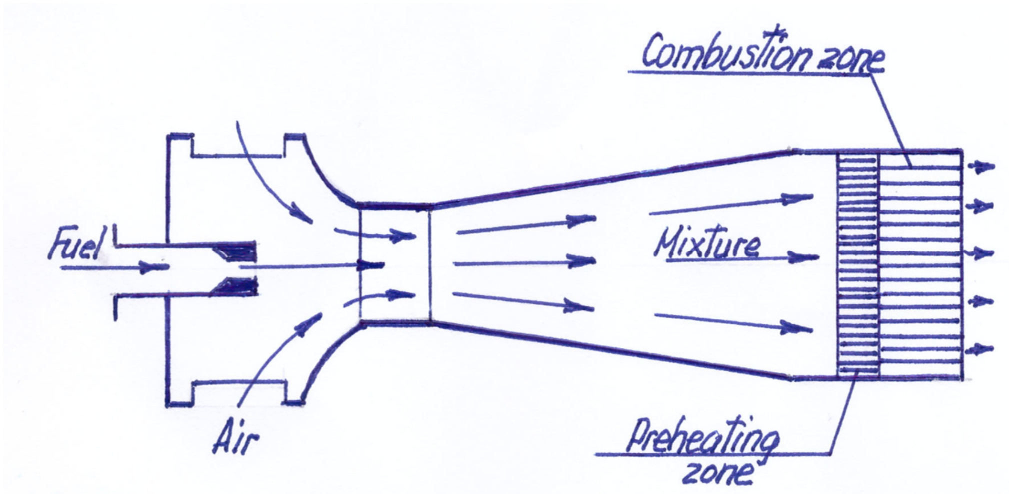


Figure 1. Construction and functional scheme of the porous burner

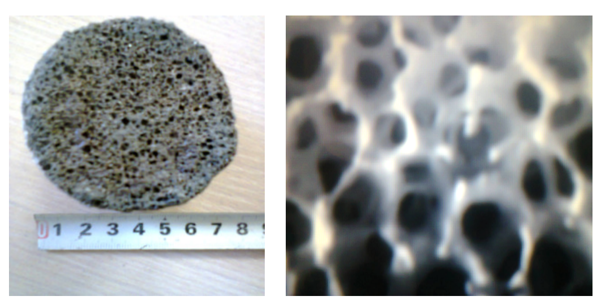
The metal construction of the burner including the natural gas supply, the air aspiration mode and the mixing of the two fluids is similar to that of the self-aspirating burner using catalysts to intensify the combustion process [11] made by the main author of the current paper. The honeycomb type front ceramic piece made by extrusion, whose channels are impregnated with catalysts of the burner previously made compared to the two porous ceramic pieces of the porous burner constitutes the main constructive difference between the two burners.

For the front porous area of the burner, two types of porous material manufactured on a small scale on a 0.8 kW-microwave oven were adopted in the Romanian company Daily Sourcing & Research, the partner in performing this project. The basic component of the front area was a SiC ceramic foam made of SiC powder (65 wt.%), recycled red clay waste (23 wt.%) and coal fly ash (12 wt.%) sintered at 1600 ºC. The main characteristics of this material were: apparent density of 1.39 g/cm^3, porosity of 36.8%, thermal conductivity of 6.85 W/m·K and compressive strength of 58.0 MPa [10]. The thickness of the ceramic piece used in the combustion zone of the burner was 25 mm and its diameter was 95 mm. Figure 2 shows a cross section of the piece (a) and its microstructural configuration (b). The pore size of this ceramic foam was between 2-5 mm, the microstructure containing partially open cells (about 60%).

a b

Figure 2. Ceramic body that composes the combustion zone of the burner
a – cross section; b – microstructural image.

For the preheating zone of the fuel and air mixture, a glass foam made of glass waste (87 wt.%), coal fly ash (10 wt.%) and SiC (3 wt.%) as a foaming agent, by sintering at 960 ºC in the 0.8 kW-microwave oven was adopted. The thickness of this glass foam was 15 mm and its diameter was 80 mm. The features of this material were: apparent density of 0.34 g/cm^3, porosity of 82.3%, thermal conductivity of 0.071 W/m·K and compressive strength of 1.9 MPa [12]. The pore size of the glass foam was between 1.0-1.2 mm, the microstructure containing partially open cells (about 50%). Figure 3 shows the cross section and the microstructural image of the glass foam body that composes the preheating zone of the burner.



a b

Figure 3. Glass foam body that composes the preheating zone of the burner
a – cross section; b – microstructural image.

The main data used for designing the experimental porous burner were:

Nominal thermal power:	20 kW
Nominal natural gas flow:	2 m^3N/h
Natural gas pressure:	250 mbar
Natural gas rate in the nozzle:	120 m/s
Nozzle size of natural gas:	2.5 mm
The size of the critical section:	5.5 mm
Divergent piece angle:	12 °
Metal box size for the porous material	
- length:	44 mm
- outer diameter:	105 mm

3. EXPERIMENTATION METHODS

Several constructive variants of the porous ceramic piece for the combustion zone of the burner have been preliminarily tested being assembled in the metal construction of the self-aspirating burner designed according to the above data. SiC ceramic foams previously manufactured in the Daily Sourcing & Research company were used in four experimental variants according to the own recipes from SiC powder, red clay waste and coal fly ash within the limits mentioned above, sintered at different temperatures between 1560-1610 ºC. The optimal solution that allows the combustion of the natural gas-air mixture in a porous media without the flame leaving the ceramic piece, ensuring an intense thermal radiation of its surface was determined being manufactured at 1600 ºC from 65 wt.% SiC powder, 23 wt.% recycled red clay waste and 12 wt.% coal fly ash. The compressive strength (58 MPa) and the shock resistance of this material were very high, the porosity being 36.8% [10].

The testing of the experimental burner was performed outdoors, its upper area being protected with a ceramic tube. The following functional parameters were determined: hourly flow and pressure of natural gas, waste gas composition (CO_2, CO, O_2, NO, NO_x as NO_2) measured with a portable AFRISO MAXILYZER analyzer as well as the radiant surface temperature of the burner determined with a Pyrovar type radiation pyrometer.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Experimental results

The experimentation of the porous burner, the first burner of this type made in Romania, took place in Daily Sourcing & Research. Five thermal regimes were tested, the hourly flow of natural gas having values between 2.0 and 0.9 m^3N/h. The results of the measurements are presented in Table 1.

Table 1. Functional parameters of the 20 kW-porous burner

No. test	Natural gas		Chemical composition of waste gas					Waste gas temperature ºC
	Hourly flow m^3N/h	Pressure mbar	CO_2 vol.%	O_2 vol.%	CO mg/m^3N	NO mg/m^3N	NO_x mg/m^3N	
1	2.0	250	11.55	0.28	115	0.95	1.01	1430
2	1.8	226	11.38	0.40	120	0.94	1.03	1410
3	1.5	205	11.19	0.58	103	0.81	0.89	1360
4	1.2	174	10.94	0.88	116	0.63	0.70	1310
5	0.9	139	10.68	1.33	114	0.52	0.60	1240

According to Table 1, the operation of the porous burner at nominal flow (2 m^3N/h) and at lower flows up to 1.5 m^3N/h is efficient, the volumetric proportion of CO_2 having values of over 11% (for natural gas, the theoretical maximum proportion is 11.73%). The temperature of the radiant front surface of the ceramic piece reached temperatures of over 1400 ºC (corresponding to higher natural gas flows between 1.8-2.0 m^3N/h). The effect of the heating system in a porous inert media is felt in terms of emissions. The CO emissions are low between 103-120 mg/m^3N, but the very low levels of NO and NO_x (below 0.95 and respectively, below 1.03 mg/m^3N) are remarkable.

An image of the radiant front surface of the porous burner corresponding to the nominal flow of natural gas is shown in Figure 4.

Figure 4. Image of the radiant front surface of the burner during the heating process

4.2 Discussion

The self-aspirating burner with combustion in a porous inert media without free flame is applicable in industrial or household fields for radiation heating processes. The burner presented in this paper was made entirely in the company Daily Sourcing & Research, including both its metal construction that facilitates the aspiration of combustion air and the energy fluids mixing and the porous ceramic zone that ensures the combustion process in a porous media. The porous ceramic area of the burner is the result of research in the field of nonconventional manufacture (with microwave energy) of glass foams and ceramic foams within this company.

Although the thermal resistance of the ceramic piece for combustion in a porous media does not reach the temperature level of SiSiC type materials (around 1600 ºC) made in the world (Fraunhofer IKTS Dresden, Germany) for industrial processes, the resistance of the ceramic foam used in the burner presented in the paper is adequate for temperatures in frontal area up to 1430 ºC.

The level of pollutants and the working temperature developed by the burner are much improved compared to conventional self-aspirating burners using a refractory wire mesh to stabilize the free flame, characterized by CO emissions below 965 mg/m^3N, NO_x emissions below 263 mg/m^3N and temperatures under 1200 ºC.

5. CONCLUSION

The paper presents the first achieving in Romania of a self-aspirating burner using the nonconventional technique of combustion in a porous inert media.

The originality of the work is the way of manufacturing the porous ceramic piece in the combustion zone of the burner by using the nonconventional method of producing a SiC ceramic foam by direct microwave heating.

The features of the SiC ceramic foam were: apparent density of 1.39 g/cm^3, porosity of 36.8%, thermal conductivity of 6.85 W/m·K, compressive strength of 58.0 MPa and the pore size between 2-5 mm, the microstructure containing partially open cells (about 60%).

The ceramic material used in the preheating zone was a glass foam manufactured also in microwave field by sintering at 960 ºC, using glass waste, coal fly ash and SiC as a foaming agent. The pore size of the glass foam was between 1.0-1.2 mm, the microstructure containing partially open cells (about 50%).

The combustion in porous inert media favors the heat recirculation. This increases locally the gases temperature and the oxidation chemical reactions occur at higher temperature. Compared to the free flame combustion, the burning rate in porous inert media increases.

The experimental burner was tested in the stable operation range between 0.9-2.0 m^3N natural gas/h. The natural gas supply pressure varied between 139-250 mbar, the nominal pressure being the maximum value. The radiated heat of the upper surface of the ceramic piece of the burner measured with the radiation pyrometer indicated the maximum value of the temperature of 1430 ºC. The minimum value corresponding to the minimum thermal regime was 1240 ºC.

The use of the combustion technique in a porous inert media had the effect of significantly decreasing the concentration of pollutants released into the atmosphere. The CO emissions dropped below 120 mg/m^3N and the NO_x emissions reached very low limits below 1.03 mg/m^3N.

For the next steps, the research could be developed in the direction of improving the resistance to higher temperatures of the porous ceramic material used in the combustion zone.

6. REFERENCES

1. Mach, A., Herzog, A., von Issendorff, F., Kanka, B., CERPOR-Optimized ceramic components for the porous burner technology, *Interceram: International Ceramic Review,* (2006). http://www.researched.net/publication/287350529_CERPOR_Optimized_ceramic_components_for_the_process_burner_technology

2. Wood, S., Harris, A.T., Porous burners for lean-burn applications in *Progress in Energy and Combustion Science (Elsevier)*, Vol. 34, No. 5, pp. 667-684, October (2008). https://www.doi.org/10.1016/j.pecs.2008.04.003
3. Reusse, E., Trimis, D., Innovative natural gas-fired porous burners for high temperature applications and potentials for reduced energy consumption and reduced emissions, *European Gas Research Group Academic Network Event* in Brussels, June 3-4, (2010).
4. Bedoya, C., *Stationary flames within porous inert media*, PhD thesis at the Technology Institute of Karlsruhe, Germany, January (2016).
5. Malico, I., Mujeebu, M.A., Potential of porous media combustion technology for household applications, *International Journal of Advanced Thermofluid Research,* Vol. 1, No. 1, (2015) (online). Published by: International Research Establishment for Energy and Environment, Kerala, India, (2015). http://www.ireee.net
6. End-user GHG emissions from energy. Reallocation of emissions from energy industries to end users 2005-2009. European Environmental Agency, Report no. 19, (2011).
7. Yoksenakul, W., Jugjai, S., Design and development of a SPMB (self-aspirating, porous medium burner) with a submerged flame, *Energy*, Vol. 36, No. 5, pp. 3092-3100, (2011).
8. Muthukumar, P., Anand, P., Sachdeva, P., Performance analysis of porous radiant burners used in LPG cooking stove, *International Journal of Energy and Environment*, Vol. 2, No. 2, pp. 367-374, (2011).
9. Adler, J., *Open-celled silicon carbide foam ceramic and method for production thereof*, US Patent 6887809B1, (2005).
10. Axinte, S.M., Paunescu, L., Dragoescu, M.F., Silicon carbide ceramic foam produced by direct microwave heating, *Nonconventional Technologies Review,* Vol. 24, No. 2, pp. 45-51, (2020).
11. Paunescu, L., Hritac, M., Despa, M.M., Craciun, A., Covaleov, V., Surugiu, G., Innovative solution of catalyzers using at self-aspirant burners destined to blast furnaces spouts drying, *Metallurgy and New Materials Researches*, Vol. 21, No.4, pp. 1-11, (2013).
12. Paunescu, L., Axinte, S.M., Cosmulescu, F., Experimental manufacture of heat insulating plates by expanding the glass waste in the microwave field, *Nonconventional Technologies Review,* Vol. 24, No. 4, pp. 7-12, (2020).