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Development of a novel catalytic burner for natural gas combustion for gas stove and cooking plate applications

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Abstract

On the request of Gaz de France Research Department, Catator AB has designed, constructed and evaluated a catalytic burner, based on Catator's patented wire mesh catalysts, for natural gas combustion in gas stoves or cooking plates. The results have shown that burner operation results in extremely low NO_x emissions (1–3 mg NO_x/kWh), acceptable CO-levels (0–15 mg CO/kWh), relatively high thermal efficiencies over a broad range of power inputs (40–50% for 1–4 kW) and a long catalyst life-time (>10 000 h). Other advantages of this burner design are its compactness and ease of cleaning. The critical concern is the high emissions of unburned hydrocarbons measured at slow cooking mode (<1 kW), which is believed to be overcome by developing and implementing an appropriate heat-exchanger with the burner.

Keywords: Catalytic burner; Wire mesh catalyst; Natural gas; Cooking plate

1. Introduction

Gas catalytic combustion for gas stoves or cooking plates is a very promising technique in terms of ease of cleaning, power modulation and emissions [1]. Previous investigations have shown that wire mesh catalysts, prepared and supplied by Catator AB, seem to be very well suited for such applications [2,3]. In addition to significantly reduce the unhealthy NO_x-emissions [4,5], 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 (in this case a quick start-up).

This work has been a collaboration project between Catator AB and Gaz de France. Its objective was the design, the construction and the evaluation of new catalytic burner(s), based on Catator's wire mesh catalysts, used for the combustion of natural gas in gas cooking stoves. More specifically, this new burner should provide with:

1. a high thermal efficiency;
2. low emissions;
3. a long life-time (≥5000 h);
4. a power input ~4 kW with a burner size of approximately 15 cm;
5. a good turn-down ratio (~0.3–4 kW);
6. a low pressure drop;
7. an easy cleaning (flat ceramic plate);
8. a thin design, i.e. ≤10 cm.

In this work, the evaluation of different burner designs were performed by the use of theoretical simulations, using a computational fluid dynamic model (CFD) developed in ANSYS™ and a dynamic model written in Ithink™, and experimental verification tests. Since the performed experimental work was motivated and based on prevailing simulation results, we have in this paper chosen to entirely focus on the experimental results obtained with that burner concept with

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which the most promising results have so far been obtained, without going into any details of the theoretical part.

2. Experimental

The support material of the wire mesh catalysts evaluated in this work consists of a woven wire mesh made of high temperature resistant iron alloy (Kanthal AF). To increase the surface area and the adhesiveness of the substrate, a porous layer of metal was thereafter deposited onto the material according to Catator's patented thermal spray technology [6]. The substrate was then wash-coated with a ceramic layer of 50/50 wt.% ceria/γ-alumina (approximately 130–150 g/m^2), which was thereafter impregnated with 0.5 M Pd(II)-acetate ($Pd(OAc)_2$), resulting in the approximate Pd-loading of 1.4–1.7 wt.%.

A schematic drawing of the burner prototype is shown in Fig. 1. As can be seen, it included a fuel distribution plate and in most tests, two wire mesh burner catalysts where the latter were held in fixed positions by placing O-rings of high resistant steel between the meshes. For improving the emissions and to some extent also, recuperating heat from the exhausts, emission catalysts (platinum-impregnated wire mesh catalysts) were placed in the outlet. The ceramic plate of the burner was made of Neocerum-0, which is an IR-transparent and heat resistant ceramic material (tolerates up to ≈740 °C) commonly used in wood stoves and gas fire applications.

The performance of the burner prototype was evaluated by determining the thermal efficiency, the emissions and the pressure drop as a function of input power load, both at transient and at steady-state conditions. Some optimization work of the burner prototype was carried out by investigating the influence of parameters such as the number of wire meshes incorporated inside the burner, the wire mesh structure (mesh number, planar/folded structure), the critical distances inside the burner, and the operation conditions such as the fuel-to-air ratio (i.e. lambda value). Evaluation tests were carried out at both Catator AB and Gaz de France facilities, using compressed air and natural gas as fuel. The fuel–air mixture was controlled by mass flow controllers. For calculating the input power corresponding to each fed flow rate, the low heating value (LHV) of the fuel was used, which for the natural gas in this case was equal to 11.1 kWh/Nm^3.

The thermal efficiency was estimated by water heating according to a standard procedure: 1 kg of water was heated from room (approximately 20 °C) to 100 °C with a thermocouple inserted into the water, see Fig. 2a and b. The efficiency was measured in cold (i.e. for a burner ignited at room temperature) and in hot conditions (i.e. at steady-state), without having a lid on the top of the pan. The pan used for the water heating measurements was made of stainless steel 18/10 and had the same diameter (170 mm) as the ceramic glass plate.

The concentrations of NO_x, CO, unburned hydrocarbons (UHC) and O_2 in the exhaust gas were continuously measured during burner operation. The NO_x was analyzed by either an electrochemical device (Testo 350, Nordec instrument) or chemiluminescence (Ecophysics NOxMAT), CO and O_2 by IR (Siemens Ultramat 5 series and Siemens Oxymat 5 series) or an electrochemical device (Testo 350, Nordec instrument), and finally unburned hydrocarbons (UHC) by either IR (Siemens Ultramat 5 series) or a Flame Ionization Detector (FID model 3006, PALGO).

The pressure drop was measured under steady-state operation by the use of a differential pressure meter. The position of the differential pressure meter is indicated in Fig. 1.

Life-time tests of Catator's wire mesh catalysts were also performed. These measurements were, in contrast to all the other evaluation tests of this work, run in a prototype burner

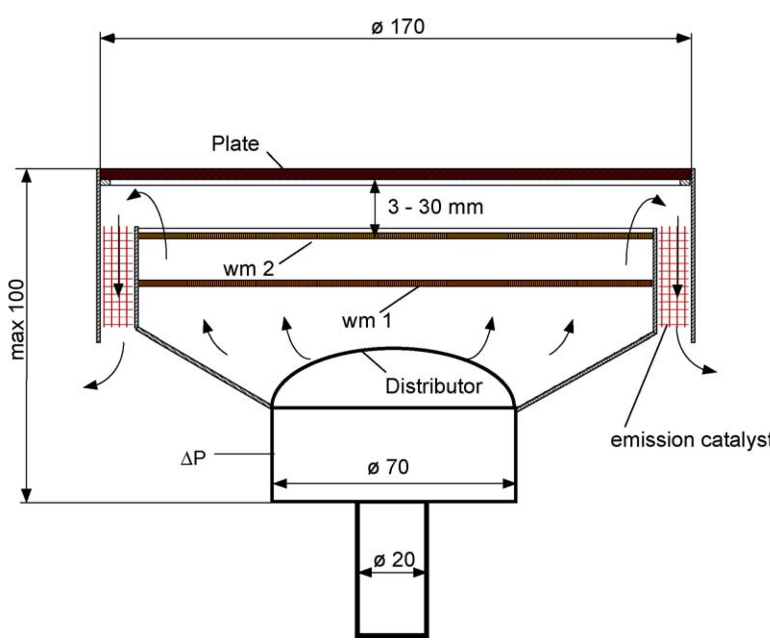

Fig. 1. A schematic illustration of the burner prototype developed for natural gas cooking plates. ΔP indicates the point at which the differential pressure meter was placed for measuring the pressure drop over the burner system under operation.

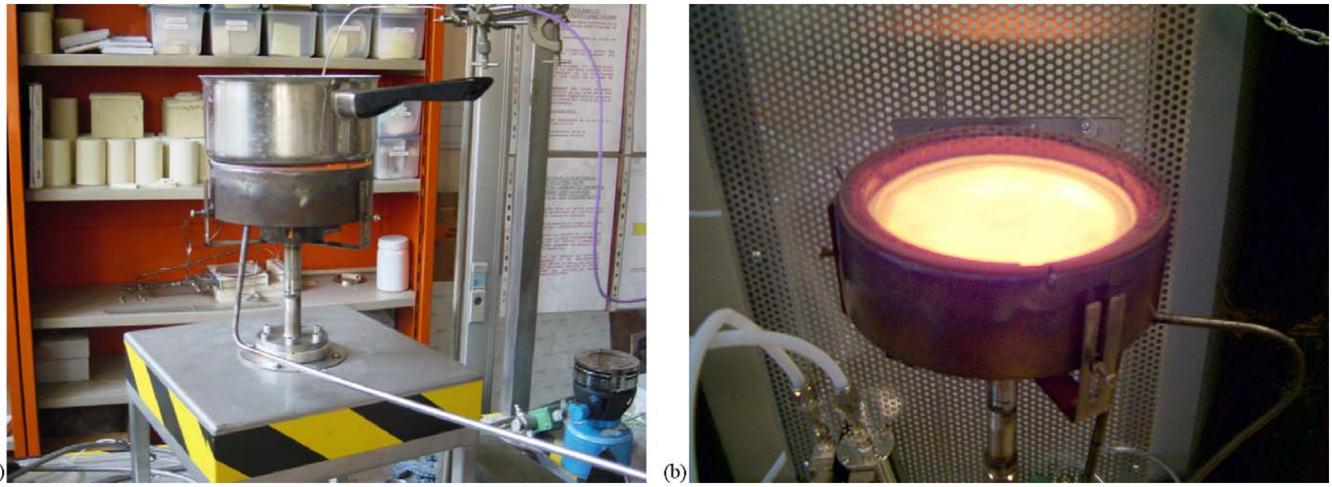

Fig. 2. (a) Photo of the experimental set-up for testing Catator's burner prototype at Gaz de France facilities. (b) Photo taken from the upper-side of Catator's catalytic burner under operation, here at 4 kW, which is corresponding to the surface load 300 kW/m^2 (estimated by dividing the power input by the geometric surface area of one single wire mesh catalyst). $\lambda = 1.2$.

originally developed, by Gaz de France, for cordierite monolith catalysts, see Fig. 3. As can be seen, this burner construction differs from the burner prototype illustrated in Fig. 1 in basically two aspects. First, it includes only one wire mesh catalyst instead of two, and secondly, the flow direction is the reversed. In spite of these design differences, the catalyst life-time results obtained in this set-up are considered to also be valid for the other burner design, since the power load and hence, the resulting catalyst surface temperature, are similar or even higher in the life-time burner.

3. Results and discussion

3.1. Performance tests at various power inputs

The burner illustrated in Fig. 1 is designed for starting up at flame combustion via an ordinary spark igniter placed above wm 2. Once the wire mesh catalysts have reached sufficiently high temperatures, i.e. 500–600 °C, the flame combustion will convert into catalytic combustion mode. The time delay before the combustion converts into catalytic and hence, before the catalysts start to radiate were found to be <20 s.

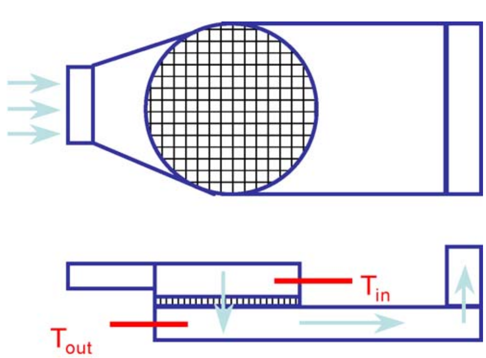

Fig. 3. A schematic illustration of the burner set-up used for life-time catalyst tests developed by Gaz de France. T_{in} and T_{out} indicate the thermocouple positions, which measured the temperature during the operation.

The burner was evaluated at different power inputs and the related results, measured at steady-state, are summarized in Table 1. As can be seen, relatively high thermal efficiencies can be obtained over a broad range of power loads (40–50%). It is believed that this value can be further increased by heat-exchanging the ingoing fuel–air mixture with the exhaust gases ($T_{exhausts} \approx 400$–650 °C depending on load) reaching at least the European standard value given for conventional blue flame cooking stoves, i.e. 52% [7]. The results also show that the thermal efficiency tend to somewhat increase with a decreasing load, most probably due to the fact that the heat loss via convection is decreasing with a decreasing gas flow rate. For comparison, the thermal efficiency was also determined for different loads with a lid placed on the top of the sauce pan. As expected, the enhancement in thermal efficiency is in this case very large (e.g. >15% at 166 kW/m^2), attributed to the significant decline in thermal loss from the heated water.

Furthermore, the NO_x-emissions (1–3 mg NO_x/kWh i.e. 0.5–2 ppm NO_x) were extremely low for all loads applied, i.e. about 100 times lower than what has been measured with conventional blue flame cooking plates [2,3], simultaneously as the CO-level was kept at an acceptable level (0–15 mg CO/kWh i.e. 0–15 ppm CO). The UHC-emissions however were only measured to be acceptable at loadings ≥80 kW/m^2, which is in turn most probably due to the low thermal inertia of the wire meshes. Different attempts for improving this mode of operation have been carried out, for example by increasing the amount of catalyst material by increasing the number of wire meshes and the mesh number of each wire mesh catalyst, by increasing the amount of emission catalyst, by insulating the external surface of the burner and finally, instead of regulating the burner with a constant (low) power input, using pulse modulation. Unfortunately, none of these efforts have resulted in any significant improvements, and will therefore not be any further discussed in this paper. The next step in this work will be to develop and to implement a suitable heat-exchanger (see text in the section above) with the burner design. The latter modification will

Table 1
Performance data measured at steady-state with the burner design illustrated in Fig. 1 ($\lambda \approx 1.2$)

Input power (kW/kWm^{-2})	4/301	2.2/166	1.1/83	0.8/60
Thermal efficiency, cold/hot (%)	26/38 (45)	27/48 (55)	32/45 (64)	35/43 (66)
Pressure drop (Pa)	200	70	15	–
NO_x (mg (kWh)$^{-1}$/ppm)	1–3/0.5–2	1–2/0.5–1	1–2/0.5–1	1–2/0.5–1
CO (mg (kWh)$^{-1}$/ppm)	u.d.	0–10/0–10	0–15/0–15	0–3/0–3
UHC (mg (kWh)$^{-1}$/ppm) C1	u.d.	0–60/0–100	900–2500/1500–4200	500–2000/800–3300

The surface load was calculated by dividing the total input power with the geometrical surface area of one single wire mesh catalyst. UHC and NO_x were assumed to consist of CH_4 and NO_2, respectively, for the estimation of mg/kWh. u.d. = undetectable values. Thermal efficiency-value given within parenthesis was measured when a lid was placed on the tope of the sauce-pan.

however be somewhat on the expense of the pressure drop and the total size of the burner.

The time to reach steady-state condition was observed to also 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 s, whereas at 2 kW, the starting-up time was closer to 60–80 s. During the start-up, the thermal efficiency of the burner is somewhat lower (see Table 1) and the NO_x and CO concentration in the exhausts may be higher than at steady-state (5–15 mg/kWh NO_x, 25–50 mg/kWh CO). 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_x) to hybrid or pure catalytic combustion mode.

3.2. Life-time tests

Life-time tests have, until the time of writing this paper, been running at 200 kW/m^2 for approximately 10 000 h and at 300 kW/m^2 for almost 7000 h, see Fig. 4a and b. No catalyst deactivation has so far been detected. The combustion results in low and stable emissions (close to zero UHC and CO-emissions, 3–8 mg/kWh NO_x), and also, a stable ignition time delay, i.e. <20 s, before the catalyst starts to radiate. The inlet and outlet temperature (see indications given in Fig. 3) were measured to be around 300–400 and 800–1000 °C, respectively. For comparison, life-time tests were, in the same burner set-up, also run with cordierite monolith catalysts (Pt/YSZ), which life-time was found to be significantly shorter, i.e. <700 h at 200 kW/m^2.

4. Conclusions

On the request of Gaz de France Research Department, Catator AB has designed, constructed and evaluated a new catalytic burner prototype, based on Catator's patented wire mesh catalysts, for natural gas combustion in gas cooking stoves. The results are very promising with respect to the catalyst life-time (>10 000 h), the NO_x (1–3 mg NO_x/kWh i.e. 0.5–2 ppm) and the CO-emissions (0–15 mg CO/kWh i.e. 0–15 ppm), respectively. In addition, a relatively high thermal efficiency could be measured over a broad range of power inputs (around 40–50% for 1–4 kW). The major concern found with the suggested prototype burner was the slow cooking mode (i.e. power output <80 kW/m^2), which, as a consequence of the low thermal inertia of the wire mesh catalysts, resulted in high emissions of unburned hydrocarbons. Different approaches for solving this problem have been investigated, e.g. by placing a ceramic crown around the burner, by studying the influence of the number and the type of wire mesh (planar or folded) installed inside the burner and by running a series of different pulse modulation tests. Unfortunately, none of these investigations have so far resulted in any significant improvements as regards the present burner's slow

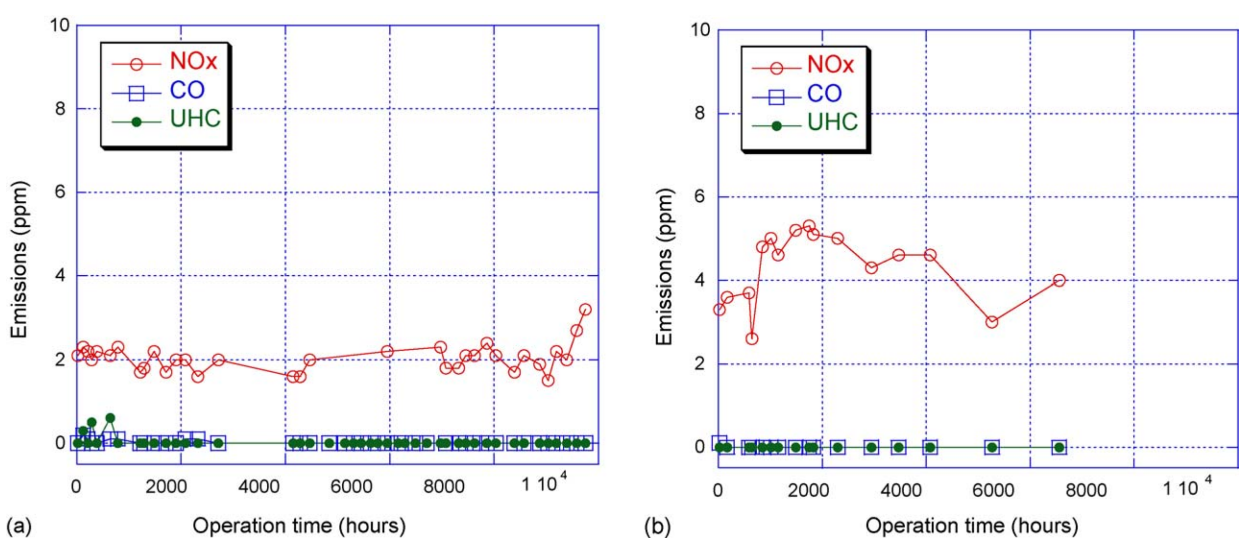

Fig. 4. (a) Life-time tests with Catator's wire mesh catalysts. Emissions measured as a function of operation time at 200 kW/m^2 natural gas combustion. λ = 1.2. (b) Life-time tests with Catator's wire mesh catalysts. Emissions measured as a function of operation time at 300 kW/m^2 natural gas combustion. λ = 1.2.

cooking characteristics. The next step in this optimization work is to increase the thermal efficiency by developing an appropriate heat exchanger to be integrated and tested with the burner. Then, the burner will be installed into a cooking top and evaluation tests will be carried out with not only natural gas but also natural gas–hydrogen mixtures as fuel.

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