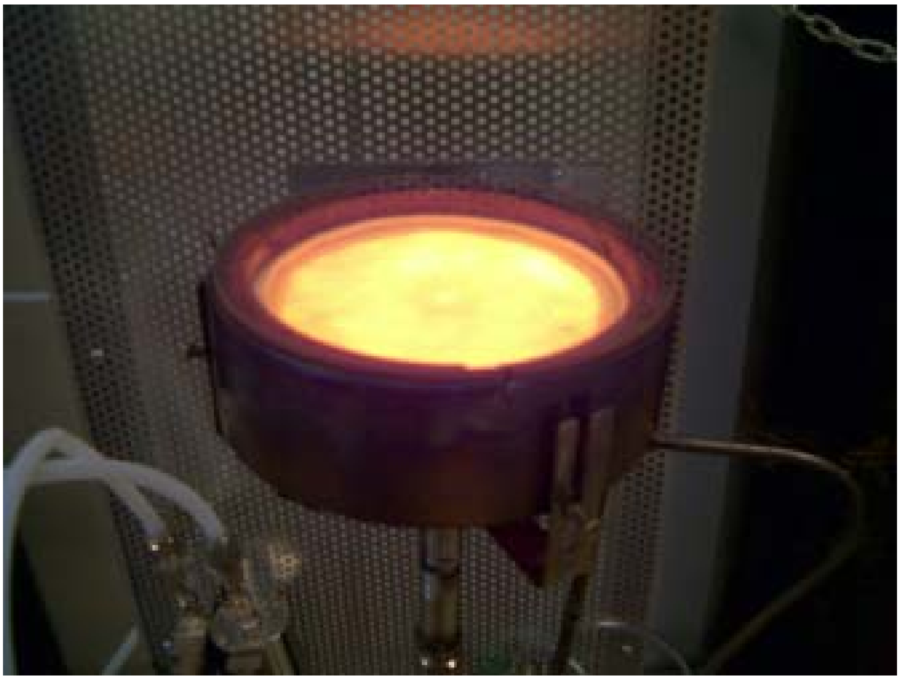
Rapport SGC 145

Development of Catalytic Cooking Plates



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Följande parter har gjort det möjligt att genomföra detta utvecklingsprojekt:

Gaz de France
Catator AB
Statens Energimyndighet

SVENSKT GASTEKNISKT CENTER AB

Johan Rietz

Sammanfattning

Katalytisk förbränning för gasspisar eller kokplattor (slutna system med keramisk häll) är en mycket lovande teknik med avseende på möjligheten till lätt rengöring, effektreglering samt emissioner. Tidigare undersökningar har visat att nätkatalysatorer, tillverkade och levererade av Catator AB (CAT), är väl lämpade till att användas i sådana applikationer. Förutom att markant reducera emissionerna av NO_x så möjliggör dessa fördelar såsom god designflexibilitet, lågt tryckfall samt hög värmetransportkapacitet, vilket leder till snabb termisk respons.

Innan arbetet inom detta projekt initierades, utförde Gaz de France (GdF) en rad tester med Catators nätkatalysatorer i deras katalytiska gasspisbrännare. Resultaten jämfördes med de resultat de tidigare mätt upp med deras egna monolitkatalysatorer installerade i samma brännarsystem. Det visade sig att nätkatalysatorn i jämförelse med monoliten är mycket lovande i avseende på både emissioner (< 10 mg NO_x/kWh, < 5 mg CO/kWh) och livslängd (ingen märkbar degradering under 8000 h @ 200 kW/m^2, vilket skall jämföras med data uppmätta med monoliten, i.e. < 700 h). Det fastställdes däremot att strålningen och därmed den termiska verkningsgraden till den keramiska hällen var väsentligt lägre med nätkatalysatorn än vad som uppmätts med monoliten (15 % jfr. med 32 %). Resultaten pekade dock på att den termiska verkningsgraden skulle kunna avsevärt förbättras genom att utveckla en ny brännardesign. Till följd av dessa resultat så skapades ett samarbetsprojekt för vidare utvecklingsarbete inom området mellan GdF, CAT och Svenskt Gastekniskt Center (SGC AB).

Detta arbete rapporterar om design, konstruktion och utvärdering av nya katalytiska brännare för naturgasförbränning i gasspisar. Brännarna är baserade på Catators nätkatalysatorer. Utvärderingen utfördes med avseende på nyckelfaktorer såsom termisk effektivitet, emissioner, och tryckfall med hjälp av både matematiska simuleringsmodeller och experiment. Inverkan av parametrar som t ex nätkatalysatorns meshtal, struktur (plan eller vågig), substratmaterial, kritiska avstånd i brännare (avstånd mellan nät och keramisk häll, avstånd mellan ingående nät) samt driftsvillkor (lambdavärde) undersöktes. En av de undersökta brännarna uppvisade relativt höga termiska effektivitetsvärden över ett brett effektintervall, 40-50 % för 60-300 kW/m^2, samtidigt som både NO_x (1-3 mg/kWh) och CO (0-15 mg/kWh) emissionerna uppmättes till att vara mycket låga. Nackdelen i dagsläget med den föreslagna prototypen är att då brännaren körs på låg last (< 80 kW/m^2), observeras höga emissioner av oförbrända kolväten. I rapporten diskuteras möjliga orsaker till detta problem samt åtgärder som eventuellt skulle kunna lösa detta dilemma.

Summary

Gas catalytic combustion for gas stoves or cooking plates (closed catalytic burner system with ceramic plates) is a very promising technique in terms of ease of cleaning, power modulation and emissions. Previous investigations show that wire mesh catalysts, prepared and supplied by Catator AB (CAT), seem to be very well suited for such applications. Except for significantly reducing the NO_x-emissions, these catalysts offer important advantages such as good design flexibility, low pressure drop and high heat transfer capacity, where the latter leads to a quick thermal response.

Prior to this project, Gaz de France (GdF) made a series of measurements with CAT's wire mesh catalysts in their gas cooking plates and compared the measured performance with similar results obtained with theirs cordierite monolith catalysts. Compared to the monolith catalyst, the wire mesh catalyst was found to enable very promising results with respect to both emission levels (<10 mg NO_x /kWh, <5 mg CO/kWh) and life-time (>8000 h *vs.* 700 h at 200 kW/m^2). It was however established that the radiation and hence, the thermal efficiency of the cooking plate was significantly less than is usually measured in combination with the monolith (~15 % vs. 32 %). It was believed that the latter could be improved by developing new burner designs based on CAT´s wire mesh concept. As a consequence, a collaboration project between GdF, CAT and the Swedish Gas Technology AB (SGC AB) was created.

This study reports on the design, the construction and the evaluation of new catalytic burners, based on CAT´s wire mesh catalysts, used for the combustion of natural gas in gas cooking stoves. The evaluation of the burners was performed with respect to key factors such as thermal efficiency, emission quality and pressure drop, etc, by the use of theoretical simulations and experimental tests. Impacts of parameters such as the the wire mesh number, the wire mesh structure (planar or folded), the catalyst substrate material, the critical distances inside the burner, and the operation conditions such as the lambda value, etc, were investigated. With one of the suggested burner designs, it was found that relatively high thermal efficiencies could be obtained for a broad range of power inputs, i.e. i.e. 40-50 % for 60-300 kW/m^2. It was also seen that the resulting NO_x and CO emissions were very low, 1-3 mg NO /kWh and 0-15 mg CO/kWh. The major concern with the suggested prototype was the observation of that slow cooking (i.e. power output < 80 kW/m^2) results in high emissions of unburned hydrocarbons. Explanations to this problem and suggestions for solving it are discussed in the report.

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1. Background of project

Gas catalytic combustion for gas stoves or cooking plates is a very promising technique in terms of ease of cleaning, power modulation and emissions. Previous investigations show that wire mesh catalysts, supplied and prepared by Catator AB (CAT), seem to be very well suited for such applications [1, 2]. Except for significantly reducing the NO_x-emissions, these catalysts offer important advantages such as good design flexibility, low pressure drop and high heat transfer capacity, where the latter leads to a quick thermal response.

Gaz de France (GdF) have made a series of measurements with CAT's wire mesh catalysts in their gas cooking plates (i.e. a closed catalytic burner system) and compared the measured performance with similar results obtained with theirs monolith catalysts. Compared to the monolith catalyst, the wire mesh catalyst was found to enable very promising results with respect to both emission levels and life-time. It was however established that the radiation and hence, the thermal efficiency of the cooking plate was significantly less than is usually measured in combination with the monolith (~15 % *vs.* 32 %). It was believed that the latter could be improved by developing new burner designs based on CAT´s wire mesh concept or by solely modifying the present catalytic burner design in combination with eventually some modifications of the properties of the wire mesh catalyst. As a consequence, a collaboration project between GdF, CAT and the Swedish Gas Center AB (SGC AB) was created. More specifically, the aim of this project was to develop a catalytic burner, based on the wire mesh concept, for a cooking plate which provides:

1. easy cleaning (flat ceramic surface)
2. input gas power of 4 kW with a burner size of approximately 15 cm
3. thin design (no more than 10 cm thick)
4. high thermal efficiency
5. good turn-down ratio. It is desired that the design should allow the same efficiency, with respect to the emissions, at slow cooking (~0.3-1 kW) as at full power level.

The project was divided into three different steps. The activities included and performed in the different phases at CAT and GdF, respectively, were as follows:

-The Design step

CAT: i) Mathematical simulations of different burner design alternatives.
ii) Initial experimental tests.

GdF: i) Experimental tests with a new burner concept, which provides, compared to the originally existing catalytic burner prototype (shown in Figure 1), a reversed flue direction, i.e. the gas is flowing from the bottom of the burner to the top.
ii) Testing the best rearrangement for a SiC reemitter in combination with the modified burner.

-Prototype manufacture and evaluation phase

CAT: i) Based on the results obtained in the prevailing design step at CAT, a prototype was constructed and evaluation tests were run.

-Delivery of final prototype to GdF for final evaluation tests

CAT: i) Final modifications of the constructed burner prior to the delivery to GdF.
ii) Documentation of the results, i.e. report writing.

GdF: i) Final evaluation tests of the prototype received from CAT.
ii) Documentation of the results, i.e. finalizing the report of the project.

2. Evaluation of different burner designs developed at GdF

2.1. Burner design 1

CAT´s wire mesh catalyst (details about the wire mesh catalysts can be found in ch. 4.1) has been evaluated in a prototype burner originally developed for a cordierite monolith catalyst, coated with precious metal, at GdF. The burner system, herein abbreviated as burner design 1, can be seen in Figure 1 and 2, respectively. The performance of the wire mesh catalyst was evaluated with respect to the emission levels, the thermal efficiency and the life-time. The results were compared to those obtained with the monolith catalyst, and are summarised in the following.

The ageing tests, performed with natural gas, showed that the catalytic wire meshes (planar wire-meshes of mesh no. 25) do not suffer any deactivation after 8000 hours of ageing at a power input load of 200 kW/m^2. The combustion resulted in stable pollutant emissions (<10 mg/kWh NO_x, <5 mg/kWh CO, un-detectable emission concentrations of unburned hydrocarbons) and a stable ignition time delay (less than 20 seconds before the catalyst starts to radiate). It should be underlined that this result is extremely good compared to the life-time observed with the monolith, i.e. < 700 h at 200 kW/m^2. It was however observed that the wire mesh catalysts were far less radiating to the ceramic plate and hence, the cooking pan than the monolith catalysts at the same surface power (200 kW/m^2), which can be qualitatively established solely from comparing the visual aspects of the two burners in Figure 1. Temperature measurements also confirmed this visual observation, Figure 2. When the monolith was installed, the inlet and the outlet temperatures were 450°C and 700°C, respectively, whereas the temperatures were 300°C (inlet) and 950°C (outlet) in the case of the wire mesh. This result is attributed to differences in mass and heat transfer capacity. The significant higher mass and heat transfer capacity of the wire mesh catalyst results in a significantly lower radiation energy contribution to the ceramic plate than what is obtained with the monolith catalyst (which honeycomb structure works as a heat exchanger itself), and hence, a larger amount of energy is in this case lost, i.e. both irradiative and convective, downstream the burner. It was believed that these heat losses could be significantly reduced by reversing the flue direction in the burner design, which was also what was done when designing the next generation burner designs which were evaluated within the frame of this project.

Figure 1. Cordierite catalyst (left) vs. Catator wire mesh catalyst (right).

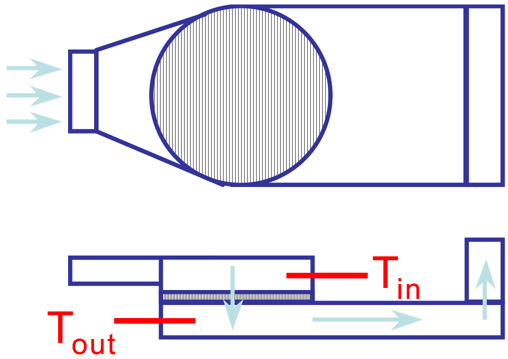


Figure 2. Temperature measurements during operation with burner design 1.

Furthermore, to facilitate a quantitative comparison between the performance data obtained with this burner and with the other burner prototypes that have been developed and evaluated within this project (discussed in the following sections of the report), the thermal efficiency of this burner in combination with the two catalyst types was measured. The efficiency was determined from tests with water heating according to a standard procedure: 1 kg of water is heated up in a saucepan without cover from room temperature with an elevation of 75 K. The burner gas input power was in this case equal to 1 kW (corresponding to approximately 200 kW/m^2) calculated from the natural gas flow rate (based on the low heating value (LHV) of the fuel). The thermal efficiency is defined and calculated according to the following expression:

η=(power received by water with ΔT=75 K)/(power provided by natural gas combustion) x 100

Two different values of thermal efficiency were measured: for a burner ignited at room temperature (cold start) and for an already functioning and hot burner (hot start). The pan used throughout these measurements had no lid on and had the same size as the ceramic plate. The results are displayed in Table 1.

***Table 1.** Estimated values of the thermal efficiency obtained with the burner design 1 in combination with the monolith catalyst and the wire mesh catalyst, respectively, at the power input 200 kW/m^2. The thermal efficiency is measured by water heating using a pan without a lid.*

	Cold start efficiency (%)	**Hot start efficiency (%)**
Cordierite Monolith (Pt/YSZ)	22	32
Wire mesh (Pd/Ce-Al)	11	15

2.2. Burner design 2 and 3

In order to reduce the significant heat losses obtained with burner design 1, a new burner prototype was designed and constructed. Compared to the original burner, the direction of the flue gases is reversed. The design is illustrated in Figure 3. As can be seen, the wire mesh catalyst is in this concept (abbreviated as burner design 2) surrounded by a crown of silicon carbide foam (SiC > 85%, delivered by Ceramiques Techniques et Industrielles", Salindres, France), having a surface ratio SiC/mesh equal to approximately 1.9. The use of silicon carbide foam was incorporated in order to attempt to convert hot fumes (convective energy) into radiant infrared energy before those are leaving the system, and in this way, increase the overall thermal efficiency even further. Silicon carbide foam was motivated to be a good choice for this matter, since this material is known to have a high emission coefficient (ε=0.9 or more [3]) when it is heated up in combination with the fact that a foam itself has the advantage to maximize the gas-solid heat exchange.

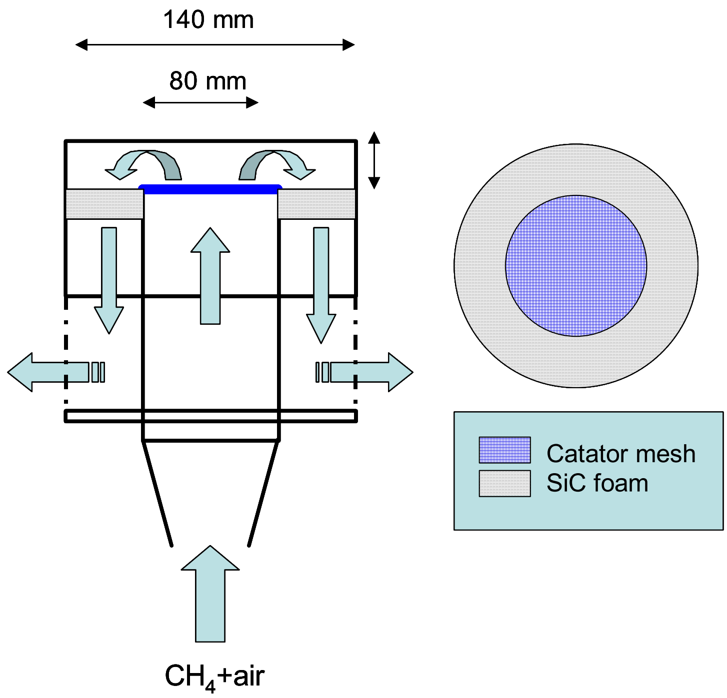


Figure 3. *Schematic illustration of the burner design 2 with the SiC foam installed.*

Burner design 2 was evaluated in terms of thermal efficiency by using the same procedure as previously described (section 2.1). The fuel used in these experiments was pure methane. The results are summarized for different power inputs in Table 2. In order to distinguish the effect of having SiC present from the effect of having a reversed flue gas direction, the thermal efficiency for the surface powers 250 and 300 kW/m^2, respectively, were also estimated with the SiC foam removed.

These investigations showed that

-burner design 2 provides for a significant higher thermal efficiency compared to burner design 1, i.e. 39 % vs. 15 % at 200 kW/m^2.

-the presence of SiC foam brings very small benefits to the thermal yield, i.e. 0-3 %. This result is also illustrated by the visual aspect shown in Figure 4 and 5, respectively, which present photos of the burner in "on" and "off"-mode, respectively.

Table 2. *Estimated values of the thermal efficiency obtained with the burner design 2 in combination with the wire-mesh catalyst + SiC (* without SiC) at the power input 200 kW/m^2 at 20 % excess air.*

Surface power (kW/m^2)	Cold start efficiency (%)	Hot start efficiency (%)
100	22.5	34.0
150	25.4	36.4
200	25.2	38.8
250	26.6	39.2
250*	24.0	37.9
300	23.2	36.8
300*	24.3	36.6

Thus, from the above given conclusions, it is obvious that the significant increase in thermal efficiency obtained with this burner compared to the original one is attributed to the burner configuration itself: burner design 1 uses only radiant energy (hot gases are leaving on the opposite side of the ceramic plate) whereas in burner design 2, convective energy from hot gases is also used to heat up the saucepan. Furthermore, considering the small impact of SiC foam in this burner in combination with the bulk and the cost of this foam, it seems that there is no point of using this material in this specific burner design.

Figure 4. *Burner "on"*

Figure 5. *Burner "off"*

It should also be mentioned that another attempt to improve the burner's efficiency by the use of SiC was made by placing a large SiC foam disk, upstream, on the top of the wire mesh catalyst. A schematic illustration of the configuration is given in Figure 6. Test results showed that the thermal efficiency of this burner type (abbreviated herein as burner design 3) is by far lower than for the simple burner with no SiC foam present (burner design no.2). In addition, it was found that this burner configuration was difficult to ignite (the spark has to light up a flame between the catalyst and the SiC).

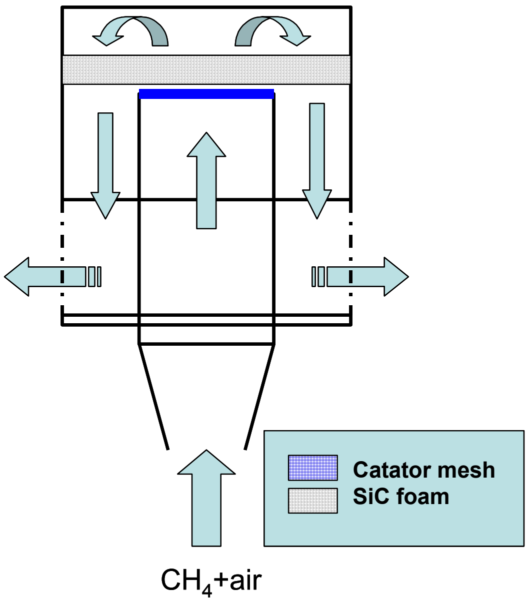


Figure 6. *Schematic illustration of burner design 3.*

3. Documentation of work performed at CAT.

3.1. Theoretical part

3.1.1. Descriptions of the simulation models

Figure 7 shows a schematic illustration of the burner prototype that was theoretically, and thereafter, experimentally evaluated at CAT in this project. As seen, the flow direction of the fuel/flue gases is similar to the flow direction in burner designs 2-3 (GdF-burners). However, for reasons that will be clarified in the following sections, this prototype includes two wire meshes (wm1 and wm2), instead of one single as in the GdF-burners. As can also be seen, there is a fuel distribution plate positioned in the inlet of the burner, and there are emission catalysts placed in the outlet. For a more detailed description of the burner and its components, see section 4.1.

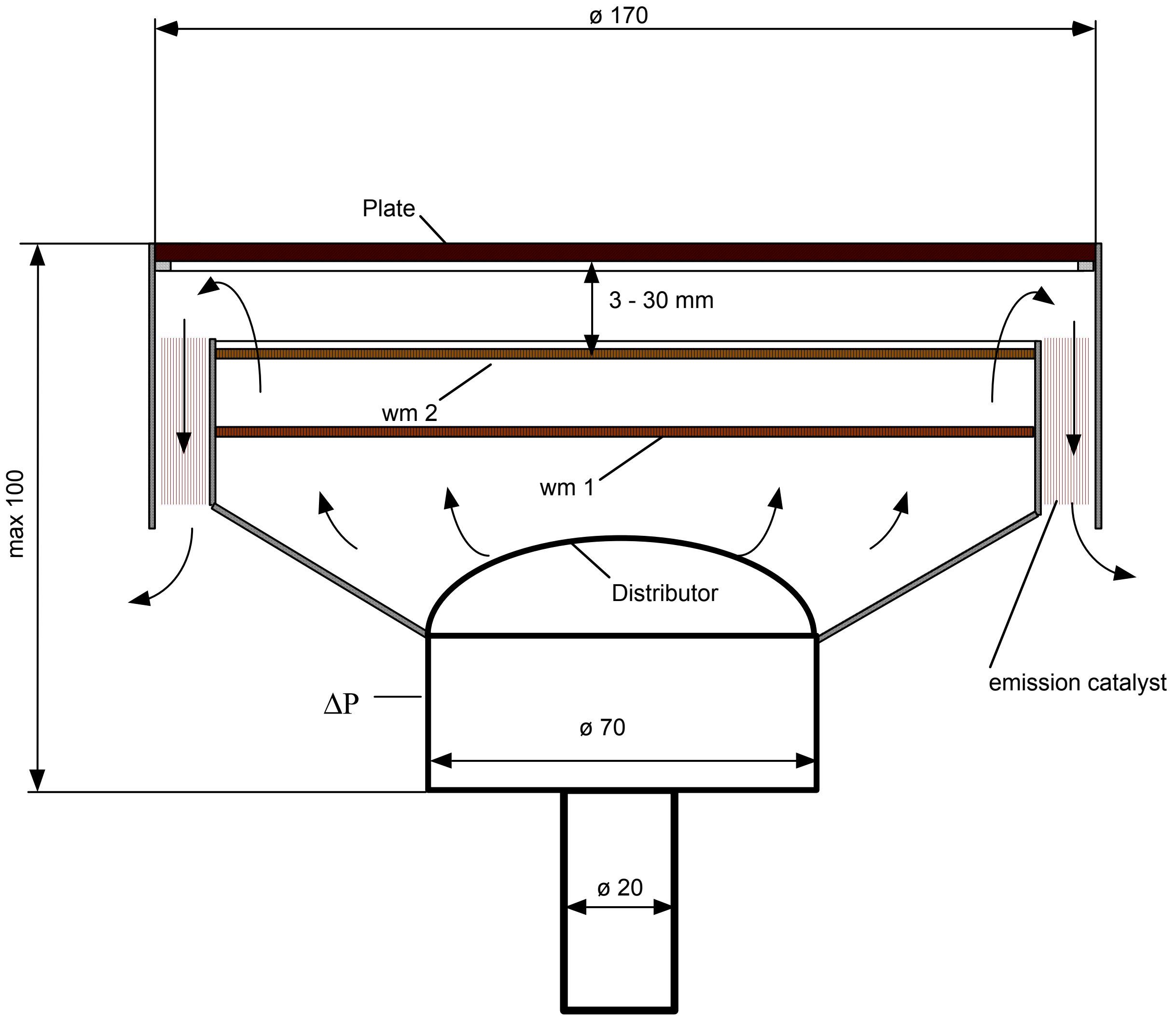


Figure 7. *A schematic illustration of the burner prototype evaluated in step 1 and 2 in this project. ΔP indicates the point at which the differential pressure meter was placed for measuring the pressure drop over the burner system under operation.*

Two different simulation tools were used to analyse the performance of this burner type, i.e. a dynamic simulation model which code was written in the commercial software Ithink™ and a computational fluid dynamic model (CFD) which was developed in ANSYS™. In brief, the dynamic simulation model takes into account the catalytic combustion reaction occurring on the two wire mesh catalysts (wm1 and wm2), the heat transfer by radiation, convection and conduction, respectively, the pressure drop over the wire meshes and the thermal inertia (start-up simulation, response time). This model enables valuable approximate predictions of how the performance of the burner, e.g. the thermal efficiency, the pressure drop and the NO_x formation, is influenced by for example

-the start-up, change in load (thermal response)
-the mesh geometry (mesh number, wire thickness etc)
-the catalytic activity
-the size and the critical distances inside and/or of the burner, e.g. the distance between the ceramic plate and the wire meshes.

Furthermore, the secondly mentioned modelling tool, i.e. the CFD-model, is a good complement to the Ithink™-model in that it gives important information of how the fuel distribution is expected in the burner and more importantly, how it can be influenced by for example the size of the burner and the pressure drop over an inlet or over the wire meshes, etc. A good fuel distribution is essential in order to arrive at a good emission quality at different power inputs and thus, it has a large impact on the turn-down ratio of the system.

3.1.2. Theoretical results

In this section, interesting results that can be predicted with the use of the two models described in the previous section will be exemplified. It should be underlined that the models' predictions should herein, as always in the case of theoretical work, be considered as a valuable help for increasing the understanding of the system, and thereby act as great tools that facilitate the design work of the burner. However, since "..the reality is always much more complicated than the theory..", the calculated predictions should be seen as approximate values and as for indicating valuable trends of the performance with for example a variation in the wire mesh geometry, etc.

3.1.2.1. Change in load

Figures 8a and b show an example of how the performance of the burner is expected to vary with a changing load. The thermal efficiency is significantly increasing with a decreasing power input, due to a decreasing loss by convection heat through the exhaust gas as the flow rate is decreased, Figure 8a. The latter is evident from the variation of the exhaust temperature with the load, i.e. the lower the load, the closer the exhaust temperature, T23, becomes to the temperature of the wire mesh no. 2, Twm2, which in turn results in an increased radiation contribution of the total heat capacity transferred to the pan, Figure 8b. Moreover, other valuable information that this type of simulation enables is the change in temperatures of the two wire meshes, Tw1 and Tw2, and the variation in pressure drop over the catalysts, deltaPloss. As expected, the pressure drop is decreasing with a decreasing load and with decreasing temperatures of the wire meshes.

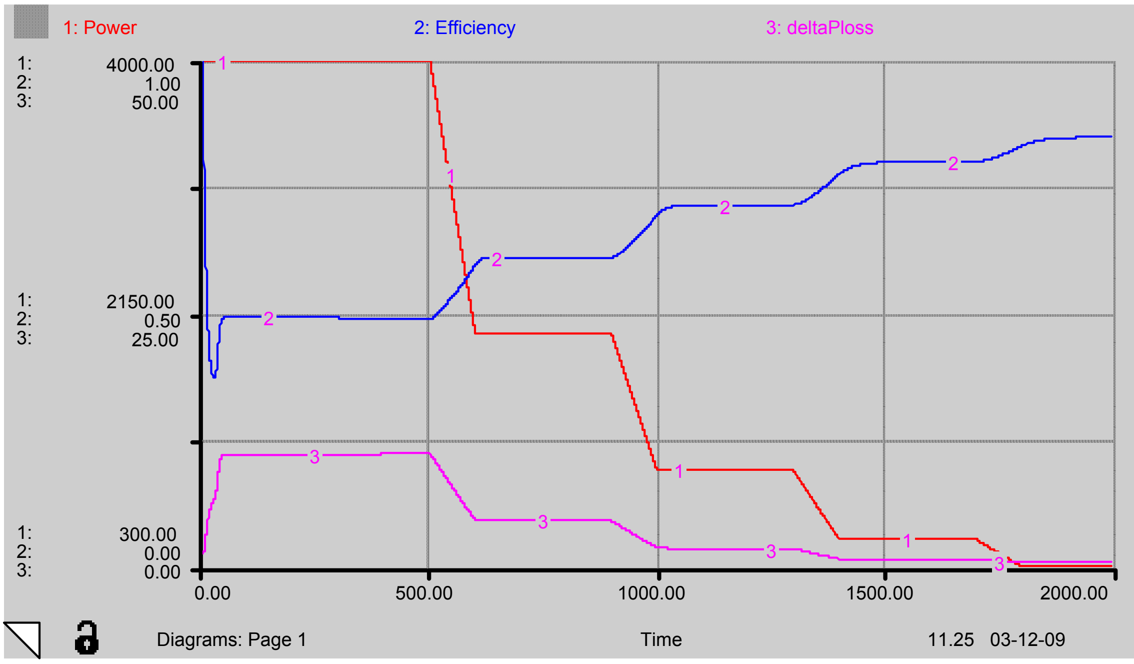


Figure 8a.

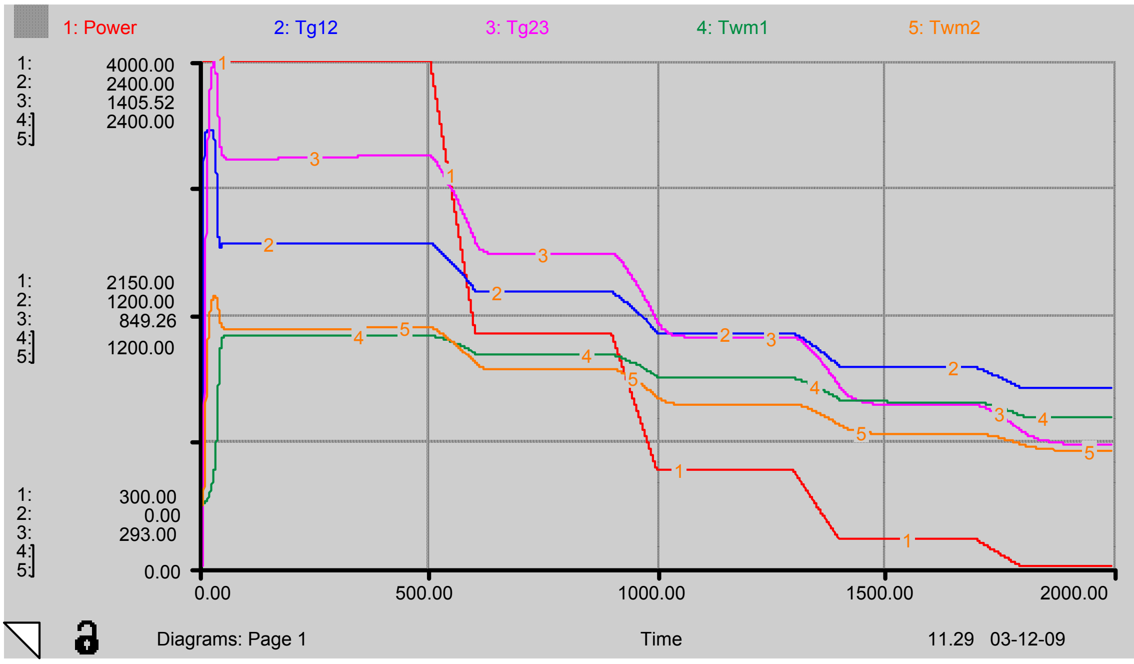


Figure 8b.

Figures 8a and b*. Simulation results showing the performance of the burner as a function of load/power input. The in-data used for the simulations were: wm1=35 mesh, wm2=25 mesh, lambda=1.2, distance wm2-ceramic plate=5 mm, distance wm1-wm2=5 mm, wire mesh diameter=150 mm, glass plate diameter=170 mm. a) thermal efficiency and total pressure drop over the wire meshes as a function of power input. b) Temperatures of the wire meshes (Tw1 and Tw2) and temperatures of the gas phase between the two wire meshes (T12) and the wm2 and glass plate (T23), respectively.*

3.1.2.2. Influence of the wire mesh geometry

The influence of the wire mesh number of the two primary burner catalysts was studied. The simulation results obtained by the model written in Ithink™ showed that the parameter that is the most significantly influenced by the mesh number is the pressure drop; the higher the mesh number, the higher the pressure drop over the wire meshes. Furthermore, the results also indicate that the thermal efficiency can somewhat be increased by an increase in mesh number, see Figures 4a and b. It should be underlined that these simulations were made under the assumption that the thickness of the active catalyst layer, so also the fuel distribution are completely independent of the wire mesh number of the catalyst, which might not be the case in the real situation, see the experimental results presented in 4.2. For predicting the fuel distribution over wire meshes of different mesh numbers, and hence, over various pressure drops, the CFD modelling results should instead be considered, see paragraph 2.2.5.

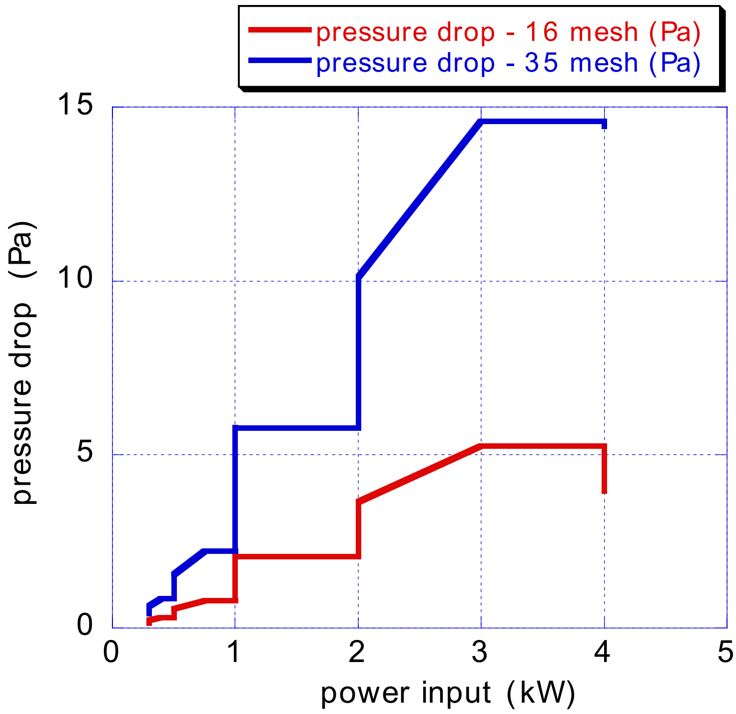


Figure 9a.

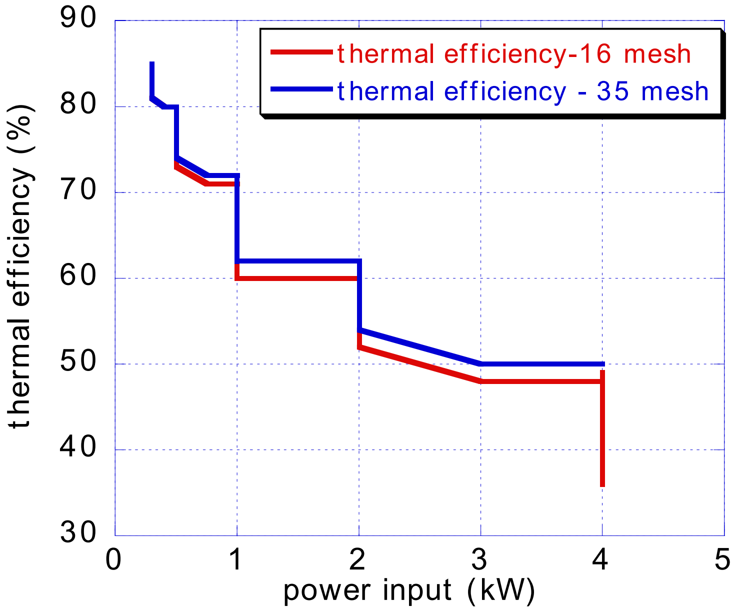


Figure 9b.

Figures 9a and b. *Simulations showing the influence of the wire mesh number of the catalysts (wm1=wm2). The in-data used for the simulations are: lambda=1.2, distance wm2-ceramic plate=5 mm, distance wm1-wm2=5 mm, wire mesh diameter=150 mm, glass plate diameter=170 mm. a) the influence on the pressure drop over the wire meshes b) the influence on the thermal efficiency.*

3.1.2.3. Influence of critical distances

The model written in Ithink™ takes into account two different critical distances that may have an impact on the performance of the burner system, i.e. the distance between the two wire meshes and the distance between wm2 and the ceramic plate, respectively. According to the simulation results, the distance between the two wire meshes may only influence the levels of NO_x-concentration in the exhausts. The results show that the larger the distance, the larger the amount of produced NO_x. This is explained by the fact that the larger the distance, the longer the residence time of the gas in the hot zone becomes (i.e. the volume between the two wire meshes), which favourites the production of NO_x.

Moreover, in contrast to the distance wm1-wm2, the simulations illustrate that the distance between the ceramic plate and the wire mesh no.2 has an impact on the thermal efficiency. As seen in Figure 10, the thermal efficiency may be increased by 3-5 % by decreasing the distance wm2-ceramic plate from 2.5 to 0.5 cm. This increase in efficiency is also evident from a significant decrease (about 50-100 °C) of the gas phase temperature between the ceramic plate and the wm2, i.e. T23.

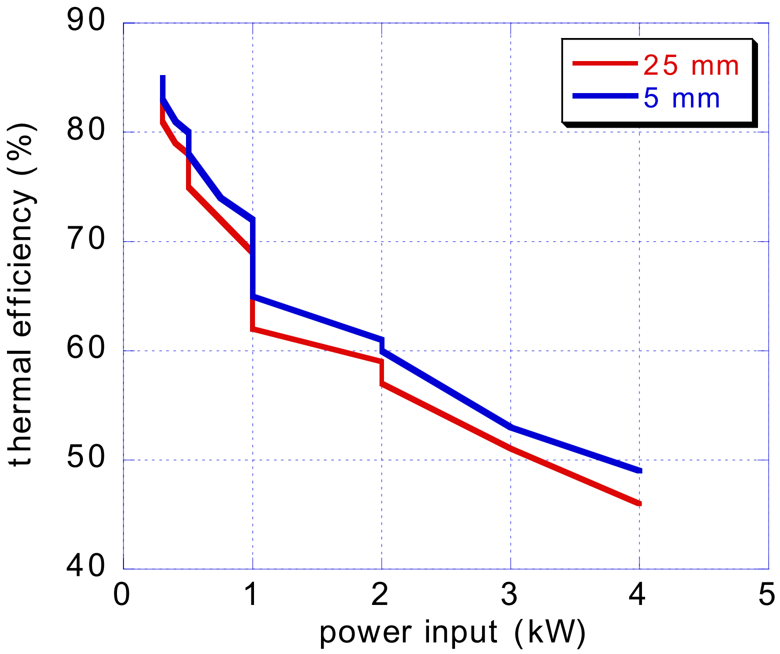


Figure 10. *Simulations showing in the influence of the distance between the ceramic plate and the wm2. The in-data used for the simulations were: wm1=35 mesh, wm2=25 mesh, lambda=1.2, distance wm1-wm2=5 mm, wire mesh diameter=150 mm, glass plate diameter=170 mm.*

3.1.2.4. Influence of the temperature of the catalyst

To obtain a high thermal efficiency, it is of most importance to develop a system that enables as much radiation as possible between the wire mesh catalyst and the ceramic plate. As is well-known, the magnitude of radiation can be influenced by the emission coefficients, the temperatures and the surface areas of the catalyst material and the ceramic plate, respectively. In this work, the focus has been on the temperature effect since this parameter is the one that has the most significant impact on the radiation magnitude (which easily can be established by considering Stefan Boltzman´s law: $dE/dt=\sigma*A*T^4$ (σ=emission coefficient, A=surface area, T=temperature), which describes the energy of radiation emitted from one body to another). The temperature of the wire mesh can be increased by decreasing the excess of oxygen in the gas mixture (i.e. decreasing the lambda value) and/or by increasing the amount of catalyst, e.g. increasing the wire mesh number. From a practical and economical view-point, the best alternative in this case is to decrease the lambda value. For example, by decreasing the lambda value from 1.4 to 1.2 (i.e. from 40 % to 20 % excess of oxygen), the thermal efficiency may be improved by as much as 8-9 %, see Figure 11.

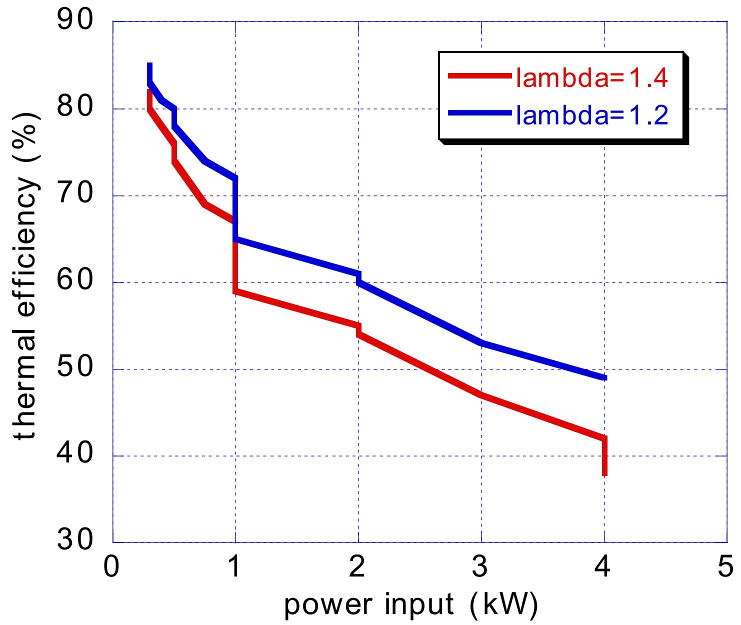


Figure 11. *Simulations showing the influence of the lambda value on the thermal efficiency of the burner system. The in-data used for the simulations were: wm1=35 mesh, wm2=25 mesh, distance wm2-ceramic plate=5 mm, distance wm1-wm2=5 mm, wire mesh diameter=150 mm, glass plate diameter=170 mm.*

Except for increasing the thermal efficiency of the system, a higher catalyst temperature also leads to advantages such as less emission concentrations of CO and UHC. However, the disadvantages of having a high combustion/wire mesh temperature are that the NO_x levels in the exhausts, so also the pressure drop over the system may increase somewhat and that the life-time of the catalyst may be markedly affected, see Figure 12.

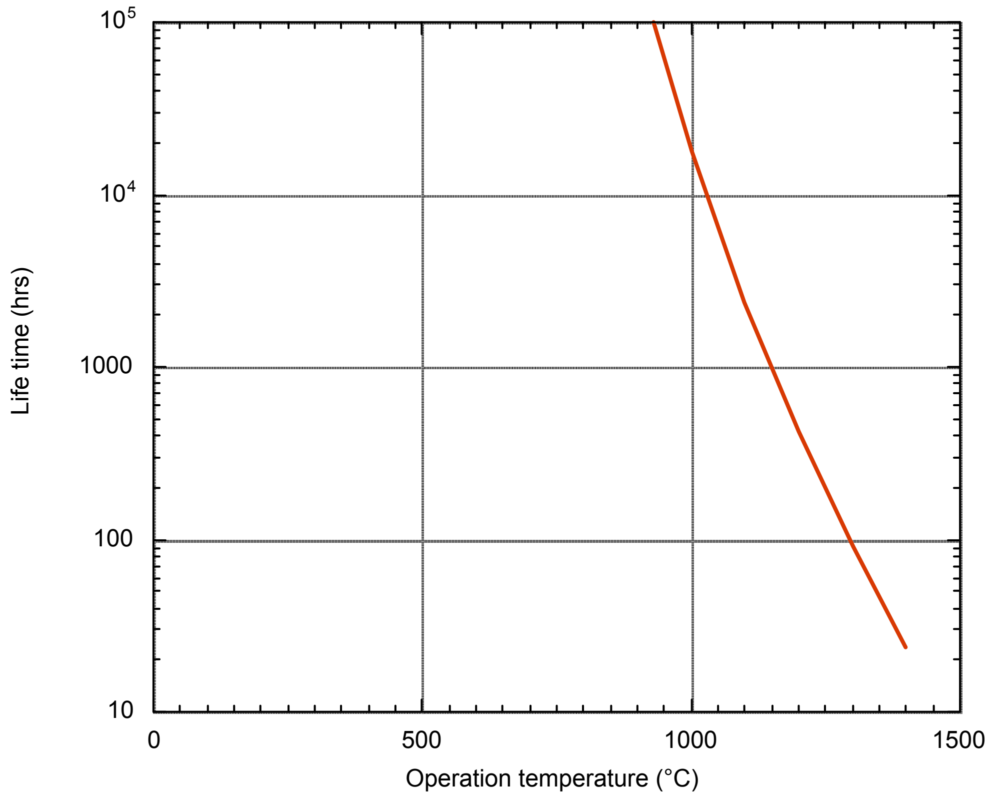


Figure 12. *Simulated data predicting the life time of the wire mesh as a function of the operation temperature, i.e. the temperature of the wire mesh.*

3.1.2.5. CFD results

The CFD modelling results illustrate very well the fuel distribution that can be expected in the burner prototype. Figure 13a shows the expected fuel distribution in the burner in the absence of a fuel distribution plate, whereas Figure 13b illustrates the expected situation in combination with a fuel distribution plate that provides for a significant pressure drop over the inlet. As seen, without a significant pressure drop, the flow of the gas will be entirely concentrated to the centre of the wire mesh catalyst, resulting in a poor burner performance with respect to both thermal efficiency and emission quality since the hot zone of the catalyst will be very limited to the centre of the wire mesh catalyst surface, especially at low powers. To avoid this phenomenon to occur, a significant pressure drop over the inlet is thus necessary to include in the burner's design.

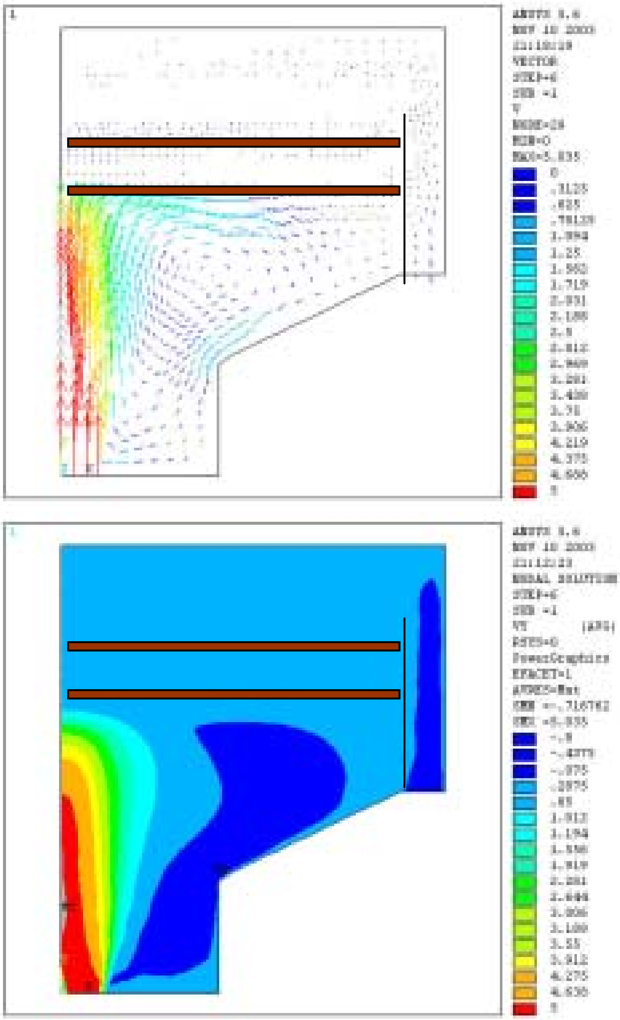
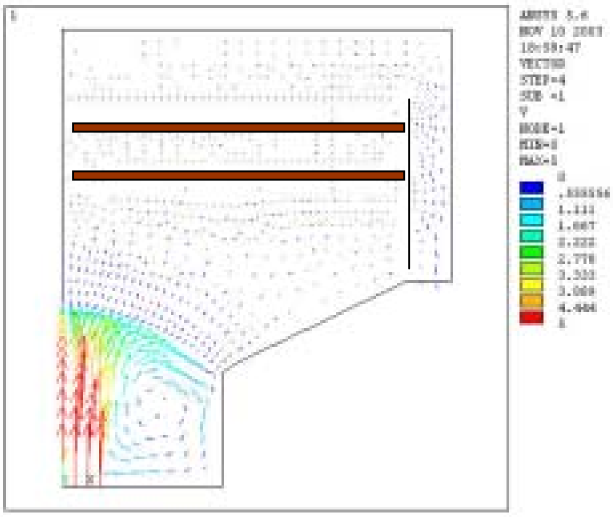


Figure 13a.



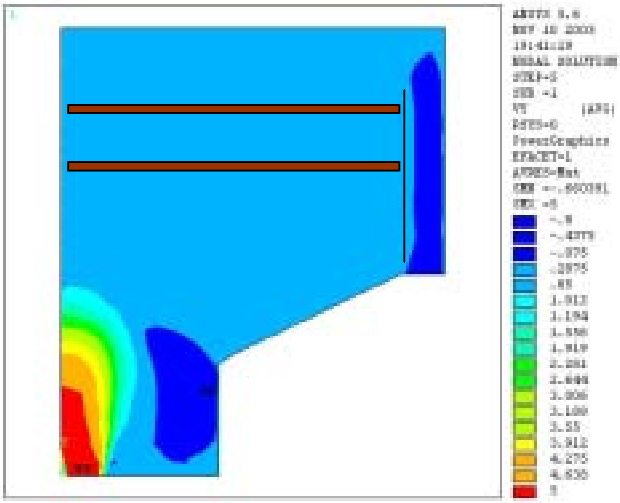


Figure 13b.

Figure 13. *Simulation of the fluid dynamics expected in the burner at 4 kW (226 kW/m^2) in the case of that a) a fuel distribution plate is not positioned in the inlet of the burner b) a fuel distribution plate is positioned in the inlet of the burner. The two brown coloured bars illustrate the wire mesh catalysts.*

3.1.2.6. Summary of the simulation results

As has been shown in the previous paragraphs, the burner's performance can be optimised by varying a couple of different operation parameters, e.g. the combustion temperature and the wire mesh number, etc. According to the simulations, it can be concluded that the thermal efficiency and the emissions of CO and UHC are favoured by

- a minimised distance between the ceramic plate and the wire mesh catalyst no. 2.
- the use of wire mesh catalysts with as high mesh number as possible.
- a minimised excess of oxygen, thus, working at as low lambda value as possible.
- a fuel distribution plate which provides for a significant pressure drop in the inlet of the burner.

Besides improving the thermal efficiency and the emission quality with respect to CO and UHC, it is important to consider the fact that the above listed actions may also lead to effects such as increased pressure drop, higher concentrations of formed NO_x and a decline in life time of the wire mesh catalysts, etc. Thus, the optimisation work of this catalytic burner must include, as is very commonly the case, some compromises between several aspects.

4. Experimental part (CAT)

4. 1. Experimental set-up

Figures 14a and b show photos of a planar and a "two-way folded" wire mesh catalyst (diameter=150 mm), respectively, that have been evaluated in this burner concept. The support material of the catalyst is a woven wire mesh, made of a high temperature resistant iron alloy (Kanthal AF).

To increase the surface area and the adhesiveness of the substrate, a porous layer of metal was deposited onto the material according to Catator's patented technology. The substrate was then wash-coated with a ceramic layer (50/50 wt% ceria/γ-alumina), about 150-200 g/m^2. Finally, the wire-mesh was impregnated with palladium, which acts as the active substance of the catalyst.

Figure 14a.

Figure 14b.

Figures 14a and b. *Photos of wire mesh catalyst used in the burner. a) A photo of a planar 35 wire mesh catalyst b) A photo a folded 35 wire mesh catalyst. The black paste put on the outer side of the catalyst is the high-temperature sealing paste "Firestop". It should be noted that the black coloured paste turns yellow when the catalyst/the burner has been heated/used.*

As is illustrated in Figure 7, CAT´s burner includes two wire meshes, with a distance of 5 mm in between. Different combinations of wire mesh numbers (16, 25, 35) were tested and evaluated with respect to thermal efficiency, emissions and pressure drop over the system. Planar wire mesh catalysts were also compared to folded wire mesh catalysts (two-ways folded wire meshes of mesh no. 35, settings for folding preparation: height=5 mm, angle= 90°). Furthermore, to improve the fuel distribution over the whole catalysts' surfaces, and thereby to optimise the performance of the burner, a fuel distribution plate was placed in the inlet of the burner, see paragraph 3.1.2.5. In order to further improve the emission quality of the exhaust gas, emission catalysts were positioned in the outlet, see Figure 7. The emission catalysts also improve, especially at slow cooking, the efficiency of the primary combustion inside the burner, since they recuperate, by radiation, somewhat the heat back to the burner chassi. The emission catalysts were the same type of catalysts as the earlier described primary burner catalysts, except for that the active substance was platinum instead of palladium. Finally, the ceramic glass plate used was an iR-transparent and heat resistant ceramic material (trade name: Neocerum-0, tolerates continuous temperatures up to about 740°C), which is a commonly used material in wood stoves and gas fire applications. The thickness of the ceramic plate was 4 mm.

To minimise the leakage of unburned fuel gas through the outer sides of the wire mesh catalysts (which normally are of significantly less temperature than the rest of the surface), it is of most importance to seal the wire meshes well in theirs positions as well as possible. In this case, the wire meshes were held in fixed positions by placing O-rings of high resistant steel between the two primary wire meshes and another one on the upper side of the wire mesh no.2. The leakage of unburned fuel gas was further minimised by putting a thin layer of high temperature resistant sealing paste called Sika Firestop (for more information, see www.sika.se), see Figure 14b, in combination with a thin layer of ceramic material around the outer side of the wire meshes. It should be noted that as a consequence of the usage of the O-ring and the sealings, the diameter of the wire mesh surface exposed to the fuel-air mixture was decreased from 150 mm to 130 mm. Thus, the geometric surface area used for the calculation of the surface power load is 0.013 m^2.

The fuel/air mixture was controlled by mass flow controllers. Compressed air and natural gas were used throughout all measurements. The composition of the fuel is given in Table 3. For calculating the input power corresponding to each fed flow rate, the low heating value (LHV) of the natural gas was used, i.e. 11.1 kWh/Nm^3.

Table 3. *Composition of the natural gas used in the series of experiments.*

METHANE	88.16 %
ETHANE	6.49 %
PROPANE	2.70 %
n-BUTANE	0.57 %
i-BUTANE	0.41 %
n-PENTANE	0.09 %
i-PENTANE	0.11 %
HEXANE	0.05 %
NITROGEN	0.32 %
CARBONDIOXIDE	1.10 %

Analysis of emissions was performed, in the outlet at different position points, throughout operation of the burner, and the source strength (mg/kWh), considering correction for dilution, of emissions was calculated. NO_x ($NO+NO_2$, where about 90-100 % of the NO_x was in the form of NO), CO and O_2 were measured with an electrochemical device, whereas unburned hydrocarbons (UHC) were analysed with a Flame Ionisation Detector (FID), giving the concentration of UHC in propane equivalents.

The thermal efficiency was estimated from tests with water heating. 1 kg of water was heated from room temperature (approximately 20°C) to 100 °C with a thermocouple inserted into the water. The efficiency was in this case measured in hot conditions, i.e. hot start (see definition on p.3). The pan used for the water heating measurements was made of stainless steel 18/10 and had the same diameter (170 mm) as the diameter of the ceramic glass plate. It should be noted that in contrast to equivalent experiments performed at GdF, the thermal efficiency was herein estimated using a pan covered with a lid, thus, all the heat transported to the pan was assumed to be used to the water heating.

The pressure drop was measured, under operation and thus, in hot condition, by the use of a differential pressure meter. The position of the differential pressure meter is shown in Figure 7.

4.2. Experimental results

4.2.1. The influence of power input

In order to investigate the overall performance and the turn-down ratio of CAT´s burner, the performance with respect to the thermal efficiency, the emissions and the pressure drop were measured as a function of the power input. Figures 15a-b show photos of the burner under operation at loadings equal to approximately 1, 2 and 4 kW (80, 150 and 300 kW/m^2), respectively, and typical related performance data are presented in Table 4. It can be concluded that

- the thermal efficiency of the burner is very good at all loadings applied, i.e. about 45-55 % and 67-76 % at 4 kW (300 kW/m^2) and 0.6 kW (45 kW/m^2), respectively. The thermal efficiency is thus increasing with a decreasing power input, which is in agreement with the simulated predictions, see paragraph 3.1.2.1.
- the NO_x emissions are extremely low, approximately 1-3 mg NO /kWh.
- the CO emissions are acceptable, around 0-10 mg CO/kWh
- the UHC emissions (0-25 mg CH_4/kWh) are acceptable at loadings > 1 kW (80 kW/m^2).
- the UHC emissions are high at loadings ≤ 1 kW (80 kW/m^2). The large emission range given in Table 4 can probably be somewhat explained by some leakage of unburned fuel gas due to an insufficient sealing of the outer-side of the wire meshes.

It should be noted that the data displayed in Table 4 correspond to the analysed performance at steady-state. The burner was ignited with a blue flame at 4 kW, and thereafter, after that the steady-state conditions had been reached and that the measurements analysis had been made, the loading was decreased step-wise down to 0.6 kW. Moreover, the measured pressure drop values given in Table 4 are the sums of the pressure drops related to the fuel distribution plate (in the order of 80-90 Pa at 4 kW), the two wire meshes and the outlet of the burner, respectively.

The time to reach steady-state condition was seen to depend on the power input. For example, the time to reach steady-state at 4 kW after starting-up from a cold burner was found to be approximately 30-45 seconds, whereas at 2 kW, the starting-up time was closer to 60-80 seconds. During the start-up, the thermal efficiency of the burner is somewhat lower and the NO concentration in the exhausts may be higher than at steady-state (in the range of 5-15 mg/kWh NO). These effects are attributed to the fact that it takes some time to heat up the whole catalyst surface and consequently, some time to go from pure blue flame combustion (which produces significantly more NO) to hybrid or pure catalytic combustion mode.

Figure 15a.

Figure 15b.

Figure 15c.

Figure 15. *Photo of the burner prototype operating at a) 1 kW (80 kW/m^2) b) 2 kW (150 kW/m^2) c) 4 kW (300 kW/m^2). The photos are showing the burner in operation when planar wire mesh catalysts are used.*

Table 4. *Performance data obtained at steady-state with planar wire mesh catalysts under the following conditions: lambda=1.2-1.3, wm. no. (of wm1 and 2): 35, distance wm1-wm2=5 mm, distance wm2-ceramic plate≈15 mm. For reasons of simplicity, UHC is assumed to consist of pure CH_4. The surface load was calculated by dividing the total input power with the geometrical surface area of one single wire mesh catalyst. The thermal efficiency was measured by water heating using a pan covered with a lid.*

Input power (kW)/ (kW/m^2)	4.0/ 301	3.5/ 263	2.2/ 166	1.1/ 83	0.6/ 45
Thermal efficiency (%)	45-55	50-56	55-61	65-75	67-76
Pressure drop (Pa)	180	-	60	20	5
NO (mg/kWh)	1-3	1-3	1-3	1-3	1-3
CO (mg/kWh)	0-5	0-5	0-10	5-10	5-10
UHC (mg CH_4/kWh)	0-25	0-25	0-25	100-2000	100-2000

4.2.2. The influence of the wire mesh number

Different combinations of wire meshes of various mesh numbers (mesh numbers tested: 16, 25 and 35) were evaluated in the prototype burner. The general trend found was, even though the difference in result was very small between the combinations 35+25 wire mesh and 35+35 wire mesh, that the higher the mesh number, the better the performance obtained.

This result is also in line with the theoretical predictions, see paragraph 3.1.2.2. The most significant difference in results between the different combinations was the variations in the analysed UHC concentration in the exhaust gas. For example, in the case of using two catalysts of wire mesh number 16, the UHC emissions were seen to increase with as much as 10-100 times, depending on the loading. The reason for this result is most probably twofold:

1) the lower the mesh number, the poorer the fuel distribution becomes as a consequence of a decline in pressure drop over the wire mesh. The fact that the pressure drop of the wire mesh was found to play such a significant role indicates in turn that the fuel distribution caused by solely the existing fuel distribution plate is not yet fully optimised in this burner prototype.
2) the lower the mesh number, the lower the temperature of the wire mesh as a consequence of less amount of active surface area exposed to the fuel-gas mixture.

4.2.3. Folded wire mesh vs. planar wire mesh

Evaluation tests of the burner were also conducted in combination with folded wire mesh catalysts. Thanks to the folded structure, this type of wire mesh provides in general for several advantages compared to the equivalent planar wire mesh catalyst. First, the surface area is estimated to be about 30 % larger. A larger surface area implies a larger amount of active catalytic material exposed to the fuel-air mixture, which may in turn leads to reduced emission levels. Second, the folded structure increases the formability, so also the mechanical stability of the wire mesh catalyst.

The results obtained with folded wire mesh catalysts are displayed in Table 5. As expected, it can be concluded that the CO and UHC emissions are somewhat reduced compared to the results obtained with the planar catalysts (see Table 4).

***Table 5**. Performance data obtained at steady-state with two-way folded wire mesh catalysts (mesh no. 1 and 2: 35) at lambda=1.2, distance wm1-wm2=5 mm, distance wm2-ceramic plate≈15 mm. For reasons of simplicity, UHC is assumed to consist of pure CH_4. The surface load is calculated by dividing the total input power with the geometrical surface area of one single wire mesh catalyst, without considering the actual surface area increase caused by the folded structure. The thermal efficiency is measured by water heating using a pan covered with a lid. * u.d.-undetectable concentrations*

Input power (kW)/ (kW/m^2)	4.0/ 301	2.2/ 166	1.1/ 83	0.6/ 45
Thermal efficiency (%)	45	55	64	66
Pressure drop (Pa)	200	70	15	8
NO (mg/kWh)	1-3	1-3	1-3	1-3
CO (mg/kWh)	u.d.*	u.d.*	u.d.*	u.d.*
UHC (mg/kWh)	u.d.*	0-50	50-300	100-500

4.2.4. The influence of the distance between the wire mesh catalyst no. 2 and the ceramic plate

To verify the simulated predictions of the impact of the distance between the ceramic plate and the wire mesh catalyst no. 2 (paragraph 3.1.2.3.), the performance of the burner was evaluated at 2.2 kW with this distance equal to about 15 and 26 mm, respectively. The results are summarised in Table 6.

Table 6. *Performance data measured steady-state at loading 2.2 kW (166 kW/m^2) under the following conditions: lambda≈1.25, wm. no.1: 35, wm no.2:25, distance wm1-wm2=5 mm. The thermal efficiency was measured by water heating using a pan covered with a lid.*

	Distance=15 mm	Distance=26 mm
Thermal efficiency (%)	61	53
Pressure drop (Pa)	51	42
NO (mg/kWh)	1-2	1-2
CO (mg/kWh)	10	20
UHC (mg CH_4/kWh)	0-50	0-50

As seen, the results point to that the thermal efficiency can indeed be significantly improved by positioning the ceramic plate closer to the wire mesh catalyst, with the expense of a somewhat higher pressure drop over the burner system. With the attempt to optimise the efficiency even further, a measurement was also performed by placing the ceramic plate as close as 4-5 mm from the wire mesh catalyst. The combustion was in this case found to be much poorer than what have been observed previously with respect to both the start-up response and the emission quality. It seems thus as the optimal distance for this system is somewhere in between 15 and 5 mm.

4.2.5 The influence of the lambda value

The impact of the lambda value was tested by comparing the performance of the burner at 2 kW for lambda equal to 1.15-1.20 and 1.40-1.45, respectively. The results indicated that the thermal efficiency can be increased by almost 10 % by decreasing the lambda value from ~1.4 to 1.2. This is in good agreement with what is expected according to the theoretical results, see paragraph 2.2.4. Except for the advantage of obtaining a higher efficiency, the emissions and the pressure drop over the system were also seen to somewhat decrease. One drawback of operating at a lambda value close to one (=stoichiometric conditions) is however that the life time of the catalyst might be affected due to fact that the operation temperature of the wire mesh is significantly increasing with a decreasing lambda value.

4.2.6. Results obtained with CAT´s burner prototype at GdF

According to the activity plan (summarised in ch. 1), the burner prototype developed and evaluated at CAT was as a last step in this project delivered to GdF for some series of verification tests. The burner was tested as received. All the measurements performed at GdF were conducted having two 35 two-way folded wire mesh catalysts (wm1+wm2) installed in the burner. Similar to the tests run at CAT, compressed air was used for the air supply, but instead of having natural gas as fuel, pure methane was used.

The flow rates were controlled by mass flow controllers. The performance of the burner was investigated for the power input range 0.6-4 kW (corresponding to 45-300 kW/m^2). In similar to the evaluations run at CAT, the emissions (CO, NO_x, CH_4, CO_2 and O_2) were measured during the tests from the time of ignition of the burner until stable steady-state values were obtained. The NO_x concentration was analyzed by chemiluminescence, whereas CO, CH_4, and O_2 were measured by IR. Corrections for dilution have been applied to the measured concentration values, which are herein expressed as mg/kWh. Furthermore, the thermal efficiency was measured according to the standard procedure explained under paragraph 2.2.1, thus no lid was covering the pan during the water heating. To enable a correct comparison to the thermal yields estimated at CAT, measurements were for some power inputs also conducted using a pan covered with a lid. In all experiments, the pan used was, in similar to the equivalent tests run at CAT, made of stainless steel and its diameter was equal to 170 mm. Figure 16 shows a photo of the testing area for CAT´s burner at the facilities of GdF´s Research Department.

Figure16. *Photo of the burner set-up for testing CAT´s burner prototype at GdF´s facilities.*

Table 7 recapitulates the results obtained at GdF at the different power inputs. To facilitate a comparison to equivalent data obtained at CAT, data from Table 5 have been copied and also inserted into this table. It should be noted that an appropriate comparison of the thermal yield can only be made for 2,2 kW, since it is only at this load that the measurement has been done with a lid put on the saucepan. However, in order to point out the actual heat lost when no lid is used, the results obtained at the other loads are also given. The thermal yields measured at CAT were all obtained at hot conditions.

Table 7. *Performance data obtained at steady-state with two-way folded wire mesh catalysts (mesh no. 1 and 2: 35) at lambda=1.2 with CAT's burner at GdF's facilities. The surface load was calculated by dividing the total input power with the geometrical surface area of one single wire mesh catalyst, without considering the actual surface area increase caused by the folded structure. The values given within the parenthesis are copied values from Table 5, thus, values measured at CAT with the same burner set-up. To be noted that the thermal efficiencies estimated at CAT were all obtained at hot conditions. u.d.=undetectable values*

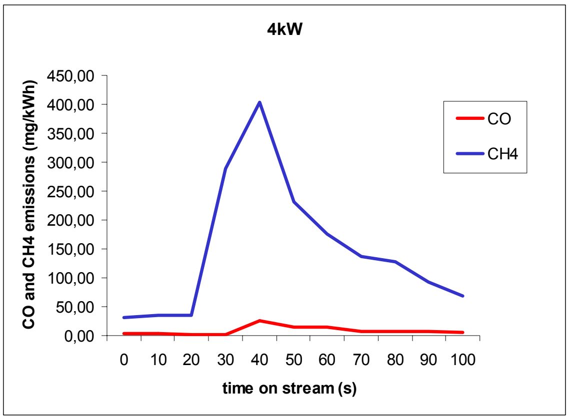
Input power (kW)/(kW/m^2)	4/301	2.2/166	2.2/166 (lid)	1.1/83	0.8/60
Thermal efficiency (cold/hot) (%)	26/38 (45)	27/48 (55)	36/56 (55)	32/45 (64)	35/42
NO_x (mg/kWh)	1 (1-3)	1.5 (1-3)	1.5 (1-3)	1.5 (1-3)	1.5
CO (mg/kWh)	u.d. (u.d.)	7 (u.d.)	7 (u.d.)	15 (u.d.)	3
CH_4 (mg/kWh)	u.d. (u.d.)	60 (0-50)	60 (0-50)	2500 (50-300)	2000

As can be seen in Table 7, no data is given for the lowest load applied, i.e. 0.6 kW (45 kW/m^2). The reason for this is that, which is in contrast to what was achieved at CAT (see Table 4 and 5), no stable combustion conditions could be reached at this power input. This difference in result could probably be explained by the fact that pure methane was hereby used as fuel instead of natural gas, where the latter has a lower adiabatic flame temperature than pure CH_4 and thereby a lower ignition temperature due to that the gas mixture also contains significant amounts of heavier hydrocarbons (see composition of natural gas given in Table 3).

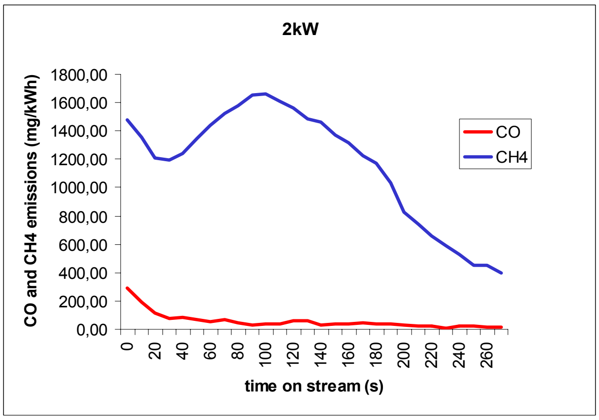
As far as the thermal efficiencies are concerned, the lowest value is, as expected (see paragraph 3.1.2.1.) found for the highest power input (4 kW). However, in contrast to what was established at CAT, the maximum value measured at GdF is not obtained at the lowest power input, but at moderate loads (2 kW). This unexpected trend might in this case be explained by the fact that the combustion becomes poorer the lower the flow rate, causing high emissions of CH_4 and thereby low thermal yields. Finally, as expected, the enhancement in thermal yield is very large when a lid is placed on the saucepan, i.e. from 48 to 56 % at 2.2 kW (an increase of more than 15 %). This increase is of course attributed to the significant decline in thermal loss from the heated water.

For the pollutant concentrations in stabilized regime (after at least 15 minutes after ignition of the burner), NO_x and CO values were found to be extremely low for all loads tested. On the contrary, unburned CH_4, which was undetectable for 4 kW, was present at moderate concentration at medium power and its value rises quickly to reach more than 2000 mg/kWh at the lowest power inputs. The CH_4 concentration in the fumes is, as discussed in ch. 3, closely related to the level of temperature on the burner, and especially at the exit where the emission catalyst is located (see Figure 7). At low power, the energy released from the combustion is low and the main catalyst not hot enough to succeed in burning all the methane. In addition, the flow rate of combustion products is too small to sufficiently heat up the emission catalyst for unburned CH_4 oxidation (which occurs significantly at T > 300°C). A solution to solve this problem (which also, as mentioned above, lowers the thermal yield) is by no way trivial but could partially comes from a better arrangement (see the suggestions for future modifications given in ch. 6) and higher quantity of the emission catalyst.

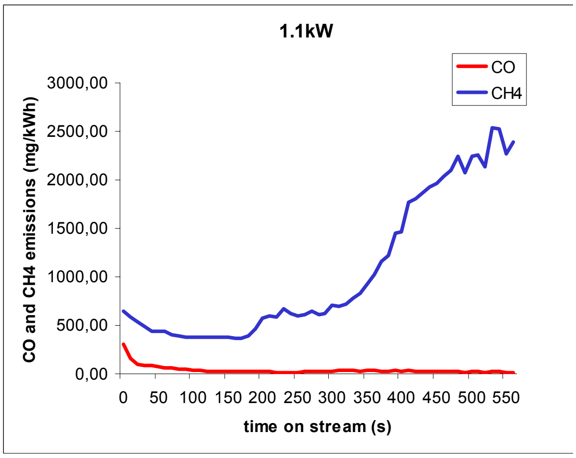
To investigate the transient behavior of the burner, emission plots showing the evolution of CO and CH_4 concentrations, respectively, as a function of time, where t=0 corresponds to the ignition of the burner, are displayed in Figure 17. The graphs show data collected until near steady-state or steady-state conditions have been achieved.



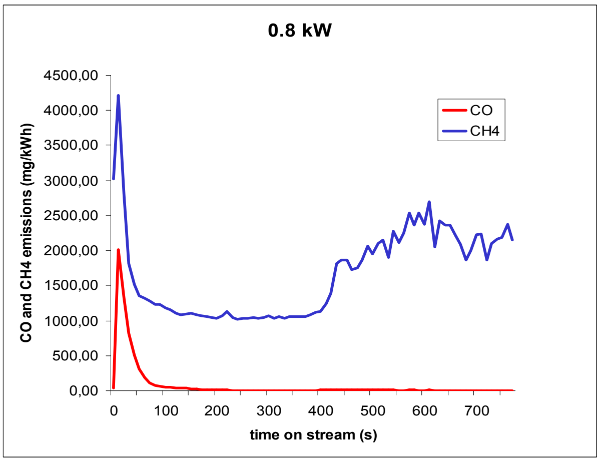
4 kW– ignition emissions profile



2.2 kW – ignition emissions profile



1.1 kW - ignition emissions profile



0.8 kW - ignition emissions profile

Figure 17. *Evolution of CO and CH_4 concentrations, respectively, plotted as a function of time. t= 0 corresponds to the time of ignition.*

At full power (4 kW), a short peak of the CH_4 emission appears 20 seconds after the ignition of the burner (i.e. during the transition from flame to catalytic combustion). This peak was however seen to more or less disappear within about 2 minutes, for thereafter reaching stabilized steady-state combustion conditions (at t≥15 minutes, CH_4 levels were undetectable). Further, the CO concentration was close to constant with time at this power input, with a source strength that did not rise above 25 mg/kWh. Moreover, at medium power (2 kW), the CO emissions were found to be less than 50 mg/kWh at t >1 minute. At the same load, the level of unburned methane was found to be as high as >1000 mg/kWh during the first 2-3 minutes after ignition, followed by a continuous decline towards the steady-state value of approximately 60 mg/kWh. At 1.1 kW, the CO concentration profile was found to be close to similar to what was observed at 2 kW.

On the contrary, the methane concentration was seen to rapidly increase at t>5-6 minutes for thereafter reaching a steady-state value of about 2500 mg/kWh. Finally, the emission data collected at 0.8 kW shows quite a similar behavior as for 1.1 kW, except for a sharp peak for both CO and CH_4 at around t=20 seconds, which is followed by a rapidly decreasing CO concentration ending up at a low stabilized steady-state value, but at a high steady-state CH_4 level (2000 mg/kWh).

5. Conclusions

Evaluation tests performed at Gas de France (GdF) prior to the start of this project have shown that wire mesh catalysts, prepared and delivered by Catator (CAT), seem to be very well suited for catalytic combustion of natural gas in gas cooking plates. Compared to monolith catalysts, the wire mesh catalysts were found to result in very low emissions (<5 mg CO/kWh, <10 mg NO_x/kWh) and in a long operation life-time (> 8000 h *vs.* <700 h). However, the thermal efficiency was measured to be significantly lower for the wire mesh catalyst than for the monolith (15 *vs.* 32 %). It was believed that this observed weakness of the wire mesh could be overcome by re-designing the burner construction of the cooking plate. Design work, construction and evaluations of new burner systems were therefore performed, partly at CAT and partly at GdF, and the main conclusions of the work are summarised below.

To enhance the thermal efficiency, GdF designed and constructed a new burner concept (based on CAT´s wire mesh catalyst), which, compared to their original one, has a reversed flue gas direction (from the bottom to the top instead of the reversed) and also, a re-emitter, consisted of SiC foam, installed as an emission catalyst. It was established that

- the thermal efficiency could be increased from 15 to 39 % (@200 kW/m^2) by changing the flue gas direction.

- the influence of the SiC foam on the thermal yield of the burner is more or less insignificant, and consequently, that there seems to be no point in using this material for a catalytic cooking plate.

In parallel, CAT designed, constructed and evaluated a new catalytic burner prototype, also based on the wire mesh catalyst. The burner design was evaluated (initially at CAT, and also, as a final step, at GdF) with respect to key factors such as thermal efficiency, emission quality and pressure drop, etc, by the use of theoretical simulations and experimental tests. Measurements were conducted for different loadings at several lambda values and different critical distances between the ceramic plate and the upper wire mesh catalyst. The performance was investigated for both planar and folded wire mesh catalysts of various mesh numbers. Both steady-state and transient behaviour were studied.

It was concluded that this catalytic burner

- provides for a relatively high thermal efficiency over a broad power input range, i.e. 40-50 % for 60-300 kW/m^2.
- results in extremely low NO_x emissions, 1-3 mg NO /kWh (to be compared with a blue flame burner: ~100 mg NO_x /kWh).
- results in acceptable CO emissions, 0-15 mg CO/kWh.
- gives high emissions of UHC at slow cooking mode (power output < 80 kW/m^2).

It was found that the wire mesh number of the catalyst plays an important role. The higher the mesh number, the better the performance obtained. This is mostly due to the fact that the higher the mesh number, the better the fuel distribution over the wire mesh surface becomes, which in turn improves the turn-down ratio of the system. The results also showed that the emission quality could be somewhat further improved by using two-way folded instead of planar wire mesh catalysts.

The investigations showed that the lambda value has a great impact on the burner's performance. According to the experimental results, the thermal efficiency could be increased by as much as 10 % by decreasing the lambda value from 1.4 to 1.2. In addition, a decline in lambda value was seen to lead to a decline in emission concentrations of CO and UHC, respectively, as a consequence of a higher combustion temperature.

With respect to the thermal efficiency and the emissions, the experimental tests indicated that the optimal distance between the upper wire mesh catalyst and the ceramic plate is somewhere in between 15 and 5 mm.

6. Suggestions for further optimisation work

As mentioned, the herein described catalytic burner is a prototype and thus, there is still need for significant optimisation work before it reaches the status of being a commercial product. One aspect that has been identified during this work to be of major concern is the problem with the high UHC emissions at slow cooking. Suggestions for solving this problem are

- to further increase the amount of catalyst material, both the amount of primary combustion catalyst and the amount of emission catalyst.

- to find a way for controlling the available catalyst surface with the power input in order to keep catalyst loading/surface area constant over the whole working range, for example 150-200 kW/m^2.

- to use pulse modulation (the power input is controlled by for example the temperature of the ceramic plate) instead of using a constant power input. This would avoid the use of the burner at slow cooking mode for any longer operation time.

7. References

1. SGC rapport 121, Catalytic Combustion in Gas Stoves-Feasability Study, Fredrik Silversand, Catator AB, 2002
2. SGC rapport 135, Catalytic Combustion in Gas Stoves-Phase II, Anna-Karin Hjelm, Catator AB, 2003
3. EP 1225 393 A2, Y. Yamada, N. Kuyosihi, Tokyo Gas Company Ltd., 2002

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