

Radiant Catalytic Cooktop Burner

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1. 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 (thermal NO_x, CO, unburned hydrocarbons, soot).

Recently we have extended the concept of fuel-rich catalytic combustion [1-2] proposing a novel staged hybrid catalytic gas burner, with integrated interstage heat removal by IR radiation from the catalytic module [3-4]. The scope of the innovative technology herein presented [4] is to provide a 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 concurrent advantages of lower pollutant emissions, higher stability and safety under operation, and same simplicity of use.

2. Description of the catalytic burner

As shown in Figure 1 the 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 (Figure 2) 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.



Fig. 1 Schematic drawings of the novel catalytic hybrid cooktop burner and images of the prototype developed and operated at IRC. The InfraRed picture shows the high temperature radiating cap of the burner.

The catalytic active phase, is chosen among those known in the art for the reaction and the process of production of synthesis gas by catalytic partial oxidation of hydrocarbons, 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_2O and CO_2).

The catalytic partial oxidation reactor is specifically designed to act as a hot radiating element (Fig. 1) in order to transfer a significant fraction of the heat of the heterogeneous reaction to the heat sink [3-4]. 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. In a further design option the catalytic element itself is characterized by a continuous top surface impermeable to gas flow and directly transmitting heat by IR radiation and eventually conduction to the saucepan without interposition of any covering plate.

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 (ϕ): 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.

An additional advantage of staging the combustion consists in the reduction of the adiabatic flame temperature of a fuel. In fact, due to the transfer to the saucepan by means of infrared emission and/or thermal conduction by the same catalytic element of a fraction of the heat of reaction produced on the catalyst, the partially converted gas mixture is characterized by a lower heating value. It is hence possible to reduce the pollutant emissions of thermal NO_x without the use of excess air or the recycle of exhaust gases and without increasing the emissions of CO and unburned hydrocarbons.

The hybrid cooktop burner can be used also with fuels, such as pure hydrogen or in mixtures, characterized by extremely high adiabatic temperatures and hence leading to the formation of large amounts of NO_x when burned in traditional flame-diffusion burner, since for safety reasons of operation cannot be burned in pre-mixed devices.

3. Experimental

3.1. 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 $1200^\circ C$) from Porvair inc. were cut in the shape of thin disks (Figure 2), and washcoated by dipping samples in a water slurry of

finely grounded $\gamma\text{-Al}_2\text{O}_3$ powder (type SCFa140-L3 from Sasol, $140\text{m}^2/\text{g}$), diluted nitric acid solution and pseudoboehmite (Disperal, Sasol) [5]. The amount of alumina washcoat loading 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 (Fig. 2).

Rh was selected as the catalytic active phase for its well documented high activity and selectivity for partial oxidation and reforming of hydrocarbons [6]: it was deposited onto washcoated samples by the incipient wetness impregnation method using an acid aqueous solution of Rh $(\text{NO}_3)_3$ (Aldrich). The actual loading of precious metal (measured by ICP-MS after MW-assisted digestion in $\text{HNO}_3\text{-HCl}$ solution) was limited to 0.25 - 0.5%, w./w. with respect to the applied alumina washcoat layer.

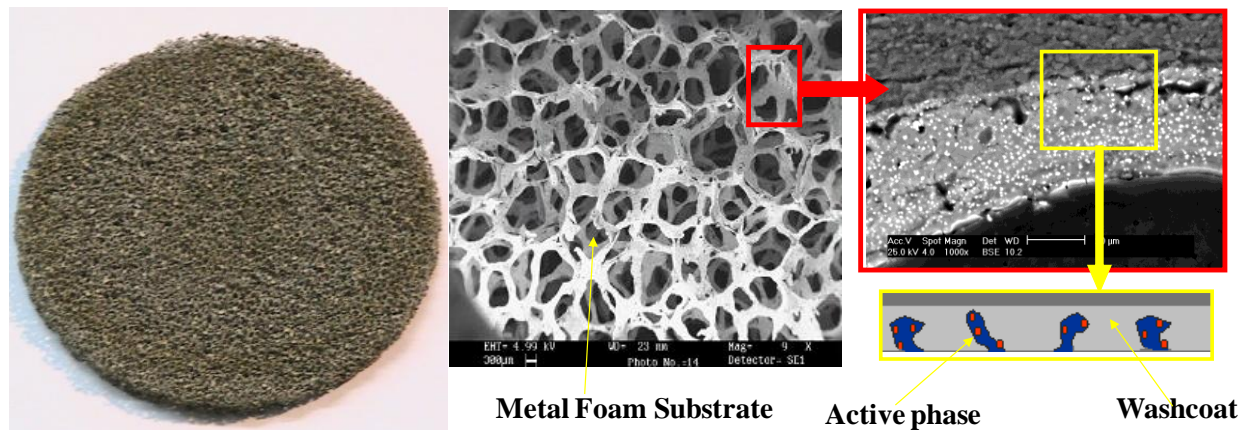


Fig. 2 Structured catalytic reactors for the hybrid cooktop burner obtained by deposition of active phase within the washcoat layer (alumina) covering a metal (FeCrAlY) foam substrate cut in the form of thin disks.

3.2. Combustion Tests

Pure methane (>99.5%) or commercial LPG (S-odorized) and primary air were independently regulated by two mass flow controllers and mixed at roughly atmospheric pressure in order to obtain a fuel rich feed with equivalence ratio ϕ ranging from 2 to 4 (i.e. above the upper flammability limit $\phi_{\text{UFL}}=1.69$ at ambient conditions). The nominal input power was varied between 0.1 and 10 kW. 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. Emissions of CO , NO_x and CH_4 are normalized to air-free conditions (AF) dividing the measured values by the correction factor given by the ratio of measured CO_2 concentration to that corresponding to stoichiometric combustion of methane in air.

Temperatures of the burners were recorded by thermocouples embedded in the catalyst seat and by a IR thermocamera for the measurement of the temperature of the irradiating hot catalyst surface (FLIR ThermoCAM SC500, spectral range $7.5\text{-}12\mu\text{m}$, $T_{\text{max}} 1500^\circ\text{C}$).

The experimental setup was also equipped for the efficiency measurements as prescribed by the *ASTM 1521-03 Standard Test Methods for Performance of Range Tops* which was used as a general guideline for the test performed. The cooking energy efficiency (η_{cook}) is defined according to the following equation:

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

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

where:

W_{water} = weight of water in the sauce pot, that is specified as 1500 or 800 g of water,

Cp_{water} = specific heat of water = 1.0 kcal/kg·°K,

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

Cp_{pot} = specific heat of cooking container, specified as either: aluminium = 0.22 kcal/kg·°K, or steel = 0.11 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_{input} = energy consumed by the cooking unit during the test, kW, including any electric energy consumed by a gas range top.

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. The emissivity of the outer side of the black coated aluminium pot was estimated at 0.93 and this value was used for estimation of temperature profiles with the IR-thermocamera; for polished aluminium pot the emissivity was below 0.1. The third pot is 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 burners) with a maximum nominal power on natural gas of 1 and 2 kW were tested to obtain benchmark performances.

3. Results and discussion

Water heating curves (not shown) 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 [7,8]) 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.

In Figure 3 it can be observed that the catalytic hybrid burner constantly outperforms both the benchmark commercial burners: the efficiency improvement is much larger with black coated pot (with high emissivity) than with the partially reflective Stainless Steel pot with a difference larger than 8 points %. The 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 figures are obtained comparing the thermal efficiencies at an higher input power (1.1kW): the catalytic burner outperforms the standard counterparts by 5.5-15.5 points % when operated in conjunction with the high emissivity pot. In this case the catalytic burner shows a smaller decrease in the efficiency, since for a fixed operating temperature and geometry (i.e. a fixed radiating surface), the radiative heat transferred from the burner cap to the pot is reduced with respect to the total input power.

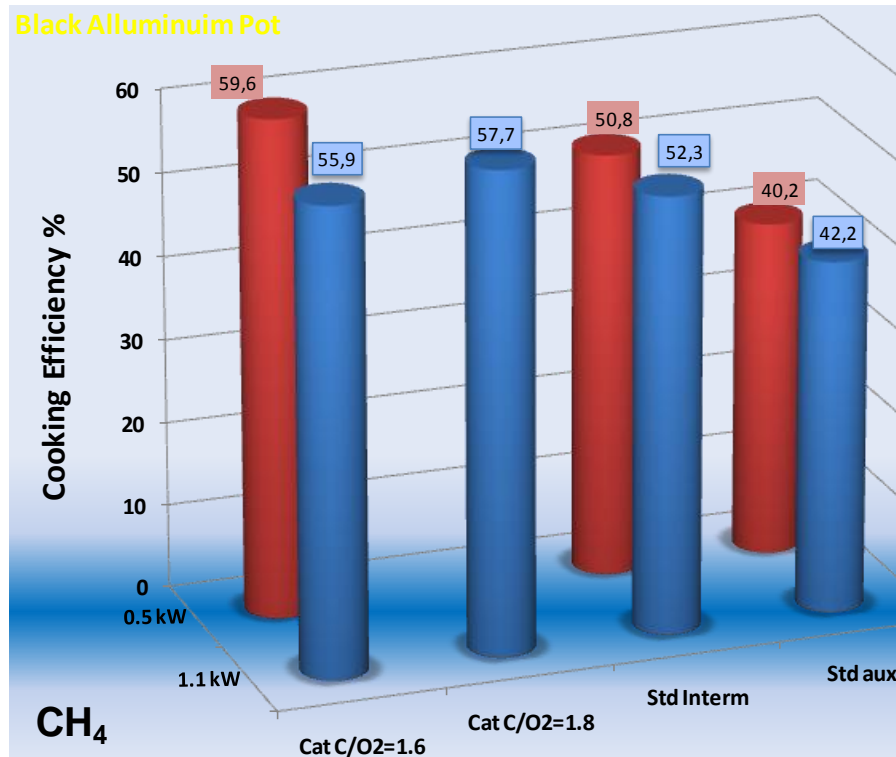


Fig. 2 Comparison of cooking efficiency of catalytic and commercial burners (standard and auxiliary) operated with methane at 0.5 and 1.1kW with a black coated aluminium pot. Catalytic burner was operated at C/O₂ feed ratio of 1.6 and 1.8 (i.e. equivalence ratio $\phi=3.2$ and 3.6).

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 ϕ . 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 $\phi = 3.2-3.8$, since hotter and longer flames, directly impinging on the pot, are expected to improve convective heat transfer efficiency [7,8].

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 [7,8].

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.

4. References

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