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Manufacturing of a Burner Plate by Diffusion Bonding to Investigate Premixed Fuel-Rich Oxy-Fuel Flames at Increased Pressure and Preheating

Combustion of hydrocarbons with pure oxygen as oxidizer is used, e.g., in high-temperature processes such as the partial oxidation (POX) of hydrocarbons to produce synthesis gas of high purity. Due to the prevailing temperatures, active cooling is required for many parts. For laboratory-scale experiments, the dimensions of key parts are too small for conventional manufacturing processes. One example is the manufacturing of a burner plate especially developed for POX processes. The complex geometries of several hundreds of burner nozzles and perpendicular cooling channels across the diameter of the burner plate cannot be manufactured in a conventional way. For this burner, the advantage of chemical etching of thin sheet material and stacking of multiple sheet layouts was used to assemble the layout of the burner. The burner plate was then diffusion-bonded, allowing the complex design to be realized. The partial oxidation of CH_4/O_2 flames at the laboratory scale could thus be studied under industrially relevant conditions.

Keywords: Additive manufacturing, Burner plate, Diffusion bonding, Chemical etching, Oxy-fuel

Received: September 14, 2022; *revised:* March 10, 2023; *accepted:* April 26, 2023

DOI: 10.1002/ceat.202200442

1 Introduction

Combustion with pure oxygen as oxidizer is used, e.g., in high-temperature processes such as the partial oxidation (POX) of hydrocarbons to produce synthesis gas. Due to the absence of nitrogen, higher temperature levels can be realized and lower exhaust gas volumes and improved product qualities can be achieved [1]. The increased temperature level and the fact that these processes are usually operated at high inlet gas temperatures with a preheating of up to 600 °C result in a high thermal load on the burner plate. Active cooling of these plates is therefore required. Industrial plants offer sufficient space for the integration of an active cooling system (see, e.g., [2]). On the laboratory scale, however, the dimensions are too small for conventional manufacturing technology.

For the experimental determination of concentration profiles in one-dimensional laminar fuel-rich CH_4/O_2 flames at industrially relevant pressures and preheating temperatures, a test rig was developed at the Engler-Bunte-Institute, Division for Combustion Technology at KIT (Karlsruhe Institute of Technology, Germany). One of its core elements is a burner plate with 658 nozzles, each with a diameter of 0.5 mm, which was manufactured. 153 of these nozzles were co-flow nozzles for nitrogen, surrounding the burner nozzles as a double-circled structure. Preheating temperatures of up to 600 °C were expected at the top of the burner plate. Therefore, the burner plate must be actively cooled, and an austenitic stainless steel like AISI 304 (1.4301), the operating temperature of which is limited to 550 °C, cannot be used.

Stainless steels are difficult to machine due to their toughness. Drilling holes with a diameter of 0.5 mm and a depth of several millimeters is very challenging and quite expensive. Manufacturing of cooling channels in between the combustion nozzles by mechanical means was a completely unsolved task. Even die-sinking is likely to fail because only a few tenths of a millimeter of material remain on the burner nozzles.

Therefore, a completely different way of manufacturing was chosen. The Institute for Micro Process Engineering (IMVT) at KIT has decades of expertise in manufacturing microstructured components by diffusion bonding. Chemically etched plate

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material is often used for this. Two layers each are stacked face-to-face to form microchannels. Additionally, cooling channels can be realized. Individual layers are joined by diffusion bonding at approximately 80 % of the melting temperature of the materials under external pressure in a vacuum. Finally, a monolithic component is obtained that has excellent pressure resistance.

2 Experimental Setup and Results

The material chosen was Alloy 800 (1.4876), which is suitable for an operating temperature of up to 800 °C [3]. The chromium content is 19–21 % and the nickel content is 30–32 %.

This material is a good example of how a material is more than its chemical components: Depending on the previous heat treatment, there are different modifications to which different material numbers are assigned (1.4958; 1.4859) and whose specifications vary greatly with regard to the maximum operating temperatures [4].

2.1 Design of the Burner Plate and Chemical Etching

The developed burner plate was to achieve a flat (quasi one-dimensional) premixed flame under well-defined boundary conditions, in order to experimentally investigate temperature and species concentration profiles in CH_4/O_2 POX flames under increased preheating and elevated pressure (maximum pressure and preheating temperature of 12 bar_a (absolute pressure) and 873 K, respectively). Both the high pressure and the preheating temperature increase the thermal load the burner plate must withstand; so, active cooling must be considered. As this by far exceeds the limits of a heat flux burner (HFB), an adapted burner plate was designed to handle these harsh conditions. The chosen geometry is based on the design of the burner plate of an HFB [5, 6]. The HFB was developed to precisely measure adiabatic laminar burning velocities at ambient pressure. To stabilize adiabatic one-dimensional premixed flames, a perforated burner plate (hexagonal hole pattern) with a single hole diameter of $d_{hole} = 0.5$ mm and a hole-to-hole distance of $s_{hole} = 0.7$ mm, was used. The plate is tempered with thermal oil by an external heating ring. Due to the applied tempering concept, this setup is limited to moderate preheating temperatures of at most 150 °C and low thermal loads.

The same hole size of $d_{hole} = 0.5$ mm was chosen for the POX burner. The main differences between the burners are the hole patterns and the temperature control of the perforated burner plates.

In the temperature control of the burner plate, thermal oil is supplied through an external channel at the outer diameter of the burner plate. In the case of the developed burner, 168 channels for temperature conditioning are integrated in the burner plate. To realize this principle, a square hole pattern with $s_{hole} = 1.7$ mm was used.

A computer-aided design (CAD) template of the nozzle positions was created, taking into account the position of the cooling channels (Fig. 1). While the burner nozzles were regularly arranged in rows and columns, the positions of the co-flow nozzles around them had to be arranged in accordance with the cooling channels. Note their irregular positions in Fig. 1.

The etched sheets were supplied by Ätztechnik Herz GmbH & Co. KG, Epfendorf, Germany. The maximum possible material thickness for etching is 80 % of the smallest breakthrough. Since the nozzles had a diameter of 0.5 mm, the thickness of 1.4876-sheet material was 0.4 mm.

To ensure sufficient material thickness for welding of adapters to the burner plate in order to be able to supply the cooling channels with thermal oil, there are six layers each without cooling channels at the top and bottom. In between, seven layers of cooling channels are formed by stacking the sheets face-to-face with etched cooling channels. A total of 26 sheets were stacked, resulting in a total thickness of the burner plate of 10.4 mm before diffusion bonding. This stack was stitched by laser welding employing a TruLaser Cell 3010 combined with a TruDisk 3001 with 3 kW, both supplied by Trumpf, Ditzingen, Germany.

A light conduction cable with a diameter of 100 µm, combined with a lens with a focal length of $f = 150$ mm, was used. A continuous wave power of $P = 800$ W, a travel speed of $v = 3$ m min^{-1}, and a focus position of $F = 1$ mm with regard to the surface level was used. Three weld seams under 120° were welded.

Another approach was to use powder-based laser sintering to form the complex geometry of the burner plate. The main issue was the minimal wall thickness, which had to be at least 0.6 mm to guarantee gas-tight walls between holes and cooling channels. This would lead to a distance between two holes of $s_{hole} = 2.1$ mm. Furthermore, the depowdering of the cooling channels across the burner plate cannot be accomplished due to the small cross-sections of the cooling channels compared to their length.

With the approach described above, the distance between two holes could be reduced by 24 % ($s_{hole} = 1.7$ mm) compared to 3D printing.

2.2 Diffusion Bonding and Adaptation

Diffusion bonding was performed in the diffusion bonding furnace I by Maytech, Singen, Germany, with a maximum load of 20 kN (Fig. 2). Additional plates, made of TZM (titanium-zirconium-molybdenum), an oxide dispersion-strengthened (ODS) molybdenum alloy, were used to protect the pressure dies from damage. These plates were coated with an alumina suspension to prevent the specimens from sticking. After the burner plate was placed in the center of the pressure dies, the furnace was evacuated to a vacuum threshold of better than 1*E-04 mbar. Then, the temperature was raised to $T = 1250$ °C with a gradient of 10 K min^{-1}. After a soaking time of 10 min, the load was applied, corresponding to a contact pressure of $p = 6$ MPa, and a dwell time of $t = 1$ h was applied.

After finishing, the temperature was lowered with a gradient of 10 K min^{-1} and the furnace was vented below 150 °C with nitrogen.

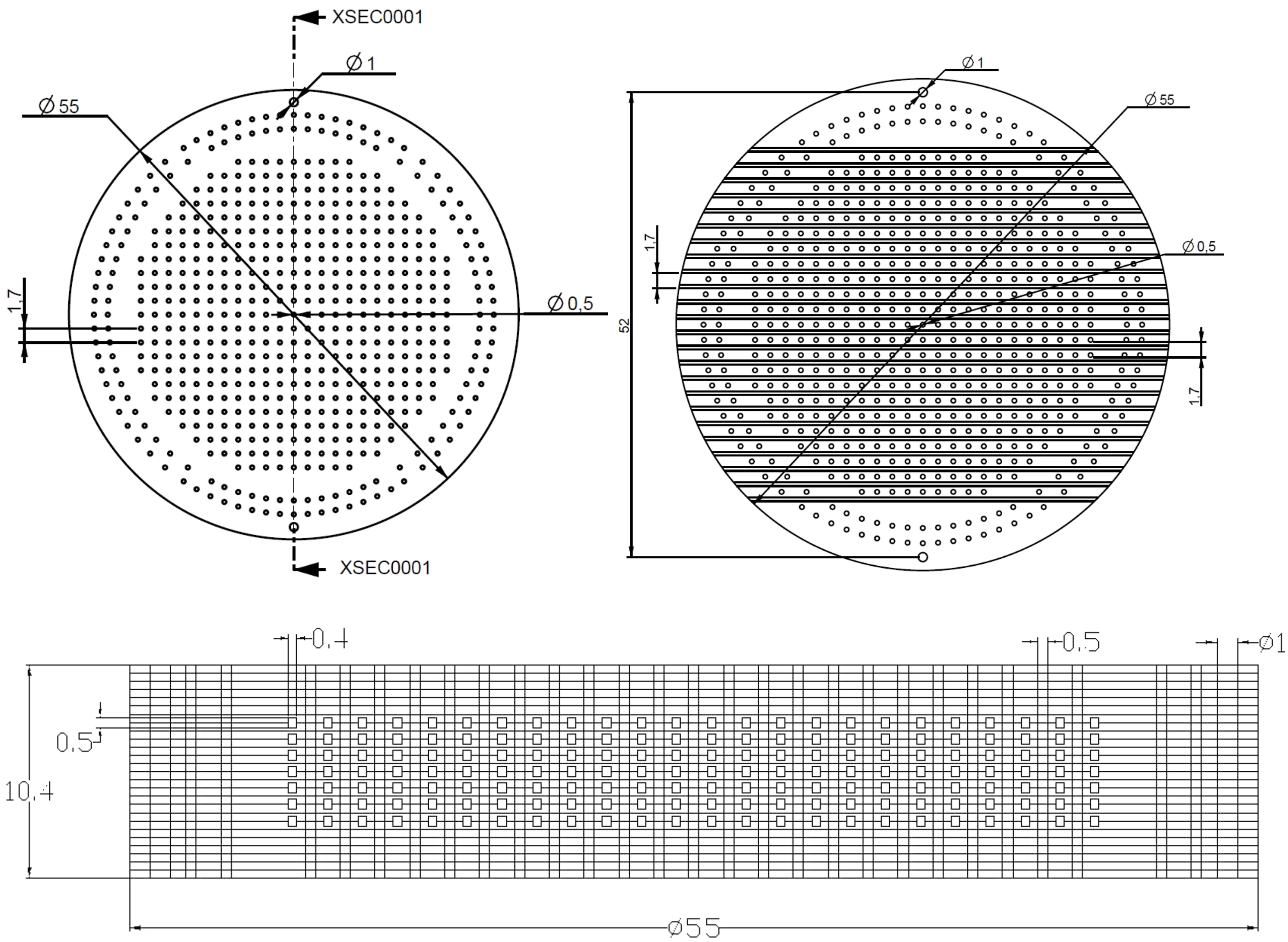

Figure 1. CAD of the burner plate. Top left: Top view including double circled cover gas nozzles. Top right: Design of layers with cooling channels. Bottom: Cross-section.

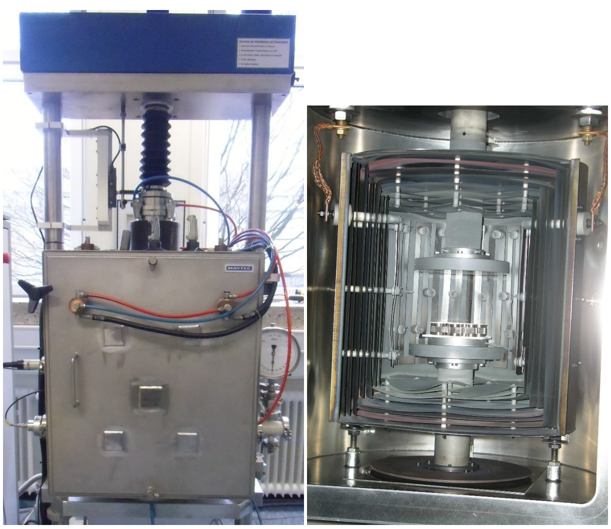

Figure 2. 20-kN diffusion bonding furnace.

Since the aspect ratio of the burner plate was only about 0.2 and the percentage of the bonding area was about 90 %, the deformation was only 1.85 %.

It was found that, due to the high-alloy material, a very high bonding temperature of 1250 °C is necessary for achieving grain growth across the bonding planes. Due to the high contents of chromium and nickel, very stable passivation layers form on the sheet surfaces, so that a standard bonding temperature of $T = 1075\,°C$, as applied elsewhere, is not sufficient [7]. The diffusion-bonded burner plate is displayed in Fig. 3.

After diffusion bonding, each nozzle was phased with a bevel of about 0.2 mm on a CNC machine HSPC 2522 supplied by Kern Microtechnik GmbH, Murnau, Germany.

The adapters for thermal oil were milled from Alloy 800H, which is designated as 1.4958, which corresponds to the solution-annealed state of Alloy 800 (1.4876).

After removing the alumina residue from the diffusion-bonded burner plate in the area of the welds, the adapters were laser-welded to the burner plate using the equipment mentioned above. As parameters, a continuous wave power of $P = 1$ kW, a travel speed of $v = 1$ m min^{-1}, and a focal position of $F = -1$ mm with regard to the surface level were used, resulting in a welding depth of about 1.5 mm.

Figure 3. Burner plate after diffusion bonding.

Then, a two-in-one gas funnel was welded on (Fig. 4). The inner part was supplied with a combustible CH_4/O_2 mixture. The outer circular part, the co-flow, was fed with inert gas.

Figure 4. Assembled burner plate with laser-welded adapters.

2.3 POX Burner Setup and Experimental Results

A sectional drawing of the burner module, which consists of the mixer (1), the diffusor (2), and the burner plate (3), is shown in Fig. 5. Detailed information about the entire test rig can be found in [8].

Immediately upstream of the static mixer, the pure reactants methane and oxygen were homogeneously mixed in the mixer.

To realize a uniform flow field at the inlet of the burner plate, a diffusor in the form of a double cone (Fig. 5) was used to widen the cross-section from the outlet of the mixer (d_M = 4.8 mm) to the inlet of the burner plate (d_{BP} = 40 mm). The half-opening angle was 7°, to prevent stalling inside the cone. Integrating the burner plate N_2 curtain flow in the outer cone of the diffusor had the advantage that, firstly, the N_2 flow was also conditioned to the preheating temperature of the reactants and, for this reason, acted as an insulating layer that minimized the heat losses from the premixed gases. Secondly, the mass flow was controlled so that the exit velocity of the N_2 stream was similar to the exit velocity of the premixed reactants, in order to protect the flame front area above the burner plate from shear forces.

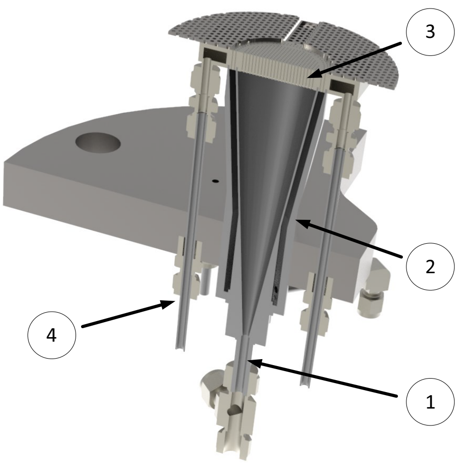

Figure 5. Sectional drawing of the burner unit, including a static mixer (1), diffusor (2), burner plate (3), and thermal oil circuit (4).

In the flange of the burner module, there were two accesses to the thermal oil circuit (4) to condition the temperature of the burner plate.

Two different measurement techniques were applied. Tunable diode laser absorption spectroscopy (TDLAS) is an optical noninvasive and calibration-free measurement technique, which was used to determine the temperature and H_2O concentration profiles. The principle of TDLAS is summarized by, e.g., Goldenstein et al. [9] and Bolshov et al. [10], and the setup and analyzing procedures are described by Sentko et al. [8, 11]. Additionally, invasive gas sampling using a quartz probe, including a subsequent analysis via gas chromatography, was used to determine major combustion species. The setup is described in detail elsewhere [8, 12].

In a first step, a series of experiments were performed with the developed pressure burner to evaluate how accurately the flames stabilized at this burner correspond to an adiabatic flat flame. For this purpose, temperature and concentration profiles of the atmospheric CH_4/O_2 ($\phi = 2.7$, $T_P = 300$ K, $p = 1$ bar_a) were compared with the results of the HFB. Identical boundary conditions ($T_{BP} = 433$ K and $u_{UG} = s_L = 17.3$ cm s^{-1}) were set for both burners. Flatness was investigated using CH* chemiluminescence imaging as a line-of-sight technique. No flame jets were observed under the operating conditions of the results presented.

The results of these measurements are shown in Fig. 6, where the concentration profiles of the major combustion species are plotted against the spatial coordinate. This is chosen as the reference system because the position of the flame is shifted 2 mm downstream in the pressure burner. The changed flame position can be attributed to the increased hole spacing and the associated greater momentum of the individual jets.

The results of the validation measurements show that, in the area of the steep gradients in the flame front, only minor differences occur between the results of the HFB and the pressure burner. These differences may be traced back to the influence of the used probe on the flame, as shown by Sentko et al. [12]. In the post-flame zone, the results of the major combustion species deviate by less than 8 %, showing the excellent performance of the developed POX burner. This similarity between the results of the HFB and the POX burner indicate that the new burner is suitable for investigating POX flames.

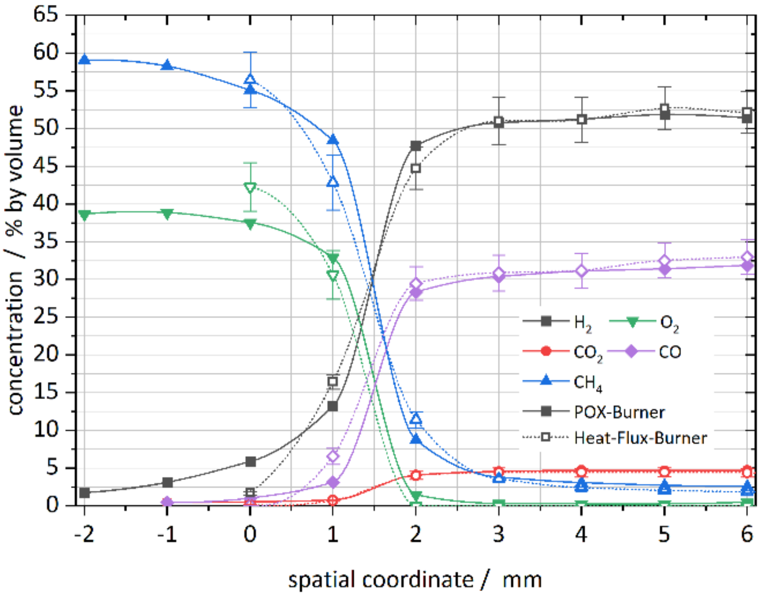

Figure 6. Comparison of the major combustion species profiles of CH_4/O_2 flames ($\phi = 2.7$, $T_P = 300$ K, $p = 1$ bar$_a$) on the HFB and the POX burner, measured by invasive sampling and analyzed by gas chromatography (full symbols: POX burner, empty symbols: HFB).

3 Conclusion

When it comes to miniaturization, conventional manufacturing processes such as mechanical chipping and drilling are prone to errors, decrease productivity and reach the limits of feasibility. With strictly sequential manufacturing techniques, the machining time increases considerably, or selected features, e.g. the cooling channels, can no longer be produced. Therefore, for complex designs, special manufacturing techniques such as diffusion bonding may accelerate realization despite higher intrinsic costs.

The chemical etching of thin sheets, the stacking of different layers to form a complete burner plate, and diffusion bonding enabled a kind of additive manufacturing technique. Also, unlike in the case of selective laser melting (SLM), excess unsintered powder does not have to be removed, which would not be possible with the cooling channels due to the small cross-section and high aspect ratio. In addition, the surface roughness is lower compared to SLM, and despite the small cross-sections between the burner nozzles and the cooling channels of a few tenths of a millimeter, He-tightness could be achieved.

In real diffusion bonding, grain growth occurs across bonding planes, forming a monolithic part of high compressive strength. However, the entire part is exposed to high temperatures and a long dwell time, so that the effects of strain hardening disappear and unfavorable changes of the materials' microstructure, e.g., formation of precipitations at grain boundaries, may occur.

This underlines the fact that the designer has to consider quite different aspects when manufacturing intricately structured parts.

The aim of developing and manufacturing a temperature-adjustable burner plate for investigating the POX of CH_4/O_2 flames at the laboratory scale under industrially relevant conditions (equivalence ratio, preheating, and pressure) was fully met.

A comparison of the experimental results of the developed burner plate and a widely used HFB for investigating laminar premixed flat flames shows an excellently functioning system under mild inlet conditions. The determined concentration profiles well reflect both the steep gradients in the flame and in the post flame zone. The functionality of the burner plate was also successfully tested at elevated pressure and preheating [8], which confirms these results.

Data Availability Statement

Data available on request from the authors.

Acknowledgment

The present research work contributes to the MTET program, Resource and Energy Efficiency, Anthropogenic Carbon Cycle (38.05.01) of the Helmholtz Association. Open access funding enabled and organized by Projekt DEAL.

The authors have declared no conflict of interest.

Symbols used

d_{BP}	[mm]	diameter of the funnel for the burner plate
d_{hole}	[mm]	diameter of the holes
d_M	[mm]	diameter of the mixer outlet
F	[mm]	focal position of laser welding
p	[bar$_a$]	pressure
P	[W]	power of the laser
s_{hole}	[mm]	distance between two holes
s_L	[cm s^{-1}]	laminar burning velocity
T_{BP}	[K]	temperature of the burner plate
T_P	[K]	preheating temperature
u_{UG}	[cm s^{-1}]	velocity of the unburnt gases
v	[m min^{-1}]	velocity of laser welding

Greek symbol

ϕ	[–]	equivalence ratio

Abbreviations

CAD	computer-aided design
HFB	heat flux burner
POX	partial oxidation

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Chem. Eng. Technol. **2023**, *46 (XX)*, XXX … XXX

DOI: 10.1002/ceat.202200442