Clean and efficient energy conversion processes

Development of a non-premix radiant burner

Final Report

Andersen, P.
Myken, A.N.
Rasmussen, N.B.

Danish Gas Technology Centre a/s

Contract JOE3-CT95-0011

Period: February 1996 to March 1998

Research funded partly by
THE EUROPEAN COMMISSION
in the framework of the
Non Nuclear Energy Programme
JOULE III
Development of a non-premix radiant burner

Final Report

Project report

Andersen, P.
Myken, A.N.
Rasmussen, N.B.

Danish Gas Technology Centre a/s
Hørsholm 1998
Title : Development of a non-premix radiant burner
Subtitle : Final Report
Report Category : Project Report
Author : Andersen, P, Myken, A.N, Rasmussen, N.B.
Date of issue : 03-03-98
Copyright : Danish Gas Technology Centre a/s
File Number : 715.16
Project Name : Clean and efficient energy conversion processes (CECON)

For services of any kind rendered by Danish Gas Technology Centre a/s (DGC) the following conditions shall apply:

- DGC shall be liable in accordance with "Almindelige Bestemmelser for teknisk Rådgivning og bistand, ABR 89" ("General Conditions for Consulting Services (ABR 89)"), which are considered adopted for the assignment.
- DGC's liability per error and negligence and damages suffered by the client or any third party is limited to 100% of the fee received by DGC for the respective assignment. The client shall indemnify and hold DGC harmless against all losses, expenses and claims which may exceed the liability of DGC.
- DGC shall - without limitation - re-perform its own services in connection with errors and negligences contained in the material delivered to the client by DGC.

This report is copyright, and must not be reproduced in whole or in part without the prior written consent of DGC.

This English translation is provided for convenience only and in case of discrepancy the Danish wording shall be applicable.

June 1992
# Table of Contents

1 Introduction ......................................................................................................................... 1  
  1.1 DGC's assignment ........................................................................................................ 1  
  1.2 Design parameters for the non-premixed radiant burner ............................................. 1  

2 Conclusion .......................................................................................................................... 3  

3 Summary of project activities ............................................................................................ 4  
  3.1 Evaluation of design possibilities .................................................................................... 4  
  3.2 Experimental results ...................................................................................................... 7  

References ............................................................................................................................. 14
1 Introduction

This is the Final Report from the Danish Gas Technology Centre a/s (DGC) within the project “Clean and efficient energy conversion processes” (CECON).

DGC is responsible for task 3 of the CECON project: Development of a non-premixed radiant burner (NPRB). The task has been divided in two sub-activities, which have been individually reported /1,2/.

This report summarises the work carried out in the framework of task 3.

1.1 DGC’s assignment

The overall objective for DGC is, referring to ANNEXE I in the EC-contract:

Development of a non-premixed radiant burner, that will be designed for high temperature conditions, i.e. high furnace temperatures (above 800°C) and high preheat temperatures (up to 700°C) (task 3).

The goal for the preheat temperature has later been changed to 1000°C.

In continuation of the development, also laboratory tests have to be performed.

The objective for the first project period is to make a study into materials suitable for the non-premixed radiant burner and choose the materials for the construction as well as to make proposals for the design of the NPRB. The different proposals must be tested with a CFD-model (Computational Fluid Dynamics).

The objective of the second project period is to establish and test the developed prototypes for material deterioration, radiant efficiency, thermal load, excess-air interval, and emissions.

1.2 Design parameters for the non-premixed radiant burner

The overall conditions for the NPRB are shown in Figure 1.1.
Figure 1.1. The overall conditions for the non-premixed radiant surface burner.

The design activities have been based on the following burner parameters/restrictions:

- height x width: \( \leq 300\text{mm} \times 300\text{mm} \)
- fuel input: \( 50\text{ kW} \)
- combustion air temperature: \( 800^\circ\text{C} \)
- furnace temperature: \( 900^\circ\text{C} \)
- excess air: \( 5\% \)

The specific load (550 kW/m\(^2\)) is very high and it has therefore been decided also to test the burners with a smaller fuel input.

The restriction on burner dimensions has later been changed to:

- height x width: \( \leq 1000 \text{ mm} \times 1000 \text{ mm} \)

This change makes it possible to construct a burner with a more suitable (lower) specific load than 550 kW/m\(^2\).
2 Conclusion

The objective of task 3 of the CECON project was to develop and test a non-premixed radiant burner. An investigation has been conducted on feasible materials for production of porous burner foams and the thermal properties of these materials.

A burner concept, prototype 1, was developed with special attention to minimise emissions and foam peak-temperatures. A central problem in this context is to obtain the highest possible homogeneity of the combustion, which means that gas/air mixing should be optimised. In order to fulfil this, prototype 1 was designed with ceramic gas distribution tubes perforated with small holes. The design was supported by numerical simulation of flow, combustion and radiation of the burner with the CFD-code TUFCA.

During the test of the prototype it became evident that the construction was not feasible, because the ceramic gas distribution tubes eventually were blocked by soot. Experiments to investigate if the gas would crack conducted prior to the construction of the burner did not indicate that any problems would occur. It can therefore be concluded that the experiments did not simulate burner conditions adequately.

In order to identify possible modifications to avoid this, the gas temperature profile in the tubes has been evaluated. The gas temperature rises to the temperature of the outer surface of the tube almost immediately after entering the tube from the manifolds on both sides of the burner. Compared to the cracking test which was carried out prior to the construction of the burner, the residence time at the final (high) temperature in the real burner tube is much lower. This means that, as far as residence time is concerned, the test was conservative. An explanation of the fact that the gas cracked in the burner tubes, and not in the test, can be that the tube temperature in the test was too low to simulate burner conditions.

The outlet temperature of the gas when it leaves the distribution tubes can theoretically be modified by changing parameters as tube (inner) diameter as well as the number and diameter of the holes in the distribution tubes. However, the ratio of the inlet area to the tubes and outlet area through the holes cannot be changed without compromising the homogeneity of the gas distribution. Therefore, it is not believed that the problem can be solved by simply using other tube configurations. A possible, but complicated, solution is to cool the gas through the tube e.g. with air or water. The cooling could be established in a solution with concentric tubes, in which the inner tube contains the cooling medium.

Alternative prototypes in which the gas is not heated prior to injection into the combustion chamber have been established. The concept operated satisfactorily without preheating of the combustion air, although NOX-emissions were high. The measured process efficiencies were superior to previous results for different kinds of premix surface burners. When the combustion air was preheated to 400°C, the foam sections broke down.

Possible means to improve durability, efficiency and emission level for both burner concepts have been suggested but not tested. These include cooling of the gas in prototype 1, coating of the downstream side of the foam section to improve the radiant efficiency and multistep combustion.
3 Summary of project activities

3.1 Evaluation of design possibilities

The objective of the first project period is to:

- make a study into materials suitable for the NPRB.
- choose the materials for the construction.
- make proposals for the design of the NPRB.
- test the different proposals with a CFD-model.

In pursuit of finding a suitable material it is necessary first to estimate the maximum temperature that will occur in the burner. It has been estimated that the maximum adiabatic flame temperature will be about 2400 - 2500 K. The maximum temperature in the burner will of course never reach this level. A more realistic temperature was estimated to 2100 - 2300 K.

After finding a material that can resist these temperatures it is, knowing the material properties, possible to make numerical calculations that will determine a more precise maximum working temperature.

It has been noted that it is difficult to find data about material properties for ceramics in the mentioned temperature interval. After the literature study a few materials seemed promising. The final choice was made after having contacted some of the leading producers. It was possible to find one producer that could produce burners of one of the suggested materials, zirconia.

Several construction ideas for the NPRB have been discussed and some of them tested with a CFD-model, ref. 3. The proposed burner concept has been modified in order to obtain a homogenous temperature distribution, enhance air and gas mixing and reduce the maximum material temperature.

The conditions for the CFD-calculations have been as follows:

- burner height x width: 300 mm x 300 mm
- fuel input: 50 kW (specific load: 550 kW/m²)
- combustion air temperature: 800°C
- furnace temperature: 900°C
- excess air: 5%

Discussions and calculations have shown that the most promising way to distribute the gas in the burner is by using perforated ceramic tubes. The CFD-calculations have been based on ten tubes with an outer diameter of 10 mm, each perforated with 40 1 mm holes.

From the CFD-calculations it can be concluded that a cavity for mixing gas and hot air is necessary between two layers of ceramic foam. The concept is sketched in Figure 3.1.
Figure 3.1. Burner with grooves, tubes and a cavity inside.

The height of this cavity in the direction of the bulk-flow should be not more than 5-6 mm. This small height prevents the gases to react completely, and therefore the temperature is kept at an acceptable level.

From the CFD-calculations it can also be concluded that the distance between the gas jets can be increased while the diameter of the jets should be decreased. A suggestion could be a distance of 20 mm instead of 15 mm and a diameter of 0.8 mm instead of 1 mm. This would double the velocity of the gas in the jets and enhance mixing between the gas and the hot air bulk flow.

From the CFD calculations it can be seen that a large amount of unburned fuel will leave the surface of the burner. As an option, it was suggested to add an extra ceramic foam to the construction sketched in Figure 3.1 to increase the burnout of the fuel in the burner. This layer should have a much larger poresize giving much better radiation conditions and a better opportunity for the gases to burn out. This idea is outlined in Figure 3.2. Eventually, the prototype was constructed without the extra foam in order to simplify the validation of the basic burner design.
Another idea for a prototype was found at the Netherlands Energy Research Foundation (ECN), see Figure 3.3.

This construction could be characterised as consisting of two burners, an “inlet burner” and an “outlet burner”, see Figure 3.3. The flue gases from the “inlet burner” surface are sucked out through a ceramic foam of the “outlet burner” in which burnout of unburned gases can be ensured.

This concept has been developed for traditional surface burners to reduce flue gas losses and increase the effective radiant surface area. The ceramic foam of the outlet section is heated by the flue gasses and will obtain a temperature not much lower than this. The irradiation from
this surface will increase the radiant efficiency of the system and this effect will be even more significant at high flue gas temperatures and combustible components in the flue gas.

The two NPRB prototypes to be constructed and tested will be based on the concepts illustrated in Figure 3.2 and Figure 3.3.

The calculations of the temperature in the burner sketched in Figure 3.1 give a maximum of approximately 1730°C. This means that the chosen material, ziconia, can be used for the foams. As described in chapter 3.2, another material was eventually chosen for the prototypes.

After the initiation of the project the goal for the NPRB has been changed. The combustion air preheat temperature has been raised from 800°C to 1000°C. Also the geometrical restrictions has been changed from 300 mm x 300 mm (width x height) to 1000 mm x 1000 mm. However, the qualitatively result of the design evaluation provides sufficient information for the implementation of these changed design parameters into the prototype construction. The prototypes will be constructed with a height of 300 mm and a width of 400 mm. These restrictions are made because of the shape of the test furnace in DGC's own laboratory.

3.2 Experimental results

The objective of the second project period is to construct and test the prototypes designed in the first project period for material deterioration, the process efficiency, the thermal load, the excess-air interval, and the emissions.

The prototypes have been constructed on the basis of the concepts found in the first project period, as shown in Figure 3.4.

![Figure 3.4](image)

Figure 3.4. Sketch of the two concepts for the NPRB found in the first project period.

Some practical changes have been made to make the construction simpler and cheaper. The groves in the upstream foam sections have been left out in the final construction, as it has
been estimated that the influence on e.g. flow patterns is small. At the end of the first project period it was suggested to add an extra layer of ceramic foam on the furnace side of the burner to ensure burn-out of the gas. This extra layer of foam has not been used because it would also complicate the construction. Figure 3.5 shows the outline of the constructed burners.

During the design phase, zirconia was chosen as the preferred burner material. It is possible to produce foams of this material, but the price of these prohibited that it was used for the prototype construction. The temperature distribution and thermal stresses of the burners has been thoroughly discussed with the burner supplier, ECO Ceramics. Eventually, the material “x-mullite” was chosen for the prototypes, which is a modified mullite-based material provided by ECO Ceramics.

The prototypes were planned to be tested in a water-cooled furnace (the SERB test furnace, ref. 4) and in a high-temperature furnace (ceramic furnace). The SERB test furnace provides possibilities for making performance tests (heating experiments using a metal plate), where the ceramic furnace only provides possibilities to test the behaviour of the burners in high-temperature conditions.

The performance tests were planned to be for determining the optimum working condition for the prototypes with different preheated combustion-air temperatures. Also tests of off-design conditions were planned. In the high-temperature furnace it was decided to determine burner surface temperature, emissions and which temperature profile the burners would create in the furnace.

![Figure 3.5. Outline of prototype 1, which also is the inlet burner in prototype 2, and outline of the outlet module in prototype 2.](image)

The initial experiments were performed with low combustion-air preheat-temperatures, approximately 450°C, in which case the combustion took place on the outer surface of the downstream foam. The distribution and the mixing of gas and air was poor, and the temperature distribution was very unhomogeneous. From the amount of CO and CₓHᵧ in the flue gas it was also concluded that the burner was not working very good.
Further experiments with a higher specific load with the same combustion-air preheat-temperature gave the same distribution problems.

The next step in the series of planned experiments was to raise the combustion-air preheat-temperature to 600°C. When the combustion-air preheat-temperature reached nearly 600°C the burner surface emitted visible radiation and the combustion zone moved into the cavity between the upstream and downstream foam sections. A deposition of soot started on the surface of the downstream foam a few minutes later. The deposition increased and eventually covered about two thirds of the burner surface, mainly at the two outermost foam sections, see Figure 3.6.

There was no indication that the deposited soot would disappear. It was attempted to change both the excess-air ratio and heat input, but the soot deposition could not be avoided. When the gas supply was disconnected the deposited soot slowly burned and a large part of deposited soot disappeared.

An inspection of one of the burners also revealed deposition of soot on the back of the downstream foam sections. The inspection also revealed that the ceramic tubes were partly blocked by soot in the middle section.

The small cavity of 13 mm between the upstream and downstream foam sections was changed to 150 mm. The purpose was to increase the distance between the combustion zone and the surface of the ceramic tubes and thereby lower the temperature on and inside the tube. If cracking of the gas was avoided inside the tubes, it was possible that any soot particles would manage to burn out before reaching the downstream foam sections. Unfortunately, the result was the same as described above, and the conclusion after having tried testing prototype 1, which also should have operated as an inlet burner in prototype 2, was that the designed burner cannot be utilised without major modifications.

Figure 3.6. Picture of the front of the burners after the formation of the dark areas.
It was impossible to conduct a totally new design process due to the time schedule and financial situation of the project. However, in order to demonstrate the concept of a non-premixed radiant burner, a test burner, prototype 3, based on a new and simpler construction was established, see Figure 3.7.

In this burner the gas is injected through four holes in the bottom of the burner. This means that the gas is not preheated before it enters the combustion chamber. The combustion air is supplied through eight holes, two in each side of the combustion chamber. The position of these inlets creates a highly swirling flow which insures good mixing of air and gas. The combustion chamber was built in stainless steel, which of course is only capable to withstand the high temperatures for a short period of time. However, the prototype 3 burner demonstrated that the construction worked, and it was decided to construct a high-temperature-resistant prototype in order to test the concept further.

Figure 3.7. Sketch of design of prototype 3.
The combustion chamber of prototype 4 was built in ceramic stone which could withstand the high temperatures. However, the steel frame which fixates the foam sections broke down after only a few experiments. This part of the burner was improved in prototype 5, and with this burner it was possible to carry out two series of experiments. A sketch of the prototype 5 burner is shown in Figure 3.8.

Three measurements were carried out without preheating of the combustion air, with specific loads between 240 kW/m² and 450 kW/m². Then the combustion air was preheated to approximately 400°C, and the process efficiency was measured at specific loads from 230 kW/m² to 475 kW/m². Eventually, the ceramic foam sections could not withstand the operating conditions: Both of the two foam sections that make up the burner surface curved outwards. A crack in one of the foam sections, which did not influence the burner operation during the initial tests, grew and finally the section opened completely.

Figure 3.8. Sketch of design of prototype 5.

The measured process efficiencies are shown in Figure 3.9. They are compared with results from previous experiments with four different surface burners, ref. 5.
The results without combustion-air preheating are superior to the reference data, especially at high loads. This is explained by the fact that prototype 5 is not a surface burner. At low loads the radiant efficiency of surface burners increases with the heat input. However, when the load exceeds a certain optimum, the radiant efficiency decreases because a significant amount of the supplied gas leaves the burner before it is burned. At extreme loads the combustion will turn into a blue flame mode where the entire combustion takes place downstream of the burner. This effect is not observed for prototype 5 since the combustion zone in this burner is not fixed at the surface of the foam sections.

![Figure 3.9. Measured process efficiencies with prototype 5 and reference data from previous experiments.](image)

Figure 3.10 and Figure 3.11 show the measured emissions without and with combustion-air preheating respectively.

![Figure 3.10. Emissions of CO and NOx corrected to 0% O2 from the prototype 5 burner without preheated combustion air.](image)

The NOx-emissions increase with specific load and with the temperature of the combustion air. Preheating the combustion air to 400°C has a much larger effect on the NOx-emissions.
than an increase of the specific load from approximately 240 kW/m² to 450 kW/m². Without preheating, NOₓ-levels (corrected to zero oxygen content) between 170 ppm and 390 ppm were observed, while 330-1050 ppm NOₓ was measured with combustion-air temperatures of 400°C.

Figure 3.11. Emissions of CO and NOₓ corrected to 0% O₂ from the prototype 5 burner with combustion air preheated to 400°C.

Besides one unexplainable high measured CO-content of approximately 950 ppm (corrected to zero oxygen content), the CO-emissions without preheating were between 100 ppm and 140 ppm. When the combustion air was preheated to 400°C, the emissions reached a level between 240 ppm and 510 ppm.

The experimental results can be summarised in the following conclusions:

- The developed prototypes cannot be operated with combustion air preheated to 400°C or higher.
- A relative improvement of the process efficiency by 22% has been observed when the combustion air is preheated to 400°C.
- The NOₓ-emissions increase significantly and much more than the process efficiency when the combustion air is preheated.
- The process efficiency obtained with prototype 5 is better than previously investigated surface burners, especially at high loads.
References

1. Andersen, P., Myken, A.N., Rasmussen, N.B.
Development of a non-premix radiant burner, Evaluation of design possibilities.
Hørsholm: Danish Gas Technology Centre a/s, 1996
JOE3-CT95-0011

2. Andersen, P., Myken, A.N., Rasmussen, N.B.
Development of a non-premixed radiant burner, Experimental results.
Hørsholm: Danish Gas Technology Centre a/s, 1997
JOE3-CT95-0011

3. Myken, A.N., Rasmussen, N.B.
Comparison/verification of advanced numerical tools for flow calculations.
Hørsholm: Danish Gas Technology Centre, 1993.
ISBN 8777950259
EFP-89 nr. 1323/8918

4. Jørgensen, K., Myken, A.N., Rasmussen, N.B.
Test Furnace for Radiant Burners.
Hørsholm: Danish Gas Technology Centre, 1996.

5. Jørgensen, K., Rasmussen, N.B., Myken, A.N.
Selective Emittance Radiant Burners - An Experimental Investigation.
Hørsholm: Danish Gas Technology Centre, 1996.