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Catalytic purification of H_2-rich streams by CO-PROX over Pt-Co-Ce/γ-Al_2O_3 in fluidized bed reactors

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ABSTRACT

Pt-Co-Ce/γ-Al_2O_3 catalyst has been prepared by incipient impregnation and tested in the preferential oxidation of CO in a H_2-rich stream. Fluidized bed reactors with the reactants fed at two different points have been used in order to improve the reactants contact mode. The influence of temperature, oxygen excess ($\lambda = 2Q_{O_2}/Q_{CO}$) and presence of CO_2 and water have been studied. The use of a two-zone fluidized bed reactor (TZFBR) allowed to optimize the oxidation state of the catalyst and obtain an effluent with a CO concentration of less than 10 ppm with a high selectivity (~77%) to the selective CO oxidation. This can be achieved without catalyst deactivation working only with a slight excess of oxygen (λ = 1.3) and operating at temperatures lower than 100 °C. A conventional fluidized bed reactor requires λ values higher than 1.5 to achieve CO concentration of less than 10 ppm.

1. Introduction

Proton-exchange membrane fuel cells (PEMFCs) appear to be the most suitable and commercially viable hydrogen-based fuel cell systems for static and mobile applications [1]. Hydrogen is usually produced by several processes that include steam reforming, autothermal reforming or partial oxidation of natural gas, light hydrocarbons or alcohols. The gas stream obtained after these processes still contains significant amounts of CO (0.5–2% CO). Unfortunately, suitable operation in a PEMFC can only be ensured with a content of CO below 1–100 ppm, because CO is known to poison the Pt electrodes [2].

In recent years there has been a growing interest in the development of catalysts for the preferential oxidation of CO (CO-PROX). Different catalysts [2] have been developed such as metal oxides (CoO_x, CuO–CeO_2), supported gold catalysts, and supported noble metal (Ru, Pt, and Rh) catalysts. Fixed bed reactors are commonly used but other kinds of reactors (e.g. monolith [3,4] and membrane reactors [5,6]) have been tested and work still needs to be done on the mode of contact between reactives.

CeO_2 is capable of storing O_2 and reacts in the absence of gas phase oxygen [2]. When platinum catalysts contain reducible oxides such as cerium or cobalt, the kinetics of the CO-PROX reaction can be explained by a non-competitive Langmuir–Hinshelwood mechanism with two types of active sites. CO adsorbed on the platinum surface reacts with oxygen atoms which are first dissociatively adsorbed on the support surface and then spilled over the Pt particle. Moreover, this reaction can occur on the metal/oxide interface and in this case is selective to CO oxidation [2,7]. This redox performance fits the mode of operation of a two-zone fluidized bed reactor (TZFBR) (Fig. 1), in which the catalyst is moving continuously between two zones created by feeding the reactants at two different points of a fluidized bed reactor. The characteristics and several applications of the TZFBR have been described previously [8]. The use of the TZFBR allows different ways of feeding the reagents creating two zones in the reactor with different characteristics depending on the configuration used. The aim of this work is to optimize the preferential oxidation of CO over a Pt-Co-Ce/γ-Al_2O_3 catalyst using different fluidized bed reactor configurations (Fig. 1), in order to improve the mode of contact between reactives.

2. Experimental

2.1. Catalyst preparation and characterization

The Pt-Ce-Co/γ-Al_2O_3 catalyst was prepared by incipient wet co-impregnation [9] and the nominal composition was 1.4 wt.% of Pt, 1.25 wt.% of Co and 1.25 wt.% of Ce. The support (γ-alumina, Puralox Sasol Germany GmbH, particle size 160–250 μm) was calcined at 450 °C for 2 h prior to impregnation. At room temperature, aqueous solutions of $Pt(NH_3)_4(NO_3)_2$ (Sigma–Aldrich, ≥50.0% Pt basis), $Co(NO_3)_2{\cdot}6H_2O$ (Sigma–Aldrich, 98% purity) and $Ce(NO_3)_3{\cdot}6H_2O$ (Sigma–Aldrich, 99% purity) were dripped into a

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Nomenclature

FBR	fluidized bed reactor
h	bed height [cm]
h_a	intermediate feeding height [cm]
H	total bed length [cm]
Q_{O_2}	total oxygen flow rate [cm^3 (STP) min^{-1}]
Q_{CO}	total CO flow rate [cm^3 (STP) min^{-1}]
Q_T	total gases flow rate [cm^3 (STP) min^{-1}]
T	reaction temperature [°C]
TZFBR	two-zone fluidized bed reactor
u_o	superficial gas velocity [cm^3 (STP) cm^{-2} s^{-1}]
u_{mf}	minimum fluidization velocity [cm^3 (STP) cm^{-2} s^{-1}]
u_r	relative gas velocity [u_o/u_{mf}]
u_{r1}	relative gas velocity in reaction zone [$u_{o\ reaction\ zone}/u_{mf}$]
W_r	catalyst weight where the CO oxidation happens [g]
W_T	catalyst weight in the reactor [g]

Superscripts

in	at the reactor entrance
out	at the reactor exit

Greek letters

λ	oxygen excess ($\lambda = 2Q_{O_2}/Q_{CO}$)
ξ	fraction of oxygen co-fed with H_2

flask at a rate of 5 cm^3/min. During the impregnation, the slurry was mixed by an ultrasonic mixer for 90 min in order to maintain a uniform distribution of the precursor solution; it was then dried in air at 85 °C during 16 h. Finally, the dried catalyst was heated (3 °C/min) to 450 °C in air and calcined for 2 h. The catalyst had a minimum fluidization velocity (u_{mf}) of 1.44 cm^3 (STP)/cm^2 s obtained with Ar at 120 °C.

Catalyst activation was required before performing the CO-PROX experiments. The active species of platinum is Pt^0, and this requires a reduction treatment [9–12]. However, when there are transition metals such as cobalt or oxides with redox properties such as cerium oxide, an oxidation step may also be required [13]. In this study, the activation procedure consists of a reduction step (3 h at 375 °C, gas mixture: 1:1 = H_2:Ar), followed by partial oxidation of the catalyst (0.5 h at 80 °C, gas mixture: 1:1 = O_2:Ar). A stable catalyst has been obtained after three cycles; each cycle being composed of three steps: reduction, oxidation and reaction. In this stabilization process, the reaction is at 90 °C for 6 h using a mixture 1% CO, 0.55% O_2, 60% H_2 and argon to balance. This stabilization process gives a relative error lower than 0.35 for conversion and oxygen selectivity to CO_2 (as is defined below). The stable catalyst is used for the performance analysis in the conventional fluidized bed reactor (FBR) and the TZFBR. In the following sections, all the results reported correspond to those obtained at a time on stream of 2 h, once steady state has been reached.

The surface area was obtained by the Brunauer–Emmet–Teller (BET) method with an automatic analyzer ASAP 2002 from Micromeritics. The commercial γ-alumina has a BET surface area of 193 m^2/g; after calcinations, a 185 m^2/g solid catalyst was obtained. Thus, the BET area was maintained after metal impregnation and catalyst stabilization.

The powder X-ray diffraction (XRD) patterns were measured in a Rygaku/Max diffractometer equipped with a graphite monochromator operating at 40 kV and 80 mA and using nickel-filtered CuKα radiation 1.2 (2θ = 10–90°). The "JCPDS-International Centre for Diffraction Data-2000" database has been used for the determination of the phases. As can be seen in Fig. 2, the stable and aged catalysts (250 h under operating conditions) showed clearly the broad diffraction peaks of γ-Al_2O_3. The Ce_2O_3, CeO_2 and Co_3O_4 diffraction peaks can be hardly distinguished. Diffraction peaks of Pt have not been identified; this could indicate that the preparation method allows us to obtain small metal crystallites. The XRD results also show that the catalyst structure do not change for a long time (250 h) under the operating conditions, which is essential for achieving an active catalyst for the CO-PROX reaction [10].

A temperature-programmed reduction (TPR) experiment (not shown) was performed over a sample of stable catalyst with 10 mL(STP)/min of a Ar:H_2 (95:5) mixture. A wide reduction peak was found with a maximum at around 200 °C. This peak is associated with the reduction of platinum [10] and the presence of cobalt could modify the reduction temperature of the Ce oxides, and the reduction of Ce^{4+} to Ce^{3+} could be masked at that temperature [14]. Two smaller peaks also appear, one at 425 °C and another at around 720 °C, both associated with the reduction of cobalt [14–16].

2.2. Reactor setup and calculations

The catalytic oxidation of CO from a H_2-rich stream was carried out in different fluidized bed reactors (Fig. 1). The reactor was heated by an electric furnace and the temperature was measured by a thermocouple at the centre of the catalyst bed. A PID controller maintained temperature variations within ± 0.5 °C of the set point. The reactor was a 30-mm-i.d., 300-mm-long quartz tube equipped with a sintered quartz distributor plate and a movable axial quartz probe was used to introduce gas feed at different reactor heights (h_a).

Thus, different ways of feeding the reagents were studied, resulting in different TZFBR configurations (Fig. 1). The variation was in the mode of feeding each reactant, creating two zones in the reactor with different redox atmospheres. In configuration C-1 (Fig. 1), the mixture (H_2 + CO) was fed to the lower part of the reactor mixed with inert gas, and O_2 + inert gas were fed at an intermediate point of the bed (h_a) while in the configuration C-2, these gas stream was fed in contrary way. In the configurations C-3 and C-4, the (H_2 + CO) and O_2 were co-fed. Moreover, it is possible to move from the C-1 to the C-4 or from the C-2 to the C-3 configurations of the TZFBR, i.e., by changing the fraction of oxygen that is co-fed (ξ) at an intermediate point (h_a) of the catalyst bed (Fig. 1).

The reaction products were analyzed by online gas chromatography (Agilent 3000 μGC equipped with a TCD detector and He as a carrier gas) and mass spectrometry (Omnistar GSD 301T). The CO calibration was made using two standard gas mixtures provided by Praxair S.A. the first one with 100 ppm of CO and 100 ppm of CO_2 (argon to balance) and the second one with 10% of CO diluted in argon. The detection limit of the μGC was 10 ppm of CO measured with the first standard gas mixture diluted with argon using mass flow controllers. The carbon balance closure calculated from the concentrations of CO and CO_2 typically agreed to within 2%. CO conversion and oxygen selectivity to CO_2 (calculated as the ratio of the desired reaction (CO oxidation) to the overall O_2 consumption) were defined as follows:

$$X_{CO}\ (\%) = \frac{Q_{CO}^{in} - Q_{CO}^{out}}{Q_{CO}^{in}} 100 \quad (1)$$

$$S_{CO_2}\ (\%) = \frac{0.5(Q_{CO}^{in} - Q_{CO}^{out})}{Q_{O_2}^{in} - Q_{O_2}^{out}} 100 \quad (2)$$

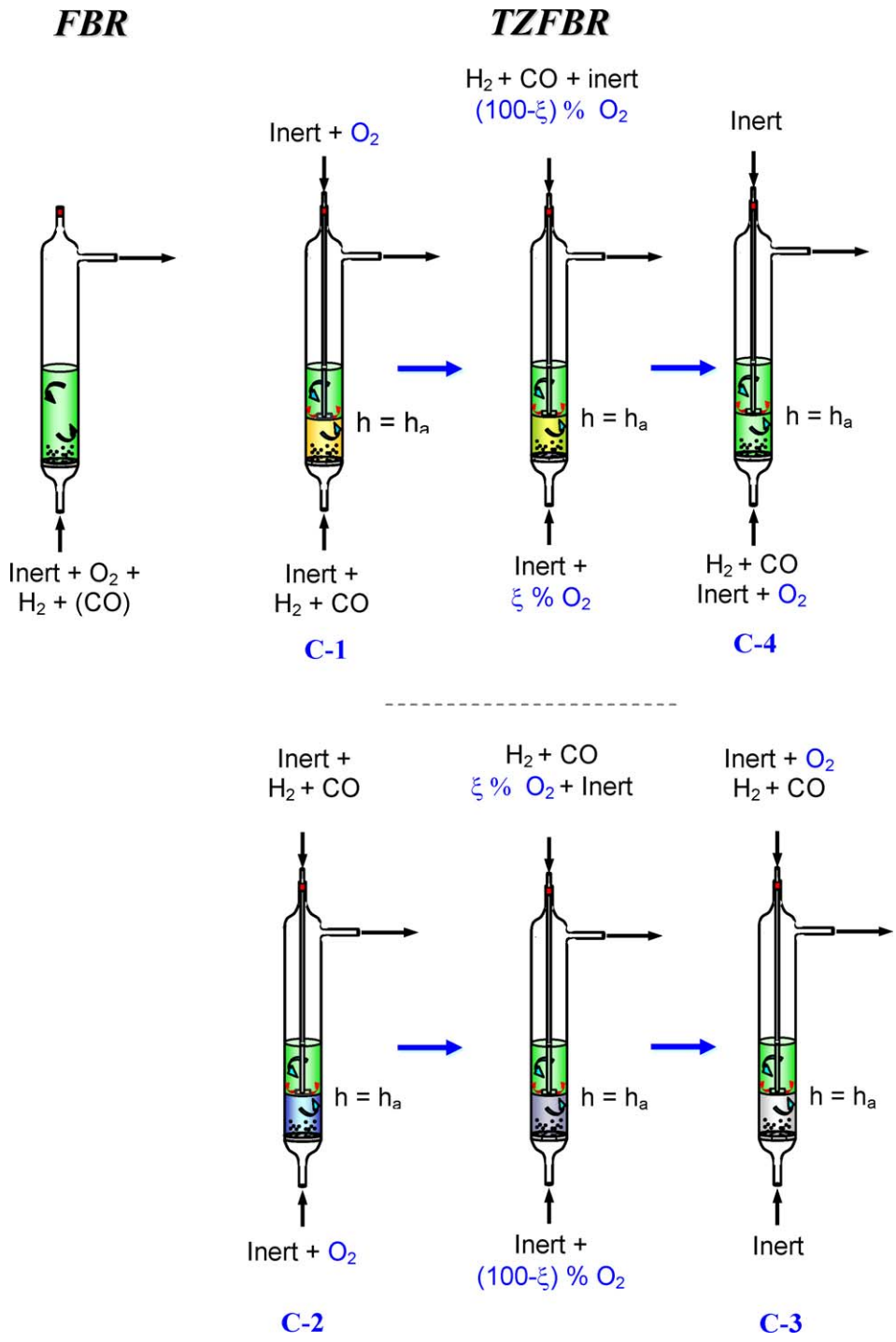

Fig. 1. Configurations of the fluidized bed reactors. Arrows inside the reactors indicate solid movement.

It should be noted that this last formula supposes that CO is exclusively converted to CO_2, since methanation or coke formation reactions can be completely discarded over Pt-Co-Ce/γ-Al_2O_3 catalyst in the temperature range studied.

The oxygen excess with respect to the amount of oxygen required for the oxidation of CO to CO_2 is commonly characterized by the process parameter λ ($2Q^{in}_{O_2}/Q^{in}_{CO}$); where λ = 1 is sufficient to provide the complete oxidation of CO to CO_2 in the absence of an oxygen-consuming side reaction (H_2 oxidation). It should be noted that in the range of operating conditions studied, the oxygen fed was completely consumed during the oxidation process.

3. Results

3.1. Fluidized bed reactor (FBR) configuration

Fig. 3 shows the effect of the reaction temperature on CO conversion and oxygen selectivity to CO_2 while the other operating parameters are kept constant. From 50 °C to 90 °C, both CO conversion and the oxygen selectivity to CO_2 decrease sharply with the temperature. The results obtained at 40 °C were slightly lower than at 50 °C where the effluent containing less than 10 ppm of CO. This could be due to the fact that at low temperatures CO molecules

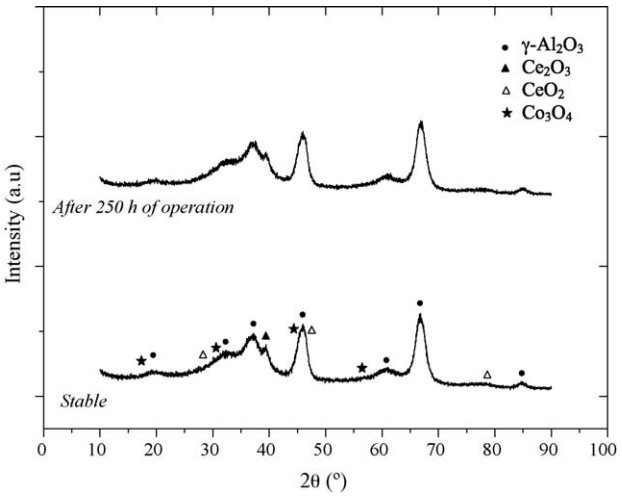

Fig. 2. XRD patterns of the stable catalyst and aged catalyst.

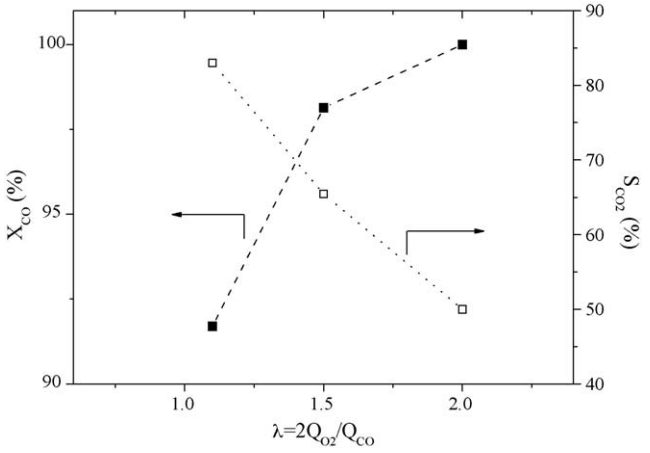

Fig. 4. CO conversion and oxygen selectivity to CO_2 for the PROX reaction in a FBR as a function of oxygen excess (λ). T = 80 °C, 1% CO, 60% H_2, u_r = 2, W_{cat} = 20 g (symbols are experimental data and the lines are guide for eyes).

completely cover the Pt centers and the reaction principally takes place between adsorbed CO and oxygen atoms adsorbed on the catalyst surface, this reaction being selective for CO. The same trends have been observed by other authors for catalysts based on Pt [9–11,17]. On the other hand, when the reaction temperature increases ($T > 80$ °C), the desorption of the CO molecules from Pt particles starts, and the adsorption of hydrogen on Pt particles is significant, so hydrogen oxidation takes place (it reacts with the active oxygen on the catalyst surface) causing a decrease in the yield of CO-PROX reaction [7,11,18]. Several studies show that the presence of cobalt in Pt-based catalysts allows relatively high conversions of CO (~80%) to be obtained at very low temperatures [2,19].

Experiments with different amounts of oxygen were performed while maintaining constant CO and H_2 total flows in the feed, the reaction temperature and the catalyst weight. In Fig. 4, CO conversion increases when the excess of oxygen increases whereas the oxygen selectivity to CO_2 decreases, in agreement with the findings of other authors [7,9,17,20]. Thus the CO-PROX reaction, like most oxidation reactions, is favored as the oxygen concentration in the inlet flow increases. Nevertheless, as has been commented above, the existence of hydrogen oxidation (a parallel reaction to CO oxidation) implies that the λ value must be as low as possible to obtain almost full CO conversion and the highest oxygen selectivity to CO_2. The values of λ that can eliminate completely the CO (<10 ppm in the exit stream) of the inlet flow are lower than those used for other catalysts based on Pt, due to the use of reducible compounds of cerium or cobalt that are capable of storing oxygen, which could react more efficiently with the CO at low λ values [7,9,14].

The influence of H_2O and CO_2 molecules on conversion and selectivity is one of the most studied phenomena in the CO-PROX reaction because these two molecules appear together with H_2 and CO in the reformed gas. Generally, and depending on the characteristics of the support, these molecules can adsorb on the active sites of the catalyst, inhibiting its activity. Numerous scientific works describe the effect that these molecules have in the catalytic behavior of this reaction [9,11,12,17,21,22], although with different conclusions. Several studies report that the presence of CO_2 negatively affects the catalyst stability due to the formation of carbonates on its surface [9,12,17]. Other works report that the CO_2 partial pressure does not significantly affect the CO_2 production rate [22–24] and other authors observe an increase in the oxygen selectivity to CO_2 [22].

Fig. 5 shows the evolution of CO conversion with the time on stream in the presence of CO_2 and $CO_2 + H_2O$ in the feed. The

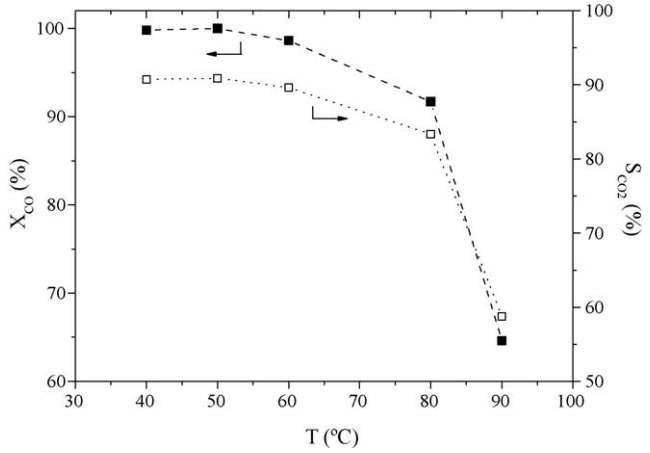

Fig. 3. Effect of reaction temperature on CO conversion and oxygen selectivity to CO_2 for the PROX reaction in a FBR. 1% CO, 60% H_2, λ = 1.1, u_r = 2, W_{cat} = 20 g (symbols are experimental data and the lines are a guide for eyes).

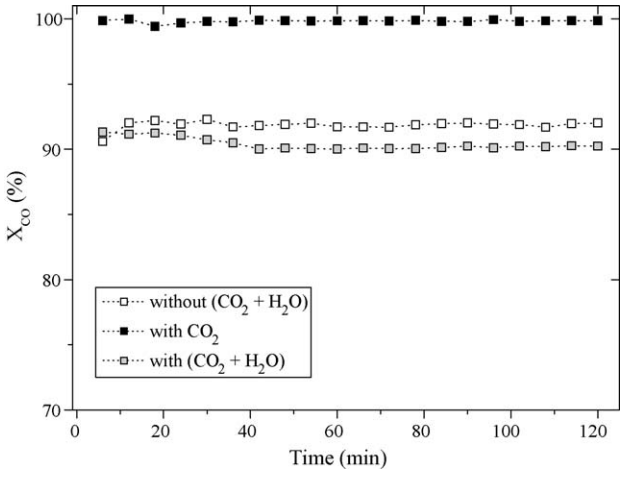

Fig. 5. Influence of CO_2 and H_2O concentrations on CO conversion for the PROX reaction in a FBR as a function of time on stream. T = 80 °C, 1% CO, 60% H_2, λ = 1.1, u_r = 2, W_{cat} = 20 g, 20% CO_2, 1.7% H_2O (symbols are experimental data and the lines are guide for eyes).

results show that in the presence of CO_2, the activity of the catalyst was notably improved, obtaining an effluent with less than 20 ppm of CO. This beneficial effect of the CO_2 might be due to blocking of the sites required for the hydrogen oxidation thus most of the feeding oxygen reacts to oxidize CO. However, when the test is carried out in the presence of CO_2 and H_2O, a small decrease in CO conversion is observed compared to when these two compounds were not present in the inlet flow. Two explanations can be proposed to explain the effect of water: the presence of water could inhibit the adsorption of CO and/or CO_2 on the Pt particles, or water could condense inside the catalyst pores, thus the reaction is strongly influenced by mass transfer restrictions [14].

3.2. Operation in a two-zone fluidized bed reactor

The oxygen excess is an essential variable in the CO-PROX reaction. Its effect has therefore been studied in the operation of the different configurations of the TZFBR (Fig. 1). The experiments have been carried out varying the oxygen excess (λ), but maintaining constant the reaction temperature, CO and H_2 concentrations in the inlet flow, the relative gas velocity (u_r), the amount of catalyst used and the ratio of heights between the redox zones in the reactor. In the four configurations of the TZFBR studied, an increase in excess oxygen leads to an increase in CO conversion (Fig. 6) and of course a decrease in oxygen selectivity to CO_2 (remember O_2 is in all cases completely consumed), in agreement with the results obtained in the FBR configuration.

Configurations C-1 and C-2 offered worse results than the other configurations and this may be related to the absence of oxygen in the zone were the main part of the oxidation reactions occurs. Configuration C-4 allowed the highest CO conversion (a CO concentration of less than 10 ppm for $\lambda \geq 1.5$), indicating that the redox state of the catalyst is more suitable than in the other configurations. In configuration C-3, the CO conversions obtained are slightly lower than those obtained in configuration C-4 because of the smaller reaction spatial time, W_r/Q_{CO}^{in}.

The use of a TZFBR allows the mixture of H_2 and CO and the mixture of O_2 and argon to be introduced at different points of the reactor. From this point of view, it is of interest to know how the CO conversion changes when the total oxygen fed to the system is distributed in two feeding zones, co-fed together with the mixture of H_2 and CO, or through another inlet of the TZFBR (see Fig. 1, intermediate configurations between the C-2 and C-3 configurations). Fig. 7 shows the CO conversion and oxygen selectivity to CO_2 by moving from the C-2 to the C-3 configuration of the TZFBR, i.e., by changing the fraction of oxygen that is co-fed (ξ) in an intermediate point of the bed, for three different temperatures. A similar procedure has been used in a two stage packed-bed reactor, the CO conversion increasing with oxygen split [25].

For a reaction temperature of 60 °C, when the amount of O_2 co-fed into the reactor together with the H_2 increases, the CO conversion increases very slightly, although worse results are obtained when the experiment is realized with a C-3 configuration of the TZFBR. On the other hand, the effect of distributing the O_2 between the different feeding points is higher when the reaction temperature increases, while increasing the quantity of oxygen co-fed (ξ) clearly gives better results. The trend with the increase of temperature is related to a greater desorption of CO adsorbed on the Pt particles so the oxidation of H_2 is therefore more important. Co-feeding 90% of the total O_2 together with the H_2, a maximum appeared in the CO conversion. This may indicate that it is necessary to optimize the redox state of the catalyst.

CO conversion and oxygen selectivity to CO_2 (not shown) have been studied by moving from the C-1 to the C-4 configuration of the TZFBR, i.e., by changing the fraction of oxygen that is co-fed (ξ) at an intermediate point of the catalyst bed (see Fig. 1 for the intermediate configuration between C-1 and C-4). Again, an increase in the amount of co-fed oxygen produces an increase in CO conversion and the oxygen selectivity to CO_2. The use of a TZFBR allows the oxygen feeding method to be optimized, and thus maximizing the CO conversion and oxygen selectivity to CO_2. In this case, the maximum CO conversion corresponds to ξ = 90%, i.e., a 90% of the total O_2 was co-fed together with the (H_2 + CO) in an intermediate point of the bed and the rest of O_2 was fed in the lower part of the reactor (this configuration of the TZFBR is named C-4′). The influence of the oxygen excess in the C-4′ configuration is shown in Fig. 6. The fact of distributing the oxygen fed between the two inlets of the reactor enables the CO conversion to be improved, even for lower values of λ, so that it is possible obtain in the exit flow a CO concentration of less than 10 ppm for λ = 1.3. The oxygen selectivity to CO_2 represented an improvement over other reaction systems where larger values of λ are needed to eliminate completely the CO from a hydrogen-rich flow. For example, Fig. 4 shows that a conventional fluidized bed reactor requires $\lambda \geq 1.5$ to achieve almost completely CO conversion. These interesting results might be due to a control of the redox state

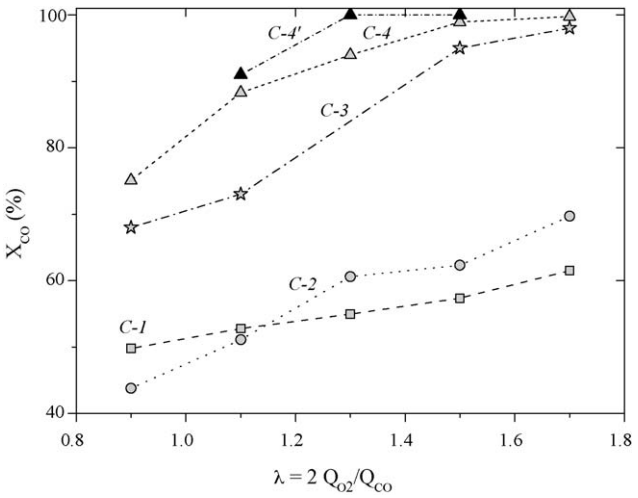

Fig. 6. CO conversion for the PROX reaction as a function of oxygen excess (λ), for different configurations of the TZFBR. T = 80 °C, 1% CO, 60% H_2, u_{r1} = 4, W_{cat} = 40 g, $(H_T - h_a)/h_a$ = 1 (symbols are experimental data and the lines are guide for eyes).

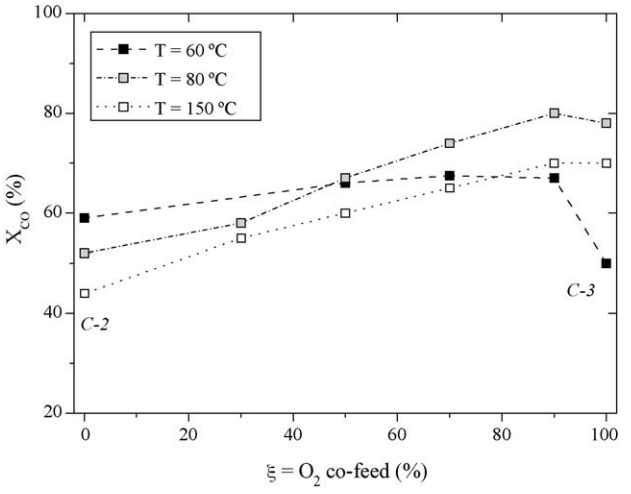

Fig. 7. CO conversion for the PROX reaction as a function of oxygen co-fed with H_2 (ξ), for different configurations of the TZFBR. 1% CO, 60% H_2, λ = 1.1, u_{r1} = 4, W_{cat} = 40 g, $(H_T - h_a)/h_a$ = 1 (symbols are experimental data and the lines are guide for eyes).

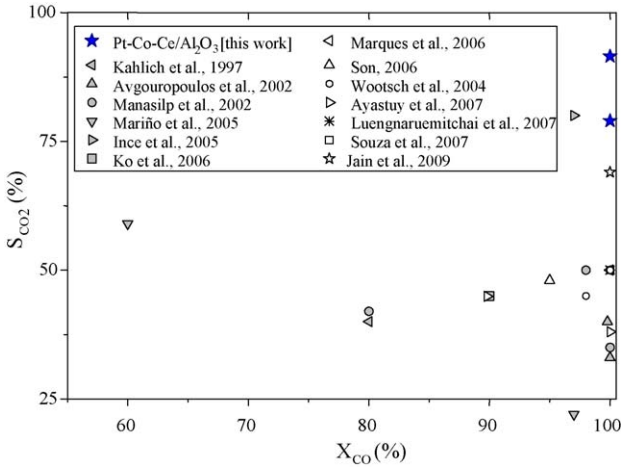

Fig. 8. Oxygen selectivity to CO_2 as a function of CO conversion. Experiments performed during this work in a TZFBR and FBR and comparison with results in the literature.

of the catalyst, which changes its selectivity in the CO-PROX reaction.

3.3. Comparison with results in the literature

Finally, Fig. 8 shows the results obtained in this work with the Pt-Co-Ce/γ-Al_2O_3 catalyst and the results found in the literature with catalysts based on Pt. Kahlich et al. [21], using a Pt/γ-Al_2O_3 commercial catalyst, obtained the best results at 225 °C and λ = 2. Avgouropoulos et al. [24] used a Pt/γ-Al_2O_3 catalyst prepared by incipient wet impregnation, and achieved $X_{CO} \sim 100\%$ at 160 °C and λ = 2.5. Manasilp and Gulari [17] used a Pt/γ-Al_2O_3 catalyst, synthesized by the sol–gel method, obtaining the best results at 110 °C with λ = 2.7. Mariño et al. [13] studied a Pt/$Ce_xZr_yO_2$ catalyst and achieved $X_{CO} \sim 60\%$ at 100 °C and λ = 1. Wootsch et al. [7] tested a Pt/$Ce_xZr_yO_2$ catalyst and obtained $X_{CO} = 100\%$ at 150 °C and λ = 2. Ince et al. [9] employed a Pt-Co-Ce/γ-Al_2O_3 catalyst prepared by the co-impregnation method (catalysts similar to that used in this work) and obtained $X_{CO} \sim 97\%$ at 90 °C with λ = 1. Ko et al. [26] achieved $X_{CO} \sim 90\%$ at 177 °C and λ = 2 with a Pt-Co/γ-Al_2O_3 catalyst. Marques et al. [27] with a Pt/Nb_2O_5 catalyst obtained $X_{CO} \sim 100\%$ at 90 °C and λ = 2. Son [12], using a Pt-Ce/γ-Al_2O_3 catalyst, obtained the best results at 200 °C and λ = 2. Ayastuy et al. [11] tested a Pt/MnO_x/γ-Al_2O_3 catalyst and achieved the best results at 139 °C and λ = 2. Luengnaruemitchai et al. [22] obtained $X_{CO} \sim 100\%$ at 200 °C and λ = 2 with a Pt supported catalyst over zeolite-A. Souza et al. [28], used a Pt/γ-Al_2O_3 catalyst and obtained the best results at 150 °C and λ = 2. Jain et al. [29] employed a Pt-Co/γ-Al_2O_3 catalyst reaching $X_{CO} \sim 100\%$ at 108 °C and λ = 1.35.

In all these works, fixed bed reactors were used and in some cases catalyst deactivation was reported [9,17,26] due mainly to the formation of carbonates on the catalyst surface that inhibits selective CO oxidation, and that can be eliminated by a treatment of the catalyst. The use of a TZFBR has several advantages over traditional systems used in the CO-PROX reaction, and it allows an effluent to be obtained with a CO concentration of less than 10 ppm with a high selectivity to the selective CO oxidation. This can be obtained by working with just a slight excess of oxygen over that necessary only to oxidize only the CO present, without catalyst deactivation and operating at temperatures lower than 100 °C.

4. Conclusions

Pt-Co-Ce/γ-Al_2O_3 catalyst was synthesized and tested in the preferential oxidation of CO in a H_2 stream in different fluidized bed reactors. The study of the operating conditions shows a beneficial effect on the CO-PROX reaction at low temperatures and with the presence of CO_2 in the inlet gas. However, water has a negative effect. The oxygen excess has opposing trends in CO conversion and oxygen selectivity to CO_2 and a compromise between them is therefore necessary.

The TZFBR allows the oxidation state of the catalysts to be controlled by changing the point at which reactants are fed. In this work the best results were obtained when feeding 10% of the total oxygen fed at the intermediate point of the reactor, while the rest of the O_2 flow was co-fed at the bottom of the reactor with a H_2 + (1%) CO stream mixed with inert gas. In this case it is possible to achieve a CO conversion ~100% and oxygen selectivity to CO_2 ~77%, at 80 °C and $\lambda = 2Q_{O_2}/Q_{CO} = 1.3$. The selectivity and conversion obtained with the TZFBR is among the best results reported in the literature using Pt-based catalyst.

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