HYBRID CATALYTIC BURNER FOR DOMESTIC APPLIANCES

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Introduction

Traditional partial premix cooktop gas burners, although widespread used, suffer from several problems mainly related to non-homogeneous heating of the saucepan (bad cooking performance) especially at high power, low thermal efficiency (slow cooking) by pure convective heating with impinging flames, high levels of emissions of indoor air pollutants (NO\textsubscript{x}, CO, unburned hydrocarbons, soot). Recently we have extended the concept of fuel-rich catalytic combustion originally developed for adiabatic gas turbine combustors [1], proposing a novel staged hybrid catalytic gas burner, with integrated interstage heat removal by IR radiation from the catalytic module [2-4] whose schematic representation is shown in Fig. 1.

![Figure 1. Schematic representation of the hybrid catalytic burner with catalytic partial oxidation stage + diffusive flame and interstage heat removal by radiation.](image)

The scope of the innovative technology [3] herein presented is to provide an atmospheric gas burner for domestic and industrial cooking appliances (gas stoves, cooktops, hobs, ranges, fry tops), with improved cooking performance, higher thermal efficiency with respect to the known burners, with the additional advantages of lower pollutant emissions, higher stability and safety of operation, and same simplicity of use.
Experimental
As shown in Figure 2 the prototype hybrid catalytic cooktop burner comprises a catalytic element (3), consisting of a thin porous ceramic or metallic substrate with high gas-solid contact surface, where a layer of catalytic active phase is deposited for the partial oxidation of a fuel-rich mixture (1) with primary air (normally above the upper flammability limit) fed to the burner. In particular, the catalytic element, made of a thin ceramic or metallic foam or gauze, is in the shape of a disc or thin plate, spherical or cylindrical cap. Within said catalytic element, the flow of the gaseous mixture is preferably radial (4), from the inner part through the porous structure towards the periphery.

Figure 2. Schematic drawings of the novel catalytic hybrid cooktop burner and picture of the prototype developed and operated at IRC.

The catalytic active phase, is chosen among those known in the art for the production of synthesis gas, and is able to promote the conversion of the hydrocarbon fraction of the fuel preferentially to partial oxidation products (H$_2$ and CO) rather than to total oxidation products (H$_2$O and CO$_2$). The catalytic partial oxidation reactor is specifically designed to act as a hot radiating element in order to transfer a significant fraction of the heat of the heterogeneous reaction to the heat sink [3]. A covering plate (6), made of high temperature resistant radiating material, is placed in close contact with the upper face of the catalytic element (3). Said covering plate (6) can be advantageously realized with a material that is transparent to IR radiation such as ceramic glass and quartz glass or in alternative with a material with high emissivity and thermal conductivity. The covering plate (6) has the further function to protect the catalytic element from accidental liquid spillovers from the saucepan. The catalytically partially reformed gas leaves the burner through the exit section (7), consisting of the void part of the peripheral lateral surface of the catalytic element (3). The outgoing gas flow is contacted with secondary air and is burned in a second diffusion flame combustion stage (8). Preferably, the exit section of the partially oxidized gases from the catalytic element is through a plurality of burner ports (14) on the lateral surface (7) of said catalytic element selected to restrict flame formation and control its shape.
The control of the relative role of the two stages in which the combustion is divided is efficiently achieved by means of the regulation of the equivalence ratio of the feed ($\phi$): since $O_2$ is the limiting reactant in the catalytic stage its content in the feed regulates the amount of heat generated on the catalyst and transferred to the saucepan by radiation and, by this way, the operating temperature of the catalyst itself.

**Catalyst preparation**

Catalytic elements for the hybrid burner were prepared starting from commercial foam monoliths, available in different materials, such as FeCrAlY, Mullite, SiC and cell densities ranging between 10 and 80 ppi (pores per linear inch). Due to their tortuous structure which enhance mixing, they are suitable for radial flow configurations. In particular, FeCrAlY substrates (20-60ppi, maximum operating temperature is 1200°C) from Porvair inc. were cut in the shape of thin disks, and washcoated by dipping samples in a water slurry of finely grounded $\gamma$-Al$_2$O$_3$ powder (SCFa140-L3 Sasol, 140m$^2$/g)[2]. The loading of alumina was limited to only 5% of the total weight of the foams in order to obtain a thin well anchored overlayer and avoid pore blockage. Rh was selected as the catalytic active phase for its well documented high activity and selectivity for partial oxidation and reforming of hydrocarbons [4,5]: it was deposited onto washcoated samples by the incipient wetness impregnation method using an acid aqueous solution of Rh (NO$_3$)$_3$. The actual loading of precious metal (measured by ICP-MS) was limited to 0.25 - 0.5%, w/w. with respect to the alumina layer.

**Combustion Tests**

Pure methane (>99.5%) or commercial LPG (S-odorized) and primary air were independently regulated by two MFC and mixed at atmospheric pressure in order to obtain a fuel rich feed with $\phi$ ranging from 2 to 4 (i.e. above the UFL at ambient conditions). The nominal input power was varied between 0.1 and 5kW. The catalytic burner was operated under a hood, for collecting exhaust gases and online measurement of CH$_4$, CO, CO$_2$, NO and NO$_2$ by ND-IR and ND-UV analyzers. Temperatures were recorded by thermocouples embedded in the catalyst seat and by a IR thermocamera (FLIR SC500, spectral range 7.5-12$\mu$m, Tmax 1500°C).

Efficiency tests were performed following general guidelines of the ASTM 1521-03 Standard Test Methods for Performance of Range Tops. The cooking energy efficiency ($\eta_{cook}$) is defined according to the following equations:

$$\eta_{cook} = \frac{(E_{water} + E_{pot})}{E_{input}}$$

$$E_{water} + E_{pot} = [(W_{water} \cdot C_{pwater}) + (W_{pot} \cdot C_{ppot})] \cdot (T_2 - T_1)$$

$W_{water}$ = weight of water in the sauce pot (1500 or 800g ),

$C_{pwater}$ = specific heat of water = 1.0 kcal/kg·°K,

$W_{pot}$ = weight of cooking container, (pot≈800g +lid≈190g)

$C_{ppot}$ = specific heat of cooking container, (kcal/kg·°K),
\( T_2 \) = ending temperature of the water, that is specified as 85°C (or 90 or 95 °C),
\( T_1 \) = beginning temperature of the water, that is specified as 25°C, and
\( E_{\text{input}} \) = energy consumed by the cooking unit during the test, kW

The cooking efficiency was measured by carrying out specific water heating tests at both full or half-energy input rate with respect to the nominal value for a standard auxiliary gas burner (that is 1.1 and 0.5 kW). As cooking container, 3 commercial sauce pots with matching lids of 200mm diameter were used. Two pots are made of aluminium: one of them has a Teflon plated inner side and an outer side painted with a black silicon based enamel. Their emissivity were estimated at 0.93 and below 0.1 respectively for the black coated and the polished aluminium one. A third pot was made of standard grade 18/10 stainless steel, with an estimated emissivity factor in the range 0.3-0.5.

Two commercial burners by Defendi (Series 3 “auxiliary” and “standard” device) with a maximum nominal power on natural gas of 1 and 2 kW were tested to obtain benchmark performance.

Results and discussion
Water heating curves (explained in Figure 3 for 0.5kW, CH\(_4\) feed) were recorded under standard conditions in order to evaluate the thermal efficiency of the novel burners in head to head comparison with state of the art commercial devices: with everything else being the same (nominal input power, load height, pot type, water content of the pot \([6,7]\)) a faster heating implies a larger burner efficiency due to more effective heat utilization (transfer to the pot) and a reduction in heat losses to the surroundings. From Figure 4 it can be observed that the catalytic hybrid burner outperforms both the benchmark commercial burners: the time reduction for water heating is much larger with the black coated pot (with high emissivity) than with the partially reflective stainless steel pot. Corresponding values of the calculated cooking efficiency \( \eta_{\text{cook}} \) are reported in Figure 4: the hybrid catalytic burner shows an outstanding maximum efficiency of roughly 60% when coupled with the high emissivity saucepan and operated at C/O\(_2\)=1.6 (\( \phi=3.2 \)); a further increase in efficiency can be obtained at slightly higher C/O\(_2\) ratio (1.8, \( \phi=3.6 \)).

Similar results are obtained comparing the thermal efficiencies at an higher input power (1.1kW): the catalytic burner outperforms the commercial counterparts by 5.5-15.5 points % when operated in conjunction with the high emissivity pot.

The main reason for the improved performance of the catalytic burner with respect to its standard counterpart is to be searched in the activation of a heat transfer mechanism by IR radiation from the hot uppermost surface of the catalytic element, which is minimal in the standard configuration where the cast iron top is inactive. The amount of heat transferred by radiation is determined by the surface temperature of the catalytic element and therefore it can be controlled by the value of the feed equivalence ratio: it increases with decreasing \( \phi \).
Figure 3. Comparison of water heating curves recorded for the prototype hybrid catalytic burner and a standard commercial device (Defendi, Pmax=1kW). Feed CH₄, P=0.5kW, φ=3.6 (catalytic burner). Legend: A.B. black coated aluminium pot; SS refers to stainless steel pot.

It should be noticed that IR radiation is not the only heat transfer mechanism active on the hybrid burner, for which hot gas convection still plays a major role since combustion process is completed in the free combustion zone outside the burner. Lower φ values imply shorter and colder flames. For this reason it is found that the cooking efficiency (at fixed load height=30mm) of the catalytic burner increases with increasing φ, and optimum values are reached for φ =3.2-3.8, since hotter and longer flames, directly impinging on the pot, are expected to improve convective heat transfer efficiency [6,7]. Similar considerations may help to explain the decrease in efficiency observed for the standard burner at reduced inlet power: the tips of the smaller flames obtained at half the input gas flow do not impinge directly on the pot, by this way entrapping more cold air from the surroundings and reducing the convective heat transfer efficiency [6,7].

On the other hand the catalytic gas burner has a heat transfer mechanism by radiation which is not affected by the input power, and becomes progressively more important when the gas flow rate is reduced.

An additional advantage of staging the combustion with hybrid burner is that the heat of reaction can be transferred to different parts of the saucepan, for instance to the bottom by radiation/conduction from the hot catalyst and to the peripheral part of the bottom and to the sides of the saucepan by convection. In this way the peak flame temperature is reduced because the partially converted gas mixture is characterized by a lower heating value [4]. It is hence possible to reduce the pollutant emissions of thermal NOₓ without the use of excess air or the recycle of exhaust gases and without increasing the emissions of CO and unburned hydrocarbons [4].
Figure 5. Comparison of cooking efficiency of catalytic and commercial burners (Defendi) operated on CH$_4$ at 0.5 and 1.1kW with a black coated aluminium pot. Feed to catalytic burner $\phi$=3.2 and 3.6 (C/O$_2$ = 1.6 and 1.8 respectively).

References

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