Influence of the Inter-structural Gap between the Combustion Zone and the Flame Trap on the Properties of the dual Layer Porous Burners in Operation

V. Jovicic*[1,2], E. Friedmann[1], C. Regensburger[1], A. Zbogar-Rasic [1], A. Delgado [1,2]

[1] Institute of Fluid Mechanics (LSTM), University of Erlangen-Nuremberg, Germany
[2] Erlangen Graduate School in Advanced Optical Technologies (SAOT), Germany

Abstract

One of the flame stabilization principles for the porous burner technology is based on the sudden change of the pore size, i.e. application of two adjacent porous zones. When the temperatures exceed 1500°C, material damage at their contact surface can occur. Conducted experimental investigation shows the influence of the existence of an axial distance between the two porous zones on the burner properties (pressure drop, flue gas composition, operation range, surface temperatures). The modified burner, i.e. with the gap between the zones, has lower CO but higher NO_x emissions and a wider operational range at the equivalent inlet conditions compared to the reference burner. Experiment showed when the axial distance between the zones is small, the operating characteristics of the burner are not significantly changed.

Introduction

Porous burner combustion is a combustion technology where a fully premixed fuel gas – air mixture burns inside the holes of a porous, inert structure, mainly made of ceramic materials [1 – 4]. Due to the presence of the porous material in the combustion zone, an intensive thermal energy transfer between the gas phase and the porous medium occurs, resulting in a homogenization of the temperature field and lower pollutant emissions (CO, NO_x) [1, 2]. This combustion technology offers, as in the literature well documented [2, 3], benefits for both domestic heating devices and different industrial applications, through its high thermal radiation output, reduced space requirement, high power modulation range, short reaction time, etc.

The flame stabilization concepts for the porous burners are based on the modified Pécklet number (dual layer stabilization) [5, 6], velocity– [7] and jet stabilization [8], and active cooling [9]. The flame stabilization based on the modified Pécklet number, shown in Figure 1, enables a wide operational range with regard to the thermal power, and is commonly applied in commercially available porous burners.

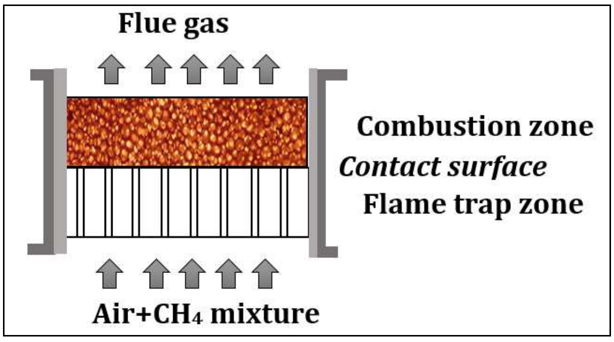

Figure 1. Scheme of the burner layout.

In this case, the flame is stabilized due to a sudden change of the pore diameter between the combustion zone (big pores) and the flame trap/preheating zone (small pores). Smaller pore diameter of the flame trap zone leads to flame quenching within it, thus preventing the flame flash-back. This stabilization principle provides the power modulation range of up to 1:10 under normal operating conditions [2, 3].

As the combustion takes place within a porous medium, the porous structure of a combustion zone commonly reaches the temperature between 1000°C and 1400°C [1, 3]. The highest operating temperature is generally limited by the physical properties of the applied (ceramic) materials. As a result, the porous burner technology is dependent on high temperature and oxidation resistant porous materials, which can withstand high temporal and spatial temperature gradients (leading to high thermal stresses), occurring e.g. during the ignition phase [1, 10, 11].

Regarding the combustion zone of a dual layer porous burner, silicium infiltrated silicium-carbide (SiSiC) is the most commonly applied. SiSiC has good thermal shock resistance, high thermal conductivity and good material stability [1, 12]. Its maximal operating temperature is limited to ca. 1450°C due to the separation of the free silica and due to the material that follows oxidation [13]. Apart from SiSiC, materials like Al_2O_3, ZrO_2, C/SiC composite ceramics, etc. [11] can be also used as porous burner components.

In comparison to the combustion zone material, the flame trap material should possess very low thermal conductivity in order to prevent flame flash-back. Most commonly, vacuum-formed aluminum oxide is applied for this purpose [1].

Further development of the porous burner technology often demands higher radiation output and higher overall efficiency, which can be achieved only by increase of its maximum operating temperature. For

---

* Corresponding author: vojislav.jovicic@fau.de

the applications of a porous burners in the temperature range above 1500°C, beside the need for the high temperature and high thermal shock resistant combustion zone materials, it is essential to develop appropriate materials and structures for the flame trap zone.

In-house experiments showed that in case when the perforated, vacuum formed aluminum oxide is applied as the flame trap zone, temperatures far above 1500°C at the contact surface between the two materials, should be avoided. Results of the experiments done with the temperatures of the combustion zone over 1600°C have often led to damaging and local melting of the flame trap zone material and further to an irregular and unsafe porous burner operation mode.

Objectives

One potential solution in order to avoid damaging of the flame trap zone in high temperature applications, is to introduce a small axial gap between the two layers of the porous burner. In this way, a direct contact between the materials of the flame trap and combustion zone in the area where the maximum temperature is reached, can be avoided. Furthermore, this approach can diminish the possibility of overheating, melting and/or high temperature chemical reactions. On the other hand, the rate of thermal energy transfer via conduction between the zones is expected to decrease, leading to increased temperatures of the combustion zone and decreased preheating in the flame trap zone.

In the scope of this work, an experimental investigation of the influence of the axial distance between the combustion- and the flame trap zone of a dual layer porous burner on its operational properties is presented.

Experimental set-up

The experimental set-up for determining the influence of the axial gap between the combustion and the flame trap zone of the dual layer porous burner is presented in Figure 2.

The flows of the combustion air and the fuel gas (methane) was independently controlled using mass flow controllers (MFC). The two gas streams were mixed inside a mixer, and then introduced into the dual layer burner, where it combusted. The burner outlet was placed in the open-end oven, with a direct connection to the atmosphere, in order to provide a visual access for the pyrometer, used for the measurement of the porous burner surface temperature. The flue gas samples for further analysis were taken approximately 100 mm below the outlet section of the oven, in order to minimize the influence of the secondary air. The pressure sensor for the measurement of a pressure drop in a burner was connected to the mixer housing, below the burner inlet.

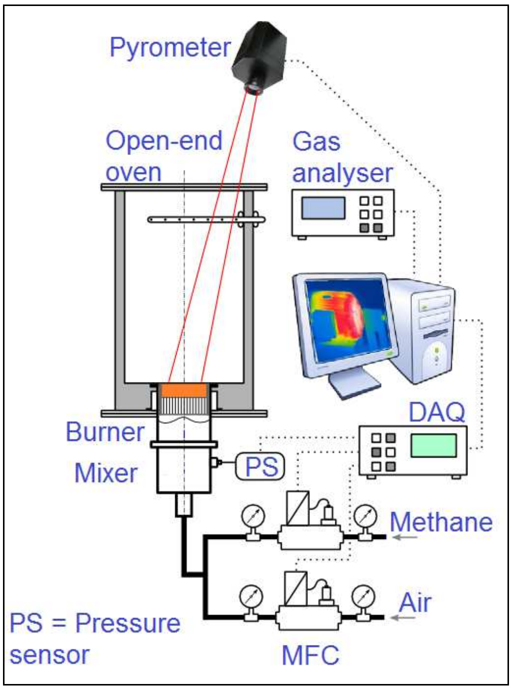

Figure 2. Scheme of the experimental set-up.

In the scope of this study two burner types were investigated, i.e. the reference burner with no axial distance between the zones (l = 0 mm), and the modified burner with the axial gap between the two zones ($l > 0$ mm).

The tested dual layer burners had a cylindrical shape with porous inert matrix diameter of d = 70 mm. Burner consisted of a 15 mm thick SiSiC combustion zone and a 20 mm thick vacuum-formed aluminum oxide flame trap zone. The ceramic material was fixed into a metal burner housing, from which it was insulated with app. 8 mm thick insulation material. The axial distance between the two zones was varied in the range from l = 0 mm to l = 50 mm. The burners were operated at thermal loads of 500 and 1000 kW/m^2 and the excess air ratios λ = 1.3 – 1.7.

Results and Discussion

Properties of the porous burner in operation were evaluated based on the pressure drop, the blow-off conditions, the ceramic surface temperature and the flue gas composition.

The pressure drop in the porous burner structure was measured under cold flow conditions. Results quantify increase of a pressure drop with increase of the axial distance (gap) between the zones (Figure 3).

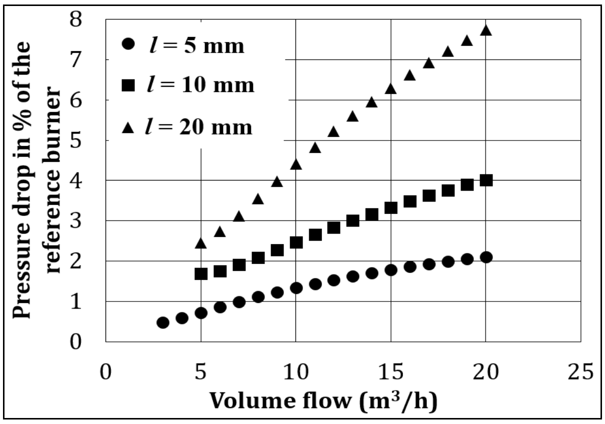

Figure 3. Pressure drop in the modified porous burner.

Experiments showed that as the inter-layer axial distance increased from l = 5 mm to l = 20 mm, the pressure drop in the burner was also increased. After the gap was further extended, the pressure drop started to decrease (not shown in the figure). This behavior can be explained by formation of a vortex region, caused by the increase of the gap length, which influences the increase in the local pressure drop. With further extension, the vortexes were still formed at the mixture entrance region, but the uniform flow was reestablished before mixture entered the burner.

The surface temperature of the burner ceramic material was measured using the two-color pyrometer. Results were acquired for the range of axial distances l = 10 – 50 mm between the two burner zone. Measurement results for the thermal load of 500 kW/m^2 and for the excess air ratios λ = 1.2 – 2 are presented in Figure 4.

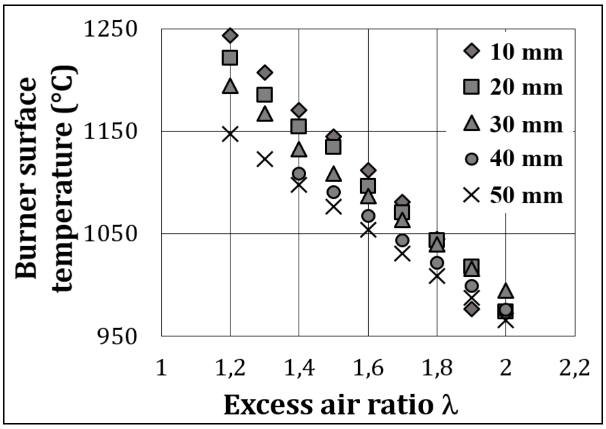

Figure 4. Temperature of the SiSiC-combustion zone at the thermal load of 500 kW/m^2.

As the excess air ratio (λ) increased, the surface temperature decreased, as could be expected in relation to the flame temperature tendency. As the gap between the zones expanded, the measured material temperature of the SiSiC zone decreased. This behavior is a consequence of a movement of the flame front stabilization plane away from the combustion zone, deeper into the inter-layer gap, i.e. towards the mixture inlet. As the flame front stabilization plane moves away from the porous structure, the free flame forms within the inter-layer gap. As a consequence the ceramic material of a combustion zone is less heated. With the formation of the free flame, the gas temperature is expected to increase, which might influence the increased NO$_x$ concentration level.

Figure 4 further shows that the maximum temperature difference for different gap values was detected for the lowest tested excess air ratio, i.e. $\Delta T \approx 100°C$ at λ = 1.2. As the excess air ratio was increased, the temperature difference was decreased, to reach $\Delta T \approx 50°C$ at λ = 1.8 at the corresponding inter-layer distances. As the excess air ratio was increased above λ = 1.8 for the axial gap distance of l = 10 mm, the material temperature decreased rapidly, due to the flame lift-off.

Overall, this set of experiments indicate that the inter-layer distance has a decreased effect on the material temperature as the excess air ratio, and consequently the flow rate through the burner, is increased. With the increased flow rate, the formation of the free flame within the inter-layer gap is suppressed.

Figure 5 shows the temporal temperature gradient of the combustion zone material during the flame blow-off process. The results are presented for the thermal load of 500 kW/m^2 as the gap was increases from l = 10 mm to l = 50 mm.

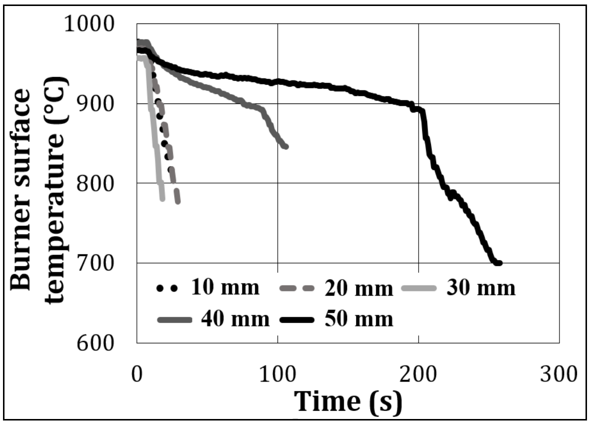

Figure 5. Comparison of the temporal temperature gradient during the flame blow-off at the thermal load of 500 kW/m^2.

Experimental results show that the blow-off behavior stays almost the same as the inter-layer distance in the modified burner increases from l = 10 mm to l = 30 mm. The gradient of the material temperature decrease is in this range of inter-layer gap distances slightly increased, i.e. up to the value of l = 30 mm the combustion zone temperature decreases faster. As the axial distance between the two zones is further increased, the temperature initially drops very slowly, indicating that the free flame stabilized itself within the porous burner structure, which temperature was stayed almost unchanged. After a certain time, e.g. after t = 200 s in case of l = 50 mm, a sudden drop in material temperature occurs, indicating the start of flame blow-off, due to the flow conditions.

Further, the influence of the distance between the zones on the emissions of CO were investigated in the range of axial inter-layer distances of *l* = 0 – 20 mm. As is shown in Figures 6 and 7, the modified burner emitted lower amount of CO over the range of the excess air ratios of λ = 1.3 – 1.7, compared to the reference burner.

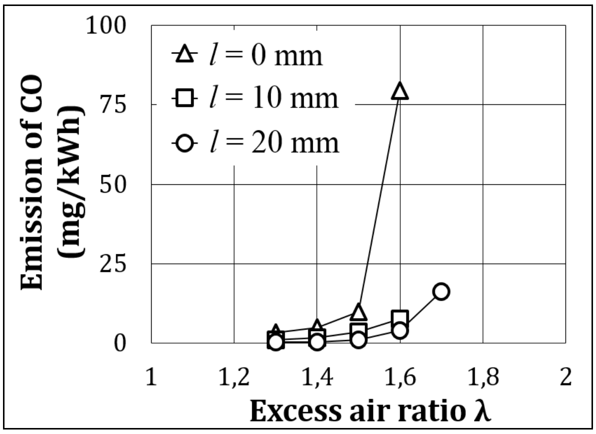

Figure 6. Emissions of CO at the thermal load of 500 kW/m^2 for different test configurations.

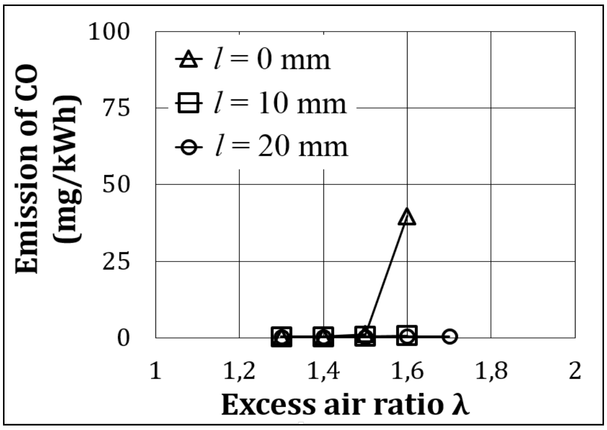

Figure 7. Emissions of CO at the thermal load of 1000 kW/m^2 for different test configurations.

Decrease of the CO-emission level in dependency to the axial inter-layer distance, especially at higher excess air ratios, can be explained by the extension of the post-combustion zone. As the free flame was formed below the porous structure, the post combustion zone for CO was formed within the hot porous structure.

As the thermal load increased from 500 kW/m^2 to 1000 kW/m^2, the overall CO emission level decreased.

The influence of the distance between the zones on the emissions of NO$_x$ were investigated in the same range of the axial inter-layer values of *l* = 0 – 20 mm. NO$_x$ emissions were increased in the modified burner, as is shown in Figures 8 and 9.

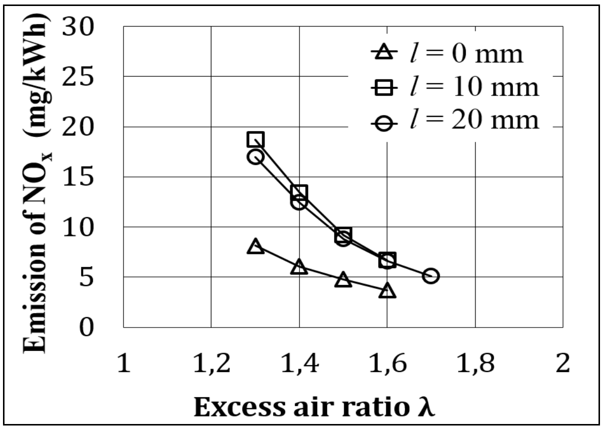

Figure 8. Emissions of NO$_x$ at the thermal load of 500 kW/m^2 for different test configurations.

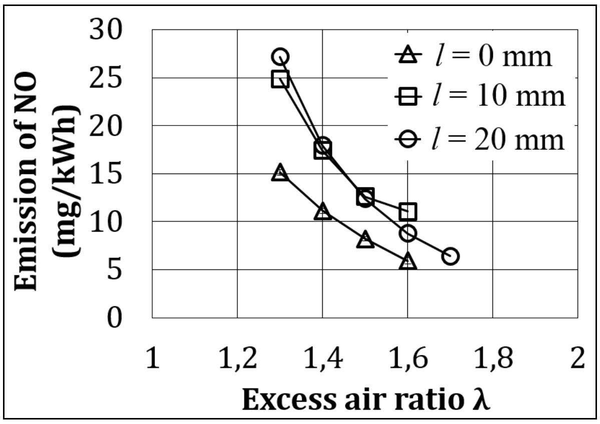

Figure 9. Emissions of NO$_x$ at the thermal load of 1000 kW/m^2 for different test configurations.

Presented results confirm that within the inter-layer gap a free flame is formed, which increases the gas temperature and consequently the NO$_x$ production rate. Overall, the difference between the NO$_x$-emission levels is significantly smaller between the modified burners with *l* = 10 and 20 mm, than between the modified and the reference burner.

Conclusions

In order to further develop dual layer porous burner technology, materials with high maximum operating temperature and high thermal shock resistance are needed. The high temperatures of the combustion zone material, engaged in the dual layer porous burner technology, may lead to serious damaging of the flame trap zone material, whose stability is essential for the burner operational stability and safety. Potential solution for preventing damages of the flame trap zone, through melting and/or chemical reactions between the materials, can be introduction of the axial gap between the combustion and the flame trap zone of the porous burner. In the scope of this study, the effect of such a gap on the burner operation, in terms of pressure drop, flame blow-off characteristics, material temperature and pollutant emissions, was experimentally investigated.

Experiments showed that the pressure drop increases with the introduction of the inter-layer axial distance up to *l* = 20 mm, due to increase in the local pressure drop. As the axial distance is further increased and the flow uniformity is reestablished, the pressure drop decreases.

Measurements of the surface temperature, the blow-off characteristics and the emissions indicate that the free flame forms in the gap between the two zones. The temperature of the combustion zone material is decreased as the axial distance between the layers is increased, since the combustion zone is moved into the gap and the porous structure is less heated. Smaller axial distances of up to *l* = 30 mm does not have a significant influence on the flame blow-off characteristics, but as this distance is further increased a certain positive effect can be noticed. As the axial inter-layer distance is increased above *l* = 30 mm, the flame stabilizes within the porous structure, thus the blow-off is postponed. After a certain critical temperature level of the porous structure is reached, the complete blow-off with a rapid temperature decrease occurs. Formation of the free flame below the porous zone has a limited positive effect on the CO emissions, due to formation of the post-combustion zone within the hot ceramic structure. Due to the increased gas temperatures, the negative effect of axial inter-layer formation is measurable as the NO_x emissions.

Overall, the presented experiments showed that if the axial distance between the zones is small, the operating characteristics of the porous burner would not be significantly changed. Thus, the proposed solution can be applied in order to prevent the damaging on the flame trap zone without the degradation of the burner operational characteristics.

Acknowledgements

The authors gratefully acknowledge funding of the Erlangen Graduate School in Advanced Optical Technologies (SAOT) by the German Research Foundation (DFG) in the framework of the German excellence initiative.

References

[1] O. Pickenäcker, K. Pickenäcker, K. Wawrzinek, D. Trimis, W.E.C. Pritzkow, C. Müller, et al., Interceram 48 (1999) 424-434.

[2] D. Trimis, K. Wawrzinek, R. Krieger, H. Schneider, in: Proceedings of the 6th European Conference on Industrial Furnaces and Boilers (INFUB), Estoril, Portugal, 2002.

[3] D. Trimis, O. Pickenäcker, K. Wawrzinek, in: M. Scheffler, P. Colombo (Eds.), Cellular Ceramics, Wiley, Weinheim, 2005, p. 484-506.

[4] S. Wood, A.T. Harris, Progress in Energy and Combustion Science 34 (2008) 667– 684.

[5] D. Trimis, F. Durst, Combustiuon Science and Technology 121 (1996) 153 -168.

[6] V. Jovicic, S. Ausmeier, A. Delgado, C. Schmidt, N. Gerlach, in: Proceedings of the 7th International Conference on High Temperature Ceramic Matrix Composites, Bayeuth, Germany, 2010.

[7] M. Altendorfner, F. von Issendorff, M. Dannehl, Int. Journal of Energy for a Clean Environment 9 (2008) 211-222.

[8] K. Beier, A. Zbogar-Rasic, V. Jovicic, H. Bauer, A. Delgado, in: Proceedings of the 9th European conference on industrial furnace and boilers (INFUB), Estoril, Portugal, 2011.

[9] A.A. Mohamad, S. Ramadhyani, R. Viskanta, Int. Journal of Heat and Mass Transfer 37 (1994) 1181-1191.

[10] A. Mach, F. von Issendorff, R. Krieger, J. Schäfer, M. Schmücker, A. Herzog, A. et al., Refractories Manual (2006) 48-55.

[11] V. Jovicic, A. Zbogar-Rasic, V. Kempe, A. Delgado, R. Weiss, M. Dannehl et al., in: Proceedings of the 10th European Conference on Industrial Furnaces and Boilers (INFUB), Porto Gaia, Portugal, 2015.

[12] A. Mach, F. von Issendorff, A. Delgado, A. Ortona, In: R. Narayan, P. Colombo (Eds.), Advances in Bioceramics and Porous Ceramics: Ceramic Engineering and Science Proceedings 29, 2009, p. 299 – 311.

[13] K. Pickenäcker, Emissionsarme kompakte Gasheizsysteme auf der Basis stabilisierter Verbrennung in porösen Medien (PhD Dissertation), University Erlangen-Nuremberg, 2000.