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Journal of Catalysis 232 (2005) 1–9

JOURNAL OF CATALYSIS

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Reaction pathway in the vapour-phase synthesis of indole and alkylindoles

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Received 12 November 2004; revised 11 February 2005; accepted 16 February 2005

Abstract

The vapour-phase synthesis of indole and its derivatives from aniline or alkylanilines and ethylene glycol or other diols was investigated with the use of a novel ZrO_2/SiO_2 (5:95 w/w) catalyst to check the applicability of this synthesis to a wide number of alkylindoles. During feeding with alkylaniline, the above catalyst showed catalytic results better than those reported in the literature, and a very good regenerability. In particular, with ethylene glycol, the best yields in the corresponding indoles were obtained when a C_2–C_3 alkyl chain was located in the ortho position to the amino group. The differences in reactivity between aniline and alkylaniline were significantly reduced when the length of the diol chain was increased and eliminated with 2,3-butanediol. On the basis of the above data and those collected sharing the synthesis in single steps, a possible overall reaction pathway was proposed to design a better tailor-made catalyst. It was also indicated that the formation of heavy compounds, which are able to deactivate the catalyst, were not derived from the reagents or the following reactions on the indole formed, but might be mainly attributed to the polycondensation of an aldehyde intermediate.

Keywords: Vapour-phase synthesis; Reaction pathway; ZrO_2/SiO_2 catalyst; Indole; Alkylindoles; Aniline; Aromatic ammines; Ethylene glycol; Diols

1. Introduction

Indole or alkylindoles are of considerable industrial interest, and are applied as intermediates in the production of pharmaceuticals, herbicides, fungicides, dyes, etc. [1–3]. Usually they are recovered from the biphenyl-indole fraction obtained by coal tar distillation, although this source no longer seems to be able to cover the increasing market demand. Alternatively, they can be obtained in high yields from well-known liquid-phase reactions, which, however, present many drawbacks [4–8]. Thus, increasing interest has been focused on the vapour-phase synthesis of these molecules [9–16] (Fig. 1), since it exhibits many advantages in comparison with the liquid-phase synthesis.

Although there is a patent literature rich in data regarding the nature and composition of catalysts and the operating conditions for the synthesis of indole, few data have been reported for the synthesis of alkylindoles. Basically, two different technologies may be identified: (i) high-temperature (773–973 K) dehydrocyclisation of dialkylanilines over oxides or chromites, followed by partial hydrogenation of the raw product [9], and (ii) lower temperature (453–623 K) reaction of anilines and glycols, operating at low liquid hourly space velocity (LHSV) [10–16]. In this latter case, many different catalysts have been claimed, making it difficult to identify the reaction requirements and optimum catalyst properties. In particular, it was reported that with copper chromites (the most widely claimed catalysts in the patent literature for the synthesis of indole) a large molar excess

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doi:10.1016/j.jcat.2005.02.014

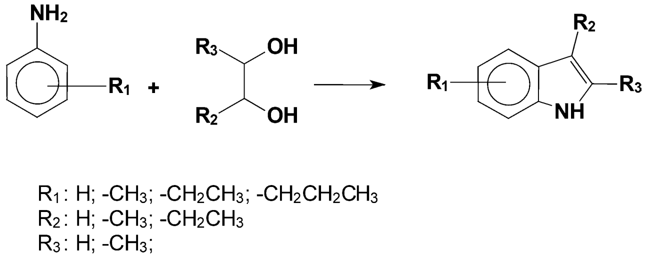

Fig. 1. General reaction scheme of the vapour-phase synthesis of indole and its derivatives.

(⩾10.0) of aromatic amine has to be used to avoid the formation of useless polyalkylated indoles. Thus a high amount of aniline derivatives has to be recycled, with significant economic and environmental drawbacks. In a previous paper [17], some of us reported that the best results can be obtained with a commercial copper chromite containing only promoters, improving the physical properties and permitting operation at low temperature and LHSV values [17]. Furthermore, with a mixture of a commercial SiO_2 and this catalyst, it was possible to operate at higher LHSV values, thus improving the yield in alkylindoles [17].

The excess of aromatic amine and carrier gas (required to operate at low contact times) has been avoided with the use of a new family of ZrO_2/SiO_2 catalysts able to operate with almost stoichiometric feeds and water as the main carrier gas [18–20]. These catalysts showed better performances than those reported in the literature and very good regenerability. Finally, innovative Si/Zr mesoporous catalysts, with a MCM41-type structure, have also been investigated, although they demonstrate poorer catalytic performances [21].

However, it must be noted that almost no data are available in the literature on either the possible reaction pathway in the vapour-phase synthesis of indole and, mainly, alkylindoles or the reactivity in these conditions of different aromatic amines or diols. The aim of this study was to shed light on these two key points to check the applicability of the vapour-phase synthesis to a wider number of alkylindoles and to design tailor-made catalysts.

2. Experimental

Catalytic tests were carried out with 4.0 ml (ca. 2.5 g, 425–850 µm particle size) of ZrO_2/SiO_2 (5:95 w/w) supported catalysts, prepared by incipient wetness impregnation of a commercial SiO_2 (Si-1803 T 1/8″; Engelhard) with a solution of Zr(IV) acetylacetonate in acetic acid and following calcination at 723 K for 5 h. The catalyst had previously been activated in situ, with a progressive increase in the temperature up to 603 K and a 6 l/h flow of a H_2/N_2 (1:9 v/v) gas mixture. Aniline (AN), 2-methylaniline (2-METAN), 3-methylaniline (3-METAN), 4-methylaniline (4-METAN), 2-ethylaniline (2-ETAN), 3-ethylaniline (3-ETAN), 4-ethylaniline (4-ETAN), 2-propylaniline (2-PRAN), ethylene glycol (EG), 1,2-propylene glycol (1,2-PDIOL), 1,2-butanediol (1,2-BDIOL), 2,3-butanediol (2,3-BDIOL), 1,2-hexanediol (1,2-HEXDIOL), Zr(IV) acetylacetonate, and CH_3COOH were purchased from Aldrich Chemicals (purity ⩾ 98.0%) and used as received without any further purification.

We prepared N-(2-hydroxyethyl)-2-ethylaniline (NEE) in liquid phase by adding 60 ml of chloroethanol to 150 ml of 2-ETAN, performing the reaction for 3 h at 403 K under a N_2 atmosphere with energetic stirring, and adding at the end 10 g of K_2CO_3 dissolved in 10 ml of H_2O to neutralise the HCl formed. Then we distilled the reaction mixture at 323 K under vacuum (395 Pa), obtaining NEE with a purity of 98%. We prepared N-(2-ethylphenyl)-2-aminoacetaldehyde (NEPA) in liquid phase by adding 50 ml of chloroacetaldehyde dimethylacetal to 75 ml of 2-ETAN, performing the reaction for 3 h at 403 K under a N_2 atmosphere with energetic stirring, and adding at the end 10 ml of a K_2CO_3 solution (50 wt%) to neutralise the HCl formed. The reaction mixture was extracted with toluene, and the product was recovered by solvent distillation at 323 K under vacuum (395 Pa). The NEPA dimethylacetal obtained was then treated with a H_2SO_4 solution (6 wt%) to obtain the corresponding aldehyde (purity ⩾ 98%).

X-ray diffraction (XRD) analyses were carried out with a Philips PW 1050/81 diffractometer (40 kV, 25 mA), equipped with a PW 1710 unit, and Cu-K_α radiation ($\lambda = 0.154118$ nm). A 2θ range from 10° to 80° was investigated at a scanning rate of 0.10°/s. BET surface area and porosity values were determined by physical adsorption of N_2 at 77 K, with a Micromeritics Asap 2020. FT-IR spectra were collected in the range of 4000–400 cm^{-1} with a Perkin–Elmer 1750 spectrometer, with the use of samples diluted in KBr (0.2:99.8 wt/wt). The catalyst surface acidity was determined with a ThermoQuest TPD/R/O 1100 equipped with TCD. The samples were pretreated under a 100 ml/min He flow at 673 K for 60 min, then at 433 K 10 pulses of NH_3 were added, and the samples were maintained at this temperature for 60 min, to favour the elimination of the physically adsorbed NH_3. Finally, under the same He flow, the samples were heated from 433 to 823 K (heating rate 10 K/min) and maintained at the latter temperature for 60 min.

The catalytic tests ($T = 583$ K, GHSV (gas hourly space velocity) $= 2900\ h^{-1}$; $H_2/H_2O = 20{:}80$ v/v; LHSV $= 1.6\ h^{-1}$; amine/diol = 1:1 mol/mol) were carried out in a fixed-bed glass micro-reactor (i.d. 7 mm, length 400 mm) placed in an electronically controlled oven and operating at atmospheric pressure. The isothermal axial temperature profile of the catalytic bed during the tests was determined with a 0.5-mm J-type thermocouple, sliding in a glass capillary tube. The organic feed and H_2O were introduced by two Infors Precidor model 5003 infusion pumps, and the gas composition and flow were controlled with Brook mass flow meters. After 1 h of time on-stream to reach stationary conditions, the products were condensed in two traps cooled at 268 K and collected in methanol, with tridecane as an internal standard. The analyses were carried out