

# Transient behaviour of dense catalytic membranes based on Cu- and Co-doped $\text{Bi}_4\text{V}_2\text{O}_{11}$ (BIMEVOX) in the oxidation of propene and propane

A. Löfberg<sup>a,\*</sup>, C. Pirovano<sup>b</sup>, M.C. Steil<sup>b</sup>, R.N. Vannier<sup>b</sup>, E. Bordes-Richard<sup>a</sup>

<sup>a</sup> *Laboratoire de Catalyse de Lille, UMR CNRS 8010, USTL-ENSCL, 59655 Villeneuve d'Ascq Cedex, France*

<sup>b</sup> *Laboratoire de Cristalchimie et Physicochimie du Solide, UMR CNRS 8012, USTL-ENSCL, 59655 Villeneuve d'Ascq Cedex, France*

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## Abstract

ME-doped  $\gamma\text{-Bi}_4\text{V}_2\text{O}_{11}$  (BIMEVOX) oxides are highly oxide ion conducting materials and this property may be profitably used in selective oxidation of hydrocarbons. The catalytic properties of BICUVOX and BICOVOX when shaped as dense membranes displayed in catalytic dense membrane reactor are examined in the oxidation of propene and of propane. Mirror-polished BICUVOX and BICOVOX membranes studied previously were poorly active for propene oxidation because of a small number of active sites but showed an excellent stability and reproducibility (lasting more than 1 month) during which products of mild oxidation (acrolein, hexadiene) and CO were formed. Membranes with depolished surfaces exhibit high conversions of propene (up to 60 mol%), and also of propane (up to 20 mol%) but – contrary to mirror-polished membranes – a complex transient behaviour is observed during which syngas production occurs. The membrane polarisation followed by in situ solid electrolyte potentiometry shows that the oxygen reservoir is far higher than expected on the reaction side which is separated (by the membrane) from the oxidising side where (diluted) oxygen is reduced to  $\text{O}^{2-}$  specie. The influence of oxygen partial pressure on the catalytic performance suggests that the electronic conductivity of the material is limiting the oxygen flux through the membrane, and thus is determining the catalytic properties and transient behaviours of depolished membranes.

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## 1. Introduction

In selective oxidation of hydrocarbons during which the redox mechanism prevails, there is generally a competition between nucleophilic lattice  $\text{O}^{2-}$  oxygens considered as the selective agents and more electrophilic adsorbed oxygens which mostly lead to the formation of carbon oxides [1]. In usual fixed or fluidised bed reactors dioxygen is cofed with the hydrocarbon to regenerate the catalyst. If it is not cofed, one can expect an increase of selectivity for two reasons: (i) the direct gas phase oxidation of the hydrocarbon by gaseous  $\text{O}_2$  cannot proceed and (ii) electrophilic adsorbed specie cannot form after dissociation of  $\text{O}_2$ . The oxidation of *n*-butane to maleic anhydride in a circulating fluid bed reactor was the first industrial and successful case of decoupling of the redox

mechanism [2,3]. Among other means to decouple the redox steps either in space or in time, catalytic membrane reactors have already been proposed. The membrane may allow the extraction (of a product) or distribution (of a reactant, e.g. oxygen), or it may act as a contactor [4]. As a catalyst can be deposited onto a porous membrane, the latter is interesting in oxidation because the reactants may be separately fed on each side of the membrane allowing higher safety and higher selectivity. Another possibility, less common in selective oxidation, is to use a dense membrane which is intrinsically catalytic and exhibits as well oxide ionic and electronic conductivities [5–7]. Indeed, catalysts of mild oxidation behave as more or less good oxygen ion conductors although these properties are not often considered in catalytic oxidation [8a,b,9]. In a catalytic dense membrane reactor (CDMR), the membrane separates two compartments. The reactant side is fed by the (diluted) hydrocarbon (low oxygen partial pressure, (LOP),  $p_{\text{O}_2}$ , or permeate side) and the oxidising side by diluted oxygen (high oxygen partial pressure (HOP), or retentate side).

\* Corresponding author. Tel.: +33 320434537; fax: +33 320436561.

E-mail address: [Axel.Lofberg@univ-lille1.fr](mailto:Axel.Lofberg@univ-lille1.fr) (A. Löfberg).

The driving force of oxide ion migration is the gradient of oxygen activity between the two compartments.

Oxidic materials based on the  $\gamma$ - $\text{Bi}_4\text{V}_2\text{O}_{11}$  structure in which V is partially substituted by a metallic cation, exhibit the highest oxide ion conductivities at moderate temperatures (623–873 K) [10,11]. For example, the ionic conductivity of  $\gamma$ - $\text{Bi}_4\text{V}_{1.8}\text{Cu}_{0.2}\text{O}_{10.7}$  is 100 times that of yttria-doped zirconia at 873 K. The BIMEVOX acronym has been accepted by the community because most cations of the periodic table can be used as ME dopants, thereby stabilising  $\gamma$ - $\text{Bi}_4\text{V}_2\text{O}_{11}$  down to room temperature. The catalytic properties of some BIMEVOX powders have been examined in the oxidative dehydrogenation of propane (Me = Zn, Cu) [12] and in the oxidative dimerisation of propene (Me = Cu, Co) [13,14] in conventional fixed bed reactors. The catalytic behaviour of BICOVOX as dense membranes for the oxidation of propene in a CDMR has recently been examined [15]. As the surface of membranes was mirror-polished in order to get accurate measurements of oxygen permeation, the surface area was very low which explained why the conversion of propene was low (1–2 mol%). In the present paper, preliminary results obtained using Cu (BICUVOX) and Co (BICOVOX)-doped  $\gamma$ - $\text{Bi}_4\text{V}_2\text{O}_{11}$  depolished membranes in the catalytic oxidation of propene and of propane in a CDMR are presented.

## 2. Experimental

Membranes of  $\text{Bi}_4\text{Cu}_{0.2}\text{V}_{1.8}\text{O}_{10.7}$  (BICUVOX) and  $\text{Bi}_4\text{Co}_{0.2}\text{V}_{1.8}\text{O}_{10.7}$  (BICOVOX) ( $\varnothing = 15$  mm, thickness 17 mm, relative density > 95% as compared with theoretical density) with two surface roughnesses (mirror-polished with 4000 SiC grit paper, further depolished by 200 SiC grit paper) were prepared [15]. The membrane was sealed in between the two mullite tubes of the reactor by means of pyrex rings. Air or oxygen was flowed in the high oxygen partial pressure (retentate) side. The low oxygen partial pressure (permeate) side was fed with He (permeation mode), or with 1% propene or 1% propane in helium (both  $F = 50$  cm<sup>3</sup> min<sup>-1</sup>) (reaction mode) at 823–1023 K and  $p = 10^5$  Pa. The CDMR assembly described in [15] allows combined studies of the solid catalyst (ionic conductivity, permeability, electronic polarisation) and of the catalytic reaction (activity, selectivity, etc.). The gas phase composition at inlets and outlets of the two compartments of the CDMR was monitored using a mass spectrometer (Omnistar Pfeiffer) for the catalytic reaction and an oxygen gauge (Setnag) for O<sub>2</sub> permeation. Gold electrodes were in contact of each side of the membrane and the difference of potential between these sides was in situ measured to follow the membrane polarisation (solid electrolyte potentiometry, SEP). The standard protocol consisted first in the measurement of oxygen permeation fluxes. Then diluted propene or propane was flowed into LOP compartment and the catalytic properties were studied as well as SEP was performed. Parameters such as temperature (823–973 K), contact time ( $\tau = 2$ –12 s) and oxygen pressure ( $p_{\text{O}_2} = 1$ – $10^5$  Pa) in HOP side of the membrane were varied. Pieces of membranes were characterised by X-ray diffraction (XRD), laser Raman spectroscopy

(LRS), scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS) before and after reaction.

## 3. Results and discussion

### 3.1. Membranes with mirror-polished surfaces

As for BICOVOX membranes [15], low conversions of propene (up to 2.0 mol%, depending on temperature, contact time  $\tau$  and propene partial pressure) were observed for the BICUVOX membrane with mirror-polished surface. For example, at 948 K and  $\tau = 6$  s, conversion was 1.0 mol% and selectivities ranged as CO = 70, hexadiene = 15, acrolein = 12, benzene = 3 mol%. These figures were similar to those obtained with BICOVOX except that no CO<sub>2</sub> was present. If a 100 mol% selectivity to CO is supposed, 600 ppm of oxygen are necessary to convert 100 ppm of propene to 3CO + 3H<sub>2</sub>O. These oxygens could be provided by permeation. However, the  $J_{\text{O}_2}$  flux measured after flowing helium in LOP instead of diluted propene is very low (e.g.  $J_{\text{O}_2} = 3 \times 10^{-4}$  to  $3 \times 10^{-5}$   $\mu\text{mol cm}^{-2} \text{s}^{-1}$  for BICOVOX at 873–953 K), producing only 1–2 ppm O<sub>2</sub> in LOP in the same experimental conditions [15]. Indeed, most of the conductivity is due to oxide ions (transference number  $t_i \approx 1$ ) and few electrons are available to ensure the dissociation of O<sub>2</sub> as well as the recombination of O<sup>2-</sup> according to  $\text{O}_2 + 4\text{e}^- \rightleftharpoons 2\text{O}^{2-}$ , as confirmed by <sup>18</sup>O/<sup>16</sup>O isotope exchange combined with SIMS [16]. On the contrary, the polarisation of the membrane remained high during all experiments, which means that the thermodynamic activity of oxygen at the surface in LOP is far higher than supposed. Indeed, calculations by the Nernst equation show that  $E = -10.5$  mV measured by SEP gives  $p_{\text{O}_2} = 0.13 \times 10^5$  Pa, instead of 0.3 Pa observed experimentally. In other words, the oxygen O<sup>2-</sup> reservoir in LOP is larger than expected, and the oxidation of propene provides an alternative pathway for oxygen extraction in place of the recombination of O<sup>2-</sup> to O<sub>2</sub>.

The stability of the membrane was remarkable during the whole experiments which lasted up to 1 month. The characterisation of the membrane by XRD, SEM, LRS and XPS showed that the LOP, as well as the HOP surfaces remained unchanged.

### 3.2. Membranes with depolished surfaces

Depolished BICUVOX membranes give far higher values of propene conversion. However, their activity is not stable and decreases with time (Fig. 1). In the first 10 min, the propene conversion reaches 60–55 mol% while CO and H<sub>2</sub> are the main products. Then it decreases and is stabilised at 25 mol% after 1 h. Most of this residual conversion can be accounted for coke and H<sub>2</sub> formation. After coke burning and membrane regeneration (by feeding air instead of propene in LOP), the oxidation of propane was performed in similar conditions of contact time and of partial pressures. A complex transient behaviour was observed. Initially, the activity is stable, the conversion of propane being at ca. 12.5 mol% (Fig. 2).

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