

**Compact Porous Medium Burner
and Heat Exchanger
for Household Applications**

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Abstract

The objective of the present project was to advance development work on a novel porous medium burner with integrated heat exchanger. This burner does not work as a catalytic combustor but burns within the pores of an inert porous medium. The combustion inside the porous medium is very intense and the reaction zone in the porous matrix has an elongated form in the streamwise direction when using premixed natural gas with air under atmospheric pressure. The matrix properties are employed to stabilise the combustion process in such a way that a power modulation of 1 to 20 results for excess air ratio values of $1.1 \leq \lambda \leq 1.7$. The emission rates are comparable to the best gas burners currently available on the market. The heat exchanger is embedded in the porous medium, so that, due to the high heat transport rates, a highly efficient, compact and integrated burner/heat exchanger apparatus results. Due to its small size compared to conventional fossil fuel heaters, new applications in household and industry are envisaged.

The goal of this project was to provide and evaluate first prototypes of this compact gas burner and heat exchanger unit concerning the applications in households. The expertise of all the partners consists of knowledge gained in research work on porous media combustion (LSTM-Erlangen), detailed knowledge on radiation heat transfer in porous media (IST-Lisbon), refined modelling capabilities in the field of chemical kinetics of pollutant formation (IMPCOL), knowledge about household heating systems (VIESSMANN), knowledge on ceramics and its employment in high-temperature systems (INSULCON) and knowledge on the development of control systems (PKO-OSMO).

The work performed by LSTM-Erlangen and the achievements can be summarised as follows. In the first period of the project, 10 kW porous media burner and heat exchanger units were designed and constructed. These units are divided into three regions. The preheating region (A), the combustion region (C) and an additional heat exchanger region D. These porous medium burner-heat exchanger (PMB-HE) units I were also distributed for test purposes to all project partners. At LSTM-Erlangen, detailed experimental investigations were performed on this prototype I. In the course of the experiments different porous media and ceramic insulation materials were tested. The result was an optimised burner Ib, which had very low CO and NO_x-emissions. In the first six months period of the project PKO-OSMO developed with the assistance of LSTM-Erlangen a control unit for these PMB-HE systems I and Ib

(control unit Ia). After the bankruptcy of PKO-OSMO, LSTM-Erlangen developed an improved control unit Ib, in order to continue the work.

Some improvements of the burner prototype I and Ib and the results of the other project partners were the basis for the design and layout of a 30 kW PMB-HE prototype II, which was made in collaboration with VIESSMANN. At LSTM-Erlangen this prototype II was extensively tested. The results of the experiments showed that for the final burner design further constructive improvements should be done on the heat exchanger, in order to reduce the pressure drop. In agreement with all partners a „Stabrippen“ heat exchanger was built by Viessmann. This heat exchanger has a very compact geometry in comparison to conventional heat exchangers and a very high efficiency. According to the design of the „Stabrippen“ heat exchanger, LSTM-Erlangen modified the design of the porous medium burner and carried out experimental investigations with this burner with the final design. These optimisations of the porous burner heat exchanger resulted in very low emissions of carbon monoxide and nitrous oxides. Moreover, the gas pressure drop of the burner is adequately now.

The Control unit II, which was also developed from LSTM-Erlangen, was available for the experiments with burner prototype II and the burner with the final design. The control unit was developed not only with respect to its functionality, which had to be adapted to the operational characteristics of the porous media burner, but also with respect to a compact design, so that it can be used as a basis for the commercial utilisation

As a result from the present project, a burner prototype was obtained, which is completely novel and provides significant advantages compared to current heating systems. Several manufacturers of heating systems in Europe have already expressed their interest in producing the porous burner unit with integrated heat exchanger.

Key words: combustion, heating equipment, compact burners, low NO_x, ceramics

1. Industrial objectives and strategic aspects

It can be foreseen that the results obtained from this project will lead to a market introduction of the Porous Burner technology. Thus, new jobs can be created and ensured. Moreover, it is expected that, as a consequence of the project and after a limited demonstration period, the Porous Burner technology can durably establish itself on the European Market over the following few years and other European companies will switch their product lines to the new technique. But apart from manufacturers of heating systems also suppliers of ceramic materials for high temperature applications will benefit from the market introduction of the Porous Burner technology. Additionally, due to the advantages of the Porous Burner technology, most compact devices could be realised that combine the delivery of heat and hot water being fed by solar power and/or photovoltaics.

Due to the excellent modulation range of the porous medium burner combined with its very small size and the low waste gas emission values, the concept of combustion inside porous media is able to reduce heating costs and allows the household heating equipment to be operated at its maximum efficiency. Moreover, the Porous Medium Burner can be integrated decentralised in small apartments easily. As a consequence, a separate heating room is no longer necessary but the Porous Burner units can rather be installed in small wall niches or even outside the housing. As a consequence, even old houses or apartments that are not equipped with a central heating system at present could be upgraded with the Porous Burner technology. This means that apart from its positive impact on the environment, the porous medium burner and heat exchanger unit will have several economic advantages for the user.

2. Scientific and technical performance

2.1 State of the art

Nitrogen oxides emitted from combustion sources have been identified for their contributions to many environmental problems, such as global warming, photochemical smog, acid rain and the destruction of the ozone layer. Therefore, much effort on combustion research has been directed to develop different NO_x reduction techniques to meet the required emission standards. NO_x can be produced by the thermal (Zeldovich) mechanism or the prompt (Fenimore) mechanism. Both mechanisms are temperature dependent. As lower temperatures result in lower NO_x levels, existing combustion techniques aim at a reduction of the combustion temperature. One possibility for reducing the temperature of the process is the combustion at high air ratios (lean combustion). An important problem of these combustion processes however is the stabilisation of the flame front, as the laminar flame velocity and the temperature decrease while the velocity of the premixed gas increases. Moreover, the efficiency of such burners is lower, due to the high excess air ratio.

Figure a) shows exemplary the EV-burner from ABB, working with a combination of lean combustion and recirculation of a part of the exhaust gases.

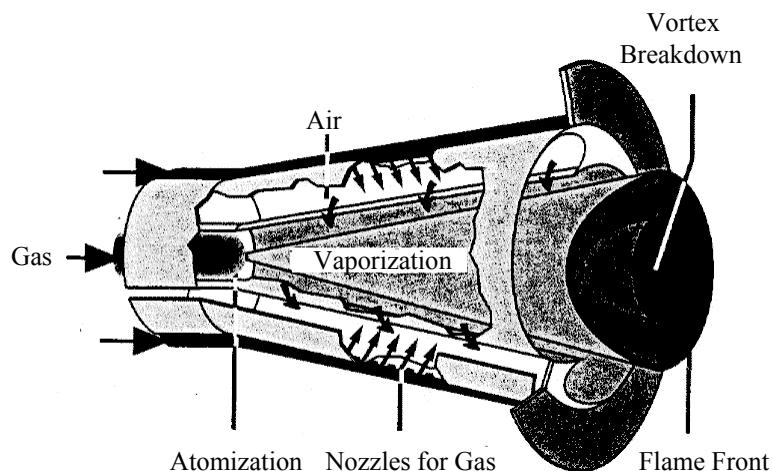


Fig.a): EV-Burner from the company ABB [1]

An alternative process is the multistage combustion [2,3]. This is a combination between a rich combustion (first stage) and a stoichiometric or lean combustion (second stage). Another possibility of decreasing the flame temperature is the recirculation of a part of the exhaust gases [4]. A burner working with this principle is the ROTRIX-burner from Viessmann. Recirculation of exhaust gases as well as multistage processes require costly constructions, which can be realised only in larger units. For this reason, most burner units for household applications (low thermal load) mainly work as radiant surface burners. In these burners a flame sheet consisting of many small premixed laminar free flames is produced over a porous solid body layer. Due to the very low distance between the two-dimensional flame sheet and the solid porous body, a significant amount of the heat, released by combustion, is transferred to the solid body and is then removed from the burner surface by the radiation of the solid body. Thus, the combustion temperature is being reduced, resulting to very low thermal NO_x-production. Examples for this burner type are the Thermomax-burner [5] from the Ruhrgas AG or the Matrix-radiant burner from Viessmann (fig. b)).

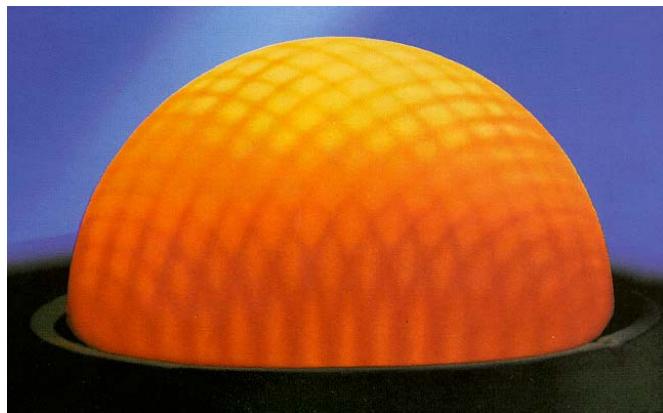


Fig. b) Matrix-burner [6]

Radiant burners can not be very compact due to their 2-dimensional structure. Thus, this concept leads to large household heating systems requiring special heating rooms. Moreover, the radiant burners are relatively unstable against changes of the thermal load or the air-ratio.

Another important point of the gas burner technology is that the modulation range of existing burner systems is very low. During the whole year a constant heat load is required for the hot water. For the heating of the house however, only within a small period of the year high

thermal loads are required. This means that the more the required thermal load for the heating of the house decreases, the higher the power modulation of the burner has to be. Existing burner systems however, can only modulate within a range of 1 : 2 or 1 : 3, although a wider dynamic range is generally considered to be of advantage. The consequence is that they have to work intermittent, but during the start-up procedure the emission values of burners are extremely high, and the overall efficiency is decreased.

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2.2 Summary of the specific project objectives

Task 4: Design, layout and construction of PMB-HE prototype I (LSTM, Viessmann, Insulcon)

In this task, a porous medium burner and heat exchanger unit should be designed and constructed. The compact burner should be filled with ceramic materials. Flame propagation should be only possible in the region where the Peclet number $\text{Pe} > 65$ and it should be stabilised by local quenching at the interface to the region where $\text{Pe} < 65$. The burner type I should act as a combustor and heat exchanger at the same time.

Task 5: Design, layout and construction of control unit Ia (PKO-OSMO, LSTM)

PKO-OSMO should develop and construct the control unit for the burner prototype I. The information already available at LSTM-Erlangen should be used, in order to fit the control characteristics to the operational characteristics of the burner. The functionality of the control unit must be tested in combination with the burner heat exchanger unit I.

Task 6: Verification experiments for PMB-HE prototype I (LSTM, Viessmann)

Detailed experimental investigations should be performed by LSTM-Erlangen and Viessmann. The experiments should include temperature measurements and emission measurements.

Task 7: Construction of experimental burners for partners (LSTM, Viessmann)

After minor improvement changes, prototypes of the type I PMB-HE should be constructed and distributed to the industrial partners.

Task 8: Summary of results of the investigations for PMB-HE prototype I (PKO-OSMO, LSTM, Viessmann, Insulcon)

Task 9: Conclusions on design and material improvements (LSTM, Viessmann, Insulcon)

Task 10: Design and layout of PMB-HE prototype II utilising results of type I (All partners)

According to the tests performed at LSTM and the computations of IST and IMPCOL, a new burner prototype should be built with the use of advanced ceramic parts.

Task 11: Design, layout and construction of control unit Ib (PKO-OSMO, LSTM)

The control unit Ib should be adapted to the high power modulation range and the high excess air modulation range of the PMB-HE burner. The unit should be developed on the basis of the control unit I.

Task 12: Radiative heat transfer in porous media for new burner design (two-dimensional computations) (LSTM, IST)

In this task an existing two dimensional general code for fluid flow should be extended to predict flow and heat transport in porous media.

Task 15: Construction of experimental burners for partners (LSTM, Viessmann)

After minor improvement changes, prototypes of the type II PMB-HE should be constructed. These prototypes should be used for test purposes by the industrial partners.

Task 16: Design, layout and construction of control unit II (PKO-OSMO, LSTM)

The control unit II should integrate the technology of control unit Ia with the power modulation technology of the control unit Ib in a complete control unit II.

Task 17: Verification experiments for PMB-HE prototype II (PKO-OSMO, LSTM, Viessmann, Insulcon)

Extensive experiments should be performed at LSTM in the same manner as for the prototype I. The experiments should include emission measurements and the measurement of the pressure drop of the burner. The control unit II should be employed for the control of the burner.

Task 18: Summary of results of investigations of PMB-HE prototype II (PKO-OSMO, LSTM, Viessmann, Insulcon)

Task 19: Conclusions on design and material improvements (LSTM, Viessmann, Insulcon)

The experimental results of the prototype II obtained at LSTM, the results of the industrial partners and the computations should form the basis for improvements.

Task 20: Modifications resulting in a PMB-HE final design (all partners)

Some final work should be done with respect to the development of a compact heating system concept, which can be used as a basis for commercial utilisation. All available results of the conclusion on design and material improvement should be utilised in the design data for the final porous medium burner with integrated heat exchanger unit.

Task 21: Final documentation (all partners)

2.3 Overview of the technical progress

Task 4/7: Design and layout of PMB-HE prototype I and Construction of experimental burners for partners (LSTM, Viessmann, Insulcon)

In the first period of the project, a 10 kW porous media burner and heat exchanger unit was designed and constructed. This unit is divided into three regions. The preheating region (A), the combustion region (C) and an additional heat exchanger region D. The schematic diagram of this first porous burner prototype and its constructive details can be seen in chapter 5.1. After minor improvement changes, prototypes of the type I PMB-HE were constructed and distributed for test purposes to all partners of the project.

Task 5: Design, layout and construction of control unit Ia (PKO-OSMO, LSTM)

In this task, a first control unit for the burner prototype I was developed and constructed by PKO-OSMO in collaboration with LSTM-Erlangen. This control unit was used for the start of the burner, its operation control and the operation control of the water circulation. LSTM-Erlangen supported PKO-OSMO with information already available at LSTM, in order to fit the control characteristics to the operational characteristics of the porous media burner and heat exchanger unit. For this reason, LSTM participated in several meetings with PKO-OSMO, where the design and layout of the control unit Ia was planned. Moreover, LSTM participated in the initial operation of the control unit Ia, where the burner unit type I was integrated.

Task 6: Verification experiments for PMB-HE prototype I (LSTM, Viessmann)

At LSTM-Erlangen experimental investigations were performed on the PMB-HE prototype I. The experiments showed that some further minor improvements were necessary. The result was an optimised 10 kW porous medium burner prototype (Ib). In the course of the experiments, different porous media and ceramic insulation materials were tested. With the prototype Ib low CO and NO_x emissions for air ratios from 1.2 up to 1.8 could be reached. A detailed description of the tested porous media (materials and forms), ceramic insulation materials and the experimental results can be seen in chapter 5.3.

Task 9: Conclusions on design and material improvement (LSTM, Viessmann, Insulcon)

The experiments with the porous media burner showed that the pressure drop across the burner was relatively high in comparison to burners with free flames. Therefore, the design of the burner had to be further optimised. Moreover, the experiments showed that constructive improvements as well as improvements of the emissions depend very strongly on the availability of better ceramic materials (mechanical stability, thermal stability, heat transport properties, etc.). Thus, the experimental results of the prototype I and Ib obtained at LSTM-Erlangen, the test results obtained from the industrial partners, and the computations at IST-Lisbon and I.C.-London, were used to define the criteria for the improvement of the burner heat exchanger unit Ib in order to get a good basis for the design of the prototype II. For this reason, several experiments were carried out at LSTM-Erlangen and new ceramic materials from Insulcon were tested. Moreover, the design of the heat exchanger had to be optimised.

Task 10: Design and layout of PMB-HE prototype II utilising the results of type I (all partners)

The results of the experiments with the prototypes I and Ib were the basis for the design and layout of the burner heat exchanger unit II. The decision on the desired thermal power and the basic geometric arrangement was made in collaboration with partner 4 (VIESSMANN). The design of the burner heat exchanger unit II is described in chapter 5.5.

Task 11: Design, layout and construction of control unit Ib (PKO-OSMO, LSTM)

Due to the difficulties at PKO-OSMO, LSTM carried out the work packages concerning the development of the control unit Ib for the porous media burner. PKO-OSMO already had developed and constructed the control-unit Ia for the porous burner heat exchanger unit. LSTM-Erlangen developed the control unit Ib on the basis of unit Ia, in order to continue the work. The unit developed at LSTM was tested with one of the burner-heat exchanger prototypes I and modified according to the test results. The control unit fulfils the following tasks:

- Start of the burner
- Operation control of the burner
- Operation control of the water circulation

The work carried out on the development of the control unit is described in detail in chapter 5.6.

Task 12: Radiative heat transfer in porous media for new burner design (two-dimensional computations) (LSTM, IST)

In a first step, the fluid flow in the porous medium was treated as one-dimensional. The basic equation which had to be solved for the 10 kW prototype by numerical methods, was the two-dimensional energy equation. The results were temperature and effective heat conductivity fields. This model was extended in order to take into account the mechanisms caused by the condensation of the liquid water formed in the cold heat exchanger region D. In a further step, a more detailed model was applied. This model considers the momentum, energy and transport equations (two-dimensional). With the two-dimensional model it is possible to calculate more detailed temperature fields and flow fields as well as concentration and pressure fields (chapter 5.7).

Task 15: Construction of experimental burners for partners (LSTM, Viessmann)

In the second period, detailed construction plans were made for the PMB-HE prototype II, which was also distributed to the industrial partners. The constructive details of the burner and heat exchanger unit are described in chapter 5.8. This prototype II construction meets the requirements for household applications, concerning the pressure drop of the gas as well as the pressure drop within the heat exchanger system. The emissions of the burner are low due to an improved temperature distribution within the combustion region. Viessmann fabricated the heat exchanger part, while LSTM-Erlangen fabricated the burner part.

Task 16: Design, layout and construction of control unit II (PKO-OSMO, LSTM)

The control unit II for the control of the porous media burner and heat exchanger unit II was developed at LSTM-Erlangen, outgoing from the control unit Ib. The control unit was developed not only with respect to its functionality, which had to be adapted to the operational characteristics of the porous media burner, but also with respect to a compact design, so that it can be used as a basis for the commercial utilisation in household heating systems. The design of the burner heat exchanger control unit II is described in chapter 5.9.

Task 17/18: Verification experiments for PMB-HE prototype II and summary of results of investigations of PMB-HE prototype II (PKO-OSMO, LSTM, Viessmann, Insulcon)

During the second six months period, a 30 kW porous media burner and heat exchanger was designed and constructed at LSTM-Erlangen. The decision on the desired thermal power and the basic geometric arrangement was made in collaboration with Viessmann. In the third six months period of the project, extensive experiments were performed at LSTM-Erlangen. The experiments included emission measurements and the measurement of the water and gas pressure drop of the burner. The major results of these investigations are summarised in chapter 5.10. The results of the experiments showed that for the final burner design further constructive improvements had to be done on the heat exchanger, in order to reduce the gas pressure drop.

Task 19/20: Conclusions on design and material improvements (LSTM, Viessmann, Insulcon) and modifications resulting in a PMB-HE final design (all partners)

The results of the experiments carried out with the prototype II showed that for the final burner design further constructive improvements had to be done on the heat exchanger. In agreement with all partners a „Stabripen“ heat exchanger with small pins was built by Viessmann. This kind of heat exchanger has a very compact geometry in comparison to conventional heat exchangers and a very high efficiency. According to the design of the „Stabripen“ heat exchanger, LSTM-Erlangen modified the design of the porous medium burner. The results of the experiments, carried out with the prototype II and the results of the calculations of Partner 3 and 4 were also the basis for the PMB-HE final design. The

experimental work carried out with this final design burner is described in detail in chapter 5.11.

2.4 State of the Work

In the first 6 months period of the project, a 10 kW porous media burner and heat exchanger unit was designed and constructed at LSTM-Erlangen (**Task 4**). After minor improvement changes, prototypes of the type I PMB-HE were manufactured and distributed for test purposes to all partners of the project (**Task 7**). PKO-OSMO with the assistance of LSTM-Erlangen developed and constructed a control-unit Ia for this porous burner heat exchanger unit I, according to the workshare chart (**Task 5**), and at LSTM-Erlangen comprehensive experimental investigations were performed on the PMB-HE prototype I (**Task 6**). However, the experiments showed that some further minor improvements were necessary. The results were a basis for the conclusions on further constructive material improvements (**Task 9**). Moreover, the experimental results from IST and Viessmann with the PMB-HE prototype I made further improvements possible. The result was a prototype Ib with very low emission values.

The LSTM results with the prototype I and Ib as well as the computations of IST and IMPCOL were the basis for the design and layout of PMB-HE prototype II, in the second six months period of the project (**Task 10**).

At LSTM-Erlangen, the control unit Ib was developed, so that the work on this task could be continued after the bankruptcy of PKO-OSMO. Due to the bankruptcy of PKO-OSMO, there had been a little delay in this **task 11**, but nevertheless the control unit Ib was completed.

According to the workshare chart the calculation of the radiative heat transfer in porous media (two-dimensional computations) (**Task 12**) started in the second 6 months period. This work was completed until the end of the project, according to the schedule.

Detailed constructions for the PMB-HE prototype II (**Task 15**) and the design, layout and construction of the control unit II (**Task 16**) were completed at LSTM. The control unit II was available for the experiments with the burner prototype II and for the burner with the final design.

The PMB-HE prototype II was extensively tested at LSTM-Erlangen in the third six months period of the project (**Task 17**). According to the results of these experiments the burner heat exchanger unit with the final design was constructed and investigated (**Task 18/19/20**).

Workplanning and Workshare Chart

Task	Description	6 Months	6 Months	6 Months
4	Design, layout and construction of PMB-HE prototype I (PARTNERS 2,5,6)			
5	Design, layout and construction of control unit Ia (PARTNERS 1,2)			
6	Verification experiments for PMB-HE prototype I (PARTNERS 2,5)			
7	Construction of experimental burners for partners (PARTNERS 2,5)			
8	Summary of results of investigations for PMB-HE prototype I (PARTNERS 1,2,5,6)			
9	Conclusions on design and material improvements (PARTNERS 2,5,6)			
10	Design and layout of PMB-HE prototype II utilising results of type I (ALL PARTNERS)			
11	Design, layout and construction of control unit Ib (PARTNER 1,2)			
12	Radiative heat transfer in porous media for new burner design (two-dimensional computations) (PARTNERS 2,3,4)			
15	Construction of experimental burners for partners (PARTNERS 2,5)			
16	Design, layout and construction of control unit II (PARTNER 1,2)			
17	Verification experiments for PMB-HE prototype II			

	(PARTNERS 1,2,5,6)												
18	Summary of results of investigations of PMB-HE prototype II (PARTNERS 1,2,5,6)											[REDACTED]	
19	Conclusions on design and material improvements (PARTNERS 2,5,6)											[REDACTED]	
20	Modifications resulting in a PMB-HE final design (ALL PARTNERS)											[REDACTED]	
21	Final documentation (ALL PARTNERS)												[REDACTED]

In general, the workplanning has been executed. The design and layout of the control unit Ib and II has been delayed due to the bankruptcy of PKO-OSMO (Partner 1). LSTM-Erlangen developed the control unit Ib and II. Thus, it was possible to continue the work with some delays on the control unit tasks, which did not affect the other tasks.

3. List of deliverables

Nr.	Work package Identification	Title	Partner	Due Date	Completed
1	WP0	Project plans and time tables	1	month 1	yes
2	WP0	Existing results on porous medium combustor and integrated heat exchanger	2	month 1	yes
6	WP6	PMB-HE prototype I and verification results	2	month 4	yes
8	WP5	Control system for burner type I	1	month 5	yes
9	WP6	Verification experiments for temperature data	2	month 6	yes
15	WP11/WP16	Control system for burner type II	1	month 12	yes
19	WP17	PMB-HE Prototype II and verification results	2	month 16	yes
22	WP20	Control system design final burner	1	month 18	yes
23	WP20	Final results on improved PMB-HE	2	month 18	yes

4. Exploitation and dissemination of results

As a result from the present project, a burner-heat-exchanger prototype was obtained, which is completely novel and provides significant advantages compared to current heating systems, that can not be achieved by any other technology. As a consequence, many households could be equipped with smaller, cheaper and better heating devices, once the new technique is introduced to the market. Since all partners worked together closely in all phases, knowledge and know-how was passed onto all of the partners, which is available for a later demonstration phase that is necessary before the actual market introduction of the new technique can take place. Moreover, several manufacturers of heating systems in Europe already expressed their interest in producing the porous burner units with integrated heat exchangers.

Besides, various demonstrations were given at LSTM in Erlangen for several companies (Siemens, Ford, Sulzer, Bosch, Windhager, and others), which are interested in the new combustion technique. These contacts showed that further industrial applications of the porous media combustion are possible, apart from the household applications (for instance for power plants, industrial furnaces etc.).

In addition, the following publications and conference presentations resulted from the project and will help to disseminate the results (see Annex):

- *Trimis, D., Durst, F., Pickenäcker, K., Pickenäcker, O.:* Porous Medium Combustor versus Combustion Systems with Free Flames, presented at ISHTEC '97, Guangzhou, China
- *F. Durst, A. Kesting, S. Mößbauer, K. Pickenäcker, O. Pickenäcker und D. Trimis:* Der Porenbrenner - Konzept, Technik und Anwendungsgebiete, GASWÄRME International - Zeitschrift für industrielle und gewerbliche Gasanwendung, Juni 1997, 46. Jahrgang, S.300-307
- *F. Durst, D. Trimis:* Combustion by Free Flames Versus Combustion Reactors, 4th International Conference on Combustion Technologies for a Clean Environment, Lisbon, Portugal 1997

In all publications the financial contribution of the Commission was gratefully acknowledged.

5. Technical report - LSTM

5.1. Description of the Work under Task 4 and 7: Design and layout of PMB-HE prototype I and Construction of experimental burners for partners

In the first six months period of the project, a 10 kW porous medium burner and heat exchanger unit was designed and constructed and after some minor improvement changes, prototypes of this type I PMB-HE were also constructed and distributed for test purposes to all partners of the project. The 10 kW burner heat exchanger-system is divided into three regions. The preheating zone (region A), the combustion zone (region C) and an additional heat exchanger region D. The schematic design of the first porous burner heat exchanger prototype constructed for the present project can be seen in fig. 1, a photograph of the burner and its construction plan in fig. 2. The premixed gas flows through the PM region A with an equivalent diameter d_m of the PM cavity space which is less than the quenching diameter at these flow conditions. At the position where the flame front should be located, a steep gradient in the porous size of the PM was realised resulting in PM cavity space diameters larger than the quenching ones. In other words, a PM region C with a d_m larger than the quenching diameter follows the region A. The flame can only propagate in region C, where $Pe > 65$, and it is stabilised by local quenching at the interface to region A, where $Pe < 65$. The different Peclet numbers are obtained by changing the size of the pebbles. A change in the load of the combustor does not affect the flame front location but only changes its length, starting always from the edge of region A. By cooling the porous medium with water, i.e. at the walls and within the porous matrix, the unit acts as combustor and heat exchanger at the same time. Because of the effective heat exchange, the water vapour produced by the combustion condenses giving its latent heat to the heat exchanger. The burner is mounted so that the gas flows from the top to the bottom in order to enable the condensed water to flow out of the burner.

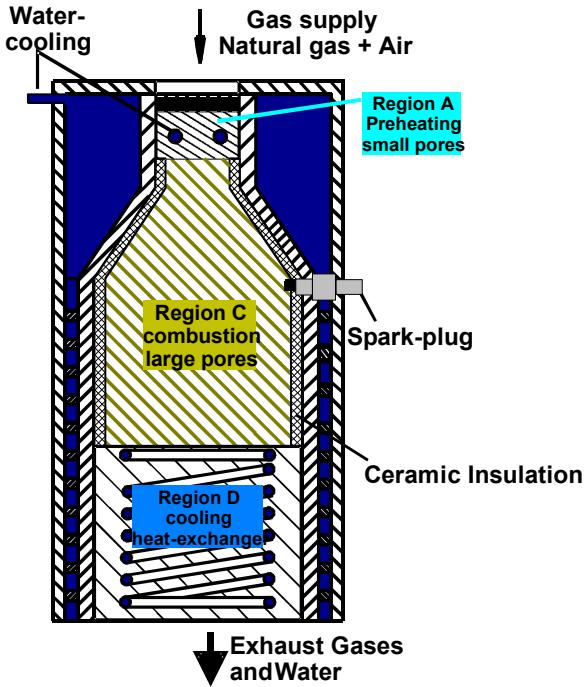


Fig. 1 Schematic diagram of the porous burner prototype with integrated heat exchanger

The burner cross-section has been reduced in the preheating zone A in order to increase the power modulation range of the burner. Due to the high heat transport in the porous matrix against the flow direction of the gas/air mixture, there are increased temperatures within the region A, especially at low thermal powers. It is subsequently possible that the temperature within the region A exceeds the ignition temperature and combustion already takes place in the preheating region at thermal loads less than 300 kW/m^2 . The combustion in the small pores of this region however, is only incomplete and an increased production of carbon monoxide results. The reduction of the cross-section causes a much higher velocity of the gas/air-mixture within this region. Consequently, the porous material in region A is better cooled and the power dynamic range of the burner improved.

In order to have complete combustion, the region C is insulated from the cold walls by a ceramic ring which provides a controllable heat flux to the mantle cooling and a high inner surface temperature. Thus, the formation of carbon monoxide due to the contact of the reaction radicals with the cold surfaces can be avoided.

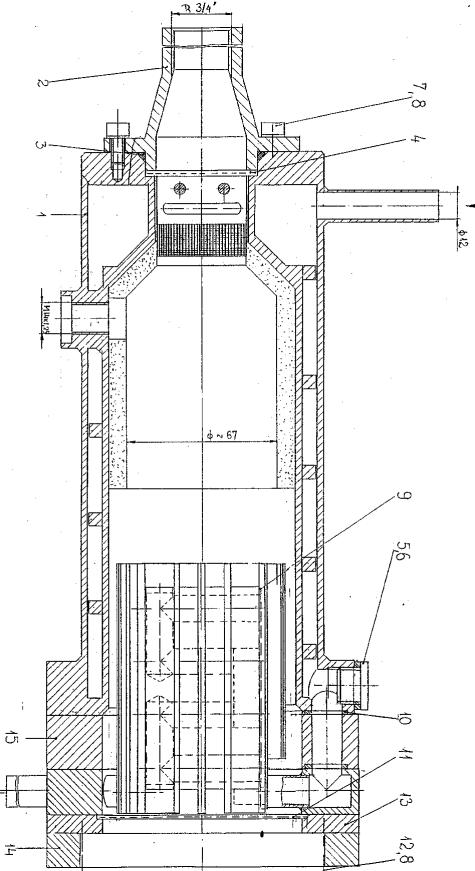
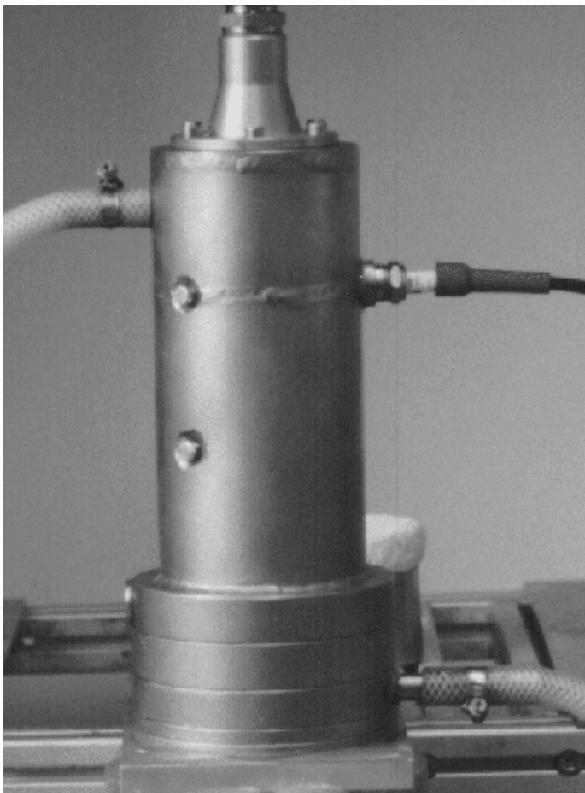


Fig. 2

10 kW porous burner prototype and construction plan

The main principal advantages of steady combustion in inert porous media may be summarised as follows:

- Large inner surface of the porous medium which results in
 - an enlargement of the reaction zone
 - increased heat transport between the gas phase and the porous medium (quasi-equilibrium)
- Superior heat transport properties of the porous medium, resulting in
 - higher combustion velocities
 - cooling of the reaction zone (low NO_x-emissions)
- The large heat capacity of the porous medium ensures a high combustion process stability against changes of thermal loads and excess air ratios.

These operational features of the porous „combustion reactor“ are schematically shown in figure 3.

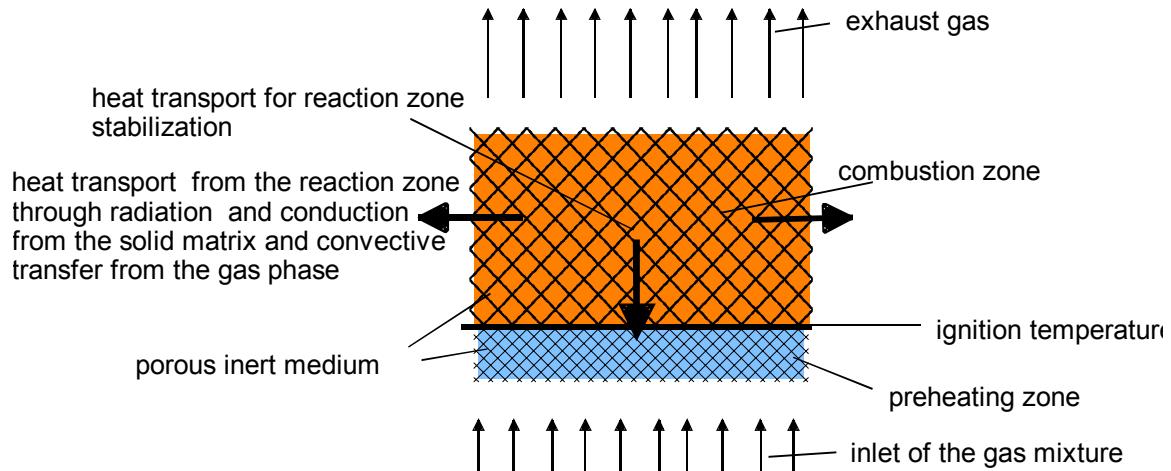


Fig. 3 Schematic diagram of the heat fluxes in the porous combustion region

5.2 Description of the Work under Task 5: Design, layout and construction of control unit Ia

One of the most important advantages of the porous media combustion for household applications in comparison to conventional heating systems is its high power modulation range. The heat demand of a one-family house is about 6 - 8 kW. For the delivery of hot water however, 12 to 14 kW are necessary, in order to guarantee sufficient comfort. Only within a very short period of the year the maximum heat load of 6 kW is required for heating the house (outside temperature: - 15 °C). In the transitional period only a lower heat output is necessary, and the lower this required heat output is, the higher the modulation range of the heating system has to be (Fig. 4) [1].

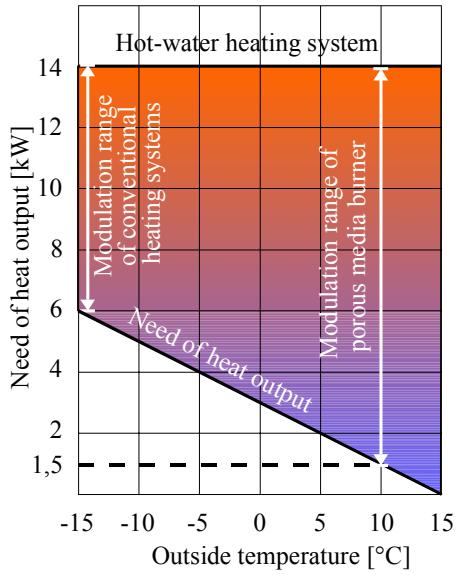


Fig. 4 Average heating power requirement within a year [1]

For most of the conventional heating systems the minimum of the modulation range is about 6 kW. This means that they can work only intermittent. The porous media burner however has a high power modulation range of up to 1 to 20. In this part of the project a control unit for the porous media burner had to be developed and built, which is adapted to these important operational characteristics of the porous burner and heat exchanger unit as well as to its special qualities concerning the combustion. The difficulty of this work was that most of the components, available on the market, are designed for burners with a minimum power of 5 kW.

In task 5 a first control unit for the burner prototype I was developed and constructed by PKO-OSMO. This control unit was used for the start of the burner, its operation control and the operation control of the water circulation. LSTM-Erlangen supported PKO-OSMO with information already available at LSTM, in order to fit the control characteristics to the operational characteristics of the porous media burner and heat exchanger unit. For this reason, LSTM participated in several meetings with PKO-OSMO, where the design and layout of the control unit Ia was planned. Moreover, LSTM participated in the initial operation of the control unit Ia. One of the prototypes type I was integrated in the developed control unit Ia.

5.3 Description of the Work under Task 6: Verification experiments for PMB-HE prototype I

Selection of porous media (materials and forms) for the PMB-HE prototype I

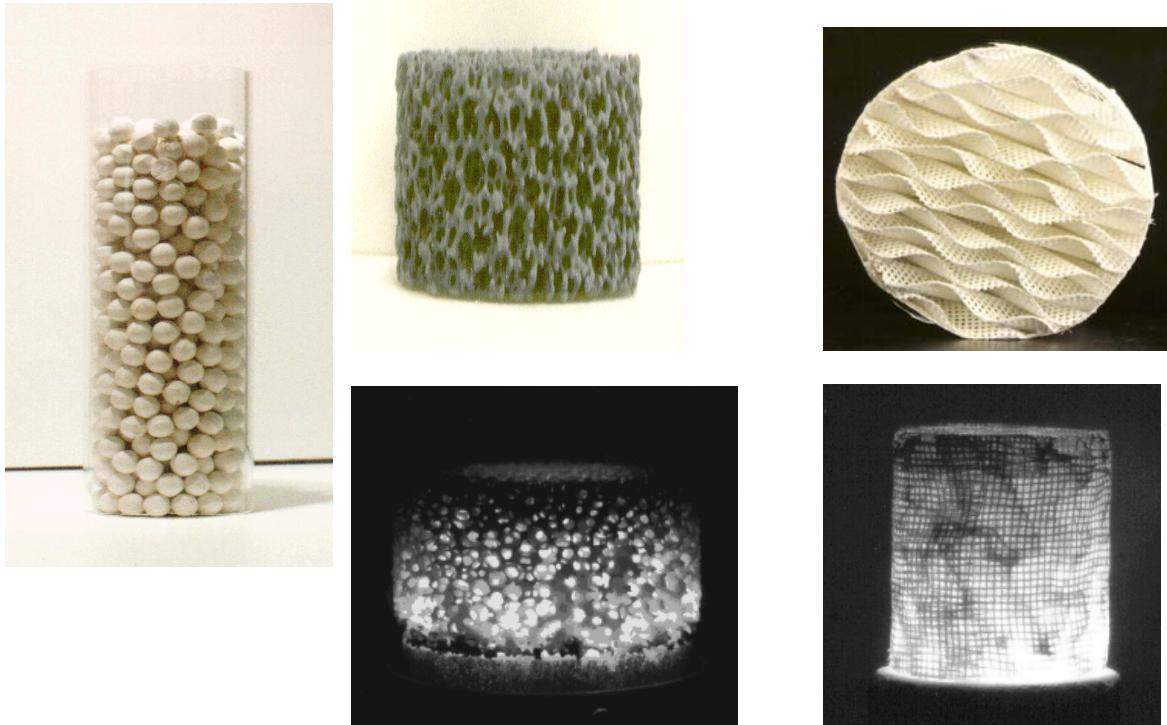
In the burner prototype I, several materials and forms of the porous matrix were applied. The most important criteria for the selection of the porous media for the different regions of the burner are the temperature resistance of the materials T_{\max} , the temperature cycle resistance, its heat conductivity λ , and the emission coefficients ε . A high effective heat conductivity in radial direction is of special advantage, as the temperature distribution within the burner becomes more homogenous and the heat transfer to the cooled walls of the burner becomes more effective. In contrast, the effective heat conductivity in axial direction should be low, especially near the area between the zones A and C, in order to avoid high temperatures and combustion within region A. At high temperatures and large pore sizes the emission coefficient has an important influence on the effective axial and radial heat conductivity.

With regard to the mechanical qualities of the porous media, the temperature cycle resistance is the most important parameter. Therefore, materials with a low thermal expansion coefficient are favourable to avoid cracks within the porous medium.

The ceramic materials, which were used for the experiments with the 10 kW prototype I are alumina, siliconcarbide and zirconia. The most important properties of these materials can be seen in table 1.

Material	T_{mp} [°C]	T_{\max} [°C]	λ [W/mK]
Al_2O_3	2050	1950	10-16
ZrO_2	2700	2400	2-3
SiC	2830	1650	50-100

Tab. 1 Properties of the most important materials



Packing of spheres

$\psi = 0,4$

material: Al_2O_3

Ceramic foams

$0,7 < \psi < 0,85$

materials: Al_2O_3 , ZrO_2 , SiC

Ceramic fibre structures

$0,95 < \psi < 0,99$

material: Al_2O_3

Fig. 5 Different ceramic porous materials used in the 10 kW porous burner prototype

The different forms of porous media, which were used in the porous burner are packings of spheres, ceramic foams, and ceramic fibre structures (see fig. 5). Packings of ceramic spheres were used within the preheating region and in the heat exchanger region, in order to improve the heat transfer to the heat exchanger. Within the combustion region ceramic foams or fibre structures are advantageous as they have higher porosities ψ . This means that the radiative heat transfer is more effective in comparison to packings of spheres and the pressure loss is less. Moreover, the operating temperature of the burner is reached more quickly.

Ceramic insulation of the combustion region

As already mentioned, the walls of the combustion region must be insulated with ceramic, in order to avoid incomplete combustion caused by contact of the reaction radicals with the cold wall surface. The insulation material should fulfil several requirements:

- The contact of reaction radicals with the cold surface must be avoided. This means that the ceramic ring has to be gas-tight. Already small cracks within the ceramic insulation can be responsible for increased CO emissions. Such cracks can also result from bad adhesion of the materials to the burner walls.
- The effectiveness of the ceramic insulation depends on the heat conductivity of the material and the thickness of the insulating layer. Thin layers of low heat conductivity are favourable in order to reduce the construction size.
- The inner part of the insulation is exposed to temperatures higher than 1000 °C, while the outer part is in contact with the cooled metal walls of the burner. This means that the material is exposed to high temperature gradients and that a low thermal expansion coefficient is of major importance.

In the course of the experiments different insulation materials were tested:

- In the beginning, the combustion region walls were insulated with a layer of Comprit®, an Al₂O₃-ceramic (8 - 10 mm layer thickness). This material, however, has a relatively high heat conductivity (about 2 - 3 W/mK). Thus, the heat flux to the mantle cooling was so high that the inner part of the ceramic insulation was not hot enough and relatively high CO-emissions resulted. In order to improve the insulation effect of the material, Comprit® was mixed with a certain amount of little wood chips, in order to produce small pores within the ceramic and reduce the heat conductivity.
- Another material with a very low heat conductivity called Pyroset® was tested ($\lambda = 0,15$ W/mK). Because of the very low heat flux to the mantle cooling, the temperature of the ceramic insulation exceeded the melting point of Pyroset® (temperature-resistant up to 1050 °C) already at the minimum layer thickness of about 4 mm (construction limitations).

- In the next step a three layer ceramic insulation was used (fig. 6). This insulation showed relatively good insulation qualities, thermal resistance and did not crack.

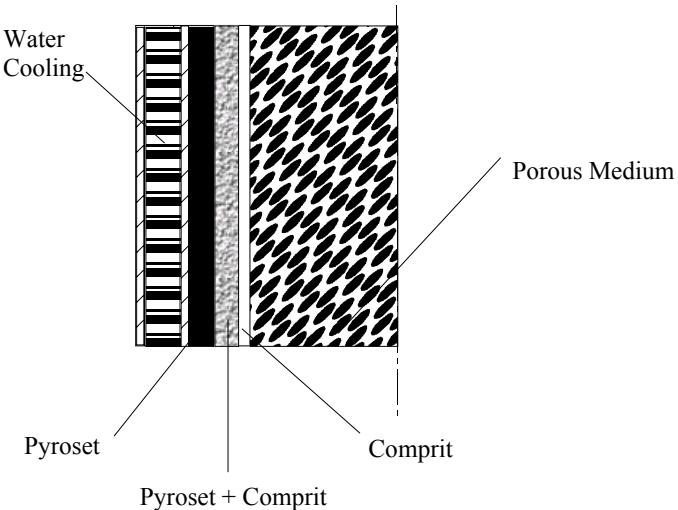


Fig. 6 Three layer ceramic insulation within the combustion region

The aim was, however, to find a better insulation material with a low heat conductivity, a high thermal resistance and a low thermal expansion coefficient, in order to simplify the manufacturing method.

Results of the emission measurements

An exhaust gas analyser working with electrochemical cells was used for the emission measurements. The analyser can measure the O₂, CO and NO concentration. From the O₂ measurement the excess-air ratio can be calculated according to German standards (BImSchV). The accuracy of the analyser is given by the manufacturer with ± 5 ppm NO and ± 10 ppm CO. However, a calibration with test-gases of known concentration was performed and lead to a better accuracy in the calibrated range (0-60 ppm NO, 0-150 ppm CO) of ± 2 ppm NO and ± 3 ppm CO.

The maximum excess-air ratio of the burner depends on the insulation of the burner walls within the combustion region and on the thermal load of the burner. The effect of the insulation can be related to the combined influence of the convective and radiative heat transfer due to the ceramic insulation. If poor insulation is used, more energy is transferred to the water in the radial direction, and the temperature level in the combustion zone decreases.

Thus, the state of incomplete combustion is reached at lower excess-air ratios. As the thermal load increases the maximum excess-air ratio decreases, since the convective losses in axial direction become more significant.

Since the first insulation materials used had a high heat conductivity (ca. 3 W/mK), the insulation layer had to be relatively thick, in order to avoid incomplete combustion at the cold walls. Consequently, the cross-section for the combustion was smaller (60 mm diameter) than planned (70 mm diameter), and the power density of the porous burner increased from the originally planned 2500 kW/m^2 to 3500 kW/m^2 . However, for such a high power density, the length of the combustion region was not sufficient for complete combustion and the combustion zone had to be extended by about 20 mm in length. Therefore, another experiment was carried out with a burner which had the same design but an increased diameter within the combustion region (80 mm combustion region diameter - burner type Ib). Thus, the power density was reduced to 2000 kW/m^2 . Simultaneously, the already mentioned three-layer ceramic, with a low heat conductivity, was used to insulate the burner. With this burner configuration stable combustion with very low CO-emissions could be achieved for excess-air ratios up to 1.8 (Fig. 7).

NO_x can be produced by the thermal (Zeldovich) mechanism or the prompt (Fenimore) mechanism. Both mechanisms are temperature dependent with lower temperatures resulting in lower NO_x levels. Although the thermal mechanism is a „slow“ mechanism, it contributes most of the NO_x . Therefore, the formation of NO_x mainly depends on the maximum temperatures reached in the centre of the combustion region and on the residence time in the hot regions. In order to avoid hot spots in the porous medium, its effective heat conductivity in radial direction should be high. If the radial temperature distribution is uniform the NO emissions depend mainly on the heat load and the excess-air ratio of the burner. In the case of the porous burner a non typical NO-emission behaviour is observed with respect to the heat load. Medium heat loads result in higher NO-emissions than high or low heat loads. This can be explained with the decreased residence times at higher heat loads and the decreased temperatures at lower heat loads. In the case of good insulation, the NO-emissions begin to decrease at very low heat loads. The excess-air ratio, however, affects the NO_x level very strongly, since with increasing excess-air ratio the residence time and the temperature in the combustion region decreases.

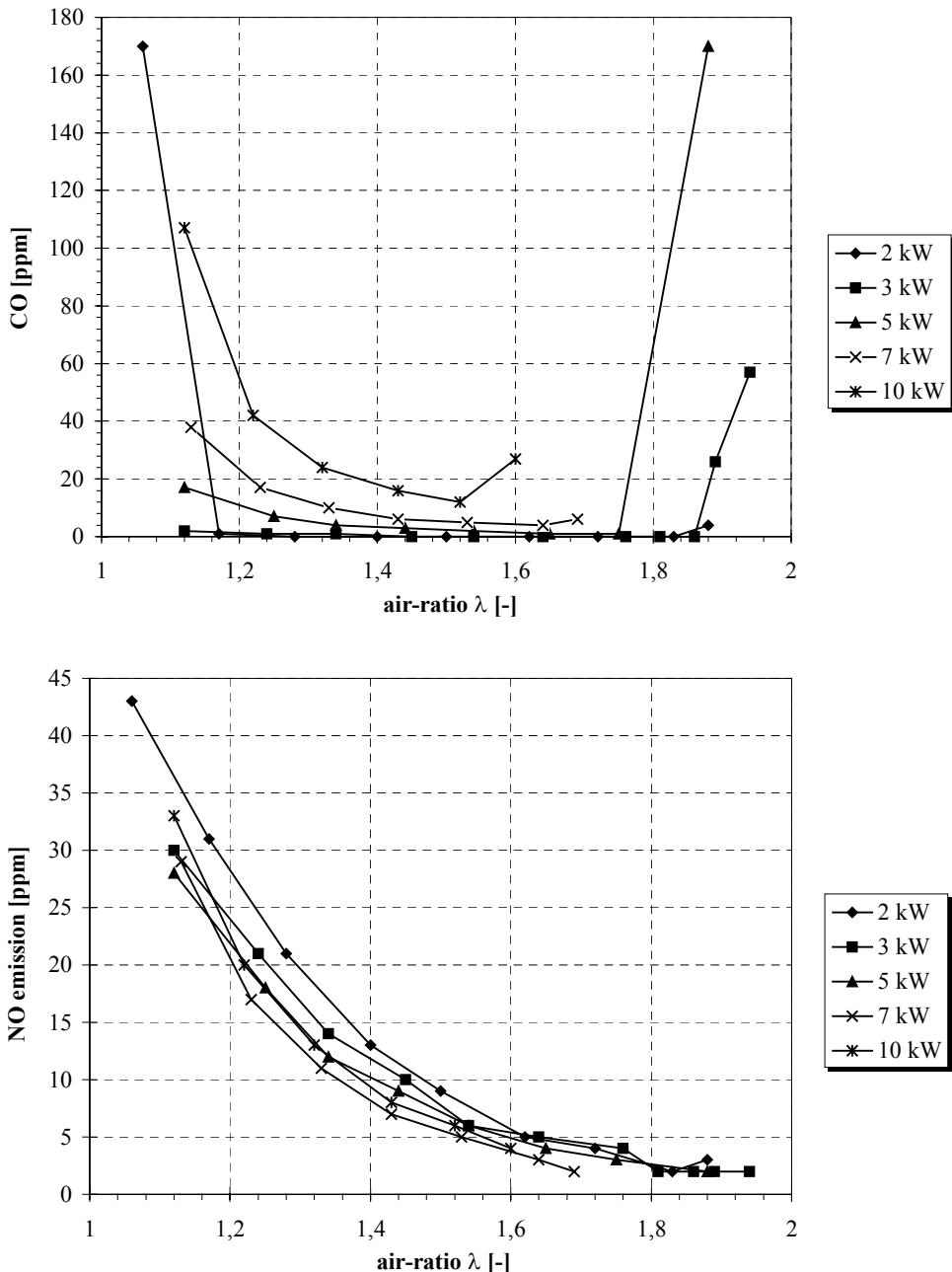


Fig. 7 CO and NO emissions (absolute measured values in ppm); configuration: region A: 5 mm spheres (Al_2O_3); region C: fibre structure (Al_2O_3); region D: 5 mm spheres (Al_2O_3)

Investigation of the pressure drop

In comparison to burners with free flames the pressure drop across the burner was relatively high, due to the porous medium and the high power density of the burner (Fig. 8).

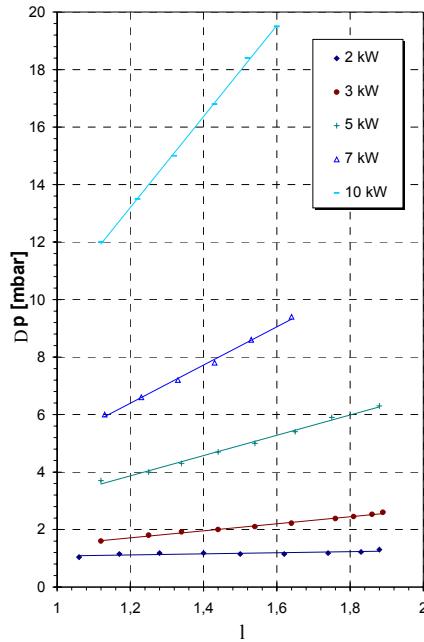


Fig. 8 Pressure drop of a 10 kW burner heat exchanger prototype

Therefore, the design of the porous medium burner had to be improved, especially in region A. Moreover, an optimised form of heat exchangers was necessary, in order to reach pressure drops below 8 mbar. Calculations have shown, that the goal of 8 mbar at maximum power and excess-air ratio was achievable.

5.4 Description of the Work under Task 9: Conclusions on design and material improvements

In the first six months of the project prototypes of a 10 kW porous medium burner with integrated heat exchanger were constructed and distributed for test purposes to all project partners. At LSTM-Erlangen experimental investigations were performed on these prototypes. In the course of the experiments, different porous media and ceramic insulation materials were tested. The

experiments showed that further constructive improvements as well as improvements of the emissions depend very strongly on the availability of better ceramic materials for the combustion region (mechanical stability, thermal stability, heat transport properties, etc.). Beyond these investigations it was necessary to find optimised ceramic insulation materials for the combustion region of the burner. As the experiments showed that the gas pressure drop of the porous media burner was relatively high, its design had to be further improved. Moreover, the design of the heat exchanger had to be optimised. Thus, the experimental results of the prototype I obtained at LSTM-Erlangen, the test results obtained from the industrial partners, and the computations at IST-Lisbon and I.C.-London, were used to define the criteria for the improvement of the burner heat exchanger unit Ib (Fig. 9) in order to get a good basis for the design of the prototype II.

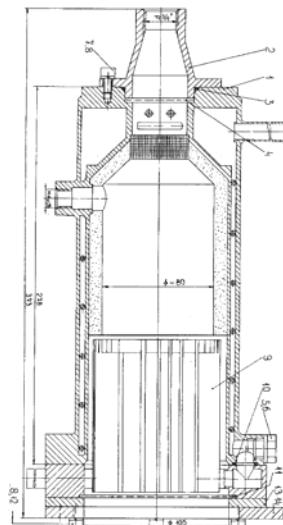


Fig. 9 Optimised 10 kW burner and heat exchanger unit Ib

According to these results obtained from the industrial partners and according to the results of the computations the following experiments were carried out at LSTM-Erlangen:

The experiments with the prototype I showed that one of the most important points was the optimisation of the ceramic insulation within the combustion region. The material must show a low heat conductivity, a high thermal resistance, and low thermal expansion coefficient, in order to simplify the manufacturing method. In the second period of work LSTM found a ceramic material which has all these important qualities. Pyrostop Coating 160 ® (Company Didier), an alumina fibre ceramic is temperature resistant up to 1600 °C and has an extremely low heat conductivity ($\lambda = 0.16 \text{ W/mK}$ (1000°C)).

Moreover, different porous materials were used within the combustion region of the burner (region C). In region C1, in which the burner cross-section was reduced, a 10 ppi ceramic foam was used, in order to improve the flame stabilisation and the distribution of the air/methane mixture. In region C2, the advantage of the excellent heat transport properties of ceramic fibre structures (large optical thickness, high internal surface) was used.

These optimisations of the porous burner heat exchanger unit Ib resulted in very low emissions of carbon monoxide and nitrous oxides (Fig. 10).

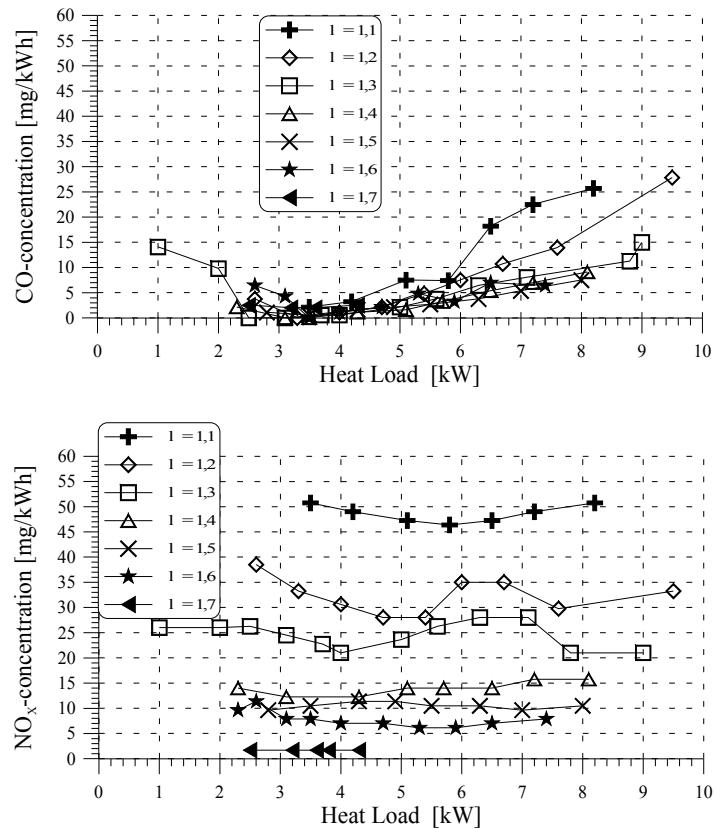


Fig. 10 CO and NO_x-emissions as a function of thermal power and excess-air ratio for the 10 kW Prototype Ib

Figure 11 indicates that the emissions of nitrous oxides and carbon monoxide are clearly below the most current European emission standards now („Blauer Engel“ and „Hamburger Förderprogramm“ are German emission standards, but are even more stringent than the general European ones).

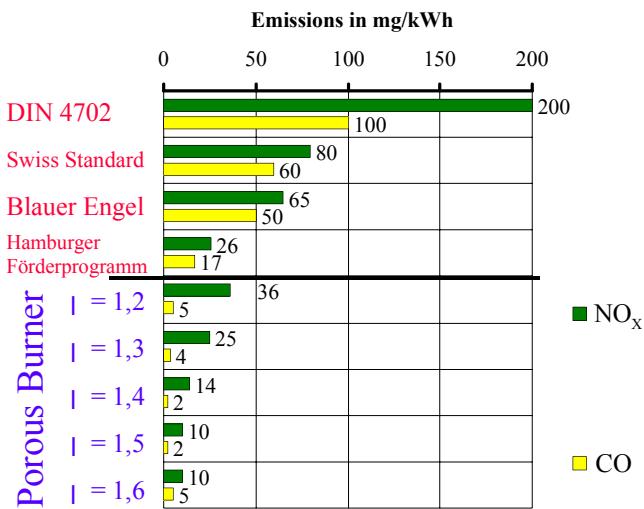


Fig. 11 Emissions of the emission-optimised burner heat exchanger unit Ib in comparison to several emission standards, averaged according to DIN 4702 Teil 8, over the modulation range 1 : 10

For the further improvement of the ceramic materials Insulcon was involved in the development and building of new ceramic parts, which were tested at LSTM-Erlangen.

To investigate the performance of the ceramic materials the burner/heat exchanger unit I (10 kW burner, see Fig. 12) was used.

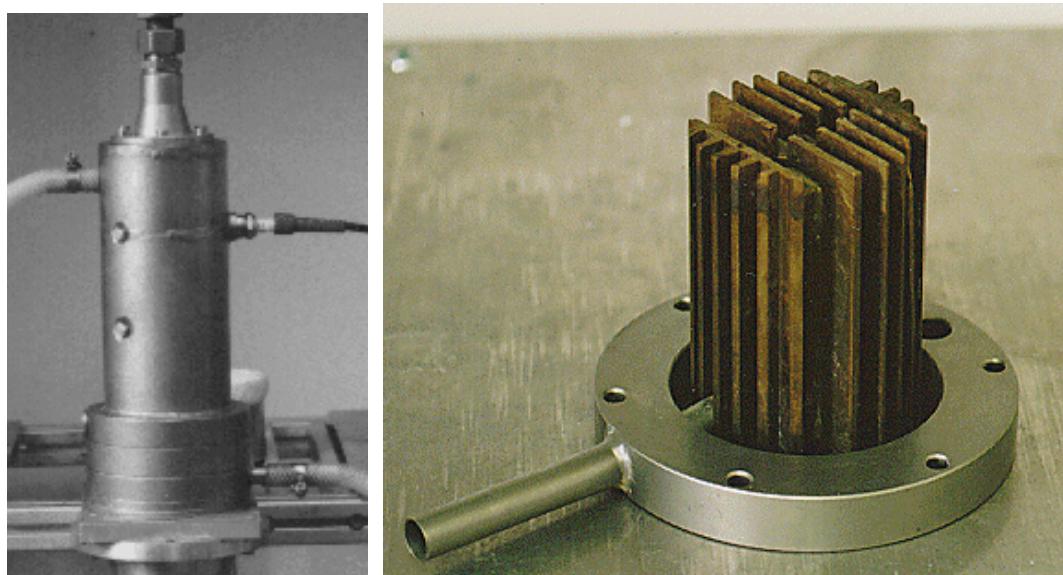


Fig. 12 10 kW porous burner and heat exchanger unit I

Fibres and static mixer like structures

Previous experiments showed that especially ceramic fibre structures are advantageous for the combustion process, as these structures can have a very high porosity and greater pore sizes. This means that the radiative heat transfer is more effective in comparison to packing of spheres and the pressure drop of the burner is less. Moreover, the operating temperature of the burner is reached more quickly. Due to these results, LSTM-Erlangen used the Al_2O_3 -textiles (Fig. 13) from Insulcon to manufacture static mixer-like structures.

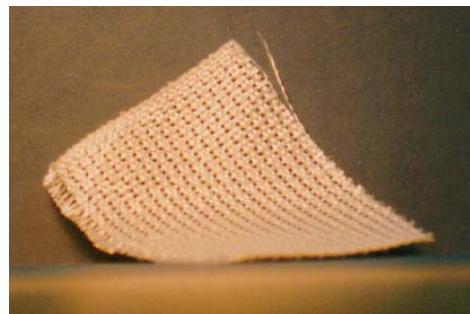


Fig. 13 Al_2O_3 -fibre textile (Insulcon)

The single layers of the textile material were coated with Al_2O_3 , in order to obtain a mechanically stable structure (Fig. 14). The result was a static mixer-like structure with pores in the wended plates.

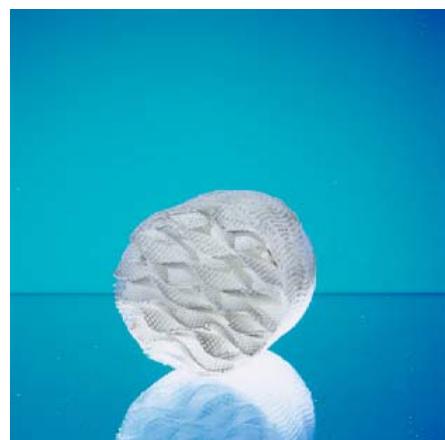


Fig. 14 Static mixer-like structure made out of Al_2O_3 -textile (Insulcon) coated with Al_2O_3

Insulation materials for the combustion region

The combustion region of the burner must be insulated from the cold walls by a ceramic ring which provides a controllable heat flux to the mantle cooling and a high inner surface temperature, in order to obtain complete combustion. This material should have a low heat conductivity, in order to reduce the size of the burner. Moreover, the ceramic insulation must be gas-tight and resistant against temperature and chemical effects. Such a material was the three layer ceramic insulation, mentioned in chapter 5.3. However, this principle was time consuming and very complicated for manufacturing. An improvement to this method was achieved by using a new ceramic insulation, PYROSTOP COATING[®], a special Al₂O₃/SiO₂ adhesive which combines the properties of high temperature resistance with low heat conductivity.

However, the use of a ceramic which has to be wetted with water, formed and dried inside the burner, is still a problem for a later mechanised manufacturing. This problem was solved by the use of a solid pipe, which only has to be inserted into the burner. In fig. 15 is presented a silicon carbide pipe from Insulcon. The remaining gap between the pipe and the burner wall was filled with an insulating cloth.



Fig. 15 SiC pipe (Insulcon)

The results of tests with the SiC pipe showed that the temperature resistance of this material was very good; no cracks were observed after testing it for hours under changing conditions of the power and the equivalence ratio. Furthermore, the insulation effect at the same thickness of the pipe/insulation cloth system seemed to be a little better with the advantage of a volume gain and normally less CO values.

New materials in the flameholder region A

Another point of research was the test of a new ceramic material for the flameholder region A. The tested material was a disc consisting of SiC granulate, which was delivered by Insulcon, (Fig. 16).



Fig. 16 SiC granulate disc for the preheating region of the burner (Insulcon)

The experiments showed that the disc has very good qualities, concerning the mechanical and thermal stability. However, there are no advantages, concerning the emission characteristics because of undesired reactions inside the SiC granulate disc, especially at low thermal loads and low air-ratios. A more insulating disc with greater pores and higher porosity is expected to be better, also in respect to better pressure drops.

Silicon carbide spheres in region D

Insulcon delivered silicon carbide spheres which should enhance the heat transport from the waste gas to the water with the effect of a compact building. However, it turned out that the thermal resistance of the material was not sufficient. Especially directly after the combustion region, where the temperatures of the exhaust gases are still very high, the material melted. A reason could be that the SiC material contained also some other ceramic components, and therefore formed an eutektikum.

5.5 Description of the Work under Task 10: Design and layout of PMB-HE prototype II utilising the results of type I

The results with the 10 kW porous medium burner unit I and the optimised unit Ib and the computations of IST and IMPCOL were the basis for the design and layout of the burner heat exchanger unit II. The decision on the desired thermal power and basic geometric arrangement was made in collaboration with partner 4 (Viessmann). The schematic design of the burner and heat exchanger unit I in comparison to unit II can be seen in fig. 17 a) and b).

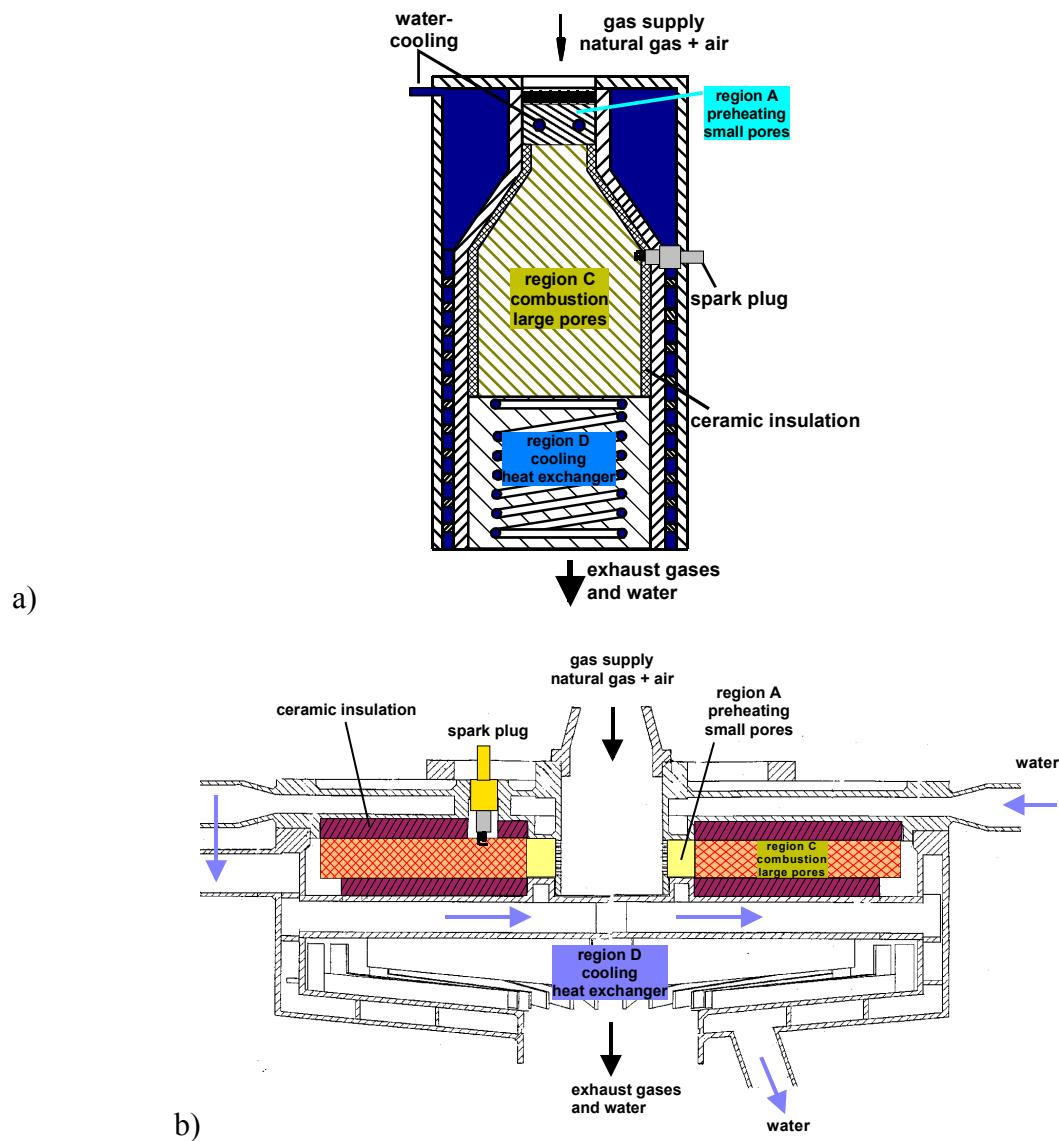


Fig. 17 Schematic diagram of a) the porous burner unit I and b) the porous burner unit II

The burner unit II is mainly axial symmetric. The gas/air mixture first flows parallel to the axis of the burner. Afterwards the flow changes into the radial direction and flows through a plate with holes.

Like the 10 kW burner/heat exchanger unit I the burner unit II is divided into three regions. The premixed gas flows through a packing of spheres in region A with an equivalent diameter of the PM cavity space which is less than the quenching diameter at all possible flow conditions from 2 to 30 kW.

The region C follows, where the combustion takes place. Dependent on the methane and air flow rate the combustion is located between the end of region A and close to the end of region C.

One important advantage is that the flow velocity is influenced by the radial symmetric geometry. In the flameholder region A the velocity is relatively high because of the small circumference at low radial positions. With decreasing radius the velocity rises, so that the stabilisation of the flame is positively influenced by this mechanism in addition to the well-known stabilisation mechanism through the pore size. The second advantage of the decreasing velocity at greater radii, i. e. in the regions C and D, is that the pressure drop is expected to become lower than in the burner unit I.

Another advantage of this design is that the distance from the centre of the combustion region to the mantle cooling is very small. The result is that the maximum temperatures of the combustion become lower than in the combustion region of porous burner unit I and the formation of thermal NO is reduced. Furthermore the temperature levels are more homogeneous over the cross flow section resulting in less CO and NO emissions.

5.6 Description of the Work under Task 11: Design, layout and construction of control unit Ib

Due to the difficulties at PKO-OSMO, LSTM had to complete the work concerning the development of the control unit Ib.

As figure 18 shows, the hot-water heater system which was designed at LSTM (control unit Ib) has the following components:

- porous media burner and heat exchanger unit I
- components for the gas supply and a mixing unit
- components of the cooling circuit
- electronic control unit
- safety components

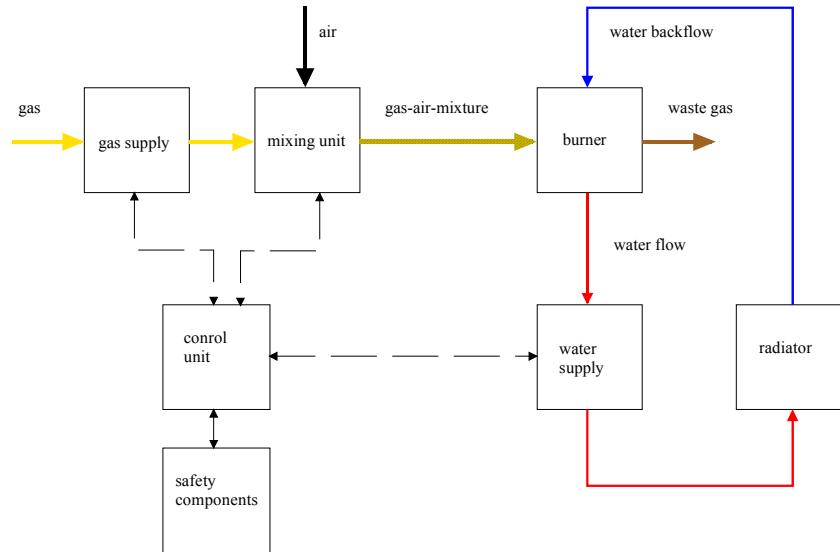


Fig. 18 Block diagram of the control unit

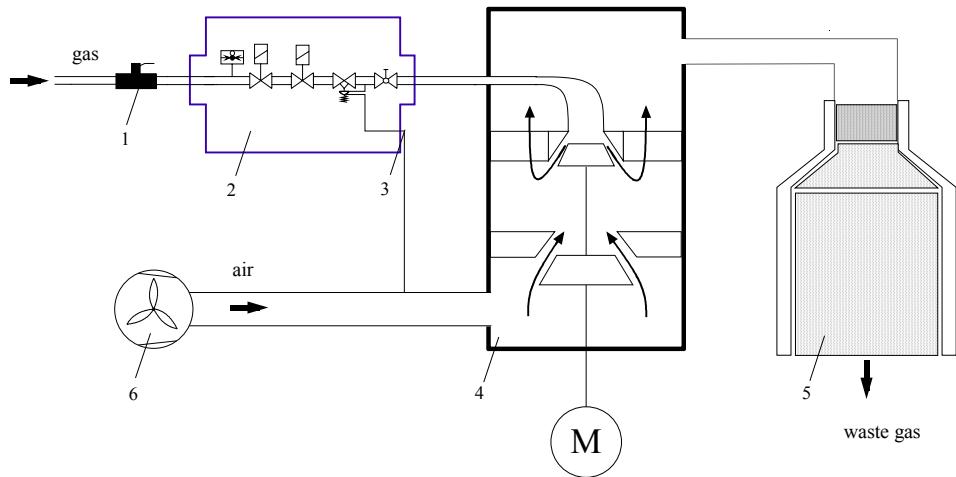
The details of some of the components are described next.

Gas supply components and mixing unit

The gas supply components and the gas mixing unit have to guarantee that the methane/air-mixture is always homogeneous. Moreover, the heat load of the burner and the air-ratio must be defined. This means that the modulating burner is a system with two desired values (heat load, air-ratio) and two control variables. The control system depends on fluctuations of the pressure within the combustion chamber, the atmospheric pressure and the pressure of the gas supply line.

The concept, which was used at LSTM for the control system Ib, is a combination between a pneumatically and a mechanically operating system. With such a system it is possible to control the flow rate of gas and air within a wide range, independent of any pressure fluctuations, for instance in the combustion chamber. Moreover, it is possible to control the

heat load of the burner and the air-ratio independent of each other. Figure 19 shows the set-up of the pneumatically and mechanically operating control system.



1. valve
2. compact gas unit
3. control pressure line
4. IMS unit
5. burner unit I
6. blower

Fig. 19 Pneumatically and mechanically operating control system

A sufficient flow of air is provided by the blower (6) and is guided to the IMS (Integriertes Misch- und Stellventil, a RUHRGAS AG development distributed through the company Kromschröder), afterwards. The control pressure line (3) gives a control signal to the compact gas unit. The compact gas unit controls the pressure of the gas in dependence of the air pressure. By shifting the valves of the IMS the heat load and the air-ratio can be determined. Simultaneously, gas and air are mixed in the IMS (Fig. 20).

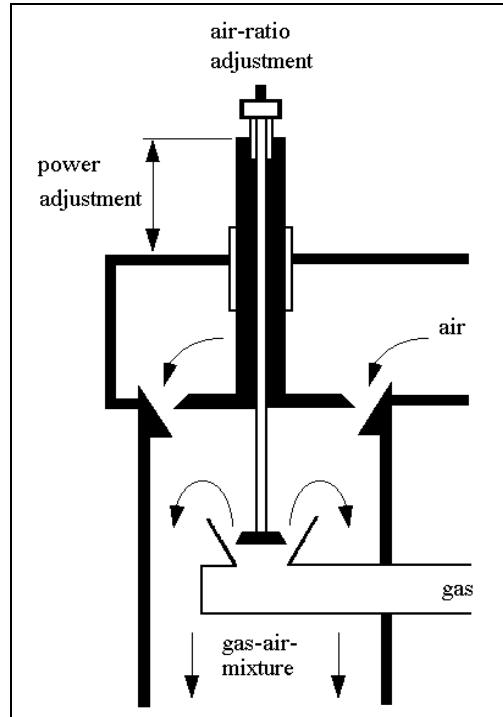
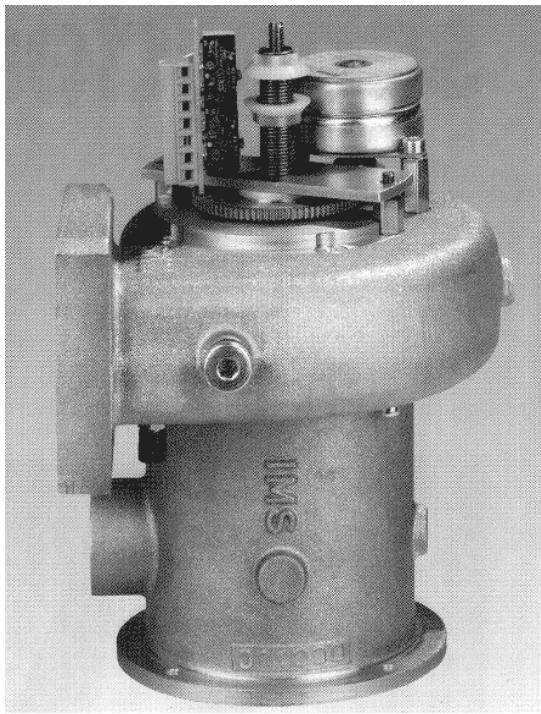


Fig. 20 IMS

Electronic control unit and safety components

An electronic control unit, which was developed at LSTM, was used for the control and surveillance of the system. Figure 21 shows the block diagram of the electronic control unit.

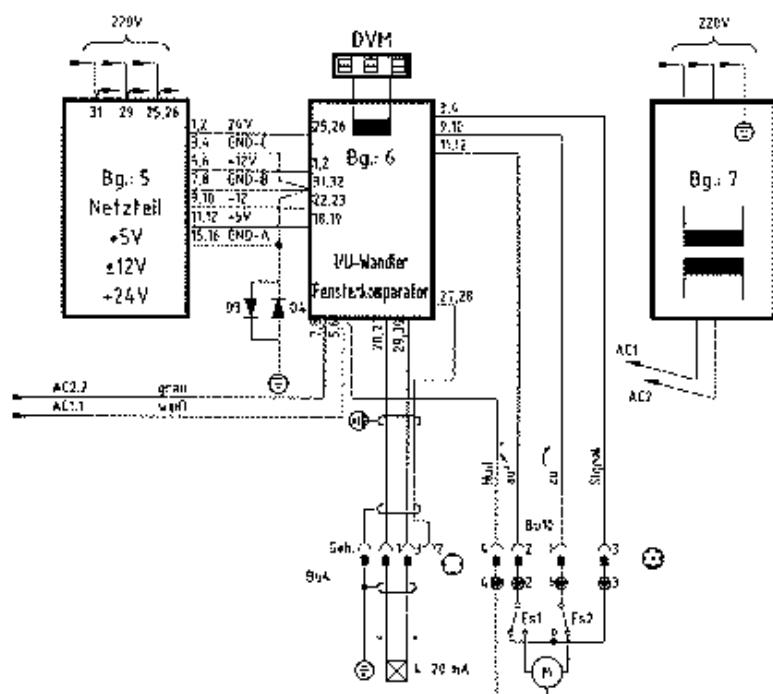
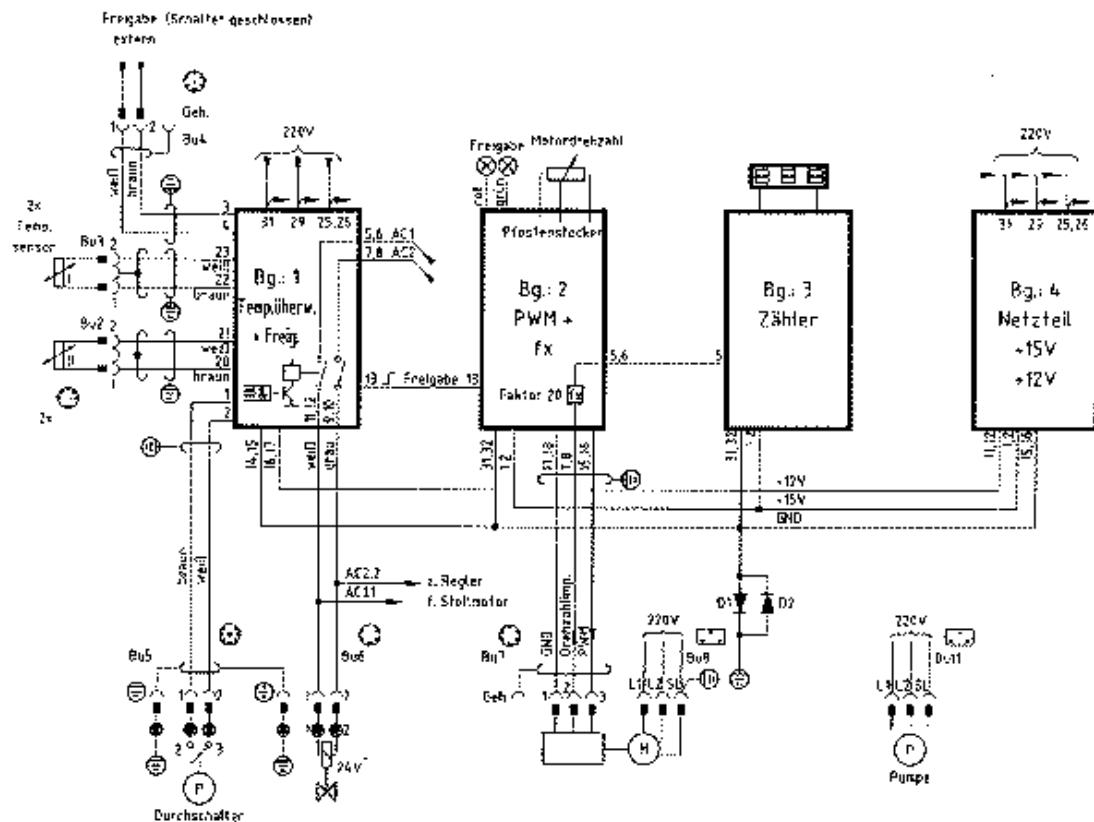


Fig. 21 Electronic control unit

This electronic unit sends gating signals to the different components. First the blower and the water pump are started and air flows through the burner for 30 seconds. After that, the gas valves are opened. Simultaneously, pulses are sent to the spark plug. After ignition, the flame is controlled by an automatic gas-firing unit.

In order to guarantee a safe operation of the heater system the following sensors were integrated:

- two temperature sensors (NTC sensors)
- a flame control (automatic gas-firing unit)
- a safety gas pressure switch

The electronic control unit initialises an emergency shutdown, if the temperature of the water exceeds a certain value, if the gas supply pressure is disturbed, or if the signal from the flame control unit breaks down. The combustion process is controlled with an automatic gas-firing unit, which measures the ionisation current. For this reason two electrodes were integrated into the porous media burner (Fig. 22). A proper ionisation current was reached 20 seconds after the start of the system (Fig. 23).

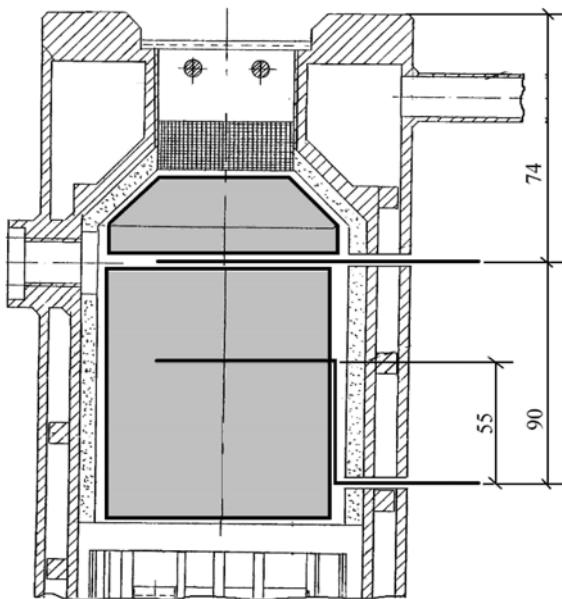


Fig. 22 Schematic diagram of the porous media burner with two electrodes

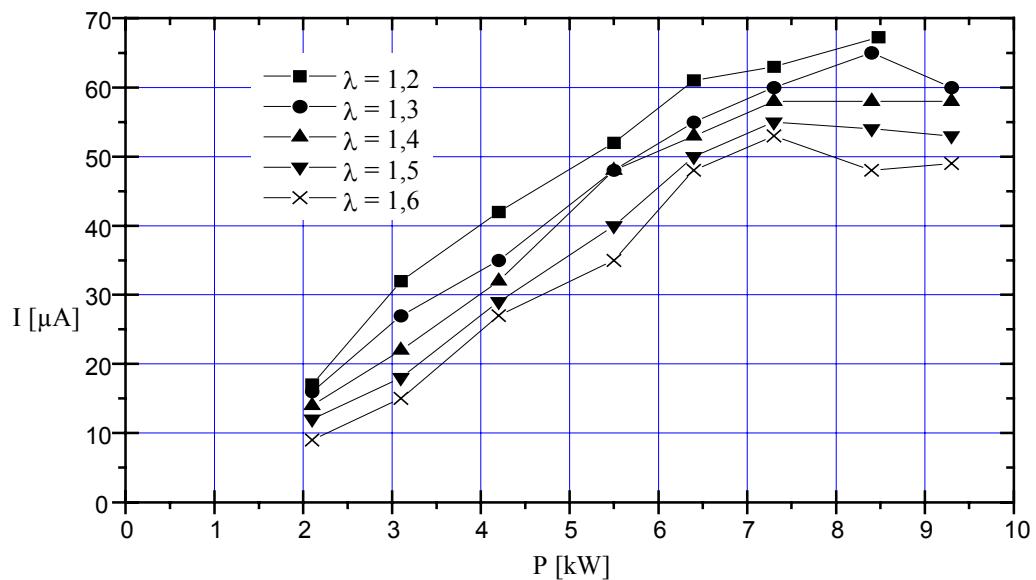


Fig. 23 Ionisation current measured in the porous media burner unit

The experiments showed however, that the electrodes, which are exposed to extremely high temperatures, were not sufficient corrosion-resistant. As a result of the corrosion the ionisation current decreased and combustion stopped due to an emergency shutdown.

The extra test-rig for the operation of the porous burner with the constructed control unit Ib is shown in figure 24.

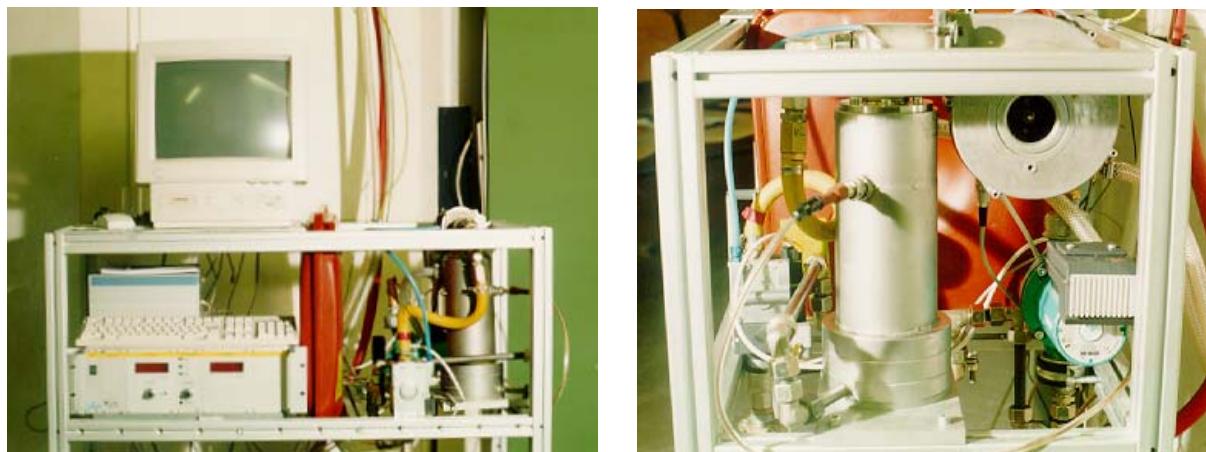


Fig. 24 Test-rig with the control unit

5.7 Description of the Work under Task 12: Radiative heat transfer in porous media for new burner design (two-dimensional computations)

In this task, development and optimisation of computer codes assisted by experimental values was performed.

Computations are a fast and cheap way to get information about CO- and NO_X- emissions, combustion stability, pressure loss and efficiency. A further advantage is the good spatial resolution. Thus, they are a great help for building burners with better properties.

For the numerical modelling of the chemical and physical mechanisms in the porous medium the fluid flow as well as the heat transport and the chemical reactions should be taken into consideration.

Modelling of a porous medium burner with one-dimensional fluid flow (simple model)

In a first step the fluid flow in the porous medium was treated as one-dimensional. This model was based on the assumption of a reaction zone where the place and its intensity is known by experimental information. Furthermore, the process was treated as stationary, isobaric and pseudo-homogenous (the solid and the gas phase are considered to be only one phase). This resulted in a very short computation time because of less mathematical expenditure. But the tendencies were in agreement with reality, because there were only few and very reliable parameters necessary. A basic equation for this model was the one-dimensional continuity equation

$$\frac{\dot{m}}{A} = \rho u_D = const.$$

with the empty pipe or Darcy velocity u_D . The basic equation, which had to be solved by numerical methods, was the two-dimensional energy equation

$$\frac{\dot{m}}{A} c_p(T) \frac{\partial T}{\partial z} = \frac{\partial}{\partial z} \left(\lambda_z(T) \frac{\partial T}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left(r \lambda_r(T) \frac{\partial T}{\partial r} \right) + \dot{q}(T)$$

with the accompanying boundary conditions. The term \dot{q} on the right edge of the energy equation represents the energy flux set free by the chemical reactions.

The heat transport in the porous medium was considered by the anisotropic effective heat conductivity λ_{eff} (λ_z in the axial and λ_r in the radial direction) [2,3,4]. This size includes heat conductivity of the solid and fluid material, radiation and dispersion and was calculated by the model of Zehner, Bauer and Schlünder [5] for irregular packings. Furthermore, the heat transfer to the walls by convection, which were computed by semi-empirical correlations [6], and radiation are important factors in order to reduce the temperatures in the reaction zone. The effective heat conductivities, the heat capacity and the boundary conditions to the walls and obstacles are strongly non-linear and were calculated in dependence of temperature and composition of fluid and material, respectively.

As a result of this model, the temperature field of a 10 kW burner without an expansion can be seen in the following figure. The heat exchanger was modelled by three cylinder rings.

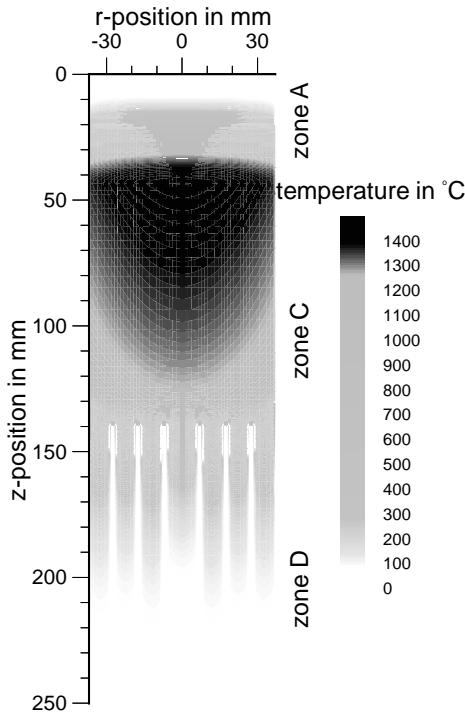


Fig. 25 Temperature field in a 10 kW porous burner without expansion zone

Other geometries are also possible. In the next figures a 10 kW porous burner with a cross section area in region D as the prototype Ib, but without expansion after the region A can be seen. Furthermore, instead of the long cylinder rings in zone D a helix-like heat exchanger

was used. In the first figure the temperature field is plotted under consideration of the condensation, which is very important for the heat transfer in region D. The following aspects were taken into account.

1. the energy set free due to the phase change,
2. the changes of the concentrations of the gas phase,
3. the diminished mass flow of the gas flow,
4. the energy flux of the liquid and the gas phase by convection and, finally,
5. the better effective heat conductivity of the porous medium due to the greater contact surface between the particles.

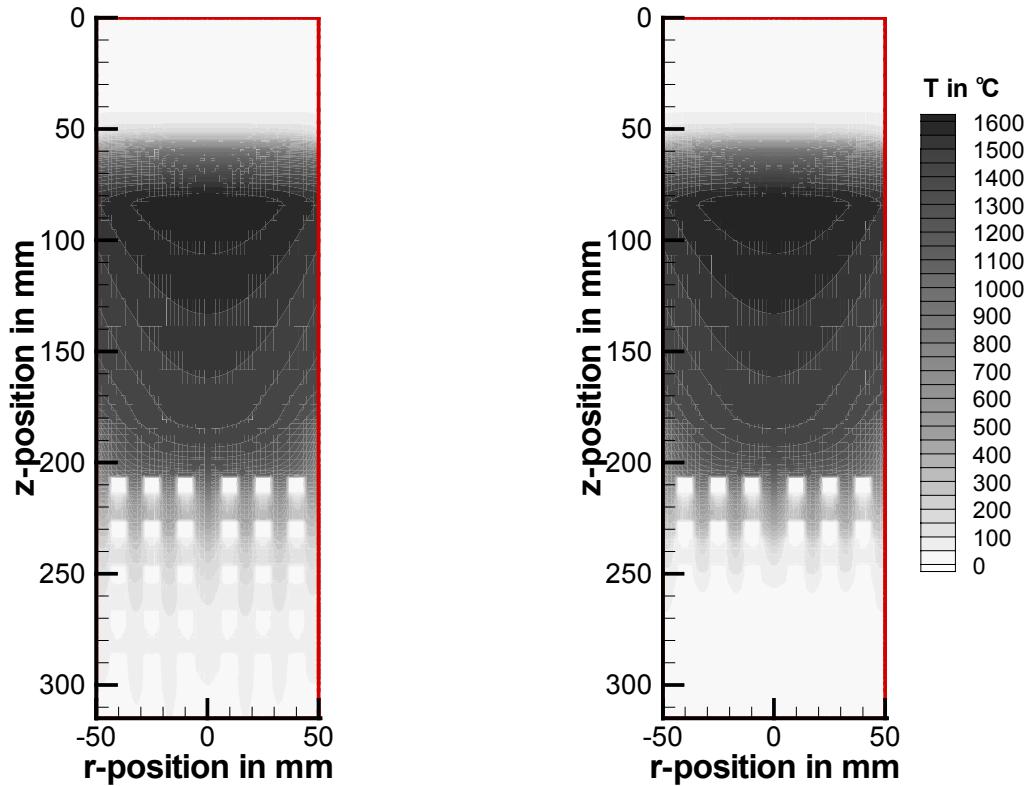


Fig. 26 Temperature field in a porous burner without expansion zone; on the left: calculation without condensation, on the right: calculation with condensation

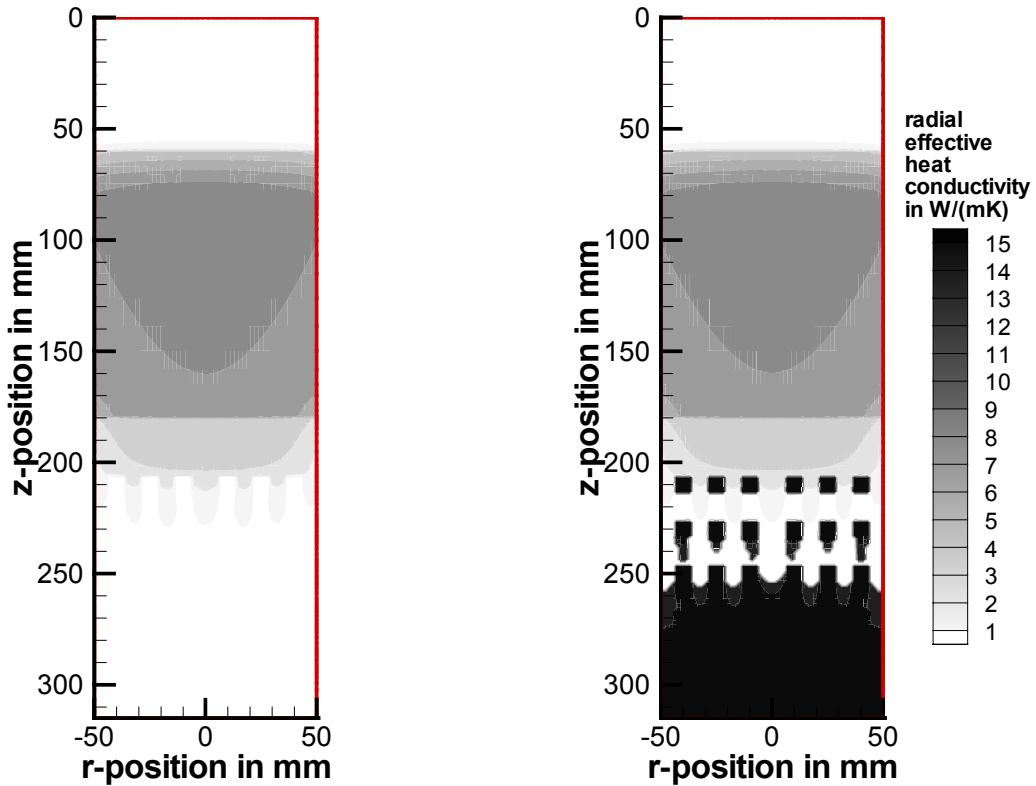


Fig. 27 Field of the radial effective heat conductivity in the porous burner (the same as in the figures before); on the left: calculation without condensation, on the right: calculation with condensation

Although the condensation has the effect of a considerable amount of released condensation enthalpy, the temperatures at the exit are clearly lower than in the other case. The better heat conductivity results in a better heat removal from the porous medium to the heat exchanger and the walls. Moreover, the effect of a change in the particle size on the heat conductivity can be seen at the interface between the different regions, especially between zone C and zone D. A reduction in the particle diameter has the consequence of a decrease of the heat conductivity, but on the other side the heat transfer to the wall is increased. Both mechanisms result in an optimum particle diameter in the range of about 5 mm.

Modelling of a porous medium burner with two-dimensional fluid flow

Moreover, the complete velocity field was computed by pseudo homogenous momentum equations. The semi-heuristic model of Vafai and Tien [7] was used for this task:

$$\frac{\rho}{\psi} \left(\frac{\partial \mathbf{u}_{Di}}{\partial t} + \mathbf{u}_D \cdot \nabla \mathbf{u}_{Di} \right) = -\nabla p + \frac{\mu}{\psi} \nabla^2 \mathbf{u}_{Di} - \frac{\mu}{K} \mathbf{u}_{Di} - \frac{F\psi}{\sqrt{K}} \rho |\mathbf{u}_{Di}| \mathbf{u}_{Di}$$

with

$$K = \frac{1}{180} \frac{\psi}{(1-\psi)^2} \delta$$

and

$$F = \frac{1,8}{\sqrt{180\psi^5}} .$$

K is the permeability of the porous medium and F is an empirical constant, which is only a function of the porosity ψ for the case of a sphere packing.

The calculation of the temperature field was made similar to the velocity field by a pseudo-homogenous model. In the numerical algorithm the transport equation for the enthalpy was solved and the transport mechanisms was treated by the above mentioned anisotropic effective heat conductivity λ_{eff} :

$$\rho c_p \frac{\partial T}{\partial t} + \nabla \left(\rho \vec{u}_D c_p T - \lambda_{eff} \nabla T \right) = \dot{q} \psi .$$

The determination of the concentrations field is made by the solution of the equations for the transport of the species contained in the mixture:

$$\rho \frac{\partial y_j}{\partial t} + \nabla \left(\rho \vec{u}_D y_j - \rho D_{eff} \nabla y_j \right) = \dot{\omega}_j \psi .$$

Here y_j are the concentrations of the components j , D_{eff} is the effective diffusion coefficient and $\dot{\omega}_j$ the chemical production rate of the species j .

The momentum, energy and transport equations for the chemical species were solved coupled, in which as a first step a simple reaction kinetic, a one step kinetic, was used to minimise the computing time.

A calculation was carried out for the 10 kW porous burner prototype Ib. A part of the results is presented in the following figure.

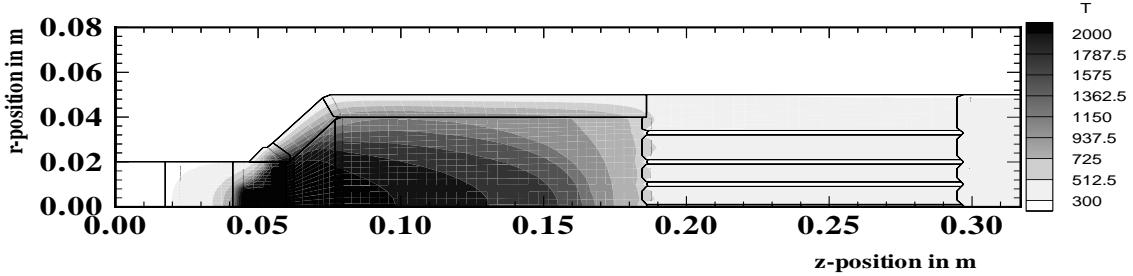


Fig. 28 Temperature field (in K) inside the 10 kW porous burner prototype Ib

In fig. 28 the boundaries of the blocks of the numerical grid as well as the heat exchanger treated as three cylinder rings can be observed. The temperature field inside the ceramic insulation of region C is also presented. The highest temperatures occur in the centre of the expansion zone after region A. In region A the preheating effect can be noticed. The temperature in the downstream cooling zone D decreases to nearly the temperature of the water circuit.

The figure below demonstrates the fluid flow in the most interesting part of the burner, the stabilising and expansion region. Because of the continuity equation one can see that in the zone of combustion an enormous acceleration due to the temperature rise takes place, while the velocity in the region of the expansion decreases slowly again. An interesting point is that after the end of the expansion no recirculation can be observed as one would expect without porous media. Because of the high temperatures and the uneven distribution of the flow the velocities in the centre of region C are the highest. The streamlines show that because of the temperature rise by the reaction the flow is pressed to the boundary at about $z = 40$ mm, but when the temperatures get lower in the radial direction the flow direction changes towards the centre again (at $z = 50$ mm). Afterwards the flow changes to the outside again because of the expansion.

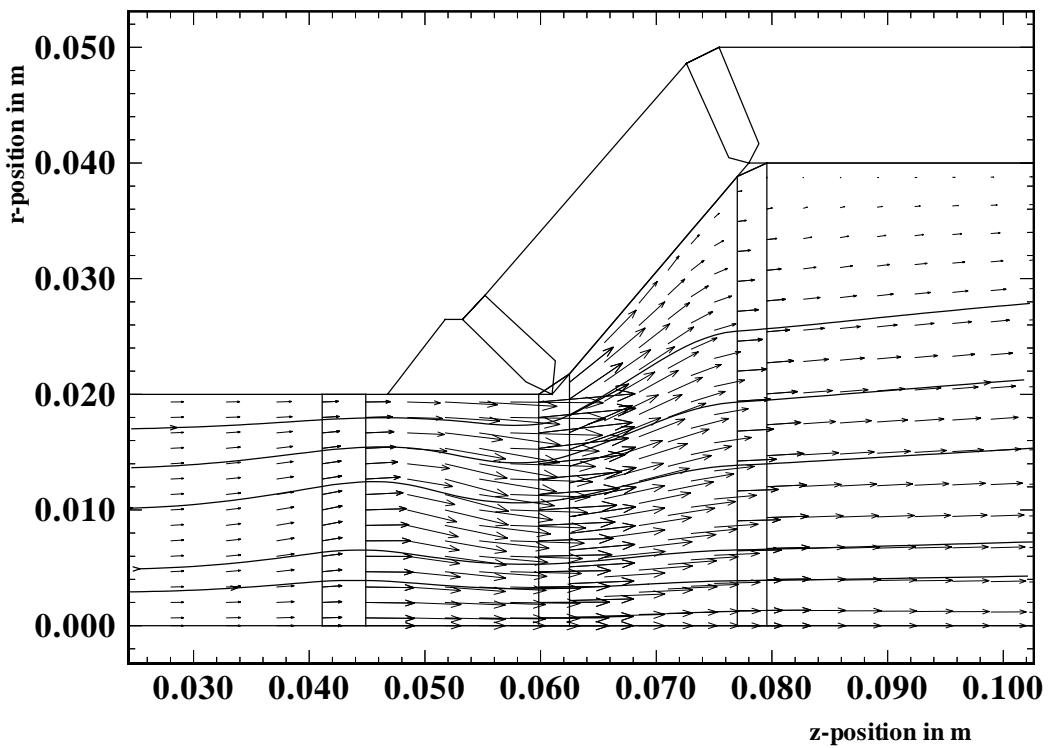


Fig. 29 Flow field in the region of the expansion section in the 10 kW porous burner prototype Ib (PBG9)

Furthermore, in fig. 30 one can see the pressure drop in the porous medium. Especially in the region A, where great velocities due to the small cross section area as well as small pore sizes and high temperatures appear, the pressure loss is not to be neglected.

In fig. 31 the mass-fraction of CH₄ is pictured and, hence, the region of the combustion can be seen.

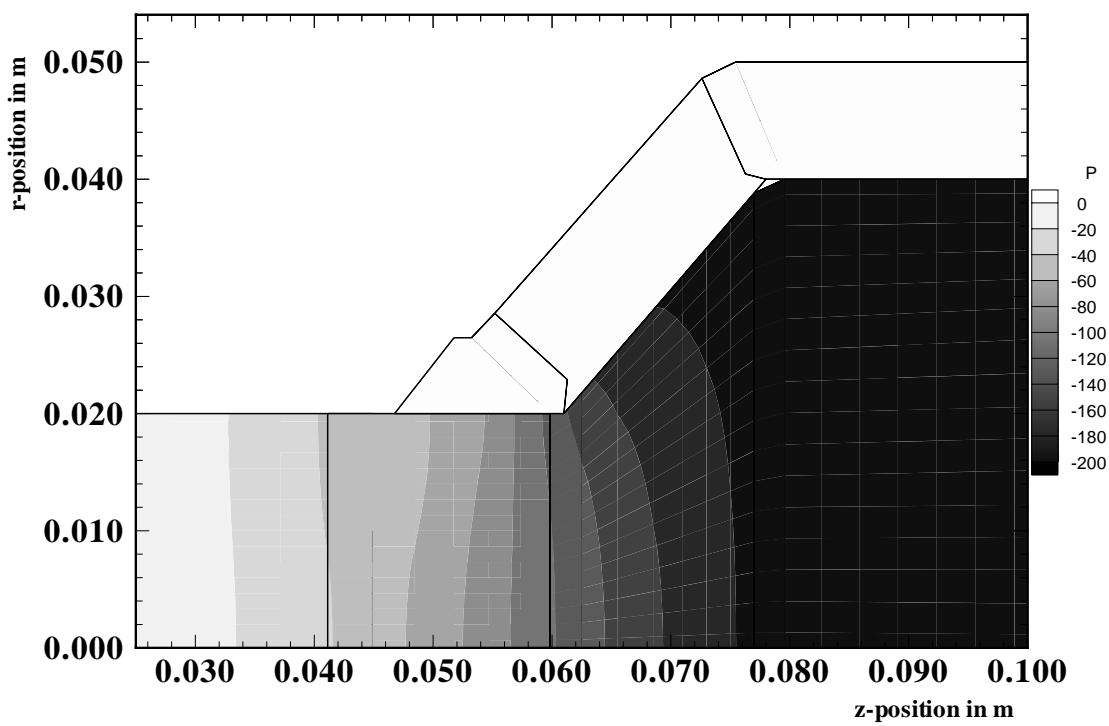


Fig. 30 Pressure field (in Pa) in the region of the expansion section in the 10 kW porous burner prototype Ib

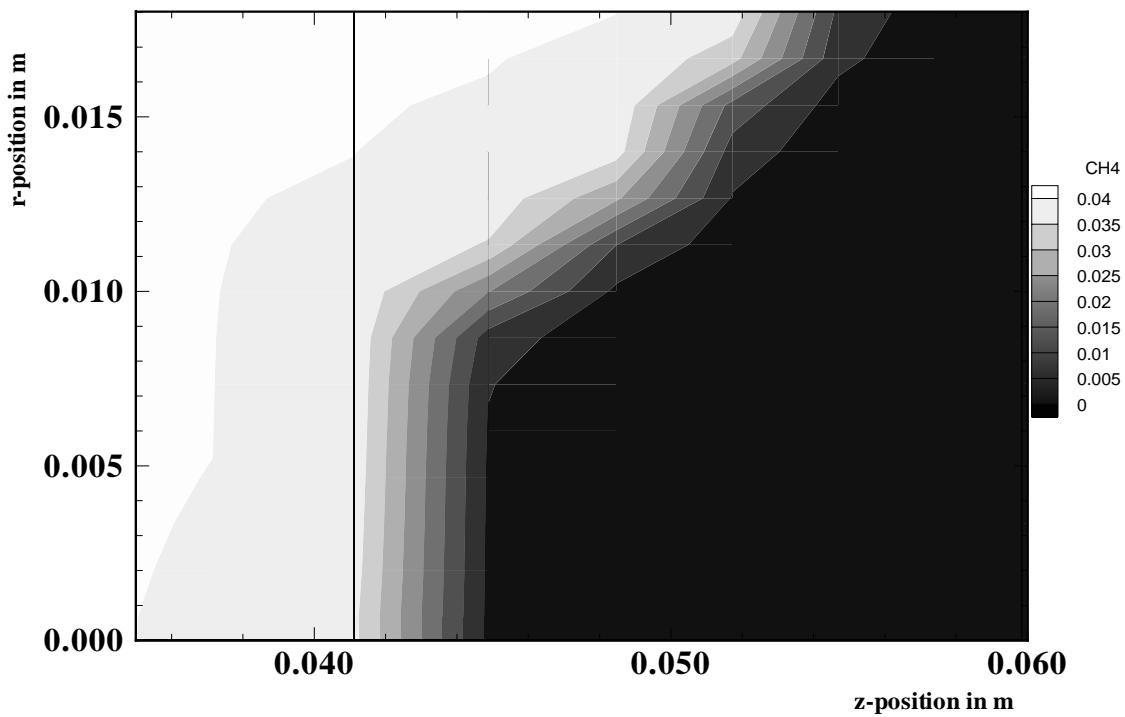
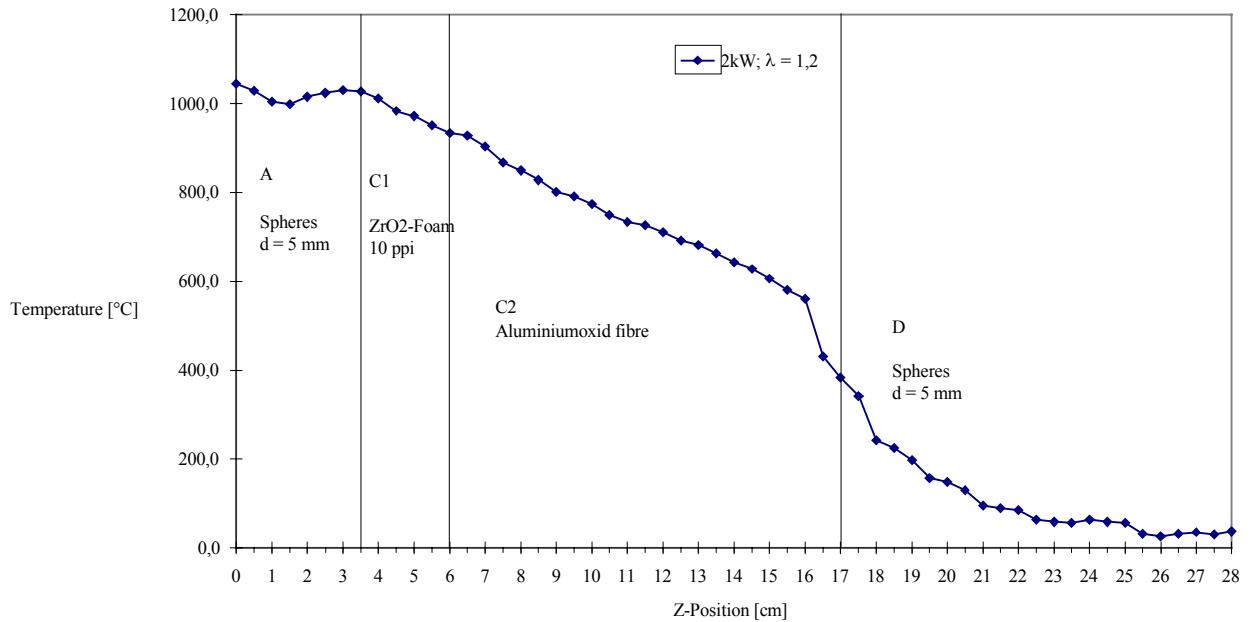


Fig.31 Field of the CH₄ mass-fraction in the 10 kW porous burner prototype Ib

The obtained temperature and flow field is independent from the pollutants formed inside the burner. Thus, it can now be used in the postprocessing step in order to make detailed chemical kinetic computations to investigate the production and destruction mechanisms of these pollutants.

Temperature measurements for the verification of computer codes

In order to compare the numerical results and the experiments several temperature profiles were measured in dependence of the air-ratio and the thermal power, within the prototype Ib. The results of these measurements, which were also used by Impcol and IST-Lisbon for their calculations, can be seen in figure 32.



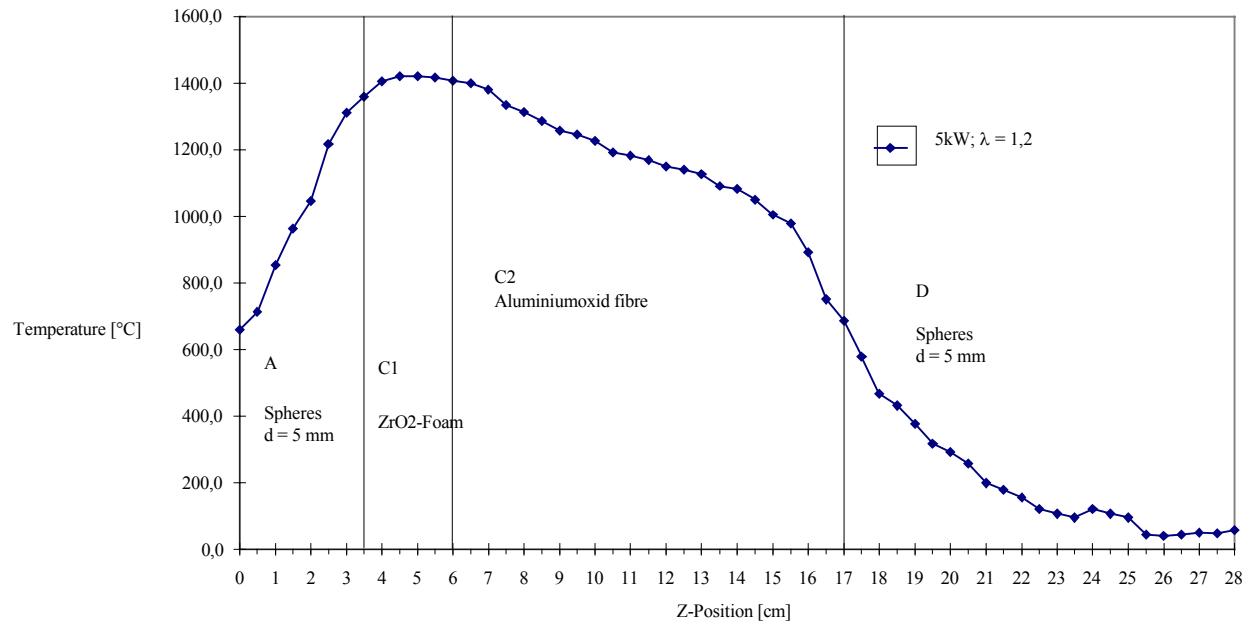


Fig. 32 Temperature distribution within the prototype Ib

5.8 Description of the Work under Task 15: Construction of experimental burners for partners

According to the design and layout of the burner heat exchanger unit II, which was described in chapter 5.5, detailed construction plans were worked out for the PMB-HE prototype II, which were distributed to the industrial partners (figure 33).

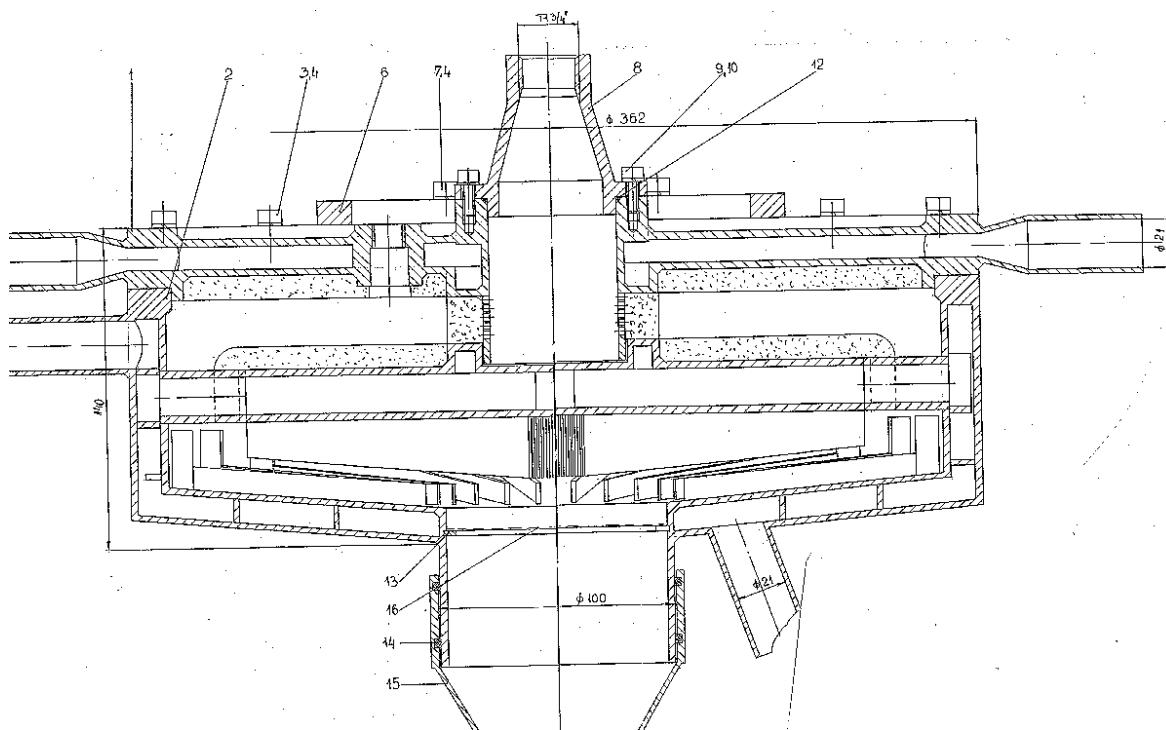


Fig. 33 Drawing of the 30 kW porous burner and heat exchanger unit II

The 30 kW prototype II can be seen in fig. 34.

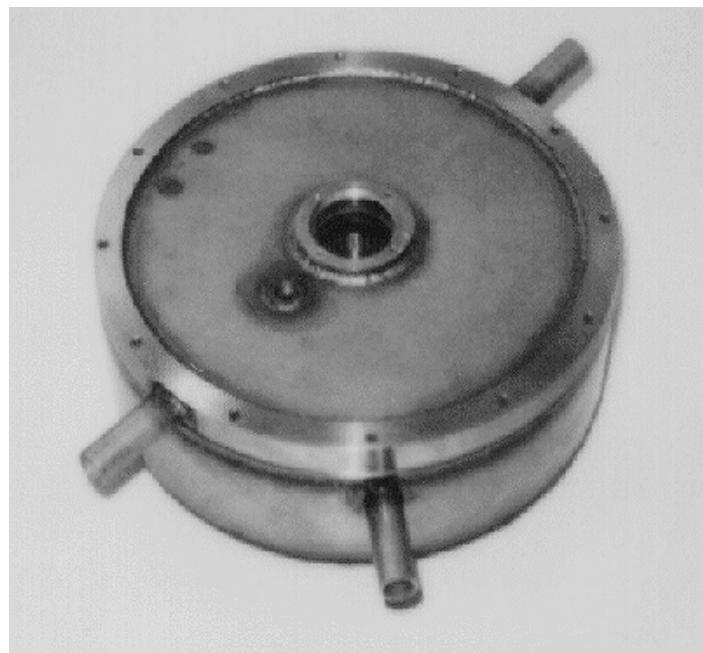


Fig. 34 30 kW porous burner and heat exchanger unit II

In order to have complete combustion the cooled walls of region C were insulated with ceramic material which provides a controllable heat-flux to the mantle cooling and a high inner surface temperature. Thus, the formation of carbon monoxide due to the contact of the reaction radicals with the cold surfaces was avoided.

Within the heat exchanger region, a packing of ceramic spheres (aluminium oxide - 5 mm) was used to improve the heat transfer to the heat exchanger which is achieved mainly by increasing the heat transfer coefficients.

An important point of the burner optimisation was that the recirculating water economy was designed with larger cross sections, in order to reduce the pressure drop of the water within the heat exchanger system, so that this prototype meets the requirements for household applications.

5.9 Description of the Work under Task 16: Design, layout and construction of control unit II

The control units of modern heating systems for household applications are equipped with temperature sensors for a control in dependence of the meteorological conditions. As figure 35 shows there is a relation between the outside temperature and the flow temperature of the water circuit.

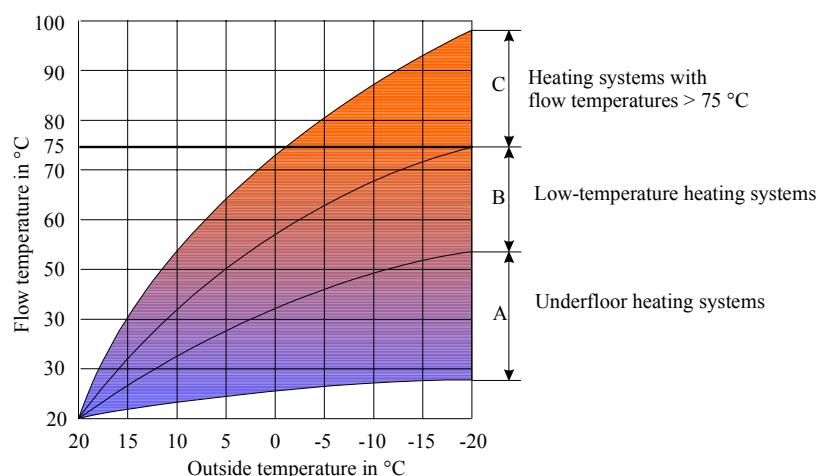


Fig. 35 Characteristic curves of different heating systems [8]

For this reason the following feedback loop (fig. 36), which depends on the flow temperature of the water circuit, was developed at LSTM for the control unit II of the porous media burner and heat exchanger prototype II.

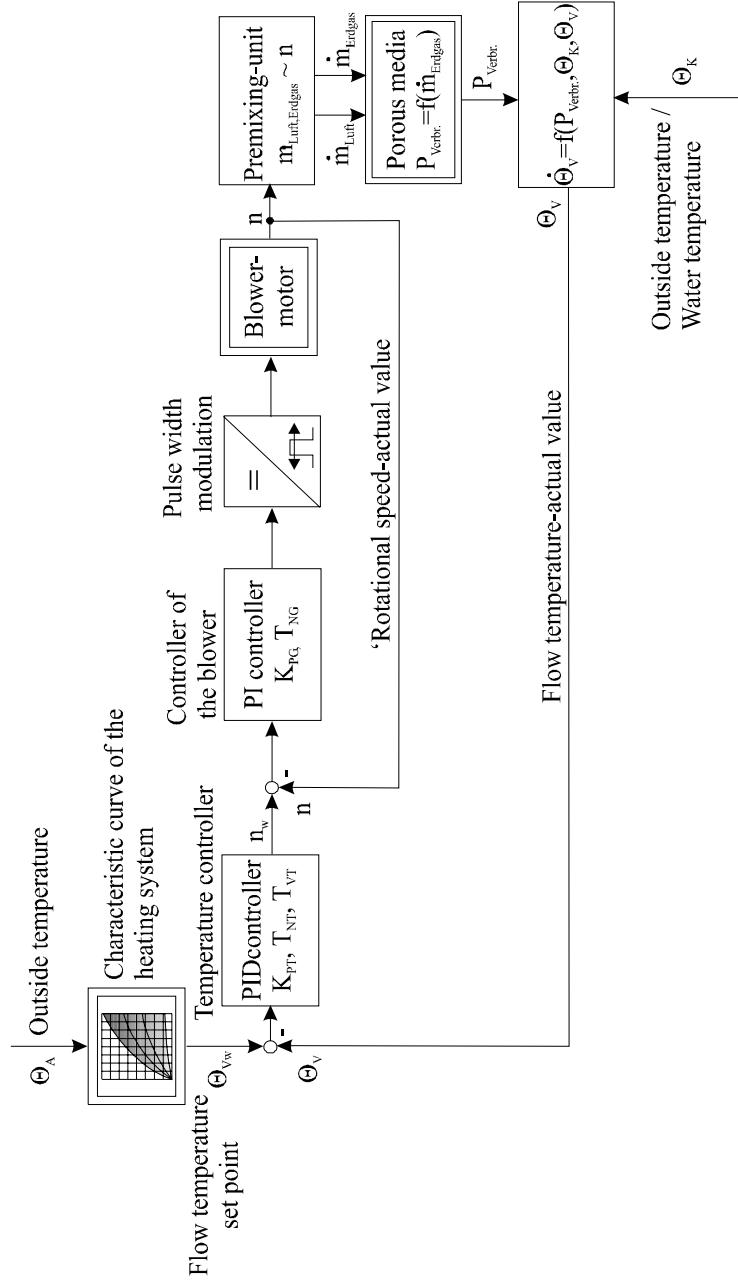


Fig. 36 Feedback loop of the porous media burner and heat exchanger unit

The gas supply components of the control unit II, which have to guarantee that the methane/air-mixture is always homogeneous, can be described as follows. In the control unit II a very simple kind of realising a very intensive premixing was reached by the entrainment

of the gas at the intake of the blower. In order to ensure a balanced pressure control, the working method of the gas compact unit had to be modified. For this reason the gas compact unit was used as a zero pressure controller. In this case the air-control line has to be open, so that the pressure at the gas compact unit is atmospheric (0 mbar excess pressure). Figure 37 shows the function of this control system.

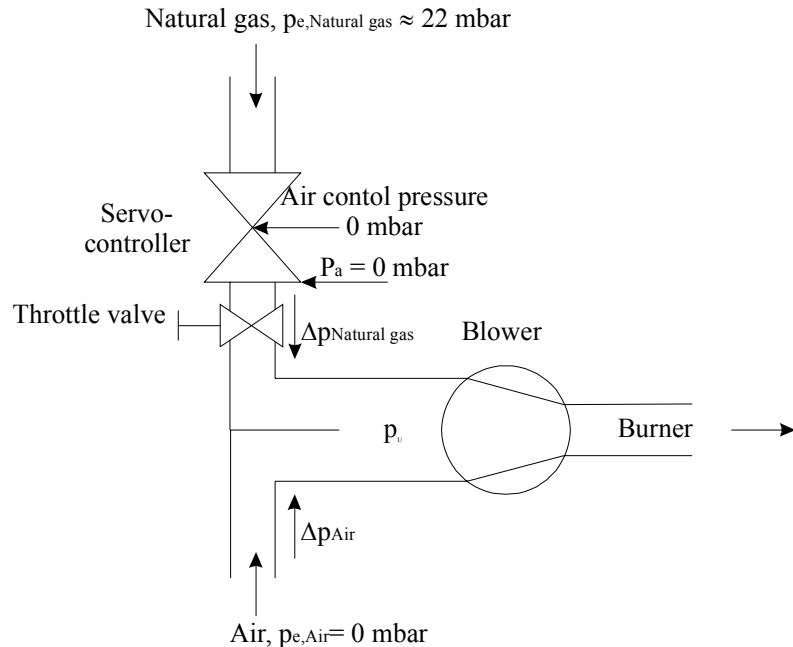


Fig. 37 Gas supply components

An important advantage of this system in comparison to the control unit Ib is that there is no further gas mixer necessary. Even at low thermal loads the premixing within the blower is sufficient.

For the control and surveillance of the whole heating system an automatic gas-firing unit with micro controller was integrated. The requirement of an automatically starting, control and switching off of the system made a fixed program run necessary (Fig. 38 and Fig. 39). This program run is deposited in the software of the automatic gas firing unit and controlled by a „watchdog“.

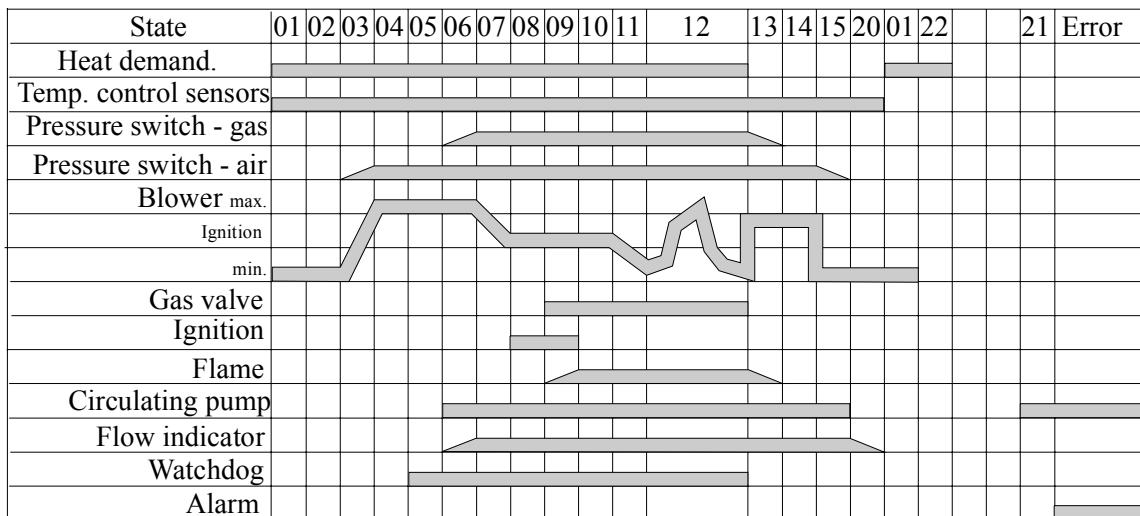


Fig. 38 Run of the program - MPA 15.04 [9]

State	description	duration
01	test for heat demand	0,5 ... 10 s
02	control of the pressure switch for air and blower	1 ... 30 s
03	run-up of blower	1 ... 30 s
04	pre-ventilation I: preparation of watchdog	10 s
05	pre-ventilation II: activation of watchdog	4 s
06	pre-ventilation III	1 ... 60 s*
07	the rotational speed of the blower is decelerated	1 ... 30 s
08	pre-ignition	0 ... 60 s*
09	safety time (start): Gas valve Y2 is opened	1,9 ... 4,9 s*
10	stabilisation of the flame	1 ... 60 s*
11	transitional period for the operating conditions	1 ... 60 s*
12	operating conditions	max. 23 h 59 min
13	after-glow time	1 ... 60 s*
14	ventilation	1 ... 60 s*
15	circulating pump is running	1 ... 60 min*

20	standby	max. 23 h 59 min
21	fault: ventilation and locking	5 s
22	fault: wait for gas pressure respectively safety chain	max. 30 min

Fig. 39 Run of the program - MPA 16.04 [9]

In order to guarantee a safe function of the heating system the following sensors were integrated for its surveillance:

- **Pressure switch for gas**

The pressure switch for the gas is integrated within the gas compact unit. For the operation of the heating system a minimum gas pressure of 14 mbar is necessary. If the gas pressure is less than this required minimum pressure for longer than one second an immediate fault lockout is initialised.

- **Pressure switch for air**

The pressure switch (fig. 40) for air can be used within a range of 0,2 - 1,5 mbar. A fault lockout is initialised if the air pressure is not in this range during the pre-purge time. During the ignition period and the operating time of the heating system, the air pressure is controlled by the rotational speed of the blower.



Fig. 40 Pressure switch for air

- **Flame control sensor**

The experiments carried out with the control unit Ib showed that the electrodes, which were used for the measurement of the ionisation current are exposed to extremely high temperatures. It turned out that metal electrodes were not sufficient corrosion resistant. As a result of the corrosion the ionisation current decreased and combustion stopped. For this reason in the control unit II SiC glow igniters (fig. 41), which are temperature resistant up to 1400 °C were used for the ignition and the flame control.

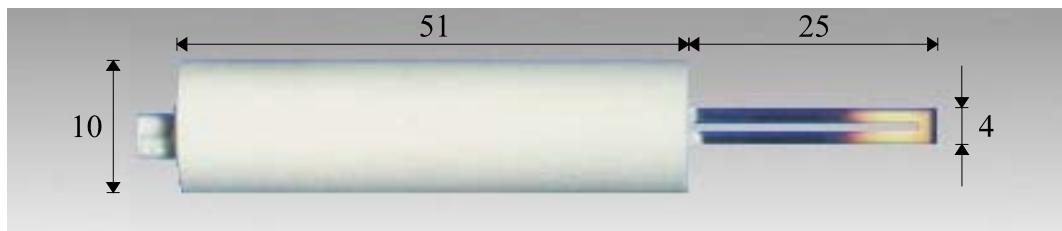


Fig. 41 SiC glow igniter

Apart from the glow igniters also optically working flame control sensors (ultra violet sensors) were tested within the framework of the project. UV-sensors (Fig. 42) respond to the ultra violet light of a flame. Therefore, they do not react to daylight or infrared radiation from the hot workpieces.

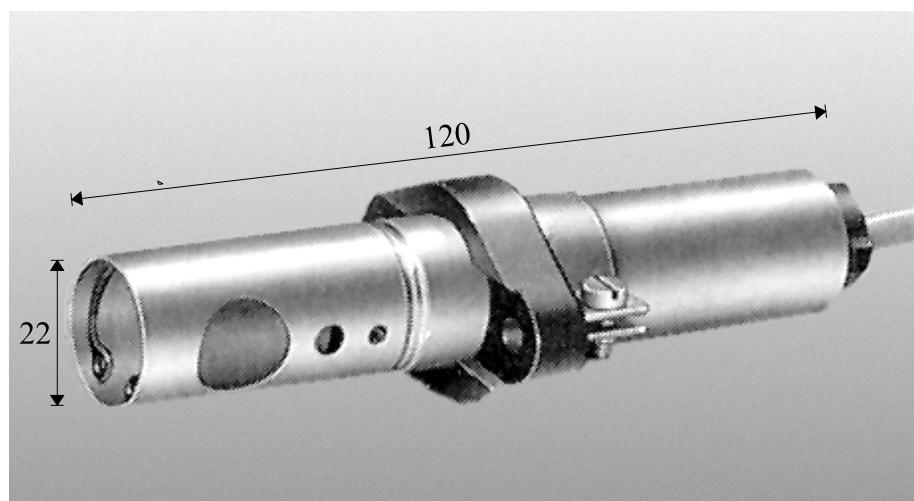


Fig. 42 UV-sensor

Experiments carried out at LSTM with an open test burner (Fig. 43) showed that the UV-sensors operate independent from the power, the air-ratio and the porous medium. There was no signal if the gas supply was stopped, even if the porous medium was still glowing.



Fig. 43 Open 10 kW test burner with a ceramic fibre structure

But as the SiC glow igniters can be used for the flame control and for ignition and as the costs are lower in comparison to UV-sensors, LSTM-Erlangen preferred glow igniters for the control unit II final design.

- **Temperature control sensors (NTC sensors)**

Several temperature sensors ensure that the flow temperature Θ_V of the water does not exceed a maximum value $\Theta_{V\max}$.

The control unit II for the porous medium burner, was developed not only with respect on its functionality, which had to be adapted to the operational characteristics of the porous media burner, but also with respect on a compact design and its simple handling, so that it can be used as a basis for the commercial utilisation in household heating systems. For this reason the control unit II was equipped also with an integrated diagnostic system. With this integrated diagnostic system it is possible to control and visualise the most important parameters of the heating system. For instance several temperatures, information about

interconnections or the functional test of different components can be scanned and controlled. A computer connected with the automatic gas-firing unit with a serial interface can be used for this control (Fig.44). Separate test equipment is not necessary.

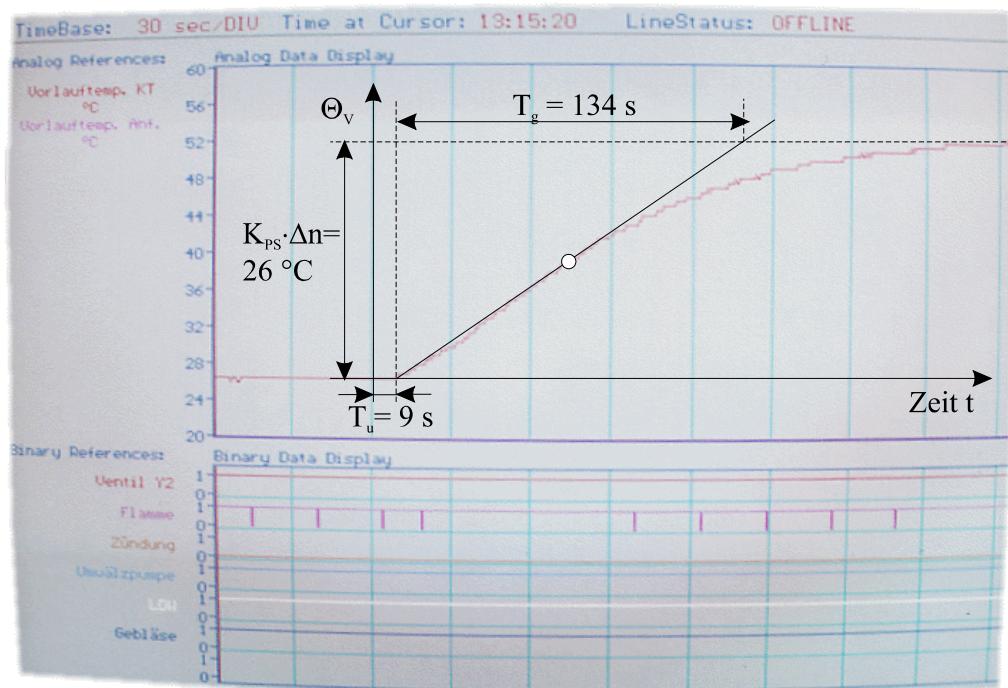
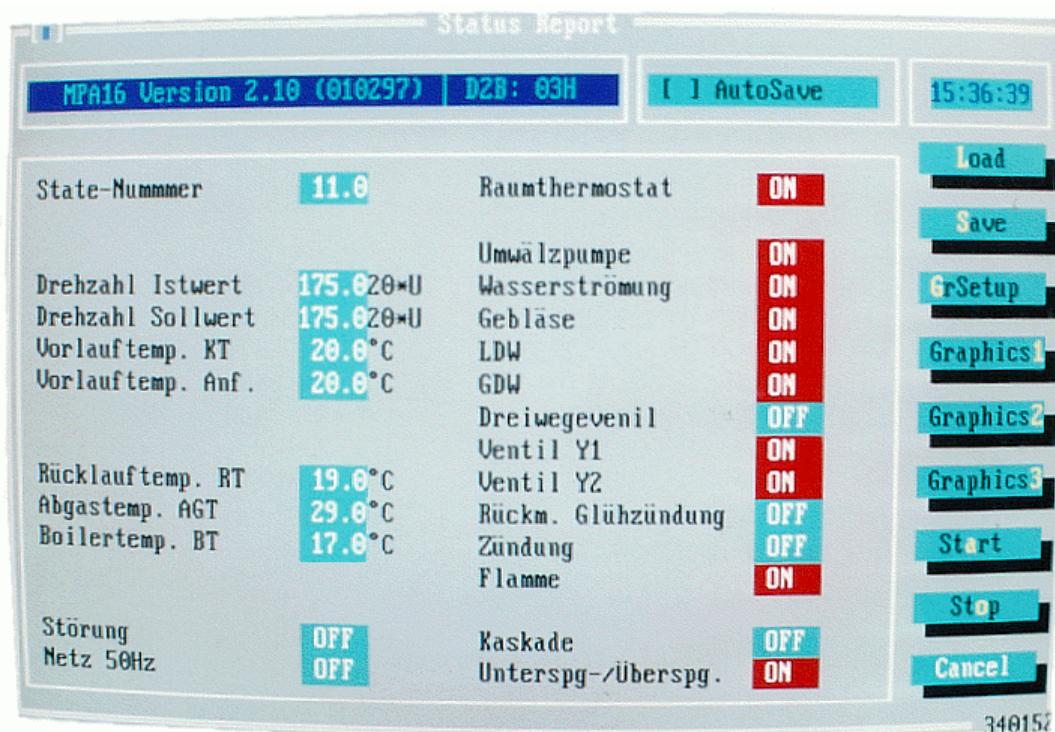


Fig. 44 Status report of the control program

A further point of the development of the control unit II was the minimisation the power consumption of the heating system. For this reason the system was equipped with a regulated differential pressure pump (Fig. 45).



Fig. 45 Regulated differential pressure pump

Despite of the higher acquisition costs of a regulated differential pressure pump, the costs during its service time are lower (Fig. 46).

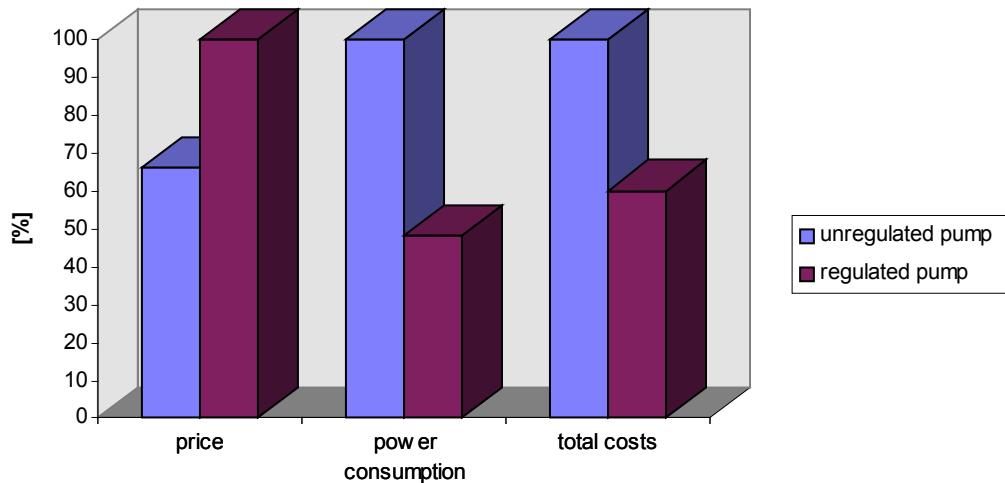


Fig. 46 Energy saving by regulation of the pump [10]

A further contribution to the minimisation of the power consumption of the control unit is the regulation of the power through the rotational speed of the blower. In this way the power of the blower is always adapted to the power of the burner. This means that at a low thermal output also the electrical power consumption is reduced.

Figure 47 shows the test-rig for the operation of the porous burner with the constructed control unit II and the burner prototype with the final design.



Fig. 47 Test-rig with the control unit II and the prototype with the final design

5.10 Description of the Work under Task 17 and 18: Verification experiments for prototype II and Summary of results of investigations of PMB-HE prototype II

At LSTM-Erlangen experimental investigations were performed on the 30 kW PMB-HE prototype II. The design and layout of the prototype was described in chapter 5.5. The burner unit was divided in a preheating region, the combustion region and the heat exchanger part. Within the preheating region a packing of aluminium oxide spheres was used. The size of the cavity spaces was adjusted in a way that flame propagation was not possible in this region. The porous materials which were used in the region C of the burner are presented in fig. 48 and 49.

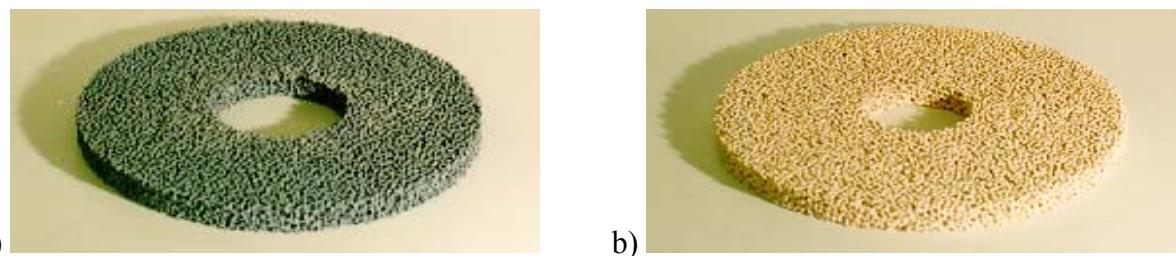


Fig. 48 Ceramic foams as porous media for the combustion region C in the 30 kW porous burner II (Hi-Tech Ceramics Inc., New York): a) Oxide Bounded SiC (OBSiC) with 65 % SiC, 25 % Al₂O₃, 10 % SiO₂; b) Fused Stabilised Zirconia (FSZ) with 96.5 % ZrO₂, 3.5 % CaO



Fig. 49 Mixer-like structure consisting of 12 components as porous media for the combustion region C in the 30 kW porous burner II (Insulcon fibres)

In order to have complete combustion the cooled walls of region C had to be insulated with a ceramic material which provides a controllable heat-flux to the mantle cooling and a high inner surface temperature. In the first experiments with prototype II Pyrostop coating 160, an aluminium oxide fibre insulation material, was used. Thus, the formation of carbon monoxide due to the contact of the reaction radicals with the cold surfaces could be avoided. However, it was difficult to estimate the influence of the increased surface on the CO emissions and on the overall heat loss in this region, because of the not well known material properties. Within the heat exchanger region, a packing of ceramic spheres (aluminium oxide - 5 mm) was used to improve the heat transfer to the heat exchanger which is achieved mainly by increasing the heat transfer coefficients.

At LSTM extensive experiments were performed in the same manner as for the prototype I. The experiments included emission measurements and the measurement of the pressure drop of the burner.

The experiments showed that the pressure drop of the recirculating water economy, which was designed with large cross sections, in order to reduce the pressure drop of the water within the heat exchanger system, is about 0,3 bar for 42 l/min (figure 50).

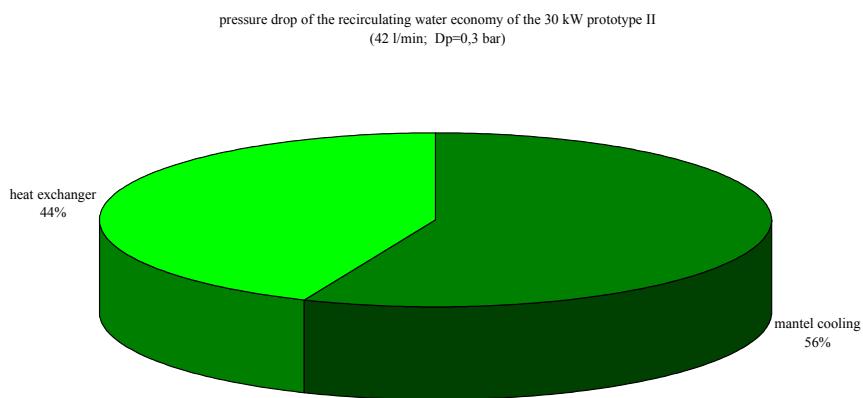


Fig. 50 Pressure drop of the recirculating water economy

One important advantage of the prototype II design is that the flow velocity is influenced by the radial symmetric geometry. In the flameholder region A the velocity is relatively high because of the small circumference at low radial positions, but at greater radii, i. e. in the region C and D, the velocity decreases. The overall effect is a lower pressure drop of the burner. According to calculations, which were carried out at LSTM-Erlangen, the gas pressure drop of the prototype II should be below 10 mbar. The experiments however showed

that the pressure drop of the prototype II is still too high. This can be related to the packing of 5 mm ceramic spheres within the heat exchanger region. This means that for the final design of the porous medium burner, the heat exchanger has to be further optimised. The goal is to build a heat exchanger, in cooperation with Viessmann, with a high efficiency without ceramic spheres.

With the porous media used in the prototype II already low emission values were reached, but the experiments turned out that the temperature resistance of the SiC foams was not sufficient for the high thermal loads. Moreover, the gas pressure drop of these ceramic foams was relatively high. For this reason, LSTM-Erlangen, in agreement with the partners Viessmann and Insulcon, decided that some further detailed experiments should be carried out with SiC foams from the Fraunhofer-Gesellschaft in Dresden, which have very open cells and thus a low pressure drop and a new aluminium oxide fibre material from Insulcon.

5.11 Description of the Work under Task 19 and 20: Conclusions on design and material improvements and Modifications resulting in a PMB-HE final design

A 30 kW porous medium burner with integrated heat exchanger was constructed by LSTM-Erlangen. With this burner several experimental investigations were performed. The results of the experiments showed that further constructive improvements should be done on the heat exchanger, in order to reduce the gas pressure drop of the burner. Viessmann made the following different proposals for the construction of a heat exchanger unit for the porous medium burner heat exchanger final design (fig. 51 to fig. 53).

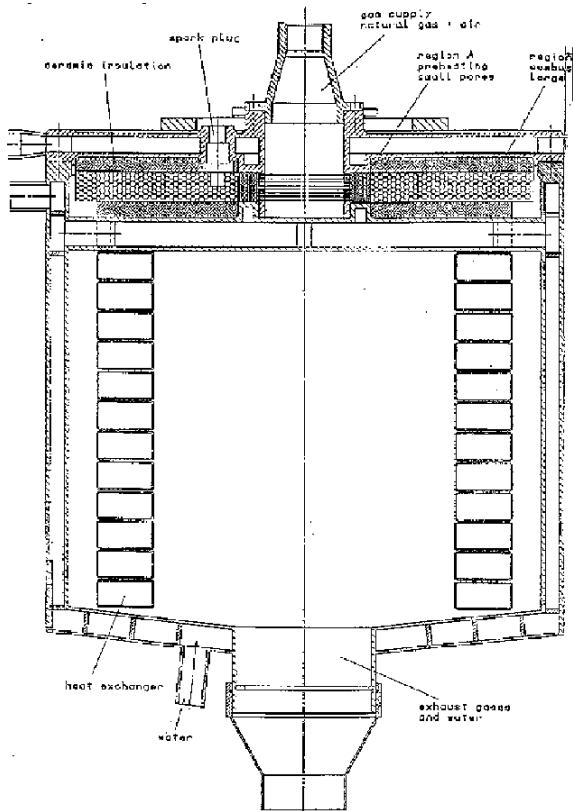


Fig. 51 „Wendelspalt“ heat exchanger

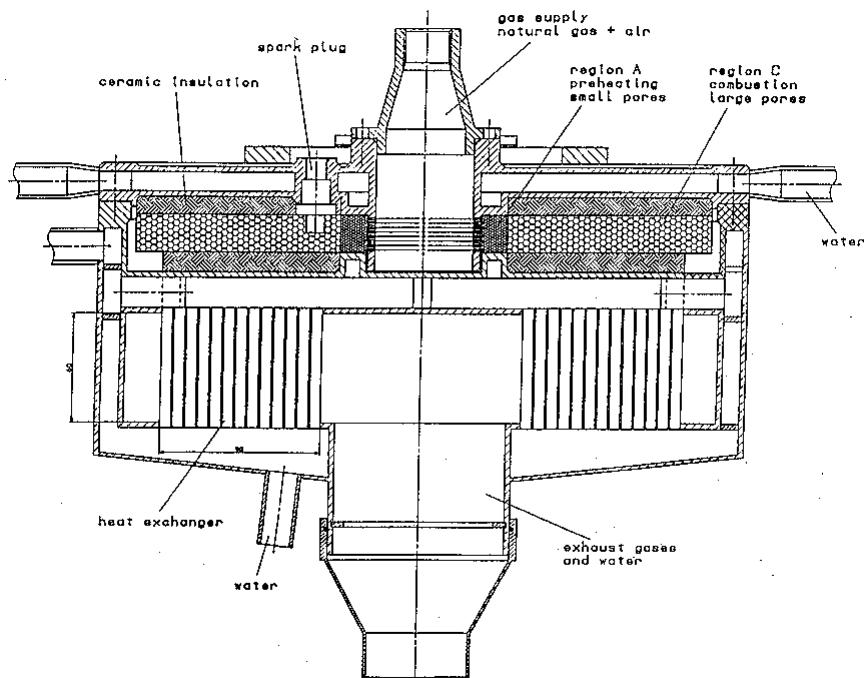


Fig. 52 „Rohrbündel“ heat exchanger

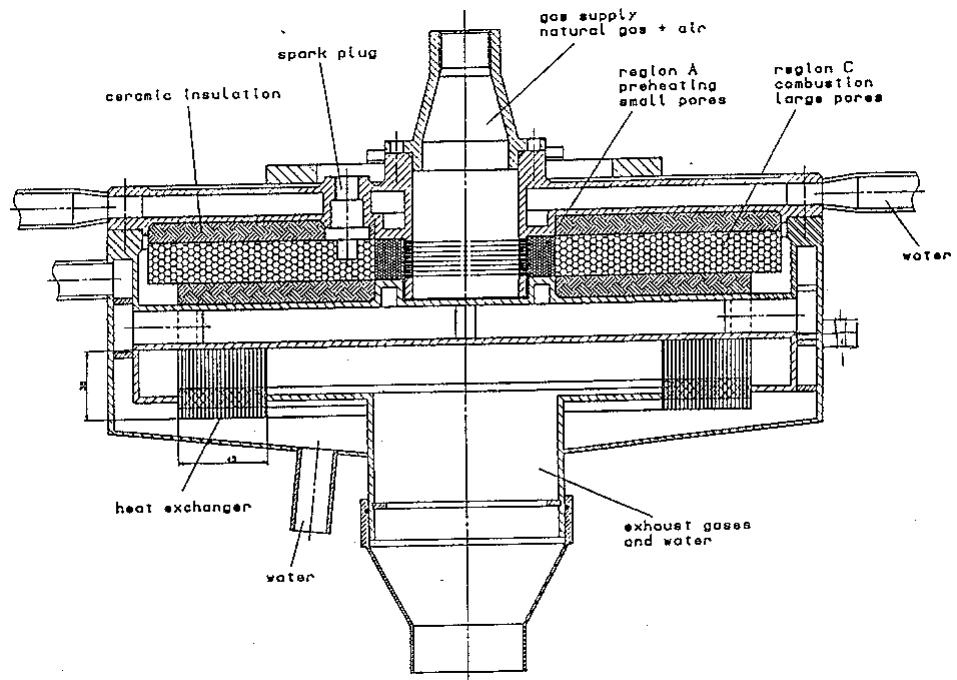


Fig. 53 „Stabripen“ heat exchanger

In agreement with all partners it was decided to build the „Stabripen“ heat exchanger with small pins, as this heat exchanger has the most compact geometry in comparison to the other heat exchangers (fig. 51 and fig. 52), which work with conventional techniques. Fig. 54 shows the working principle of the „Stabripen“ heat exchanger and the heat exchanger prototype, which was fabricated by Viessmann.

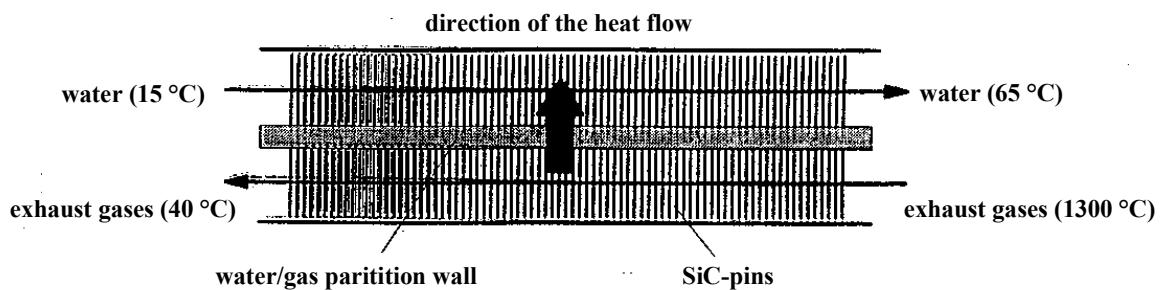




Fig. 54 Working principle - Stabripen heat exchanger and prototype

Viessmann presented the following calculations which showed that this type of heat exchanger has a very good efficiency (Fig. 55). Moreover, the pressure drop of the gas is low (Fig. 56).

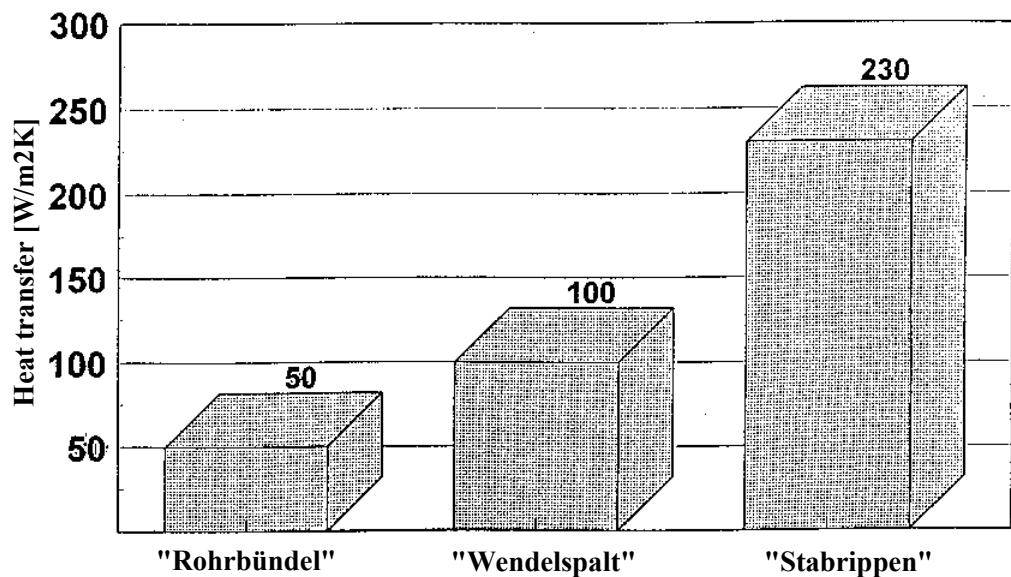


Fig. 55 Heat transfer of the proposed heat exchangers

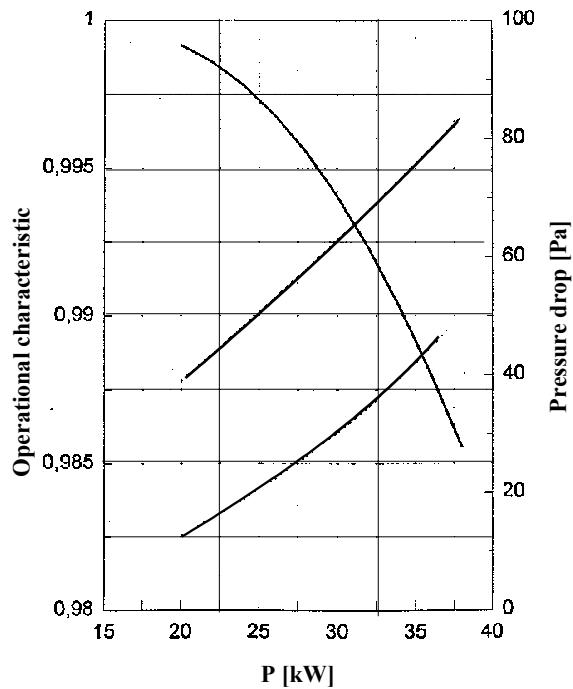


Fig. 56 Gas pressure drop of the „Stabripen“ heat exchanger

According to the design of the „Stabripen“ heat exchanger the design of the porous medium burner had to be modified (Fig. 57 and 58), but the basic design was the same like in the prototype II.

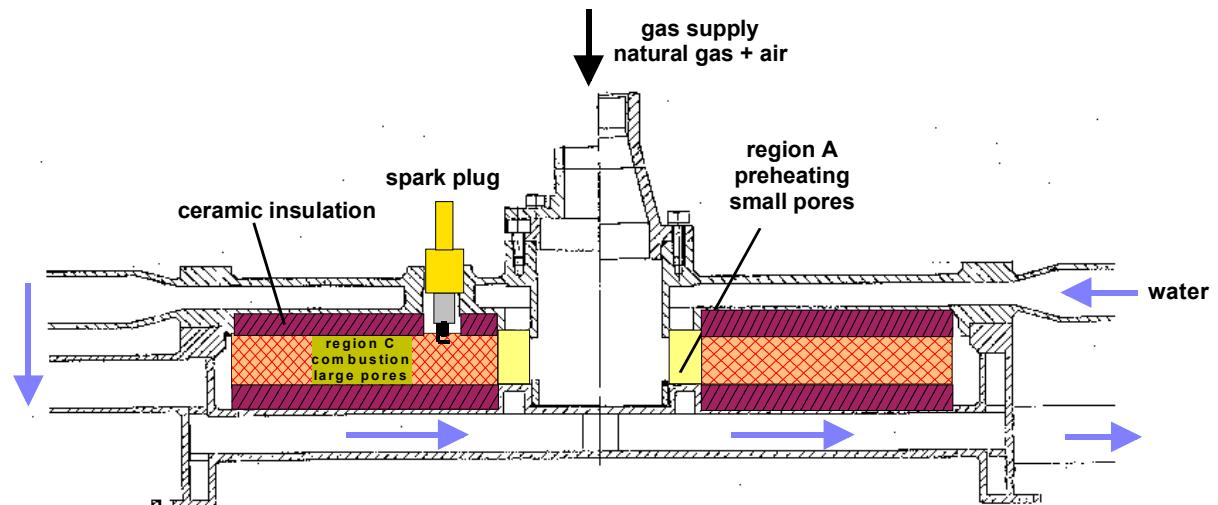


Fig. 57 Schematic diagram of the porous media burner unit II a

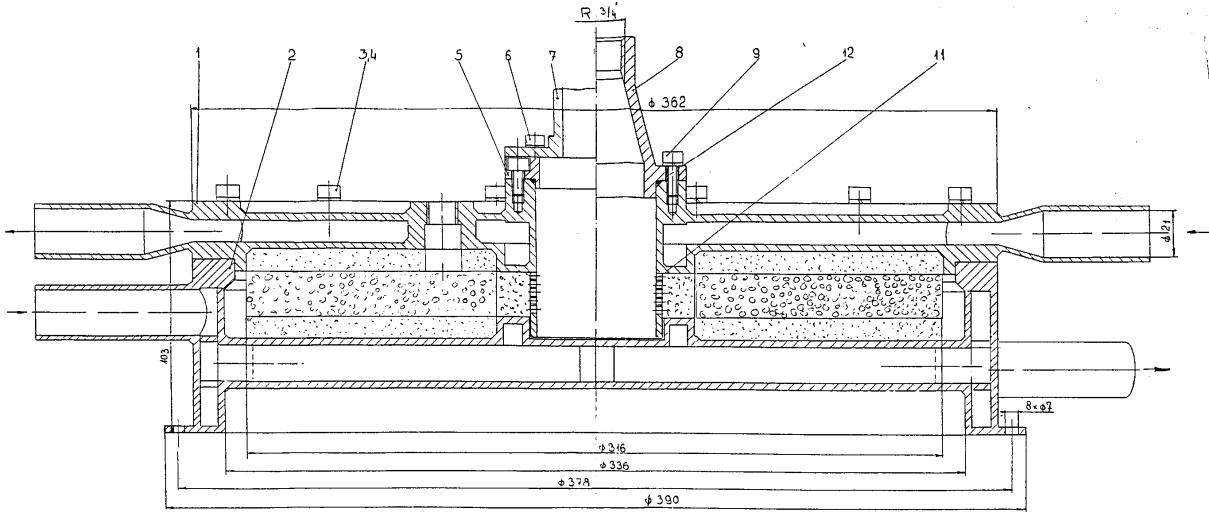


Fig. 58 Drawing of the 30 kW porous media burner unit II a

As already mentioned the temperature resistance of some of the materials, which were investigated in the prototype II was not sufficient for all thermal loads and the gas pressure drop of these ceramic materials was still too high. For this final design of the porous media burner, LSTM-Erlangen in agreement with the partners Viessmann and Insulcon decided to use two different basic material combinations. ‘The material combination 1 is shown in figure 59.

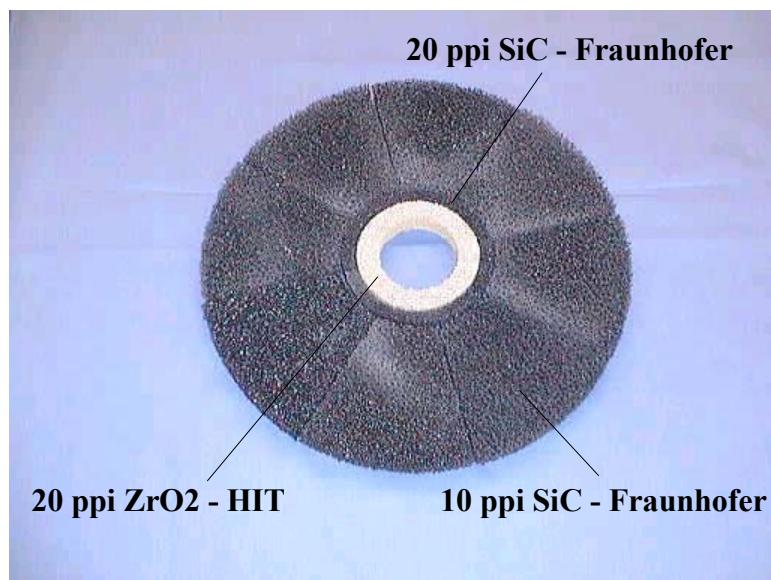


Fig. 59 Material combination 1

Earlier experiments showed that the improvement of the emissions depends very strongly on the availability of high quality materials. The silicon carbide foams from the Fraunhofer Gesellschaft Dresden, which were used in the regions C1 and C2 in this configuration have all these important qualities (thermal stability up to 1600 °C, high mechanical stability, good heat transport properties etc.) In region C1 10 mm 20 ppi ceramic foams were used as the calculations, which were carried out from partner 4, showed that the major part of the NO_x is formed within the first millimeters of the combustion region. Consequently, materials with a high heat conductivity and a great surface were used, in order to increase the heat transport. In order to have complete combustion the cooled walls of region C2 were insulated with ceramic materials to provide a controllable heat-flux to the mantle cooling and a high inner surface temperature (Al₂O₃ fibre insulation material). Within the region C1 and the inner region C2 however, an insulation material with a relatively high heat conductivity was inserted, because of the requested high heat transport within this area. The material combination 1 resulted in low emissions of carbon monoxide, but the nitrous oxide values were still relatively high (fig. 60).

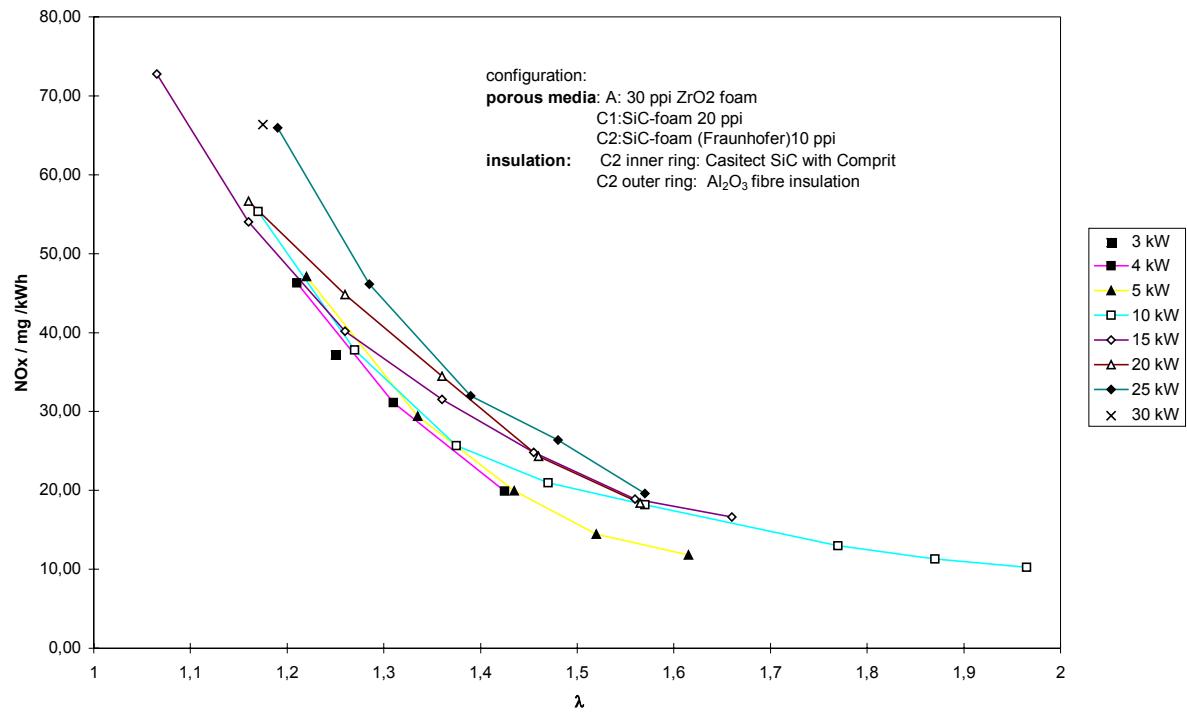


Fig. 60 NO_x-emissions of the prototype II - 20 ppi SiC foams in region C1

According to the calculations of partner 3 however, the following consideration was taken into account, in order to further reduce the formation of NO. The gas and solid temperature

profiles change with the solid conductivity is due to the internal heat transfer in porous media. For the combustion process in porous media, the most important mechanism is the internal heat feedback from the burned gas to the unburned gas through radiation and conduction through the porous media. With the reduction of the solid conductivity, the ability of heat feedback through the solid conduction is reduced so that the total amount of heat feedback is decreased. Thus, the preheating of the gases and solid matrix in the upstream region is reduced, and the peak flame temperature is reduced, too. With the reduction of the solid thermal conductivity, the peak flame temperature is reduced and consequently also the NO-emissions because the formation of NO depends mainly on the peak flame temperature [11]. According to these numerical results LSTM-Erlangen modified the basic material combination 1. In this experiment the 20 ppi SiC foam in region C1 was replaced by a material with a lower heat conductivity (ZrO_2 foams). This optimised material combination 1 b can be seen in figure 61.

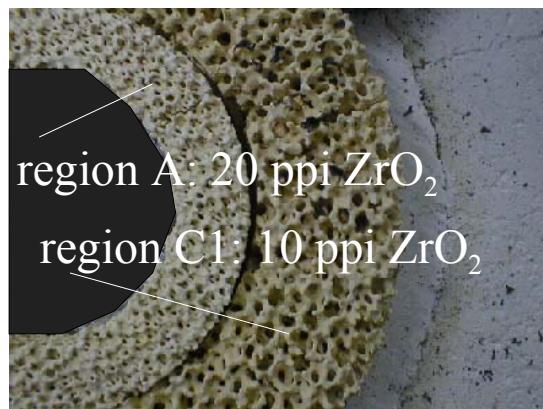


Fig. 61 Optimised material combination 1 b within the C1

The experimental investigations, which were carried out at LSTM-Erlangen confirmed these calculations of IST-Libson. The NO_x -emissions, which were measured for the prototype II final design can be seen in figure 62. A comparison with figure 60 (SiC foams in region C1) shows, that with the ZrO_2 material the NO_x -values could be lowered by about 25 % for a air-ratio $\lambda = 1,3$. Further optimisation potential for these emissions lies in the possibility to vary the dimensions of the region C1 and the size of the pores. In this way it will be possible to lower NO_x by several mg/kWh. These subsequent experiments are carried out however no more within the framework of the project.

The CO-emissions, which were measured for the prototype II final design (ZrO_2 in region C1) can be seen in figure 63.

The maximum gas pressure drop measured for this burner with the final design was 10 mbar. This means, that the aspired value for the pressure drop could be reached.

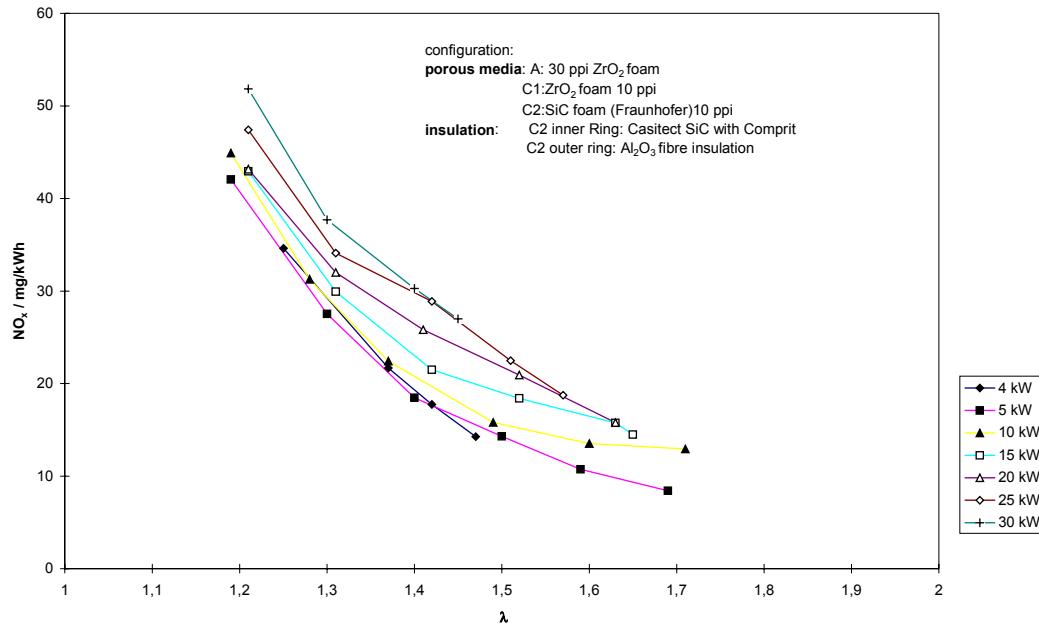


Fig. 62 Optimised NO_x -emissions of the prototype II (final design) - ZrO_2 foams in region C1

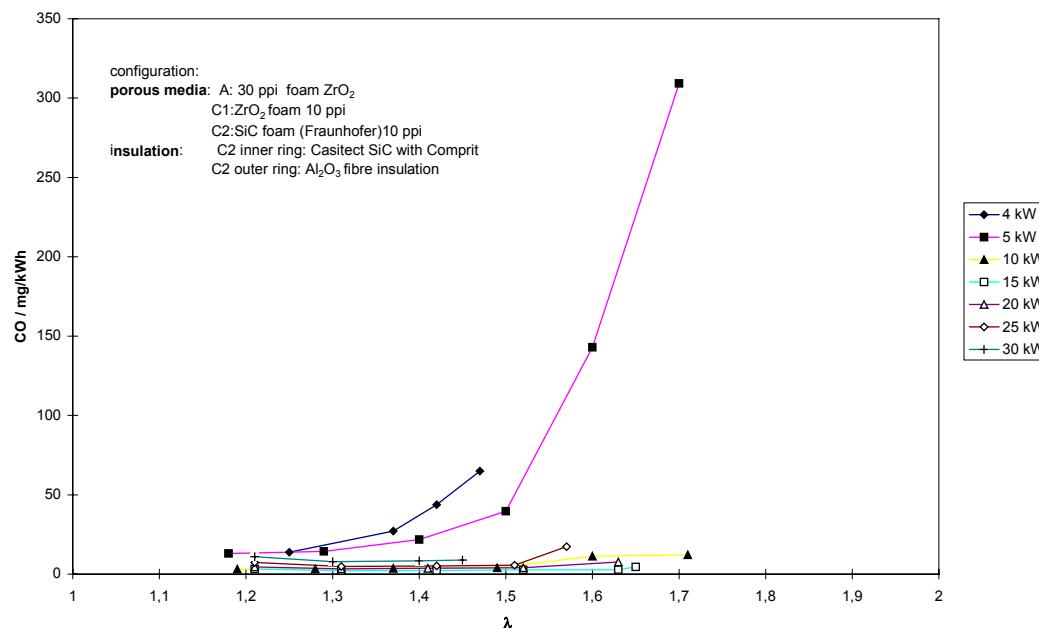


Fig. 63 CO-emissions of the prototype II (final design) - ZrO_2 foams in region C1

All the materials (except the 20 ppi SiC foams), which were used for the second basic material configuration were delivered from Insulcon (Fig 63).

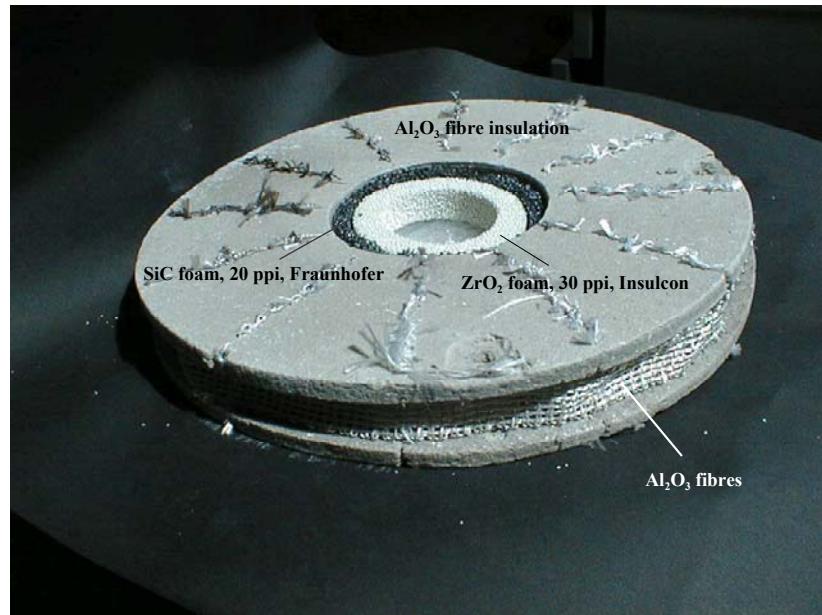


Fig. 63 Material combination 2 - Insulcon materials

The ceramic insulation of the walls and the porous medium of the region C2 was manufactured as one part. The ceramic insulation sintered however within the inner region. As a consequence the insulation material sheets deformed and crushed the Al₂O₃-fibre textile, which was winded up within the combustion region. Due to the insufficient material quality the CO emission, which were measured with this configuration, reached only an unacceptable level.

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